The French-Czech-Slovak Winter School
&
DELISA-LTO Workshop II

Application of non-destructive testing (NDT) methods in characterization of long-term treated NPP design materials

DELISA LTO

AMBASSADE DE FRANCE EN SLOVAQUIE | INSTITUT FRANÇAIS Slovaquie | INSTITUT FRANÇAIS Prague | I2EN Institut international de l'énergie nucléaire | EDF | UNIVERSITY OF WEST BOHEMIA | STU SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE

10-14 February 2025, Kočovce Slovakia

The French – Czech - Slovak Winter University

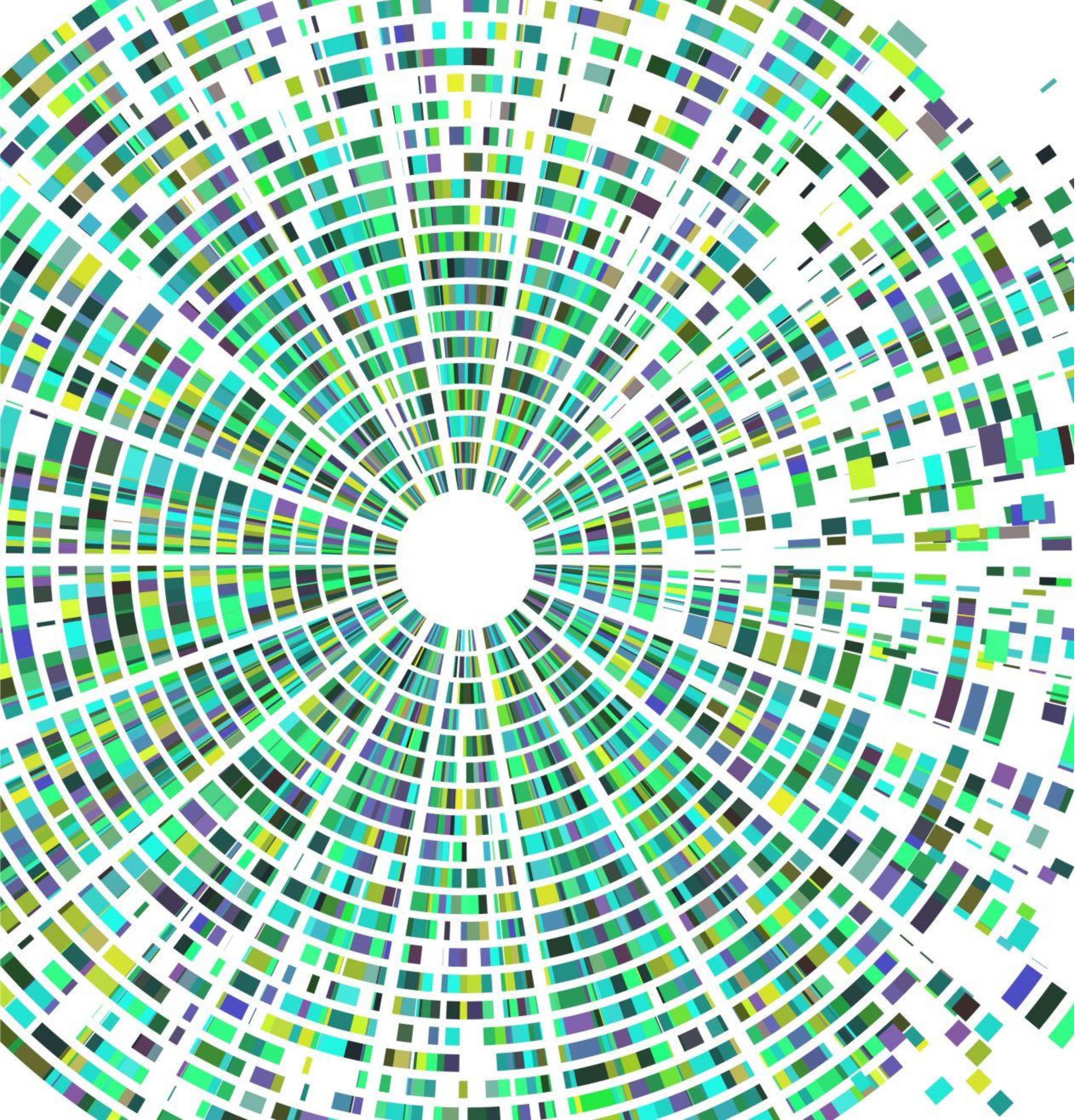
Workshop on *Application of non-destructive testing (NDT) methods in characterisation of long-term treated NPP design materials*

Monday 10th February 2025, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 841 01 Bratislava, A block, 6th floor, room A617

	8:40 - 9:40		**9:50 -** 10:40	10:40 - 11:30		**12:30 -** 13:20	**13:30** - 15:10		15:30 - 17:10	**17:30** 19:00
Monday	1. **Welcome speech** (French Embassy, STU)	Coffee break	2. International collaboration in material ageing for long-term operation (M. Berthelot, EDF)	3. Nuclear NDE – Part 1: Methods (A. Schumm, EDF)	Lunch	4. Nuclear NDE – Part 2: Modelling and Applications (A. Schumm, EDF)	**A group:** *Excursion*-AFM, MS, PAS (Pavuk, Dekan, Petriska) **B group:** Experiment with *Gama-Defectoscopy* (Stribrnsky)	Coffee break	**A group:** *Experiment with Gama-Defectoscopy* (Stribrnsky) **B group:** *Excursion* -AFM, MS, PAS (Pavuk, Dekan, Petriska)	Travel to Kocovce and Dinner

Tuesday 11th February 2025 – Friday 14th February 2025, Mansion in Kočovce

	8:00 8:30	**8:40** 9:30	9:30 10:20		**10:40** 11:30	11:30 12:20	12:30 13:30	**13:30** 14:20	14:20 15:10		**15:30** 16:20	16:20 17:10	17:10 18:00	**18:00**
Tuesday	Breakfast	5. DELISA-LTO project and NDT techniques (Slugen, STU)	6. Atomic force microscopy (Pavuk, STU)	Coffee break	7. Mossbauer spectroscopy (Dekan, STU)	Practical exercise: MS spectra fitting (Dekan, STU)	Lunch	8. Positrons in NDT (Krsjak, STU)	9. Magnetic Barkhausen noise (Degmova, STU)	Coffee break	Practical exercise: MBN measurement (Degmova, STU)	Practical exercise: PAS spectra fitting (Simeg, STU	Team project	Dinner **+ Welcome party**
Wednesday	Breakfast	10. Ageing of microstructure due to LTO / Simulation of structural integrity (Shugailo, UA)	11. Thermal ageing in NPP and its effect on Long-term operation (Zarazovskii, UA)	Coffee break	12. Eddy current testing (Benak, VUJE)	Practical exercise: ECT measurement (Benak, VUJE)	Lunch	**Social program:** Technical visit of SPA + Visit of Piešťany city or Wellness in Hotel Esplanade						Dinner
Thursday	Breakfast	Excursion to VUJE, a.s. (Non-destructive laboratories and metallographic analysis)					Lunch	Excursion to MTF STU Trnava (Accelerator laboratory, Sem laboratory)					Team project	Diner **+ Goodbye party**
Friday	Breakfast	13. LTO management and legislation (Kupca, SEAS)	14. Invited lecture - company FRAMATOME	Coffee break	Team project presentations	Closure Ceremony (French embassy in SK & CZ, STUBA)	Lunch	Departure to home						



Introduction

International Institute of Nuclear Energy

I2EN - Human capacity building for the future of nuclear

Workshop on Application of non-destructive testing (NDT) methods in characterisation of long-term treated NPP design materials

Mr Thibaud REYSSET
I2EN - Project Director

On the way to a Nuclear Renaissance

A global rising interest and confirmed nuclear activities for the French nuclear sector

- **Over 85 new reactors already planned and about 350 more are being proposed**
- **100,000 recruitments by the French nuclear sector in the next 10 years**

All projects will compete for the same critical skills and competencies

- Engineering (mechanical, electrical, process, safety, security, radioprotection…)
- Technical (welding, cabling, civil engineering…)
- Project (project management, quality control, …)

I2EN

Our Mission

Preparing human capital for the nuclear future

The International Institute of Nuclear Energy’s mission is to provide countries embarking on or expanding nuclear power programmes with access to the French education and training resources and to collaborate in building their own training capabilities.

I2EN

Our Network

I2EN Members and Partners

Members

Partners

MINISTÈRE
DE L'EUROPE
ET DES AFFAIRES
ÉTRANGÈRES
Liberté
Égalité
Fraternité

MINISTÈRE
DE L'ENSEIGNEMENT
SUPÉRIEUR
ET DE LA RECHERCHE
Liberté
Égalité
Fraternité

MINISTÈRE
DE L'ÉCONOMIE,
DES FINANCES
ET DE LA SOUVERAINETÉ
INDUSTRIELLE ET NUMÉRIQUE
Liberté
Égalité
Fraternité

Our Role

Your gateway to the world's leading nuclear experts

- **I2EN is a one-stop shop to access a training and education ecosystem forged by 60 years of French experience in developing, building and operating nuclear power plants**

➢ **Education**
- Bachelor, Master level (En/Fr)
- Student exchange programmes
- Summer schools
- I2EN quality seal

➢ **Training**
- Senior officials and Industry executives
- Civil servants
- Personnel of *embarking* and *expanding* countries
- Train-the-trainers

➢ **And also**
- Study tours
- Access to training centers

Our Ambition

Advancing Excellence and Strategic Leadership

The I2EN Seal

- ✓ Certifies the quality of academic nuclear training programs in France
- ✓ Attests to their relevance to the needs of industry and R&D organizations
- ✓ Showcases the France's best nuclear educational and training programs

- Accredited by a Committee of Experts
  - Recognized experts in their field
  - Representing both academy and industry

The I2EN Master Class

- ✓ Comprehensive and modular program mixing knowledge and practical insights
- ✓ Providing high-level training on strategic issues to future leaders of the nuclear sector
- ✓ Embedding real-world examples and leveraging France's nuclear experience

- Delivered by highly experienced professionals
  - Experts from the major key players
  - Representing the French nuclear ecosystem

Our Events

Selection of upcoming activities for 2025

- **French-Czech-Slovak Winter School**
  February 10 – 14, 2025, Kočovce, Slovakia

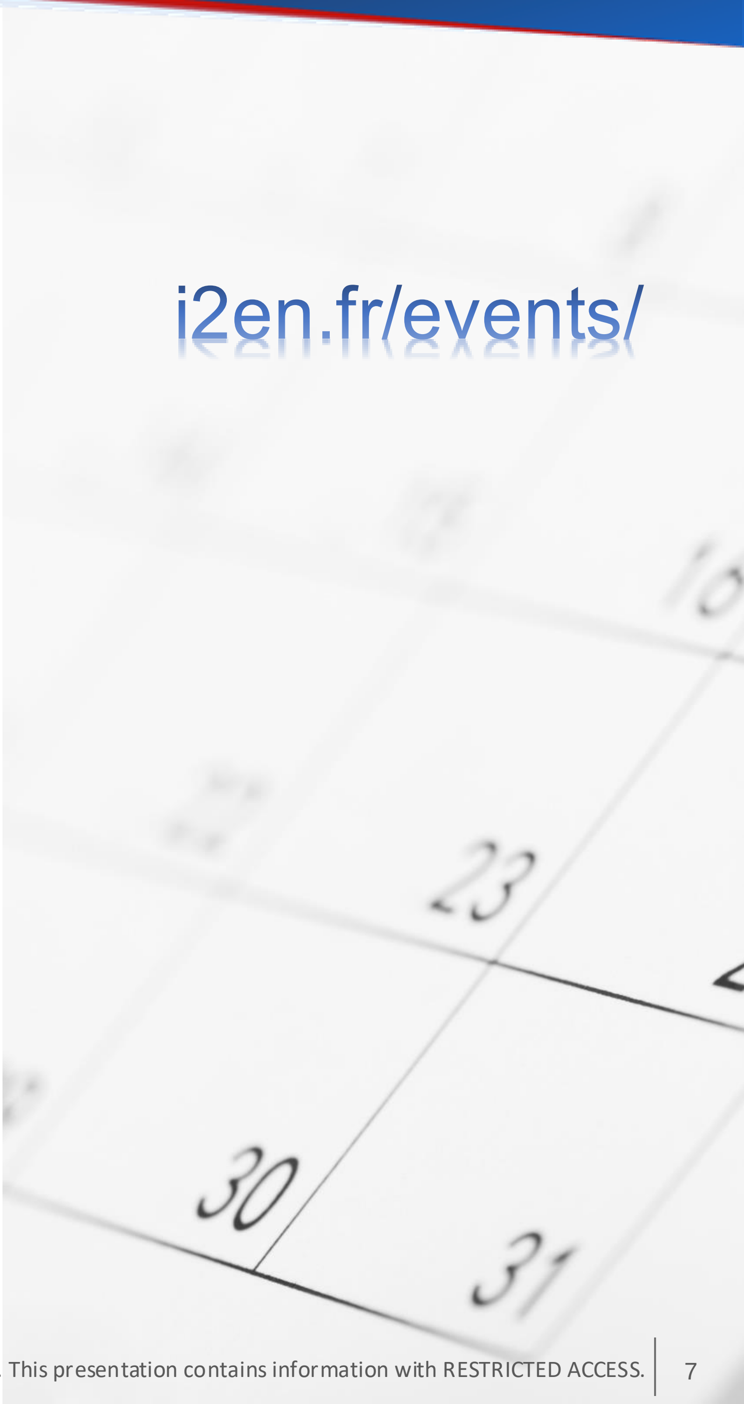
- **French Nuclear Industry Day**
  March 14, 2025, Paul Scherrer Institute (PSI), Villigen, Switzerland

- **I2EN Master Class on Strategic Fundamentals for New Nuclear**
  June 23 – 27, 2025, Paris, France

- **IAEA ITC on Human Resource Management for New and Expanding Nuclear Power Programmes**
  August 25 – 29, 2025 (TBC), Paris, France

- **ESTA – European SMR/AMR Training Academy**
  October (TBD), 2025, Cadarache, France

i2en.fr/events/



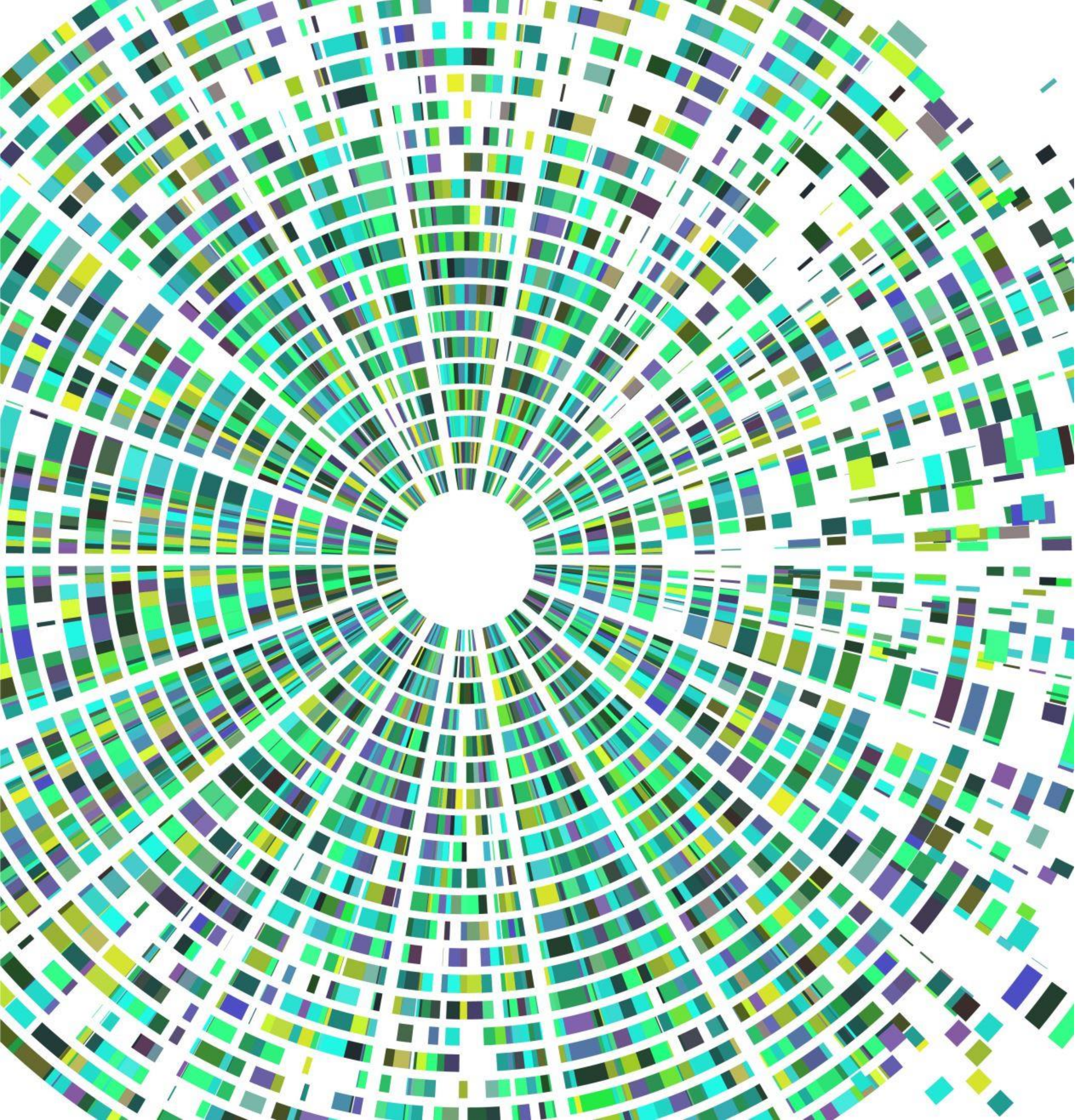
I2EN

I2EN
International Institute of Nuclear Energy

Thank You
Merci

Let’s build capacity for the nuclear future

contact@i2en.fr
www.i2en.fr



Monday's presentations

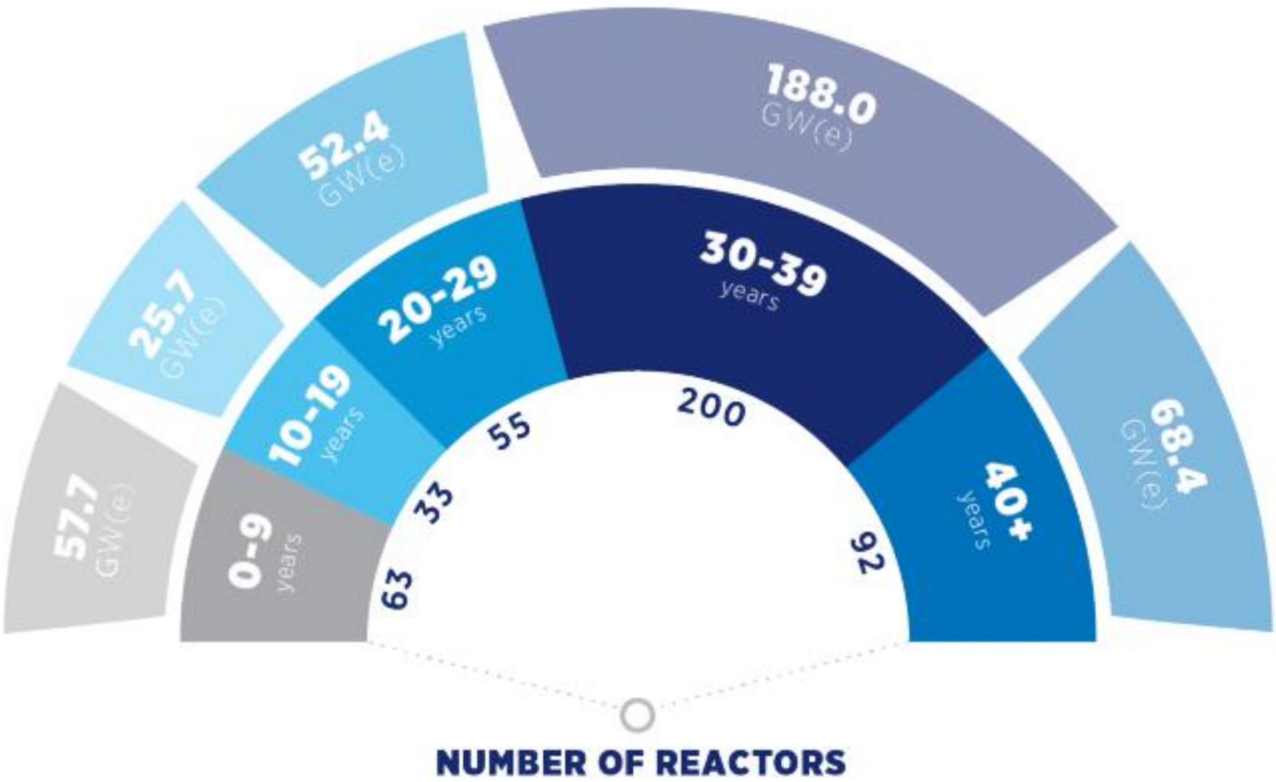
Application of non-destructive testing (NDT) methods in characterisation of long-term treated NPP design materials

Prof. Vladimír Slugeň, DSc.

Institute of Nuclear and Physical Engineering, Slovak University of Technology, Ilkovičova 3, 81219 Bratislava, Slovakia

Introduction to 2nd DELISA-LTO Workshop, Kočovce, Slovakia, February, 10-14, 2025

Distribution of operating reactors in the world by age

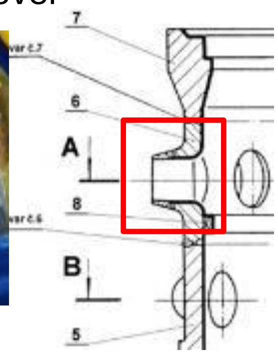


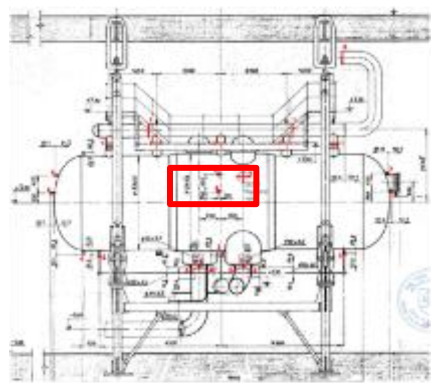
Project HORIZON-EURATOM-2021-NRT-01-01
Project start 1st June 2022
DELISA LTO
DEscription of the extended LIfetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety
Project end 31st May 2026
VVER reactors
Thermal ageing
Non-destructive techniques
Modelling
Lifetime extension

Samples from NPP V1

Bolts of RPV cover

RPV nozzles



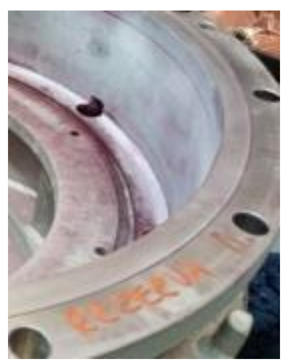


Pressurizer Surge Line

Pressurizer

Main circulation pipeline

Main circulation pump



RPV cover

Outline

- Various aspects of radiation environments foreseen for nuclear design materials were experimentally simulated via ion implantation and studied by a combination of non-destructive characterisation techniques and compared to neutron treatment.

- As-received steels
- Neutron irradiated steels
- Hydrogen implanted steels
- Helium implantation (swelling)
- Thermal aging
- Corrosion, stress corrosion, …

Non-destructive testing

- Effective tool for evaluation of structural changes
- No changes in design required
- Evaluation of defects via long-term and regular applications (surveillance specimens)
- Possible round-robin testing
- High scientific acceptance

Available techniques for material studies:

Positron Annihilation Spectroscopy: Conventional PALS 2-det. or 3-det. Set-ups (for irradiated materials), digital Doppler Broadening set-up, *experiences with PLEPS measurements at FRM-II in Garching from past*

Moessbauer spectroscopy,

Atomic force microscopy,

X-ray diffraction, Barkhausen Noises measurements,

Alfa, beta, gamma spectroscopy including low/background chamber,

In collaboration with other institutes:

TEM, SEM and Auger spectroscopy

Thank you!

Acknowledgement

Author acknowledge support from EC-project No-101061201 DELISA-LTO.

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materials ageing institute

Collaborative R&D to support Long Term Operation

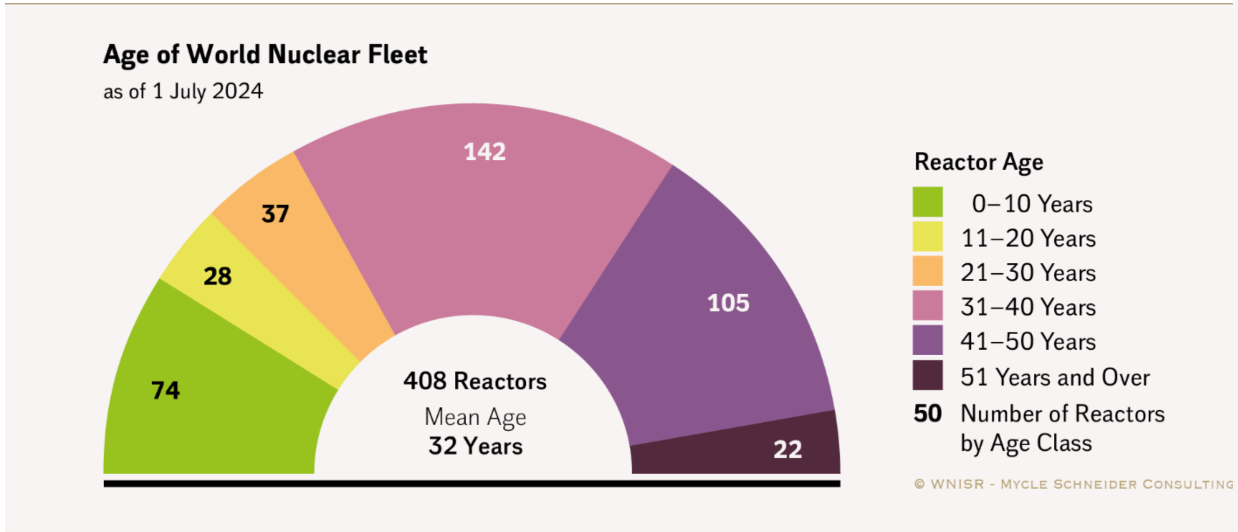
Marie BERTHELOT - MAI Director
marie.berthelot@edf.fr

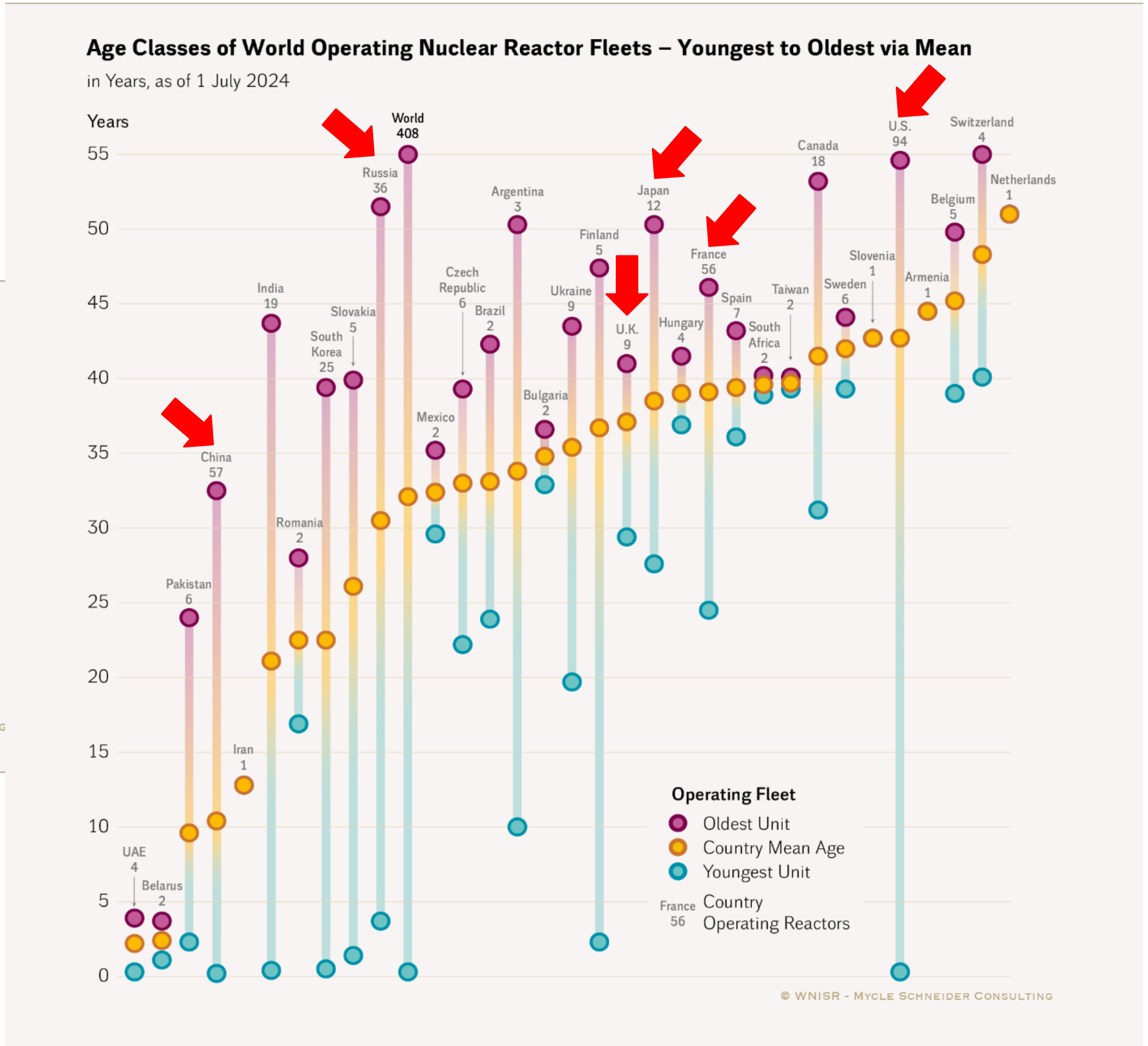
The French – Czech - Slovak Winter University – February 2025

Agenda

- Nuclear context
- R&D to support LTO 60+
- MAI organisation and objectives
- MAI Members' nuclear fleet
- Mission of the MAI

Global overview of Worldwide reactors age & Focus on French fleet





Sources: WNISR, with IAEA-PRIS, 2024

MAI Members' Nuclear Fleet

Thousands years of reactor operating experience

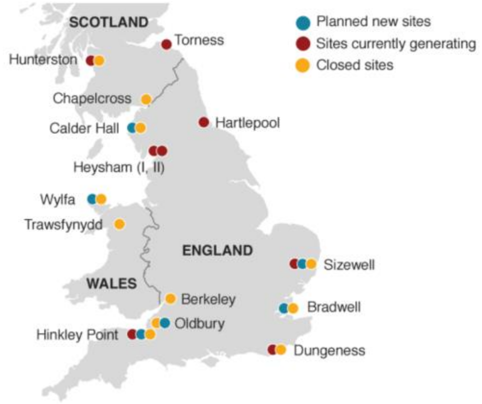
materials ageing institute

US

42 94 41 43 19

UK

2 9 36 37 13



China

27 57 1 10 5

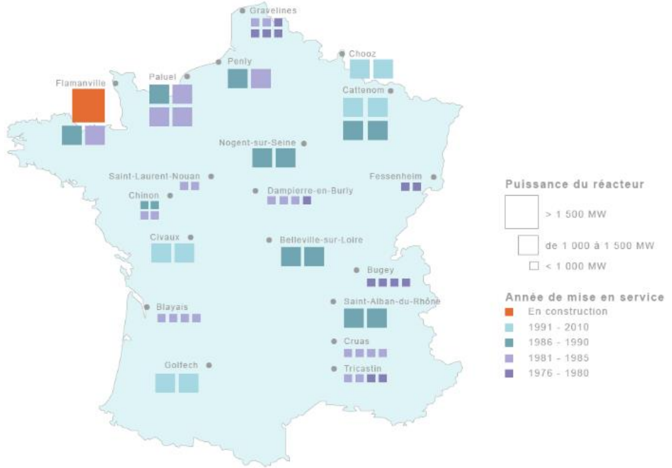
RUSSIA

12 6 36 11 30 18

Collaboration with Russia stopped since Feb 2022

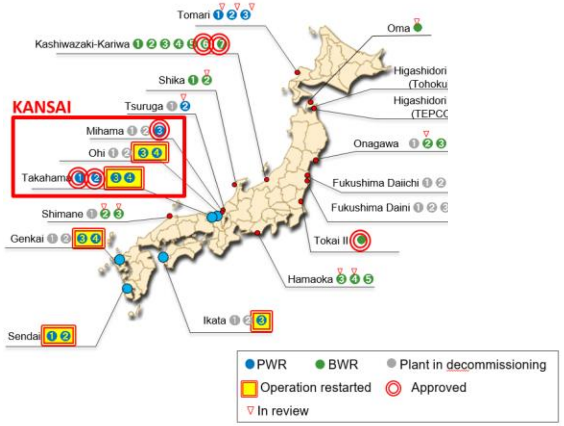
FRANCE

1 56 14 39 65



JAPAN

1 1 12 21 27 33 6



French Nuclear Fleet

The French nuclear fleet

- 18 nuclear power plants - 57 PWR in operation
- PWR Homogeneous fleet : 32 x 900 Mwe
  20 x 1300 Mwe
  4 x 1450 Mwe
  1 x 1650 Mwe
- 1 EPR in operation

Age

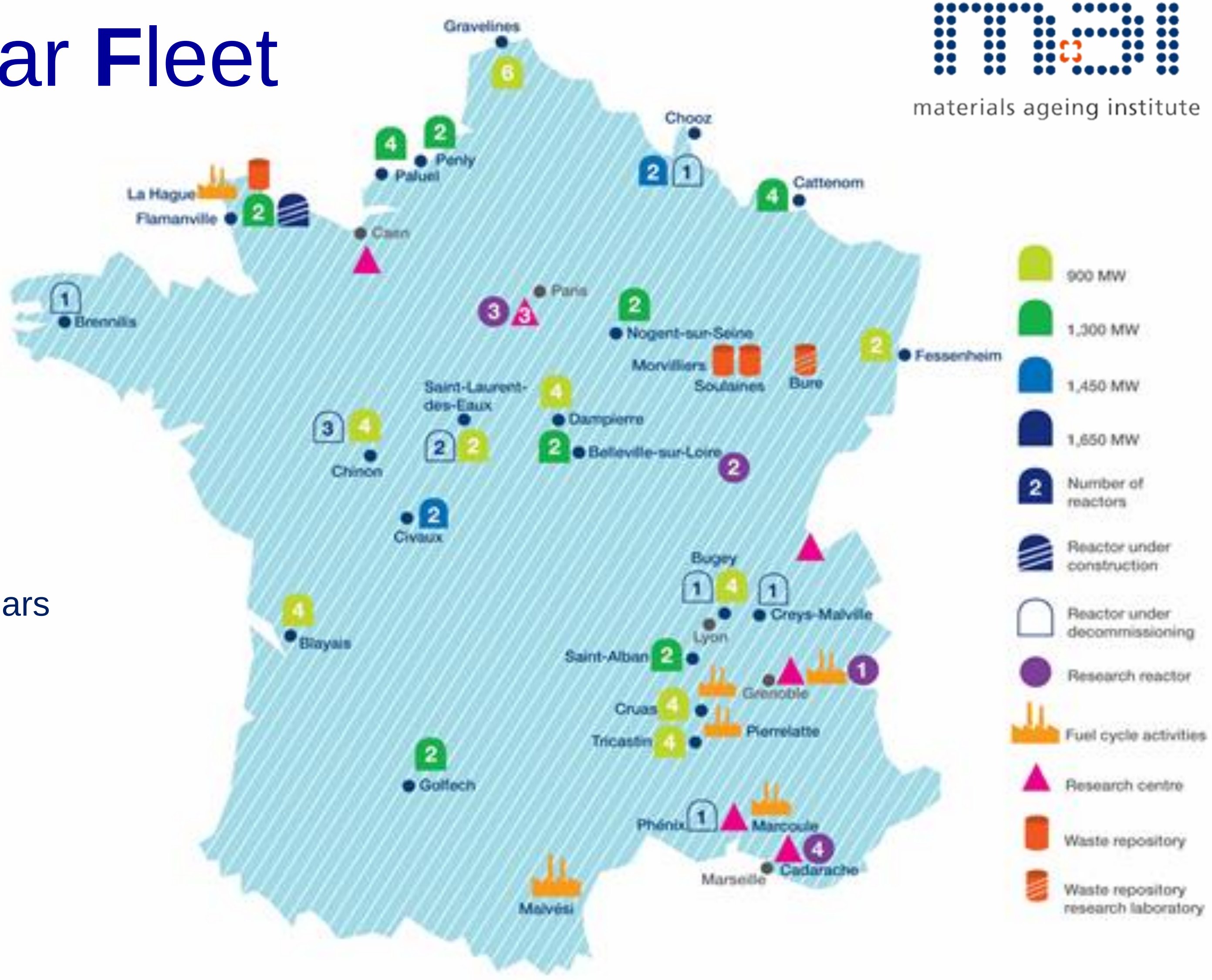
- Average of 38 years ; 17 units are older than 40 years

Fleet’s lifespan

- No technical or regulatory limitation
- Every ten years a specific authorization must be granted by the regulator

The largest LTO Program in the world

- 49,4 billions €
- Mobilization of EDF Engineering divisions and R&D as well as major contractors and vendors



Renewed interest for nuclear energy as independent energy : “life extension as long as safe “
+ New EPR reactors planned

French Energy Landscape in 2050

- **Announcement of the French President in Belfort – Feb. 2022 : "**Within 30 years, make France the first major country in the world to end its dependence on fossil fuels and strengthen our energy independence while setting an example in terms of climate care"

- As part of EDF ambition to be a major actor for decarbonated energy, EDF aims at having a sustainable fleet

Consume less energy and be more energy efficient -40% of energy consumption by 2050	Produce more low-carbon energy +60% additional electricity by 2050	EDF industrial Programs To support the energy transition

Industrial & residential energy efficiency – Reduction of fossil fuels – Uses electrification

Development of one of the major hydrogen industrial pole

Development of Renewables & Batteries in France

Development of renewable energies
Consolidation of nuclear fleet

LTO > 60 years

> 25 GW by 2050 out of which 6+8 EPR2 and SMR

100 GW

40 GW

37 GW

GRAND CARÉNAGE Phase 2

EPR2

NUWARD

LE PLAN MOBILITÉ ÉLECTRIQUE

LE PLAN excell Excellence nucléaire

LE PLAN HYDROGÈNE

LEPLANSOLAIRE

The R&D to support LTO 60+

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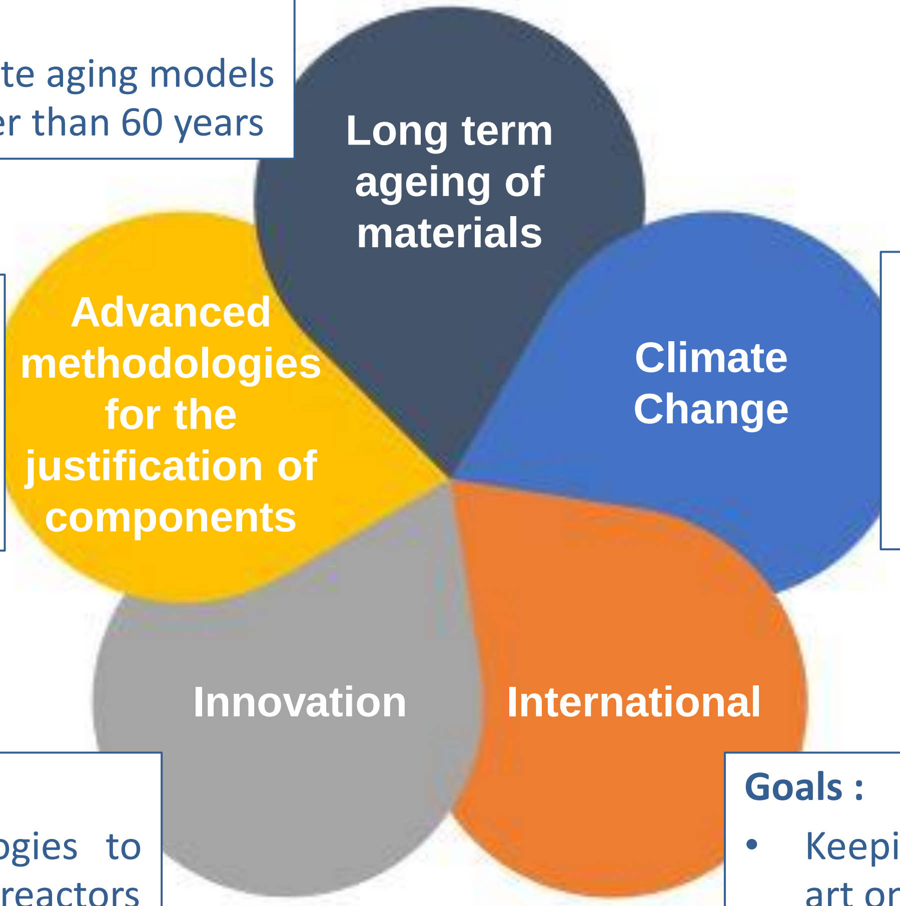
Main areas of development

Goals:

- Acquire aging data, verify the absence of deleterious effects at LT
- Develop, verify and validate aging models for operating times greater than 60 years



Goals:

- Licensing of methods determining the available margins in a more realistic manner for the justification of components and civil works

Goals:

- Adapting global scenarios to local scales
- Assessing the resilience of nuclear power plants to climate change
- Propose adaptation solutions

Goals:

- Use the best available technologies to secure the long-term operation of reactors
- Benefit from new technologies developed outside the nuclear sector

Goals :

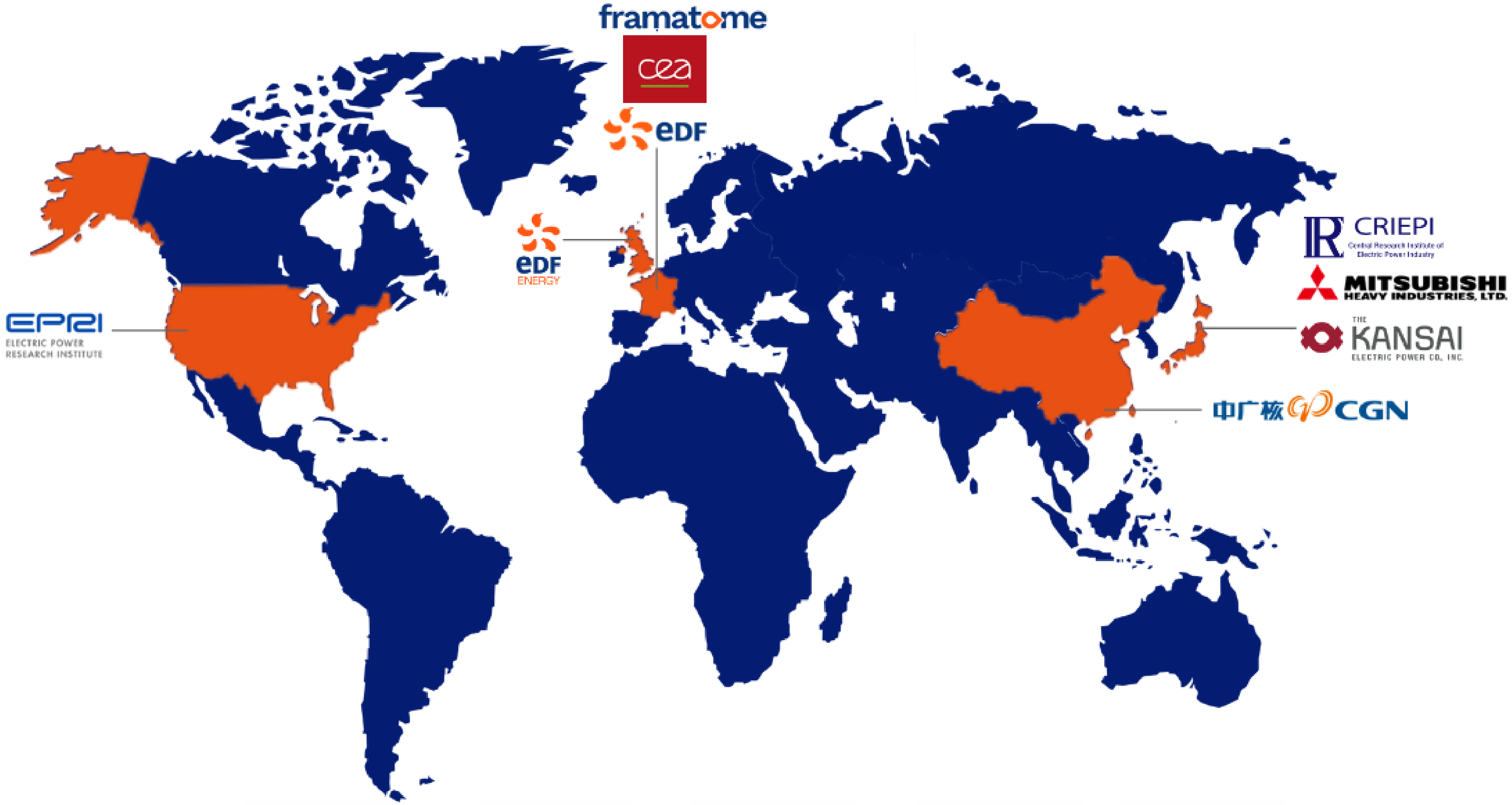
- Keeping up to date with the state of the art on issues related to operating life
- Have scientific and strategic relays outside France

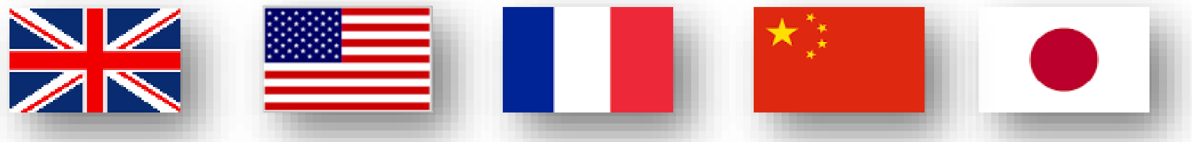
Material Ageing Institute

- In 2020, 33% of the world's nuclear fleet was 40 years old (80% in 2030)
- Materials issues have by far the largest impact on plants' safety, performance & availability
- Need to understand and anticipate the degradation of key components' materials
- Large R&D efforts needed to achieve these goals
- Importance to share knowledge and R&D efforts at international level

Material Ageing Institute

A unique collaborative institute led by nuclear utilities





MAI members & organisation

Created 15 years ago, the MAI is now an **international center of excellence** on materials ageing, gathering **utilities**, **vendors**, and **research centers** from worldwide.

The main purpose of this collaborative effort is to bring together scientific skills and research facilities to address aging of material used in nuclear power plants

The institute is led by the French nuclear EDF

A collaborative approach by sharing research experimental results, feedback and scientific information

All current members joined the institute between 2008 and 2011

Missions of the **MAI**

Safe Long Term Operation of NPPs

Knowledge-based management of materials and components

Centralize and coordinate R&D

Feedback from NPPs, data, methods and models

Improve fundamental knowledge

Study ageing mechanisms with the help of state-of-the art experimental tools and capabilities

Training & Education

Train our next generation: courses, workshops and seminars in the field of material ageing

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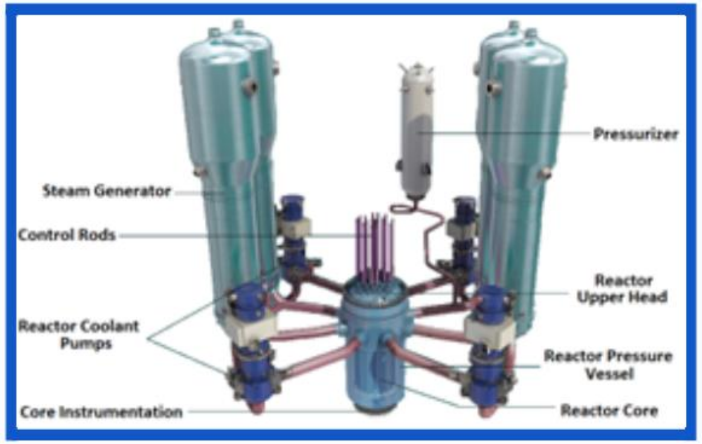
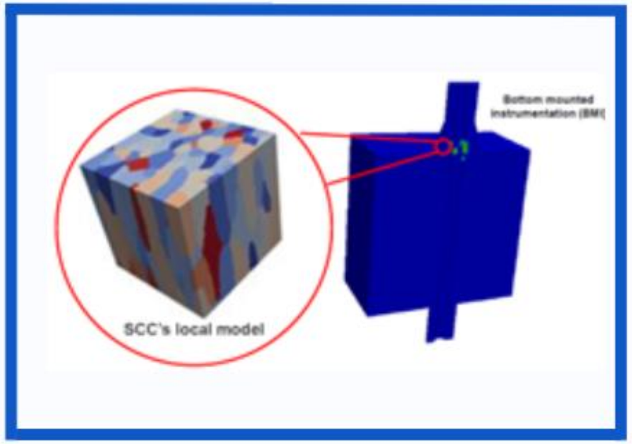
MAI Research Topics

- Non-replacable components
- Difficult or expensive components to replace
- Chemistry in the primary and secondary circuits
- Degradation and ageing mechanisms
- Non-Destructive Examinations
- Innovative processes





MAI means and created value

100 M€ of cumulative budget over the last 10 years

~100 researchers workforce all over the world

~40 technical reports / year and end-user Tools

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MAI Application Network

MAI / SNPI Seminar on LTO research & code applications, Suzhou, China, Dec. 2024

- Share research findings on material aging and the latest advancements achieved by each team. Discuss the new contributions of CGN in the MAI. Visits of CGN laboratories.

MAI-AN Seminar with Japanese utilities, MHI & CRIEPI, Japan, May 2024

- Workshops showcasing the MAI's advanced research on materials used in the nuclear field that could significantly impact the safety operations of nuclear power plants. These workshops highlighted how the MAI's research activities are specifically designed to meet the needs of nuclear engineers and operators.

MAI nuclear seminar with EDF UK R&D, Londres, May 2024

- The objectives were to build a common understanding of UK Nuclear challenges and MAI skills and capability, to positively influence the forward direction of the MAI programme, to identify areas of common interest for value added joint-working.

MAI-AN report published every year

- Examples of MAI deliverables added value for the members.

Missions of the **MAI**

Safe Long Term Operation of NPPs

Knowledge-based management of materials and components

Centralize and coordinate R&D

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Improve fundamental knowledge

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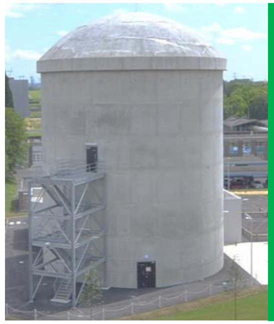
Experimental Facilities at **EDF Lab**

~80M€ Investments in experimental facilities at EDF Lab



VERCORS

Studying in an accelerated way the concrete's behavior and the structure of the inner containment of a reactor building (aging, deformation and sealing*)*

Cold Spray

Making metal deposits by projecting powder at very high speed. This additive manufacturing process is used for applications to repair damaged parts or build coatings.

Fatcor 2

Studying the fatigue and corrosion properties of nuclear reactor materials in the primary environment.

Energie Loop

Identify the fouling mechanisms of pressurized water power plant steam generators and the kinetics of deposit formation under different operating conditions.

BOREAL

Primary water chemistry mockup dedicated to the Release of steam generator tubes in Primary water

Microscopie Electronique

Understanding the aging of materials by focusing on the microstructure and local chemical composition of materials by electronic microscopy.

See other members' facilities on https://themai.org/research-capabilities/

MAI-Scientific Network

- Create a strong and active link between partners and MAI research activities
- Contribute to a common knowledge base focused on the methods and approaches required by MAI members
- Address scientific questions on ageing and related processes of materials used in electricity producing plants
- Establish scientific exchanges between the partners for the benefit of common objectives

In Collaboration with

Tohoku University

Manchester, Oxford, Bristol, Open Universities

Matcalc

Montréal, Sherbrooke Universities

Xian University

CIEMAT

Research Centers (CNRS, CEA, ARMINES, ...)

Universities (Rouen, Lille, Paris, Loraine,Sorbonne, ...)

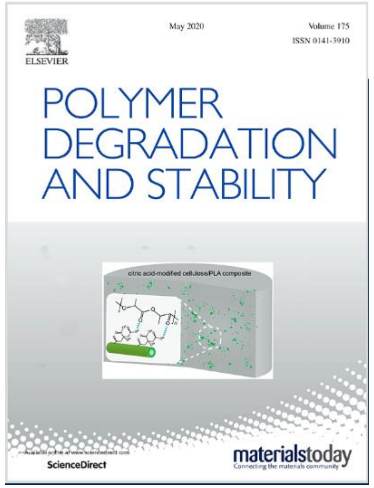
Engineering Schools (ParisTech, Mines, Ponts, Chimie, Arts et Métiers, Polytechnique, INP-Grenoble, INSA-Lyon...)

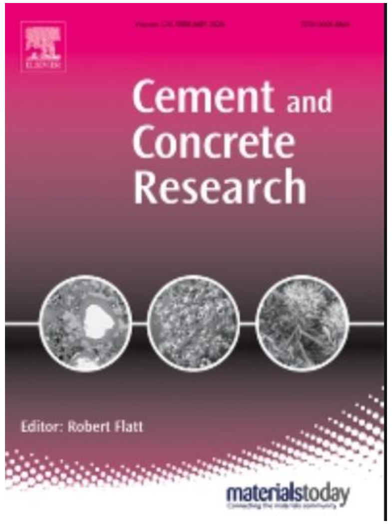
Universities (Michigan, MIT, ...), ORNL

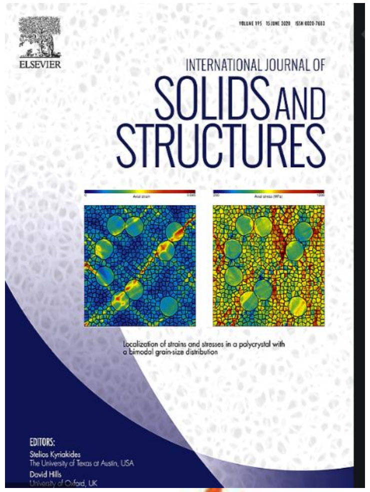
MAI-SN Publications

Publication of the MAI Handbook, **“Materials Ageing in Light-Water Reactors – Handbook of destructive assays ”, S**pringer – July 2022

- *Public version of the well-known handbook of destructive examinations funded by the MAI*
- [Handbook of material ageing management for nuclear reactors - The MAI]







Missions of the **MAI**

Safe Long Term Operation of NPPs

Knowledge-based management of materials and components

Centralize and coordinate R&D

Feedback from NPPs, data, methods and models

Improve fundamental knowledge

Study ageing mechanisms with the help of state-of-the art experimental tools and capabilities

Training & Education

Train our next generation: courses, workshops and seminars in the field of material ageing

Training & Education

MaNuEn master organised at the MAI, February 2025

- This master is a 2-year programme for students wishing to work in the nuclear industry, in R&D or for research organisations. MaNuEn covers the specificities of materials used in nuclear environment with a particular focus on their durability under irradiation.

MAI workshop on Micromechanics of cementitious materials, France, Sep, 2023

- This short course proposes an introduction to basic principles of micromechanics and some applications to civil engineering issues.
- The aim of this workshop is to provide an international forum for reporting progress and recent advances in micromechanics and its applications to cementitious materials, and to foster collaborations on these techniques.

MAI conference on European Network for Inspection and Qualification, March 2023

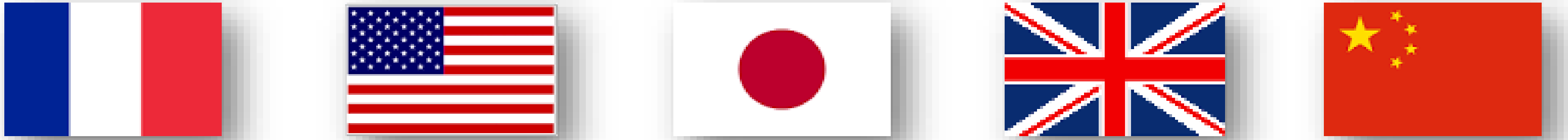
- ENIQ is a utility driven network dealing with the reliability and effectiveness of non-destructive testing for nuclear power plants and is recognised as one of the main contributors to today's global qualification codes and guidelines for in-service inspection.

Thank you

materials ageing institute

Getting the best of what materials can give

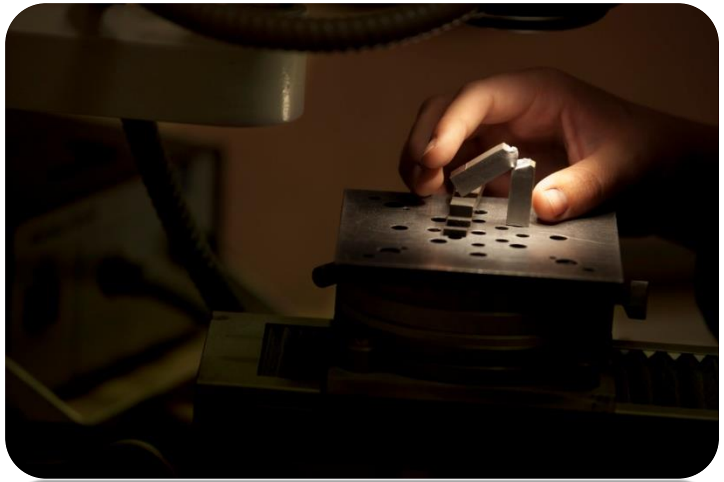
http://themai.org/



eDF

NDE for nuclear components

Winter University 2025



Andreas Schumm

EDF R&D/MMC

Outline

- Definition, key figures, actors
- ~~Regulatory Environment~~
- Defects
- Local vs. Global methods
- Acoustic emission
- Ultrasound
- Radiography
- Eddy Current
- ~~Dye Penetrant and Magnetoscopy~~
- NDE Modelling
- *Applications*

Definition

- Non Destructive Testing (NDT) refers to a set of of methods to assess the integrity of industrial components, without damaging them, either during manufacturing (NDT) or during operation (NDE).
- These methods are intensively used in:
  - the automotive industry (engine inspection)
  - the naval industry (hull inspection)
  - aviation (airplane wing, engine, landing gear, etc.)
  - Energy (vessel, pipe, turbine, etc.)
  - rail transport (axles, wheels, etc.)
  - other industries (civil engineering works, etc.)

Nuclear NDT

- **Some key figures**
  - For EDF, NDE represents 10 to 12% of the total maintenance cost of nuclear power plants (150 M€/year)
  - Steam generator inspection = 40% of yearly amount
- **Actors**
  - EDF (plant operator)
  - Service Providers (Carrying out the actual NDT – Framatome, Westinghouse, Cegelec, …)
  - Nuclear Safety Authorities
- **Highly regulated Environment**
  - Inspection Interval, Coverage, Qualification, Surveillance, Archival…

What are we looking for?

- Defects occuring during manufacturing (NDT)
  - Forging : center thinning…
  - Casting : cracks, shrinkage cavities, …
  - Welding : underclad defect, gas cavities , slag inclusion, incomplete fusion, lack of penetration, cold cracking, hot cracking, …
- Defects occuring during plant operation (NDE)
  - Ageing
  - Creep, Fatigue
  - Corrosion
  - SCC
  - Combined mechanisms (corrosion of radiation hardened materials in agressive medium under stress…)

Local vs. Global methods

Global

Visual testing
Acoustic emission
Thermography

Local
Surface-bound

Dye Penetrant
Magnetoscopy

Eddy current

Local
volume

Radiography
Ultrasound

***NDT Handbook*, third edition [in print]**

Vol. 1, *Leak Testing*
Vol. 2, *Liquid Penetrant Testing*
Vol. 3, *Infrared and Thermal Testing*
Vol. 4, *Radiographic Testing*
Vol. 5, *Electromagnetic Testing*
Vol. 6, *Acoustic Emission Testing*
Vol. 7, *Ultrasonic Testing*
Vol. 8, *Magnetic Testing*
Vol. 9, *Visual Testing*
Vol. 10, *NDT Overview*

Ultrasound NDT: The Pulse Echo Method

May 27, 1940: Dr. Floyd Firestone (U Michigan) applies for patent for the first practical ultrasonic testing method

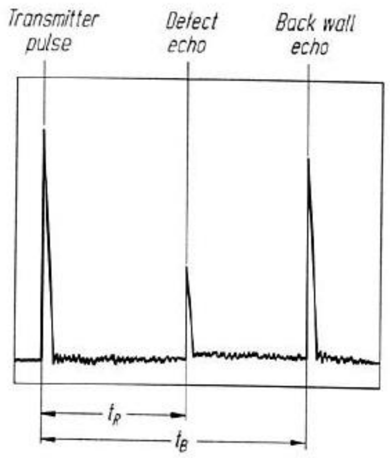
"My invention pertains to a device for detecting the presence of inhomogeneities of density or elasticity in materials. For instance if a casting has a hole or a crack within it, my device allows the presence of the flaw to be detected and its position located, even though the flaw lies entirely within the casting and no portion of it extends out to the surface.

The general principle of my device consists of sending high frequency vibrations into the part to be inspected, and the determination of the time intervals of arrival of the direct and reflected vibrations at one or more stations on the surface of the part."

The Pulse Echo Method

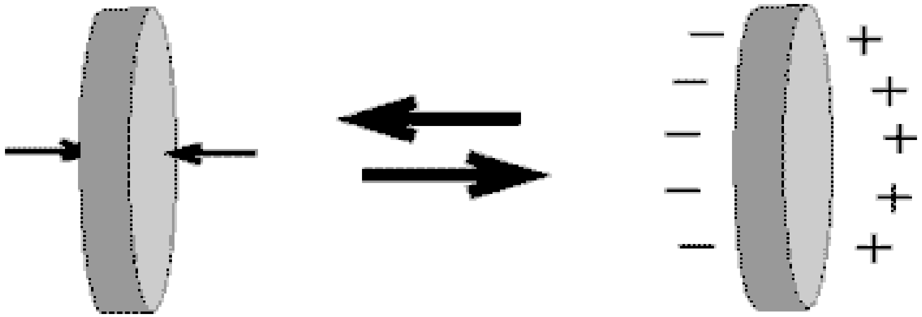
Defect detection and positioning using travel time and amplitude information

- Combined or separated transmitter and receiver
- Defect sizing possible to a certain extent
- Requires surface preparation and couplant
- Firestone used longitudinal waves with normal incidence
- Independently also discovered in England (Sproule) and Germany (Kruse)
- Spun of the wall thickness measurement device
- Commercial success (Sperry Inc. Danbury, USA, Kelvin-Hughes Ltd London, Krautkrämer, Hürth)

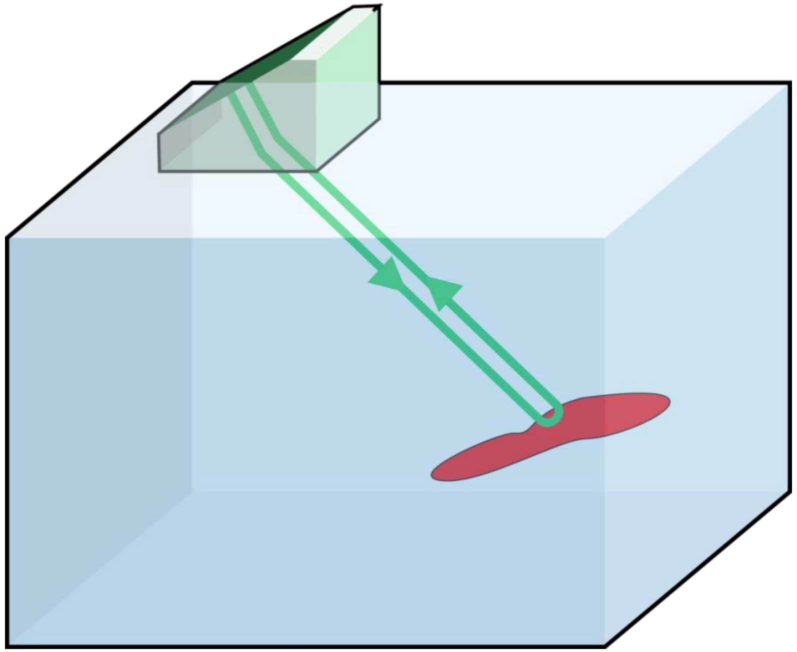


Ultrasonic testing - principle

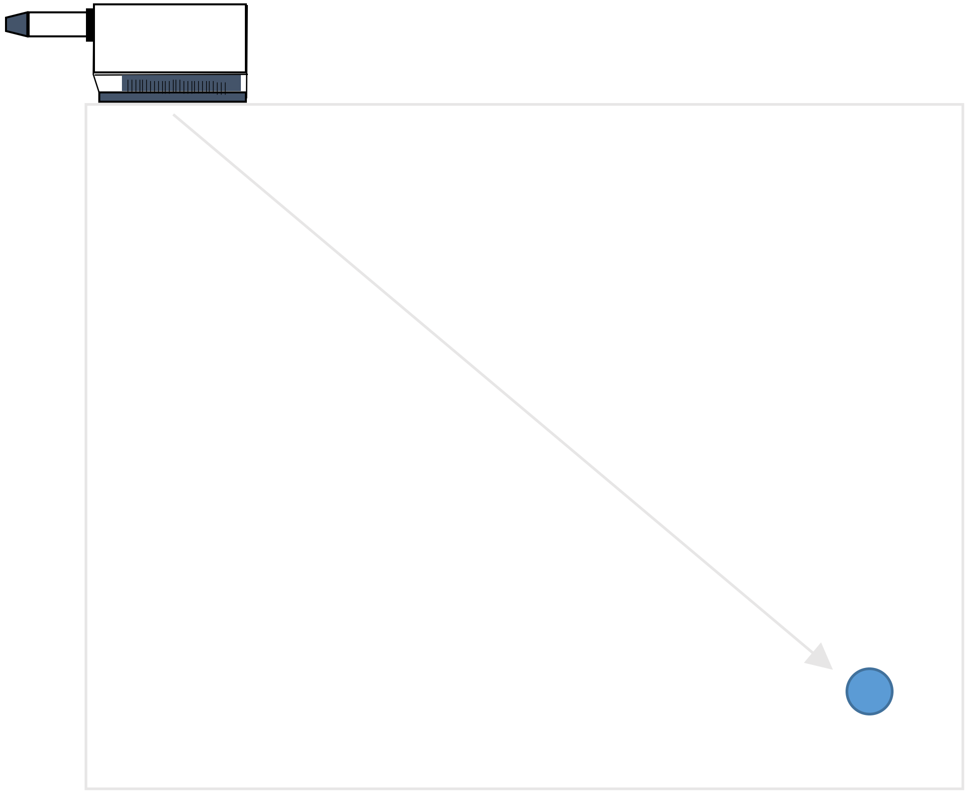
Electric pulse ⇄ Piezo-electric or piezo-composite crystal ⇄ Elastodynamic wave

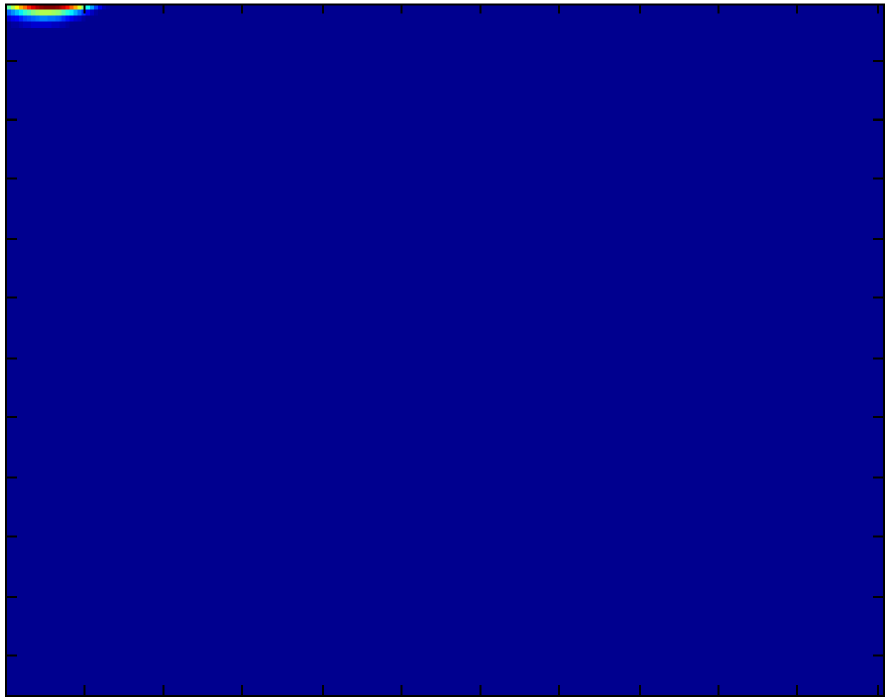


Transmission and reflection of a wave in the inspected block



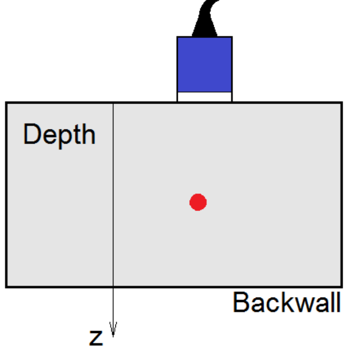
Ultrasonic testing - principle

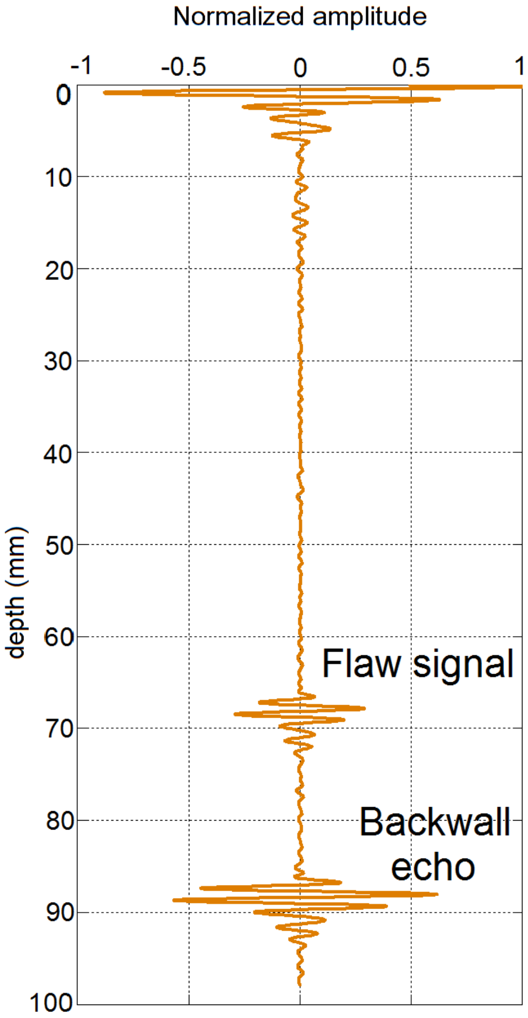


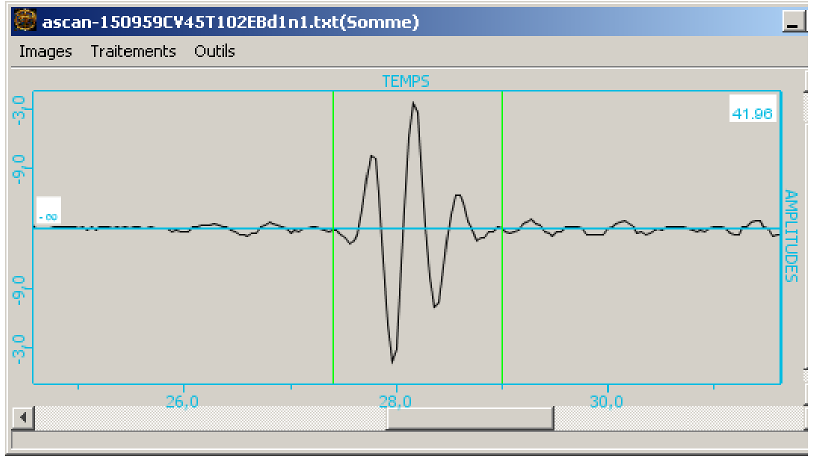


Ultrasonic testing - principle

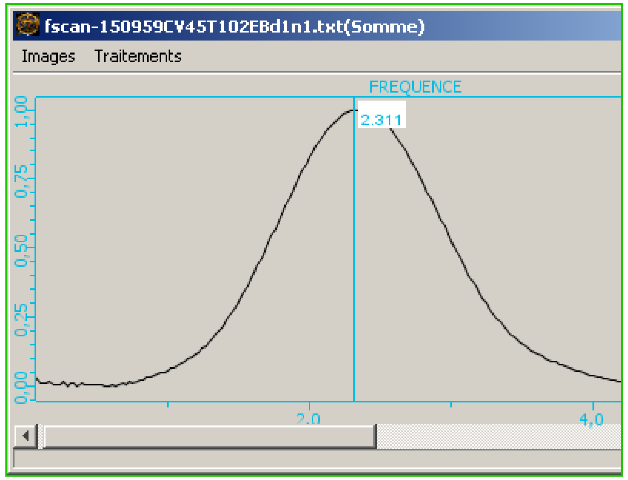
- Inspects an entire volume
- With high spatial resolution
- Relatively slow due to scanning
- **Defect location and sizing capability**







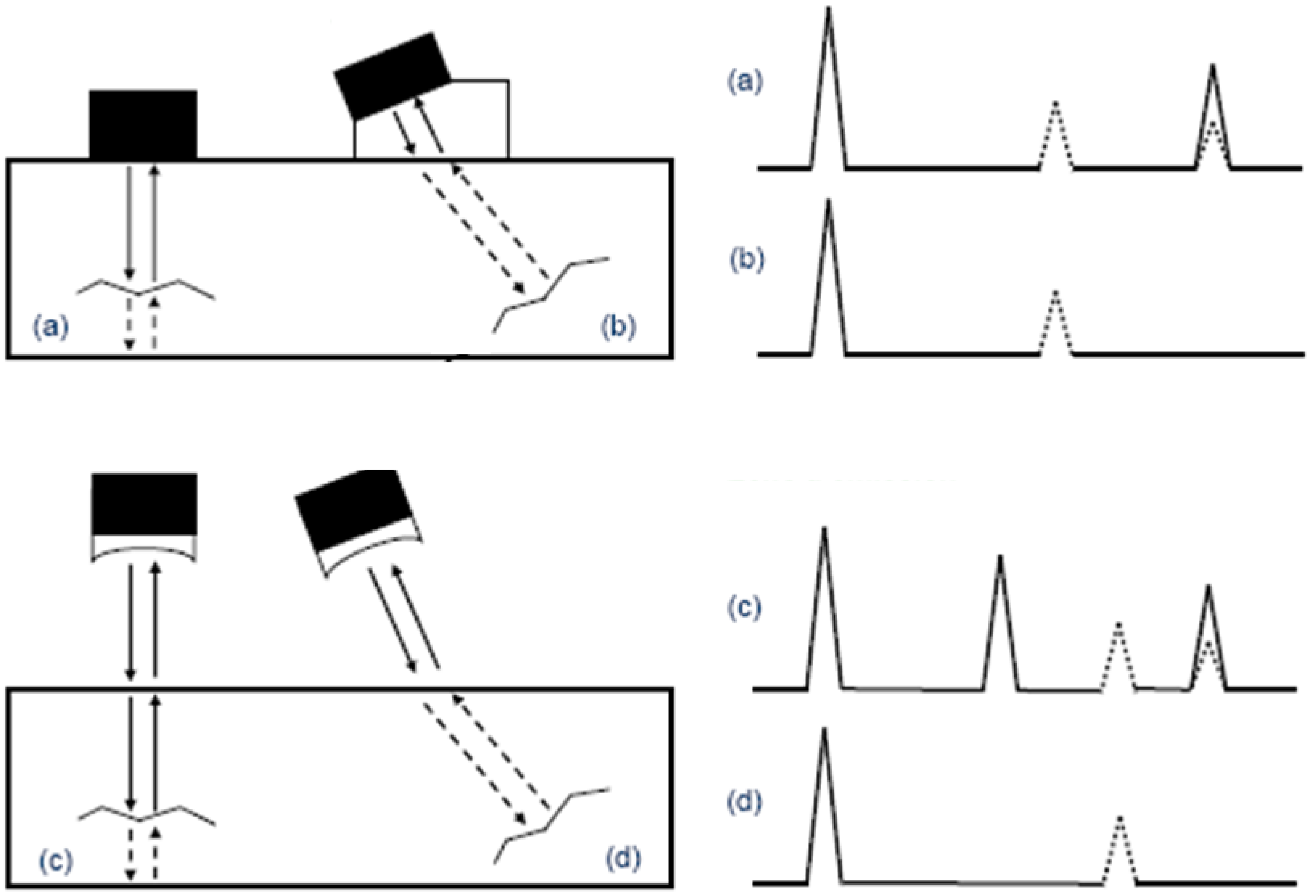
Broadband signal



Defect location and sizing

contact

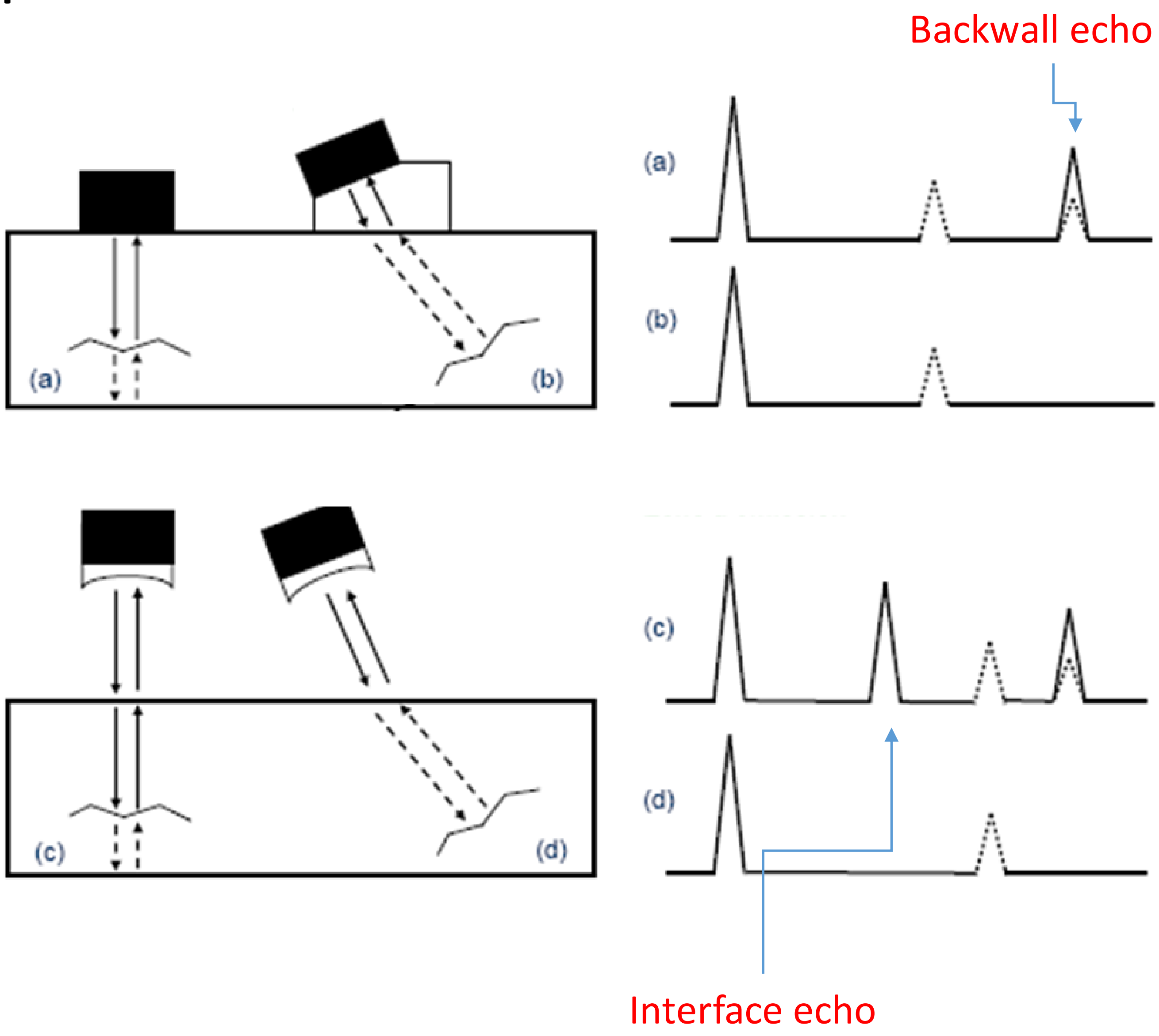
immersion



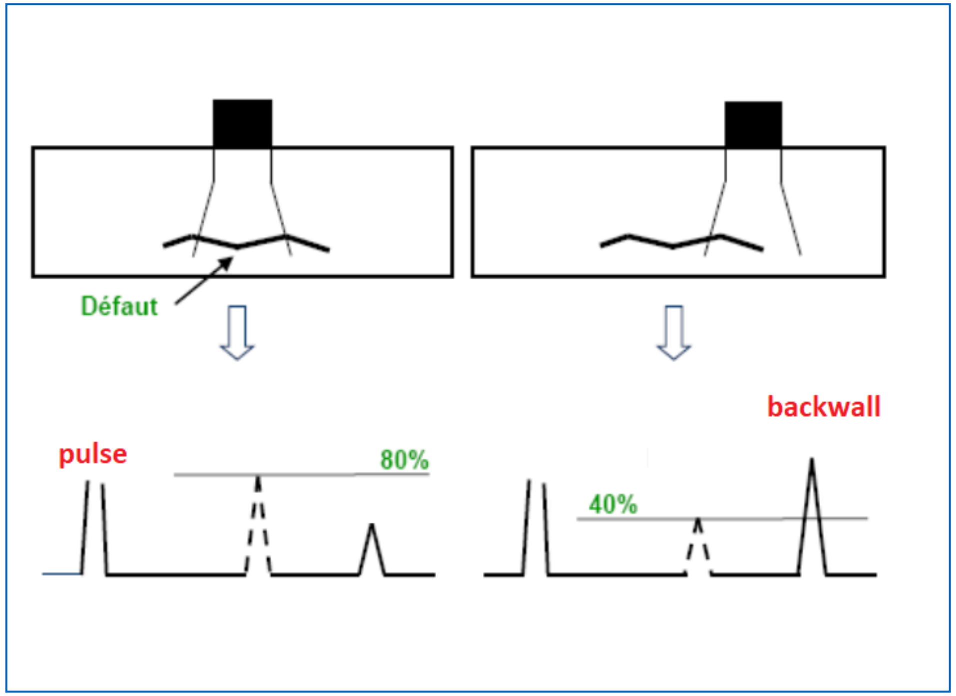
Defect location

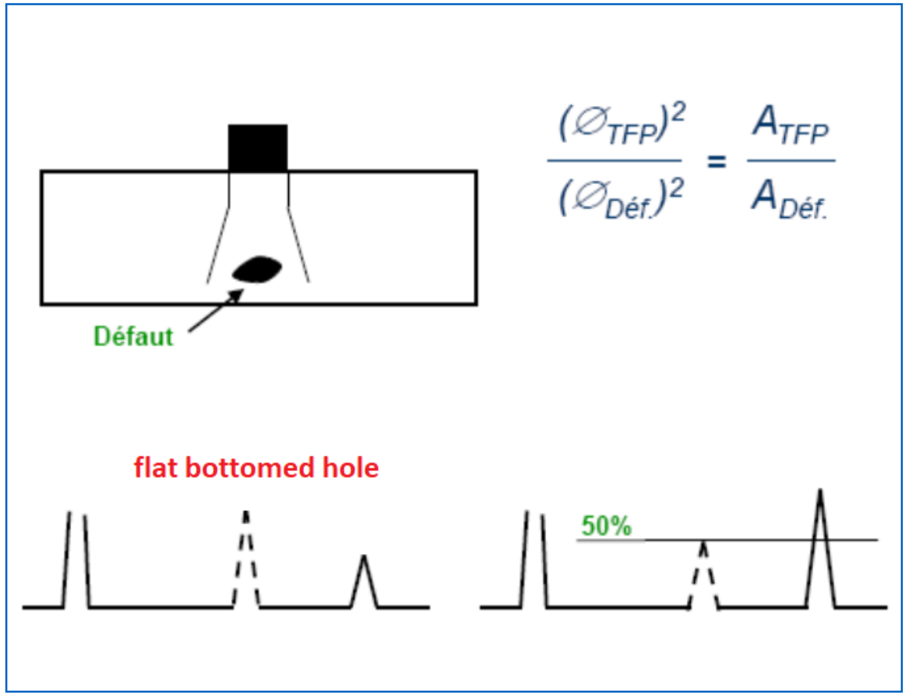
contact

immersion



Defect detection and sizing





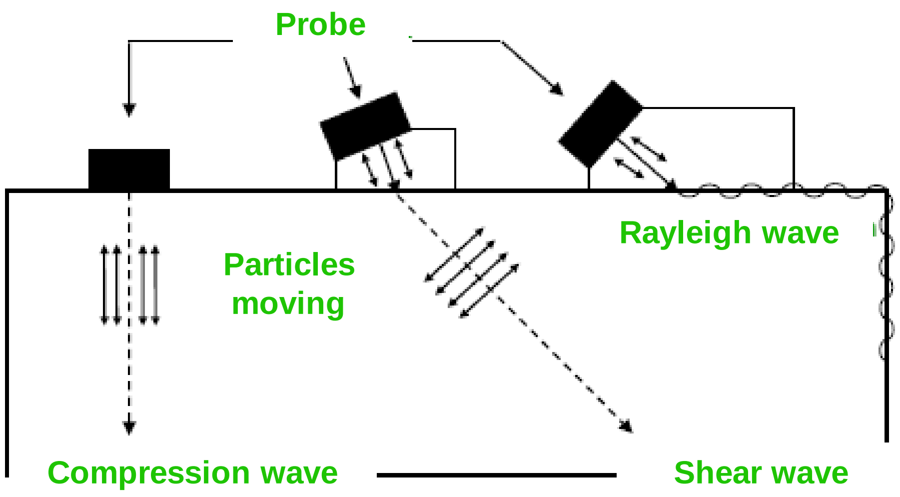
6 dB drop technique

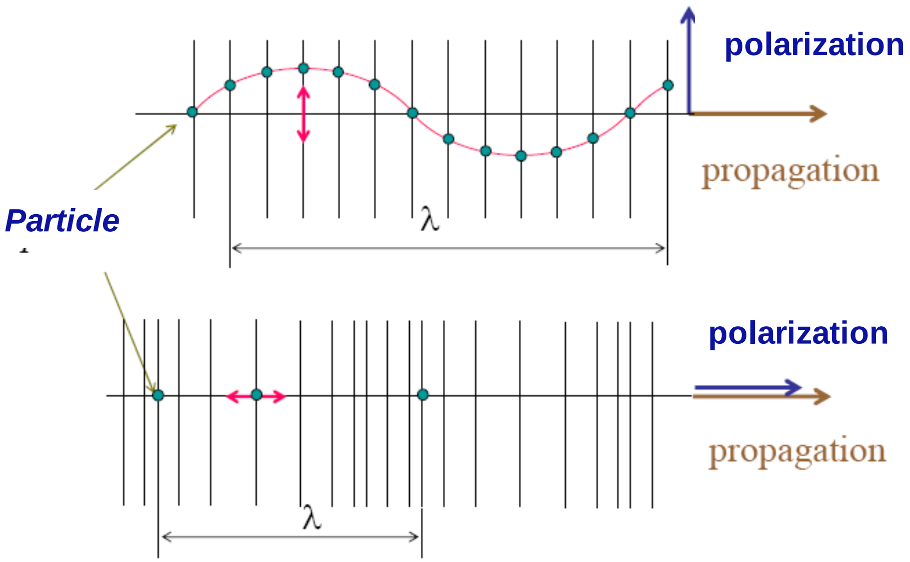
(defect larger than beam width)

Reference block method

(defect smaller than beam)

Wave types



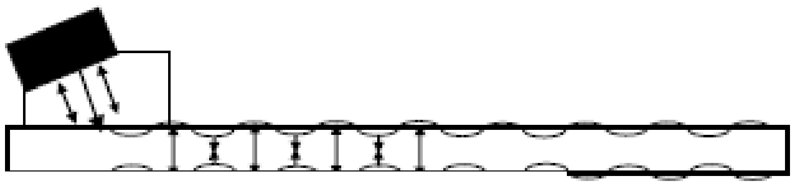


Wave frequencies

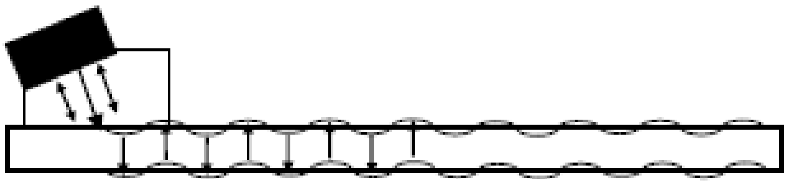
- 1 to 10 MHz ➔ $\lambda = c / f$ varying from 0.6 to 6 mm for L waves in steel

Wave types

- Bulk waves (compression and shear)
  - Liquid and gas : LW (No resistance to shear)
  - Solid : LW and SW
- Surface waves (Rayleigh) : composite waves with compression and shear displacements
- Lamb and guided waves
  - Plates and pipes (thickness close to λ)



Lamb wave : symmetrical mode



Lamb wave : antisymmetrical mode

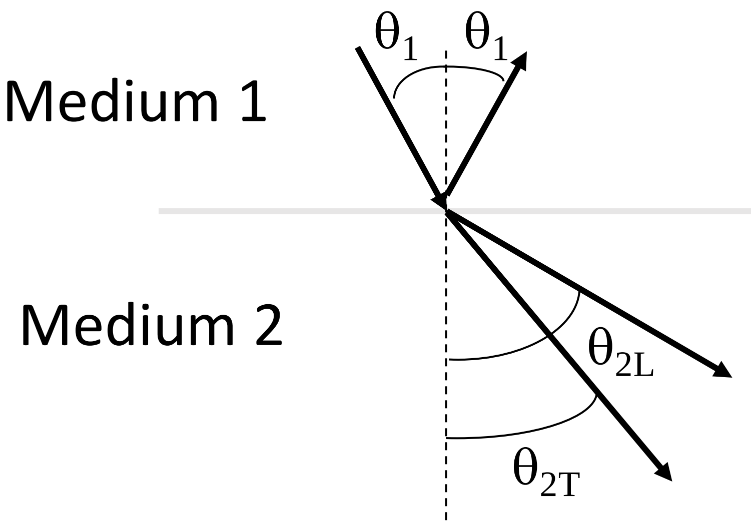
Isotropic media

Phase velocities of ultrasonic waves :

$$V_L = \sqrt{\frac{C_{11}}{\rho}} \qquad V_T = \sqrt{\frac{(C_{11} - C_{12})}{2\rho}}$$

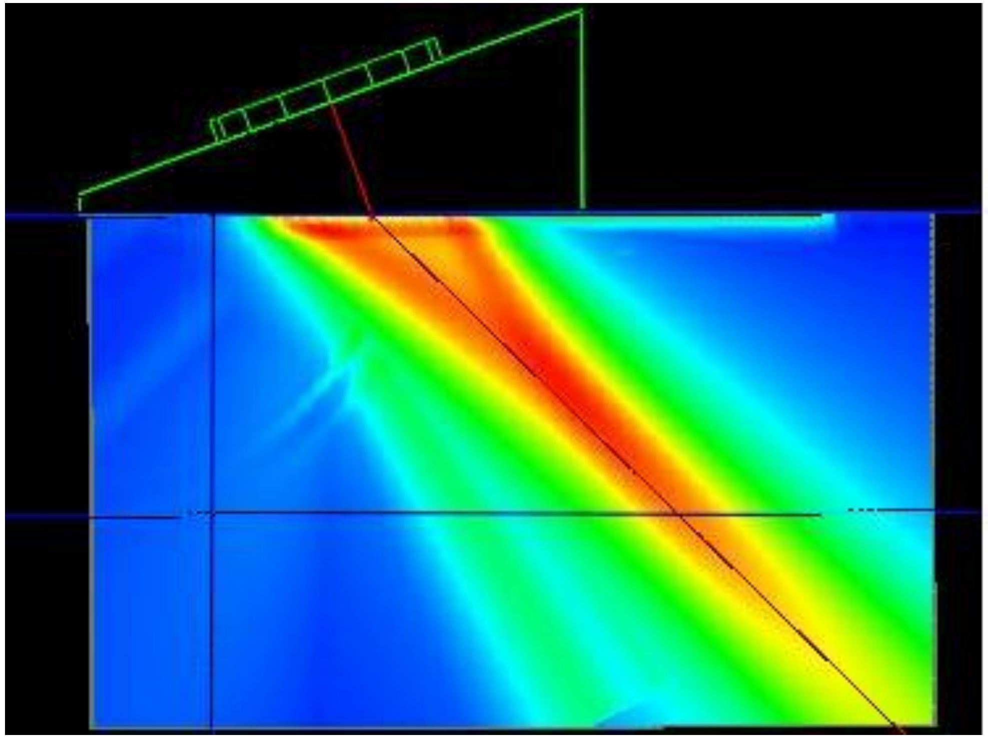
Direction of propagation determined governed by Snell-Descartes' law:

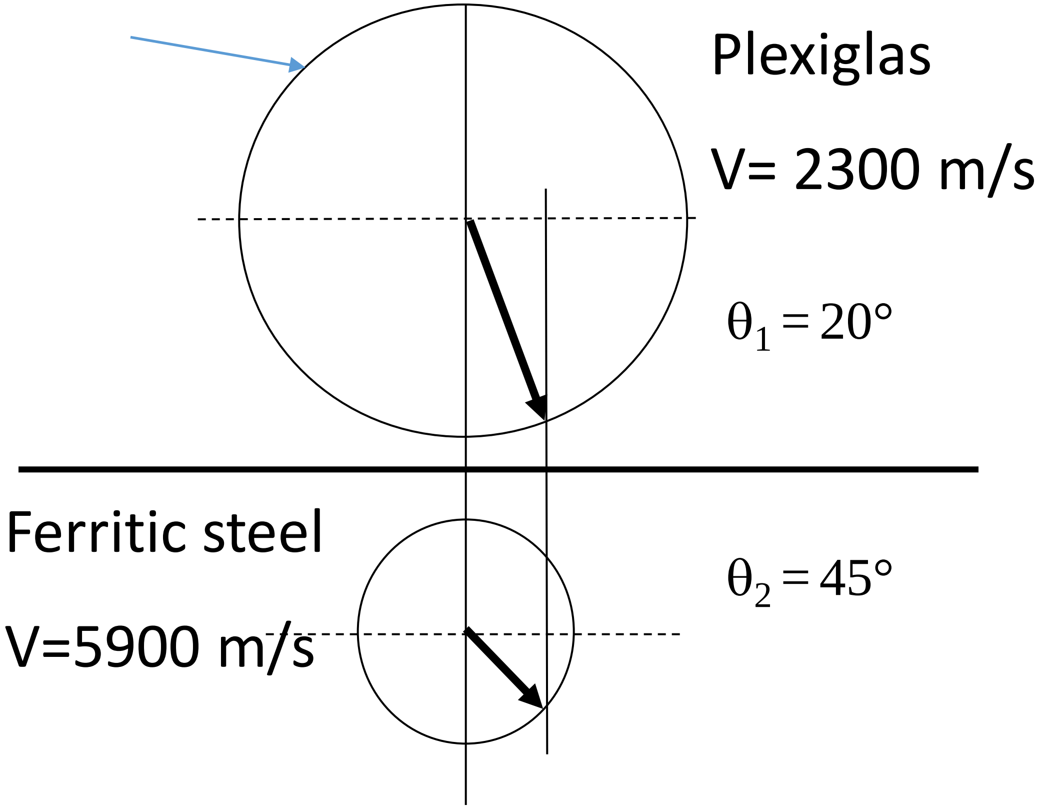
$sinq_1/V_1= sinq_2/V_2$



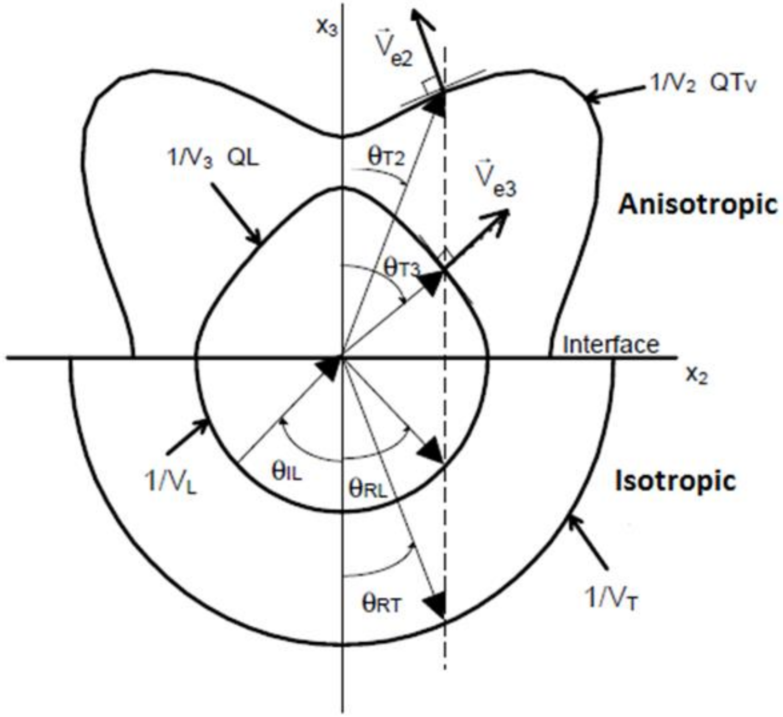
Isotropic media – slowness surface

No variation of the phase velocity versus the direction of propagation



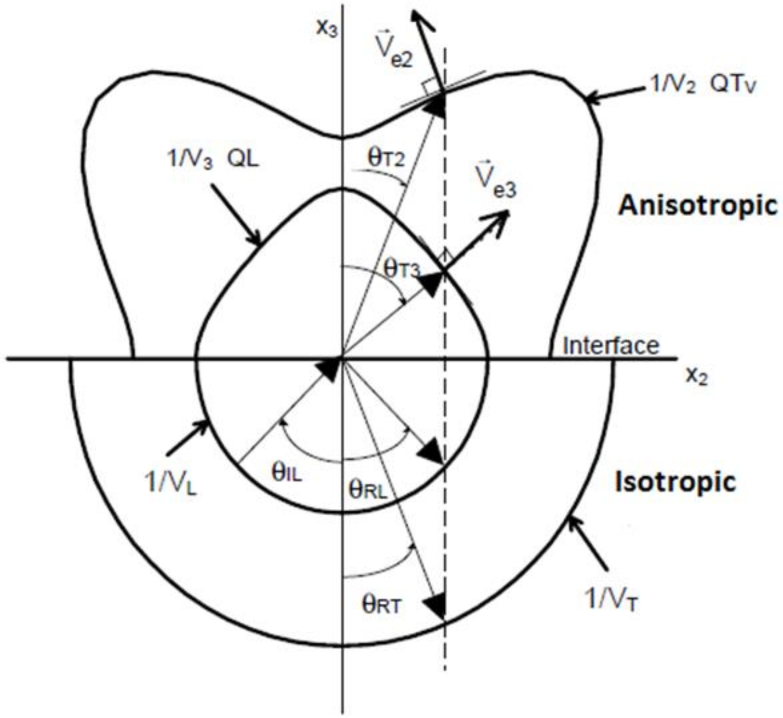


Anisotropic media

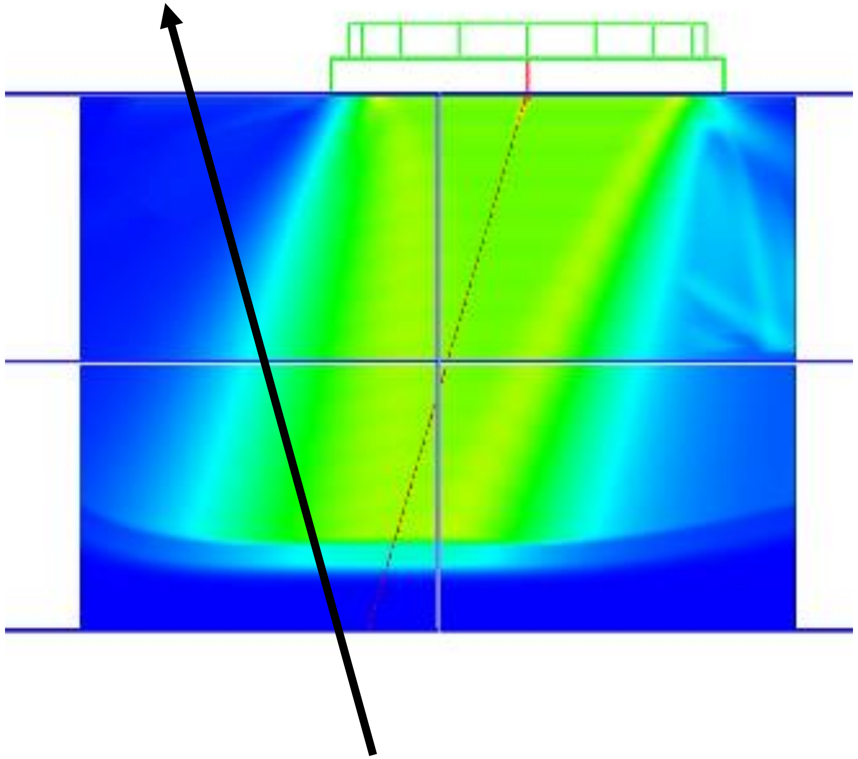


Slowness surface and refracted waves at the interface between isotropic and anisotropic media

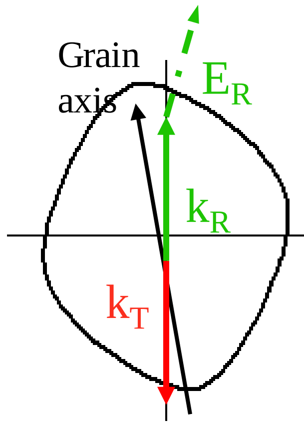
Anisotropic media



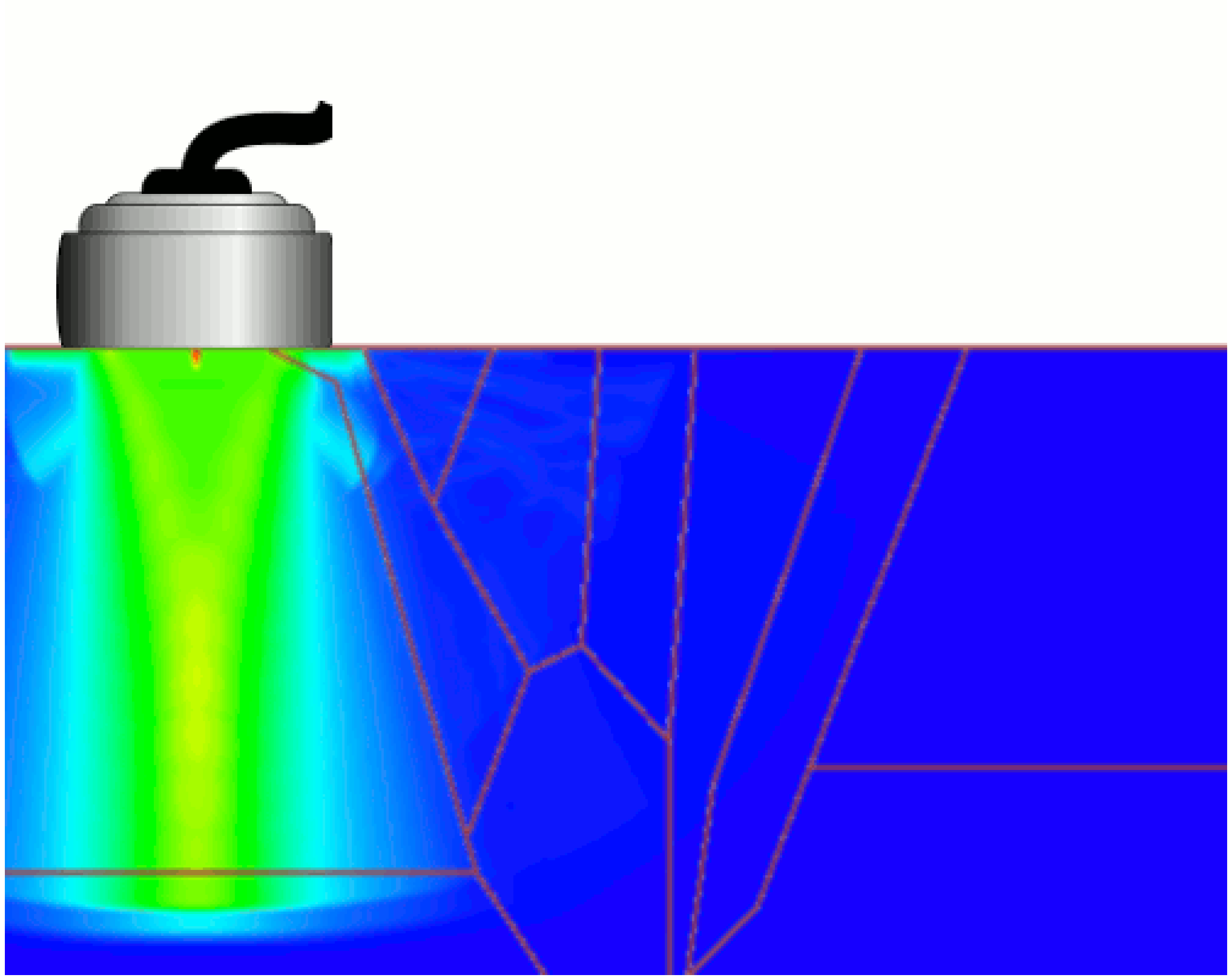
Slowness surface and refracted waves at the interface between isotropic and anisotropic media



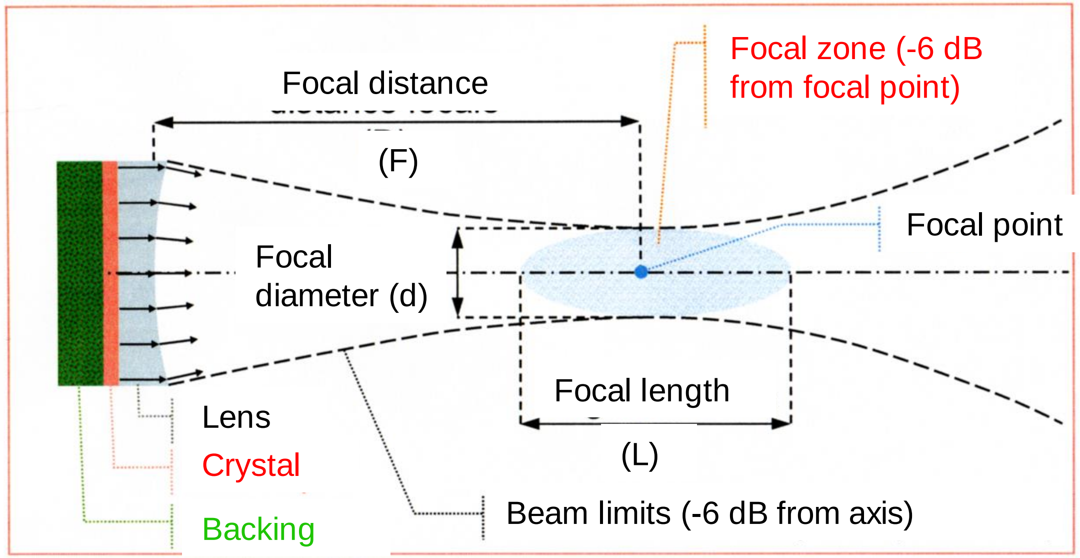
Grain axis (15°/vertical axis)

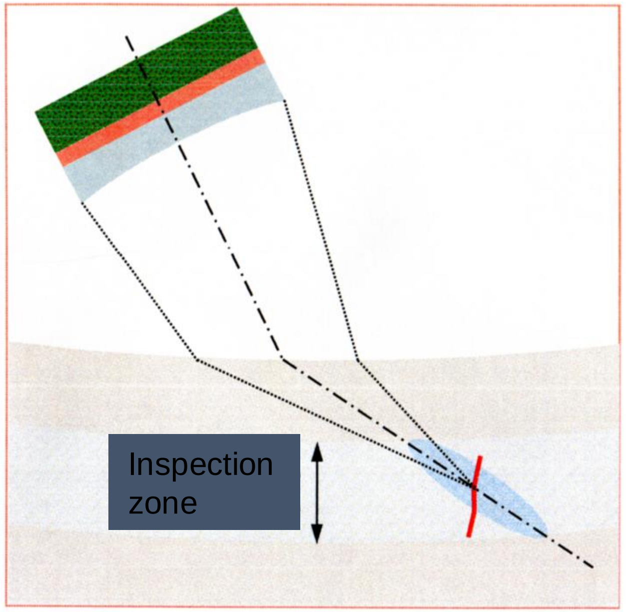


Anisotropic heterogeneous media



Focusing with conventional transducers



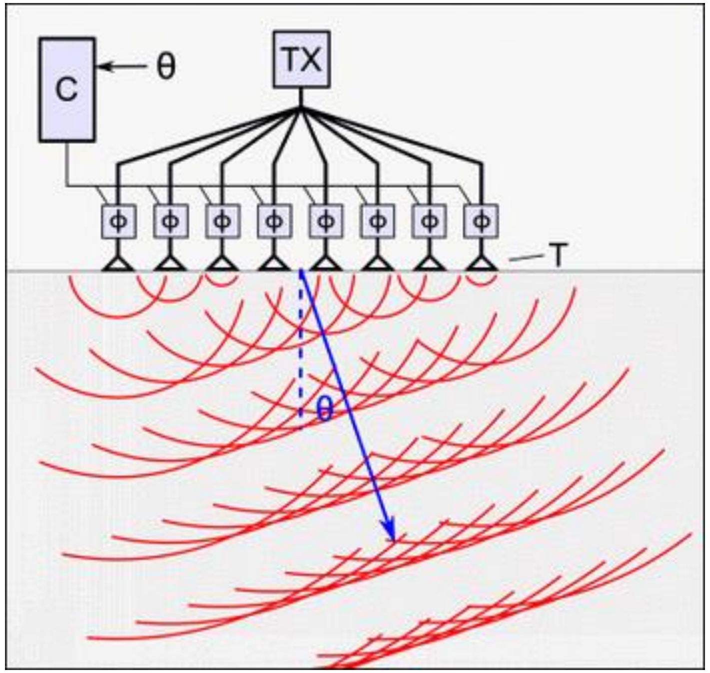


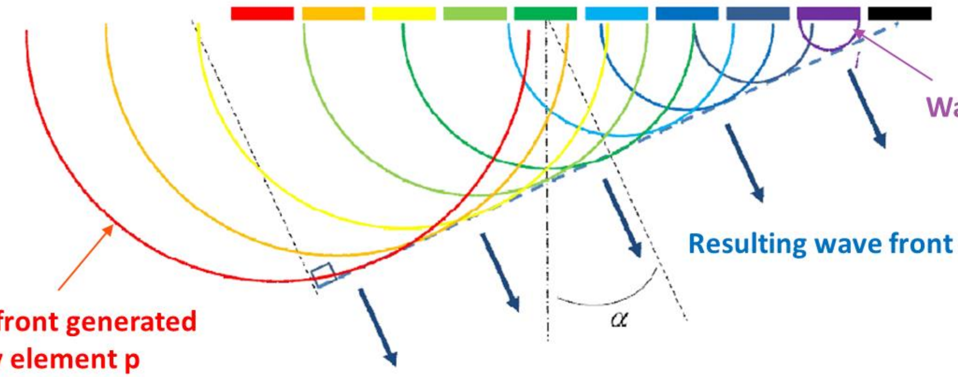
- ⇨ **Diameter of the focal zone in water (-6 dB) : $d_{water} = \lambda F/D$**
- ⇨ **Focal length in water (-6 dB) : $l_{water} = 4\lambda (F/D)^2$**
- ⇨ **Focal length in the material : $l_{mat} = (V_{mat} / V_{water})\, l_{water}$**
- ⇨ **Focal depth in the material : $p = (V_{water} / V_{mat})\,(F\text{-}WH)$**

- ***V_{water} and V_{mat} :velocities in the water and in the material***
- ***D: Diameter of the piezo-electric crystal***
- ***F: Focal distance in water***
- ***WH : «Water height »***

Focusing with phased arrays

- First systems developed for the medical domain (real time sector scan)
- Individual delay laws for each element of a transducer array allow
  - beam shaping (focusing)
  - beam steering
- Typical patterns:
  - linear
  - matrix
  - circular
- Obviously in need of modeling to determine delay laws
- Issues: grating lobes, side lobes..

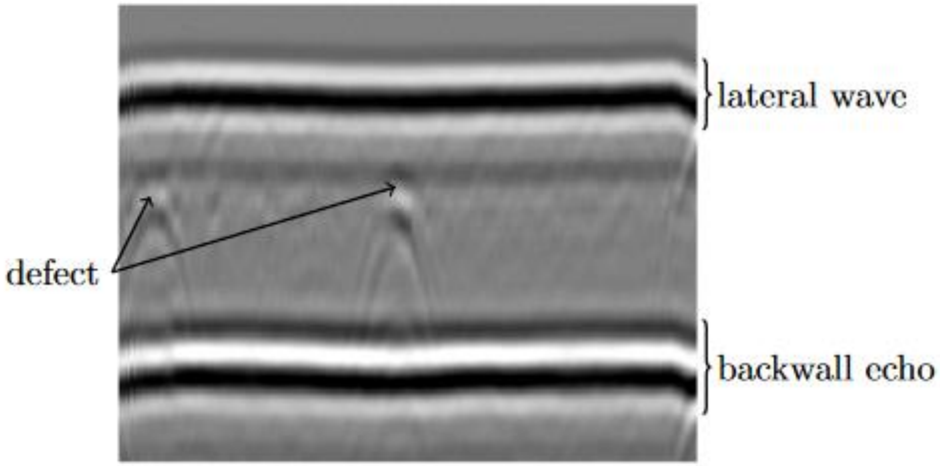


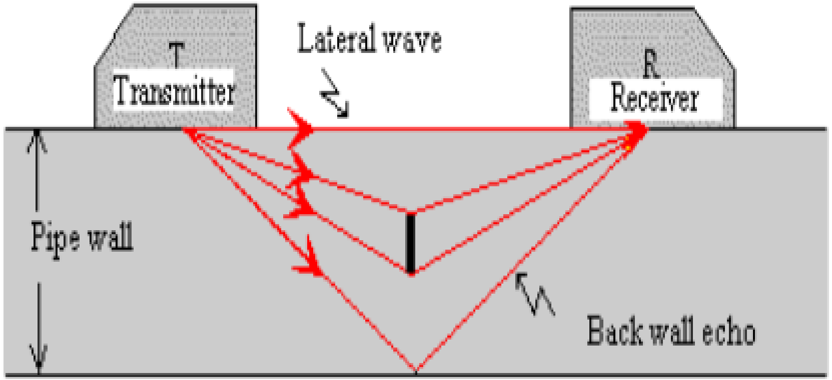


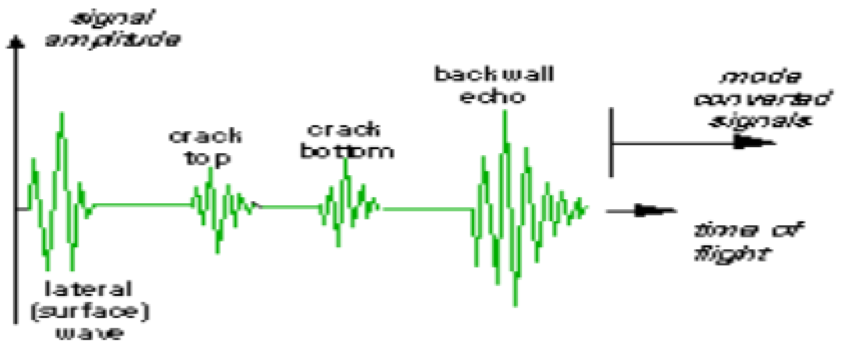
Time of Flight Diffraction

TOFD as more accurate sizing technique:

- Monitor through-wall extent of welding defects and in-service flaws for steel components in nuclear plants at the same time
- Weak sensitivity to defect orientation
- PCS determines usable depth range
- Complement to standard techniques



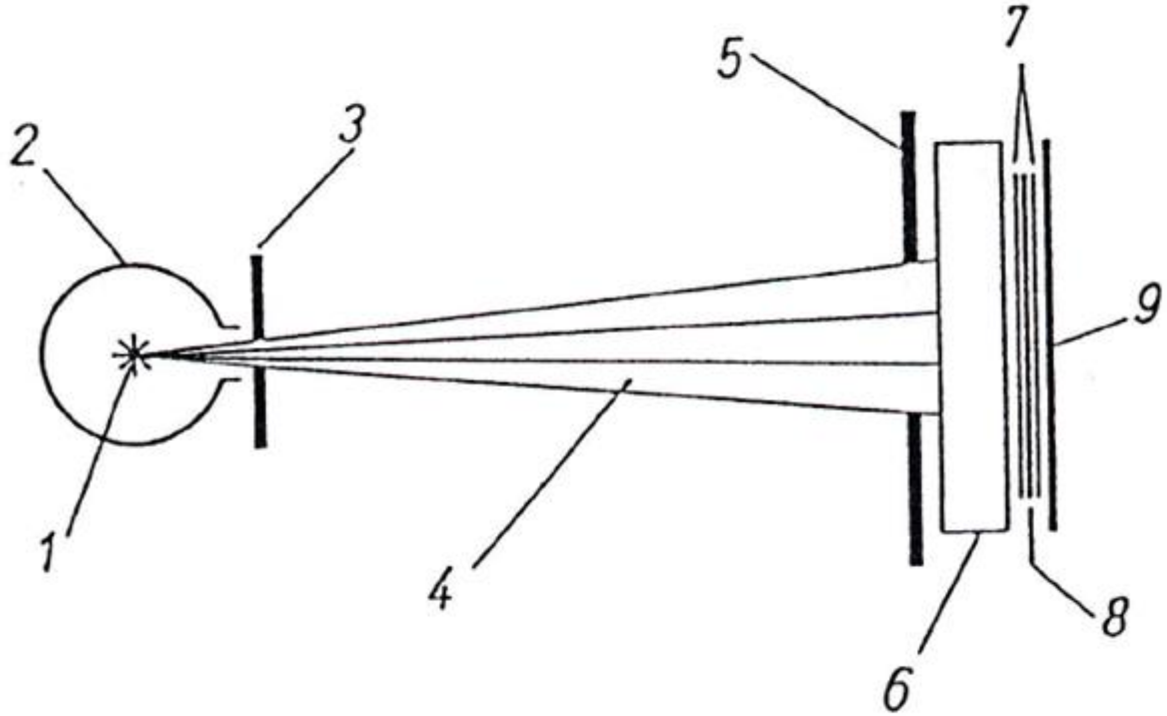




Ultrasonic Testing

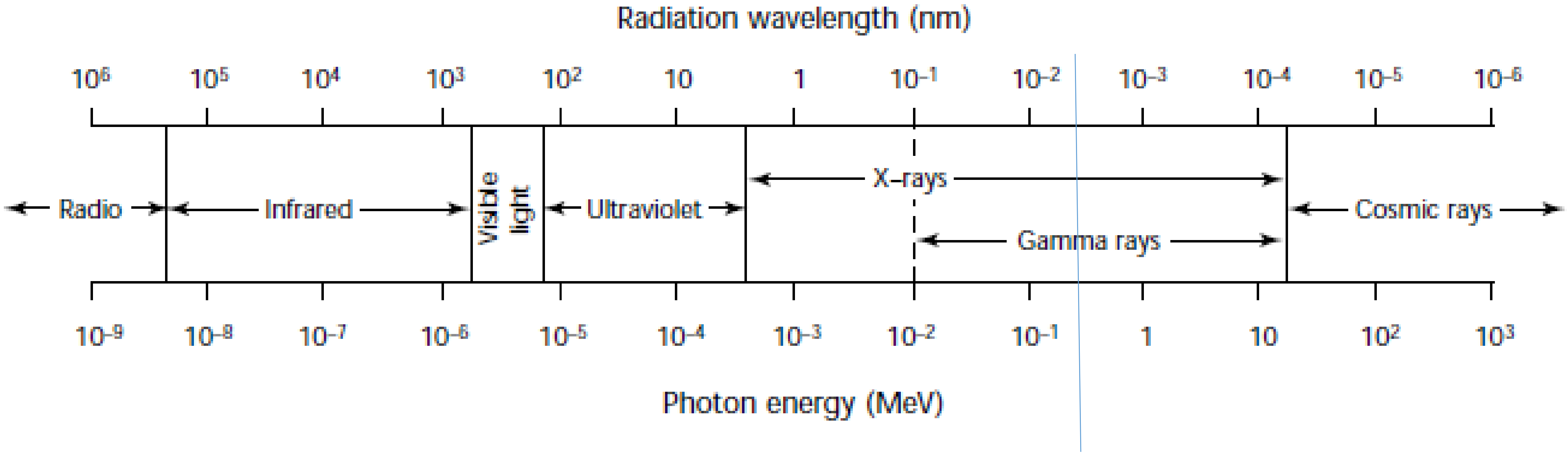
- From Pulse-Echo to Total Focusing
- Requires knowledge of the material properties to relate signals to defects
- Other aspects not mentioned:
  - noise in coarse grained materials
  - other advanced transducer concepts such as TRL
  - electromagnetic excitation of shear waves (EMAT)
  - ultrasound tomography, time reversal, advanced imaging techniques

A typical setup for industrial radiography



1 – source
2 – source container
3 – collimation device
4 – beam
5 – mask
6 – part to be inspected
7 – detector cartridge
8 – silver film
9 – blocking lead filter

Electromagnetic Radiation



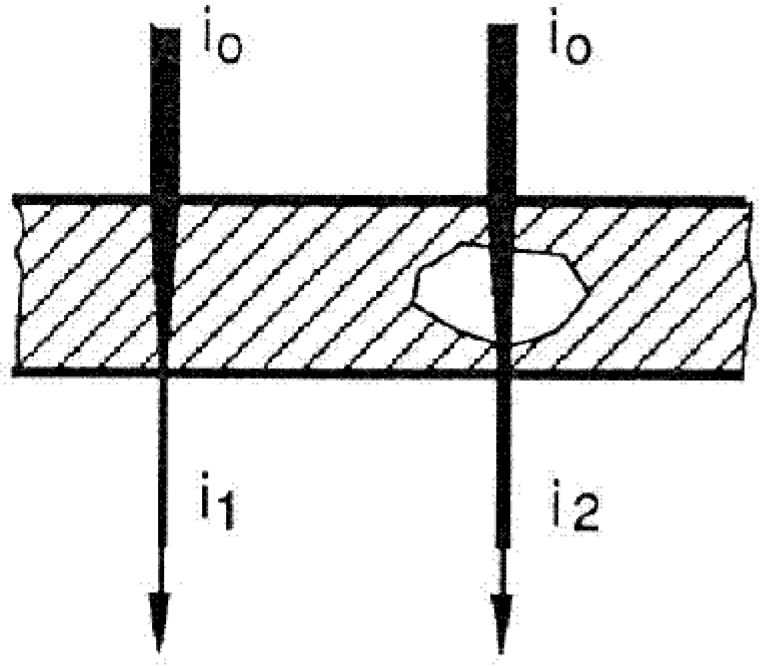
A few terms:

Ionising radiation: radiation with sufficient energy to free electrons from the atoms forming the matter traveled through

X-ray, Roentgen-Rays, Bremsstrahlung, braking radiation vs. Gamma-Rays, γ-radiation

Attenuation/Absorption

The principal effect used in radiography is absorption.



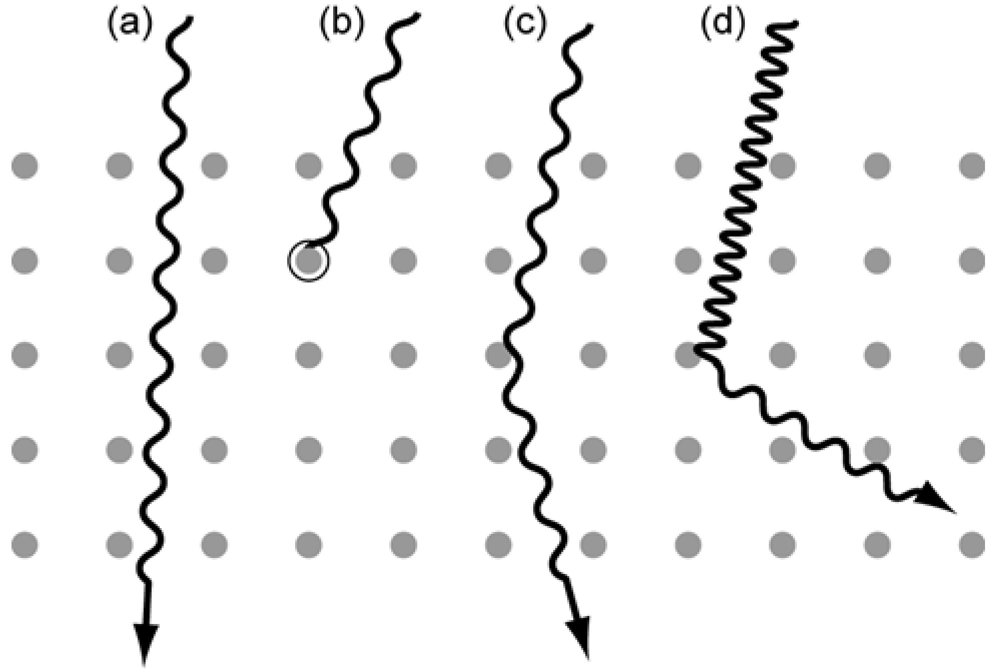
$I = I_0 \exp(-\mu d)$

μ - total attenuation coefficient, depends on the material and the quantum energy of the radiation

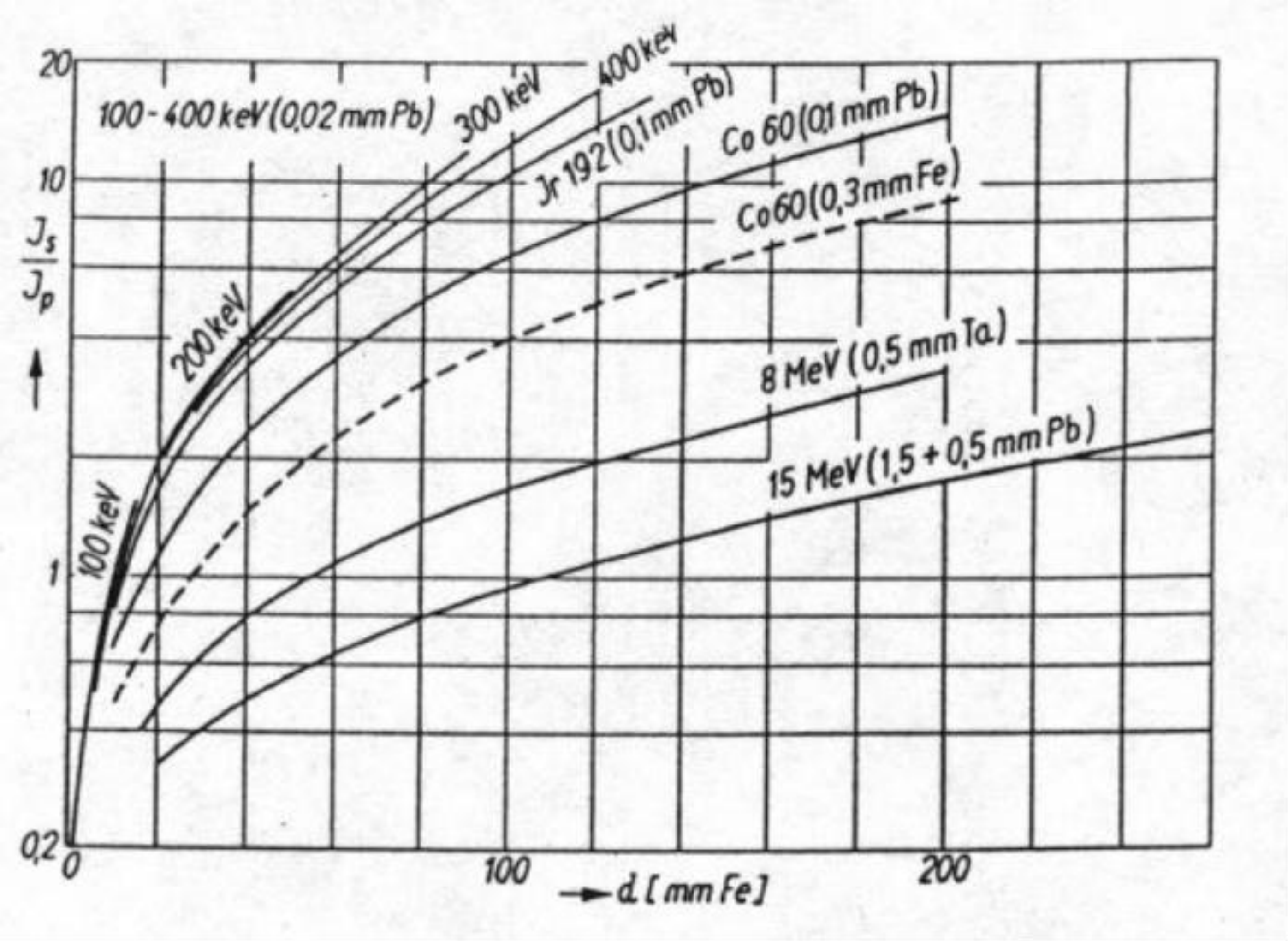
The intensity difference between I_1 and I_2 generates a contrast.

Direct vs scattered

- Direct radiation refers to unscattered particles (a)
- Scattered radiation refers to particles with scattered trajectory (c) and/or reduced energy (d)
- Some scattering events produce additional particles (photons →electrons)



Quantifying Scattering: Build-up



$I_{total} = I_{direct} + I_{scattered}$

$= I_{direct} * BU$

$BU = 1 + I_{scattered} / I_{direct}$

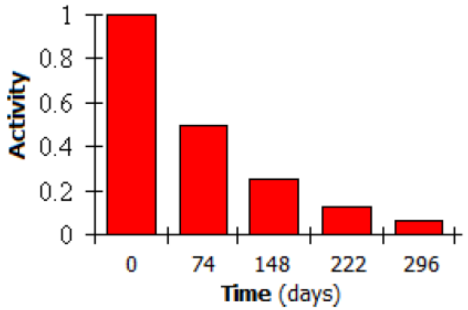
Idea: Quick estimate of total radiation using straight-line attenuation and tabulated build-up factors

Definition: Factor by which radiation intensity (at a given observation point) exceeds the value associated with only direct radiation

Gamma radiation - Units

- Produced through the radioactive decay of isotrope sources
- „Activity“ refers to the number of decay events per second [Bq][1/s]
- 1 Ci = 3.7E10 Bq (disintegration rate of 1g of pure Radium)
- One decay event ≠ one particle!
- Half-Life T (period, half decay time)

$$N = N_0 e^{-\left(\frac{ln2}{T}t\right)} \qquad decay\ fraction = \frac{A}{A_0} = 0.5^{t/T}$$



- Practical consequence: The activity of a given source depends of its age and can not be „adjusted“ to the needs of the practitioner

γ radiation

	Yb-169	Se-75	Ir-192	Co-60
Energy [keV]	63-308	66-401	206-612	1173-1333
Half decay time	32d	119d	74d	5.27a

A small radioactive pellet is enclosed in steel and stored in a shielded projector

A crank remote control permits the safe release of the isotope during the exposure

Legal framework for Ownership, transport and handling

γ radiation

	Se-75	Ir-192	Co-60
Energy [keV]	66-401	206-612	1173-1333
Half decay time	119d	74d	5.27a

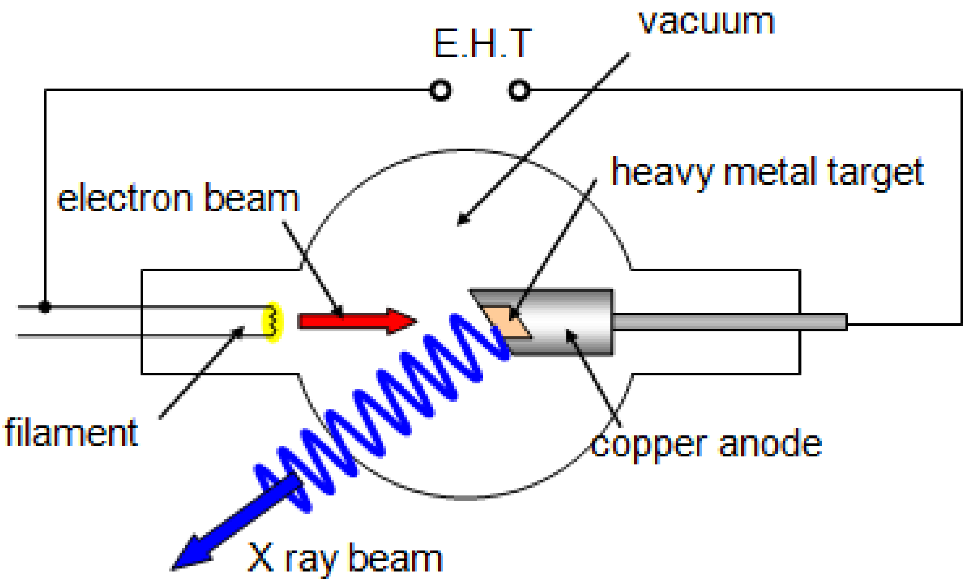
Cobalt: shielding typically 150mm of steel, weight 200kg
Iridium: shielding typically 70mm, weight 20kg

X-ray radiation

- Discovered by Wilhelm Conrad Roentgen in Nov 1895 while studying cold cathode tubes
- X-Ray / Roentgen rays / Bremsstrahlung

Coolidge tube

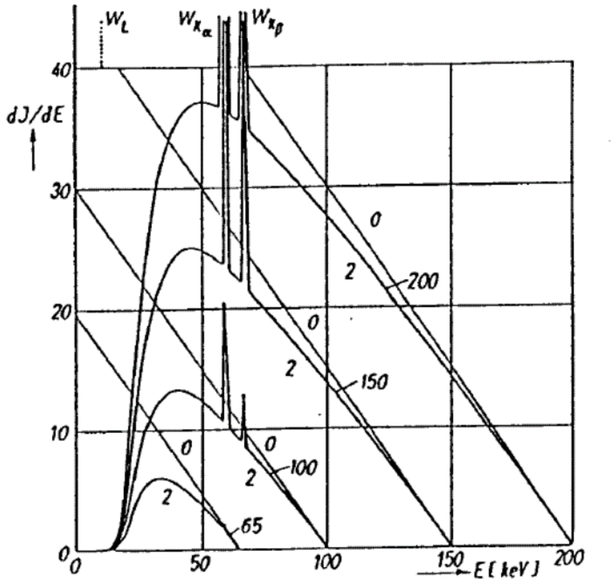
- William Coolidge invents hot cathode tube (1913) with tungsten filament

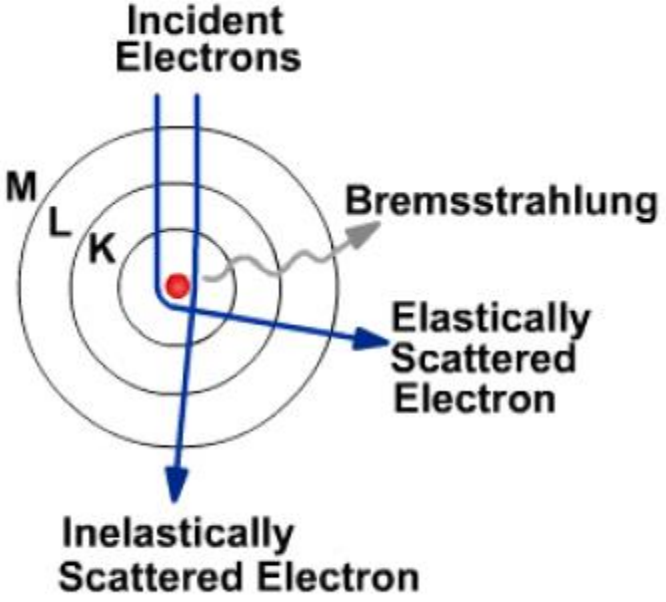


US patent 1,203,495 filed in 1913, granted in 1916

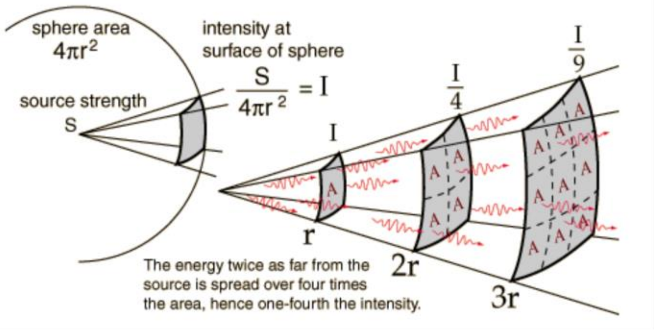
X-ray radiation (Bremsstrahlung)

- Within the target, abrupt deceleration of charged particles (electrons) produces X-ray radiation
- The deceleration takes place in the first 50u of target material (for Tungsten)





Geometrical considerations



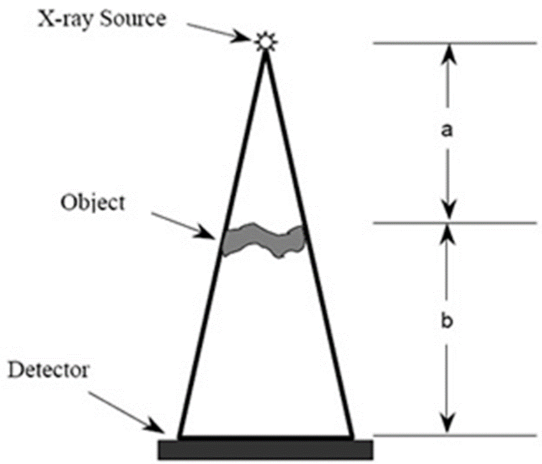
$$I_1 / I_2 = D_2^2 / D_1^2$$

I_1 = original intensity

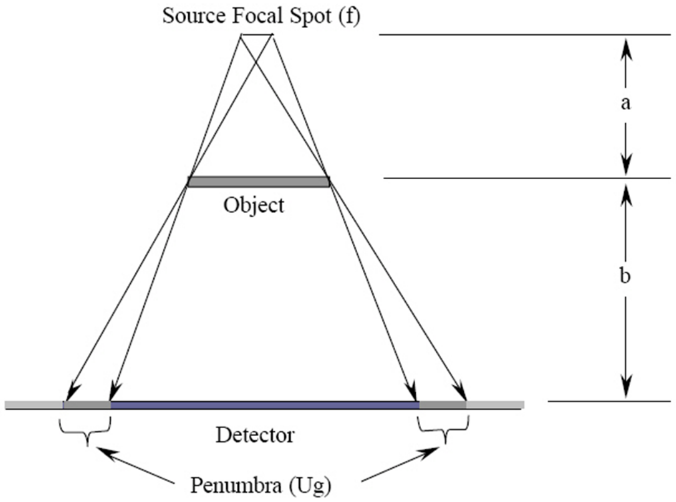
I_2 = new intensity

D_2^2 = original distance

D_1^2 = new distance



$$M = \frac{a+b}{a}$$



$$U_g = f\frac{b}{a}$$

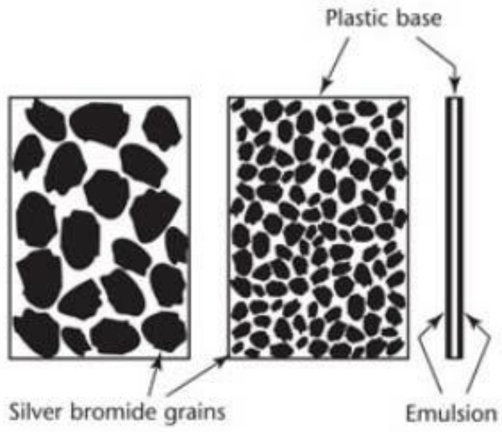
Inverse square law

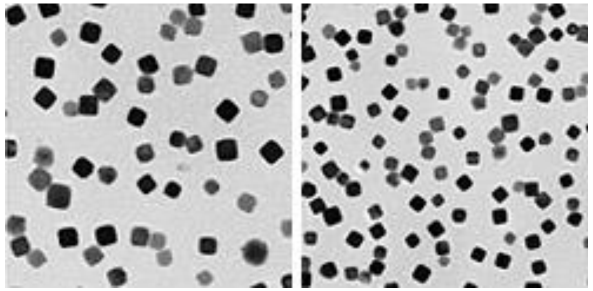
magnification

geometrical unsharpness

Radiographic film as a detector

- Industrial radiography film consists of 7 layers
- Two emulsion layers double the speed
- The emulsion contains silver halide crystals suspended in gelatine
- During exposure to light and ionizing radiation, AgBr grains get ionised, and secondary electrons activate neighbor grains (latent image)
- Development reduces activated grains to silver



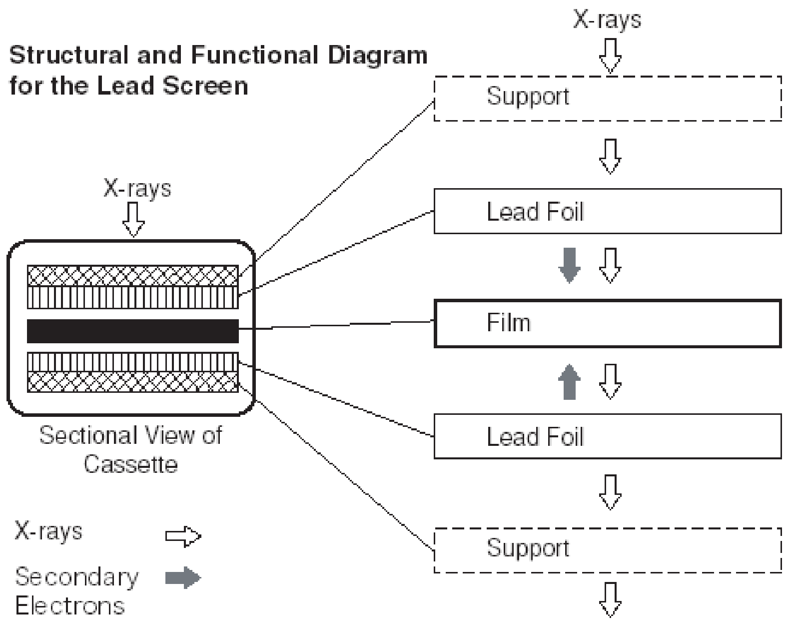


Radiographic film development

- The development process reduces activated grains to silver faster than non-activated grains
- A stop bath stops the development process
- After development, an acid neutralises non-activated grains to stabilise the image (fixer bath)
- A wash bath removes remaining residue

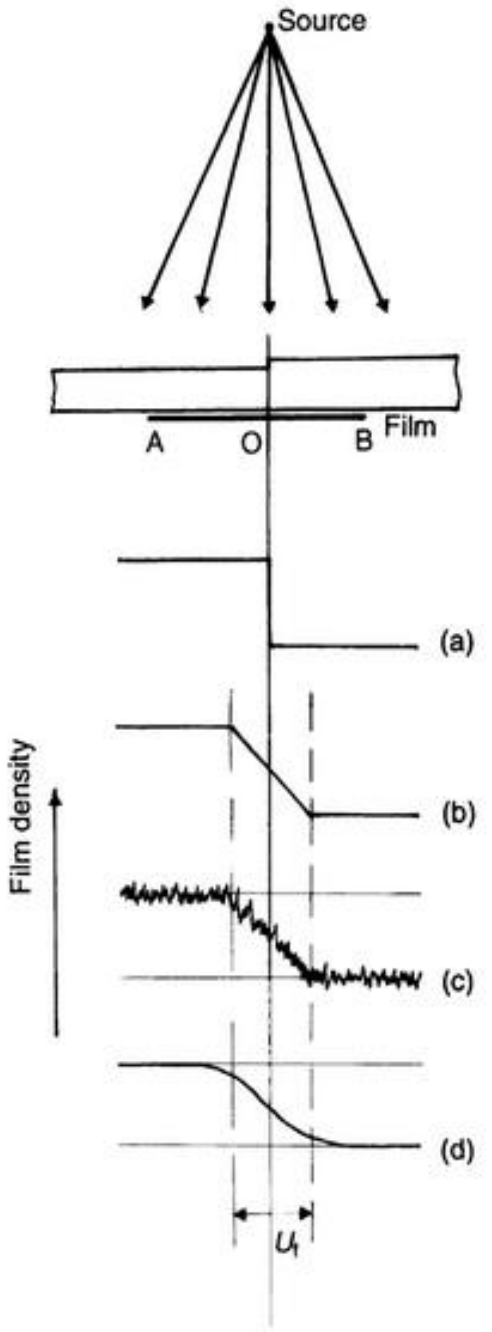
Intensifying screens

- Only about 1% of the incident radiation is absorbed in the emulsion layer
- To utilise more of the available energy, intensifying screens are used
- The basic mechanism is photoelectric absorption and Compton scattering
- An intensifying screen behind the film (back screen) is used to backscatter electrons



Inherent unsharpness

Radiation	Uf[mm]
50keV X-ray	0.03
200keV X-ray	0.09
Ir-192	0.17
Co-60	0.35
8MeV LINAC	0.6



Experimental assessment of inherent unsharpness requires precautions

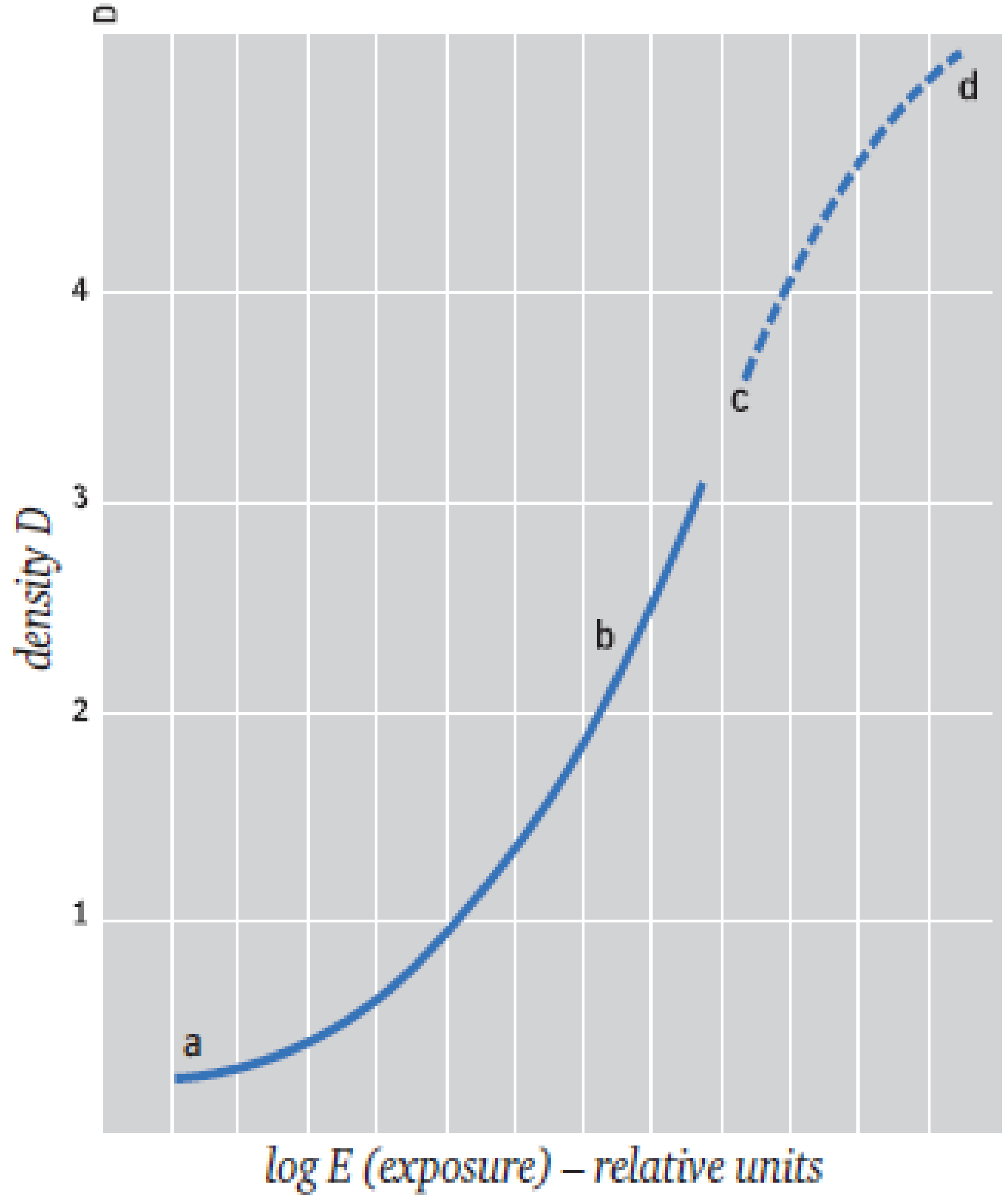
- Small microdensitometer aperture
- Density change must be as small as possible
- Source must be virtually point source-like

Filters

- Many applications at higher energy require additional filtering, in addition to the filtering provided by the front screen
- Appropriate filtering can significantly reduce scattering
- To fully appreciate the role of filters, we need to consider the spectral response of the detector
- Some applications for detectors with inappropriate spectral response, sandwiched filters made of different materials may be indicated

Film sensitivity

- Characteristic cuve log E vs. D
- Steeper gradient means more contrast
- Strong Implications!

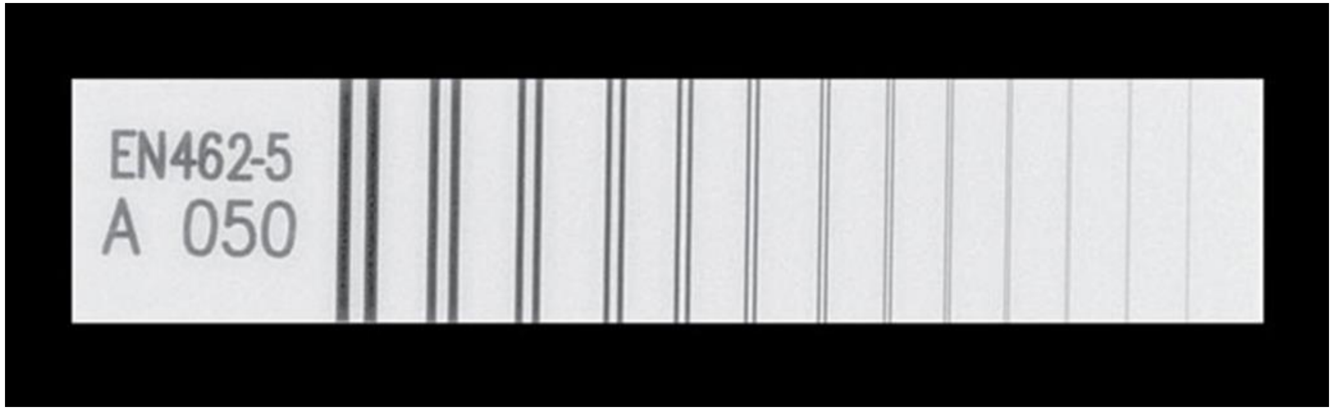


Film granularity

- Granularity refers to local statistical variations of optical density
- Granularity is a perceived property- film grains (silver particles) are 10 times smaller
- Visual clumping/clustering of particles in the emulsion
- Granularity limits spatial resolution
- Faster films have higher granularity

Finding the best compromise

Image Quality Indicators



#	diameter
1	3.2
2	2.5
3	2.0
4	1.6
5	1.25
6	1.0
7	0.8
8	0.63
9	0.5
10	0.4
11	0.32
12	0.25
13	0.20
14	0.16
15	0.125
16	0.10

Digital radiography

- Digitized film
- Imaging Plates (CR – computed radiography)
- Flat Panel Detectors (DR – direct radiography)
- Photon counting detectors

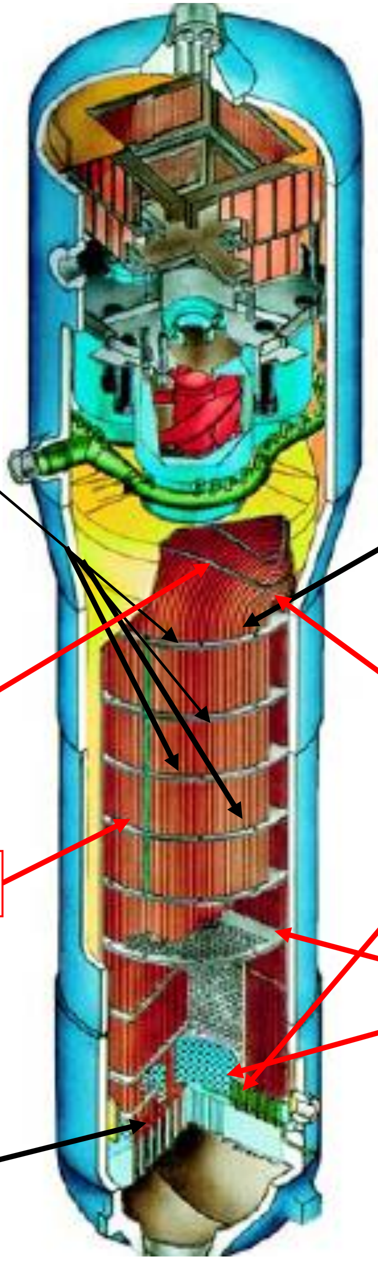
Largely driven by advances in the medical domain.
Slowly adapted in industrial NDT, facing a number of challenges for applications with moderate to high wall thickness.

Wrap up

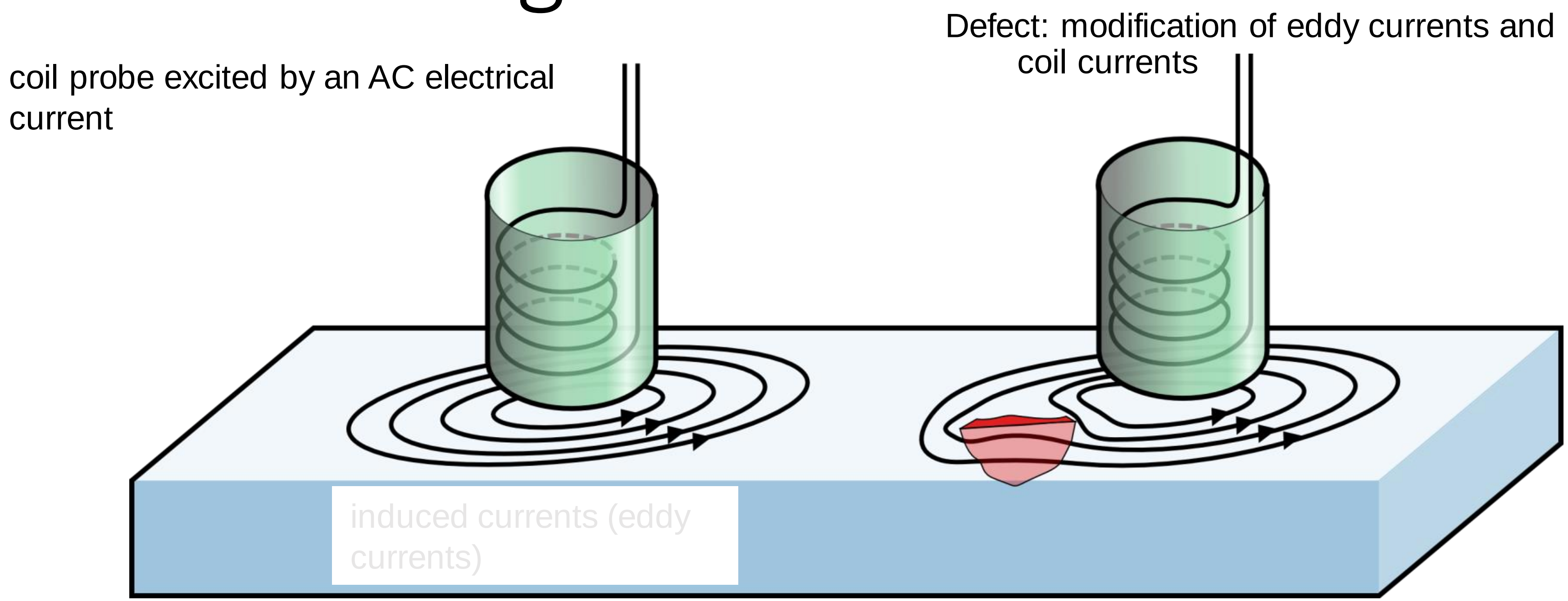
- Established technique
- migrating from silver to digital
- Health risk due to radiation
- Pace set by medical applications

„Largely a matter of finding the best compromise between contrast, resolution, exposure time“

Eddy Current Inspection



Eddy Current Testing

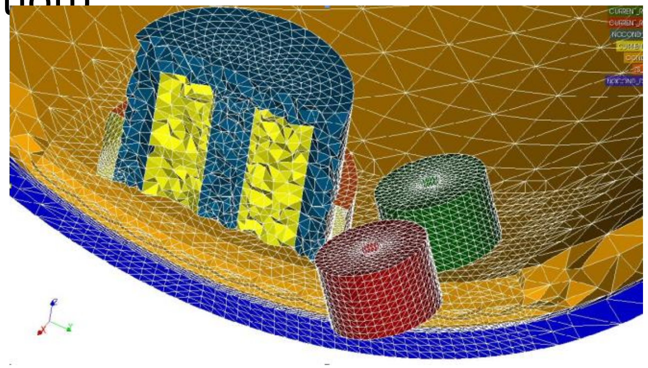


- Dedicated to the inspection of thin components or to surface inspection
- Sensitivity and penetration depth of the induced currents depend on the frequency

$$\delta = \sqrt{\frac{1}{\pi \sigma \mu f}}$$

Eddy Current Testing

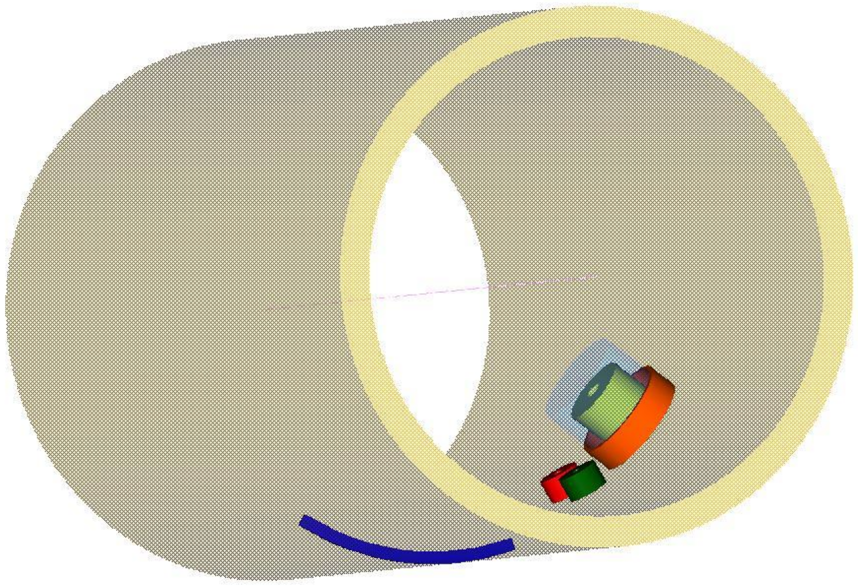
- Advantages
  - Detection sensitivity
  - Automation (to follow up the evolution of a indication)
  - Detection of emerging and underlying defects

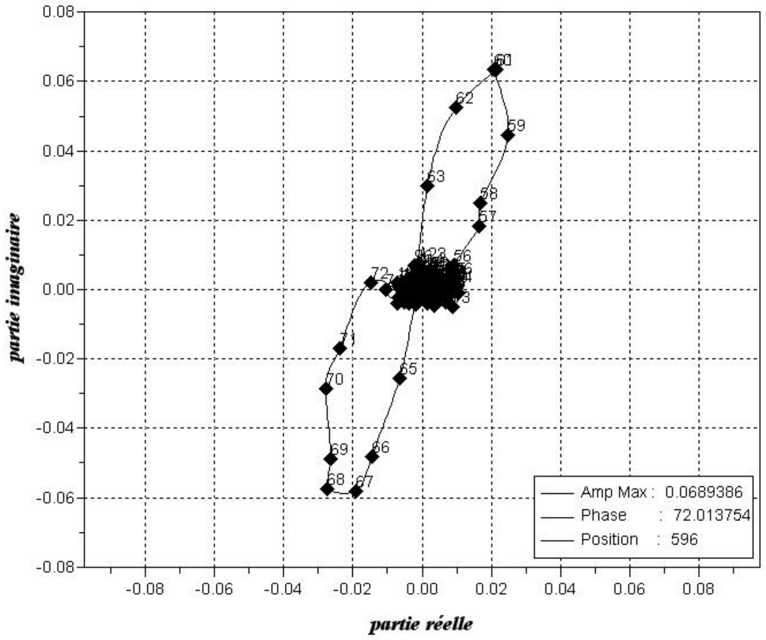


- Limit : No depth sizing
- Techniques of inspection
  - Absolute mode
    - impedance directly compared to a reference value given by a part without defects
    - combine transmit receive probe
    - separate transmit receive probe
  - Differential mode: same coils side by side and wired to provide differential signal

Eddy Current Testing – Example (STT)

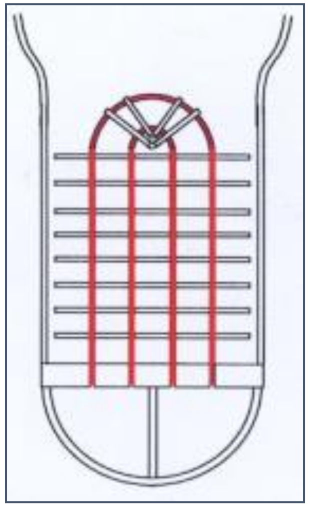
Circonferential and outer wall defect ext. ang. 50° thick. 40% + STT probe	Measurement



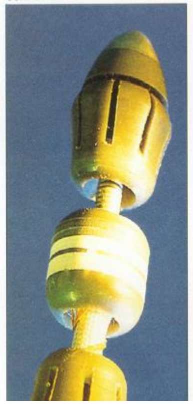


Coil voltages drawn in a XY impedance diagram = Lissajous curve

Eddy Current Testing - Example

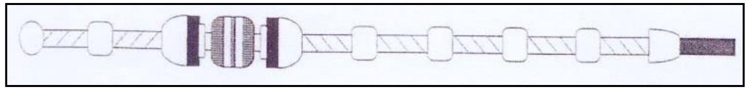


Axial probe (SAX) = « universal probe »
High rate



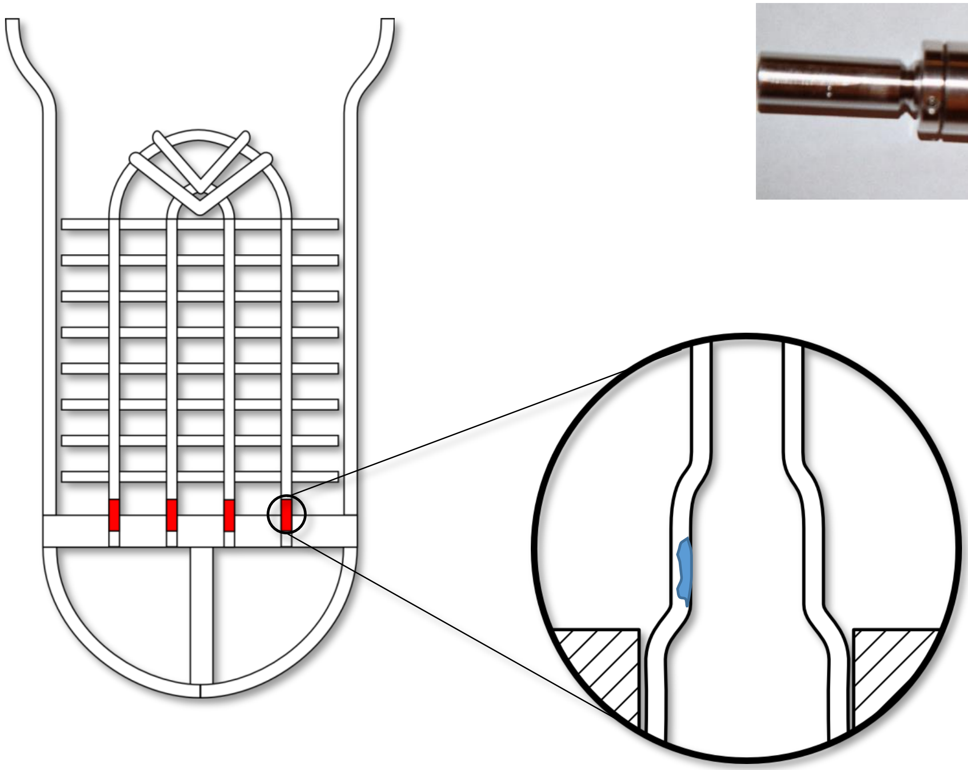
Detection, on the entire tube length, of :

Outer corrosion
Wear and lacks of material,
Tube deformation
Cracking (Expansion zone, bending)



Eddy Current Testing

- Rotating probe (STL) :
  - 2 parallel coils at 45°
  - Detection and characterization of longitudinal cracks located in the expansion zone of the tube sheet
  - High resolution



Wrap-up

- Eddy current is mostly used for the inspection of SG tubes
- We see applications for defects close to the surface in welds
- It represents a considerably amount of the total NDE budget
- Understand the difference between bobbin and rotating probes
- The first application of automatic NDE analysis
- Related applications are clogging/fouling detection

NDE Modelling

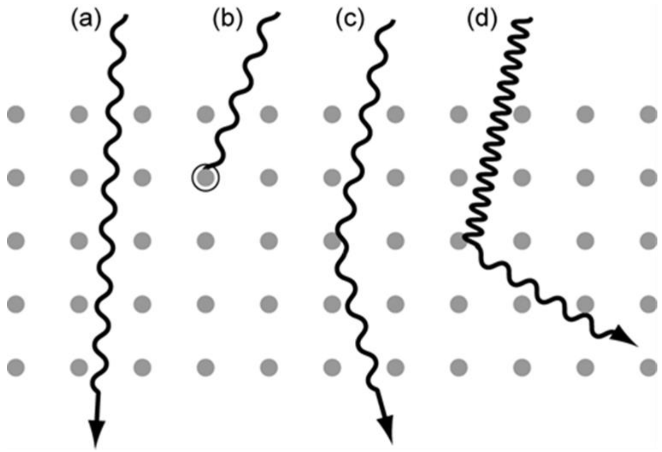
- Why Computer modelling of NDE techniques?
  - Inspection procedure design and optimisation
  - Aid in interpretation of results/understanding of phenomena
  - Training
  - Inspection procedure qualification

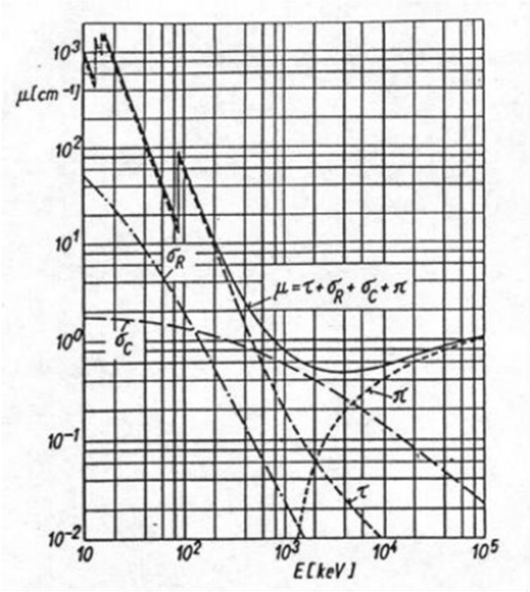
- Modelling for inspection procedure qualification
  - reduced number of mockups
  - study of influential parameters over a wide range
  - study of influential parameters not accessible experimentally

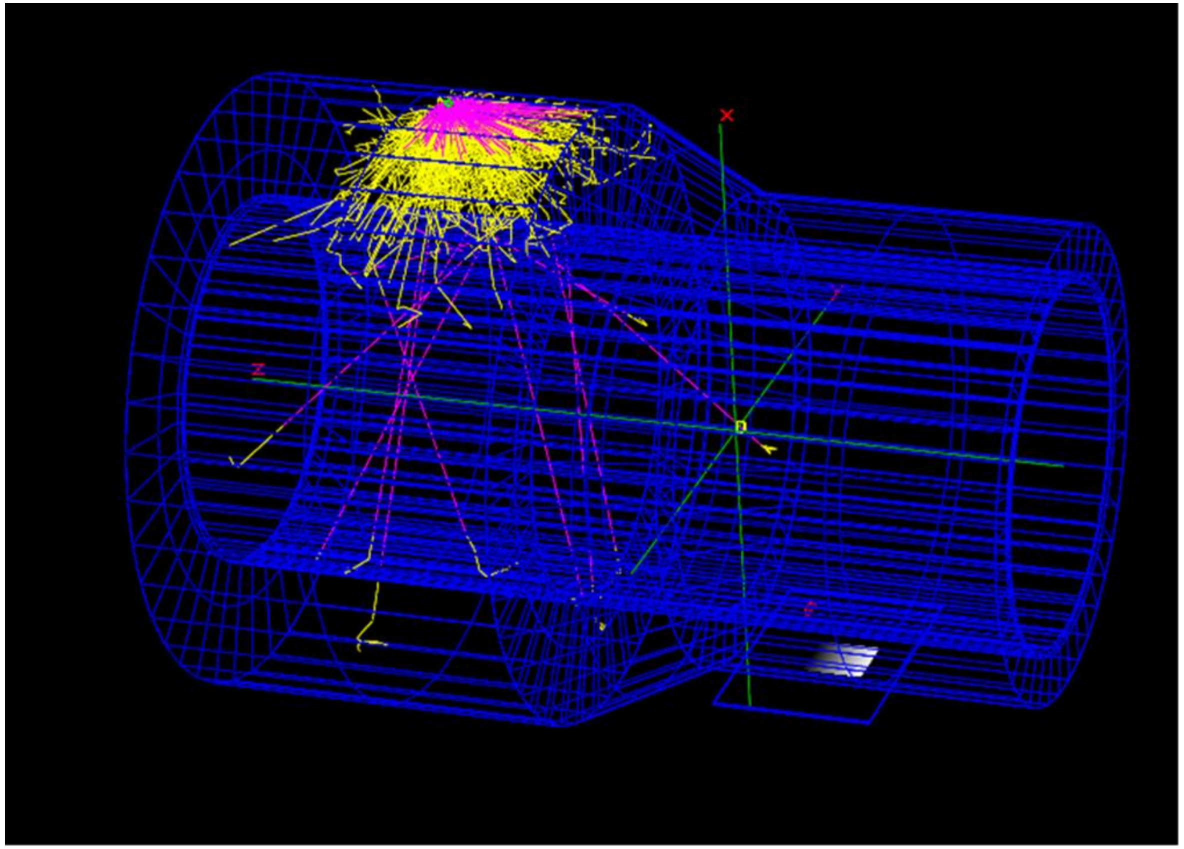
NDE Modelling: Radiography

- CIVA, Artist, Moderato:

  A Monte-Carlo model combined with straight line attenuation





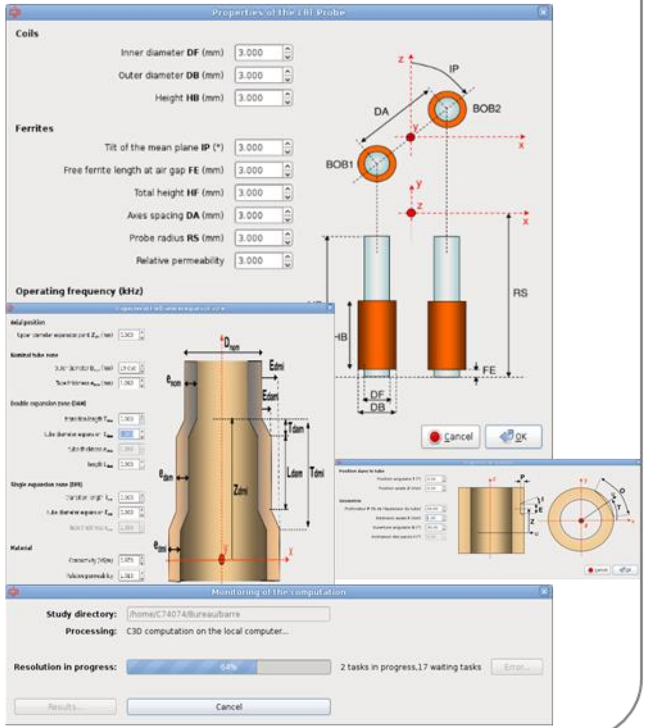


NDE Modelling: Eddy Current

- CIVA, C3D, Comsol…

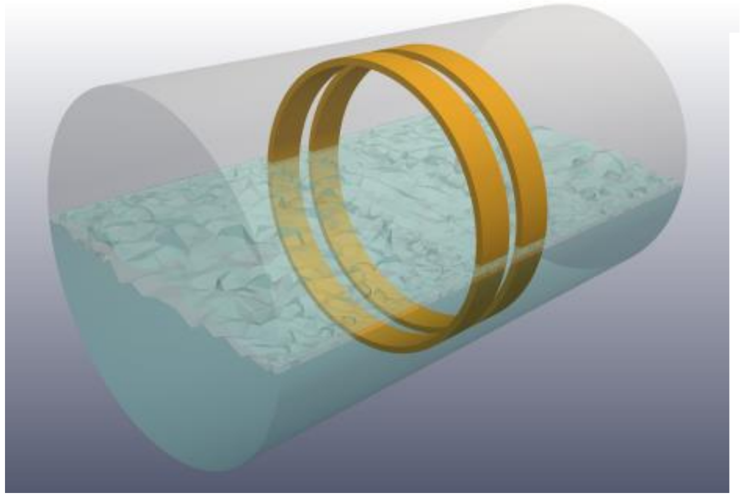
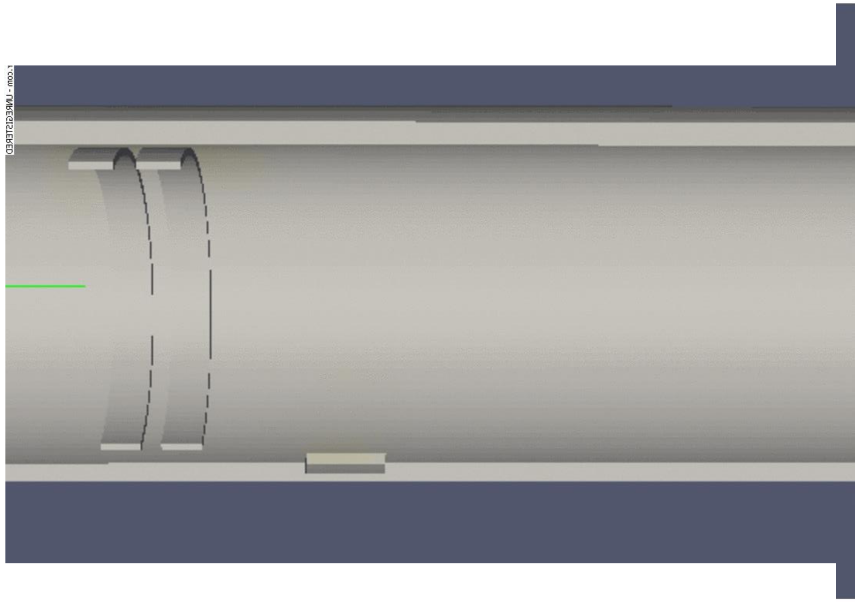
  A number of different techniques used:
  - semianalytical models for specific geometries (SG tubes)
  - finite elements
  - very computation-intensive

- Release 3 « C3D-CND » (2016)
  - CND oriented GUI in QtPy
  - Hidden SALOME calls
  - Hidden cluster calls

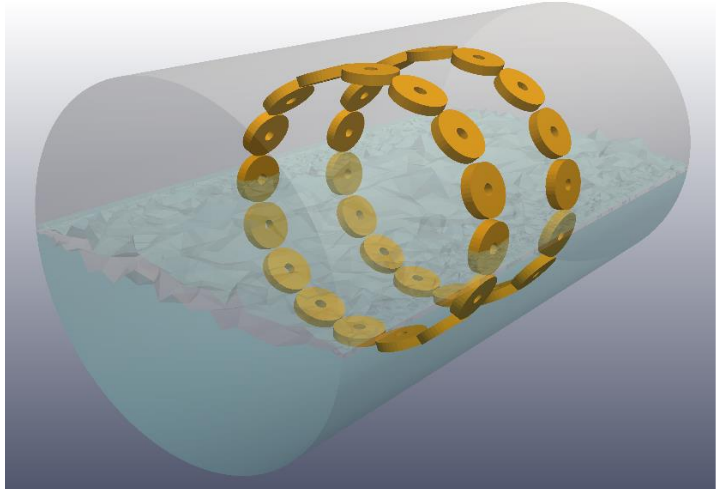
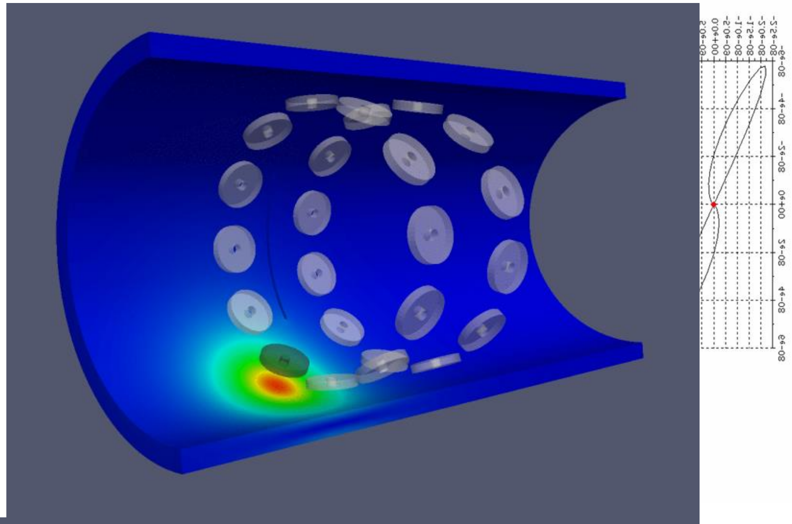


Examples of eddy current probes

- **SAX : quick detection of all types of defects**

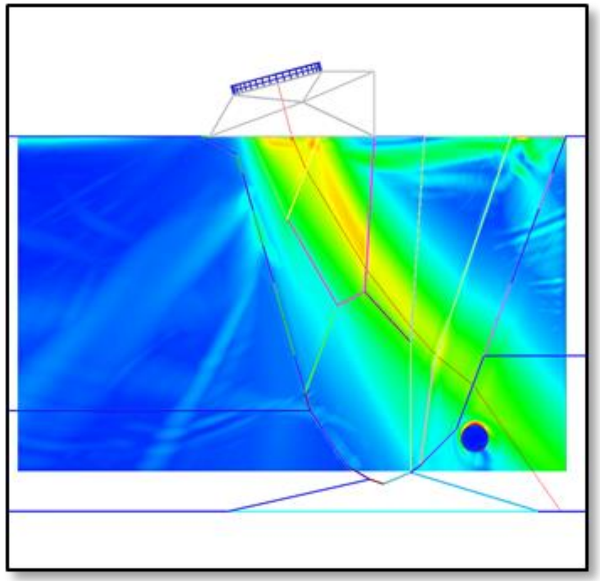
- **SMX : localization of all types of defect**

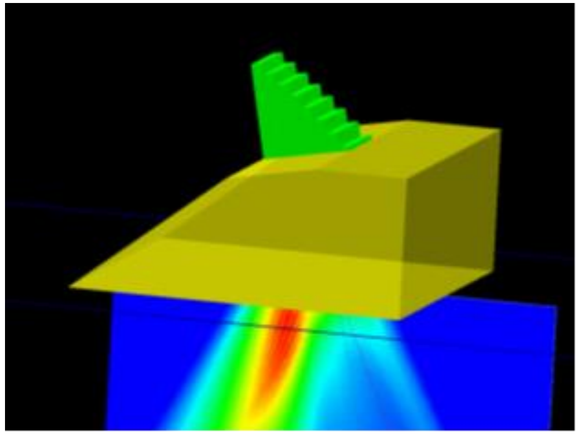




NDE Modelling: Ultrasound

- CIVA, Athena, PZ-Flex…

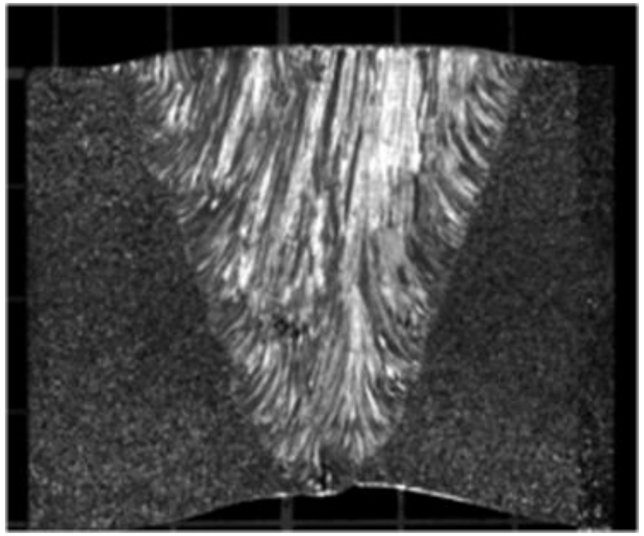
  A number of different techniques used:
  - semianalytical models, ray tracing
  - finite elements (2D and 3D)
  - point source synthesis
  - a combination of approaches to benefit of the simpler physics in the coupling medium

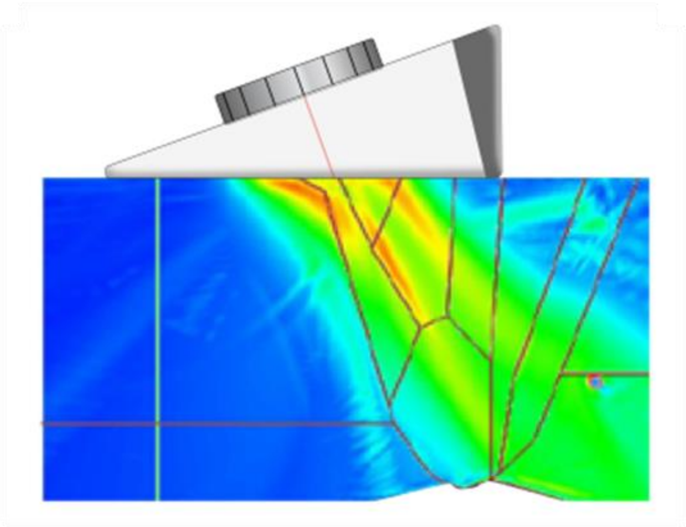




Weld inspection

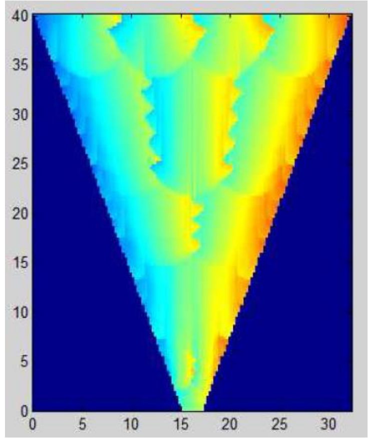
- The micro and macrostructure of the weld affects the ultrasonic beam and degrades inspection performance.
- Beam deviation due to anisotropy can lead to wrong positioning of defects
- Coarse grain structures reduce signal to noise ratio due to backscatter
- Modeling helps to understand these phenomena and to determine inspection parameters to minimize their effect
- **But requires knowledge about the structure to be inspected**

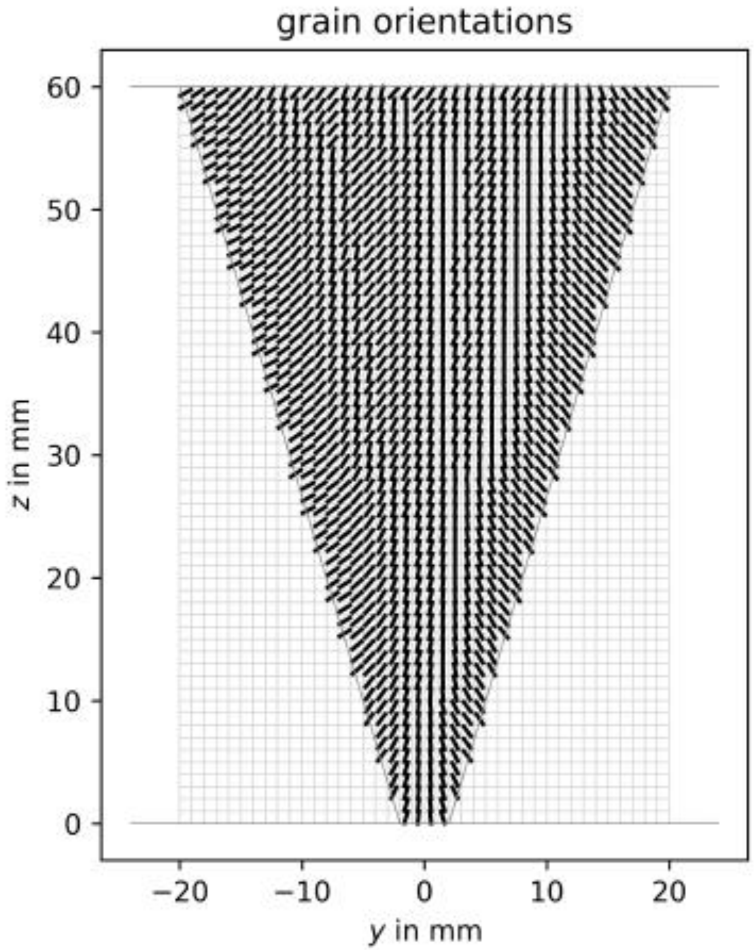




Weld modeling

- Knowledge of the actual weld structure is necessary to properly interpret UT data
- Weld modeling allows to predict the weld structure from the welding specification
- MINA is a 2D weld prediction model for TIG welds (tungsten inert gas)
- The output of MINA is a cartography of the weld, indicating local grain orientation



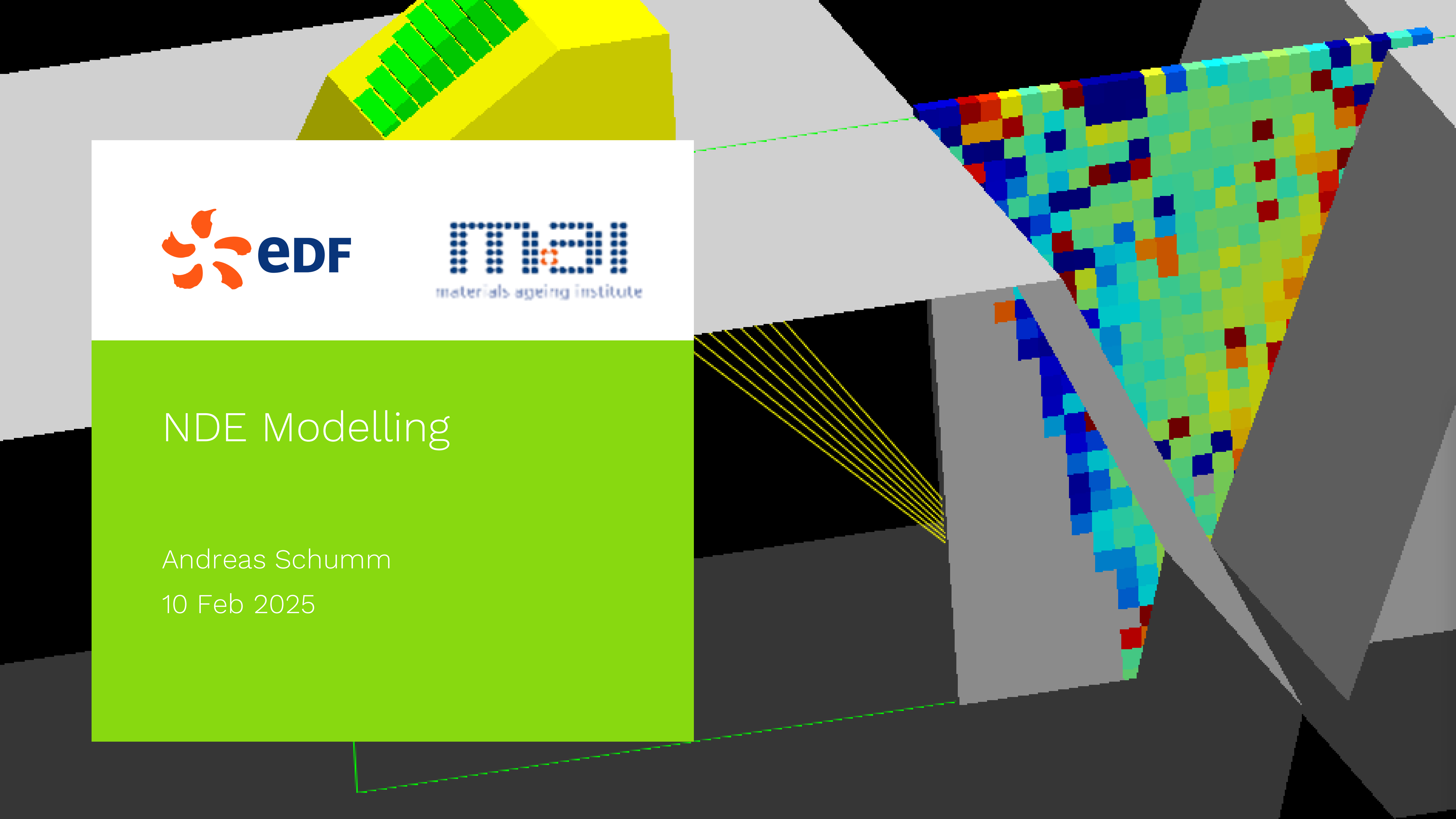


Techniques not mentioned

- Visual Inspection
- IR and Thermal methods
- …

NDT Handbook, third edition [in print]

Vol. 1, *Leak Testing*
Vol. 2, *Liquid Penetrant Testing*
Vol. 3, *Infrared and Thermal Testing*
Vol. 4, *Radiographic Testing*
Vol. 5, *Electromagnetic Testing*
Vol. 6, *Acoustic Emission Testing*
Vol. 7, *Ultrasonic Testing*
Vol. 8, *Magnetic Testing*
Vol. 9, *Visual Testing*
Vol. 10, *NDT Overview*



NDE Modelling

Andreas Schumm

10 Feb 2025

Computer Modelling of NDE techniques

- Some history
- Motivation – why develop and use computer models for NDE techniques?
- Codes and Applications for
  Ultrasound
  Eddy Current
  Radiography*

Computer Modelling of NDE techniques

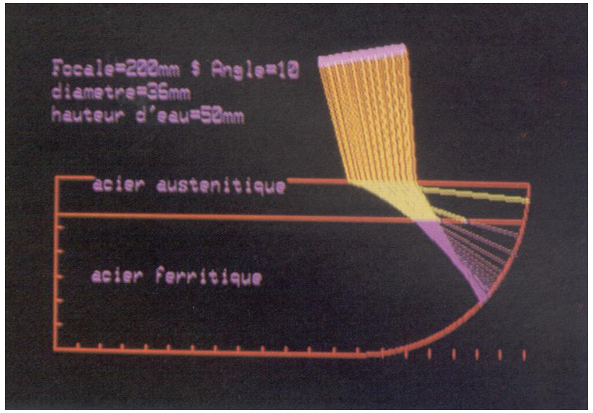
Phase 1: Exploration

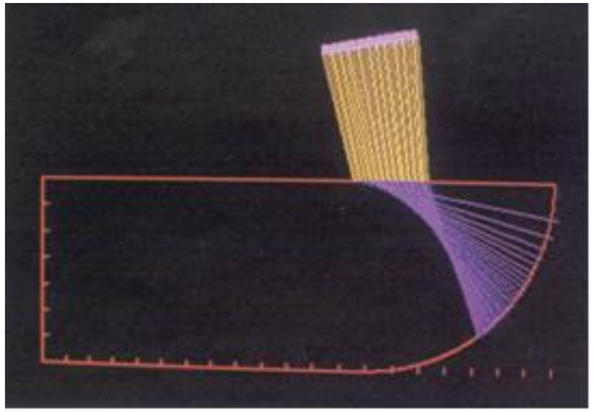
1980 1985 1990 1995 2000 2005 2010 2015 2020 2025

1979

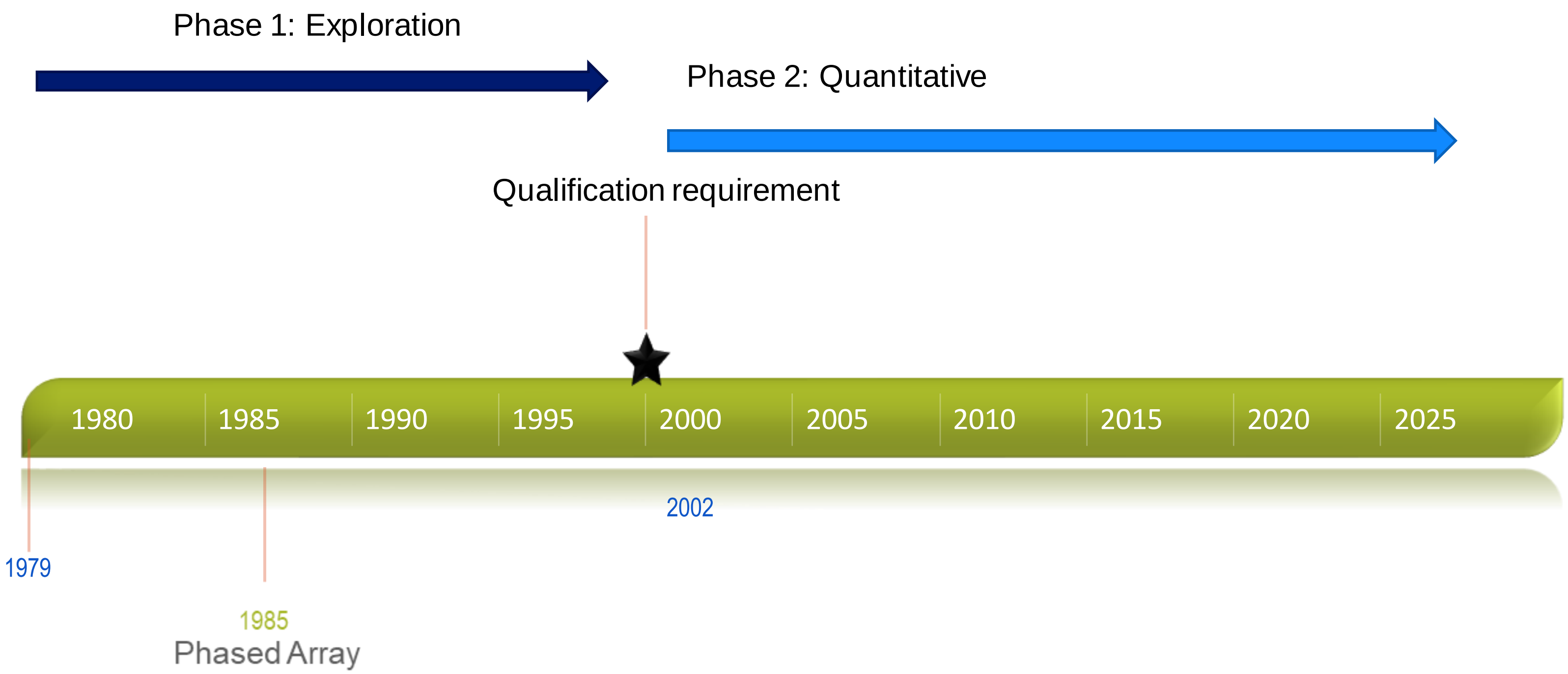
1985
Phased Array

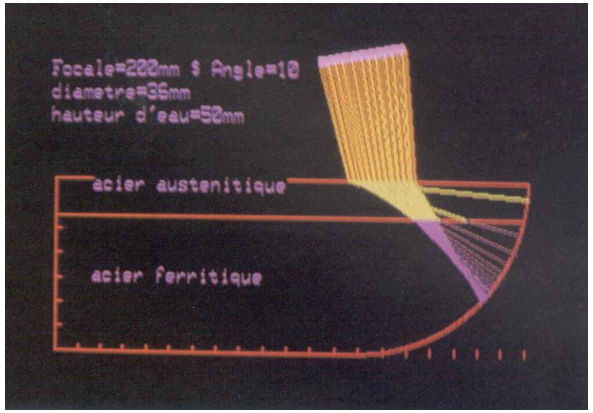
2002
Time reversal
(Fink)

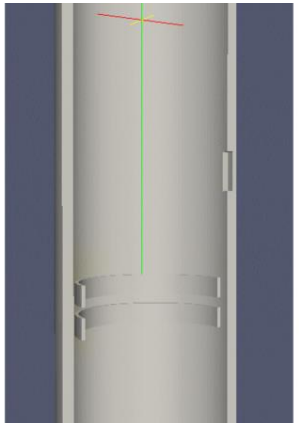


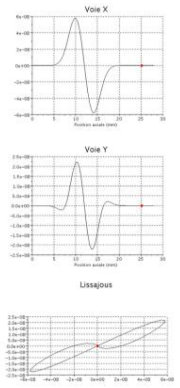


Computer Modelling of NDE techniques

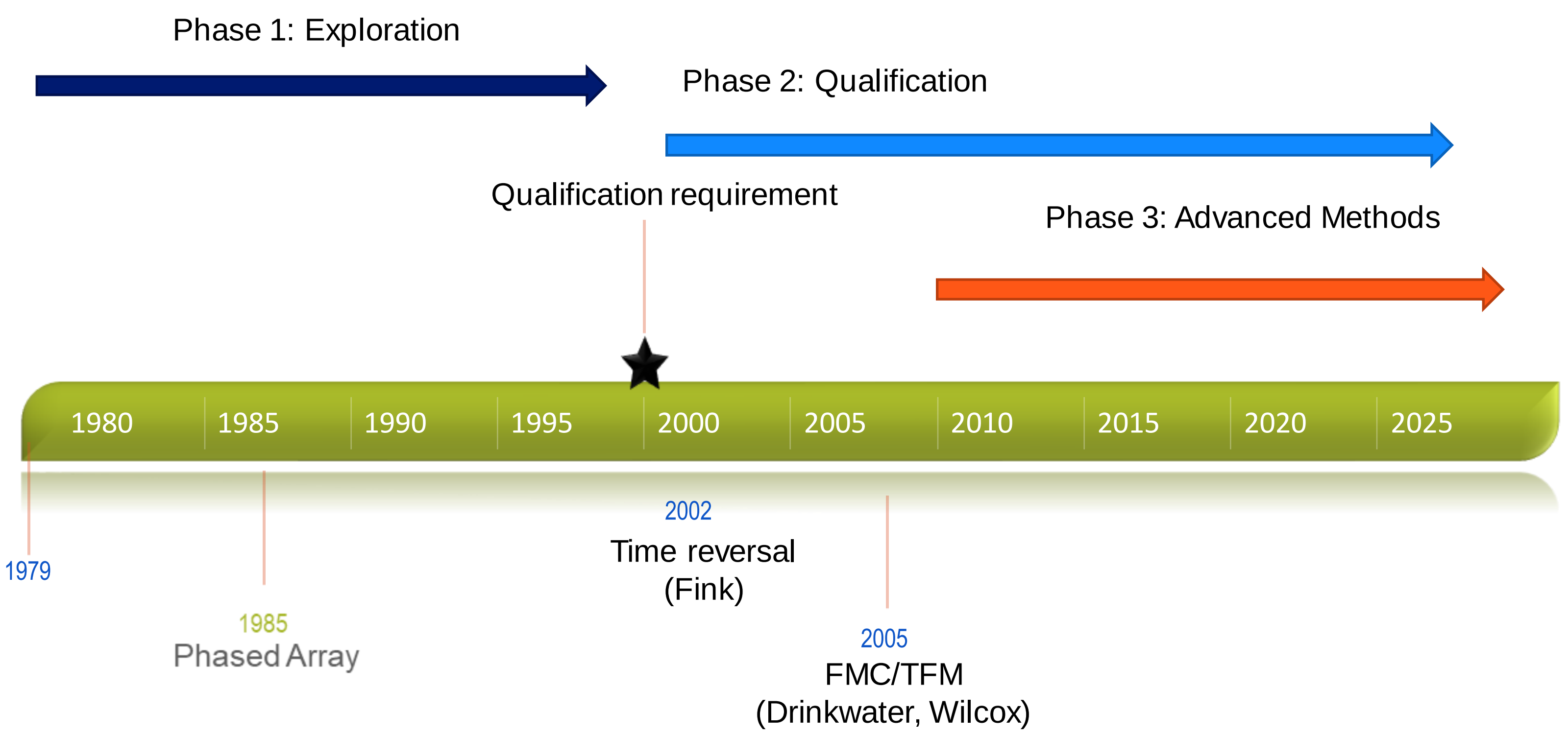


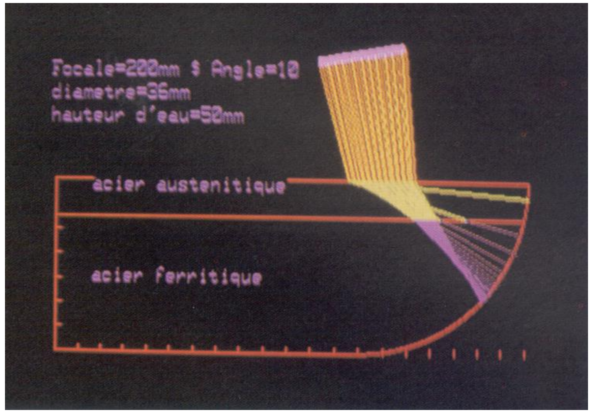


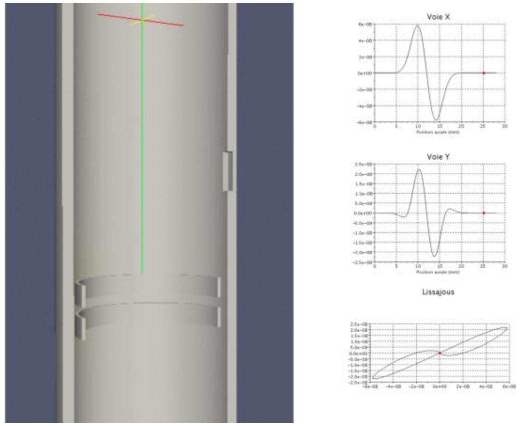


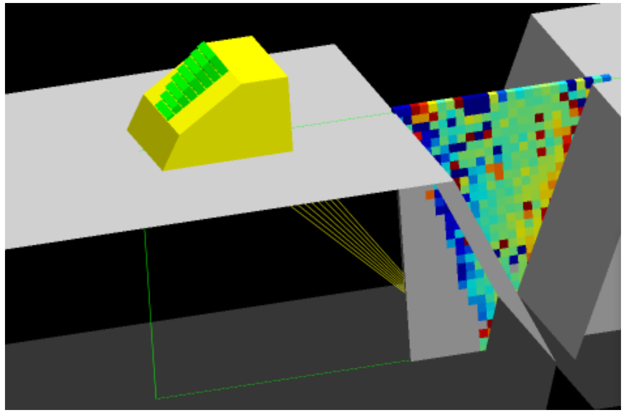


Computer Modelling of NDE techniques



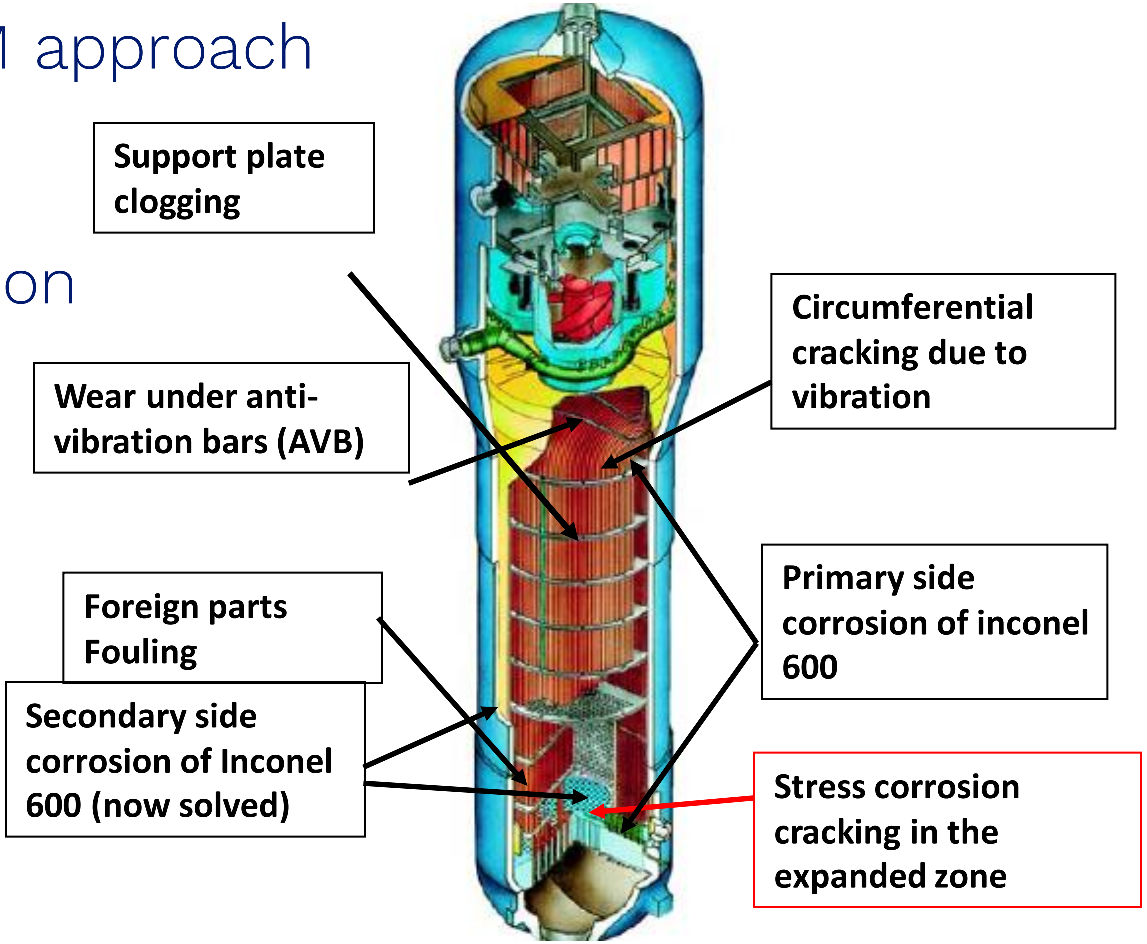




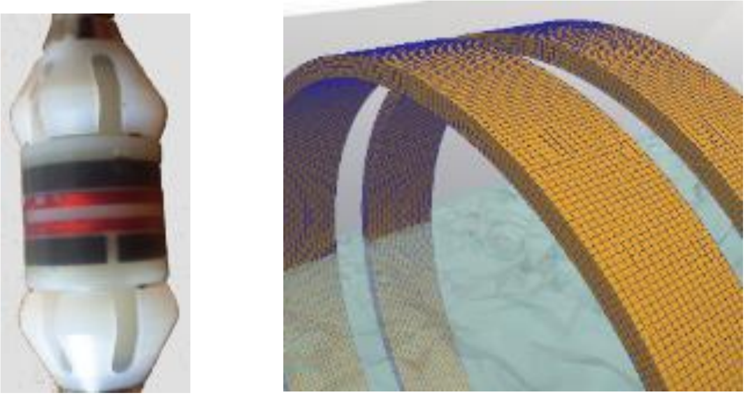


Eddy Current Modelling: Steam Generator Tube Inspection

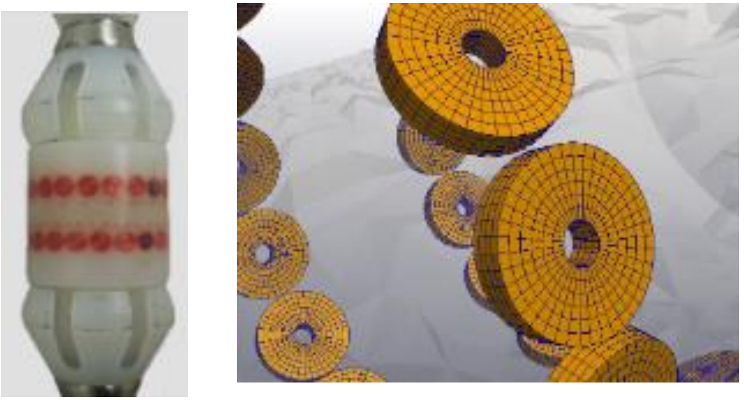
- SG tube inspection is the major ET application
- Earlier codes used combined BEM/FEM approach to avoid meshing of the air between probe and tube
- C3D uses a simpler FEM only formulation
- This allows to simulate configurations where the environment must be taken into account (AVB, TSP, fouling)



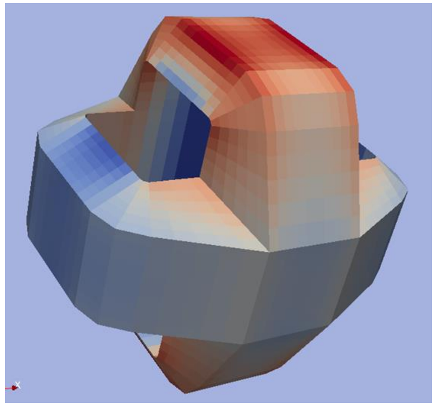
Eddy Current Modelling: C3D



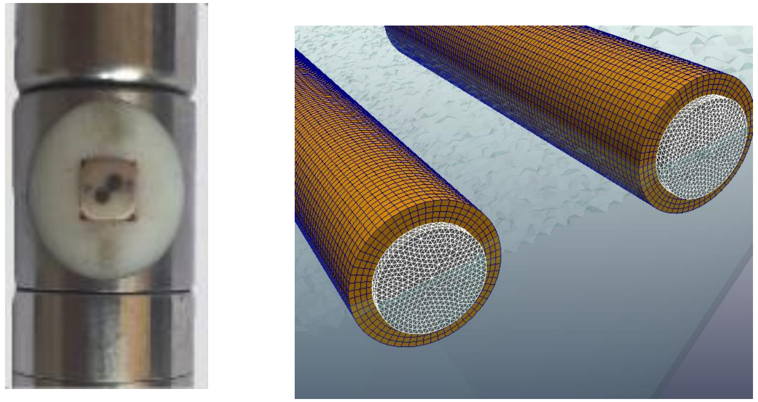
Axial Probe



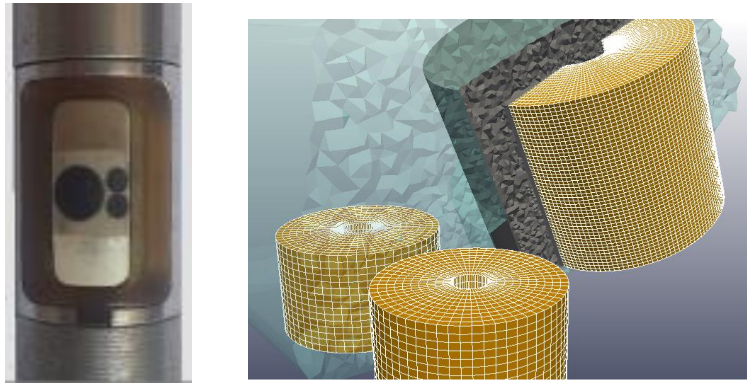
X-Probe



PlusPoint



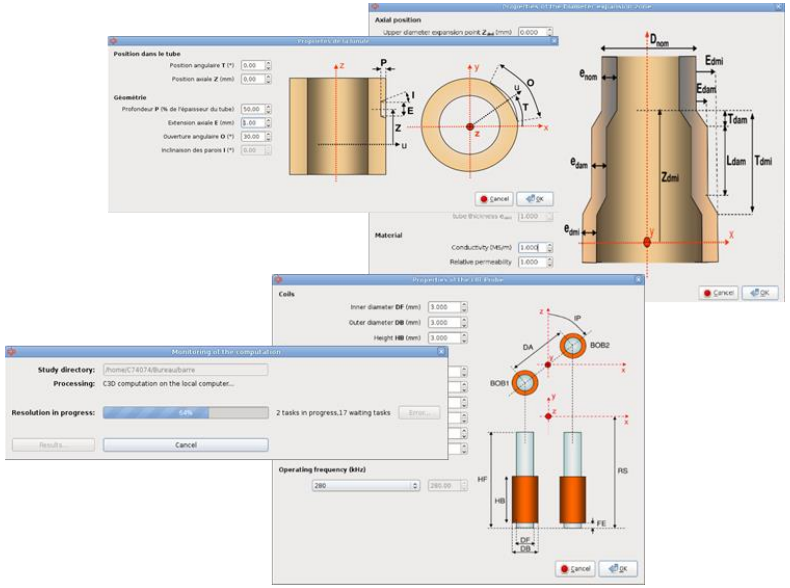
Long Rotating Probe



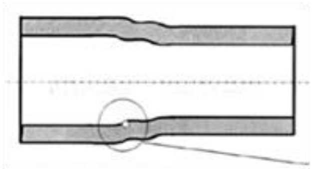
Transverse Rotating Probe

Eddy Current Modelling: Types of defects

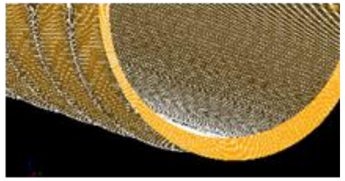
- Most of the work done with C3D concerns qualification…but not all
- This requires simulating defect response under different conditions (influential parameters)



Lunula wear



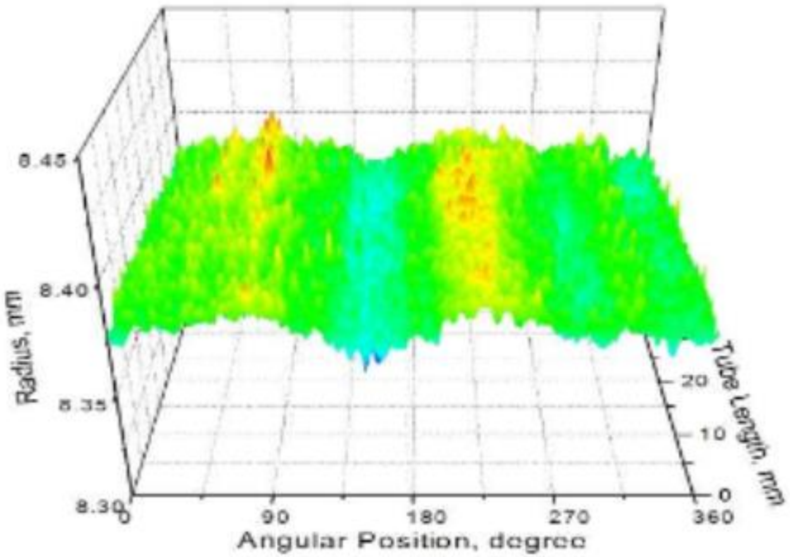
Diameter Varying Tube



Tube Profile

Eddy Current Modelling: Tube roughness

- Background noise in ET signals of SG tubes degrades inspection performance
- Prior studies [1] show that background noise is often related to irregularities of the tube inner surfaces, related to the cold pilger rolling process
- Modeling study to reproduce noise from laser scans of inner surface to confirm origin



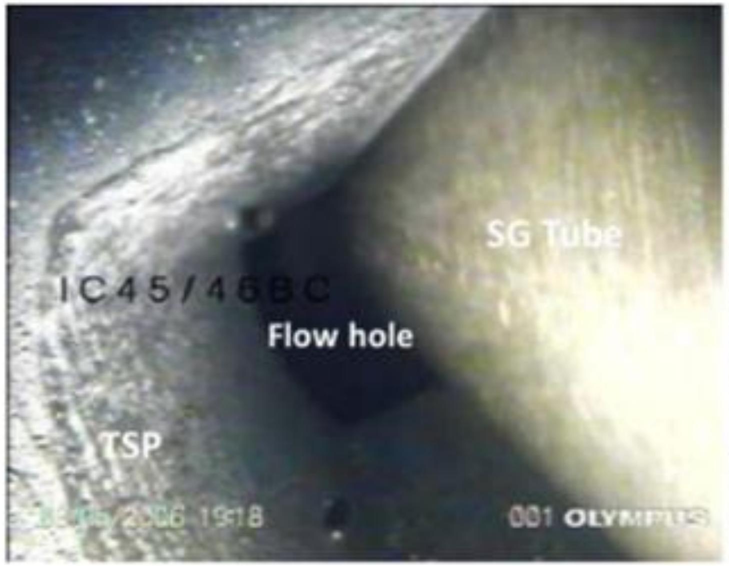
[1] A.R. McIlree, "Guidelines for PWR Steam Generator Tubing Specifications and Repair," EPRI TR-016743-V2R1, 1999

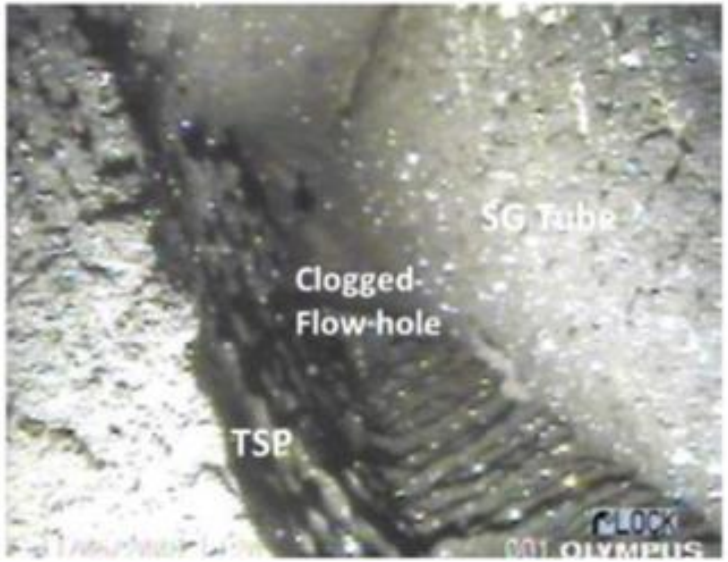
Eddy Current Modelling: Fouling and Clogging

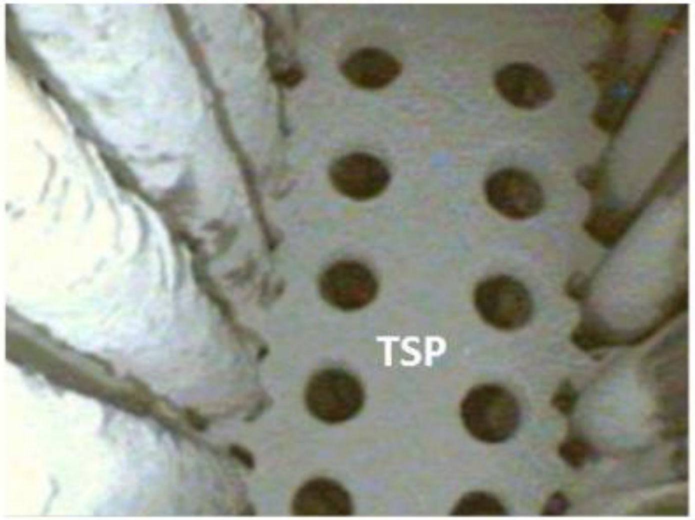
- Fouling and clogging affect the performance of the heat exchanger
- Fouling can degrade NDE performance

Two issues:

- Determine NDE performance for wear defects covered by fouling
- Can we use NDE to assess fouling?

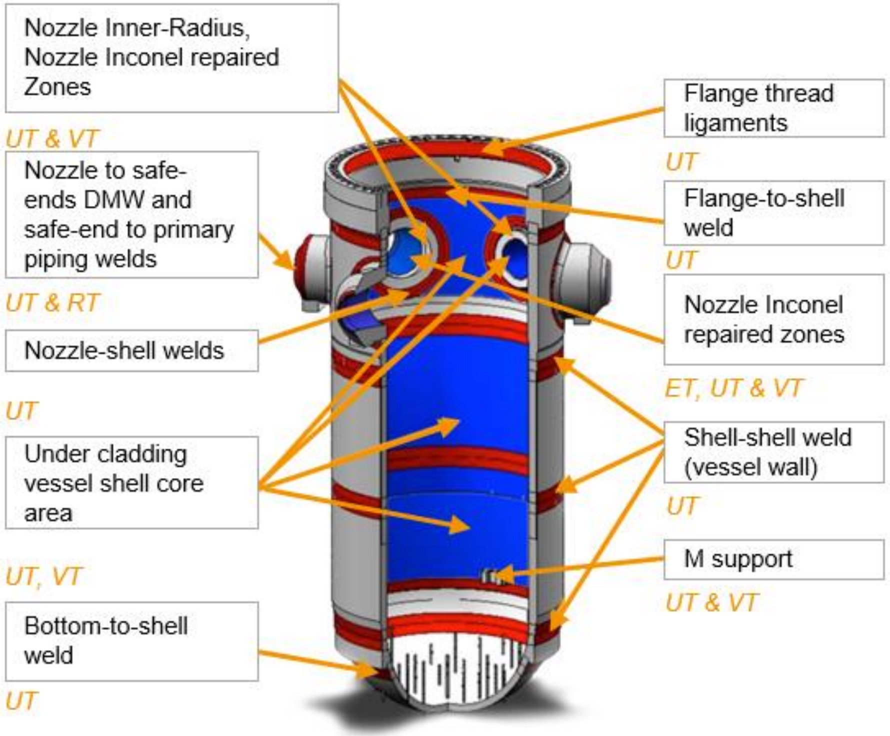


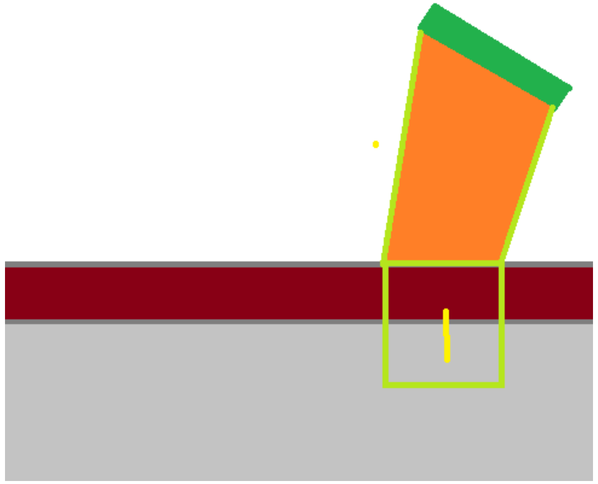


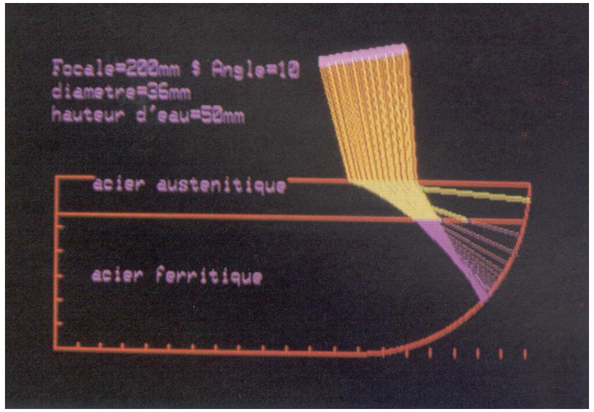


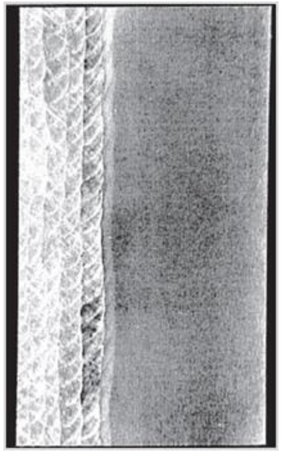
Ultrasound Modelling

- First application: Sub cladding defects in the pressure vessel (mid 80s)
- Inspection by large focused transducers in immersion
- The long water path made this problem challenging (because $\lambda = c/f$)
- A combined surface integral/FEM approach to avoid meshing the water path



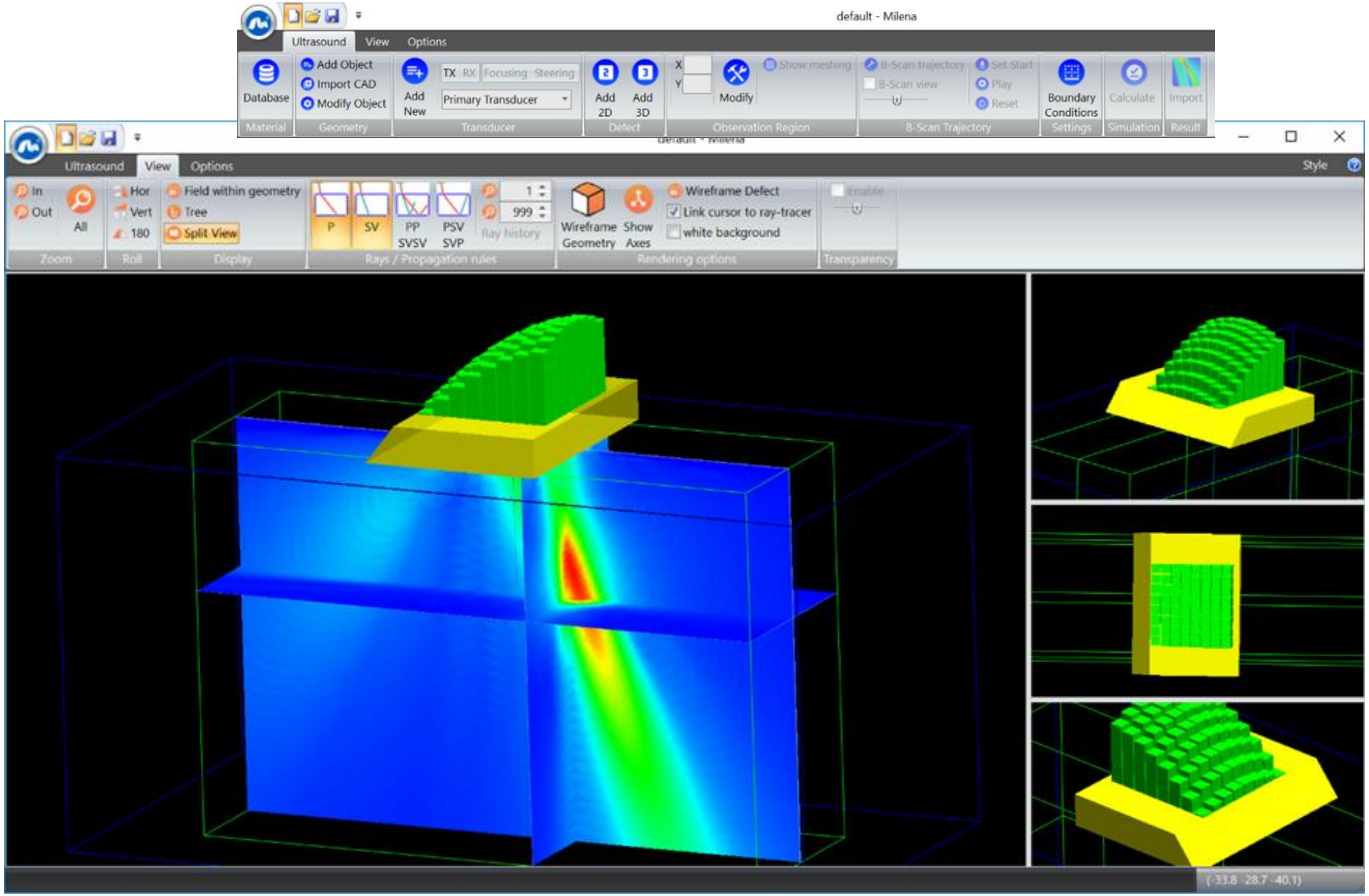


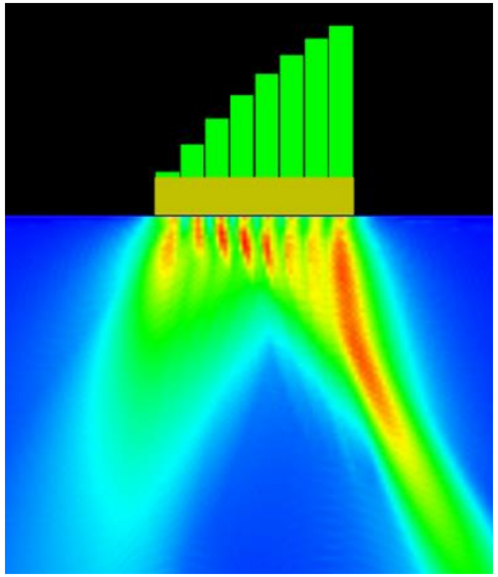


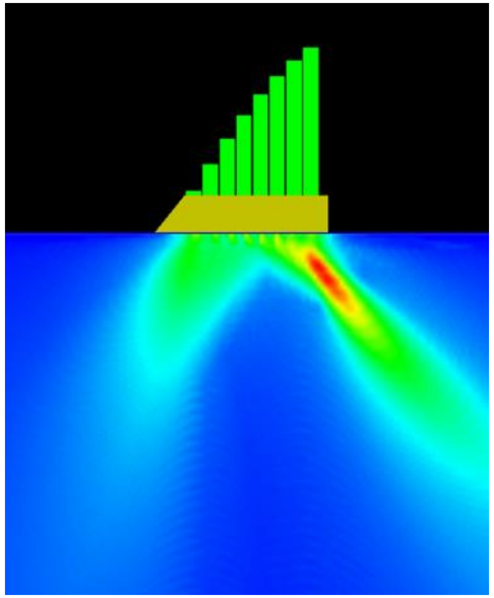


Ultrasound Modelling: Athena-2D

- Graphical user interface MILENA and solver Athena
- All transducer types

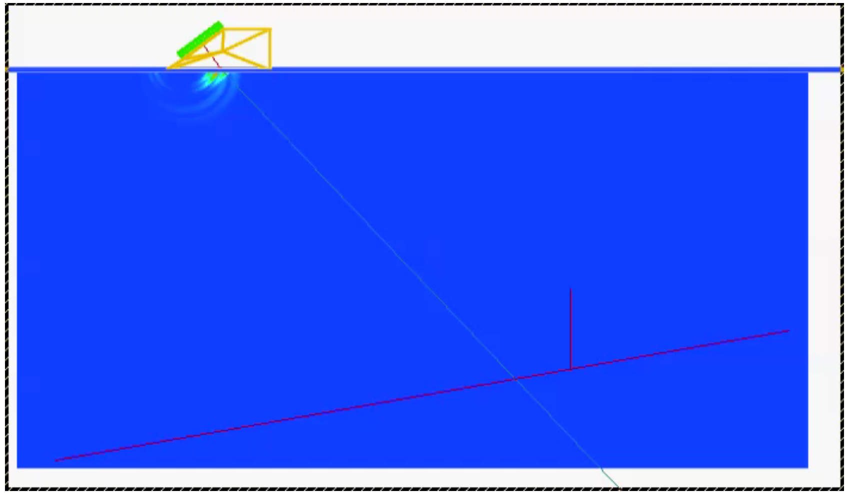


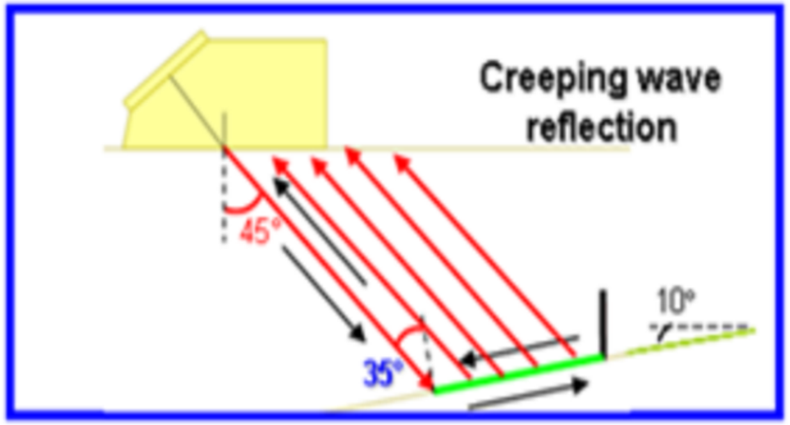


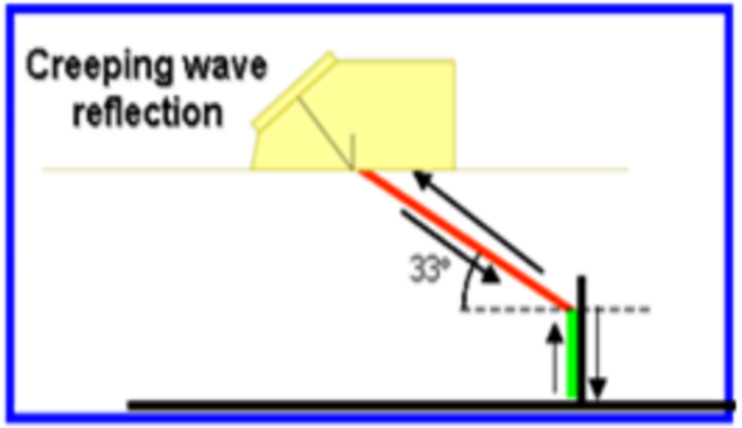


Ultrasound Modelling: Complex wave/defect interaction

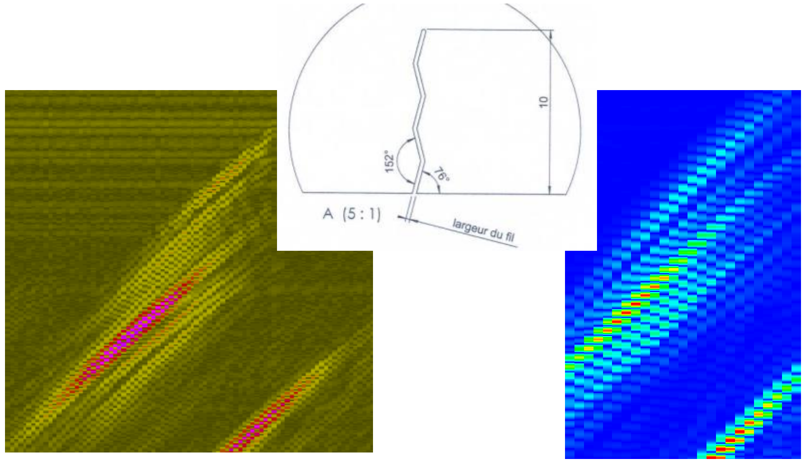
- Creeping waves

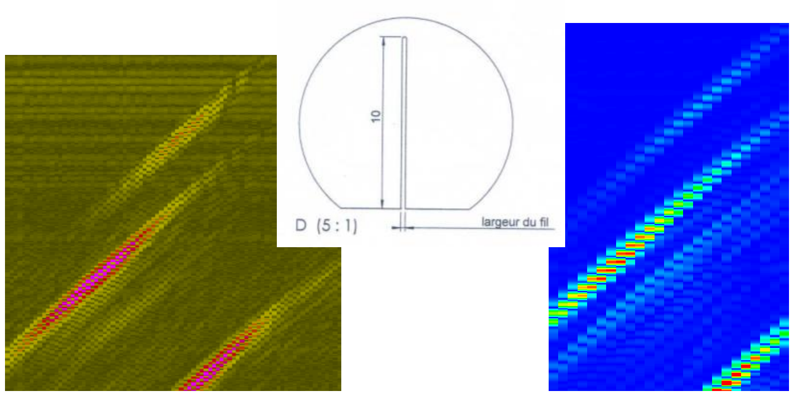






- Complex shaped defects (SCC)

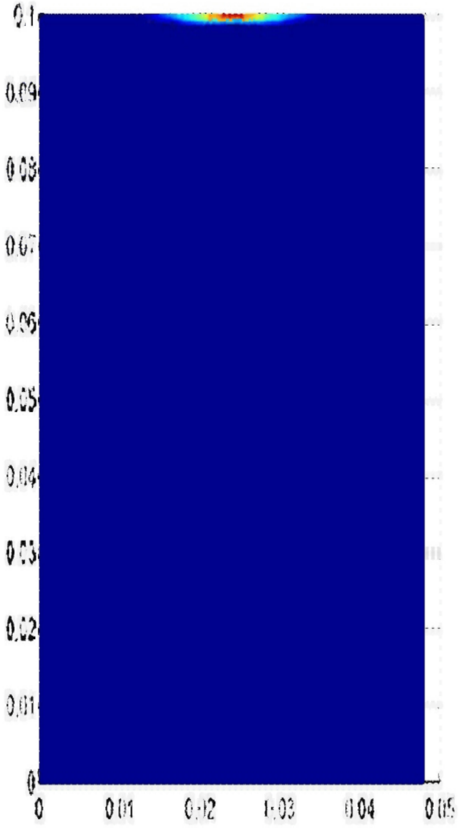


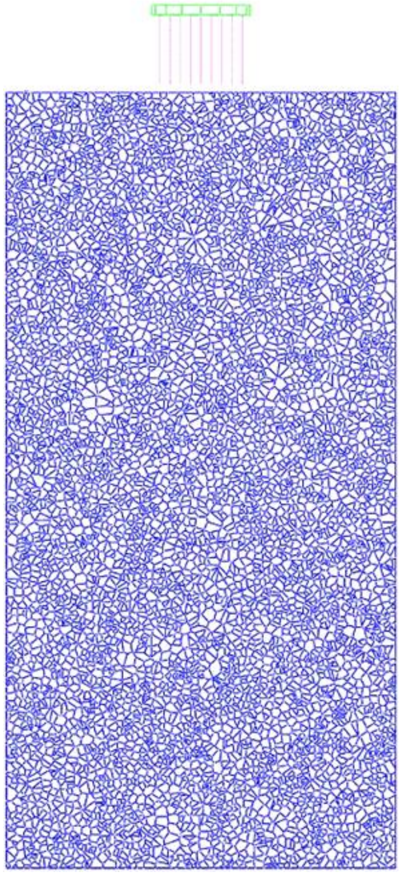


Ultrasound Modelling: Complex structured materials

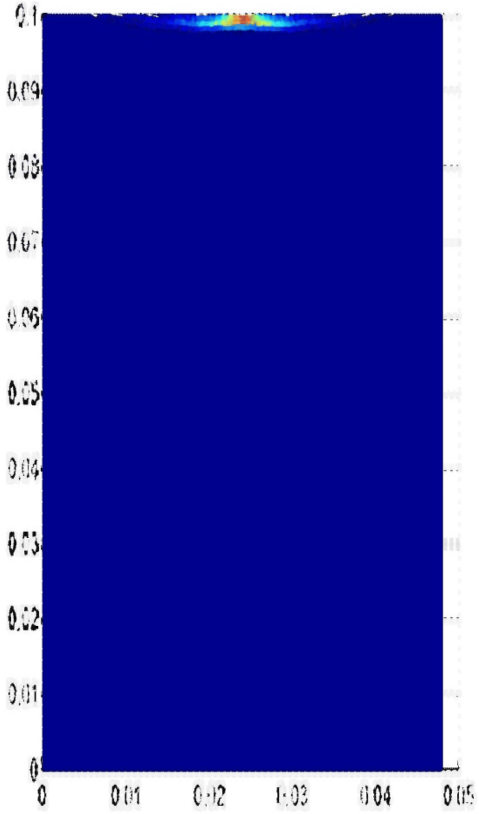
- Finite Elements are well adapted to study strongly heterogeneous materials: Cladding, welds and cast austenitic stainless steel (CASS)

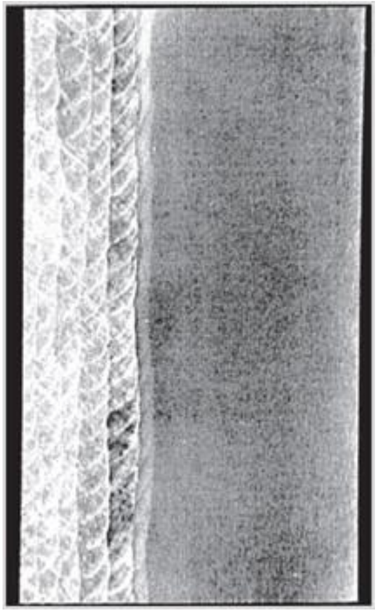
Low frequency

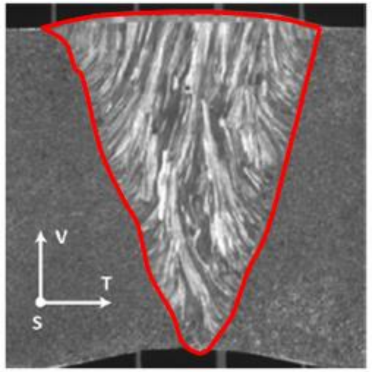




High frequency

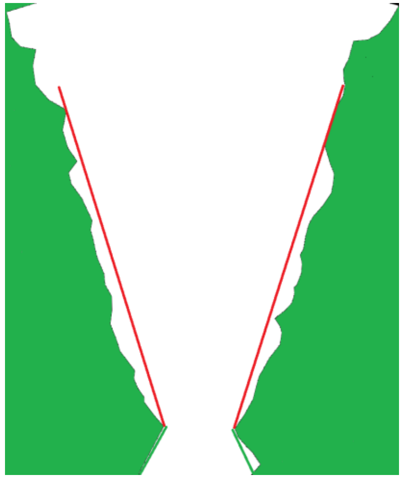


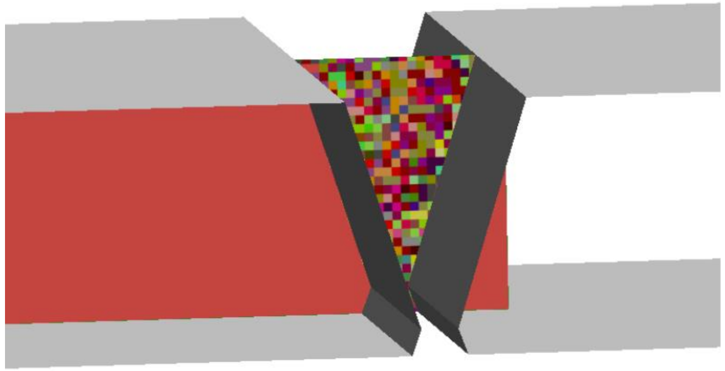


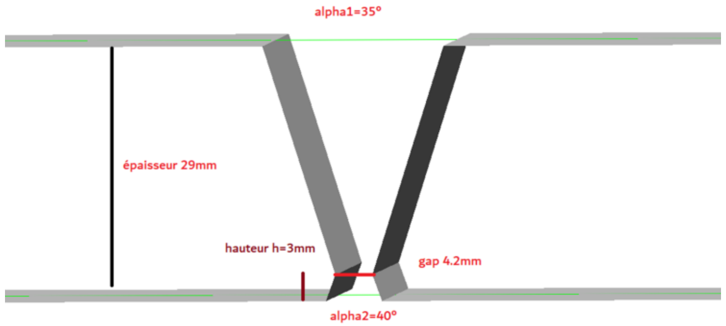


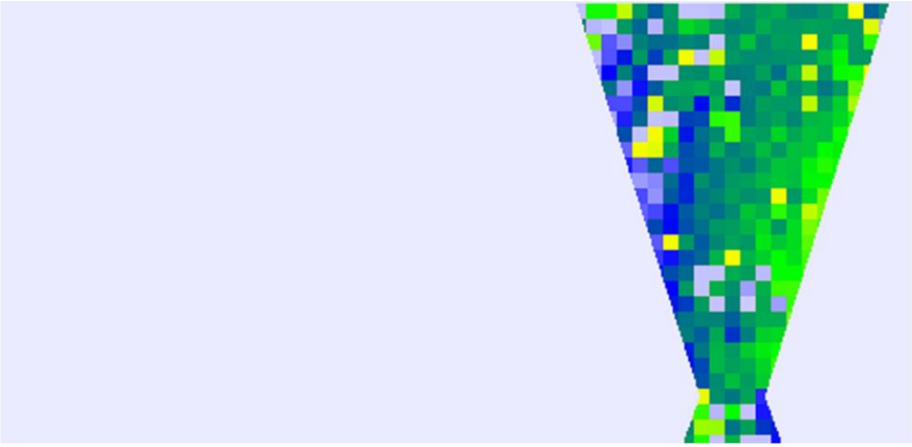
Ultrasound Modelling: SCC in safety injection line

- Combine digitized macrograph with weld chamfer model to produce finite element mesh



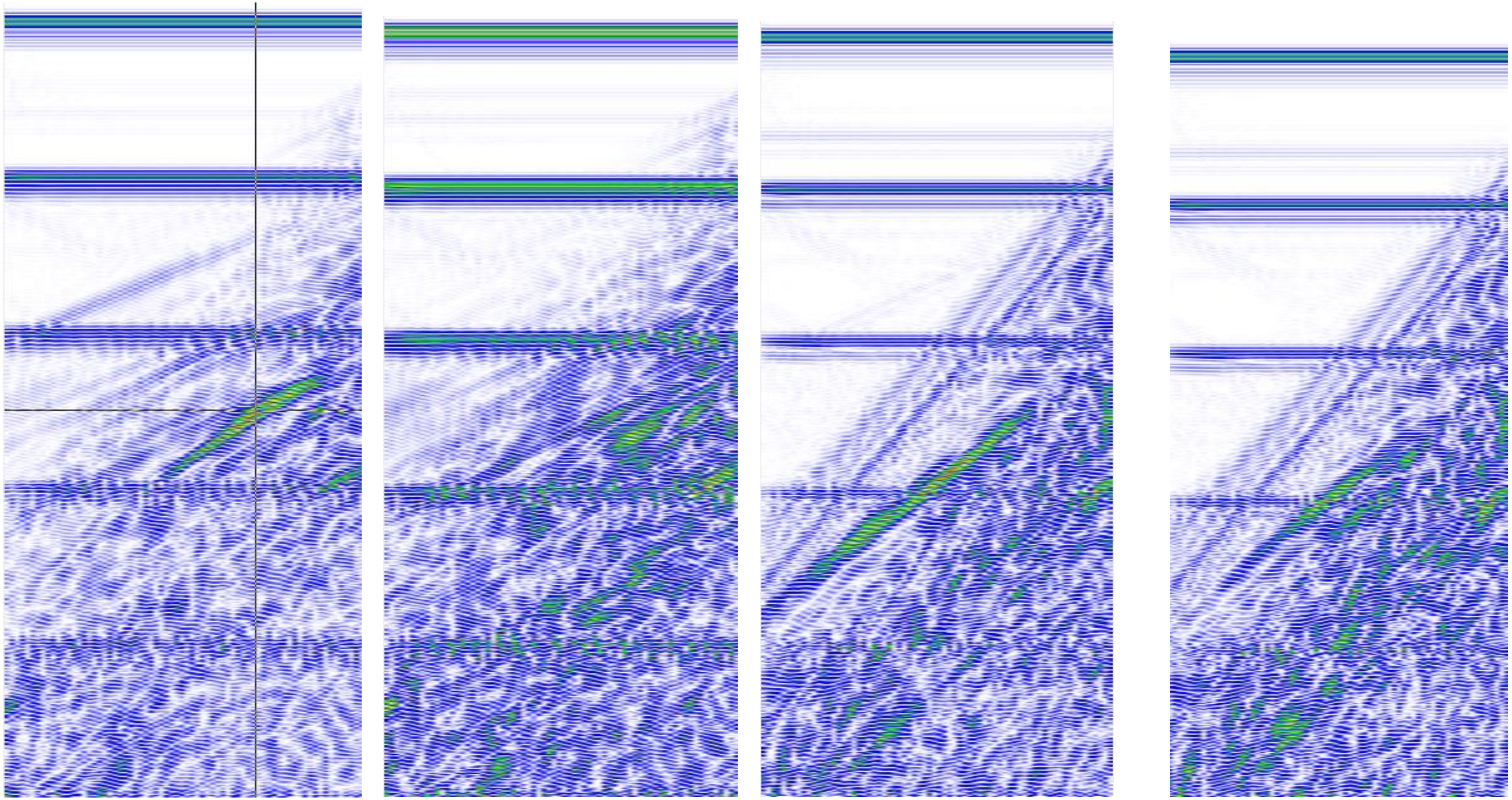






Ultrasound Modelling: SCC in safety injection line

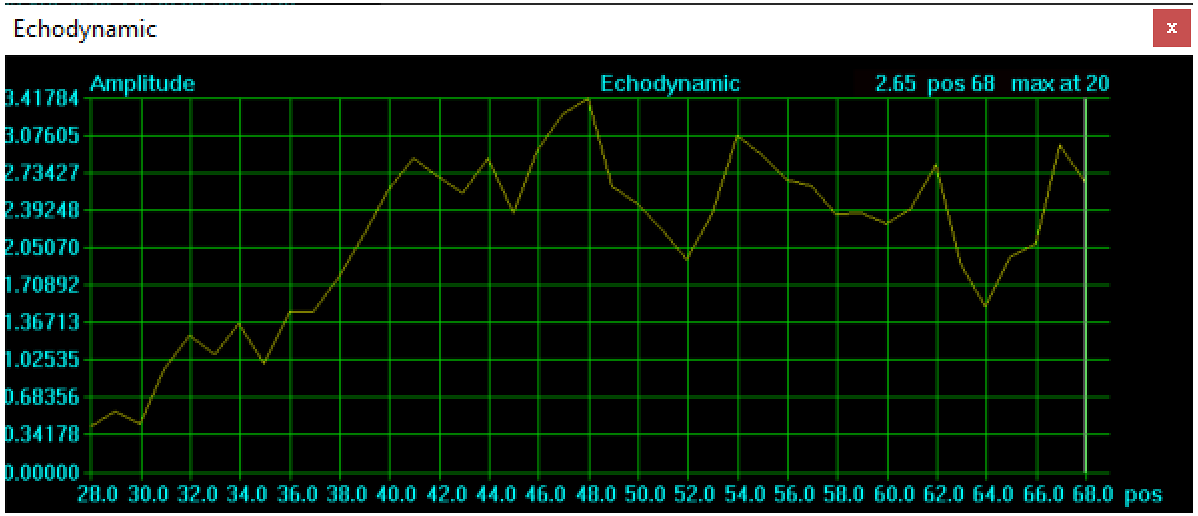
T40° plane defect +3dB | T40° weld only | T55° plan defect +1dB | T55° weld only

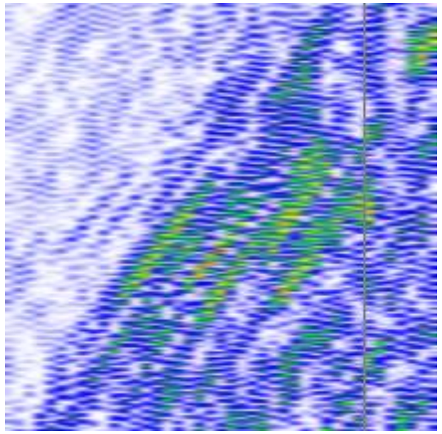


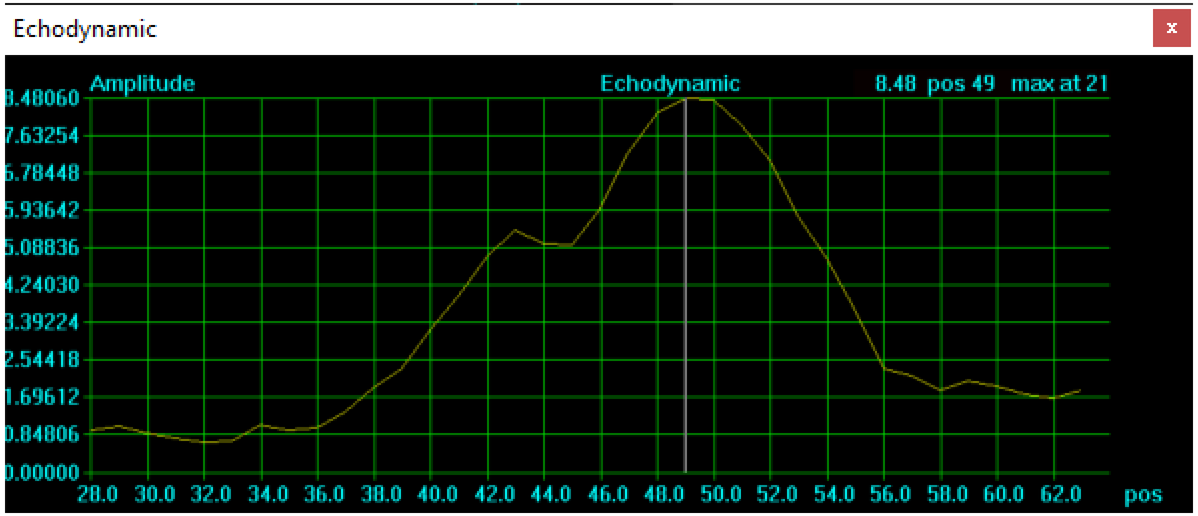
Conclusion: The weld chamfer generates form echoes which can easily be confused with a real defect.

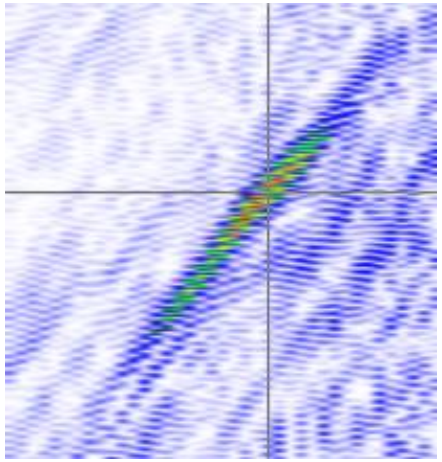
Ultrasound Modelling: SCC in safety injection line

Results at 5MHZ T45° - better focusing reduces weld form echoes









Plane defect +10dB

Ultrasound Modelling: EPR set-in weld inspection

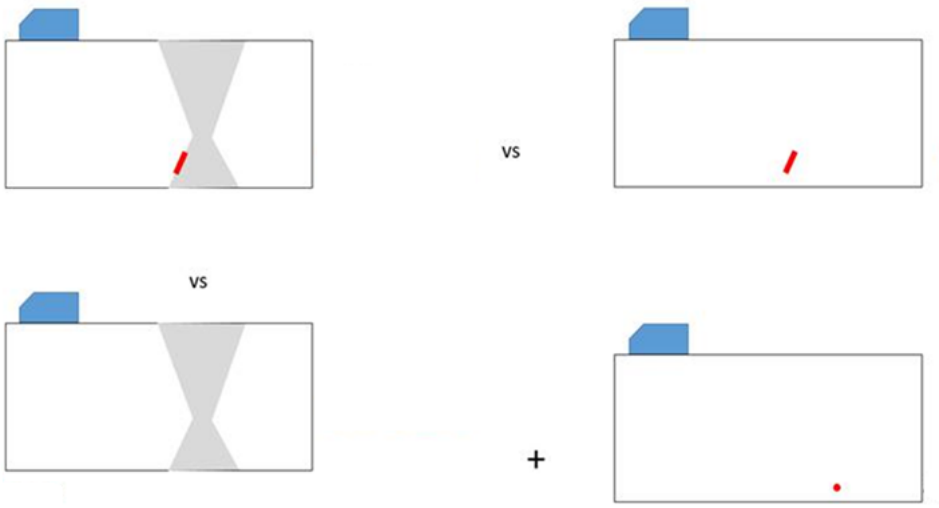
- Study the detectability of defects within the set-in weld
- To what extent does the weld affect the inspection?
- Transducer: 16 element PA with 55° L-wave delay laws
- 4 configurations

Lack of fusion on weld root

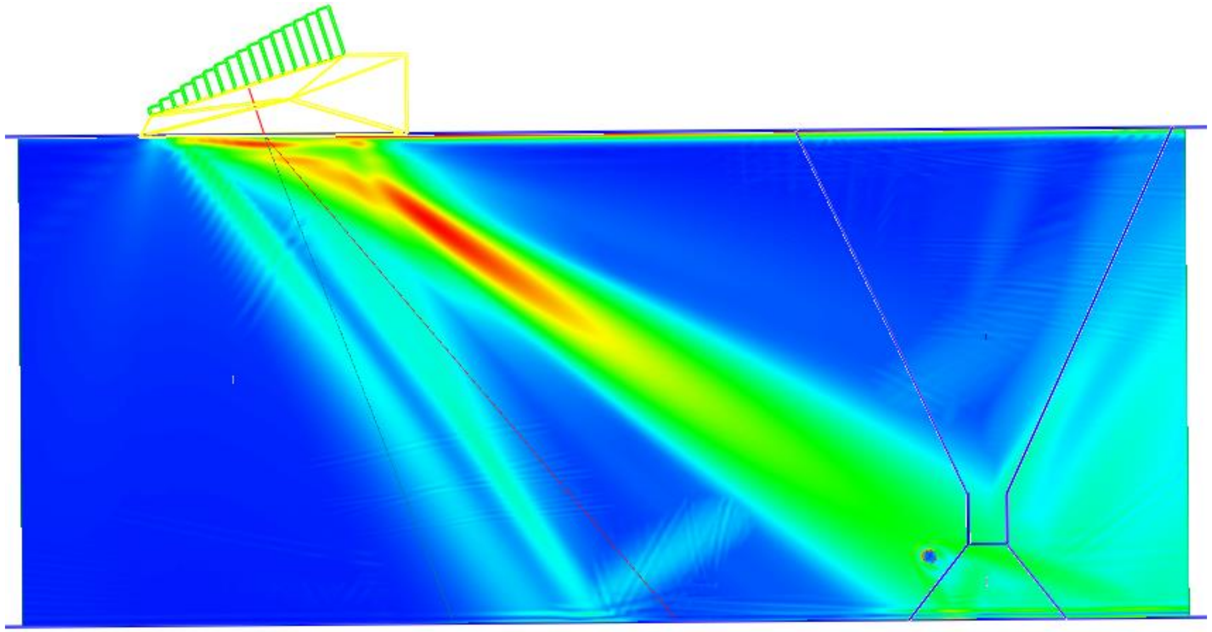
defect in base metal

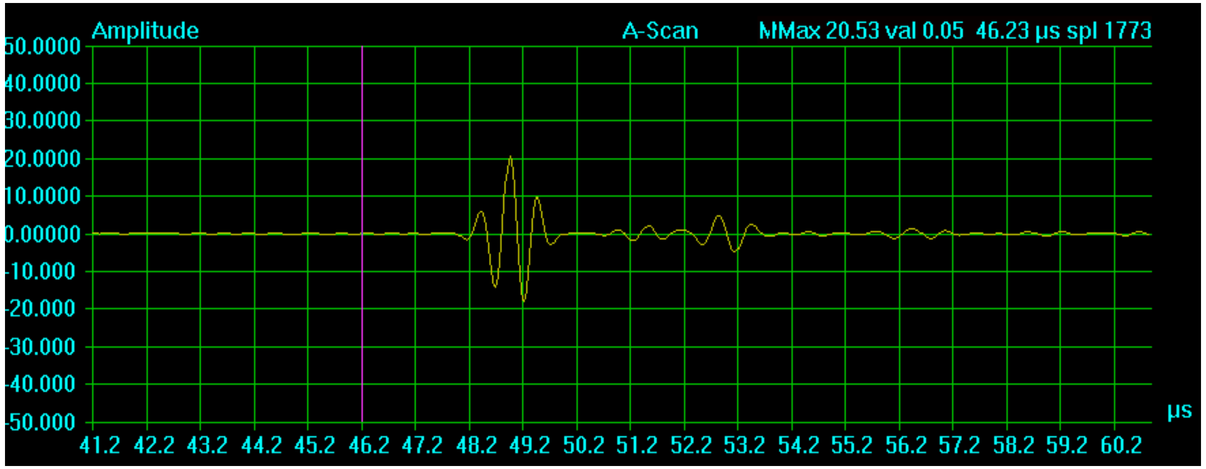
Weld alone

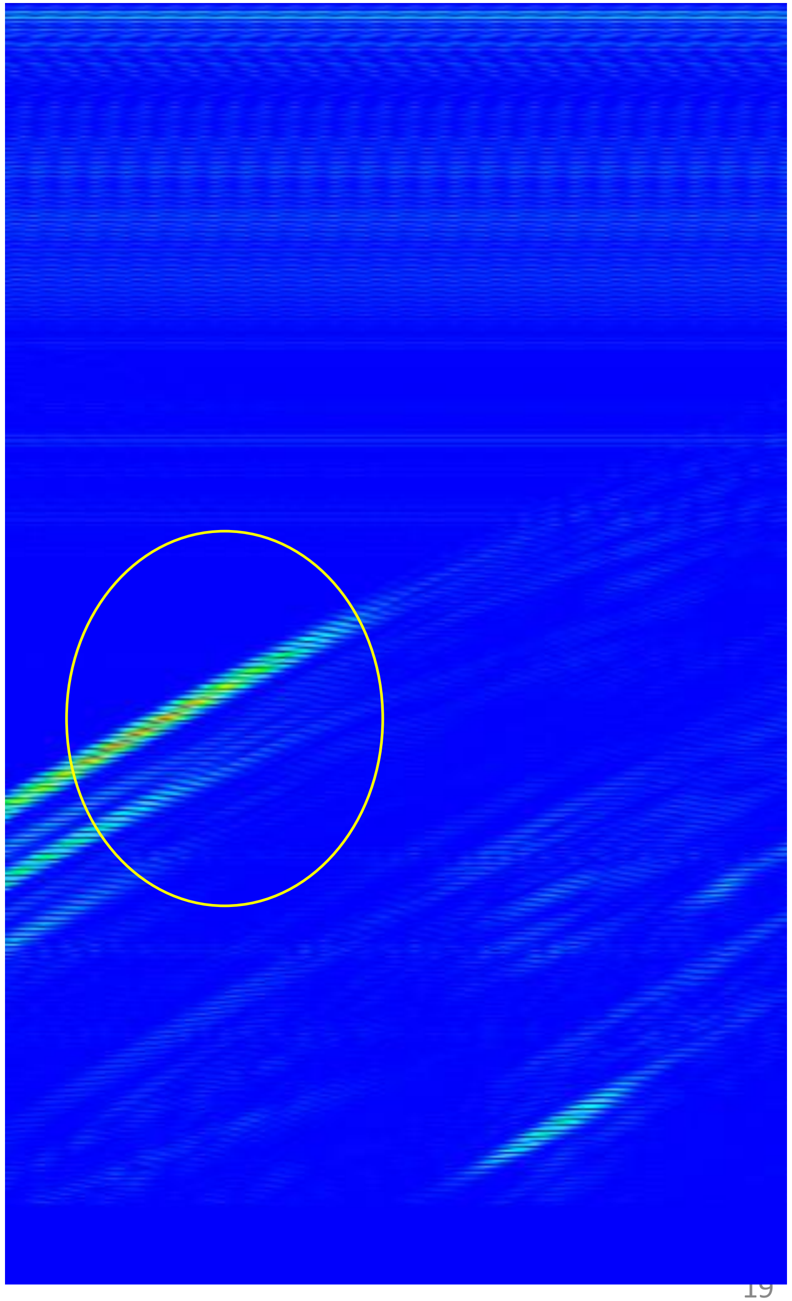
reference SDH



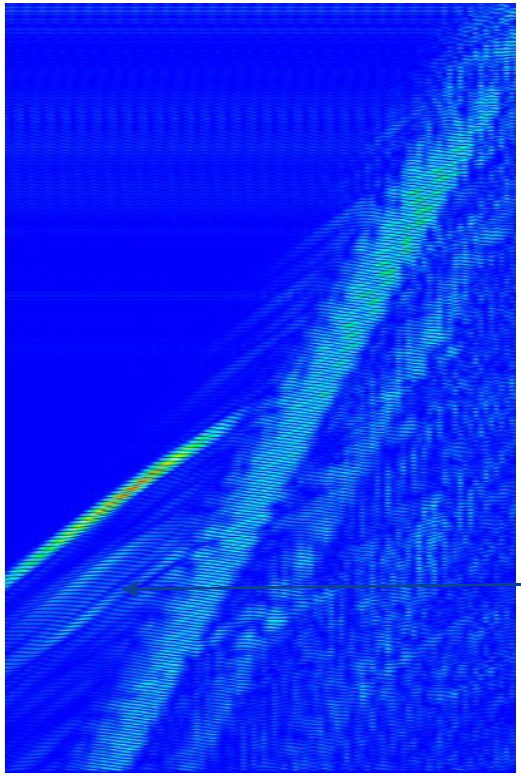
Reference: SDH 2mm 68mm depth in base metal

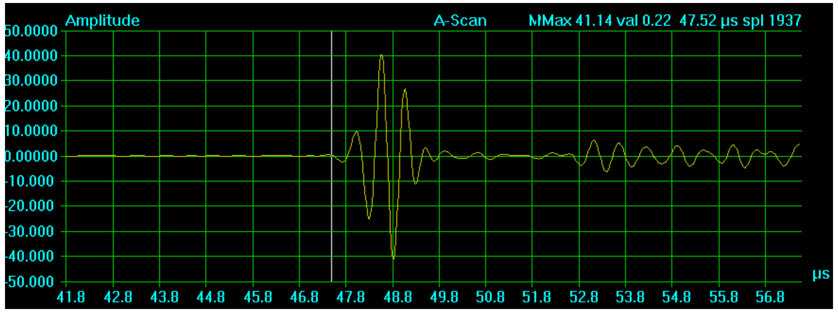


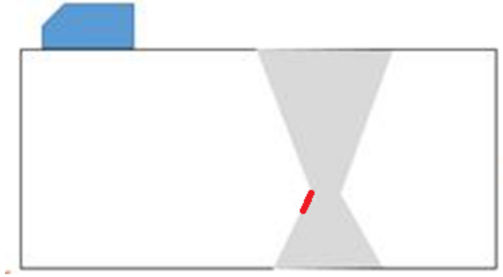


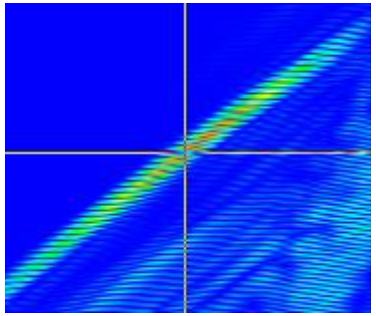


Lack of fusion on top of lower chamfer +6dB with respect to reference defect

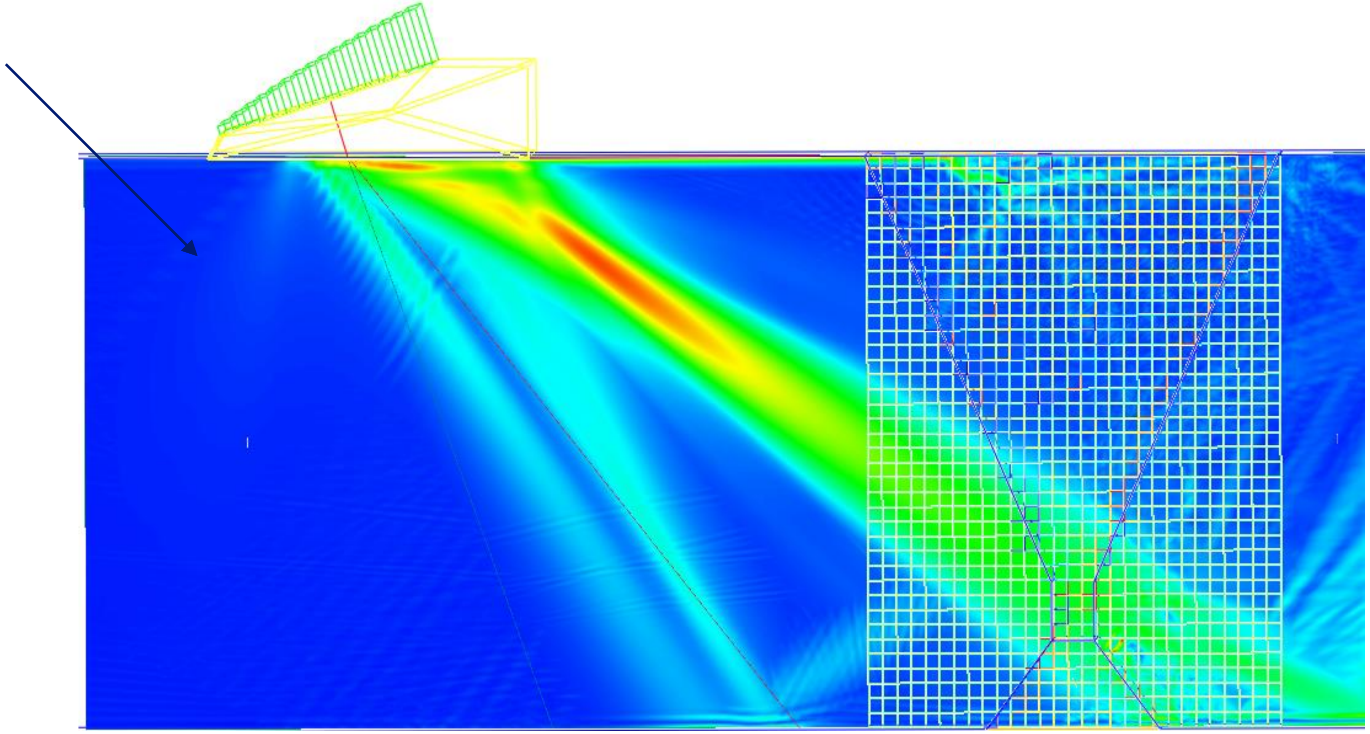


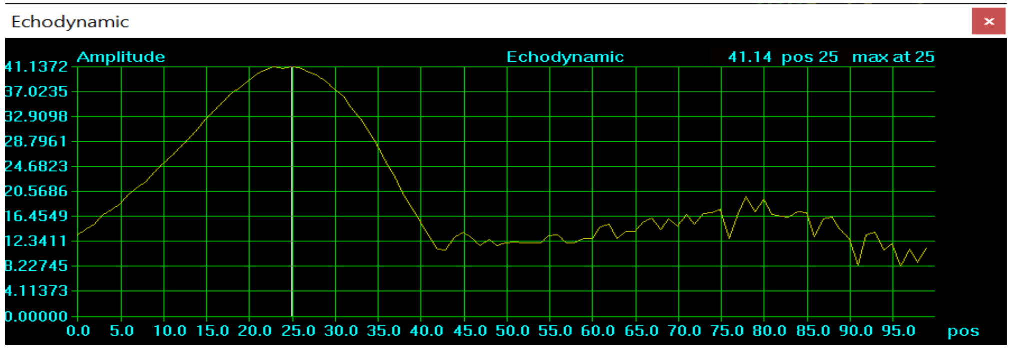




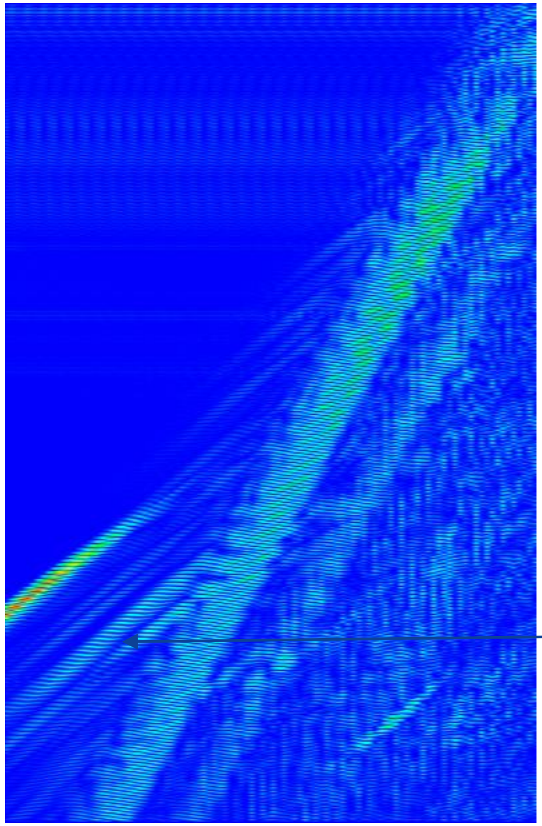


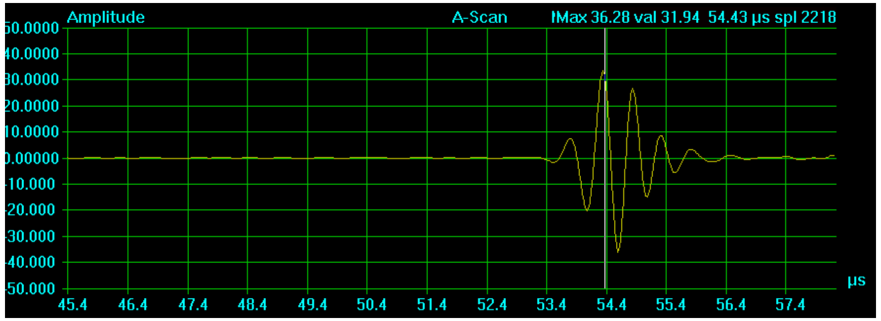
Some parasitic echoes

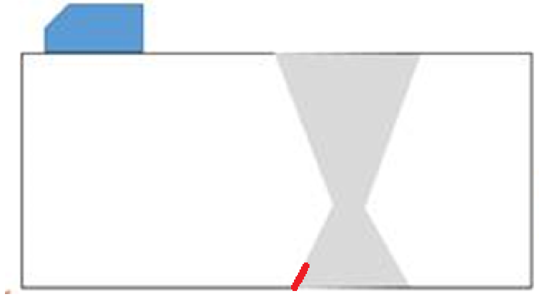


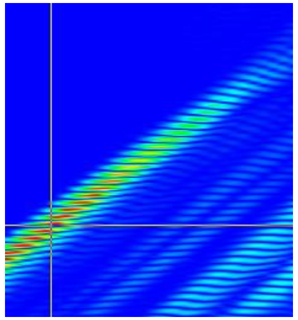


Lack of fusion on bottom of lower chamfer +5dB with respect to reference defect

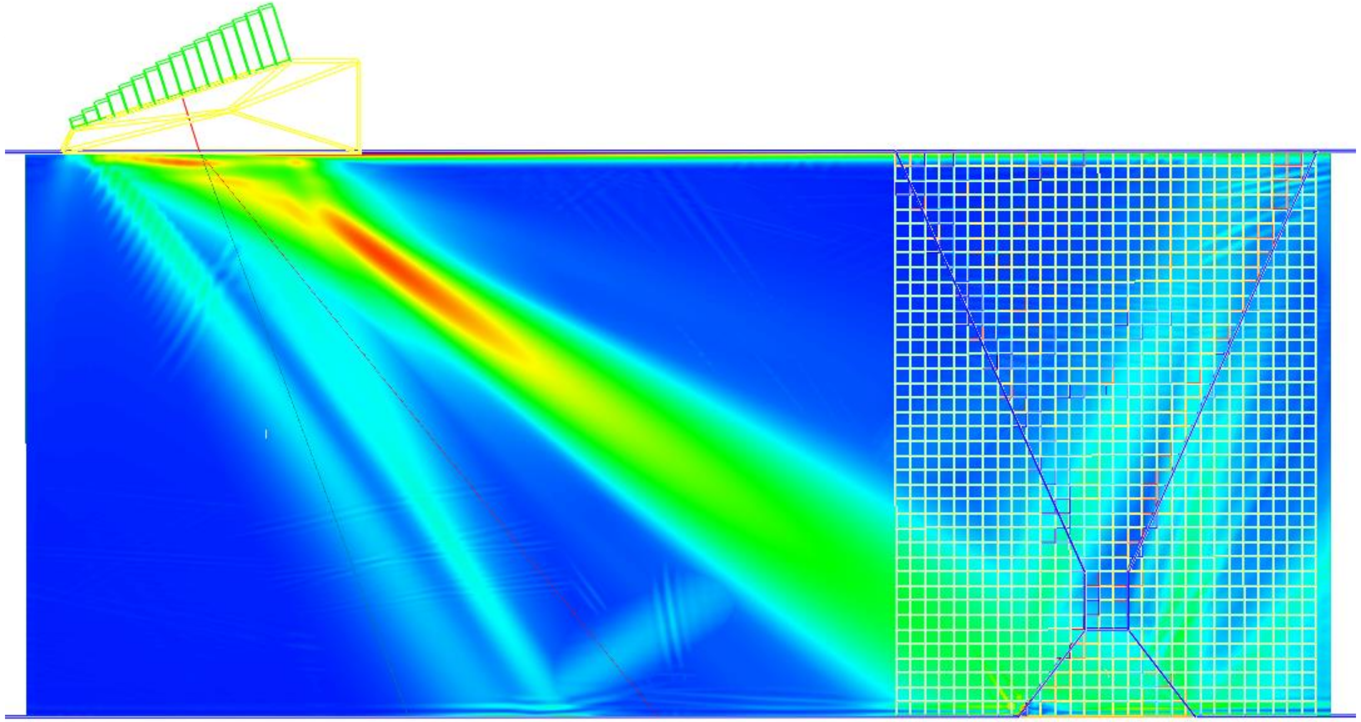


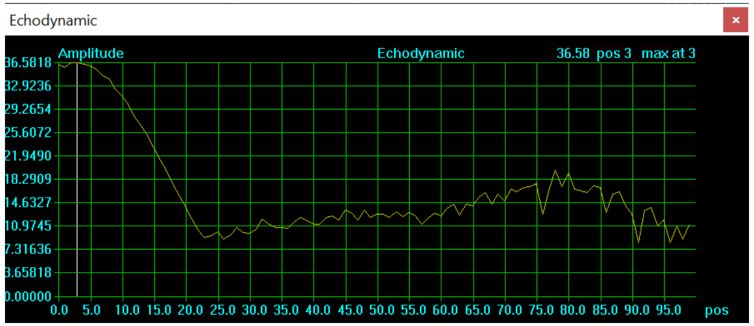




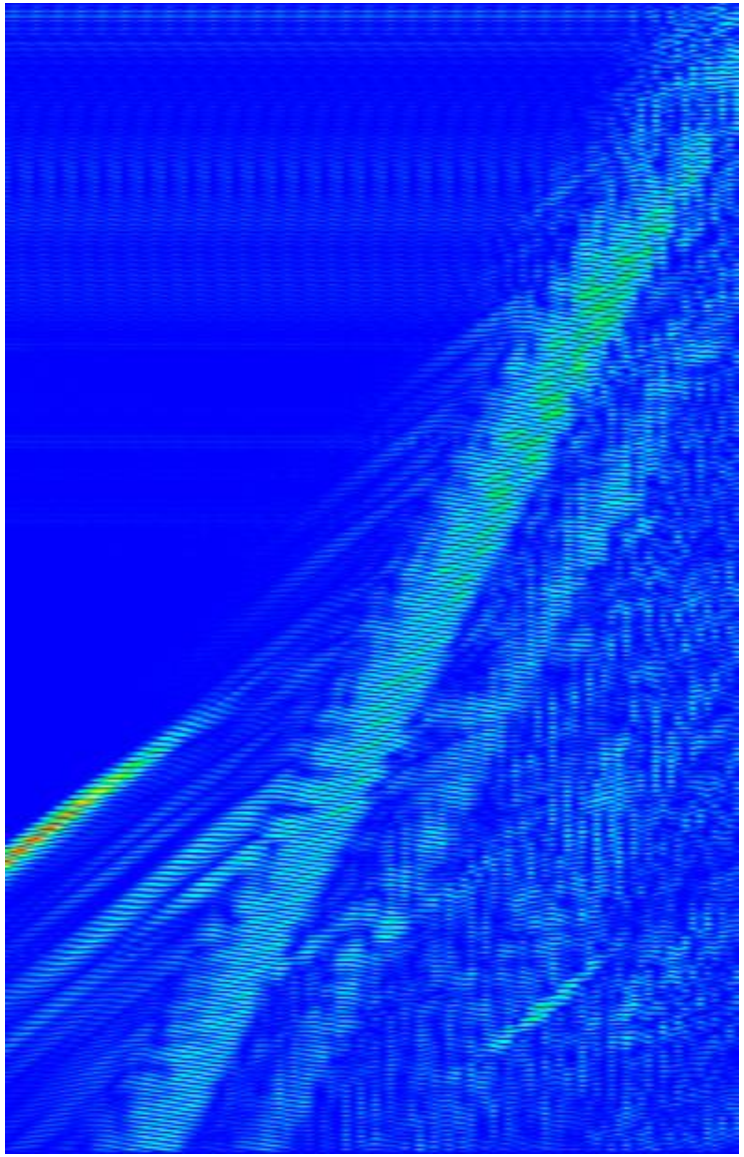


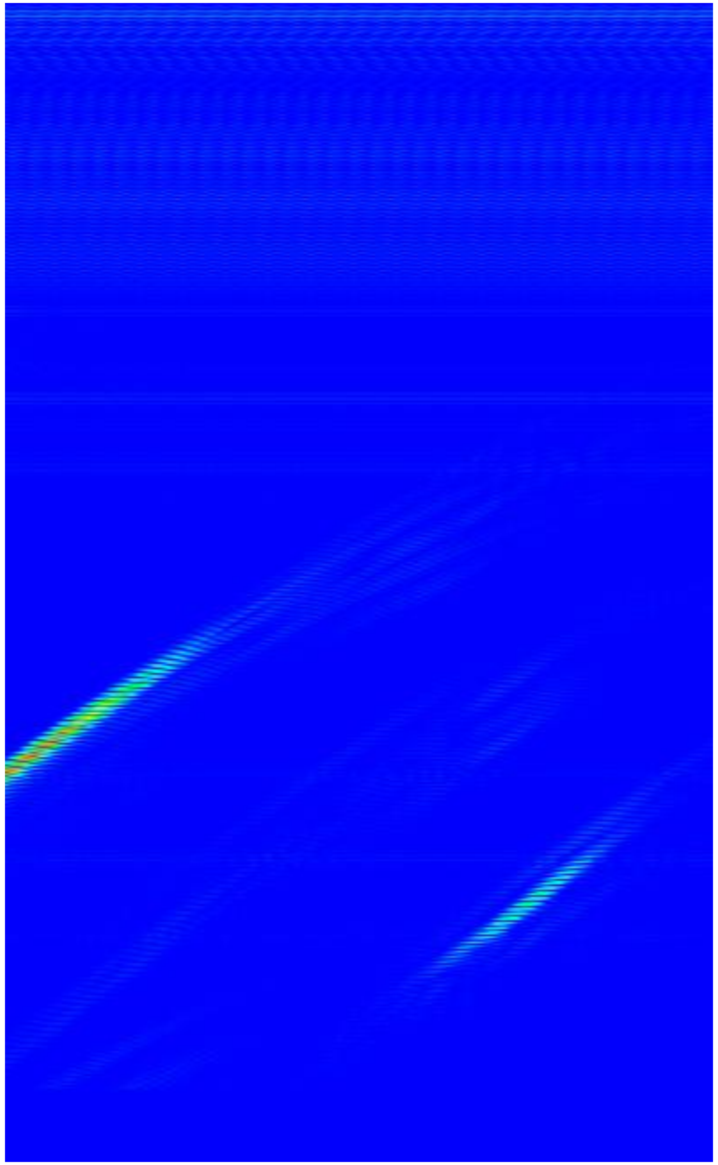
Parasitic echoes present

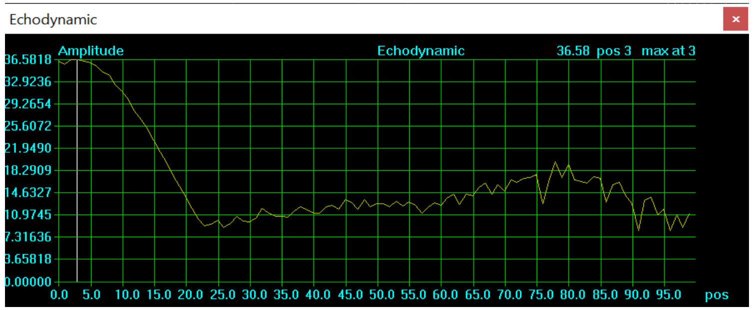


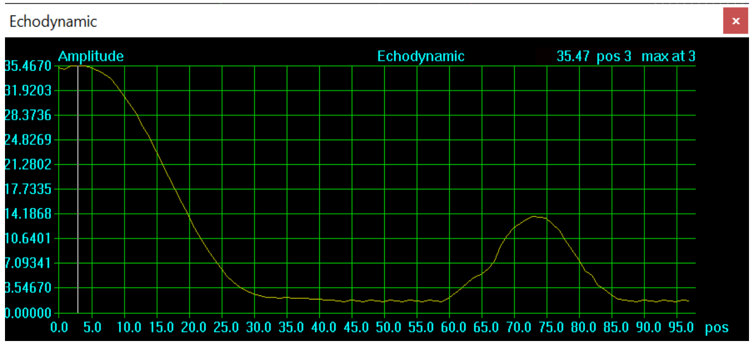


Comparing results with and without weld



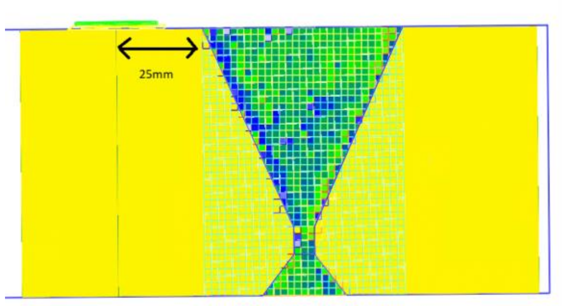




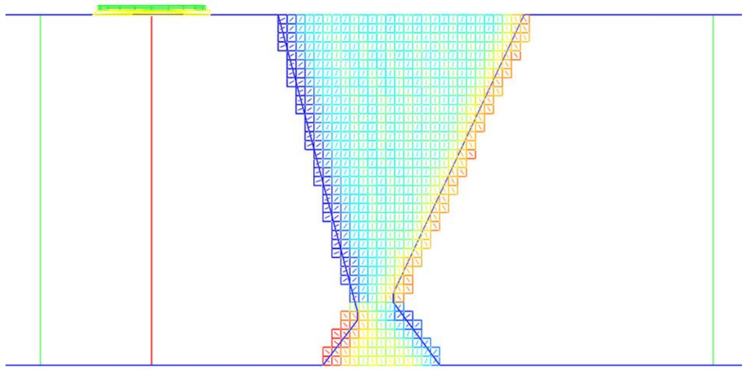


Why do we observe a backwall echo delay?

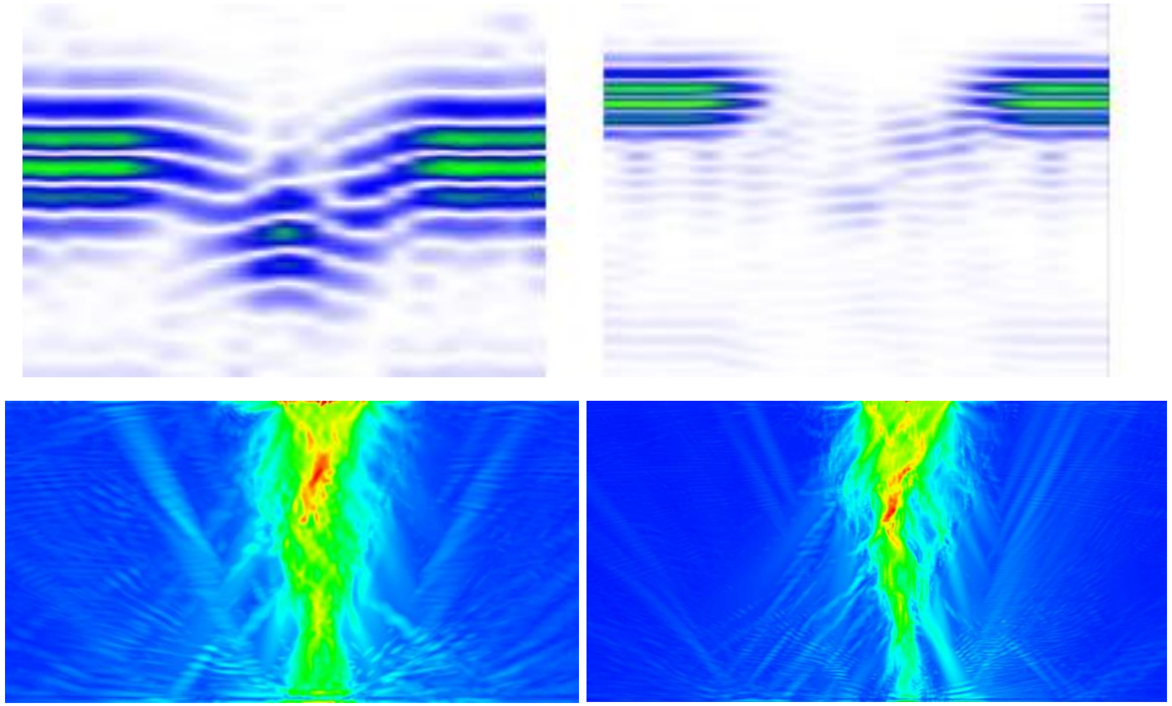
symmetrical



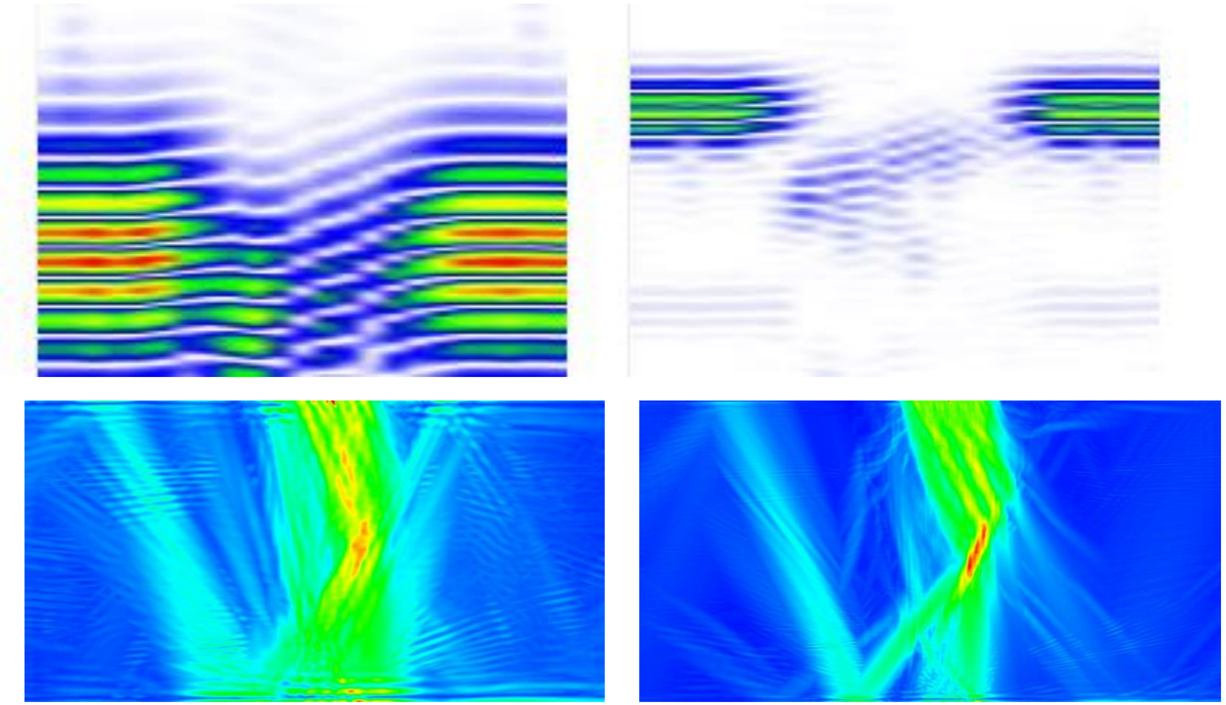
asymmetrical



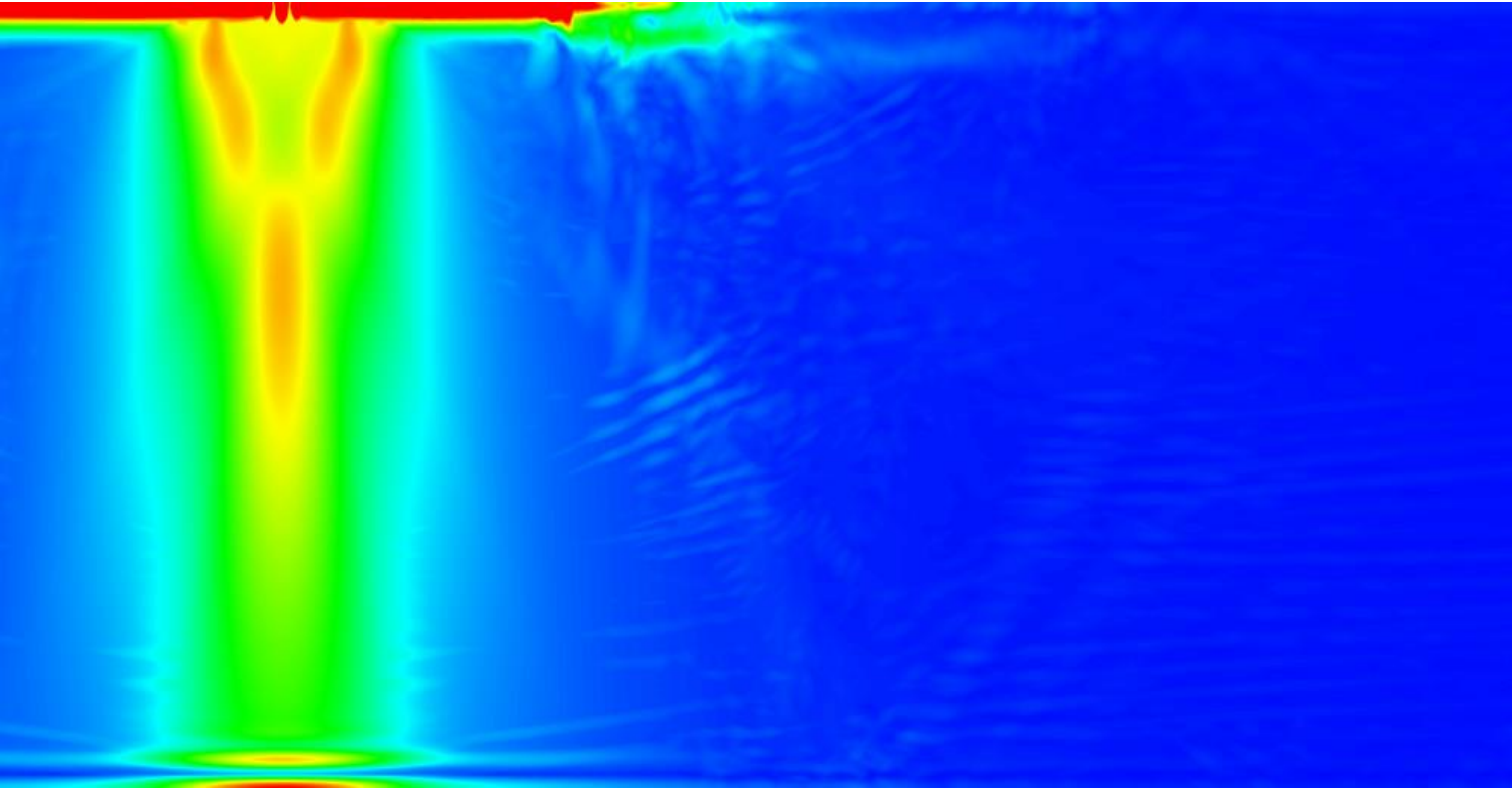
1MHz 2MHz



1MHz 2MHz



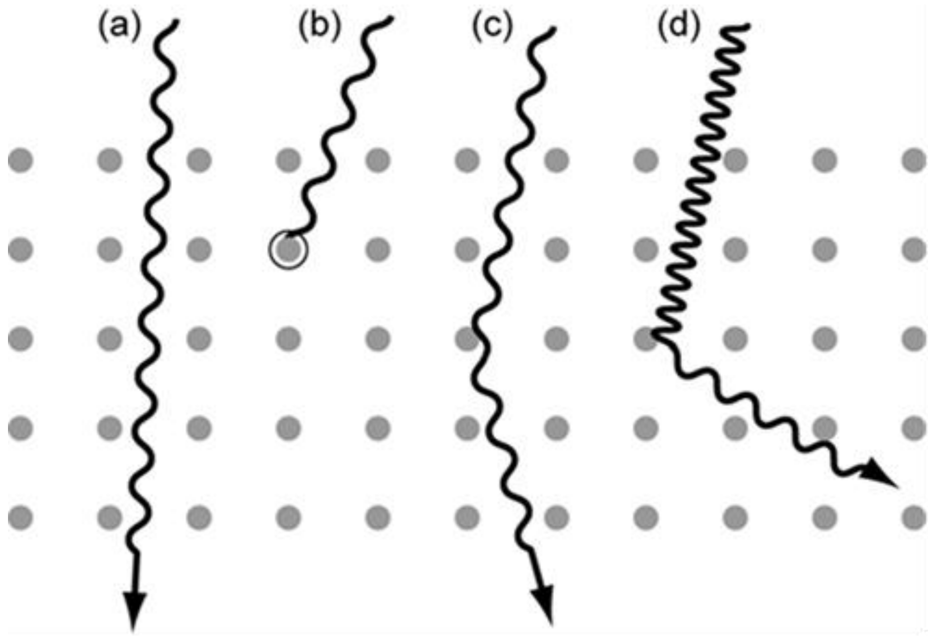
Why do we observe a backwall echo delay?



Radiography modelling: MODERATO

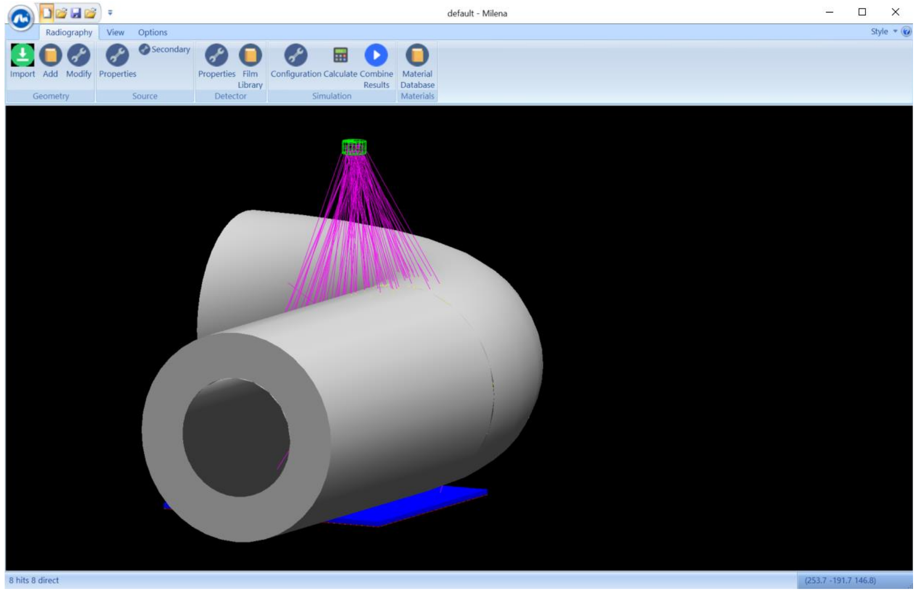
Unlike UT and ET,

- radiography does not produce an electric signal
- The image is interpreted by a human inspector (human factor)
- The physics do not lend themselves to finite elements. A Monte Carlo approach is used to simulate particle propagation
- Small memory footprint
- No reasonable 2D approximation



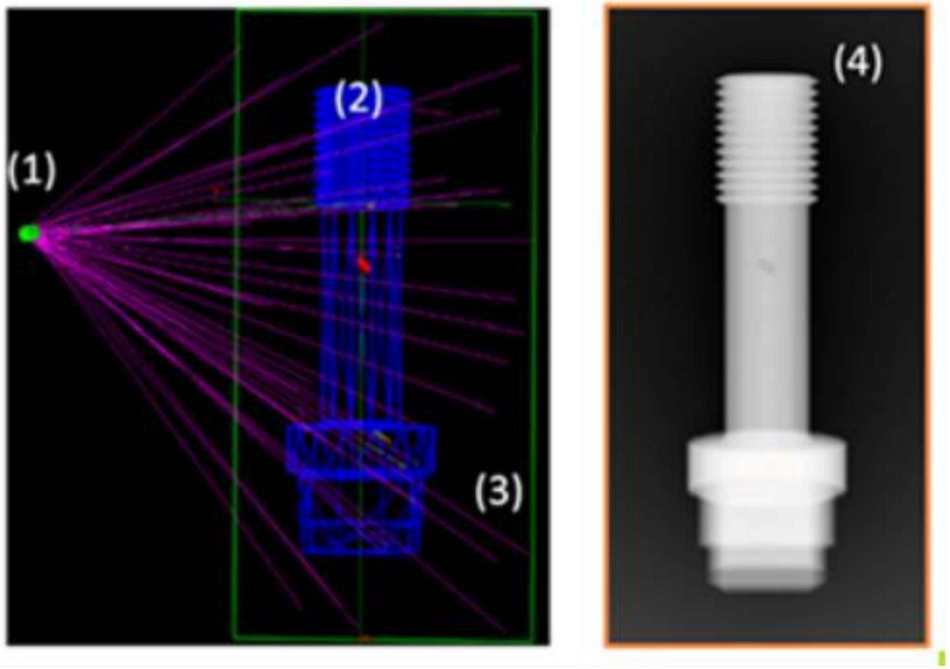
Radiography modelling: MODERATO

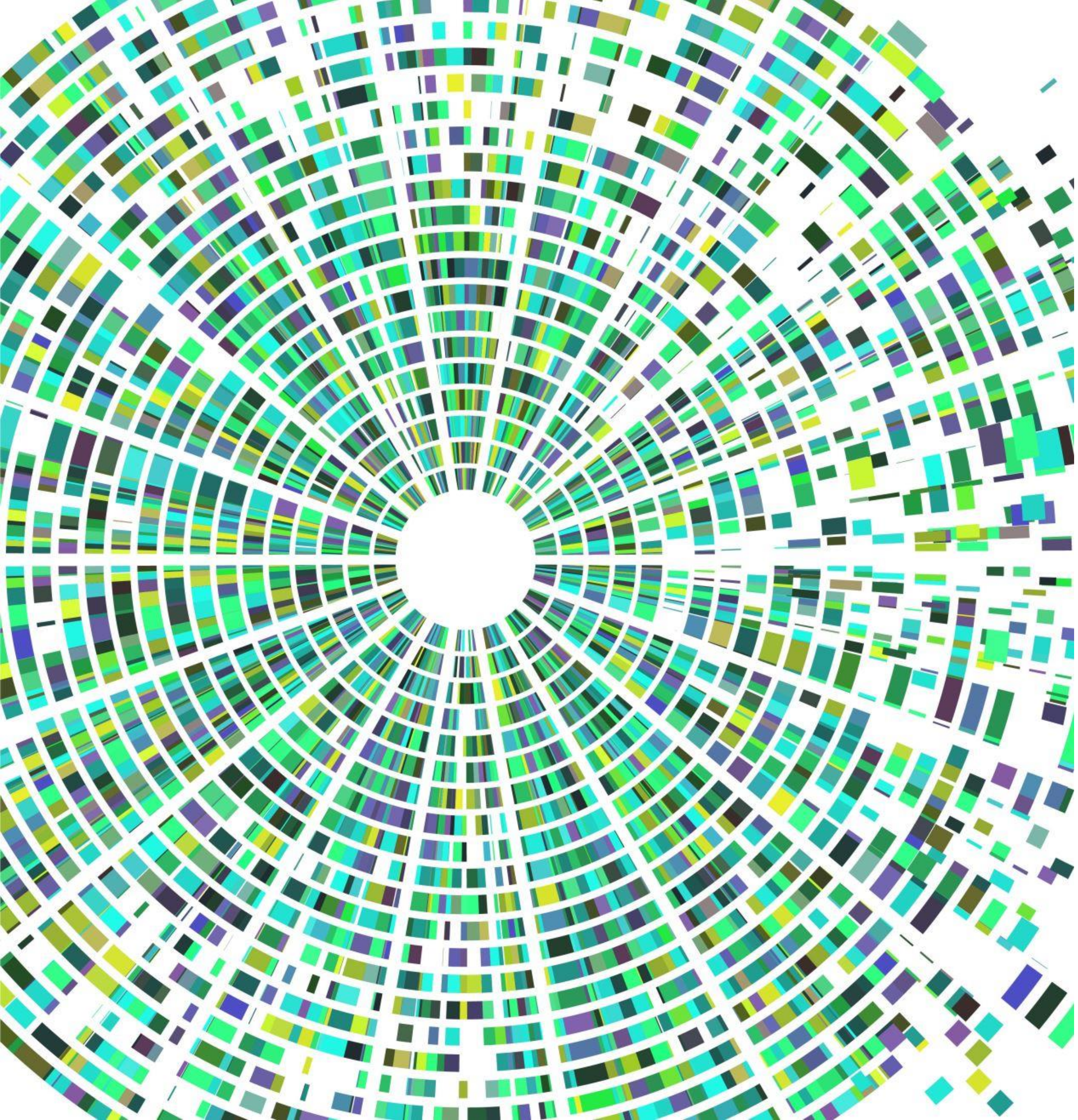
- Isotope sources, X-ray tubes and a linear accelerator
- Material database covers most nuclear materials
- A combined straight line attenuation model and a Monte Carlo model:
  - direct radiation/attenuation calculated rapidly with straight line attenuation
  - Monte Carlo provides scattered radiation
  - Combination of both gives final image
- X-Ray film library
- An integrated visibility quantifier



Recent/ongoing work:

- A model for electron propagation within film cartridges
- A more realistic noise model
- A visibility quantifier from the medical field





Tuesday's presentation

ÚJFI
ÚSTAV JADROVÉHO A FYZIKÁLNEHO INŽINIERSTVA

DELISA-LTO project and NDT methods

Prof. Vladimír Slugeň, DSc.

Institute of Nuclear and Physical Engineering, Slovak University of Technology, Ilkovičova 3, 81219 Bratislava, Slovakia

Introduction to 2nd DELISA-LTO Workshop, Kočovce, Slovakia, February, 10-14, 2025

Prof. Ing. Vladimir Slugen, DrSc.

Slovak University of Technology in Bratislava, Slovakia

- Full time professor in Nuclear Power Engineering since 2004.
- Guarantee of Slovak nuclear power engineering study program over 15 years. Lessons are focused on nuclear installations, nuclear safety and decommissioning.
- Scientific orientation on: nuclear safety, radiation embrittlement of NPP design material embrittlement, corrosion cracking, positron annihilation techniques.
- Author of 6 books and over 200 scientific papers, *h-19*
- Vice-chair of Slovak National Nuclear Fund since 2007
- Co-author of Slovak national policy and program for decommissioning and nuclear waste management.
- President of Slovak Nuclear Society (since 2004 -) and former president of European Nuclear Society (2009-2011).
- In 2021-2023 leader of Scientific council for Slovak NPP unit Mochovce 3 commissioning.

- E-mail = vladimir.slugen@stuba.sk
- Phone = +421915837843

DELISA-LTO

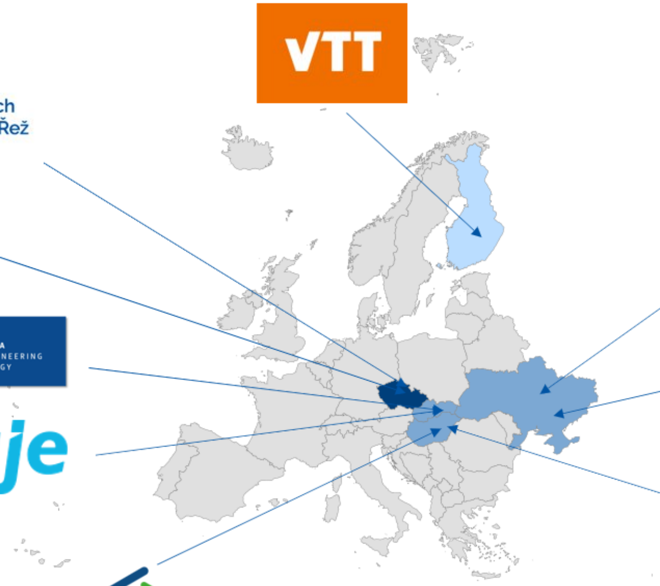
DEscription of the extended LIfetime and its influence on the SAfety operation and construction materials performance – Long Term Operation with no compromises in the safety

DELISA LTO

DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

Funded by the European Union

Consorcium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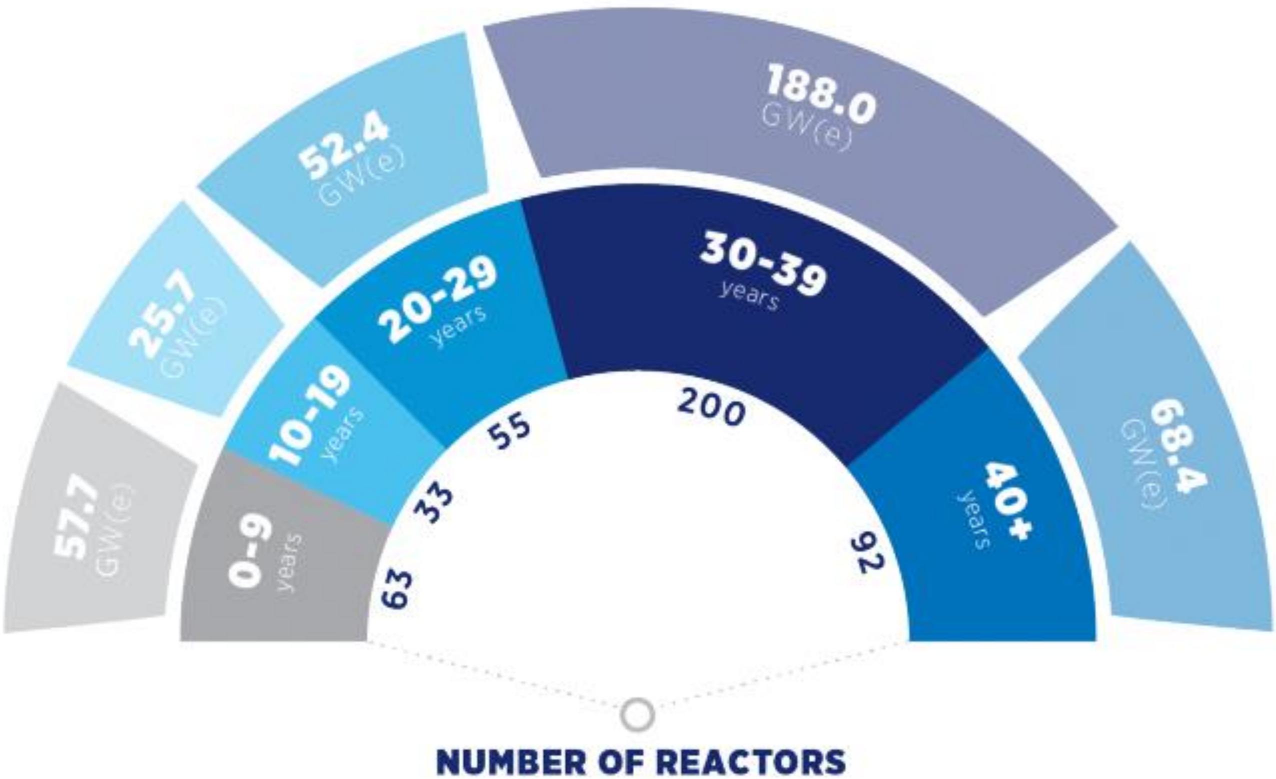
FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION TECHNOLOGY
vuje
IPP CENTRE
Intelligent Practical Profound
SSTC NRS
ДЕРЖАВНЕ ПІДПРИЄМСТВО
ДЕРЖАВНИЙ НАУКОВО-ТЕХНІЧНИЙ
ЦЕНТР З ЯДЕРНОЇ ТА РАДІАЦІЙНОЇ
БЕЗПЕКИ
bay
CIRCULAR ECONOMY INITIATIVE

PWR - VVER reactors
Long-term operation

- By the end of the year 2024 (10/2024)
- 415 power reactors were in operation, and 62 new reactors were under construction worldwide.
- 276 reactors worldwide were operating for longer than 30 years. It represents more than 66,5% of power reactors.
- The next 160 reactors will probably be shut down in 2030 if appropriate measures towards LTO are not taken.
- Only 65 (15%) new units have been put into operation during the last decade, and only 31 (7%) units in the decade before.
- Currently, 67 VVER reactors operate in 12 countries, and about 20 VVERs are under construction.
- In EU countries (Finland, Slovakia, Czech Republic, Hungary, and Bulgaria), 19 VVER units are in operation. The next 15 reactors are in Ukraine.

- https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx

Distribution of operating reactors in the world by age



Status of LTO programmes in the world

Country	Status
Belgium	Ten-year licence extension for one unit.
Canada	Ongoing refurbishments and lifetime extension process.
Finland	Twenty-year licence extension of four units.
France	No legal end to the licence. Periodic safety review (PSR) every ten years.
Germany	Phase-out planned.
Hungary	Twenty-year extension of four units.
Japan	Used to have no legal end to the licence term. Currently envisages limiting the lifetime to 40 years.
Korea (Republic of)	No legal end to the licence.
Russia (Federation of)	Licence extension of different reactors by 15-25 years.
Sweden	No legal end to the licence. Replacement of NPPs allowed, but no additions.
Switzerland	No legal end to the licence.
Ukraine	Twenty-year extension of two units and ongoing LTO programmes for several others.
United Kingdom	Licence extensions for several years.
United States	Twenty-year licence extension of 73 units approved and 13 in review.

Regulatory approaches to LTO in different countries

	Licence renewal	Periodic safety review (PSR)	Comment
Belgium		Yes	In Belgium, service life (operating licence) for NPPs is set by law at 40 years. Utilities have to conduct a PSR for their operating NPPs every ten years and have to submit the PSR report to the federal regulator for nuclear control for review and approval. In the case of Tihange 1, there will be the possibility of a one-off extension of ten years of the operating licence, under the condition that the results of the next PSR for this reactor are approved by the federal regulator.
Finland		Yes	According to the Nuclear Energy Act, the operating licences are granted for a fixed term. The licence conditions may by changed during its period of validity by the government. The licence can also be revoked if the licensee is failing to comply with the licence conditions and the nuclear regulator (STUK) is given power to monitor the operation of the plants and take any measures required to ensure public safety.
France		Yes	In France, the operating licence for a nuclear reactor does not set a limit for service life. However, article 29 of the Transparency and Nuclear Safety Act (13 June 2006) requires that the operator of a nuclear reactor performs a safety review of the facility every ten years.
Hungary		Yes	According to current Hungarian regulations the operating licence is subject to a PSR, which is performed (every 10 years) as a self-assessment by the licensee under the control and approval of the regulatory body during the original design lifetime (30 years for the currently operating NPPs). The licensee has to prepare and submit to the regulatory body a licence renewal request for permitting LTO, justifying a design lifetime, up to 20 years beyond the original design lifetime.
Korea, Republic of		Yes	A PSR has to be conducted every ten years and submitted for regulatory review and approval to justify the next ten years of continued operation. The "final ten-year PSR" may also be used to request extension of the original service life by another ten years. The service life of existing designs is between 30-40 years.
Russian Federation	Yes		The operating licence is limited to the original design lifetime of the plant (30 years for the currently operating NPPs). Relicensing by the regulator (Rostekhnadzor) is a prerequisite for the extension of the operational lifetime. The duration of the licence extension is determined individually for each unit based on residual life. The licensee has to prepare and submit to the regulatory body a proposal for permitting an LTO period of which depends on revised, justified and approved longer than the original design lifetime. The Russian plants undergo constant reviews and inspections, and Rostekhnadzor can order the shutdown of the unit or take any other actions to ensure public safety.
Switzerland		Yes	In Switzerland, the service life for NPPs is not limited. Article 10 of the Nuclear Energy Ordinance (NEO) defines the principles for the design of the safety functions of NPPs. These include, in particular, single failure criterion, principles of redundancy and diversity, functional and physical separation, automation principle and conservativism in design. In the NEO and the Nuclear Energy Act it is stipulated that the licence holder shall upgrade the NPP to the extent that it is necessary in keeping with operational experience and the current state of back fitting technology, and beyond insofar as further upgrading is appropriate and results in a further reduction of the risk to human beings and the environment.
United Kingdom		Yes	In the United Kingdom, a single non-transferable licence is granted to cover the life of the nuclear site from start of construction to final decommissioning. There is no pre-determined end date for operation. Nuclear facilities are permitted to continue to operate for as long a period as the licensee can demonstrate that it is safe do so. The PSRs (conducted with a periodicity of around ten years maximum since the early 1990s) should confirm that original safety standards will be maintained, identify any life-limiting features on the plant, and demonstrate that all reasonably practicable measures to improve the plant to modern standards are being implemented. The regulator may require the licensee to carry out plant modifications that have been identified during the PSR as reasonably practicable or undertake other activities, e.g. perform additional analyses. If the plant cannot be brought sufficiently close to modern standards, the licensee may be required to cease operation. The end points of past PSRs of UK's facilities have included all of these potential outcomes.
			The US Atomic Energy Act of 1954 allows the Nuclear Regulatory Commission (NRC) to

Age of PWR reactor round the world (2023)

Red – shut down NPP or plans for shutt down

From 35 listed NPP:

- **5x reactors 50+ years**
- **9x reactors 40-50 years**
- **11 reactors over 30 years**
- **4 NPP 20- - 30 years**
- **1 reactor in energetic sturting-up**

Country	NPP	Type	Start operation	End operation	Lifetime (years)
Armenia	Metsamor	VVER-440 V-270	1980	2026	**46 – now 43**
Belgium	Doel	PWR	1975	2025	**50 – now 48**
	Tihange		1975	2025	**50 – now 48**
Czech Republic	Dukovany	VVER 440	1985/1987		**Now 38 -36**
Finland	Loviisa	VVER 440	1977/1981		**Now 46 -42**
France	Blayais	PWR	1981/1983		**Now 42**
	Bugey	PWR	1979/1980		**Now 44**
Germany	Grafenrheinfeld	PWR	1988	April 2023	**35**
	Isar	PWR	1988/1989		
	Neckarwestheim	PWR			
Hungary	Paks	VVER 440	1983/1987		**Now 40 -36**
Japan	Mihama 3	PWR	1976	2023	**47**
	Sendai	PWR	1984/1985		**Now 38 - 37**
	Takahama	PWR	1984/1985		
Netherlands	Borssele	PWR	1973	2033	**60**
Russia	Kola	VVER 440	1973/1984		**Now 38-50**
	Novovoronezh	VVER 1000	1973/1981		**Now 42 -50**
			1972	2016	**44**
Slovakia	Jaslovske Bohunice V1	VVER 440	1980/1981	2006/2008	**26-27**
	Jaslovske Bohunice V2	VVER 440	1985	2045	**60 – now 37**
	Mochovce	VVER 440	1998/2000	2058/2060	**60 – now 25-27**
Slovenia	Krško	PWR	1983	2043	**60 – now 40**
Spain	Almaraz	PWR	1983		**Now 39**
	José Cabrera	PWR	1969	2006	**37**
Sweden	Ringhals	Westinghouse	1981/1983		**Now 42 -39**
Switzerland	Benzau	PWR	1965/1968	2029/2031	**60 – now 54**
UK	Sizewell B		1995	2023	**40**
USA	Ginna		1970		**Now 53**
	H.B.Robinson, etc.		1971		**Now 52**

LTO contributes to collection money for decommissioning

- Decommissioning costs are about 15% of the overnight construction costs, compared to less than 5% at all other energy production technologies.
- Due to prolongated lifetime of NPPs this portion get relative smaller in the discounted calculations of electricity generation costs and the utility (government) obtain additional time for upgrade of decommissioning plans and financial resources collection.
- Nuclear industry is the only one which is obliged to collect money for full decommissioning of nuclear facilities during their operation lifetime.

Expected costs for decommissioning of Slovak NPPs (mil. Euro)

		JE V2	JE MO 1, 2	JE MO 3, 4	Total
Contribution to DGR	Current prices (2023)	1 644	1 192	1 430	4 266
	Nominal prices	4 067	3 587	3 583	11 237
Decommissioning costs at NPP	Current prices (2023)	960	955	966	2 881
	Nominal prices	1 810	2 375	3 719	7 904
Costs for spent fuel storaging	Curring prices (2023)	208	96	61	365
	Nominal prices	563	349	259	1 171
Total costs	Current prices (2023)	2 813	2 243	2 456	7 512
	Nominal prices	6 440	6 311	7 560	20 311

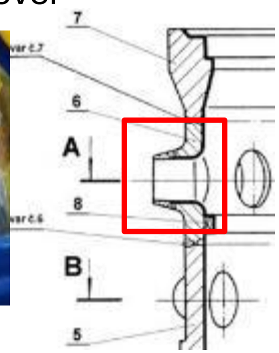
Source: NJF, ÚHP

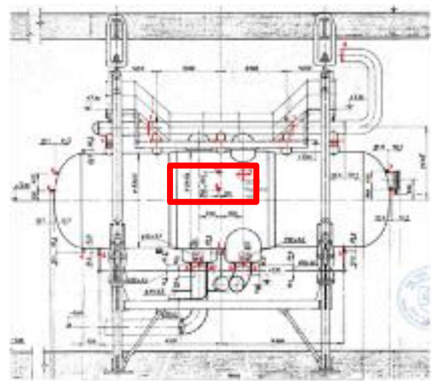

Project HORIZON-EURATOM-2021-NRT-01-01
Project start 1st June 2022
Project end 31st May 2026
DELISA LTO
DEscription of the extended LIfetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety
VVER reactors
Thermal ageing
Non-destructive techniques
Modelling
Lifetime extension

Samples from NPP V1

Bolts of RPV cover

RPV nozzles





Pressurizer Surge Line

Pressurizer

Main circulation pipeline

Main circulation pump

RPV cover

Synergies
(Fractesus, Delisa-LTO, STRUMAT-LTO)

Towards LTO to/beyond 60 years of safe operation of NPPs

Generally, the limiting factors for VVERs from the LTO point of view:

a)Radiation embrittlement of the reactor pressure vessel (RPV)

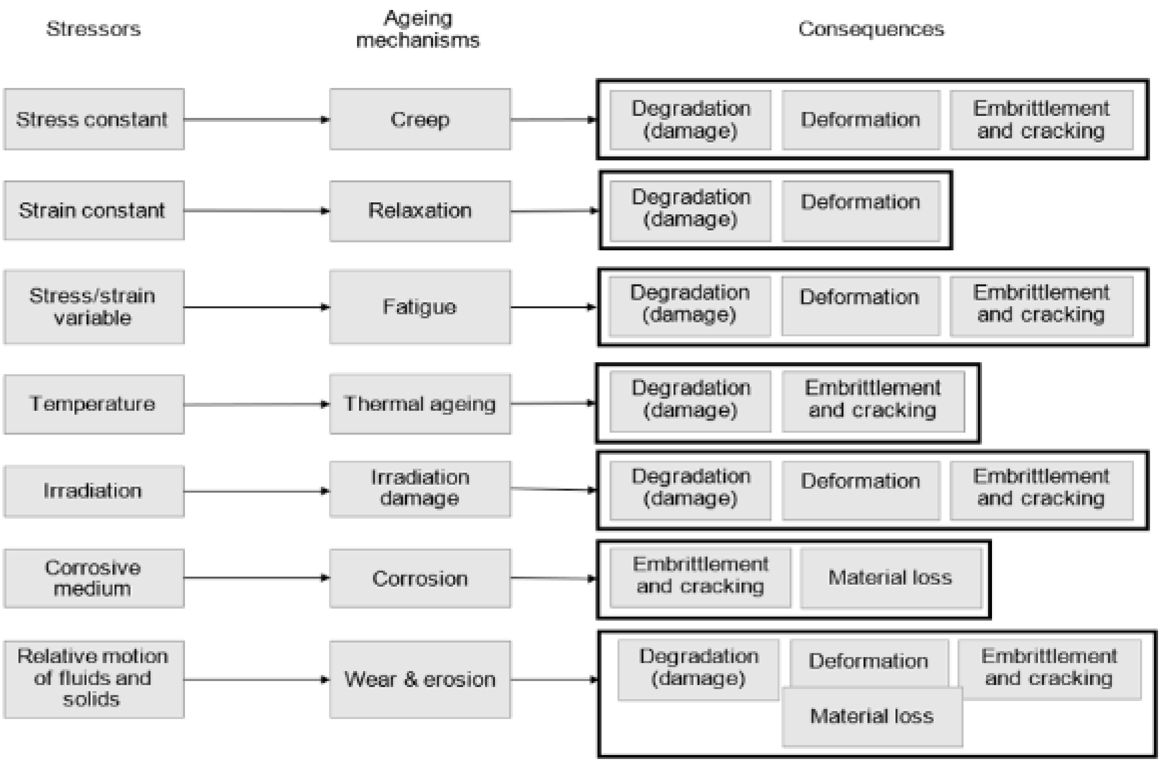
b)Thermal aging

c) Stress-corrosion cracking (SCC)

d)Low-cycle fatigue

e)General corrosion

f)Swelling



Commonly registered failures of components

Main circulation piping – **cracks of welds** – mechanisms SCC, vibration, wear

Main circulation pump – **problems with sealing** and damage of the sealing, **pressure flanges** – SCC, fatigue, mechanical wear, vibration

Pressuriser – **problems with weld joints** (dissimilar weld) - SCC

– **pressuriser electric heaters' coils** - thermal ageing

Pressuriser surge line – significant additional stresses – thermal ageing

Steam Generator (SG) – **cracks** of dissimilar **weld joint**, mostly in **nozzles** – SCC

– **auxiliary pipelines, steam generator** – general corrosion, sediments on the heat exchange surface and corrosion products accumulation

Collector bolts – **cracks** – SCC - high level of tensile stress and a complex corrosion environment

SG collector – **cracking of the lot leg primary collector** - plugs in the hole were rolled before welding, which brought additional stresses into the material of ligaments and trans-crystalline cracking occurred - SCC.

Feeding path – **leaky condensers and heaters with insufficient corrosion resistance** – Cu-containing alloys, corrosion/erosion

Emergency Core Cooling System – cracks near weld joint on piping surface - SCC

Outline

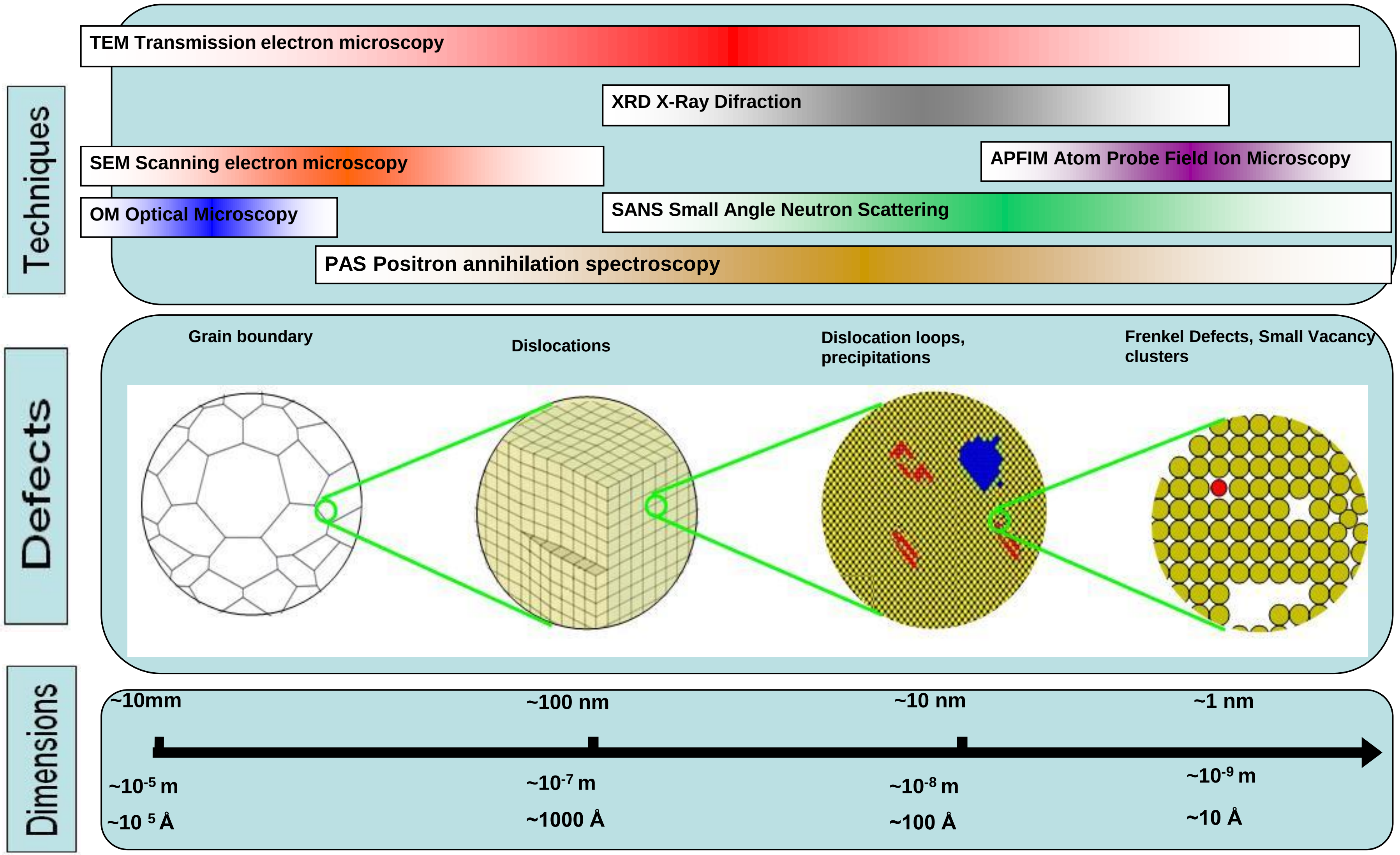
- Various aspects of radiation environments foreseen for nuclear design materials were experimentally simulated via ion implantation and studied by a combination of non-destructive characterisation techniques and compared to neutron treatment.

- As-received steels
- Neutron irradiated steels
- Hydrogen implanted steels
- Helium implantation (swelling)
- Thermal aging
- Corrosion, stress corrosion, …

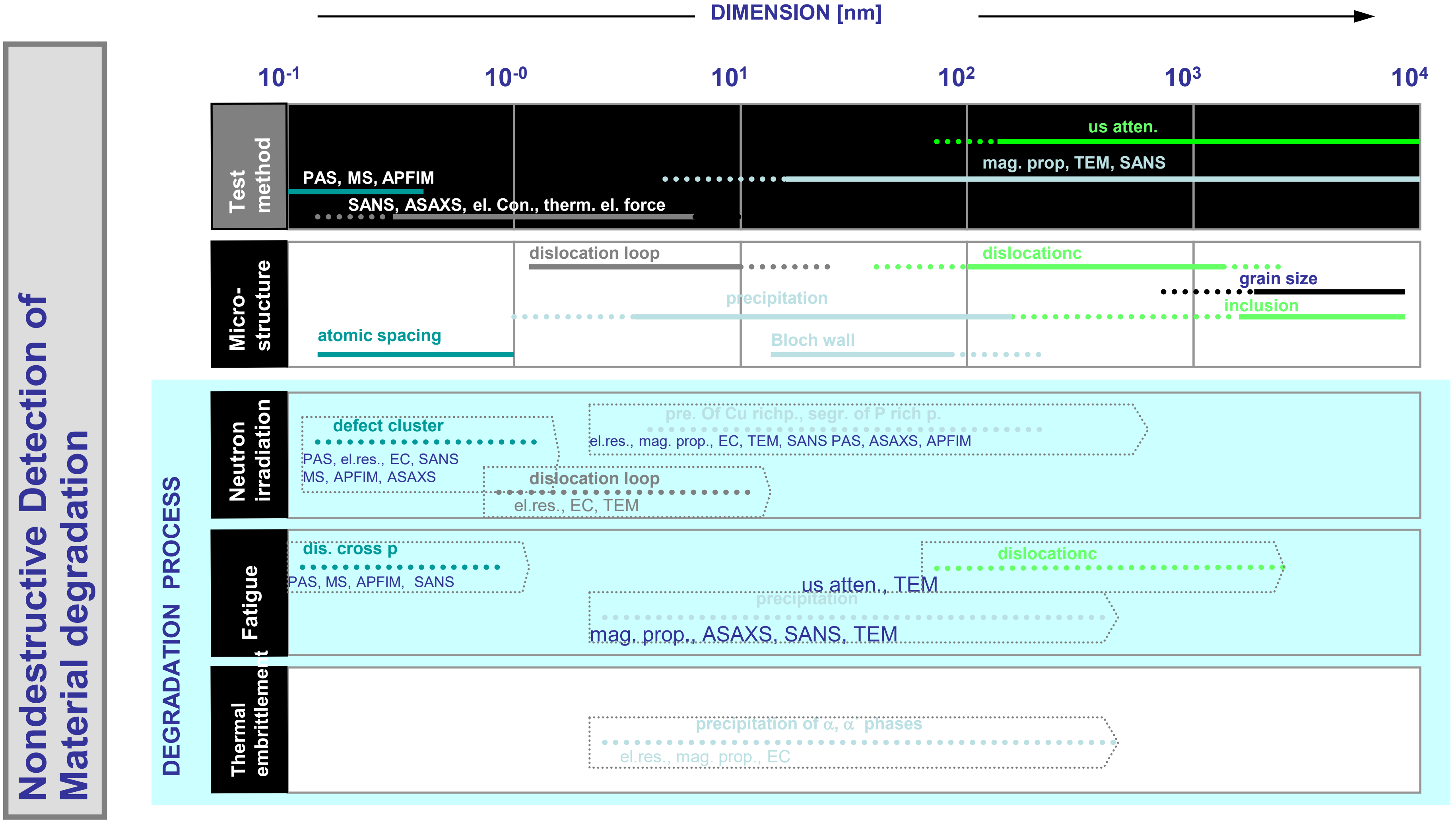
Non-destructive testing

- Effective tool for evaluation of structural changes
- No changes in design required
- Evaluation of defects via long-rterm and regular applications (surveillance specimens)
- Possible round-robin testing
- High scientific acceptance

Overview

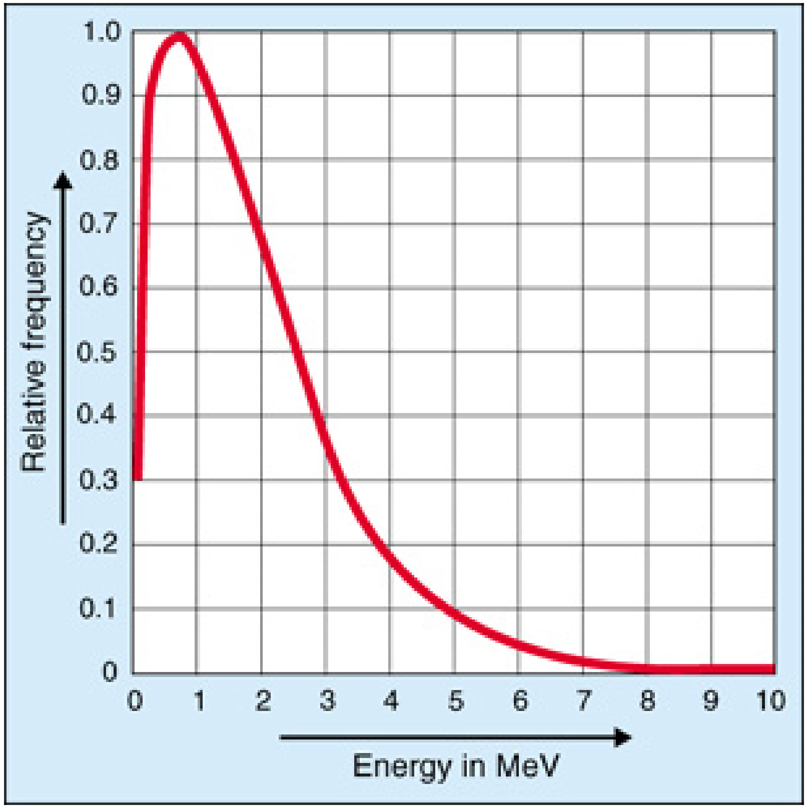

Techniques
TEM Transmission electron microscopy
XRD X-Ray Difraction
SEM Scanning electron microscopy
APFIM Atom Probe Field Ion Microscopy
OM Optical Microscopy
SANS Small Angle Neutron Scattering
PAS Positron annihilation spectroscopy
Defects
Grain boundary
Dislocations
Dislocation loops, precipitations
Frenkel Defects, Small Vacancy clusters
Dimensions
~10mm
~100 nm
~10 nm
~1 nm
~10-5 m
~10 5 Å
~10-7 m
~1000 Å
~10-8 m
~100 Å
~10-9 m
~10 Å

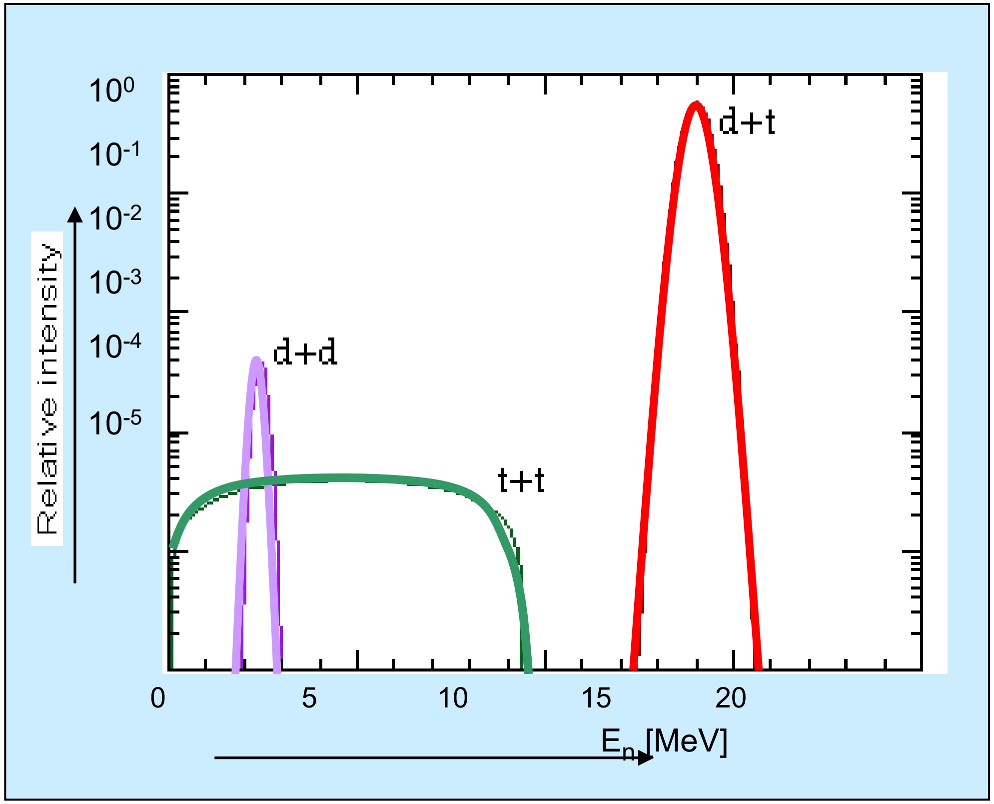
Methods - overview



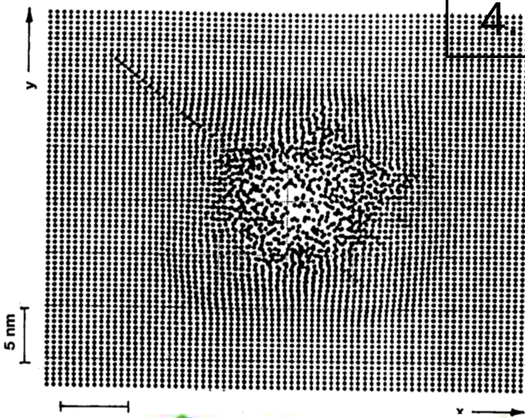
ASAXS – anomalous small angle X-ray scattering
APFIM – atom probe field ion microscopy
EC – Eddy current
MS – Mössbauer spectroscopy
PAS - positron annihilation spectroscopy
SANS – small angle neutron scattering
TEM – transmission electron microscopy
US – ultrasonic waves

Fission and fusion neutrons

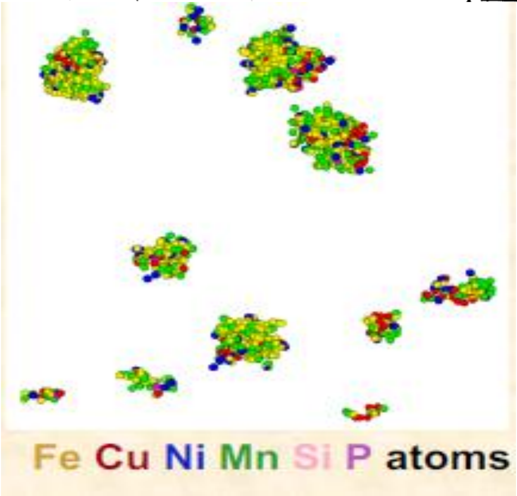




Which role can irradiation play?



- *Gamma radiation* only ionizes electrons or excites atoms.
- Neutrons: knock-out atoms from the lattice
  - Epithermal neutrons (>0,5 eV)and fast neutrons (>100 keV
  - Primary knock-out atoms with higher kinetic energy produce secondary knock out atoms with smaller kinetic energy,
  - Atom depletion area and local surrounding the place of neutron absorption,
  - Open-volume defect accumulation – change of diameters and material swelling.



- Material transmutation - changes of the nuclear-physical, chemical and mechanical properties
  - Thermal neutrons (<0,5 eV),
  - (n, α) and (n, p) nuclear reaction – accumulation of helium and hydrogen nuclei,
  - Defect immobilization by helium – residual stress increasing,
  - Hydrogen diffusion to the grain boundaries and segregation - embrittlement and intergranular corrosion.

$$^{54}Fe(n,p)^{54}Mn$$

$$^{60}Cu(n,\alpha)^{60}Co$$

$$^{10}B(n,\alpha)^{7}Li$$

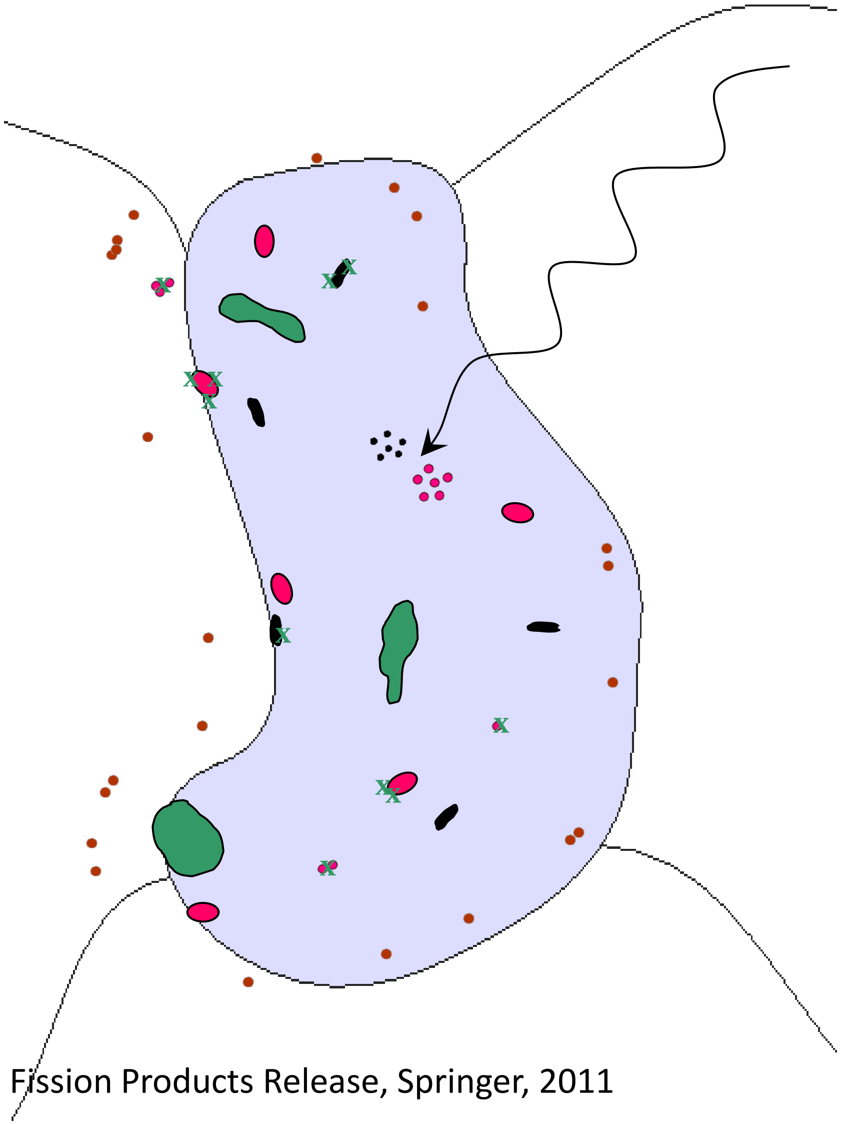
$$^{3}He(n,p)^{3}H$$

$$^{7}Li(n,\alpha)^{3}H$$

Irradiation-induced changes

✓ Neutron-irradiation

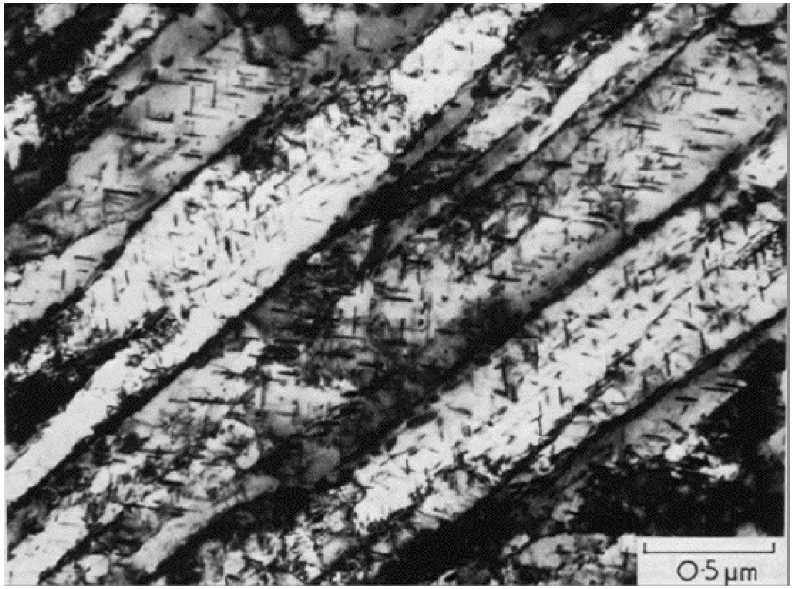
- Defect production
  - Self-interstitial atom (SIA) & vacancy (V) rich regions
- Matrix damage
  - SIA-clusters, SIA-loops
  - Micro voids
- Solute atom diffusion
  - Precipitates
  - Complex defect-solute configurations
  - GB segregation



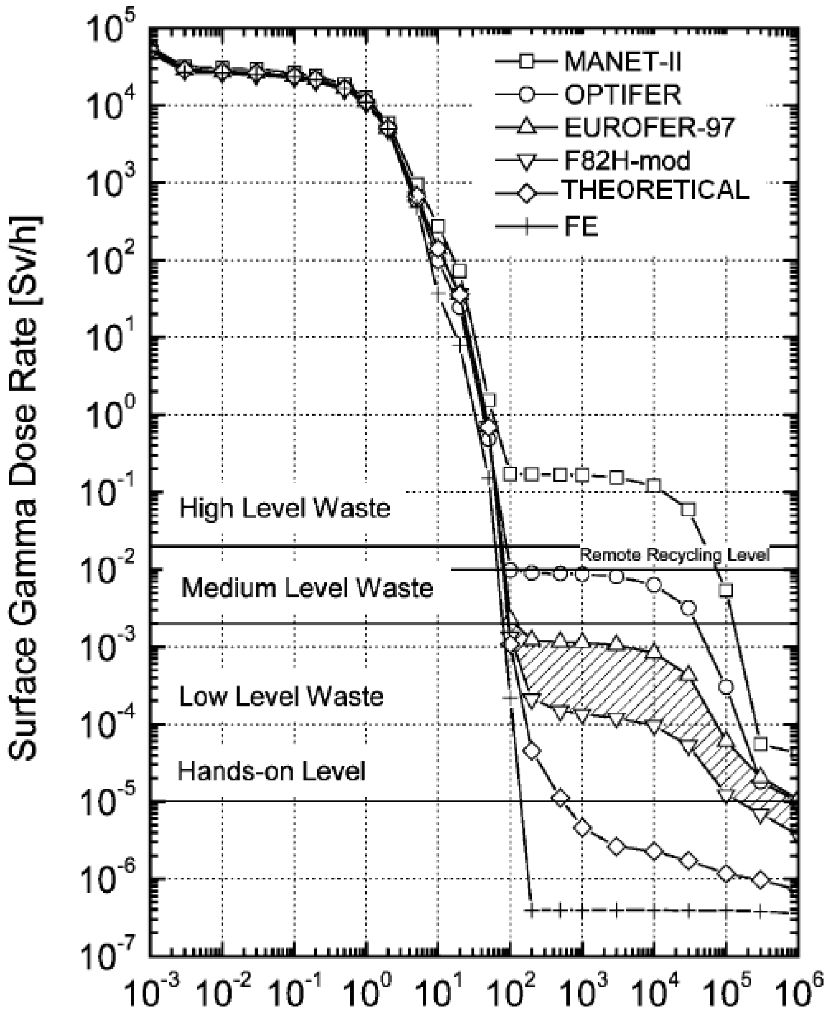
Slugeň, V., Safety of VVER-440 Reactors – Barriers Against Fission Products Release, Springer, 2011

Feritic/martensitic (FM) steels

- Temperature limit - 650°C (ductility loss),
- Appropriate values of strength (martensite) and ductility (ferrite),
- Lower content of nickel and cobalt – reduced activated FM steels (RAFM).



FM steel – martensite looks like needles.



Available techniques for material studies:

Positron Annihilation Spectroscopy: Conventional PALS 2-det. or 3-det. Set-ups (for irradiated materials), digital Doppler Broadening set-up, *experiences with PLEPS measurements at FRM-II in Garching from past*

Moessbauer spectroscopy,

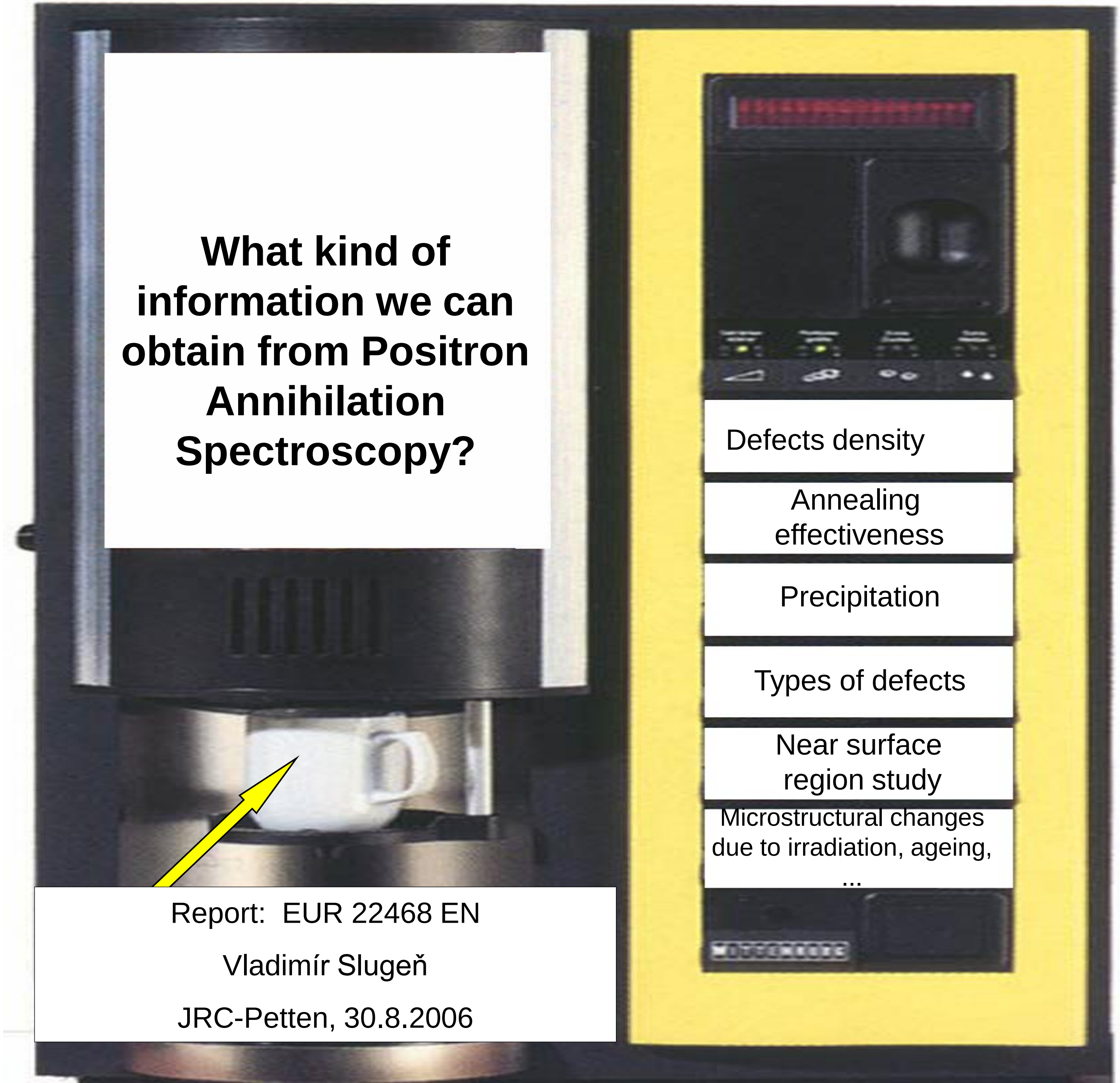
Atomic force microscopy,

X-ray diffraction, Barkhausen Noises measurements,

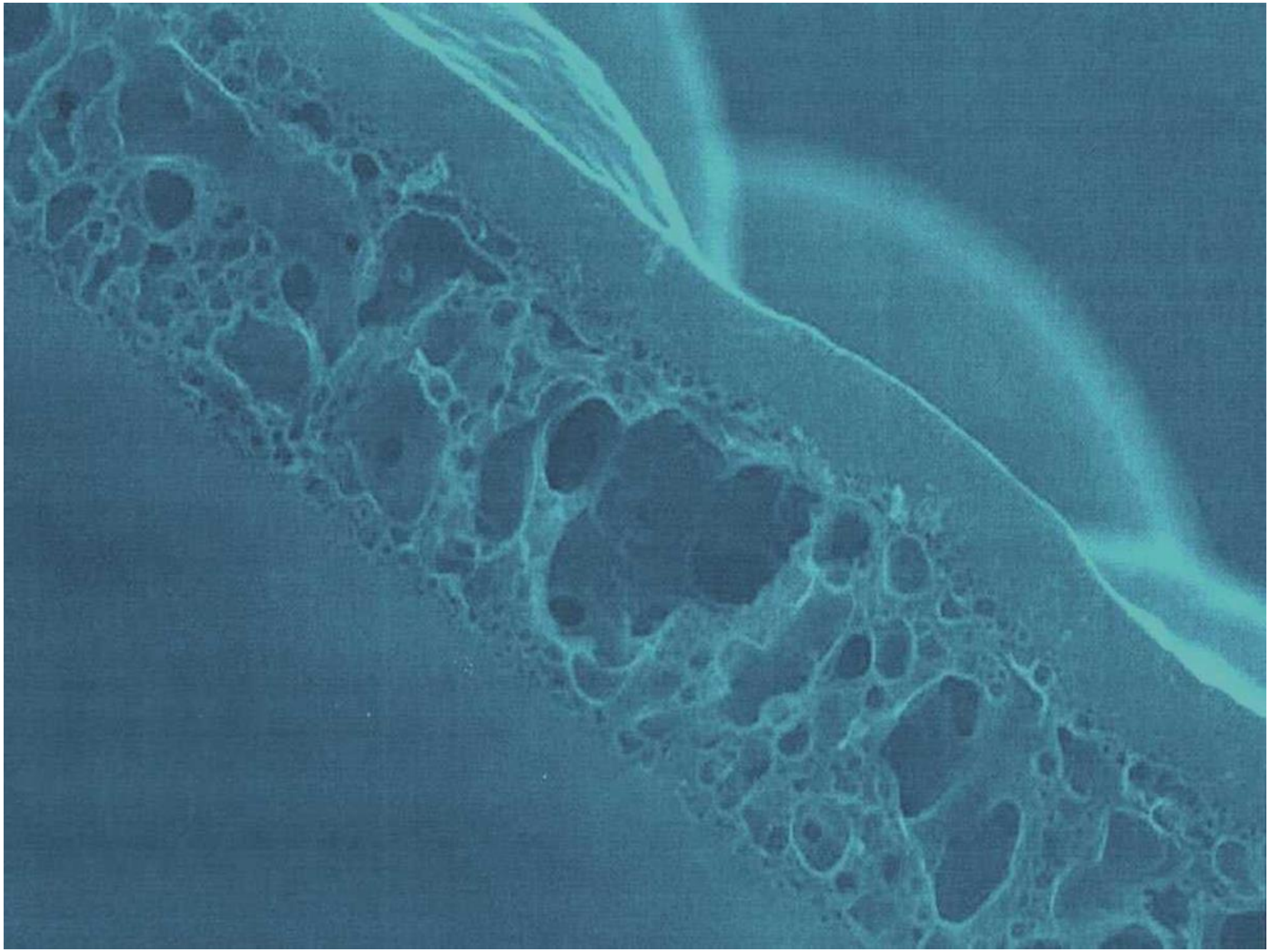
Alfa, beta, gamma spectroscopy including low/background chamber,

In collaboration with other institutes:

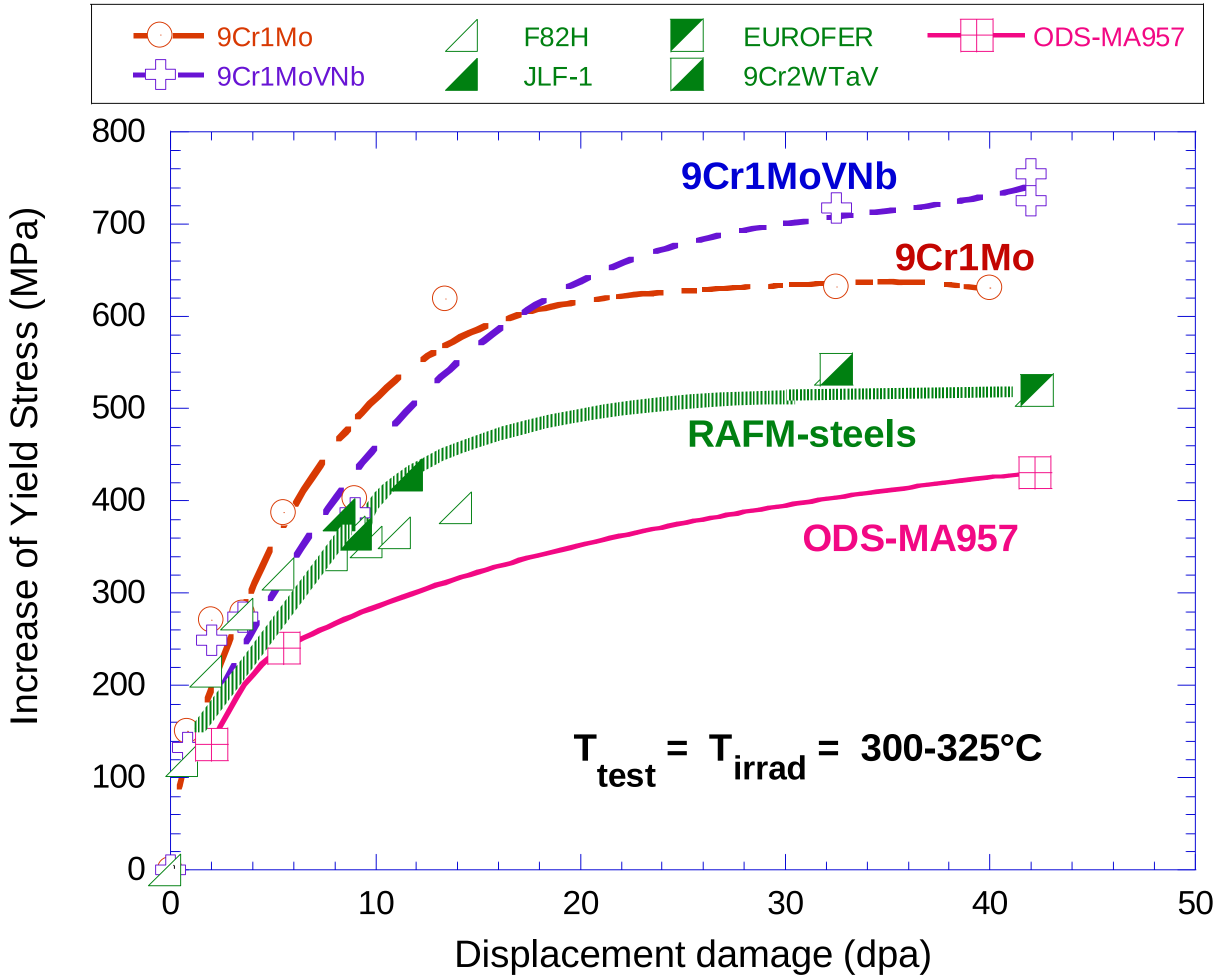
TEM, SEM and Auger spectroscopy


What kind of information we can obtain from Positron Annihilation Spectroscopy?
Defects density
Annealing effectiveness
Precipitation
Types of defects
Near surface region study
Microstructural changes due to irradiation, ageing, ...
Report: EUR 22468 EN
Vladimír Slugeň
JRC-Petten, 30.8.2006

Ion implantation damage



ODS 14%Cr ferritic steels: MA957
Less hardening than conventional and low activation F/M Steels



J. L. Boutard, IAEA Technical Meeting, Vienna, 27-29 June 2011

Relevant literature

[1] M. Ghoniem, F.H. Hammad, Int. J. Press. Vess. & Piping 74 (1997) 189.

[2] J. Koutsky, J. Kocik, Radiaton damage of structural mat., ed. Academia Prague (1994).

[3] V. Slugen, et al., J. Nucl. Mater. 274 (1999) 273.

[4] J. Cizek, I. Prochazka, J. Kocik, E. Keilova, phys. stat. sol. (a) 178 (2000) 651

[5] S.J. Zinkle, A. Möslang, Fusion Eng. Des. 88 (2013) 472.

[6] R. Lässer et al., Fusion Eng. Des. 82 (2007) 511.10.

[7] V. Slugen et al., Materials. 15 20 (2022) 7091.

[8] V. Slugen, P. Domonkos, *J. Nucl. Mater*. 557 (2021) 153164.

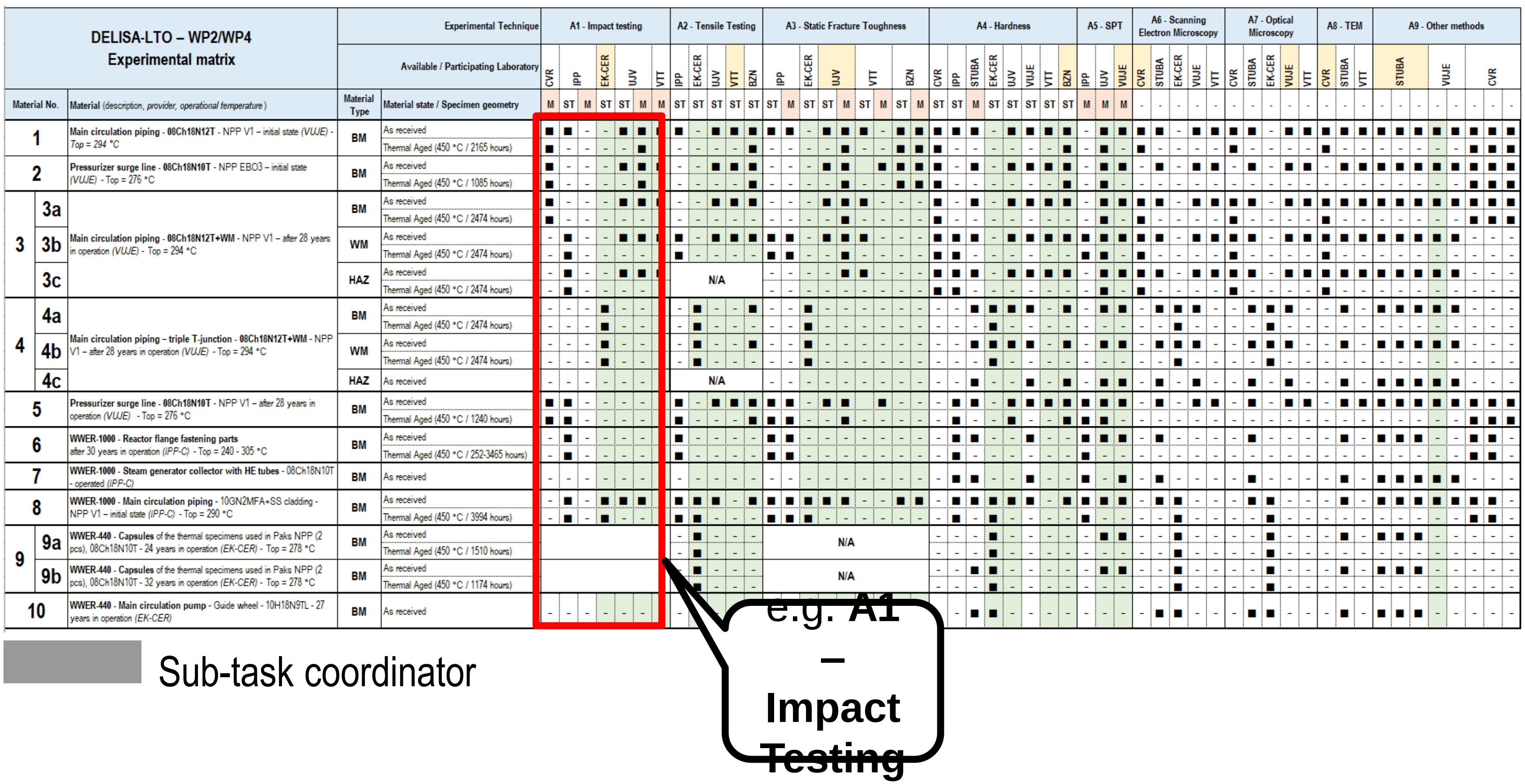
[9] V. Krsjak et a., J. Mater. Sci. & Techn. 105 (2022) 172.

[10] B. Li et al., J. Nucl. Mater. 535 (2020) 152180.

Project scope

- Effective combination of the **NDT techniques, experimental validation and simulations** in order to describe and create **a basis for the establishment of the modern and functional monitoring system** fulfilling the most advanced requirements on the safe LTO.
- The LTO possess **new challenges on materials** that need to be explored and/or described in deeper detail, even the well-known mechanisms as swelling – **almost negligible**

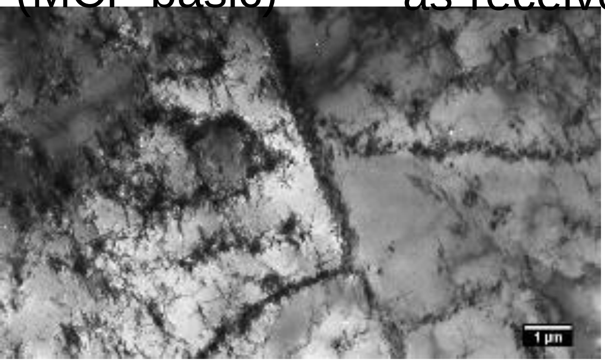
WP2/WP4 Experimental Matrix: Technical Areas



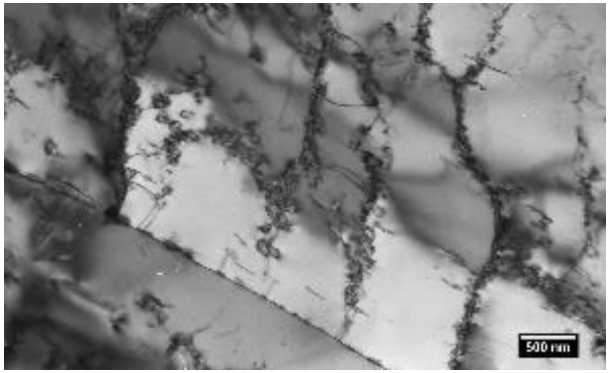
Sub-task coordinator

WP4 – First TEM results (STUBA)

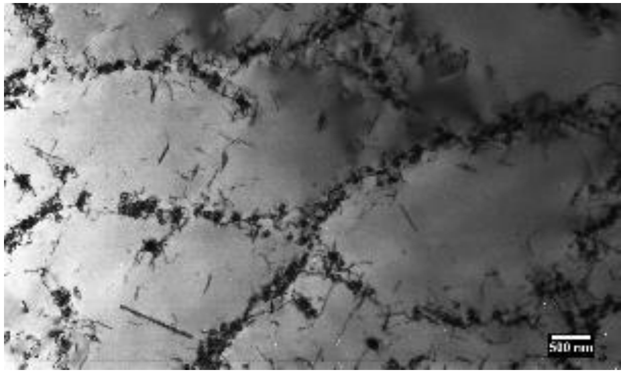
(MCP basic) as-received



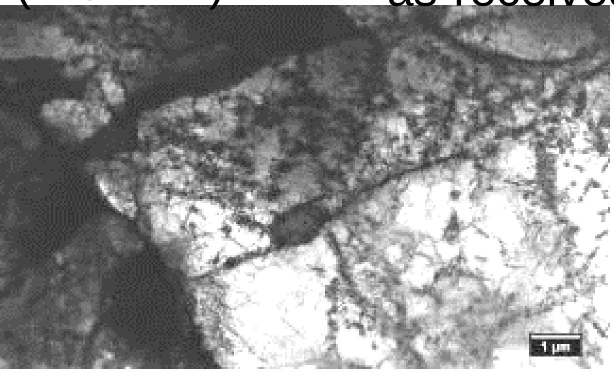
350°C+1083 hours



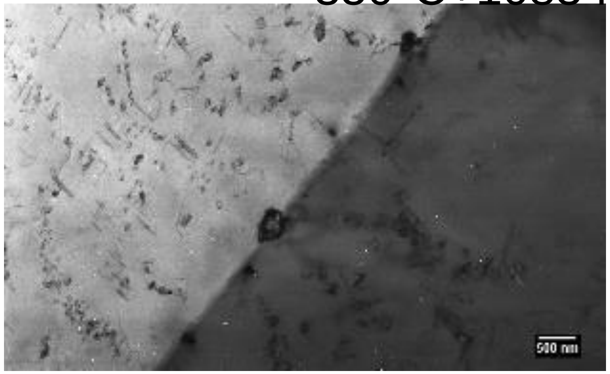
400°C+2000 ho



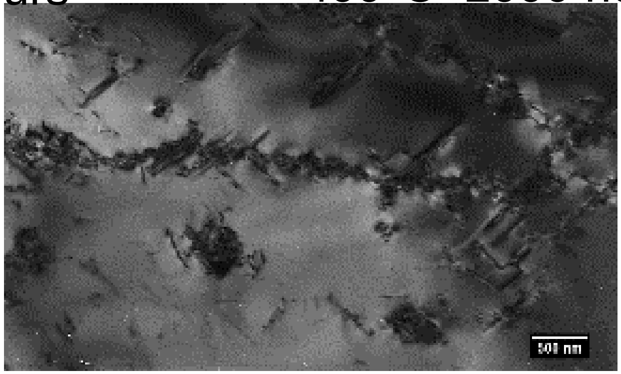
(MCP V1) as-received



350°C+1083 hours



400°C+2000 ho



Thank you!

Acknowledgement
Author acknowledge support from EC-project No-101061201 DELISA-LTO.

Vladimir.Slugen@stuba.sk

DELISA-LTO Workshop
Kočovce, Slovak Republic, 11 February 2025

Atomic and Magnetic Force Microscopy

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Institute of Nuclear and Physical Engineering,
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Slovak University of Technology in Bratislava,
Slovak Republic

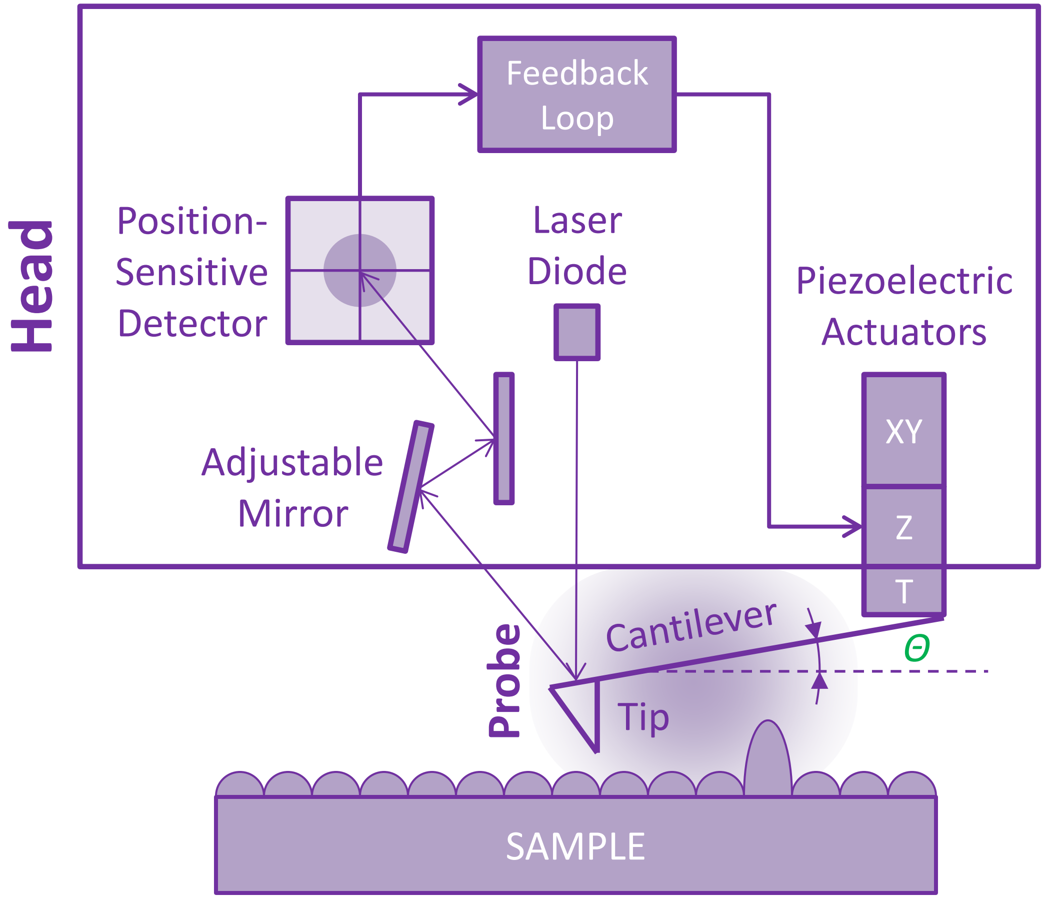
Atomic Force Microscope

- Device primarily used for studying surface properties of materials.

$\Theta \approx 11°$ (Veeco)
$\Theta = 20°$ (NT-MDT)

Principle of Operation:

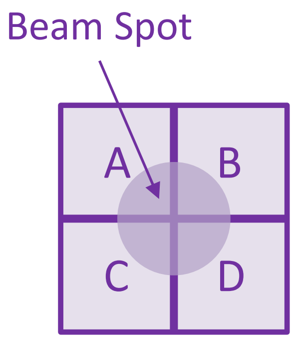
- Sharp tip scans sample surface.
- Interatomic forces between tip and sample bend cantilever.
- Bending detected as displacement of reflected laser beam.
- Probe oscillates; system monitors deviations in cantilever oscillations from reference value and compensates for them using feedback loop (by adjusting vertical probe-sample distance).
- Probe's vertical movement used to generate surface topography.



G. Binnig, C. F. Quate, and Ch. Gerber (from IBM): *Phys. Rev. Lett.* 56 (**1986**) 930.

Position-Sensitive Detector

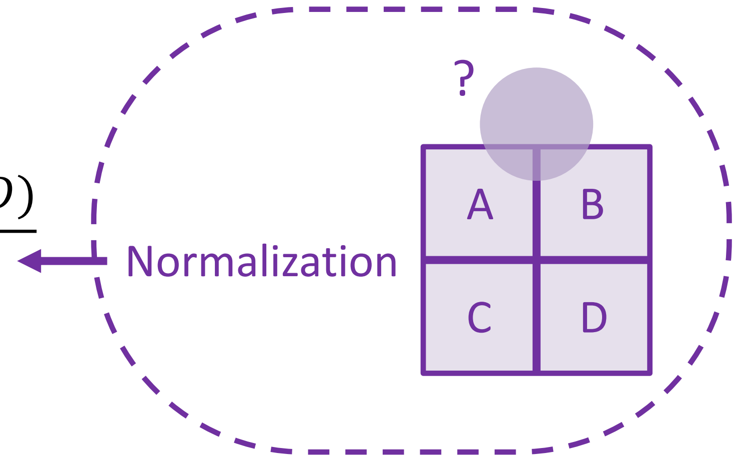
4-quadrant Si photodiode:



A, *B*, *C*, and *D* are photocurrents measured in each quadrant of diode

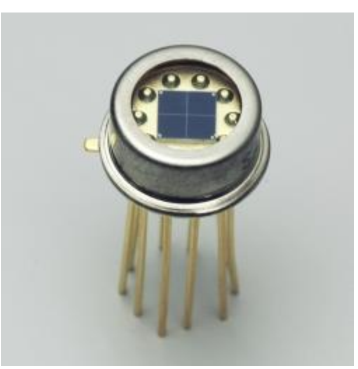
Cantilever Deflection:

$$Y = \frac{(A+B)-(C+D)}{A+B+C+D}$$



Cantilever Twist:

$$X = \frac{(B+D)-(A+C)}{A+B+C+D}$$



Example: Si PIN photodiode by **HAMAMATSU**, model S4349
Total photosensitive area: 3 × 3 mm^2
Gap width between quadrants: 0.1 mm

Probe

- Monolithic design

Material:

- Monocrystalline silicon* or silicon nitride (Si_3N_4)

*) Monocrystalline silicon is doped with antimony to enhance the tip's conductivity, thereby preventing the accumulation of electrostatic charge.

Fabrication Process:

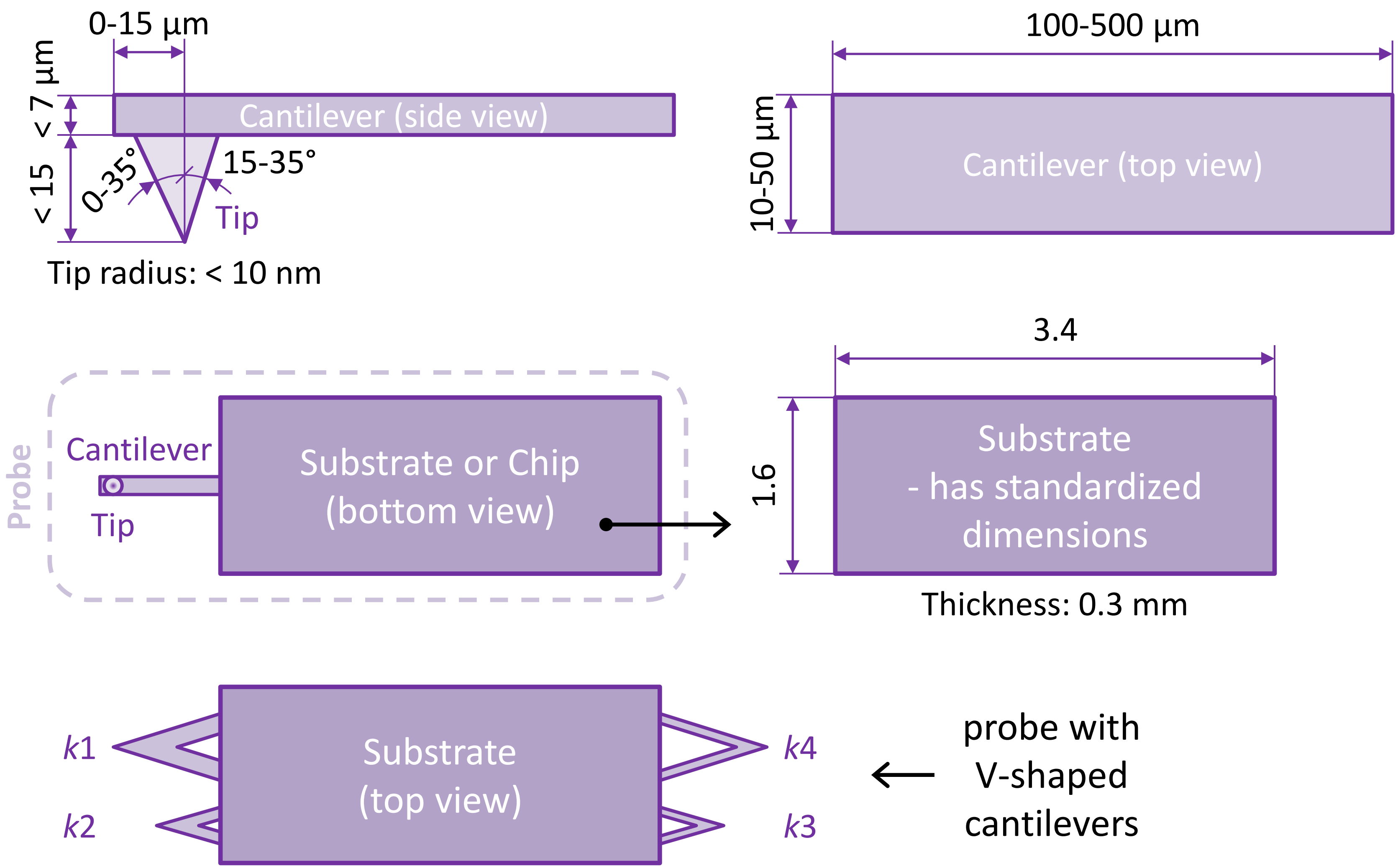
- Photolithography and etching**
- Batch Production: A single 6-inch silicon wafer yields over 1,000 AFM probes.

**) In the case of Si, anisotropic wet etching is used, where the material is removed more quickly along certain crystallographic directions.

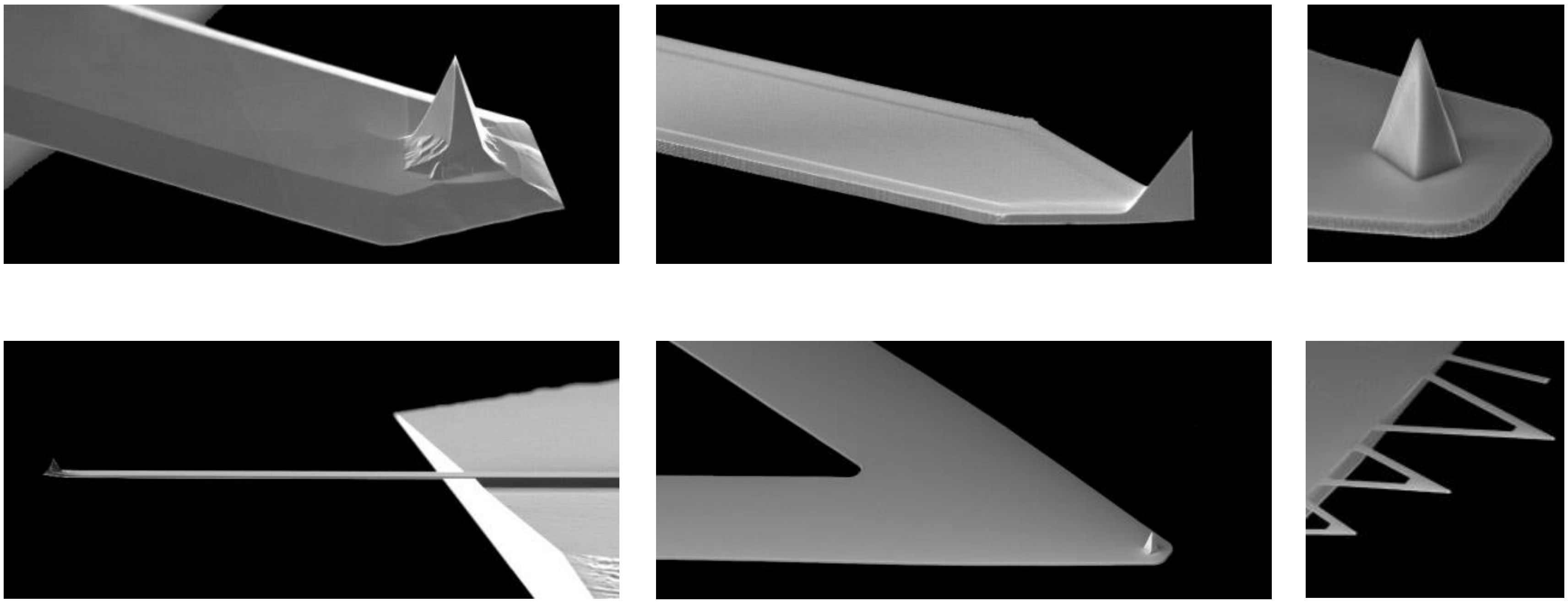
Probe Types:

- Each type of sample requires a specific probe. There are probes designed for soft samples, hard samples, magnetic samples (with tips having varying magnetic moments or coercivity), and probes tailored for specific operational modes of the microscope. They may be coated, have specific tip geometries, and so on.

Probe Geometry and Dimensions



Probes with Different Tip and Cantilever Geometries



Coatings on Tip and Cantilever

- Modify probe properties, and their presence depends on the specific model.

Coatings can be **applied to**:

- **the tip side** (facing the sample surface), where they provide:
  - Conductivity: Essential for nanolithography (using local anodic oxidation) and certain AFM techniques, such as: *Conductive AFM (C-AFM), Electrostatic Force Microscopy (EFM), Scanning Spreading Resistance Microscopy (SSRM),* and *Scanning Capacitance Microscopy* (SCM).
  - Magnetic properties of the tip: Required for *Magnetic Force Microscopy (MFM).*
  - Mechanical properties: Extends the tip's lifespan (but increases its radius).
  - Chemical properties: Used in *Chemical Force Microscopy (CFM).*

- **the cantilever side** (facing the detector), to improve laser reflectivity.
  - A reflective coating on the cantilever is especially beneficial for thin (even partially transparent) cantilevers and shiny sample surfaces.

Drawback of coatings: They have a different coefficient of thermal expansion compared to the cantilever material (causing a "bimetallic effect").

Composition of Probe Coatings

Reflective Coatings:

- Most common: Al, Au*

  ← ***higher reflectivity***

*) applied over an adhesion layer of Cr or Ti

Electrically Conductive Coatings:

← ***higher conductivity***

- Au, PtIr, TiN, polycrystalline diamond dopped with B or N

  higher hardness →

Non-Conductive Hard Coatings:

- Amorphous carbon (Diamond-Like Carbon = DLC)

Magnetic Coatings:

- Co**, or alloys such as CoCr, CoPtCr, NiFe (Permalloy)

  ← ***higher coercivity***

**) protected with a Cr coating to prevent oxidation of the magnetic layer

Coating Thicknesses:

- Polycrystalline diamond (100 nm)
- Magnetic coatings (20-60 nm)
- Other coatings (20-30 nm)

Operating Modes of AFM Microscopes

- **Contact Mode** – Continuous contact with sample surface. Feedback loop can either maintain constant deflection (adjusts height) or be disabled (fixed height).
  Tapping Mode – Probe oscillates, making intermittent contact with surface, while feedback maintains constant amplitude.
- **Non-Contact Mode** – Cantilever resonant frequency shifts due to tip-sample interaction. Can be detected in 3 ways: phase detection, amplitude detection, frequency modulation.

Contact Mode:

Advantages:

- High lateral resolution.
- High scan speeds.
- Allows detection of friction.

Disadvantages:

- Sensitive to capillary forces.
- Lateral forces exerted on tip may damage sample and alter imaging.
- Not suitable for soft samples.

Tapping Mode (Most Commonly Used):

Advantages:

- Weaker forces = Less damage to soft samples.

Disadvantages:

- Slower scan speeds.

Non-Contact Mode:

Advantages:

- Gentle on both tip and sample.

Disadvantages:

- Typically requires vacuum.
- Lower lateral resolution.

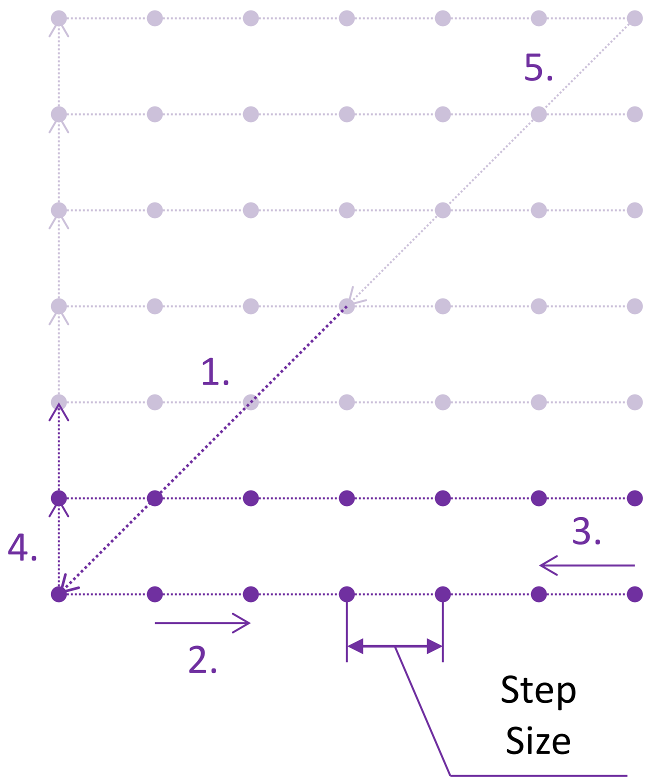
Scan Pattern

Image Acquisition Process:

1. Probe moves from center of scanned area (starting position) to bottom-left corner.
2. Topography scanned along single line. Measurements at discrete points.
3. Returns along same path, takes measurements again.
4. Moves to next line. **Steps 2-4 repeated** until area is scanned.
5. Returns to starting position.

- Each discrete measurement = 1 pixel.

- Step size determined by scanned area and image resolution.



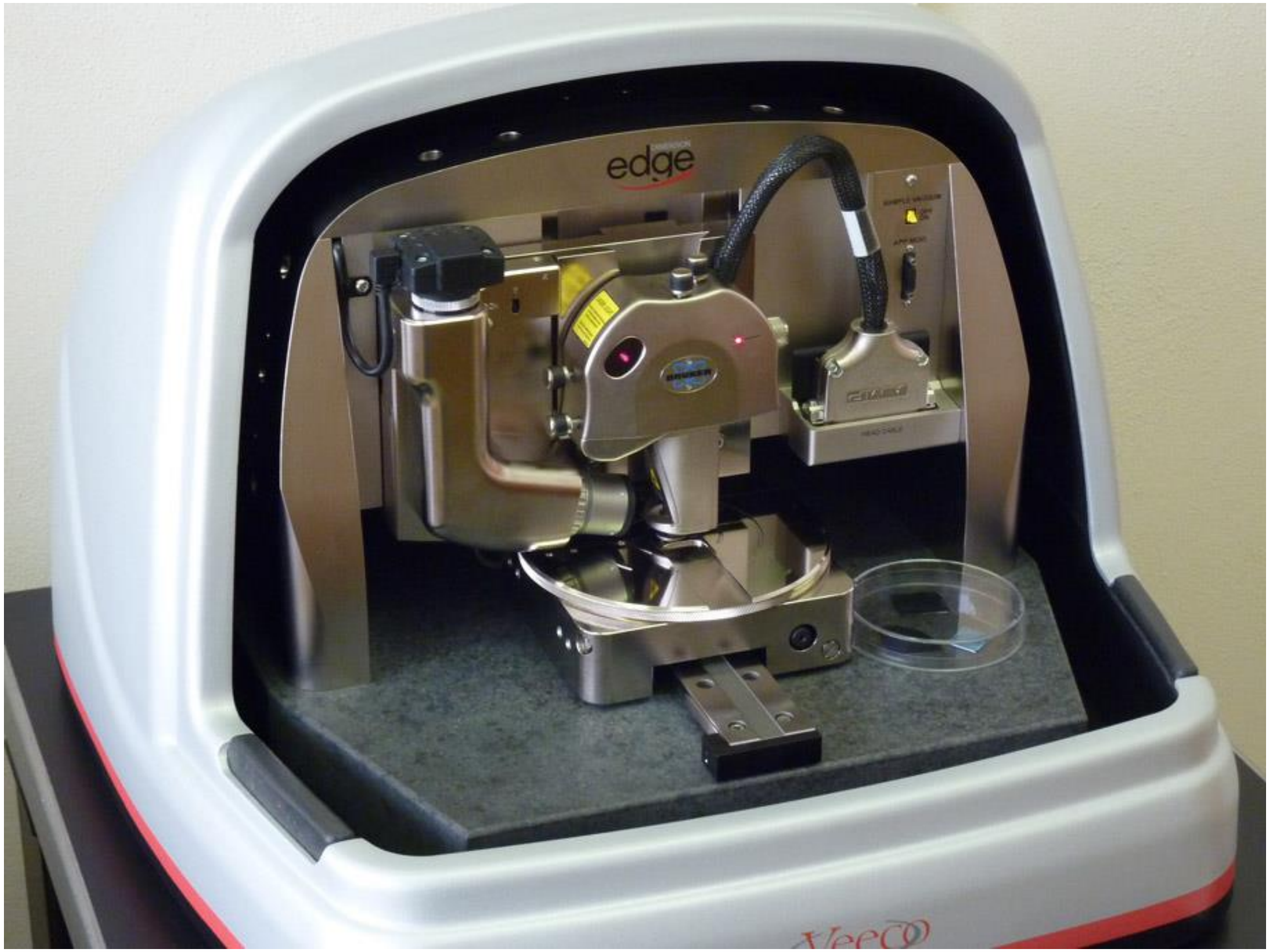
Atomic Force Microscope and Its Components

Atomic Force Microscope and Its Components

Microscope Room

Adjacent Room

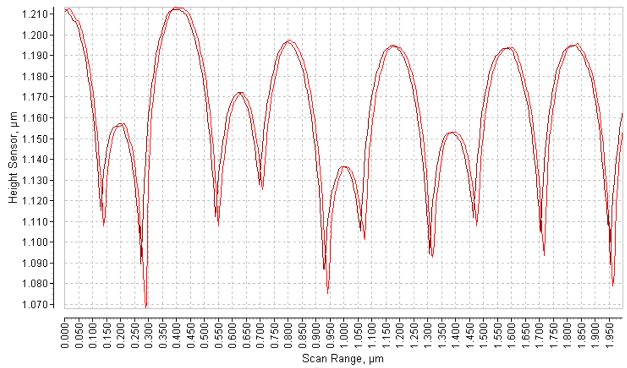
Veeco Dimension Edge™ Atomic Force Microscope

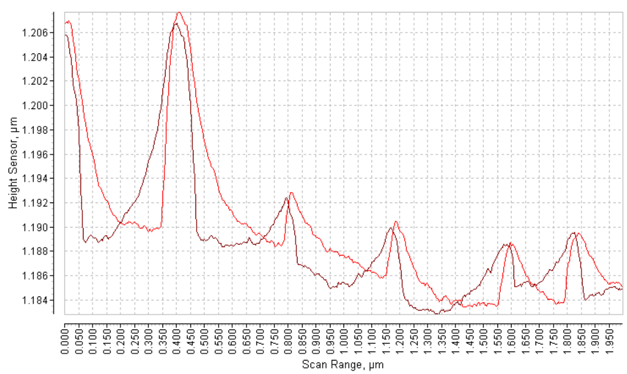


Probe Mounted in the Scanning Head

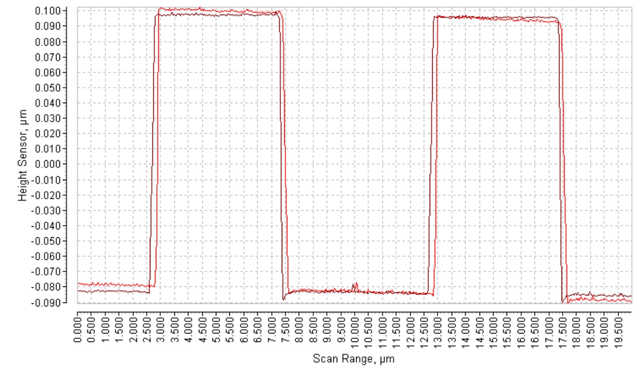
Scanning Parameters

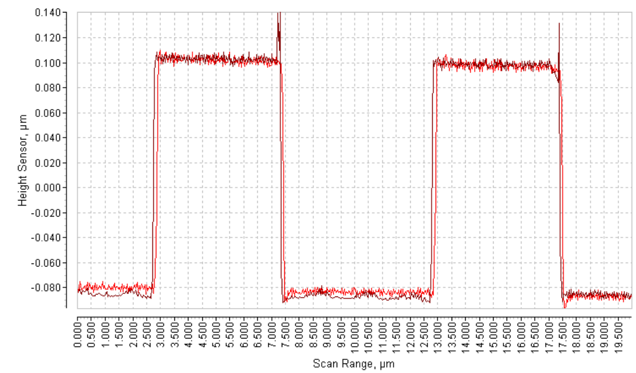
Force Applied

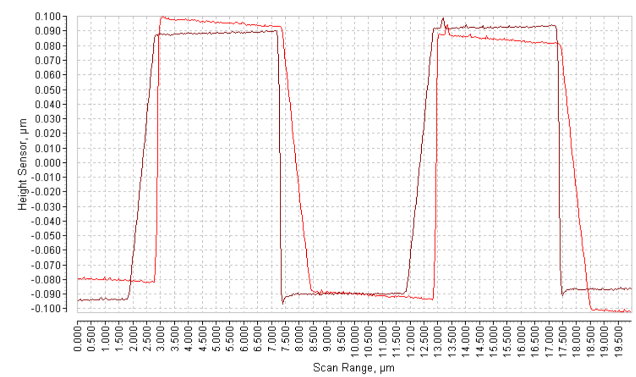




Feedback



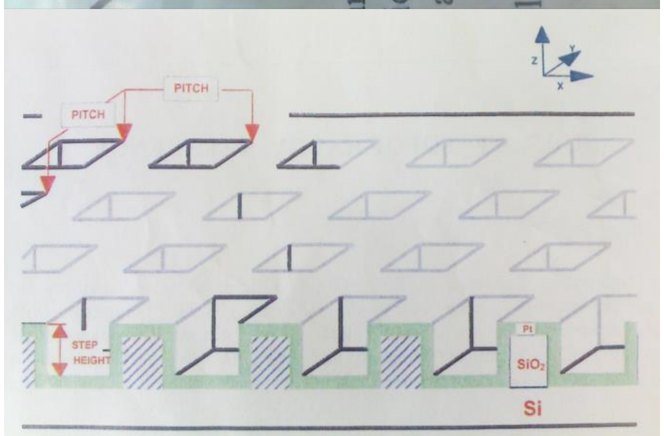


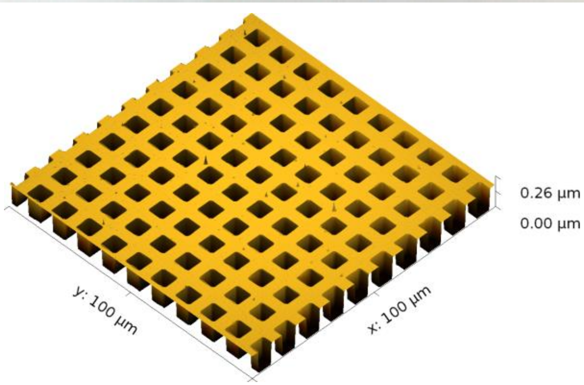


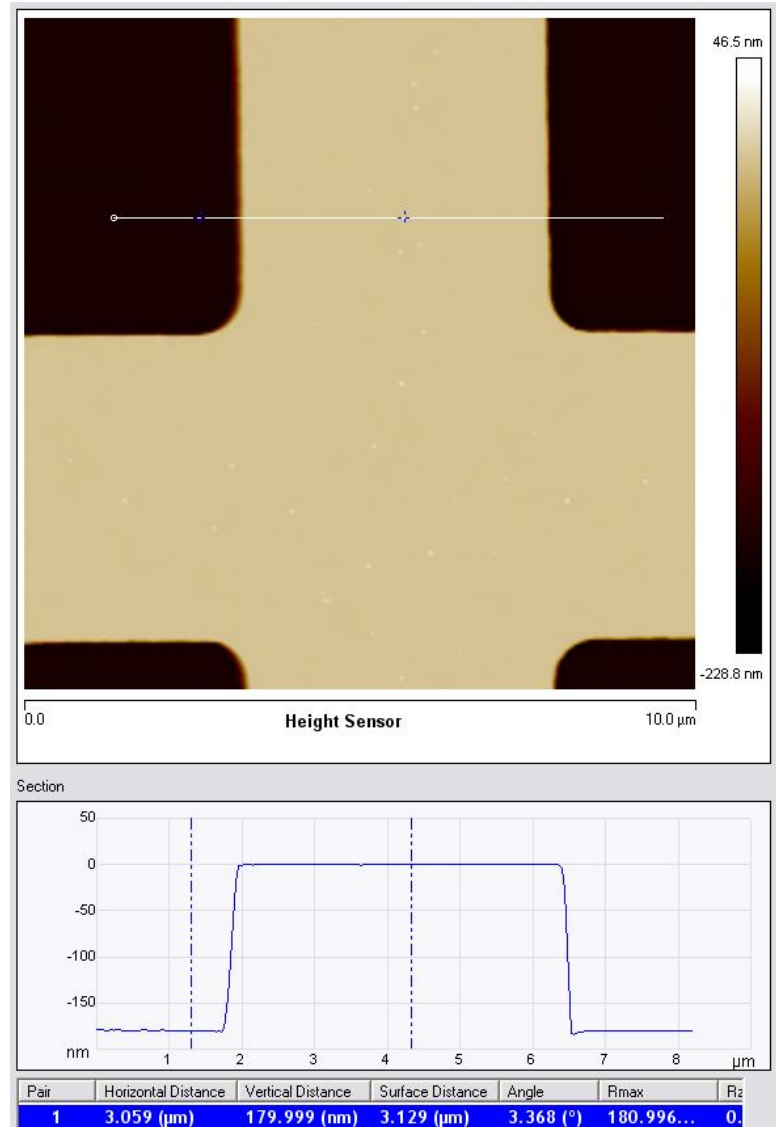
Other Parameters:

- Resonant Frequency
- Free Oscillation Amplitude
- Scanning Speed

Microscope Calibration







Quantitative Image Analysis

Surface Properties:

- Average (R_a) or root mean square (R_q) roughness
- Specific surface area
- Specific volume

Object Characteristics:

- (Average) height of protrusions
- Diameter or lateral dimensions of protrusions (less accurate than height)
- Periodicity (e.g., in stripe domain structure)

Statistical Analysis:

- Height distribution
- Power Spectral Density Function (PSDF)

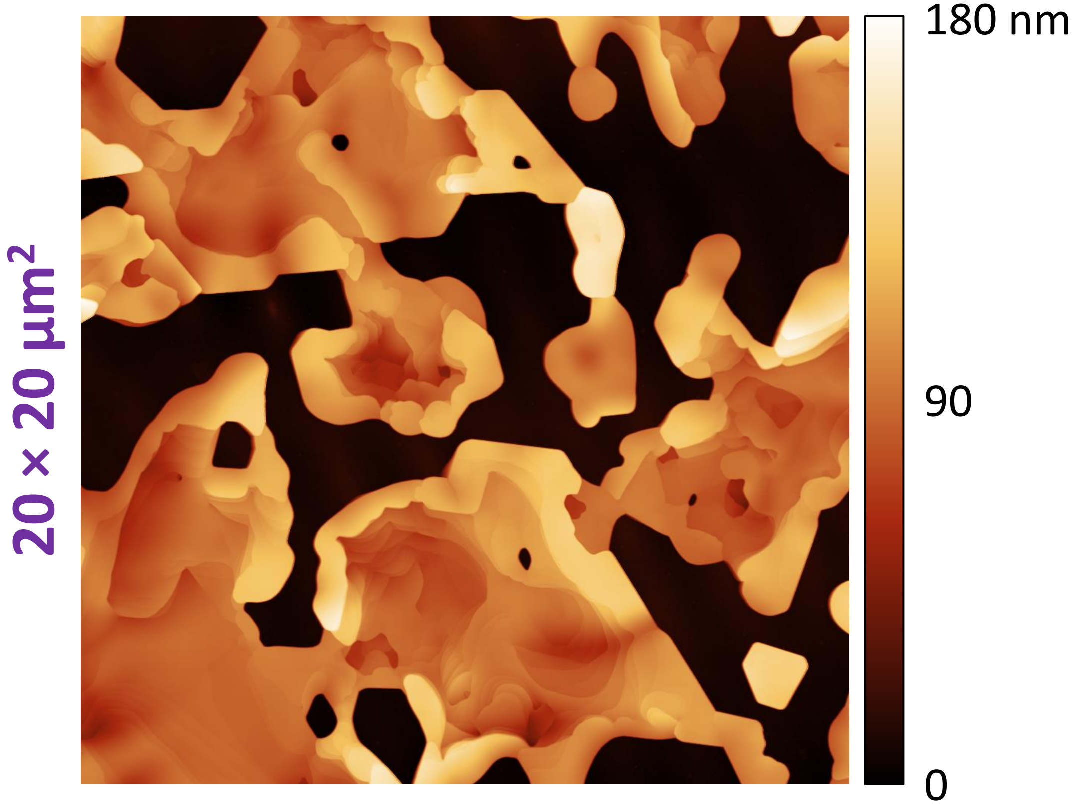
Examples of AFM Applications

Organic Semiconductors

Collaboration with student **MSc. Ľuboš Cehlárik** (PriF UK)

TASK: Examine surface morphology of prepared samples.

2,2'-Bis(4-(trifluoromethyl)phenyl)-4,4'-bithiazole

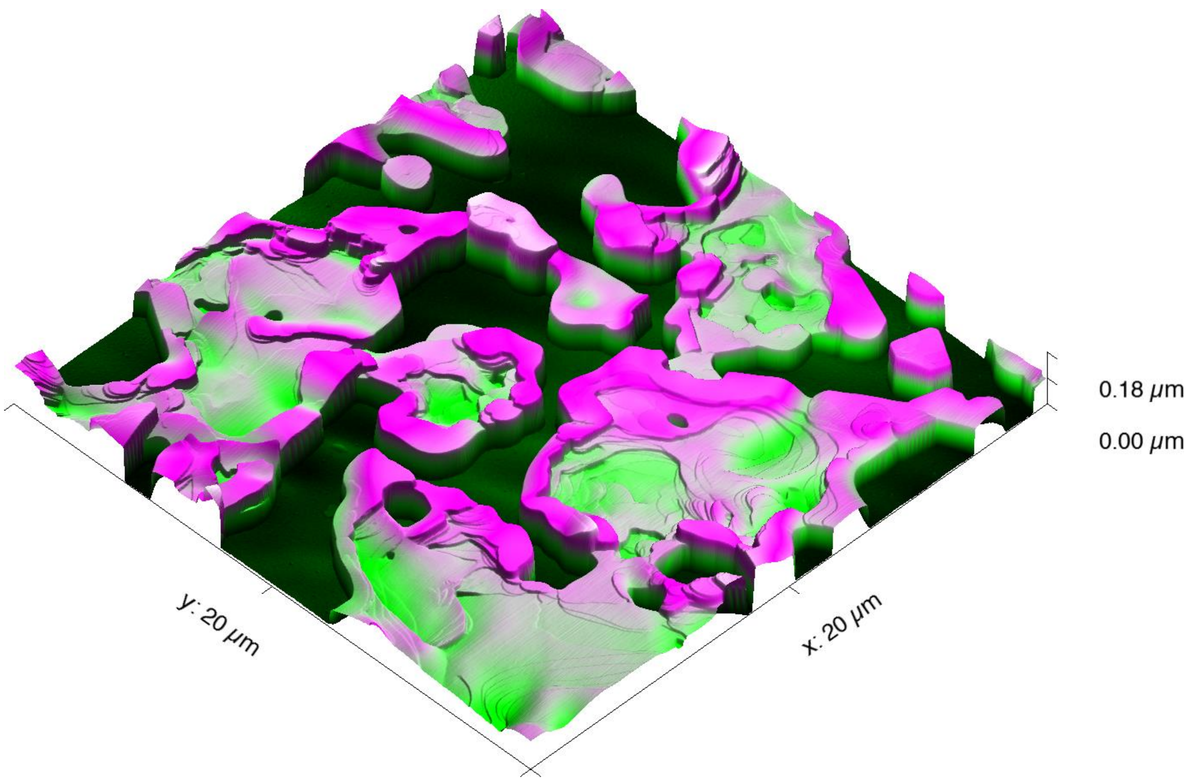


2D Visualization

Organic Semiconductors

Collaboration with student **MSc. Ľuboš Cehlárik** (PriF UK)
TASK: Examine surface morphology of prepared samples.

2,2'-Bis(4-(trifluoromethyl)phenyl)-4,4'-bithiazole

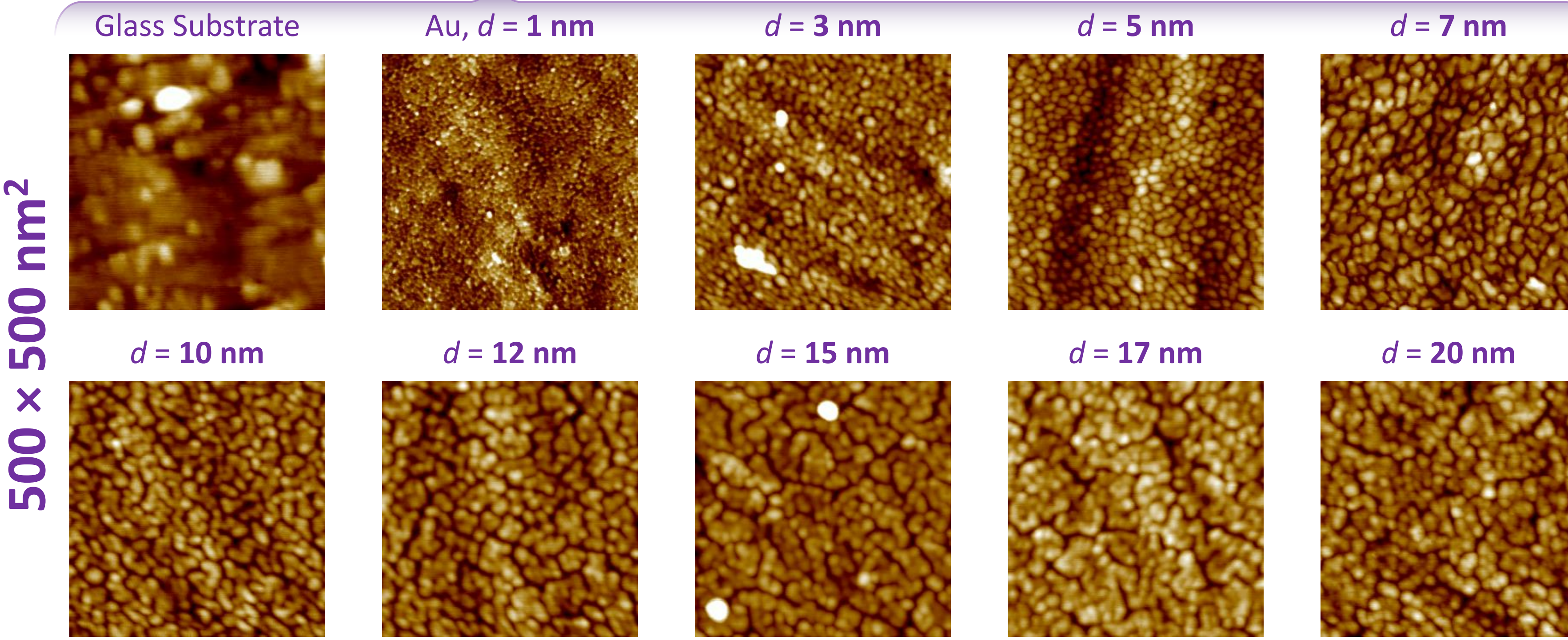


3D Visualization

Gold

Collaboration with **Assoc. Prof. Martin Weis, PhD.** (ÚEF FEI)

TASK: Investigate surface morphology of vacuum-evaporated Au as a function of layer thickness *d*.



Monitored Parameters:

1. Period
2. Average roughness
3. Specific surface area

Compared with optical measurements (ÚEF FEI).

AFM Analysis of Steels (From Literature)

Study Title: Observation of stress corrosion cracking using real-time in situ high-speed AFM and correlative techniques

Source: S. Moore et al., *npj Materials Degradation* 5 (Nature Partner Journals, **2021**) 3.

DOI: 10.1038/s41529-020-00149-y

Key Application:

Visualization of stress corrosion cracking on AISI Type 304 stainless steel in an aggressive salt solution.

Key Insight:

High-speed AFM revealed uplift of grain boundaries before cracking, suggesting a subsurface role in the cracking process. Subsurface intergranular cracks, linked to oxide formation, were confirmed by complementary techniques.

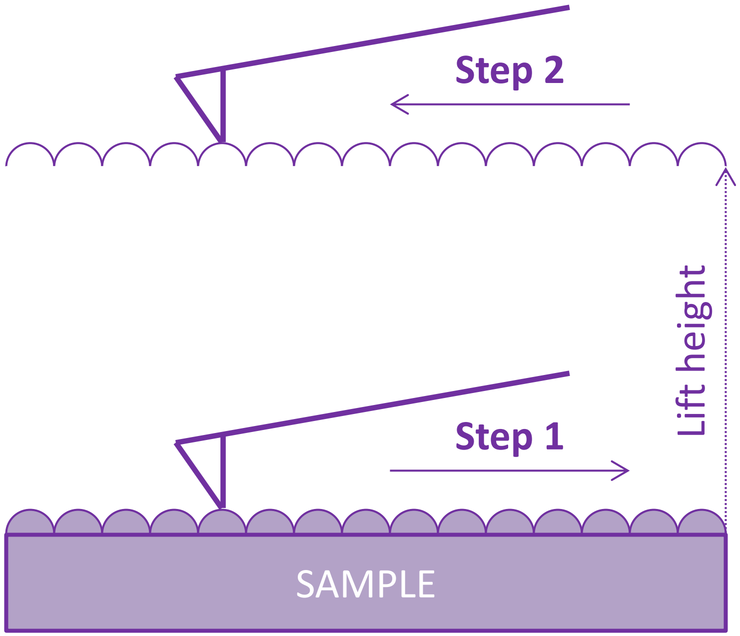
Magnetic Force Microscopy (MFM)

MFM Principle

- Technique: Based on AFM, detects magnetic interactions to visualize the magnetic structure.

- **MFM Tip:** Coated with ferromagnetic material and magnetized before measurement. The tip has a fixed magnetic moment oriented along its axis.

- Steps 1 and 2 are repeated over the entire scanned area to acquire the complete image.



Measurement technique (LiftMode™):

- **Step 1** – Topography is recorded along a single line. Then, the probe is lifted to a user-defined height (**lift height**), where magnetic forces are assumed to dominate over topography forces.
- **Step 2** – The probe retraces the previously recorded topography profile while maintaining the lift height. Magnetic interactions alter the cantilever's oscillation, causing changes in phase shift, amplitude, or resonant frequency, which can be measured.

Y. Martin and H. K. Wickramasinghe (from IBM): *Appl. Phys. Lett.* 50 (**1987**) 1455;
J. J. Sáenz *et al.*: *J. Appl. Phys.* 62 (**1987**) 4293.

Operating Modes of MFM

Dynamic (most commonly used):

- Probe oscillates
- Higher sensitivity
- Sensitivity to:
  magnetic field gradient

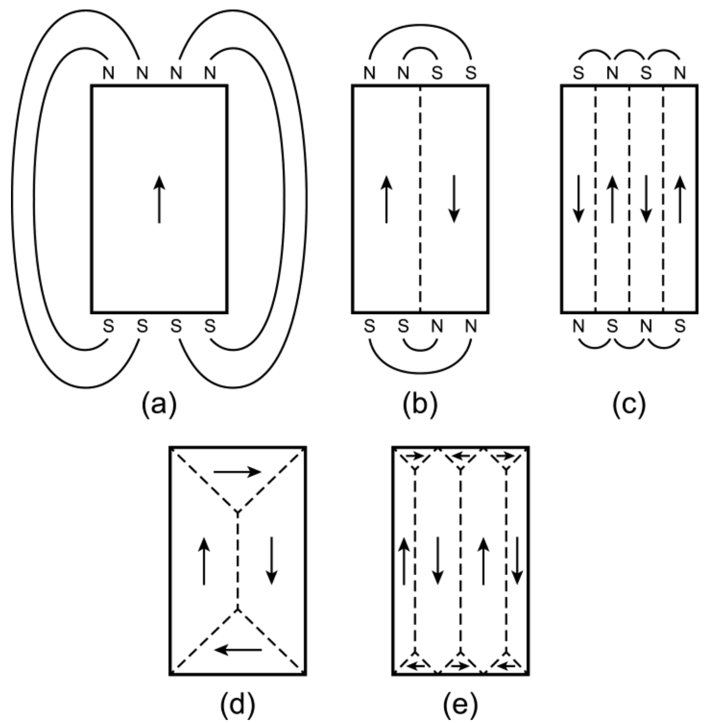
Static:

- Probe does not oscillate
- Low sensitivity
- Sensitivity to:
  magnetic field

- In **2023**, N. H. Freitag et al. (*Commun. Phys.*, Vol. 6, p. 11) introduced a method based on MFM, enabling simultaneous measurement of a sample's magnetic field and its gradient.

MFM Limitation: The MFM tip is sensitive only to the component of the magnetic field that is parallel to the tip axis, which causes ambiguity in determining the orientation of magnetic moments.

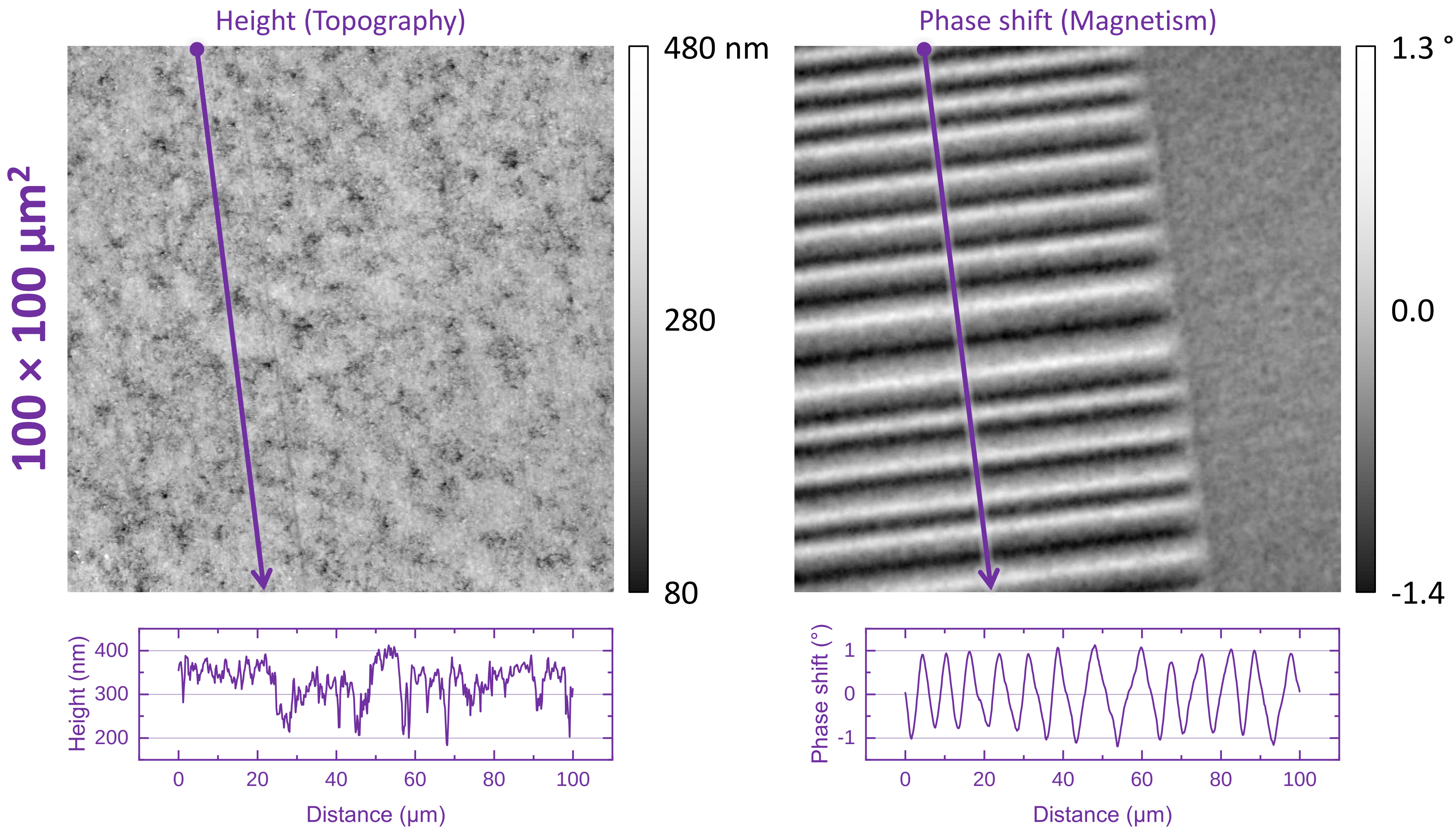
Magnetic Domains



C. Kittel: Physical Theory of Ferromagnetic Domains,
Rev. Mod. Phys. 21 (**1949**) 541.

MFM Demonstration: 5¼-inch Floppy Disk

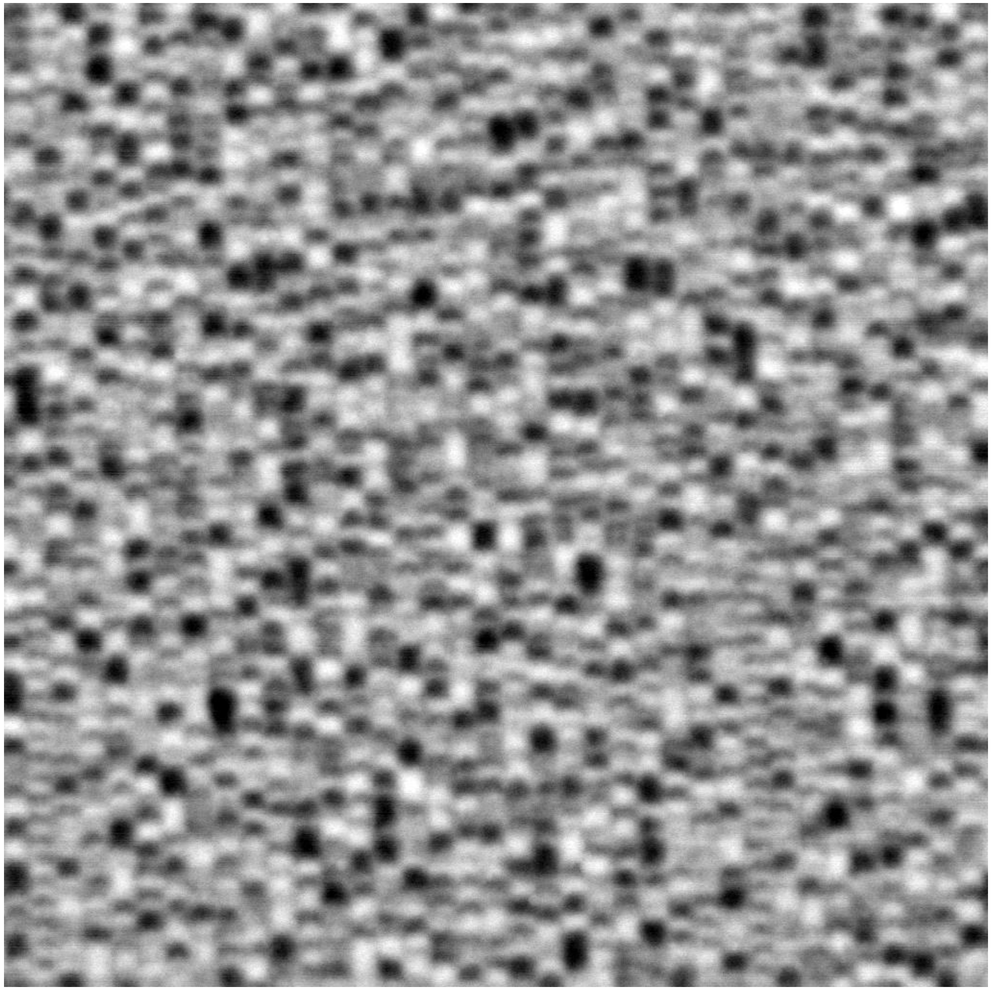
Floppy disk from Verbatim with double-sided recording, model Verex™.
MAGNETIC MATERIAL: γ-Fe_2O_3, SHAPE OF MAGNETIC PARTICLES: needle-like.



MFM Demonstration: Hard Disk Platter

2.5" disk from Seagate utilizing PMR, model Momentus ST9500423AS.
DISK CAPACITY: 500 GB, RECORDING DENSITY (specified by the manufacturer): 541 Gb/in^2.

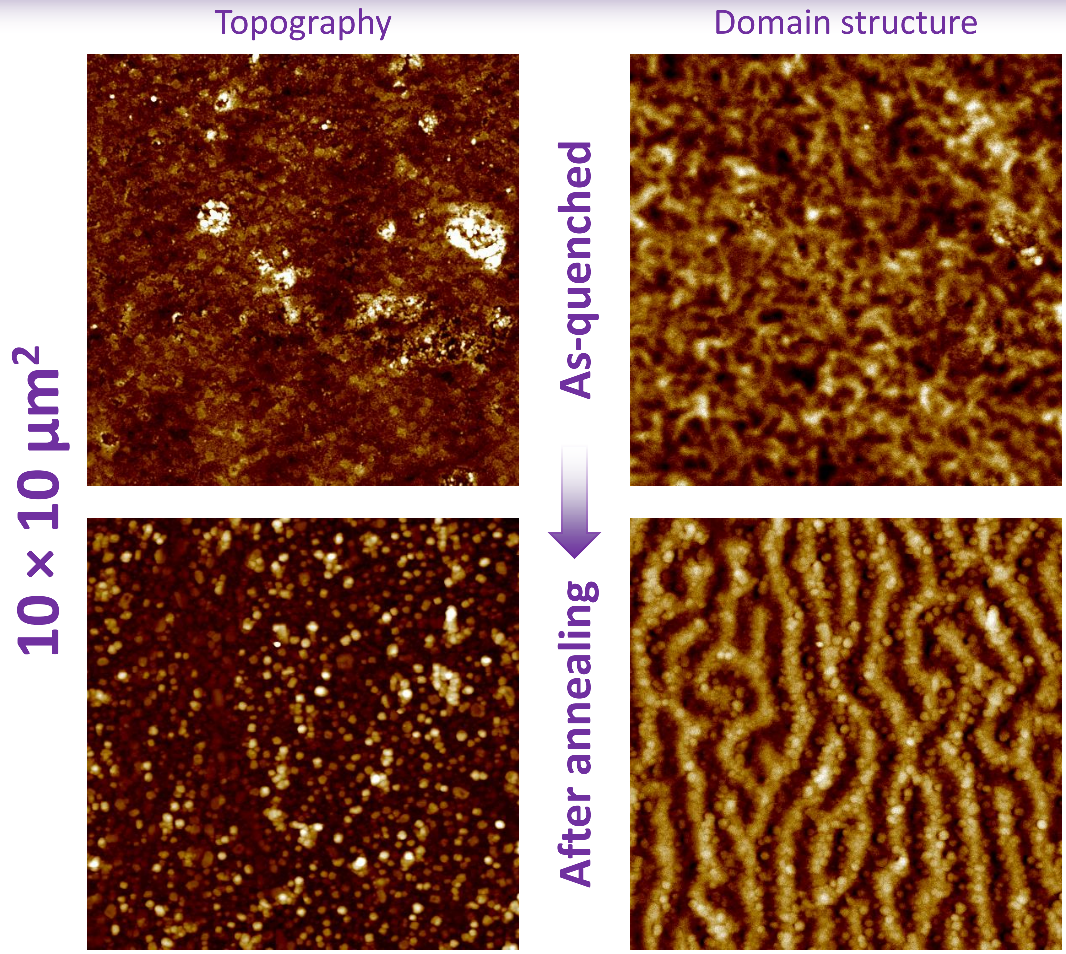
Phase shift (Magnetism)



MFM Applications: FeZrB Alloy

Collaboration with **Prof. Dr. Marcel Miglierini** (ÚJFI FEI)

TASK: Investigate magnetic structure of $^{57}Fe_{90}Zr_7B_3$ in as-quenched state and after annealing.



MFM Applications: FeZrB Alloy

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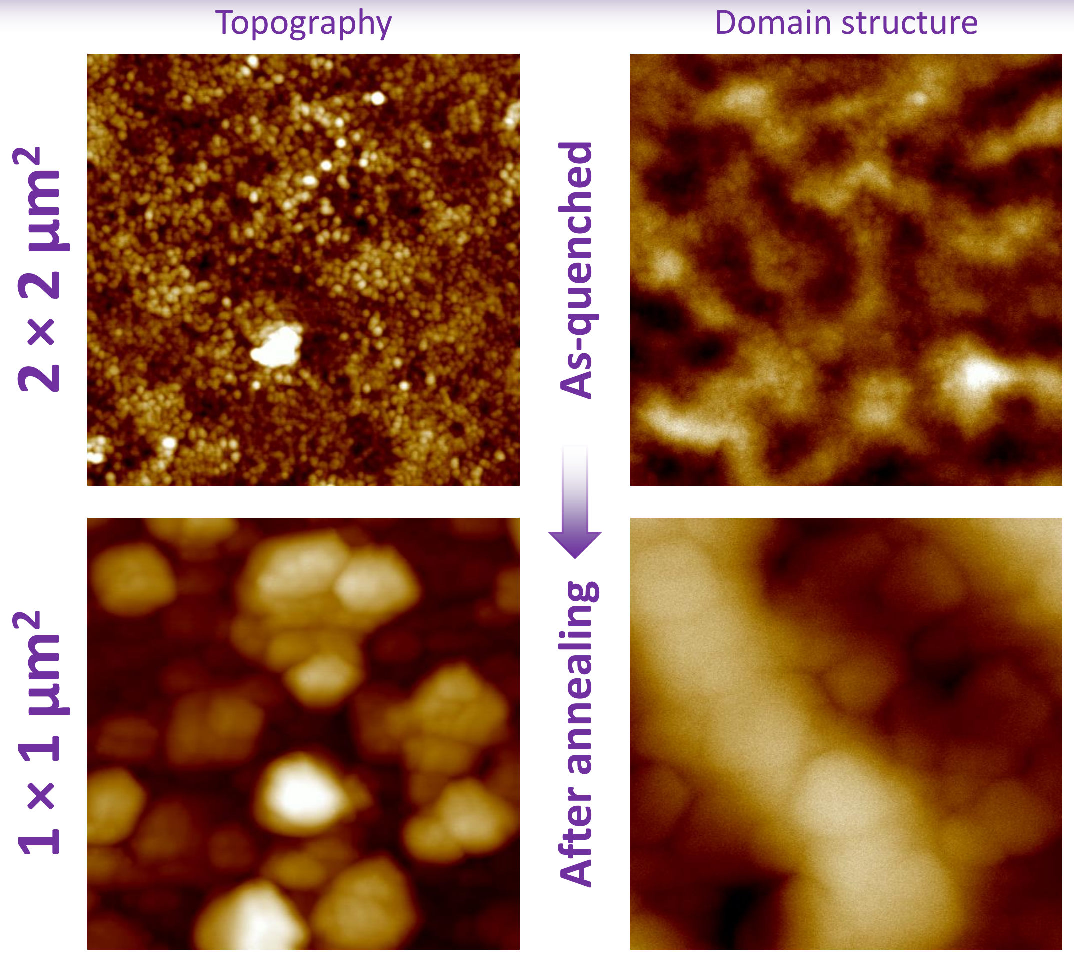
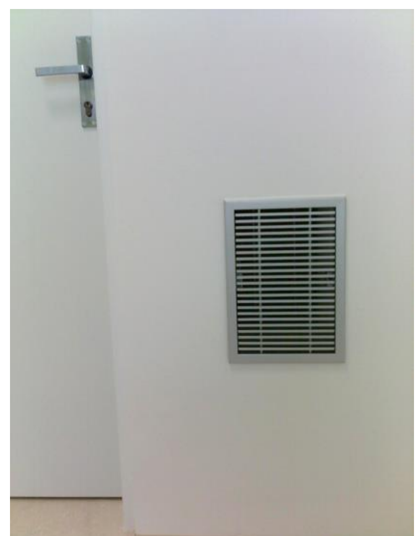


AFM/MFM Microscopy Laboratory

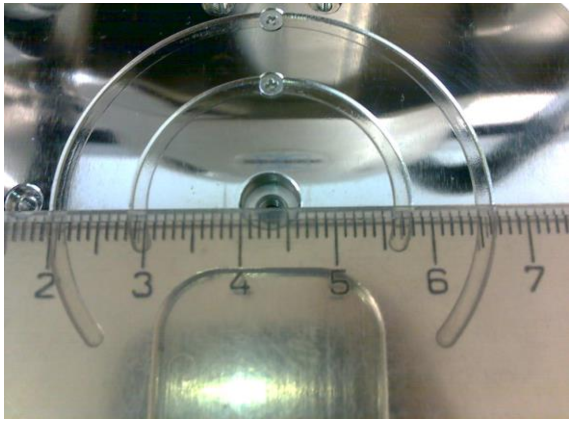


Our Specific Requirements for Samples

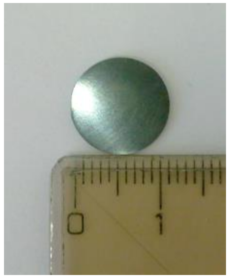
- Surface: Solid, dry, flat, clean, and low roughness (nm range ideal, µm range max.).
- Measurements on large samples possible (height up to 2cm, area up to 30×30cm^2).
- Sample can be oriented vertically, but this is uncommon.
- Knowing sample history (production and preparation) simplifies result interpretation.

Sample Mouting:

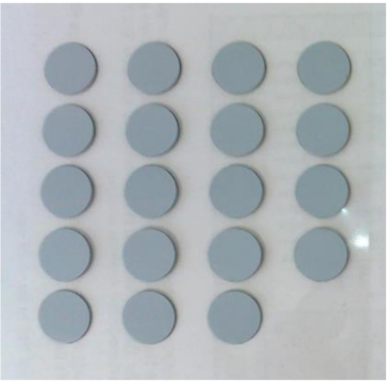
Vacuum chuck



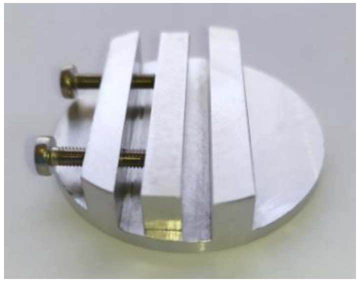
Magnetic stainless-steel support disc



Conductive double sided adhesive carbon tabs



Magnetically



Vertically

Any questions, please?

STU FEI
SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION TECHNOLOGY

ÚJFI
Institute of Nuclear and Physical Engineering

Perspective of using PAS in the research of materials exposed to extreme radiation conditions.

11. February 2024

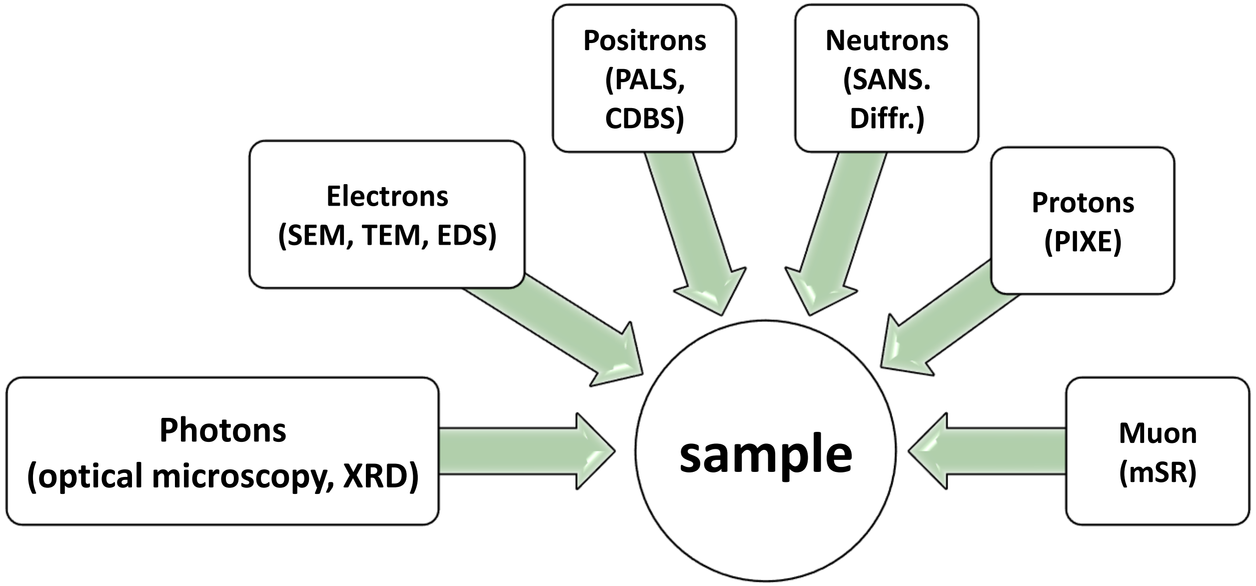
Vladimír Kršjak

Outline:

- Probing the Nanoworld
- A Brief History of the Positron
- Positron Annihilation Spectroscopy
- Positron Sources
- Radiation Effects in F/M Steels: Helium
- An Example of a Research Application

How to probe the nanoworld

How to probe the nanoworld



Source - emission

(α, β, γ, p, n, μ^- ...)

- Radioisotope sources
- Particle accelerators
- Cathode ray tubes etc.

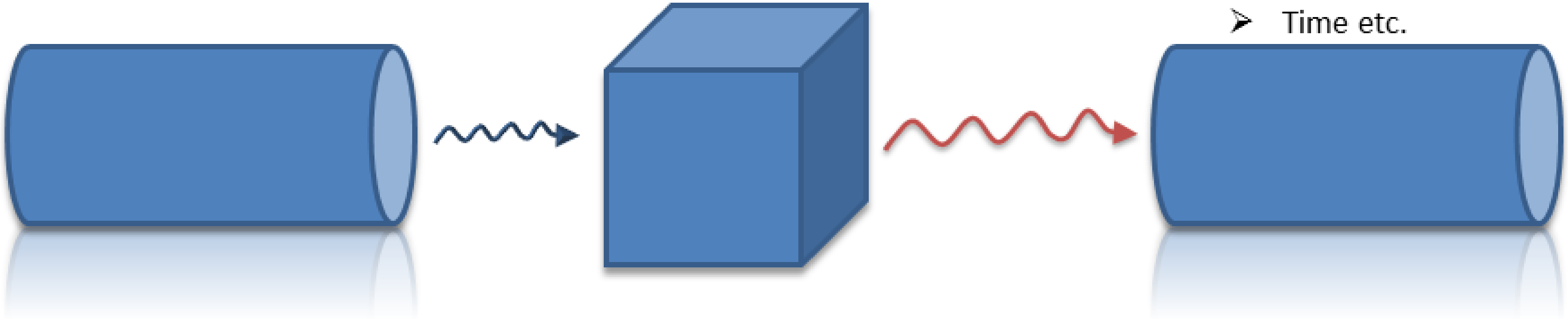
Sample – interaction

- Nuclear reaction
- Scattering / Diffraction
- Photoelectric effect
- e^- e^+ annihilation etc.

Detector - detection

(β', γ', n', $\mu^{-\prime}$ ...)

- Energy
- Momentum
- Charge
- Time etc.



How to probe the nanoworld

The Planck-Einstein equation is the starting point of quantum theory

$$E = hf = \frac{hc}{\lambda}$$

and Planck's constant h (6.62607004 × 10^{-34} m^2kg/s) is at the heart of quantum mechanics

Light (EM wave) can be quantified -> EM wave of given wavelength (λ) corresponds to a quantum of energy (E) - photon

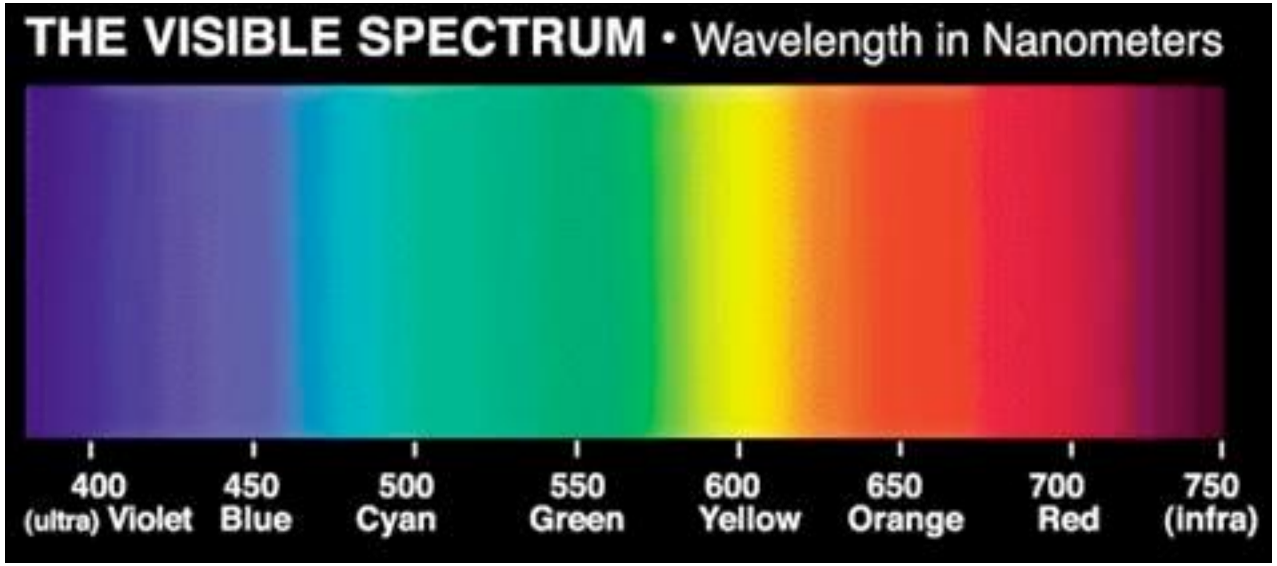
But it works also the other way around! Particles (all) with a given energy have an associated wavelength (de Broglie hypothesis)

The wavelength is given by $\lambda = h / p$ where p is the momentum of a particle.

$$E_k = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{p^2}{2m} \Rightarrow p = \sqrt{2Em}$$

The higher the energy of the particle, the lower the wavelength, the higher the resolution

How to probe the nanoworld



Let's take a nice **ORANGE** color with wavelength of 621nm

621nm ≈ 2eV (3.2×10^{-19}J)

Let's take <u>2eV electron</u>

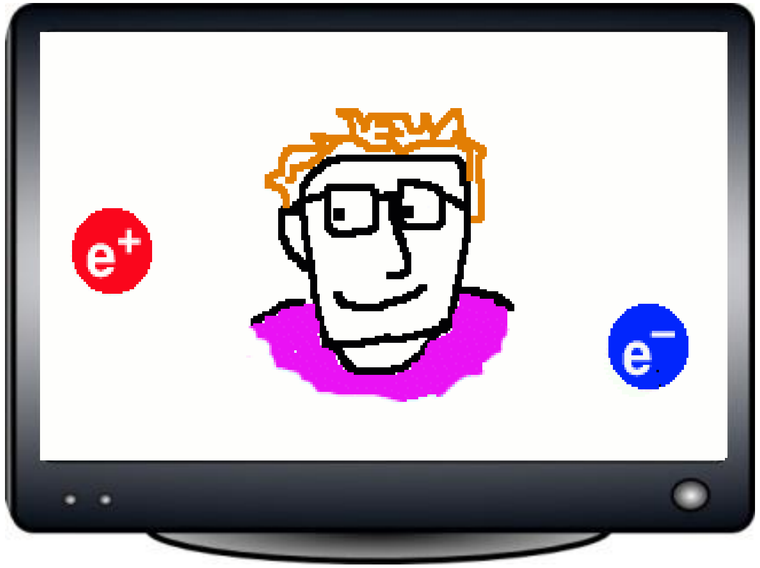
$$p = (2mT)^{1/2} = (2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 2)^{1/2} = 7.63 \times 10^{-25} \text{ kg m/s.}$$

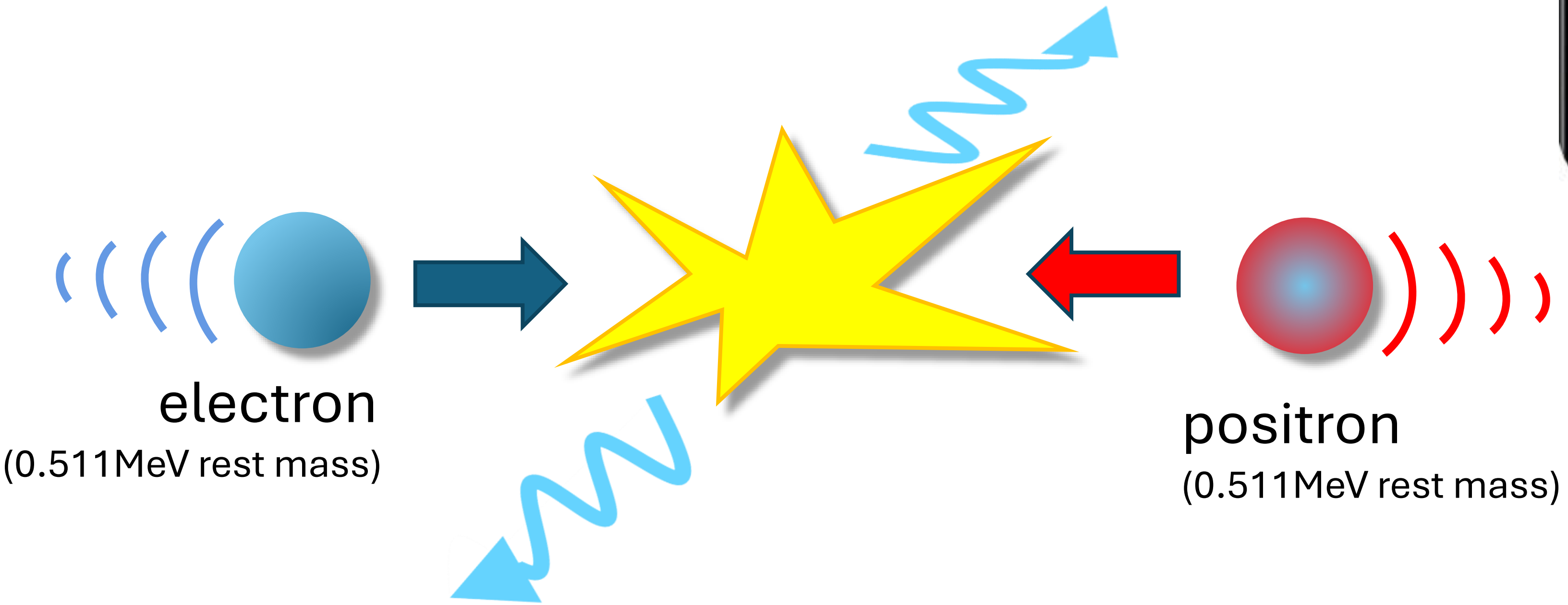
$$\lambda = h/p = 6.625 \times 10^{-34} / 7.63 \times 10^{-25} = \mathbf{0.87\ nm}$$

Electron 20keV≈ 0.272c≈ 0.01nm **Thermal neutron** ≈ 1.5nm

What about positron?

The wavelength of positron as a probing particle does not really matter in experiment



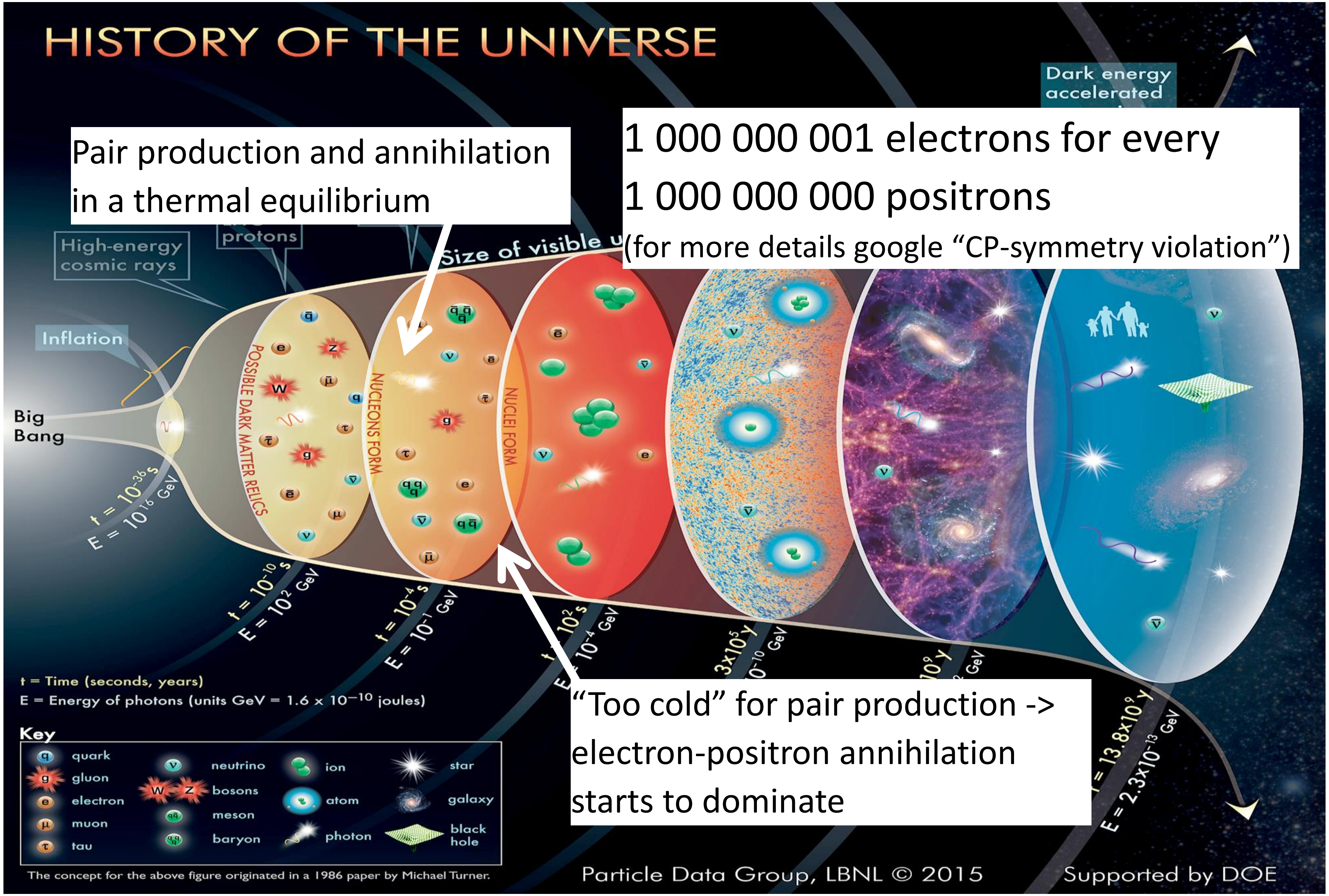


Positron sacrifices itself when it encounters with an electron.
This "illuminates" the annihilation site

A brief history of positron

….. let’s start at the beginning

How to probe the nanoworld



Pair production and annihilation in a thermal equilibrium

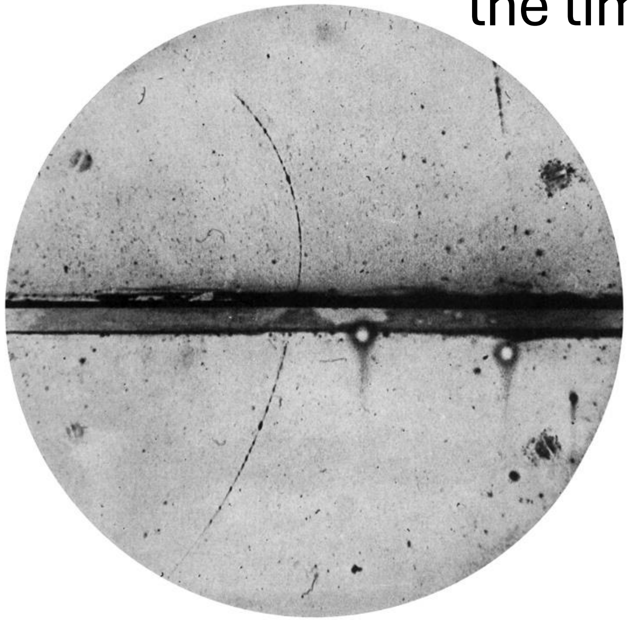
1 000 000 001 electrons for every 1 000 000 000 positrons
(for more details google “CP-symmetry violation”)

“Too cold” for pair production -> electron-positron annihilation starts to dominate

13.8 Billion years later…

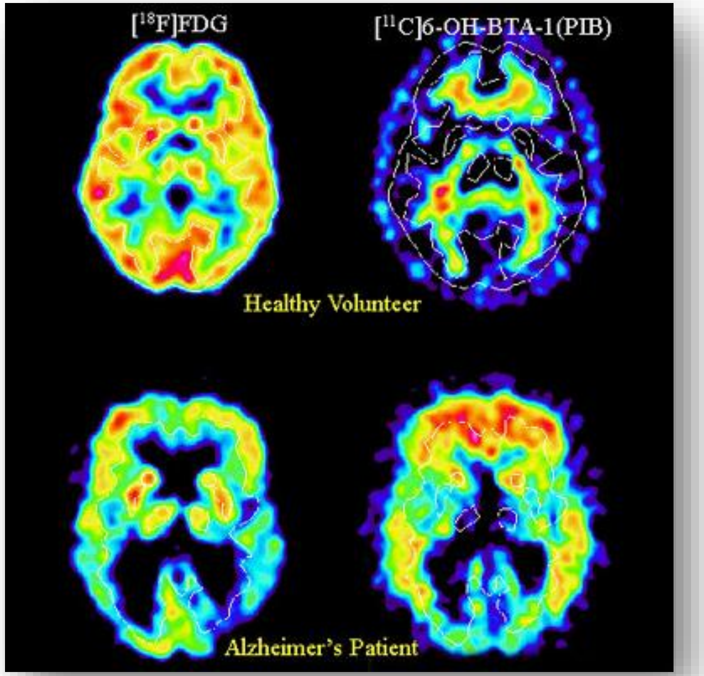
Positron as the antiparticle of the electron (the first antiparticle in physics) was predicted by Dirac in 1928 (At the time he was 26 years old)

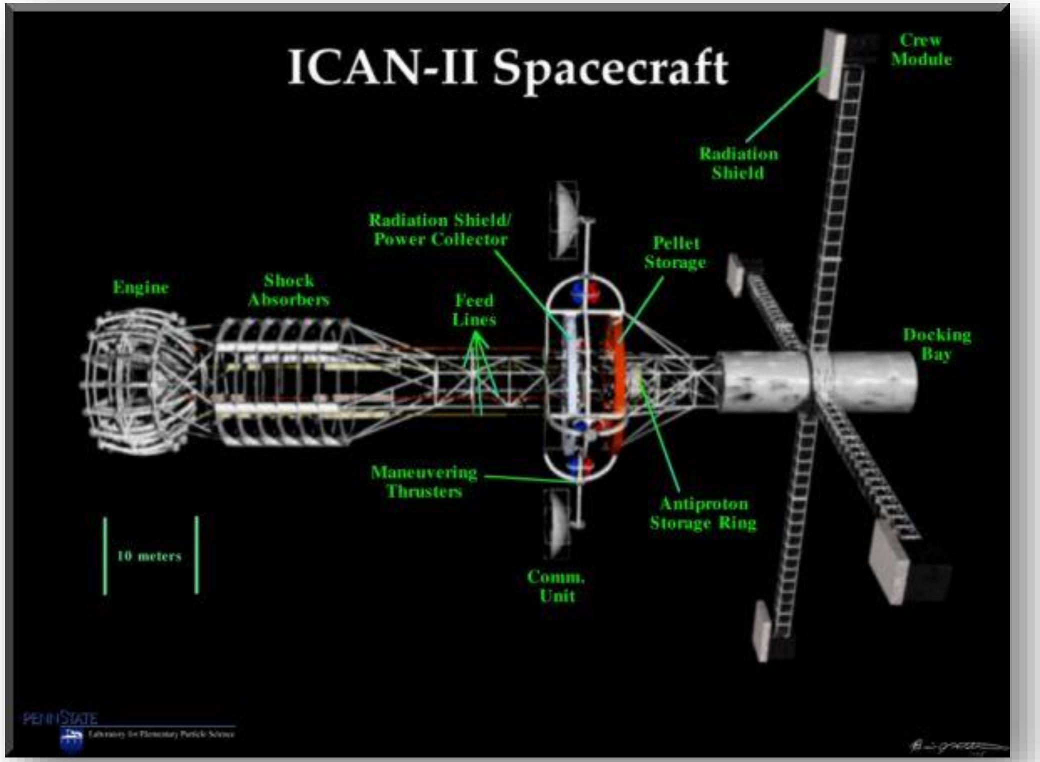
Positron was for the first time observed by Chung-Yao Chao (Caltech) in 1930, although he was not aware of this and did not investigate the strange electron-like particle any further (At the time he was 28 years old)



Discovery of positron was performed only later (1932) at the Caltech by Carl Anderson and thanks to “lack of interest” of his predecessor he got was awarded the Nobel price for it in 1936 (At the time he was 27 years old)

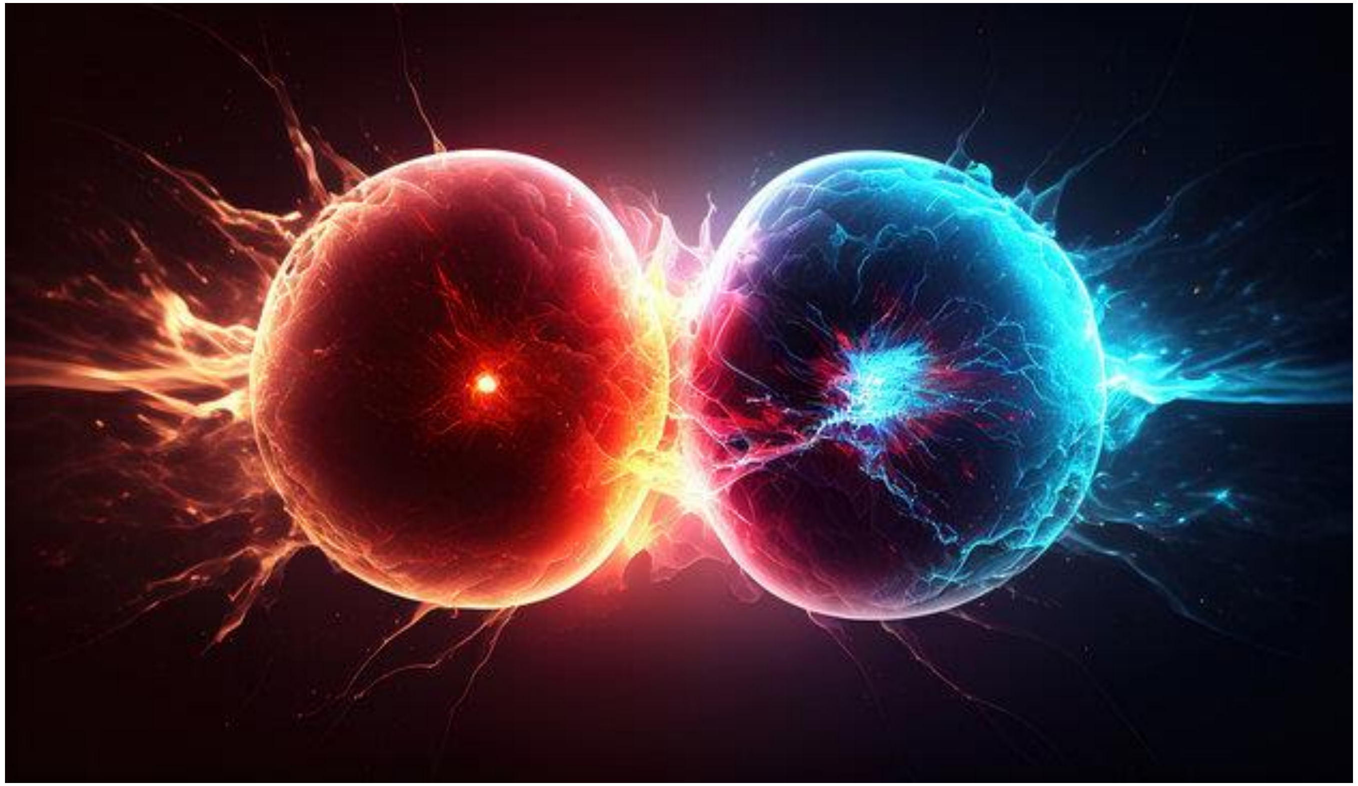
13.8 Billion years later...



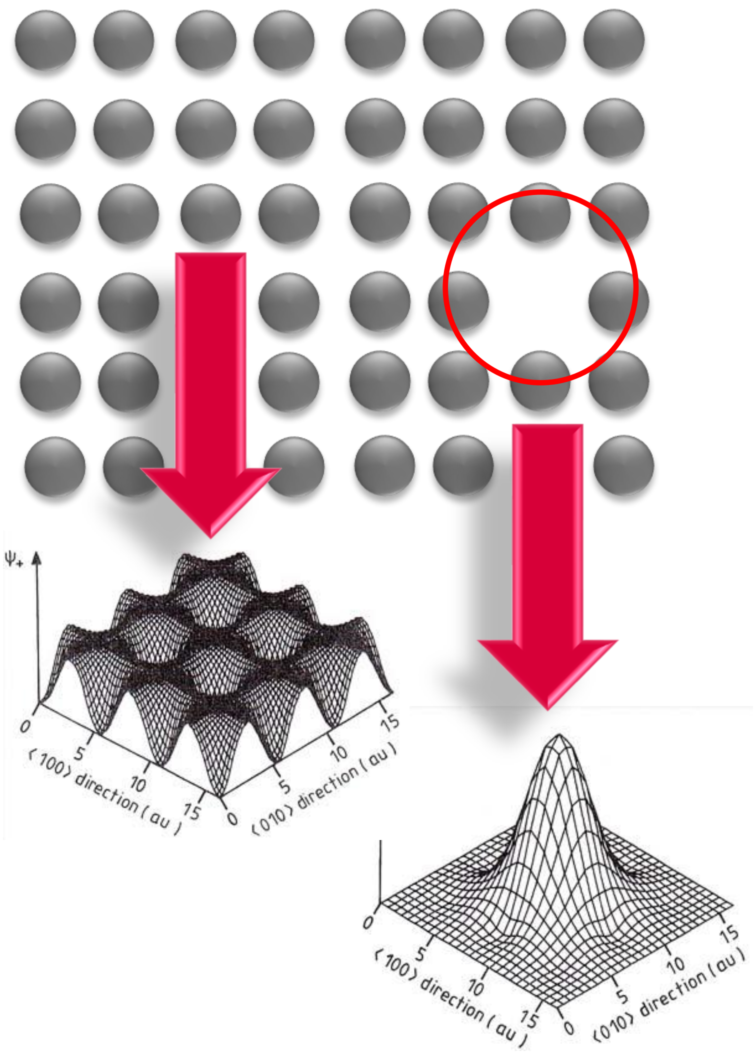


- **Energy and momentum conservation** during the annihilation process could be utilised to study properties of solids.
- 1945 – 1975 **various experimental techniques** of positron annihilation based upon the equipment of nuclear spectroscopy developed.
- nowadays - recognized as a powerful tool of microstructure investigations of condensed matter
- **advanced applications**, as positron beams, microscopy and wide range of other applications in medicine, particle physics, cosmology & astronomy were developed

Positron Annihilation Spectroscopy



What is so special about positron



Self-Seeking

(positron diffuse typically ~100nm in metals and seek for sites with higher positron affinity than bulk i.e. it is attracted by certain type of defects!)

Sensitive

Defect type	Sensitivity range (detection limit vs. saturated trapping)
neutral vacancies	**5×10^{21}... 10^{25} m^{-3}**
dislocations	**10^{12} ... 5×10^{15} m^{-2}**
precipitates (r=2 nm)	**10^{20} ... 10^{23} m^{-3}**
grain boundaries	**5 µm ... 200 nm (particle size)**
microvoids (>50 atoms)	**10^{20} ... 5×10^{23} m^{-3}**

Macroscopic samples

Information on sub-nm scale features from a large volume (few mm^3)

Sensitive to H and He.

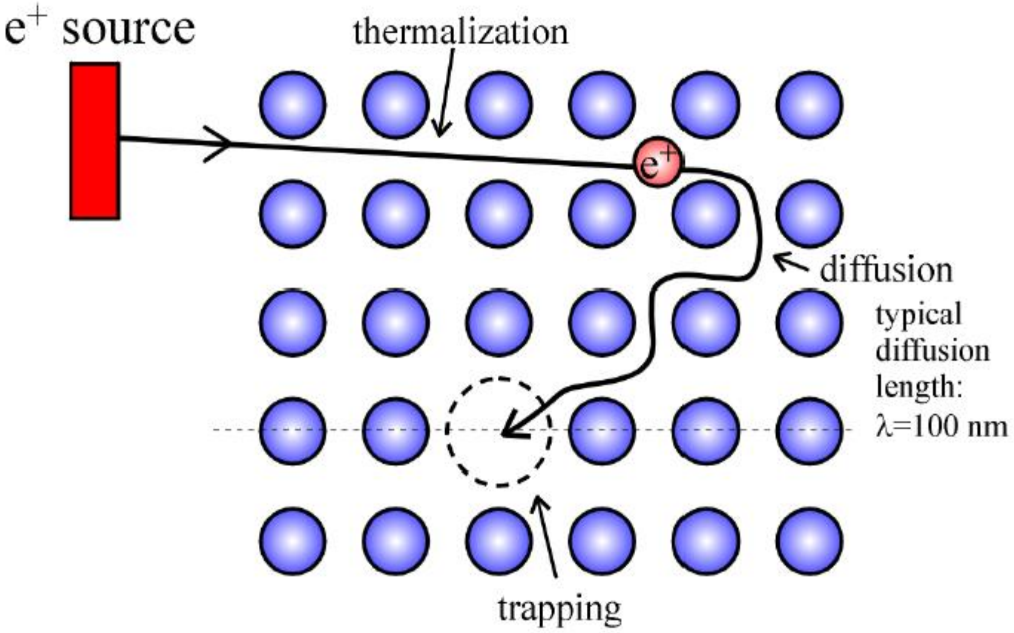
H and He presence in defects affect positron lifetime and changes the electron momentum distribution

How does it work?

Positron
Annihilation
Lifetime
Spectroscopy

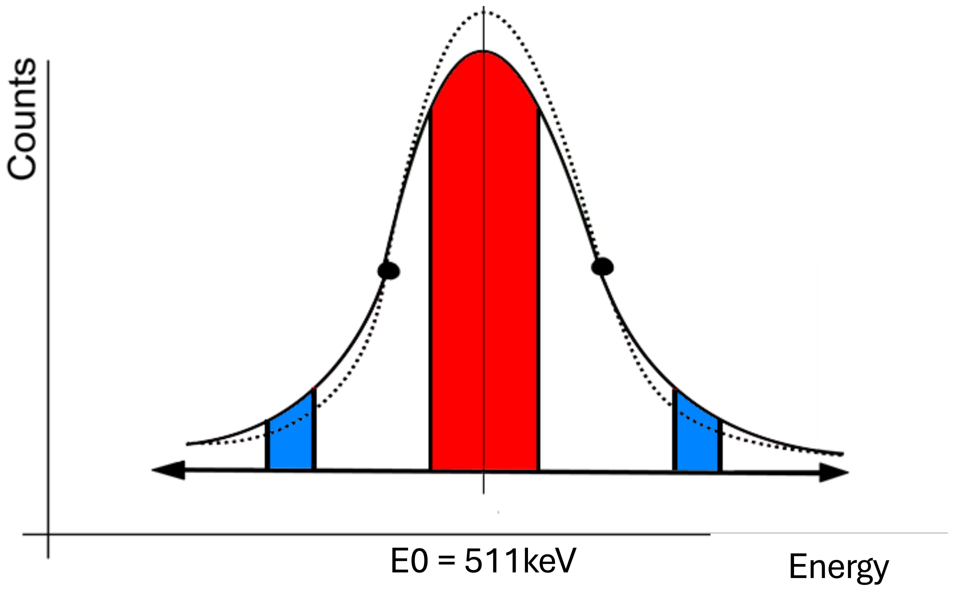
Two techniques of positron annihilation spectroscopy, based on different physical principles, have been widely established in the material research.

Coincidence
Doppler
Broadening
Spectroscopy

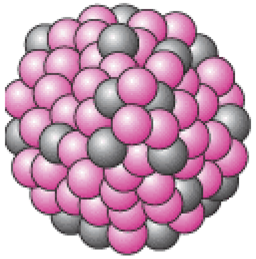


After thermalization (~ 3ps), positron diffuse through the lattice until trapping / annihilation. **Diffusion time and trapping rate are a function of the microstructure** and they can be measured.

Positrons annihilate mainly with the electrons of the outermost shell due to the repulsion of the nucleus. Such annihilation results in $E\gamma \cong 511keV$. But the annihilation occurs also with core electrons (electrons with higher momentum). Such annihilation leads to **deviation in the energy** of annihilation gamma, which is **proportional to the momentum** of the electron-positron pair.



$^{22}Na \rightarrow {}^{22}Ne + \beta^{+} + \nu_e + \gamma(1.27MeV)$

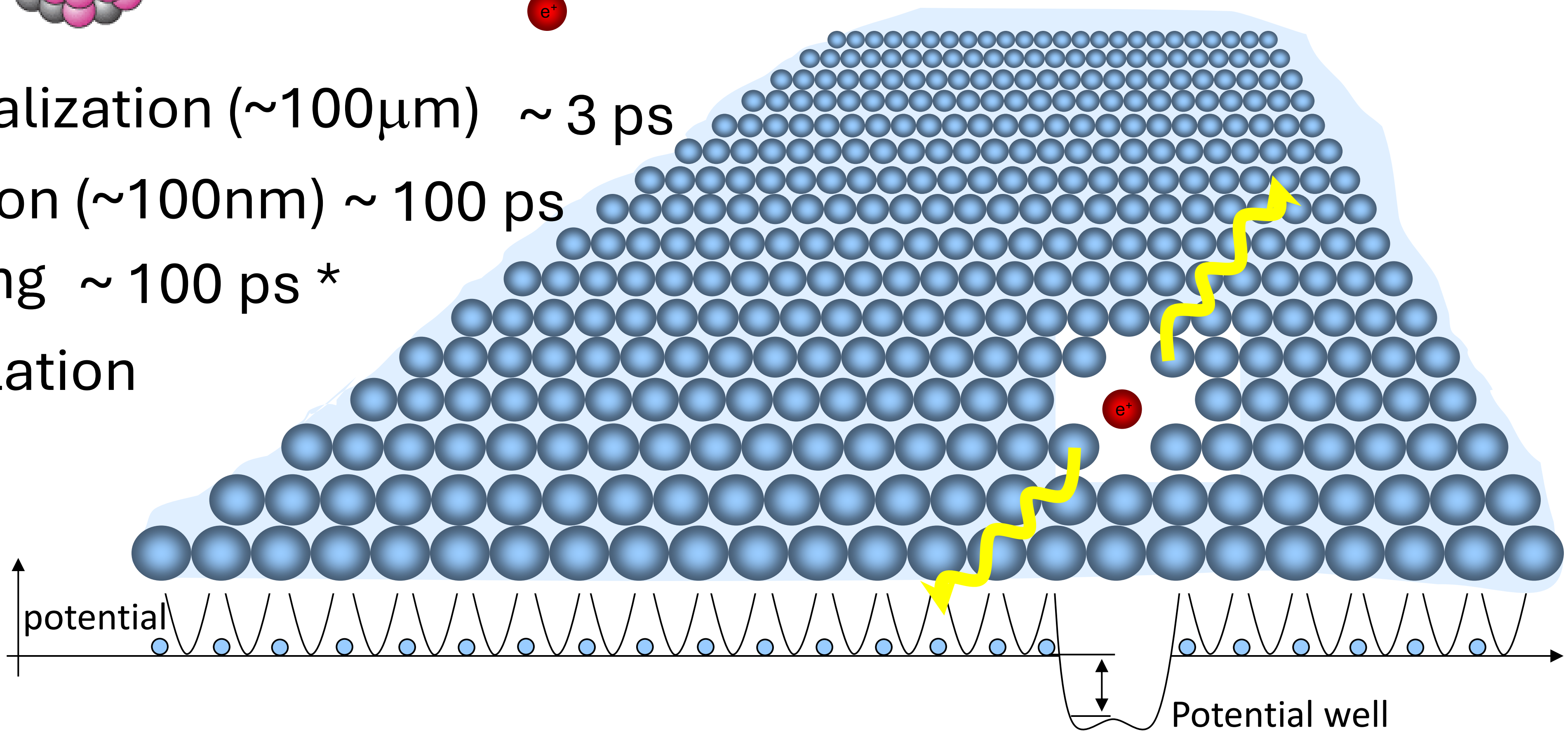


Thermalization (~100μm) ~ 3 ps

Diffusion (~100nm) ~ 100 ps

Trapping ~ 100 ps *

Annihilation

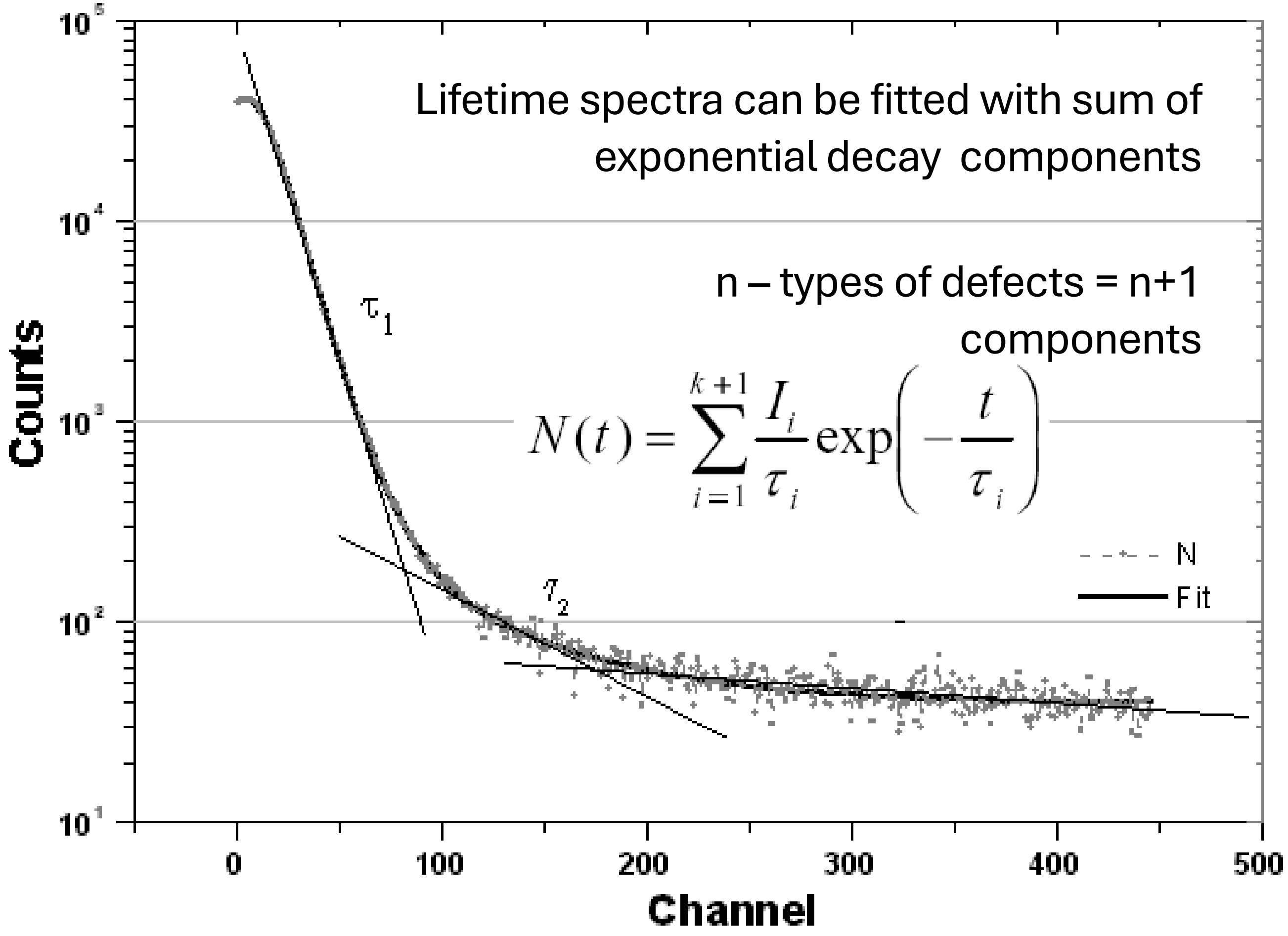


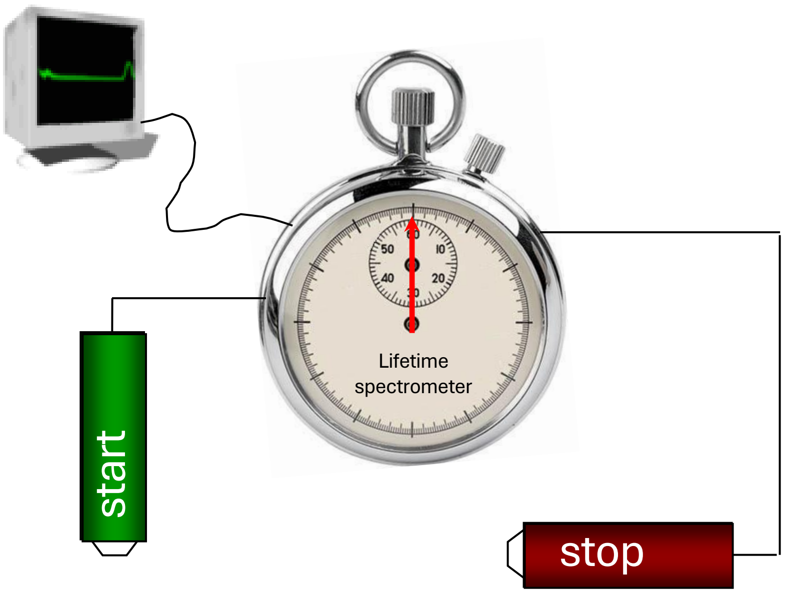
Positron Annihilation Lifetime Spectroscopy

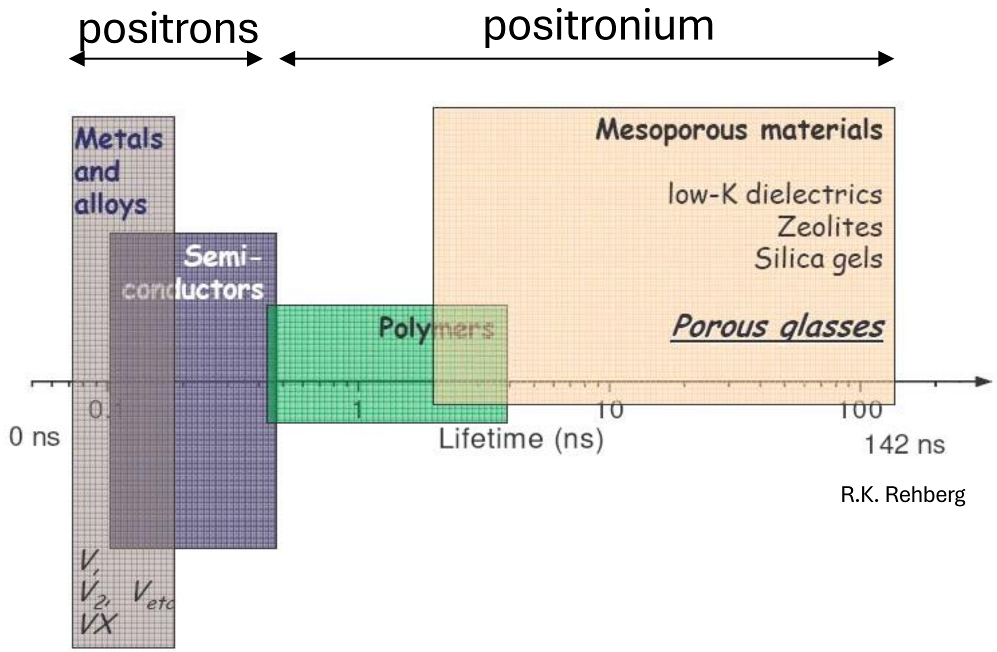
Lifetime spectra can be fitted with sum of exponential decay components

n – types of defects = n+1 components

$$N(t)=\sum_{i=1}^{k+1}\frac{I_i}{\tau_i}\exp\left(-\frac{t}{\tau_i}\right)$$





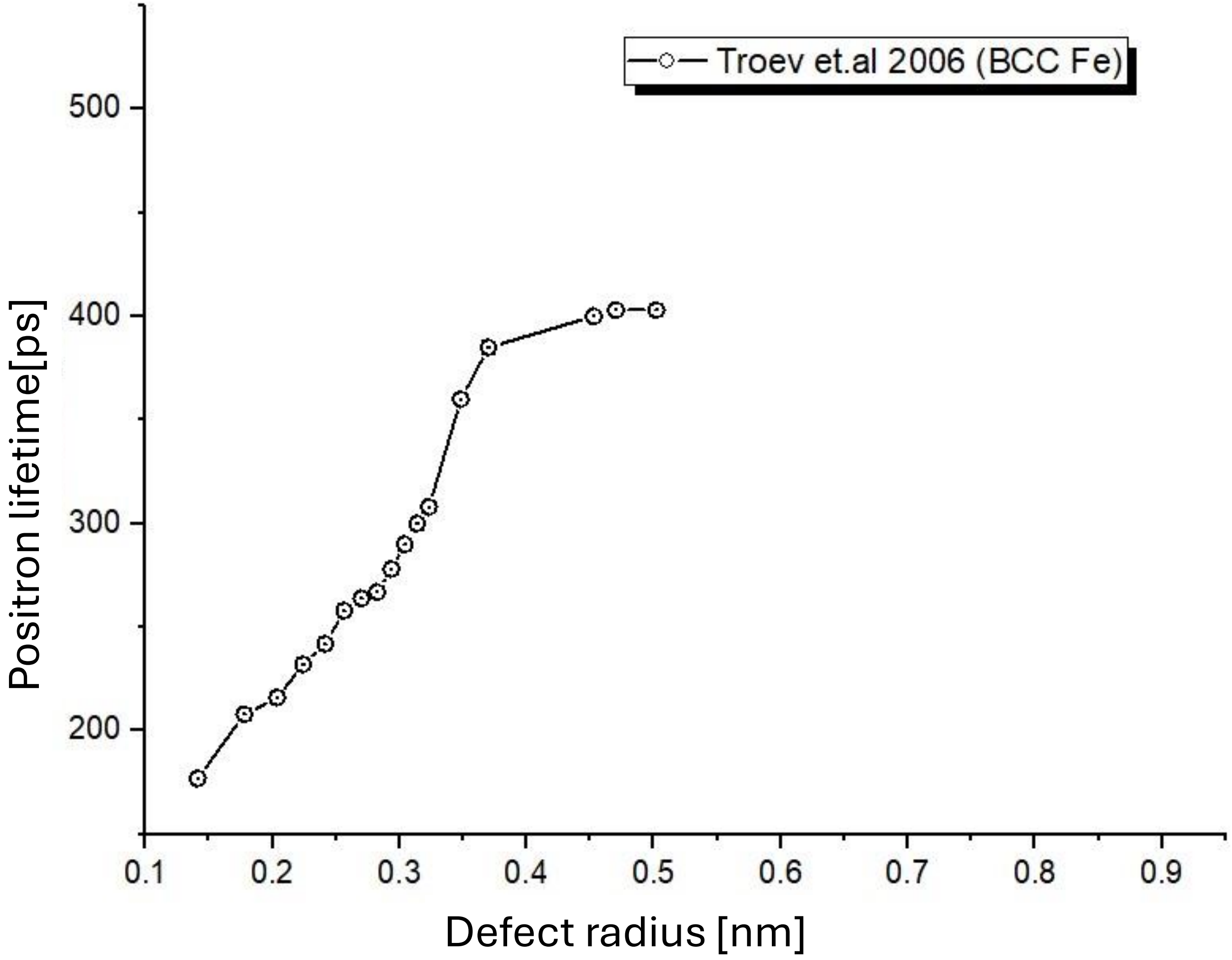


Positron Annihilation Lifetime Spectroscopy

The lifetime of a positron trapped in a vacancy cluster depends on the size of the given cluster.

Based on theoretical and empirical data, we can estimate the average size of vacancy-type defects in the material.

The intensity of the corresponding time component is proportional to the density of the given defect.



Correlation between positron lifetime and the size of the vacancy cluster in BCC iron [Troev et al. 2009]

Positron Annihilation Lifetime Spectroscopy

$$n(t) = n_0 \sum_{i=1}^{3} I_i \exp\left(-\frac{t}{\tau_i}\right) \qquad I_1 = 1 - I_2 - I_3$$

$\tau_{1,2,3}$ – lifetime components
$I_{1,2,3}$ – components intensities
$\tau_b = 1/\lambda_b$ – lifetime in defect-free bulk
D_1, D_2 (indexes) – defect 1, defect 2
$\kappa_{D1,D2}$ – positron **trapping rate** at defect (proportional to defect concentration N and positron trapping coefficient of the given defect m).

$$\tau_1 = \frac{1}{\lambda_1} = \frac{1}{\lambda_b + \kappa_1 + \kappa_2} \qquad \tau_2 = \frac{1}{\lambda_{D1}} \quad \tau_3 = \frac{1}{\lambda_{D2}}$$

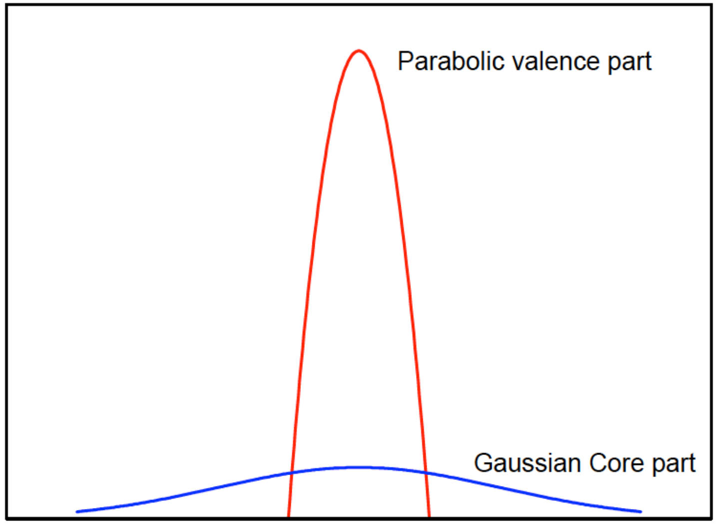
$$\kappa_1 = \frac{I_2 I_3(\lambda_{D1} - \lambda_{D2}) + I_2(\lambda_b - \lambda_{D1})}{I_1} = \mu_{D1} N_{D1}$$

$$\kappa_2 = \frac{I_2 I_3(\lambda_{D2} - \lambda_{D1}) + I_3(\lambda_b - \lambda_{D2})}{I_1} = \mu_{D2} N_{D2}$$

The trapping coefficient must be determined by an independent method.

Quite accurate values available for simple defects; only rough values available for complex defects (helium nano-bubbles)

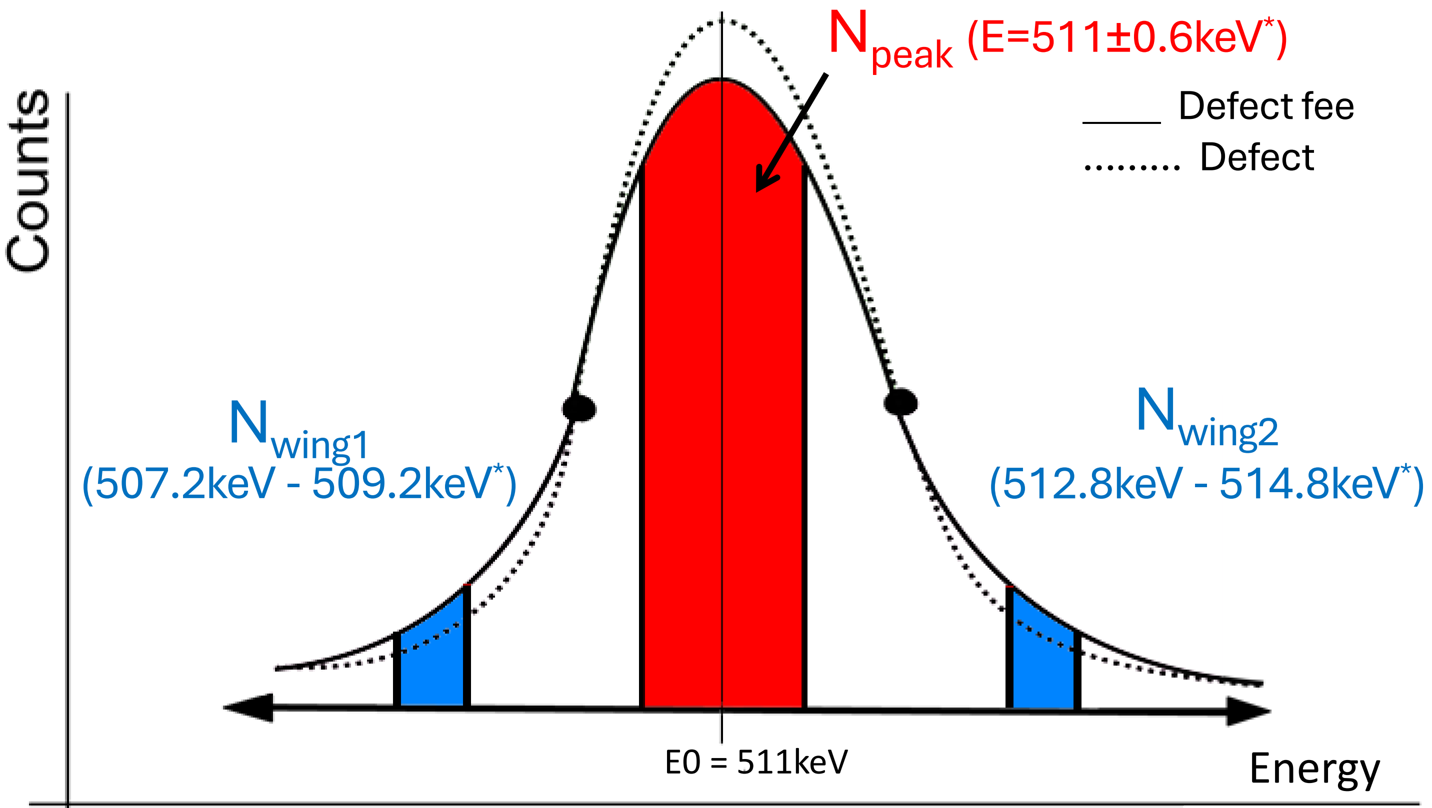
Doppler broadening spectroscopy (DBS)



$$S = \frac{N_{peak}}{N_{total}}$$

$$W = \frac{N_{wing1} + N_{wing2}}{N_{total}}$$

1keV = 3.91 x 10^{-3} m_0C

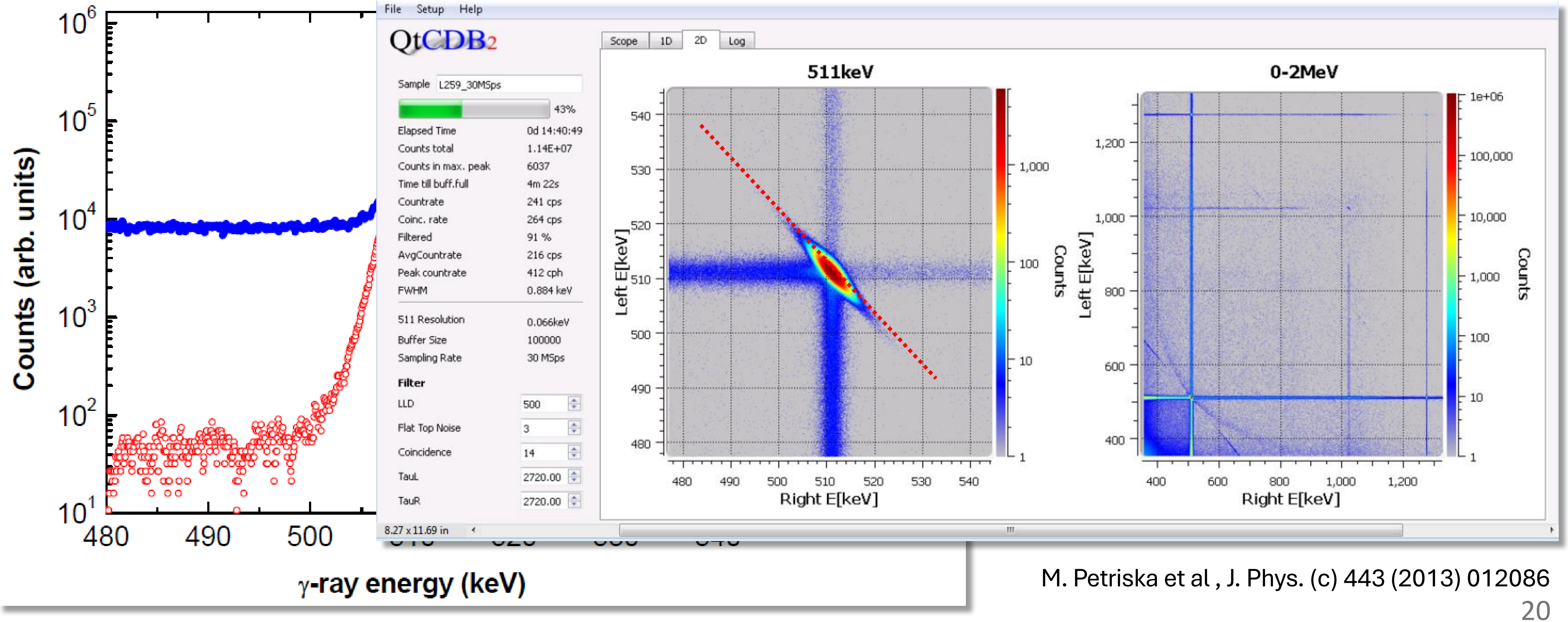


* The energy ranges for S and W are subjects of agreement. Here – the W values were chosen to cover the characteristic He peak

- S-parameter corresponds to positron annihilation with the valence electrons and W-parameter corresponds to positron annihilation with the core electrons.
- S is sensitive to open volume defects and W is sensitive to the chemical surrounding at the annihilation site.
- Increase in S-parameter indicates presence of vacancy defects.

Coincidence Doppler broadening spectroscopy (CDBS)

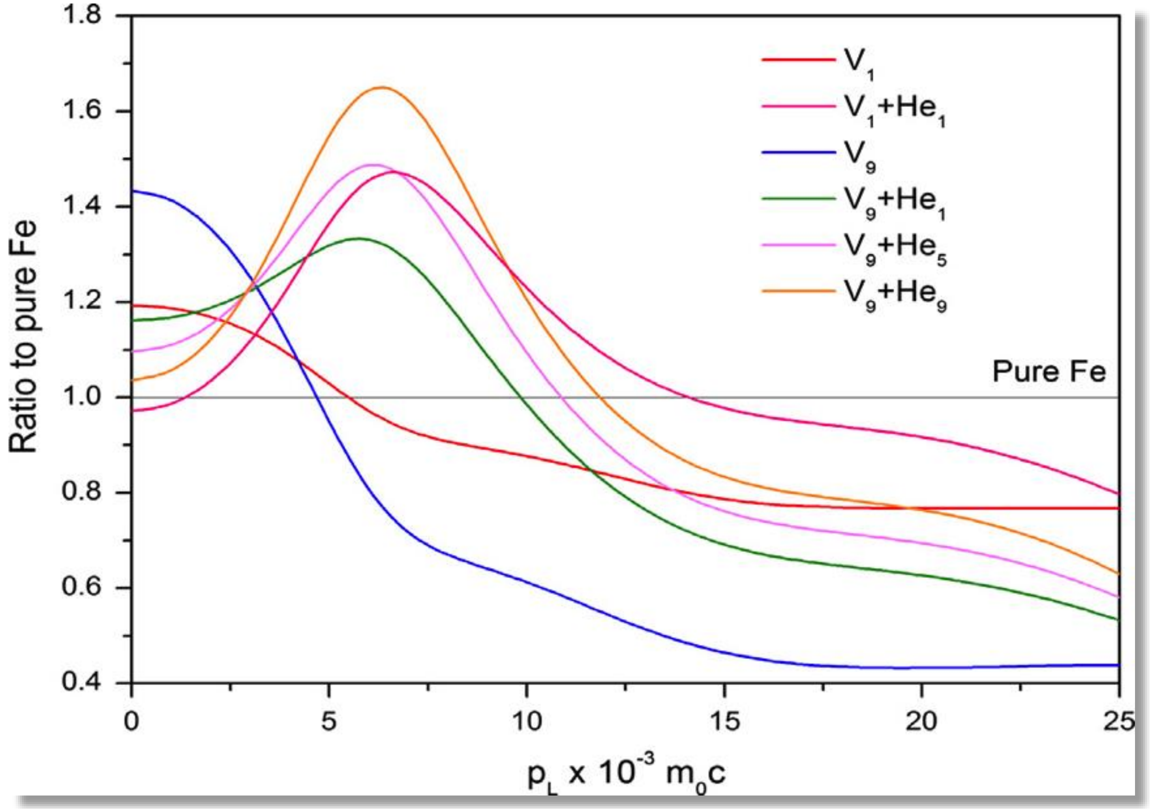
Two detectors in a coincidence setup significantly suppress the background of the spectra. The elliptical region extending diagonally with E1+E2= 1022 keV corresponds to the true Doppler shift which is $E_{\gamma 1} - E_{\gamma 2}$. This region is nearly background free.

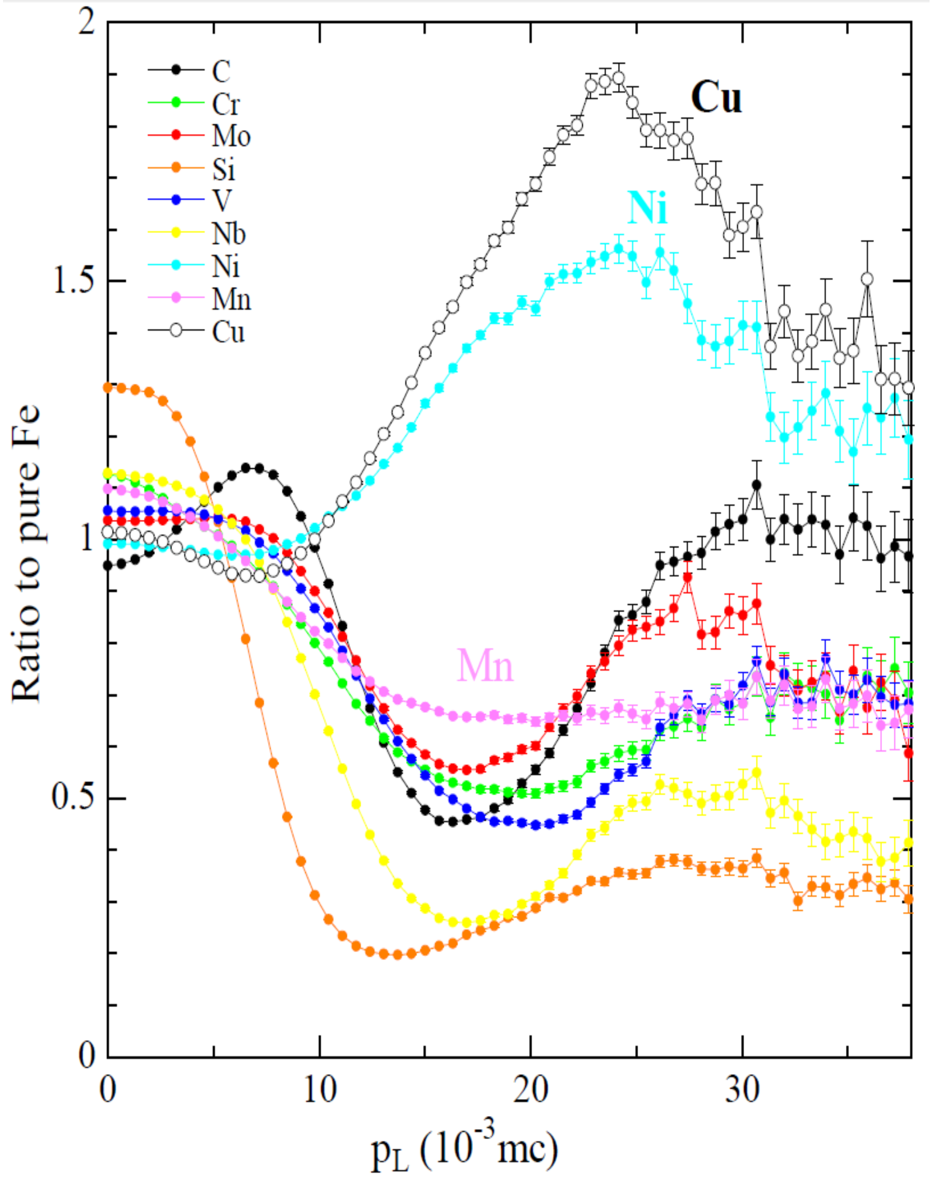


M. Petriska et al , J. Phys. (c) 443 (2013) 012086

Coincidence Doppler broadening spectroscopy (CDBS)

Ratio to the chosen reference spectra (experimentally obtained with the same apparatus) enables to obtain chemical information about the atoms surrounding positron trapping centers.
Although the use of the CDBS is necessary for this (information comes from high momentum region), Helium fingerprint (peak) is located in relative low momentum region, thus DBS is "sufficient".





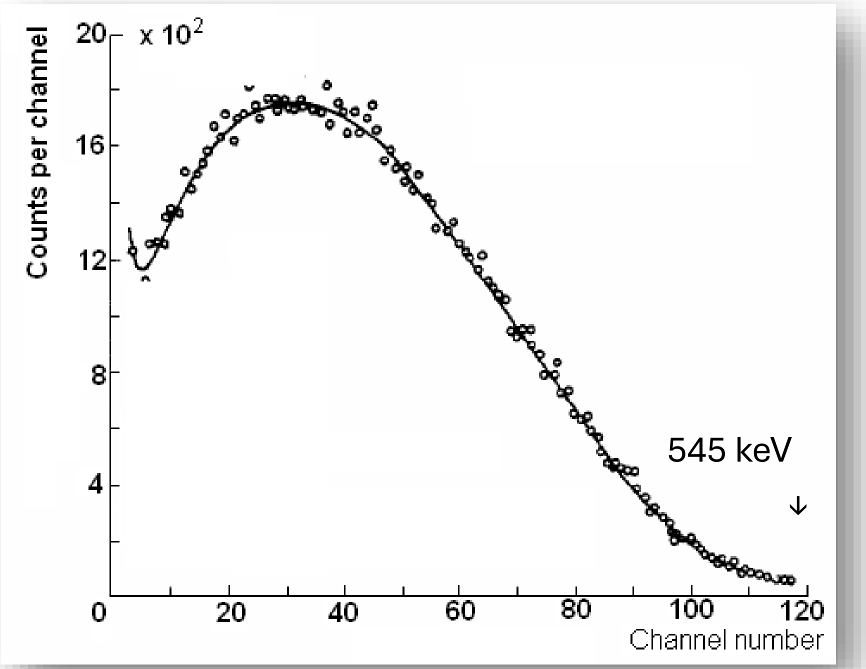
Positron sources

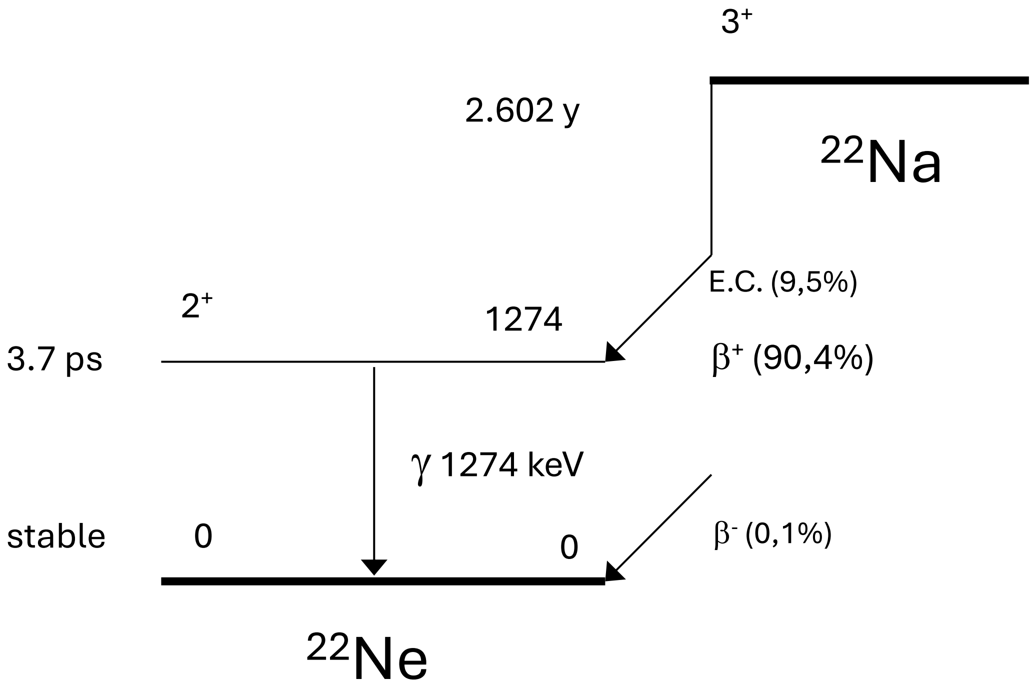
Radioisotope sources

Positrons are obtained for laboratory setups usually by the β+ decay of isotopes ^{22}Na, ^{64}Cu or ^{58}Co

$$^{22}Na \rightarrow {}^{22}Ne + \beta^+ + \nu_e + \gamma(1.27MeV)$$

Physical Half-Life: 2.602 Years



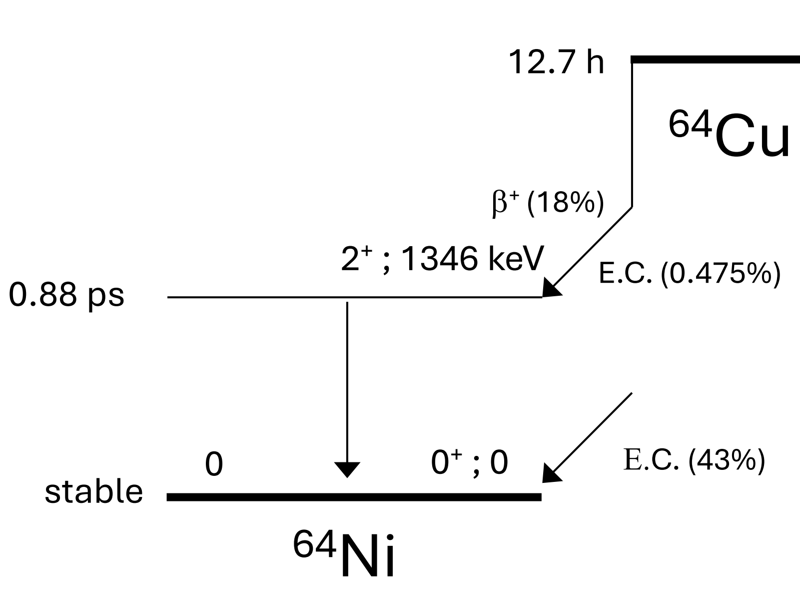


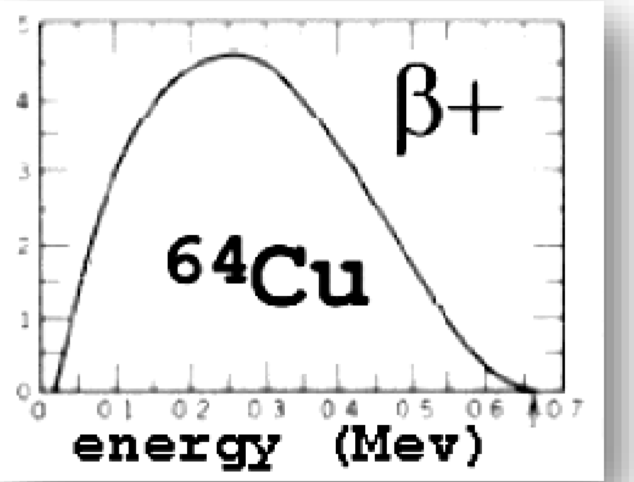
- ^{22}Na positron source - continuous spectra 0 – 545 keV
- correspondent depth in bcc iron 0 – 130 μm

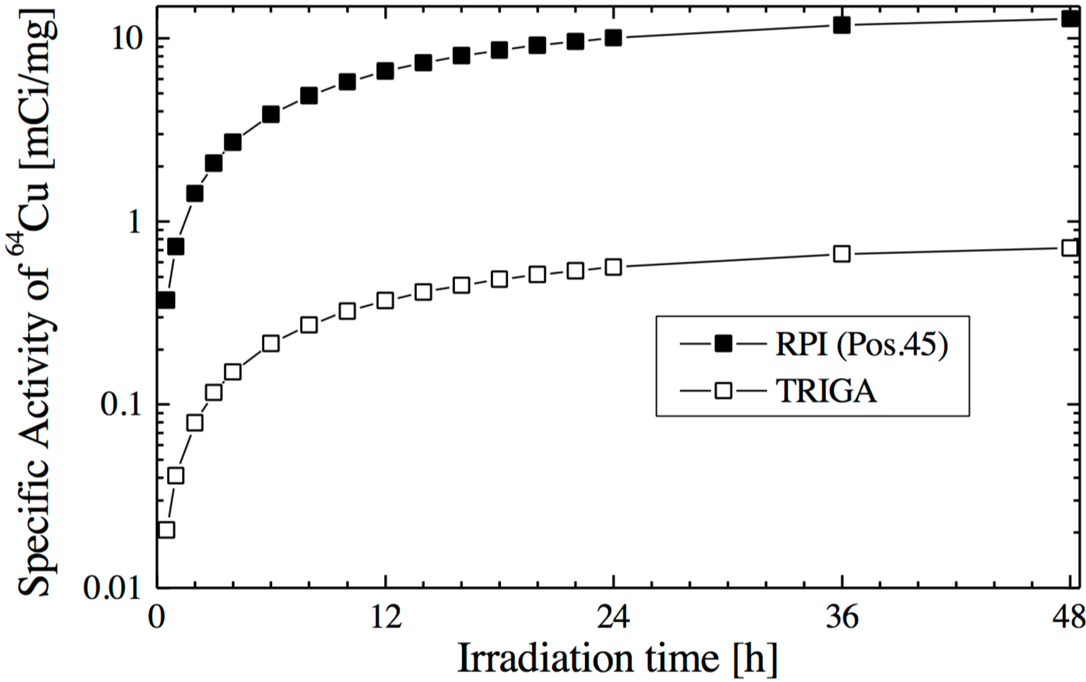
Radioisotope sources

$^{64}Cu \rightarrow ^{64}Ni + \beta^+ + \nu_e + \gamma(1.35MeV)$

Physical Half-Life: 12.7 hour



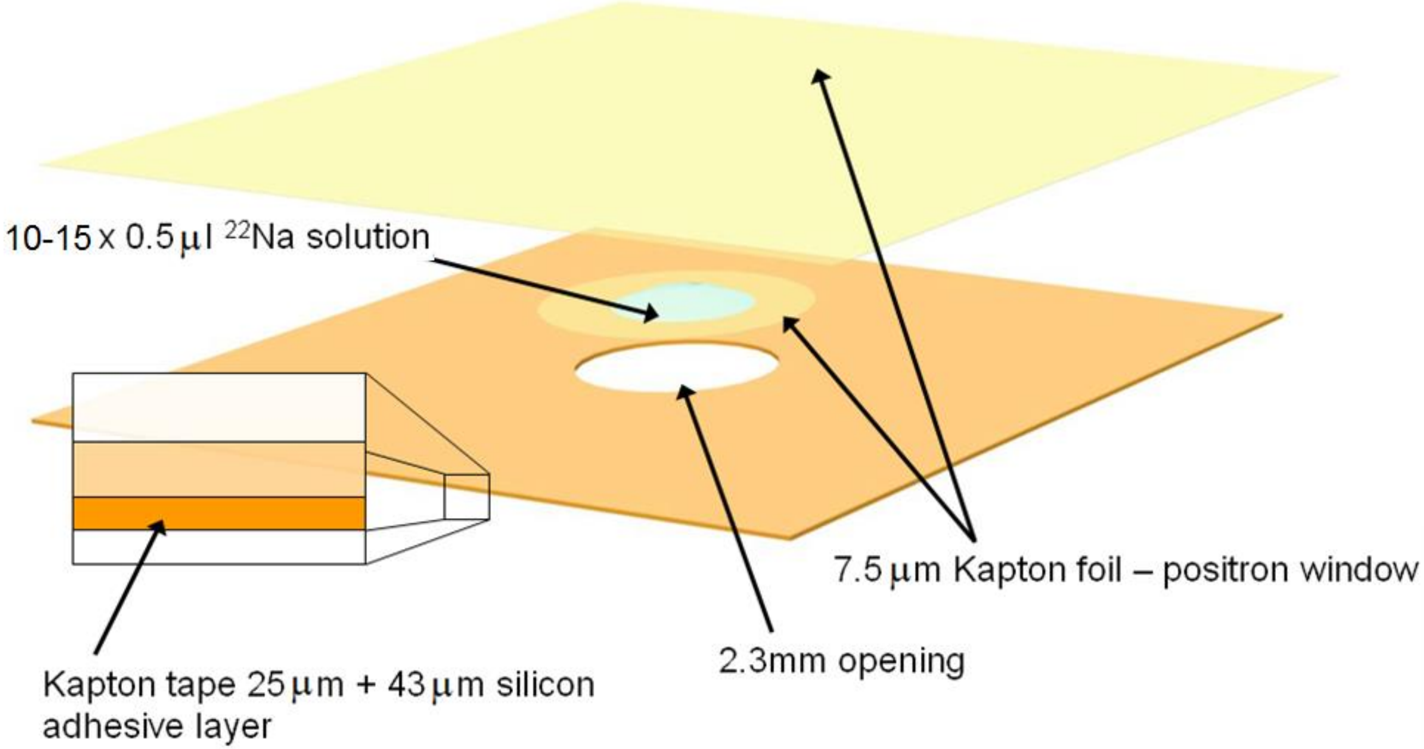


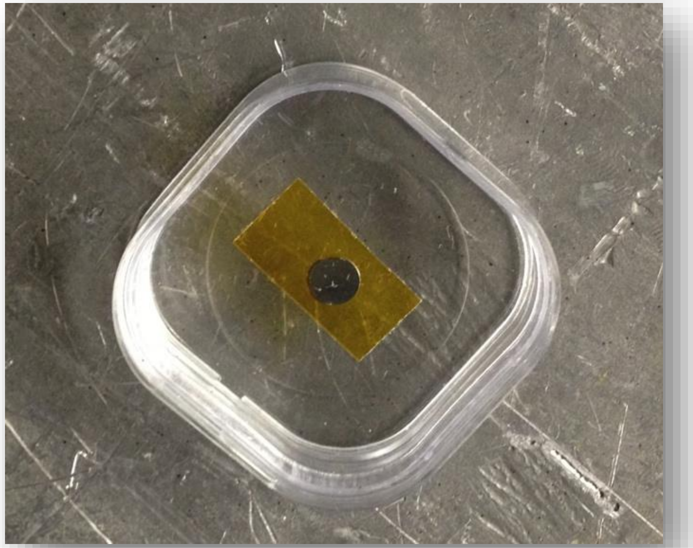


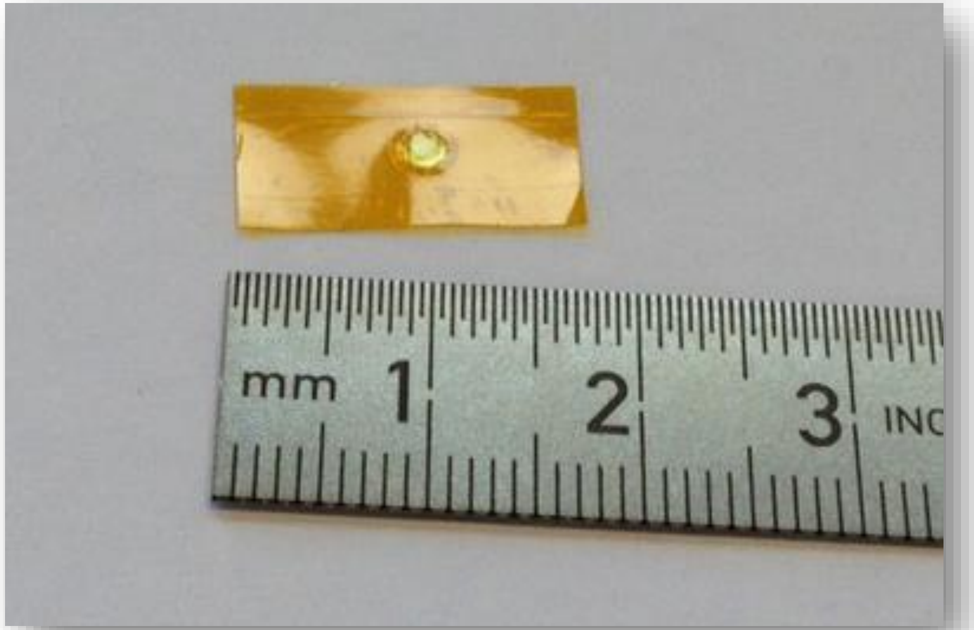
^{64}Cu specific activity vs. irradiation time, considering continuous irradiation of natural copper RPI vs TRIGA (1.6×10^{13} vs 9.7×10^{11} neutrons/cm^2.s)

Feasible ^{64}Cu production at the TRIGA Reactors

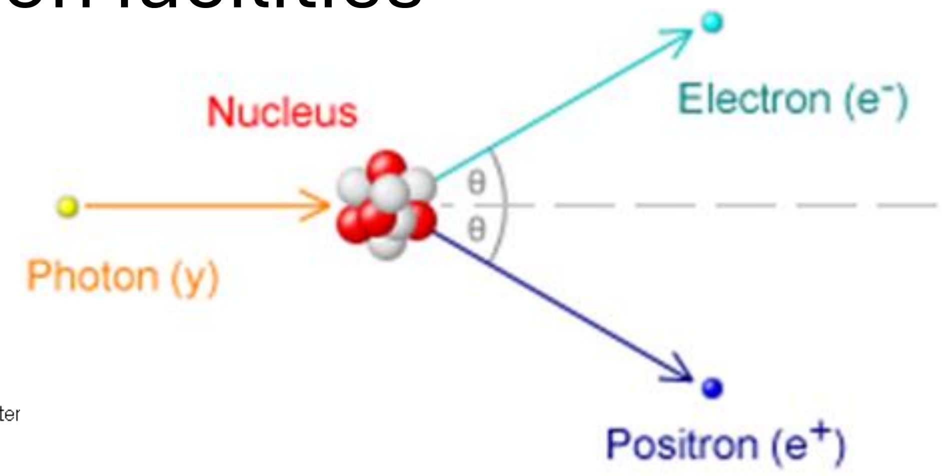
Radioisotope sources



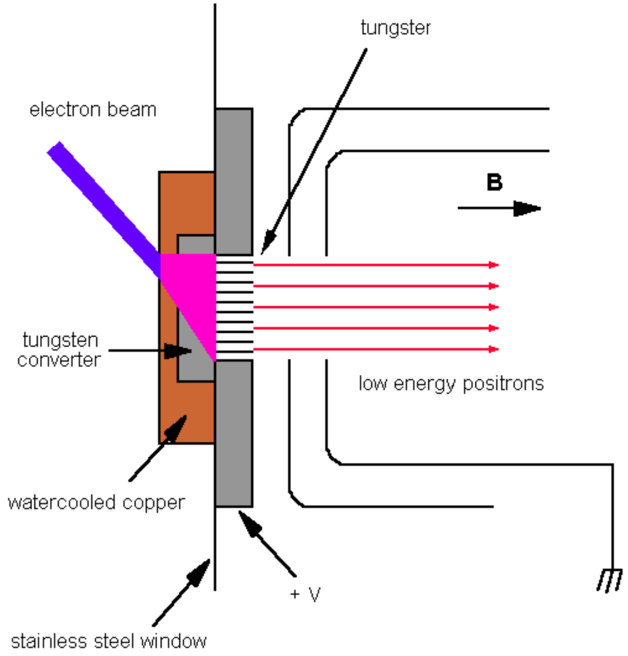




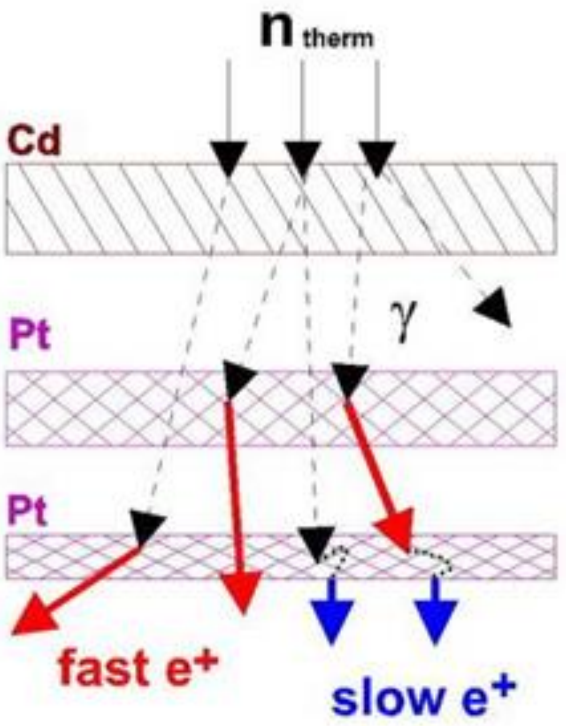
High-flux positron facilities



High energy gamma
(from fission reactions)

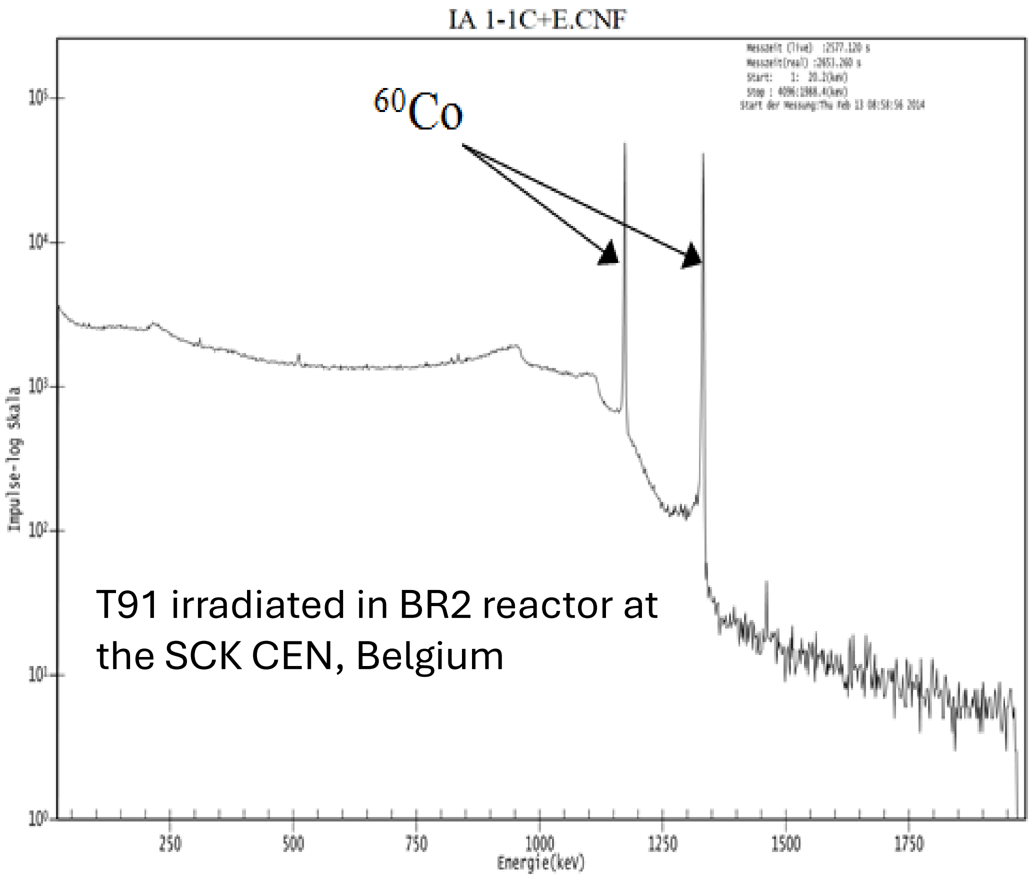


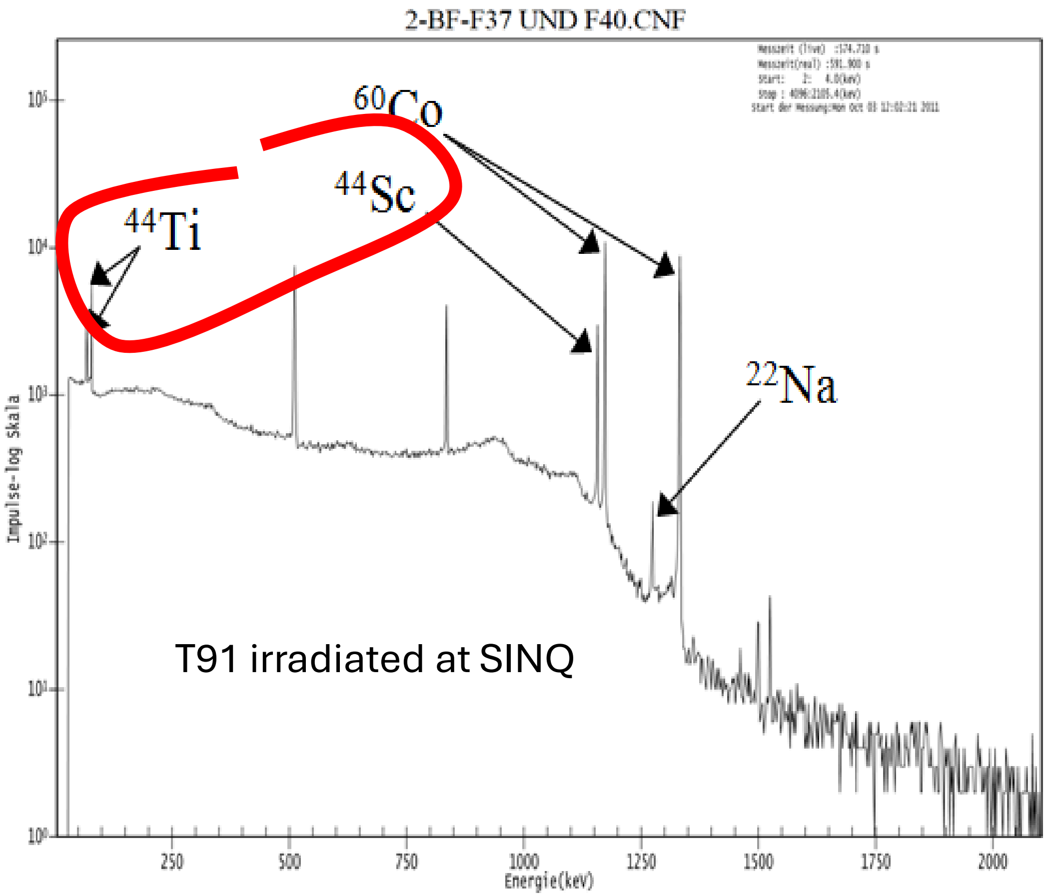
← Pair production using bremsstrahlung of a decelerated beam of MeV-**electrons**



Nuclear reaction with **neutrons** producing high energy gamma;
e.g. 113Cd(n,γ)114Cd → three γ rays and pair production →

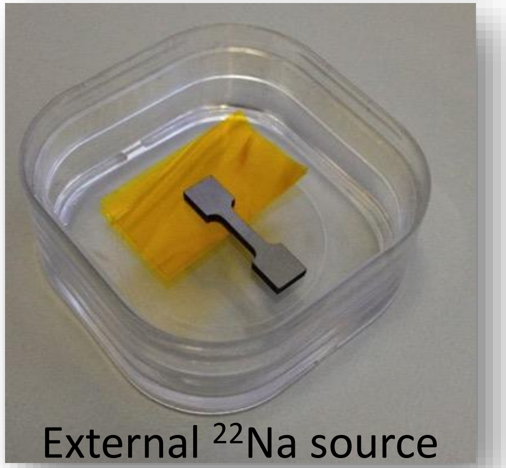
Internal positron sources – samples exposed to extreme conditions

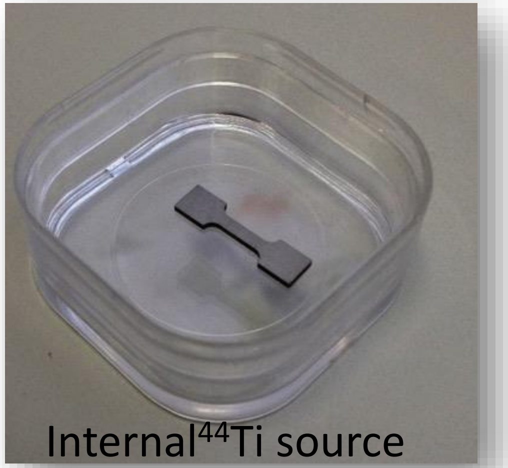


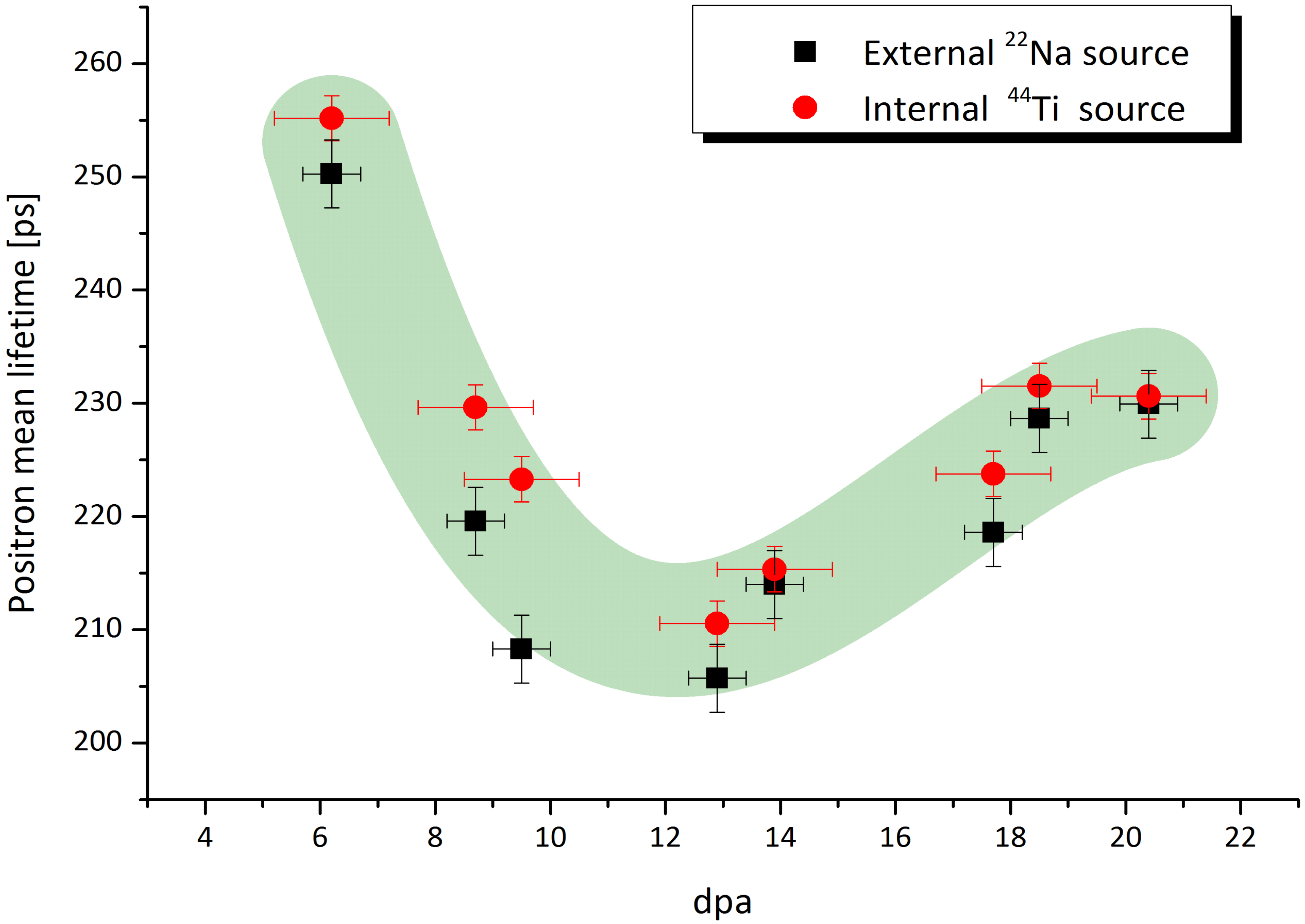


Some **isotopes** produced in spallation reactions undergo **β^+ decay**. Positrons are produced **within** the investigated sample.

Internal positron sources – samples exposed to extreme conditions

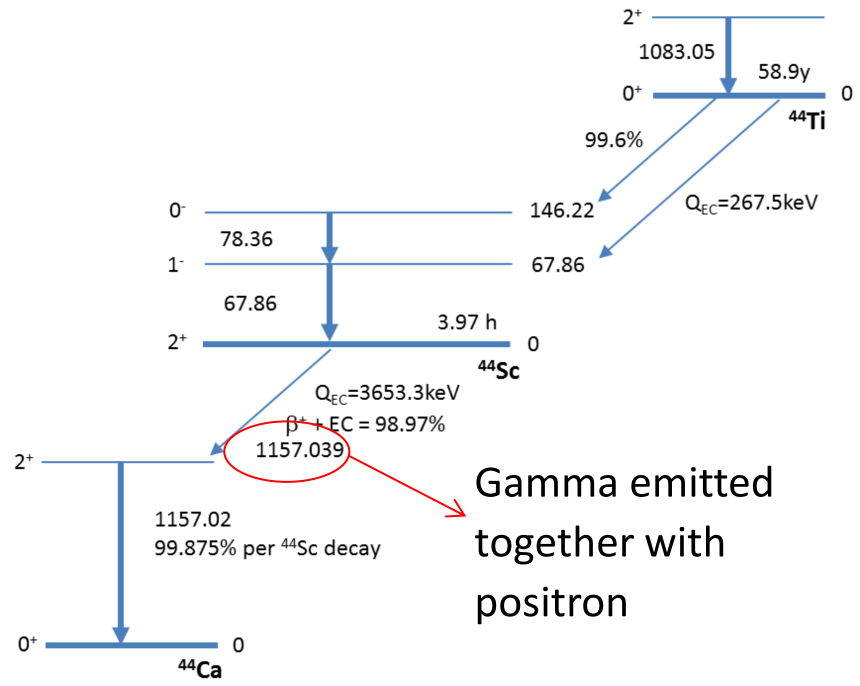






Internal positron sources – samples exposed to extreme conditions

In spallation irradiations, ^{44}Ti is a product of ^{56}Fe(p, x) reaction. It is present in all STIP samples of steels



Gamma emitted together with positron

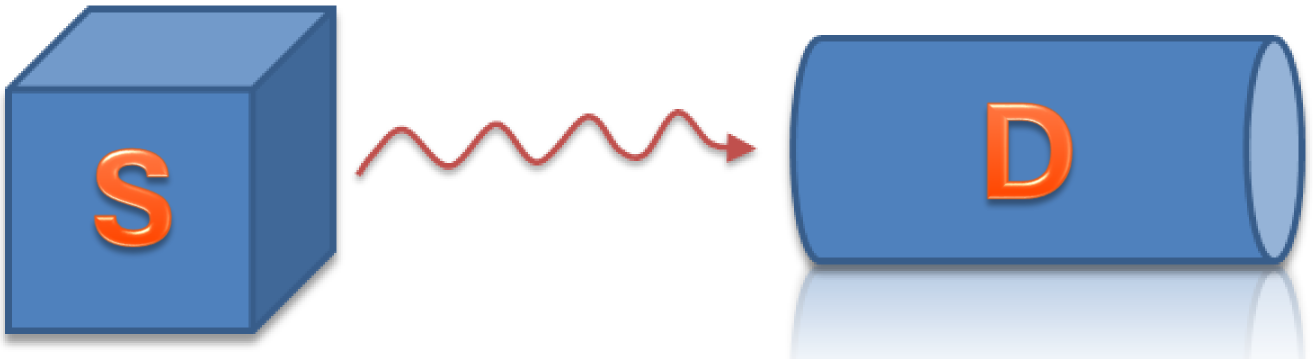
Irradiated sample containing ^{44}Ti | **Scintillation detector**

- $^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca + e^{+} + \nu_e + \gamma$ ⟶ 1154 keV
  - e^{+} diffusion = f (material)
  - e^{+} trapping = f (defects)

Time [ps] = F (material, defects)

- $e^{-} + e^{+}$ annihilation ⟶ 511 keV $\pm\Delta E$

ΔE = F (material, defects)



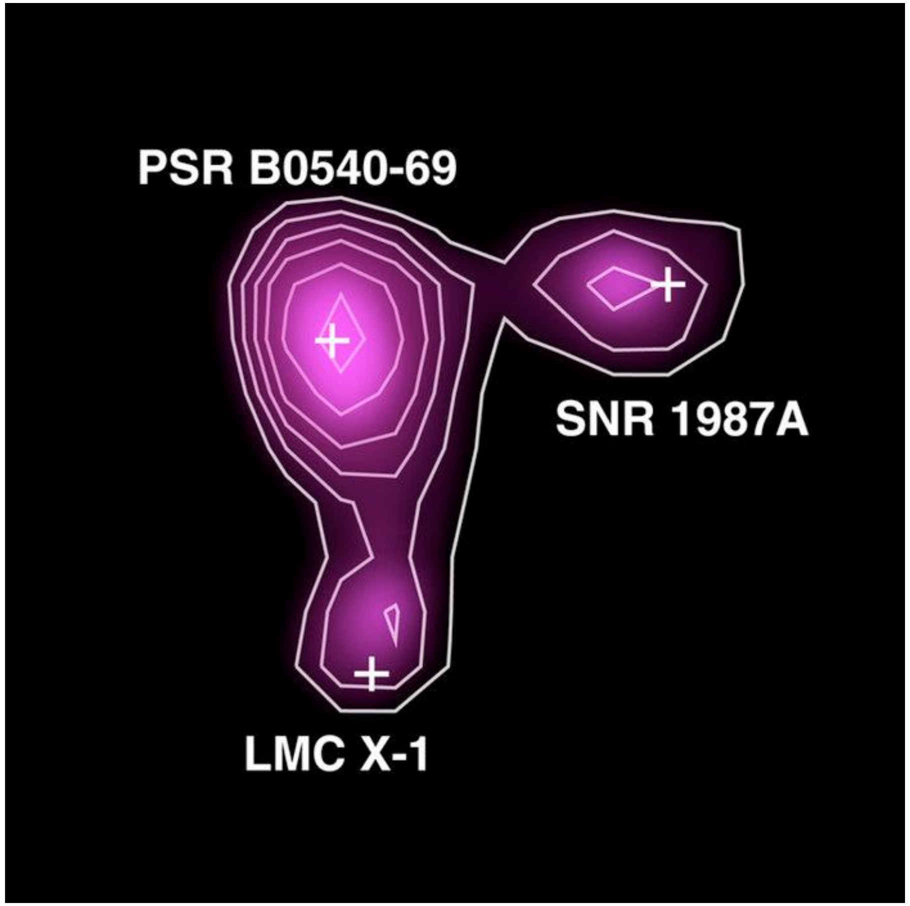
Internal positron sources – samples exposed to extreme conditions

- The $^{44}Ti/^{44}Sc$ source has a much longer half-life (59.6 y) which ensures a long-term stable production of positrons.
- Homogeneous probing of the whole bulk
- No surface treatment required
- There are practically no limitations as regards the sample size and shape.
- Methodology is suitable for very active samples (^{60}Co activity is usually equal or lower than ^{44}Ti activity).

^{44}Ti – smoking gun of supernovae

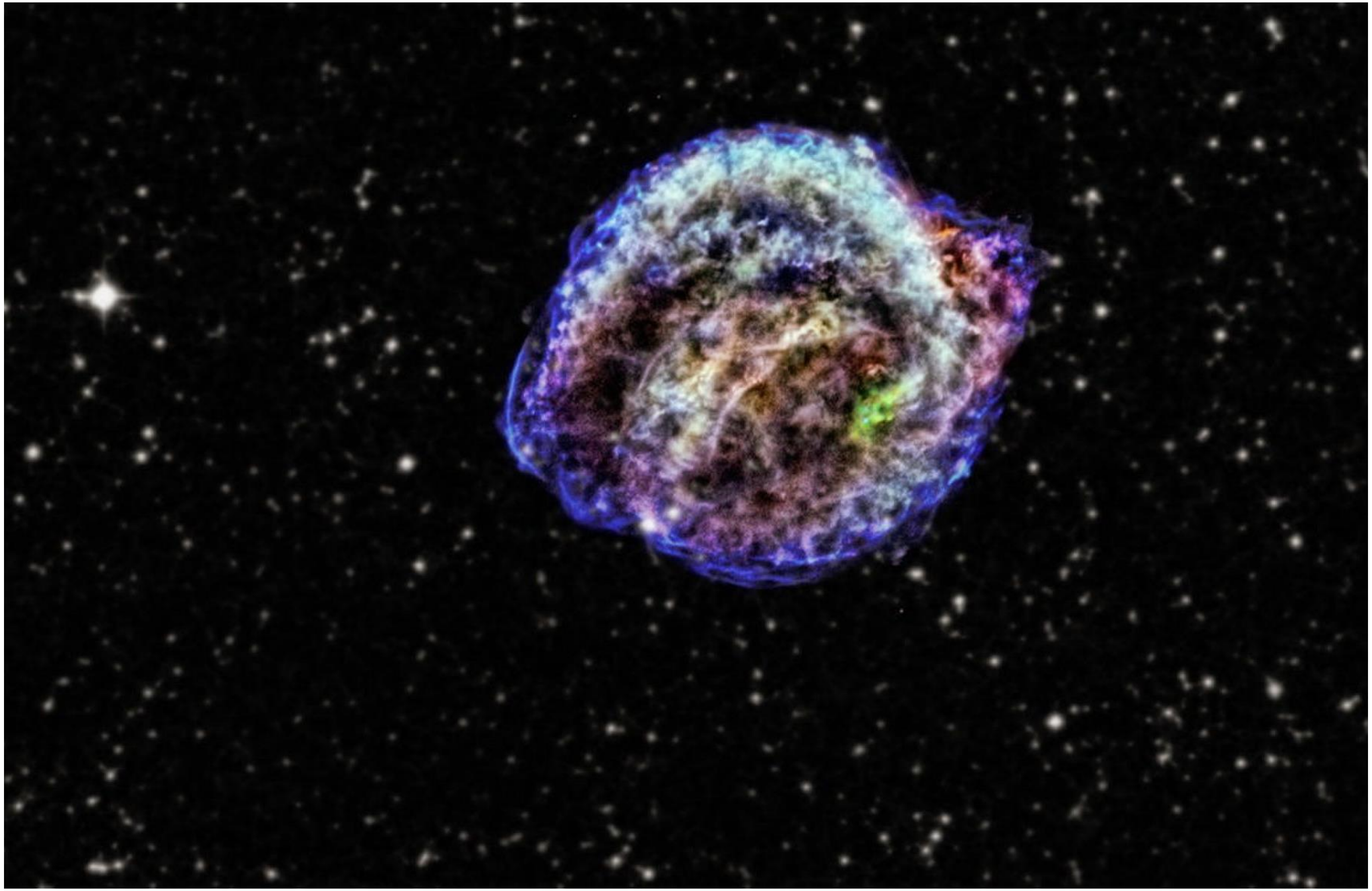
($T_{1/2}$=60y) - Extremely rare on Earth, there's lot of it out there

Hubble image shows the remnant of supernova SN 1987A, first detected in February 1987. Distance of of the object is about 166,000 light-years.



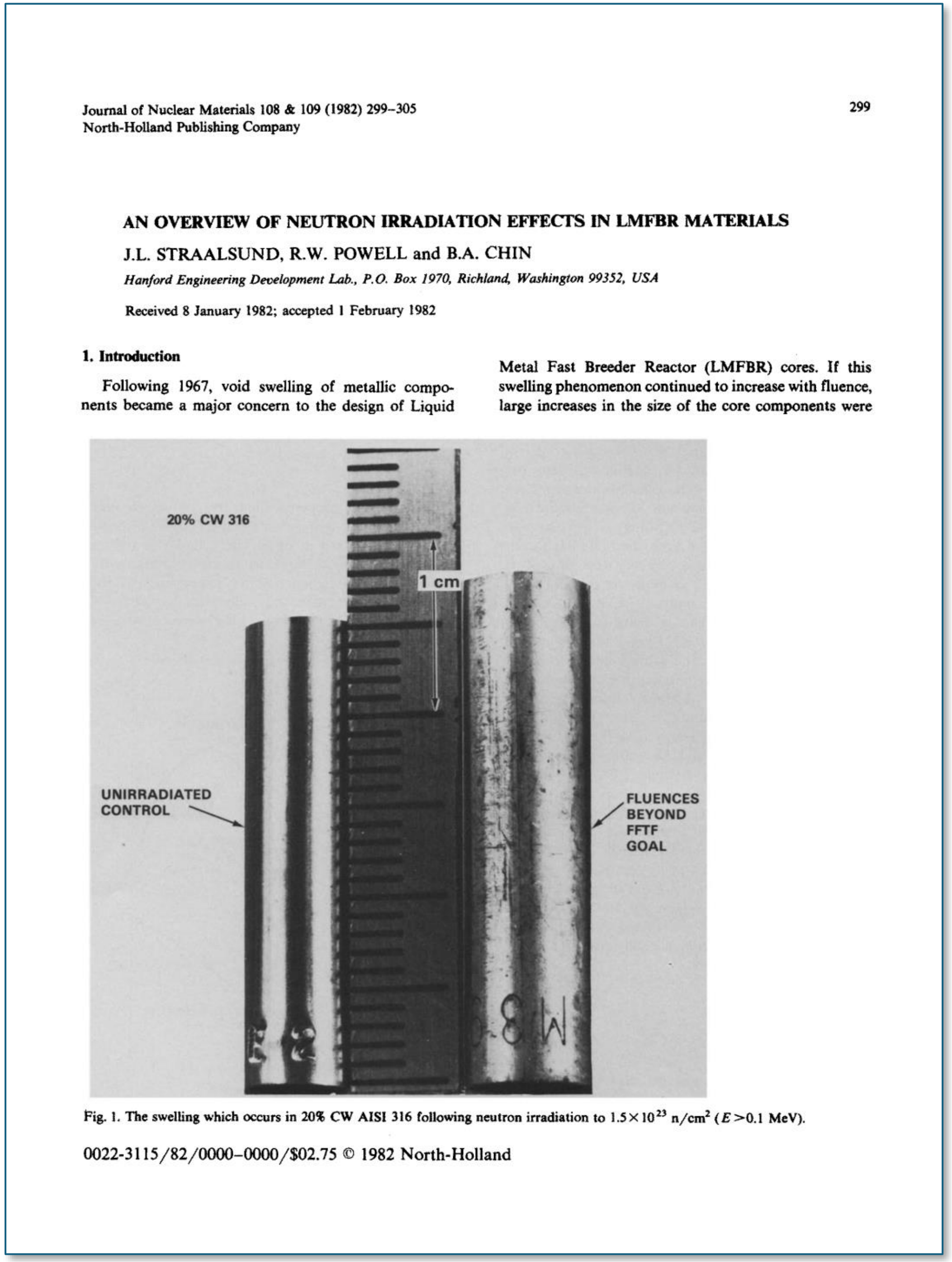
After the initial flash has faded, the total luminosity of the remnant is today provided by decay of ^{44}Ti, produced in the explosion. ^{44}Ti keeps it hot to radiate light.

^{44}Ti – smoking gun of supernovae



This is the remnant of Kepler's supernova, the famous explosion that was discovered by Johannes Kepler in 1604. The red, green and blue colors show low, intermediate and high energy X-rays observed with NASA's Chandra X-ray Observatory, and the star field is from the Digitized Sky Survey. Image released March 18, 2013

Radiation effects in f/m steels: helium



Journal of Nuclear Materials 108 & 109 (1982) 299–305
North-Holland Publishing Company

AN OVERVIEW OF NEUTRON IRRADIATION EFFECTS IN LMFBR MATERIALS

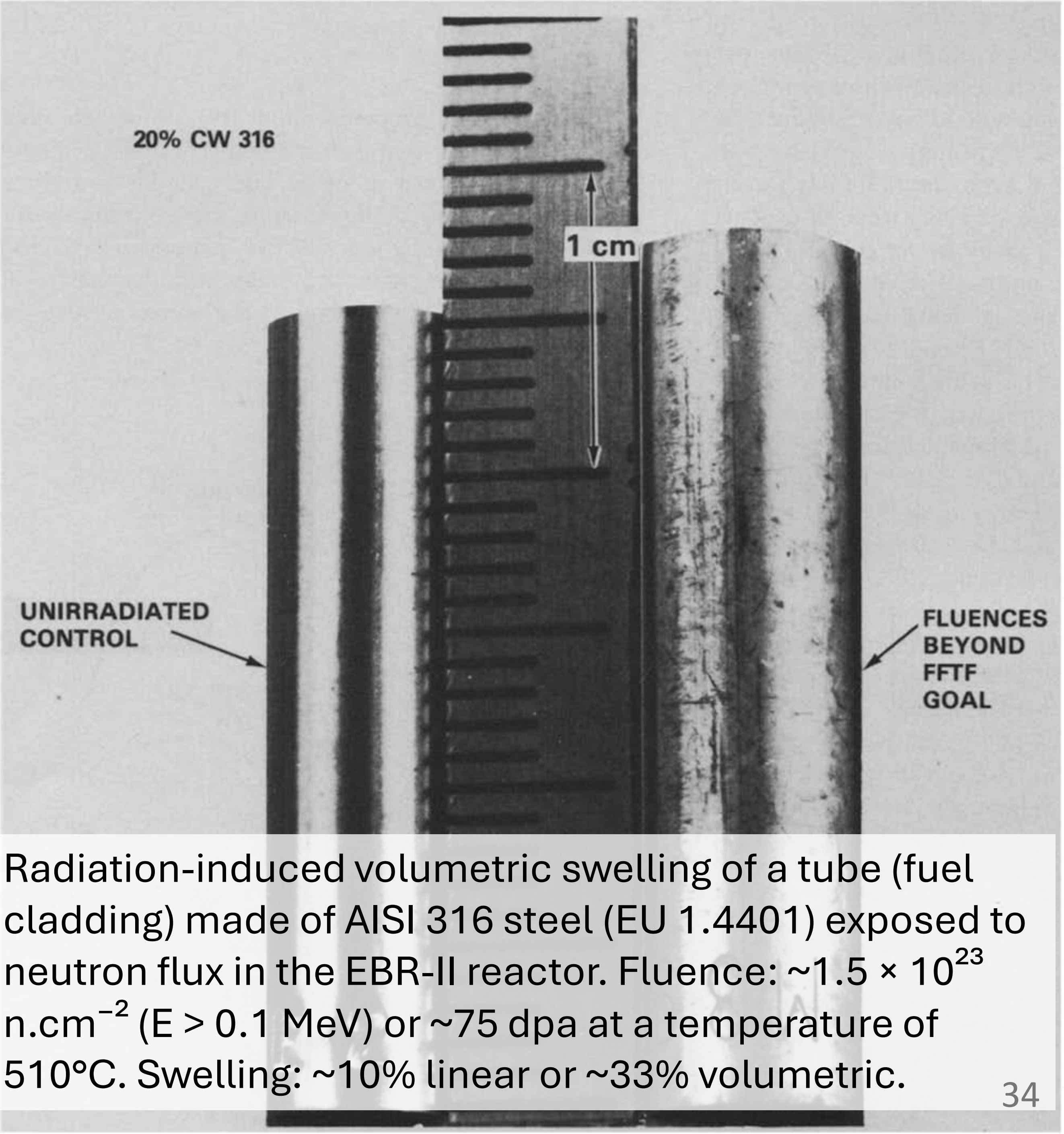
J.L. STRAALSUND, R.W. POWELL and B.A. CHIN
Hanford Engineering Development Lab., P.O. Box 1970, Richland, Washington 99352, USA

Received 8 January 1982; accepted 1 February 1982

1. Introduction

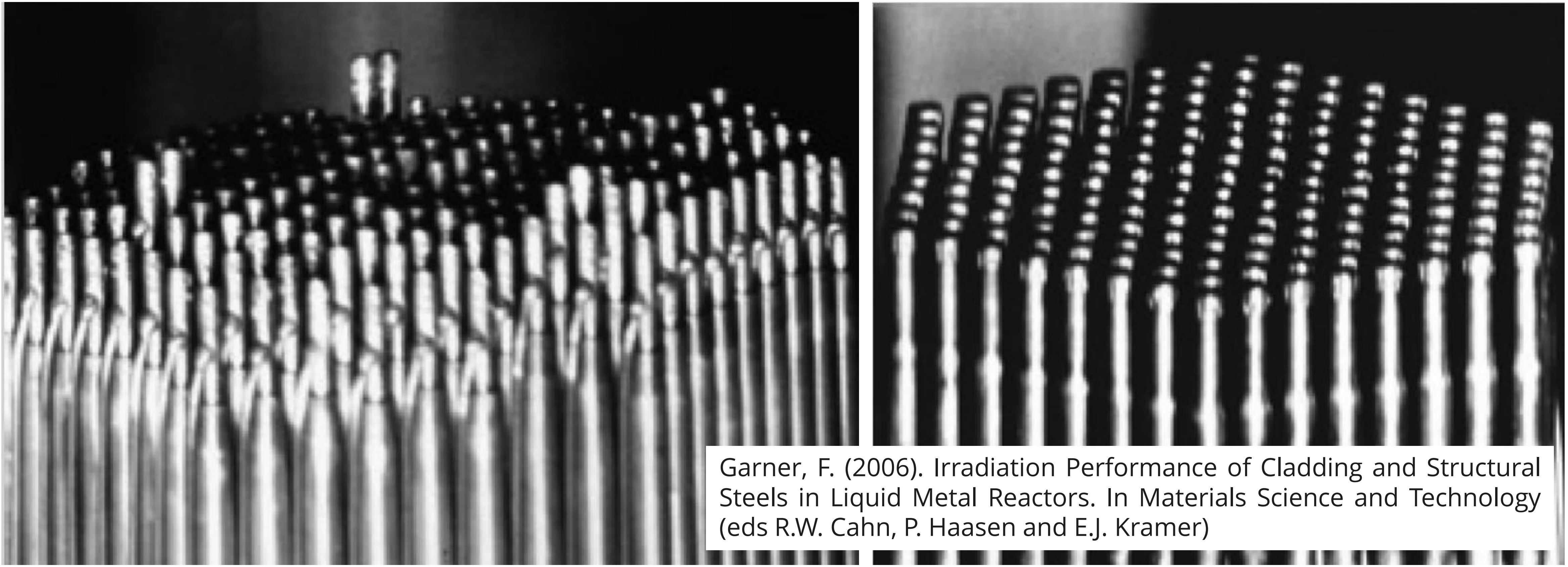
Following 1967, void swelling of metallic components became a major concern to the design of Liquid Metal Fast Breeder Reactor (LMFBR) cores. If this swelling phenomenon continued to increase with fluence, large increases in the size of the core components were

Fig. 1. The swelling which occurs in 20% CW AISI 316 following neutron irradiation to 1.5×10^{23} n/cm² ($E > 0.1$ MeV).



Radiation-induced volumetric swelling of a tube (fuel cladding) made of AISI 316 steel (EU 1.4401) exposed to neutron flux in the EBR-II reactor. Fluence: ~1.5×10^{23} n.cm^{-2} (E > 0.1 MeV) or ~75 dpa at a temperature of 510°C. Swelling: ~10% linear or ~33% volumetric.

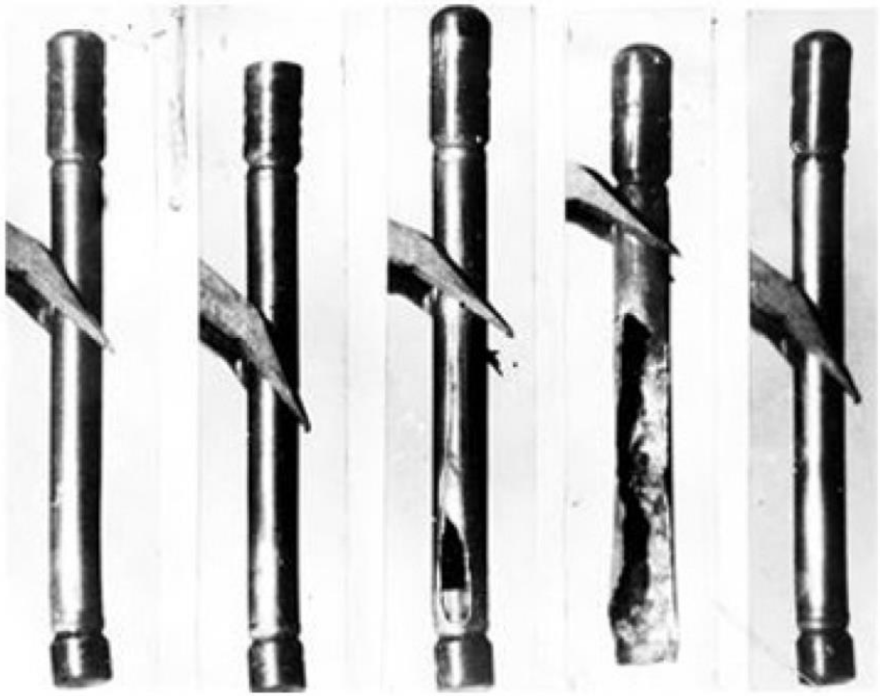
Aging of materials exposed to radiation environments - examples



Garner, F. (2006). Irradiation Performance of Cladding and Structural Steels in Liquid Metal Reactors. In Materials Science and Technology (eds R.W. Cahn, P. Haasen and E.J. Kramer)

Fuel assembly made of D9 steel after irradiation with neutrons at a fluence of 2.1×10^{23} $n.cm^{-2}$ ($E > 0.1$ MeV). The uneven elongation of some fuel rods is caused by small temperature and neutron flux gradients across the assembly and minor differences in processing and machining. On the right is an equally irradiated assembly made of a different material (HT9), which does not undergo radiation-induced volumetric swelling.

Aging of materials exposed to radiation environments - examples



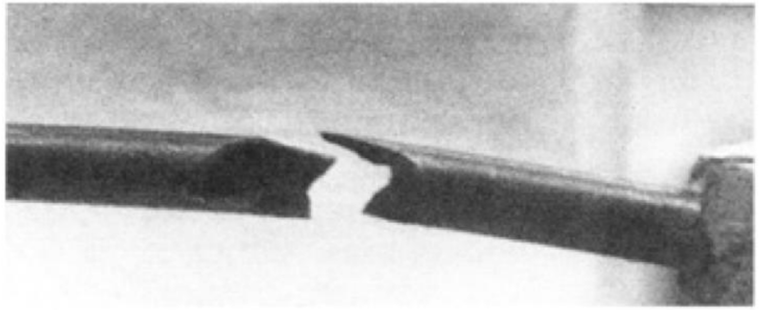
(a)

(b)

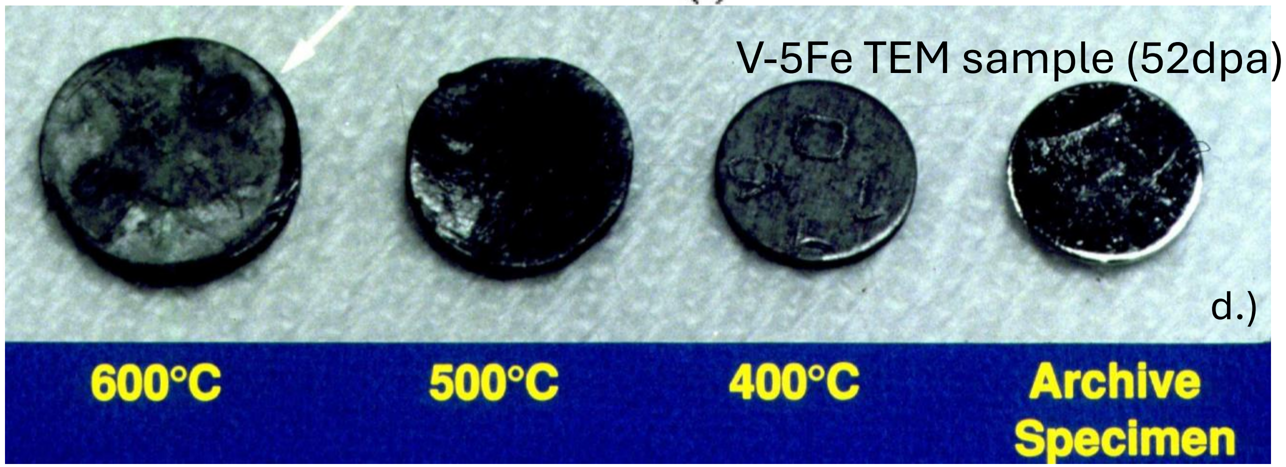
Four examples of extreme material embrittlement caused by radiation-induced volumetric swelling:

a. 6-10%
b. 14%
c. 30%
d. >100 %

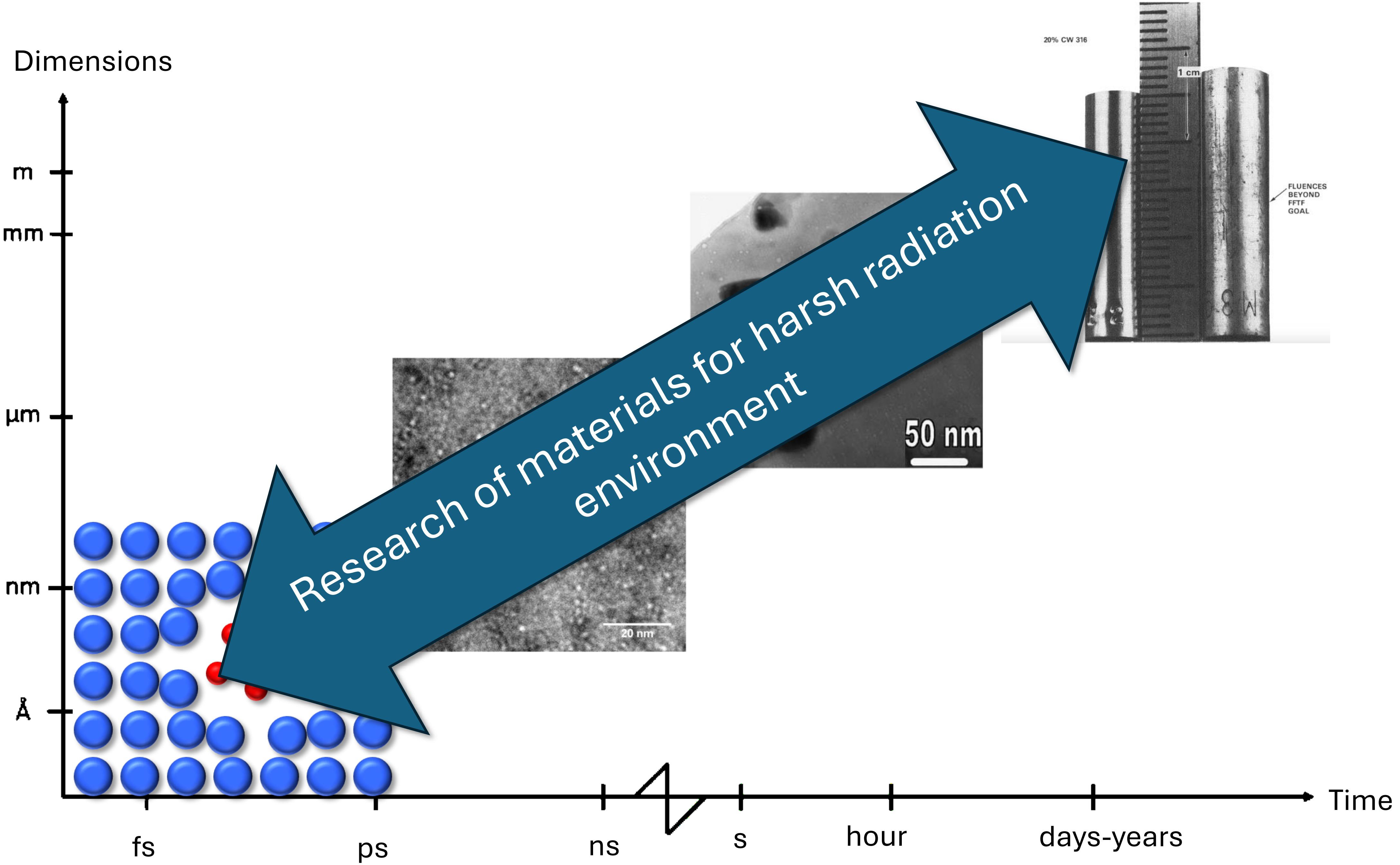
$$\frac{\Delta V}{V_0}$$



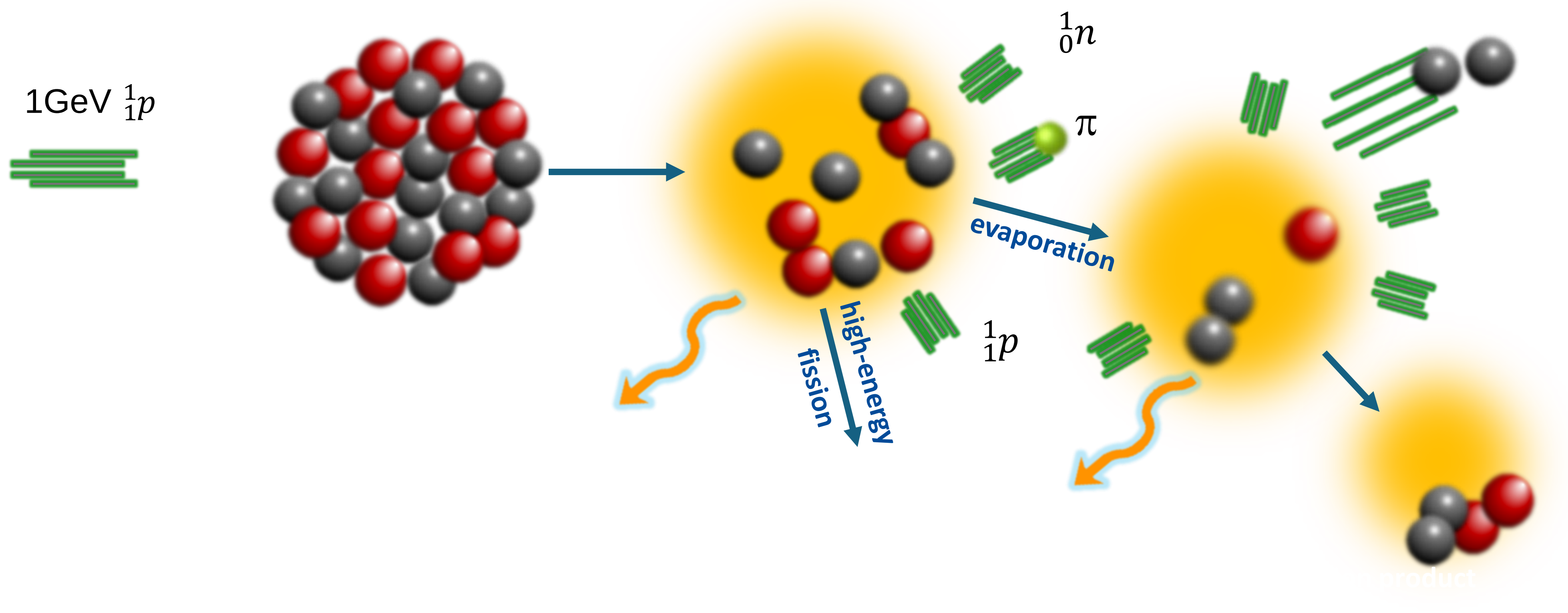
(c)



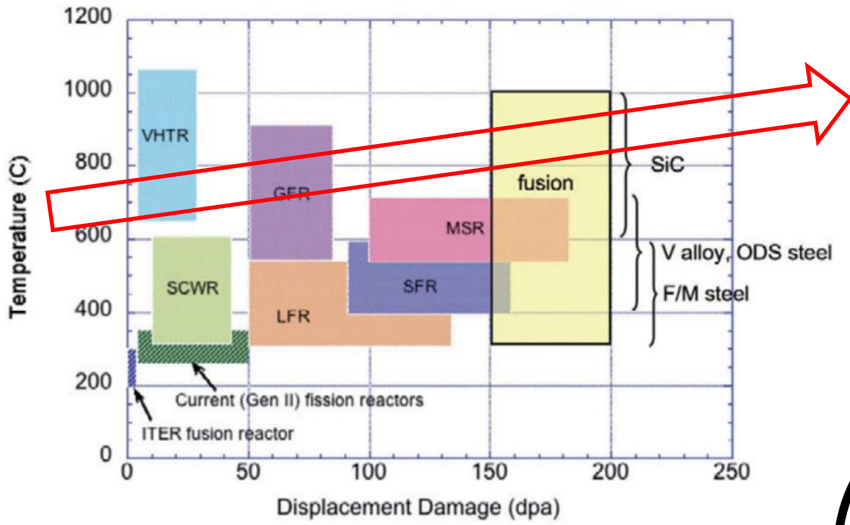
https://www-pub.iaea.org/MTCD/publications/PDF/PUB1732_web.pdf

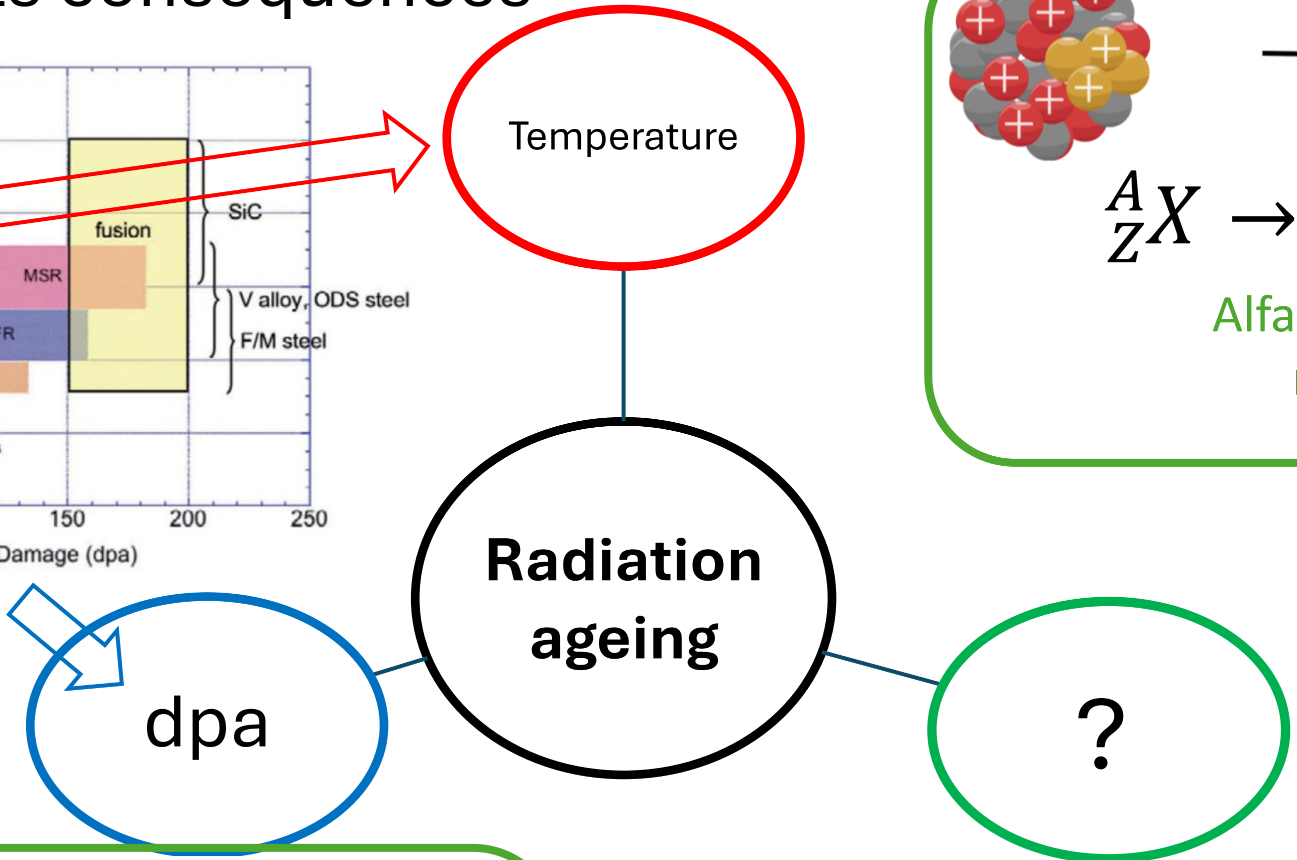

Dimensions
m
mm
µm
nm
Å
20% CW 316
1 cm
FLUENCES BEYOND FFTF GOAL
50 nm
20 nm
Research of materials for harsh radiation environment
fs
ps
ns
s
hour
days-years
Time

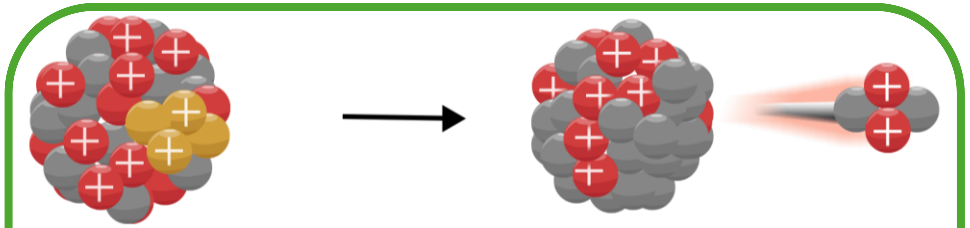
Radiation environments of modern nuclear facilities → helium and its consequences



Helium and its consequences

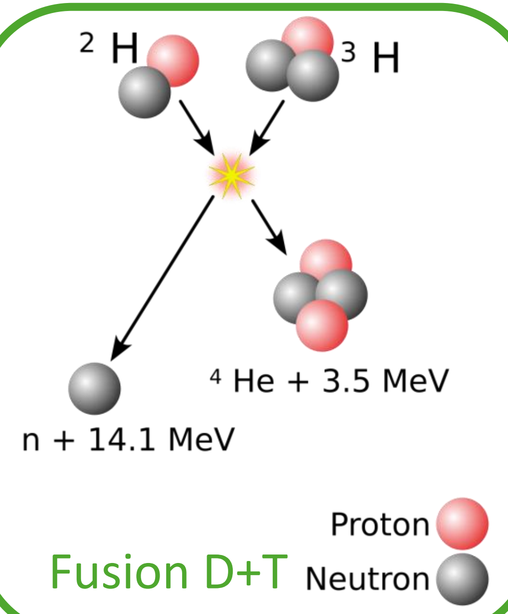




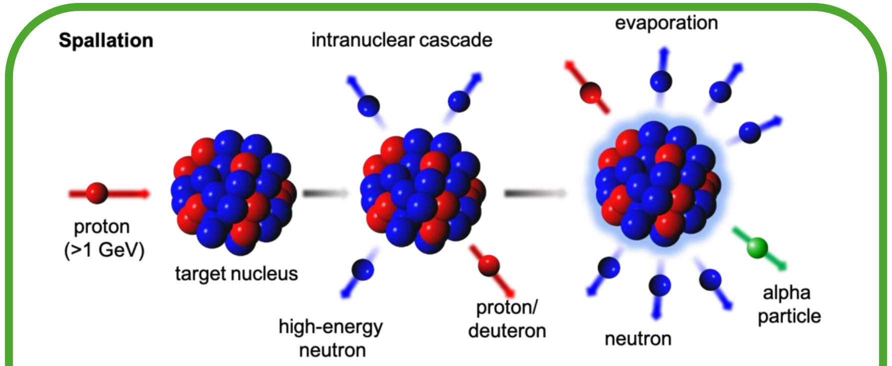


$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

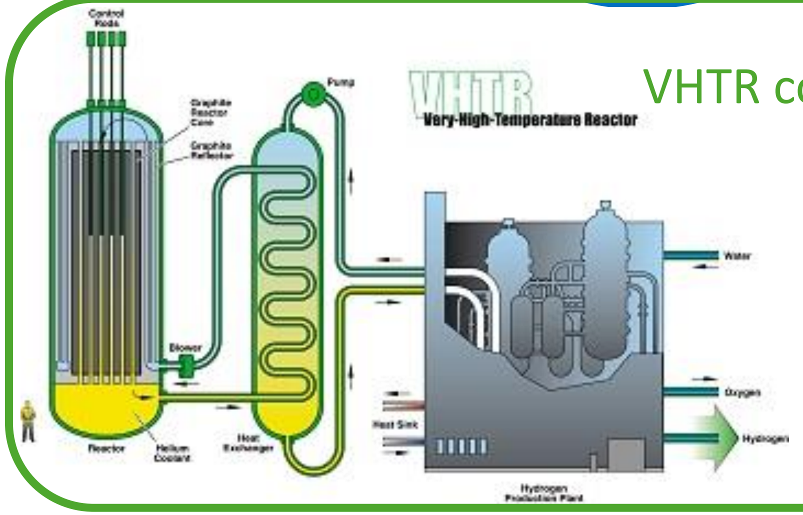
Alfa decay of heavy nuclei (fuel)



Fusion D+T

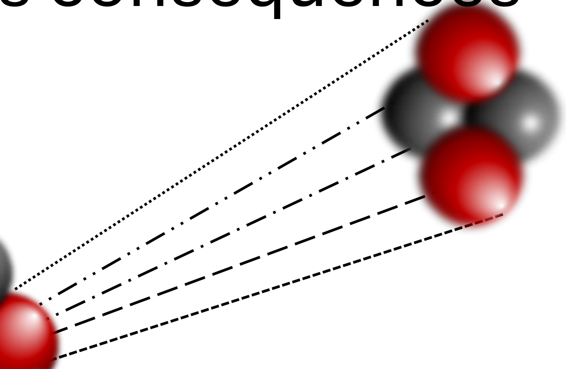


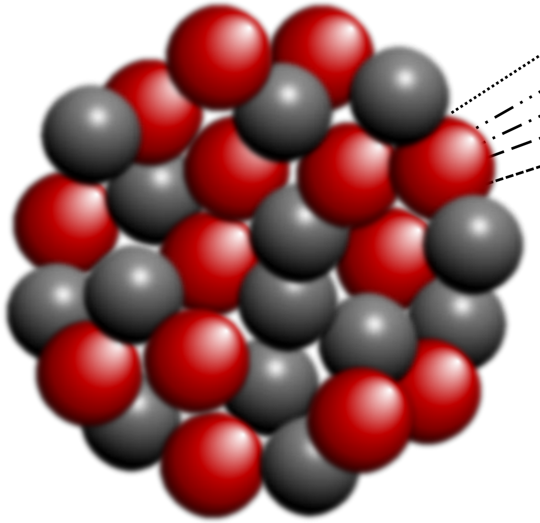
Spallation reactions



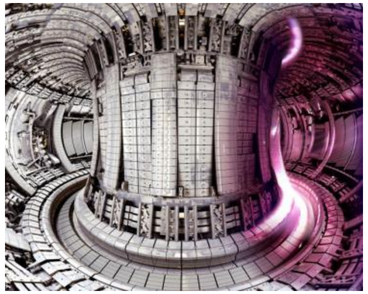
VHTR coolant

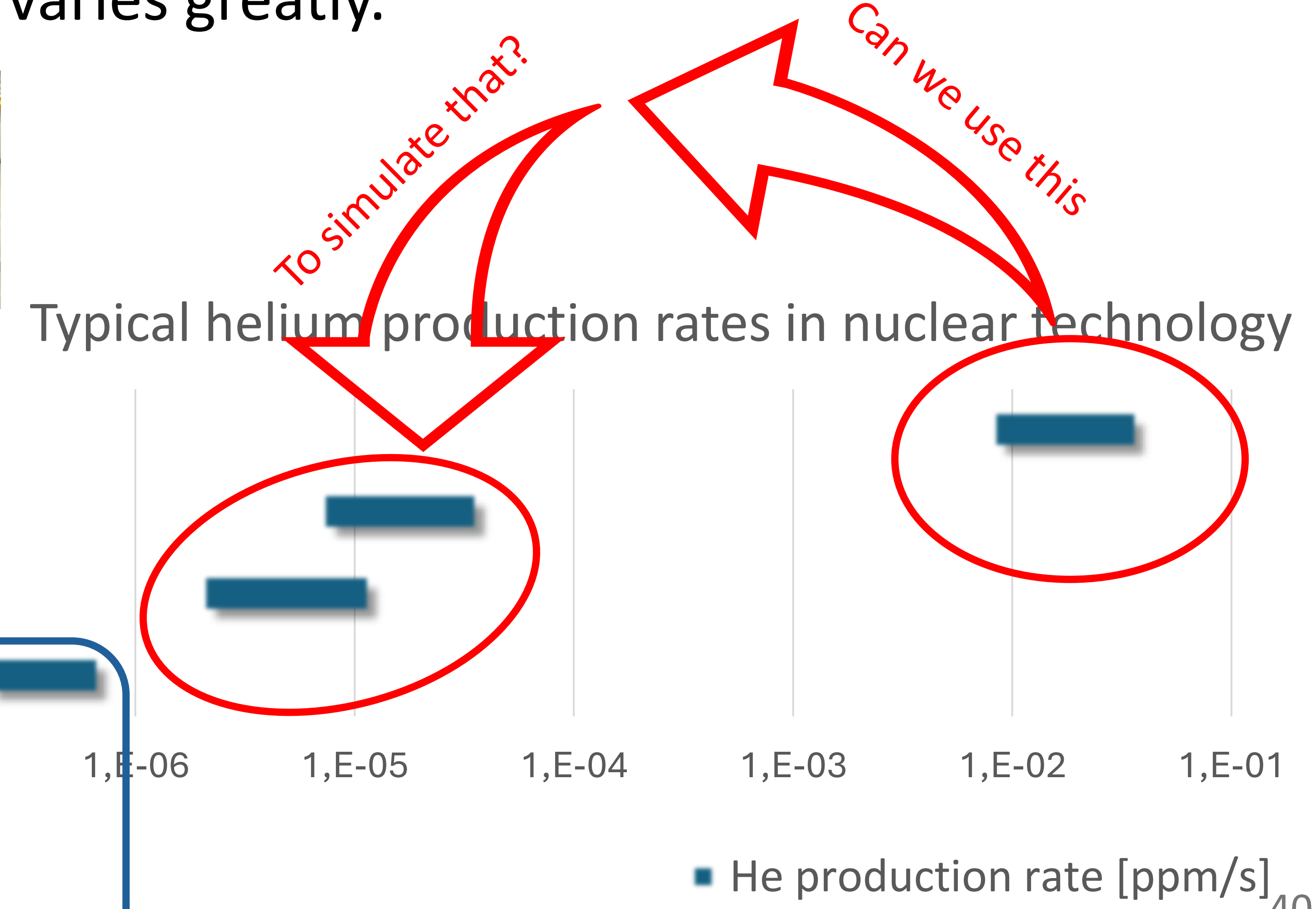
Helium and its consequences





An alpha particle (the nucleus of a helium atom) is a product of several nuclear reactions. The rate of production/accumulation, however, varies greatly.





Most high-dpa experiments conducted in fast reactors

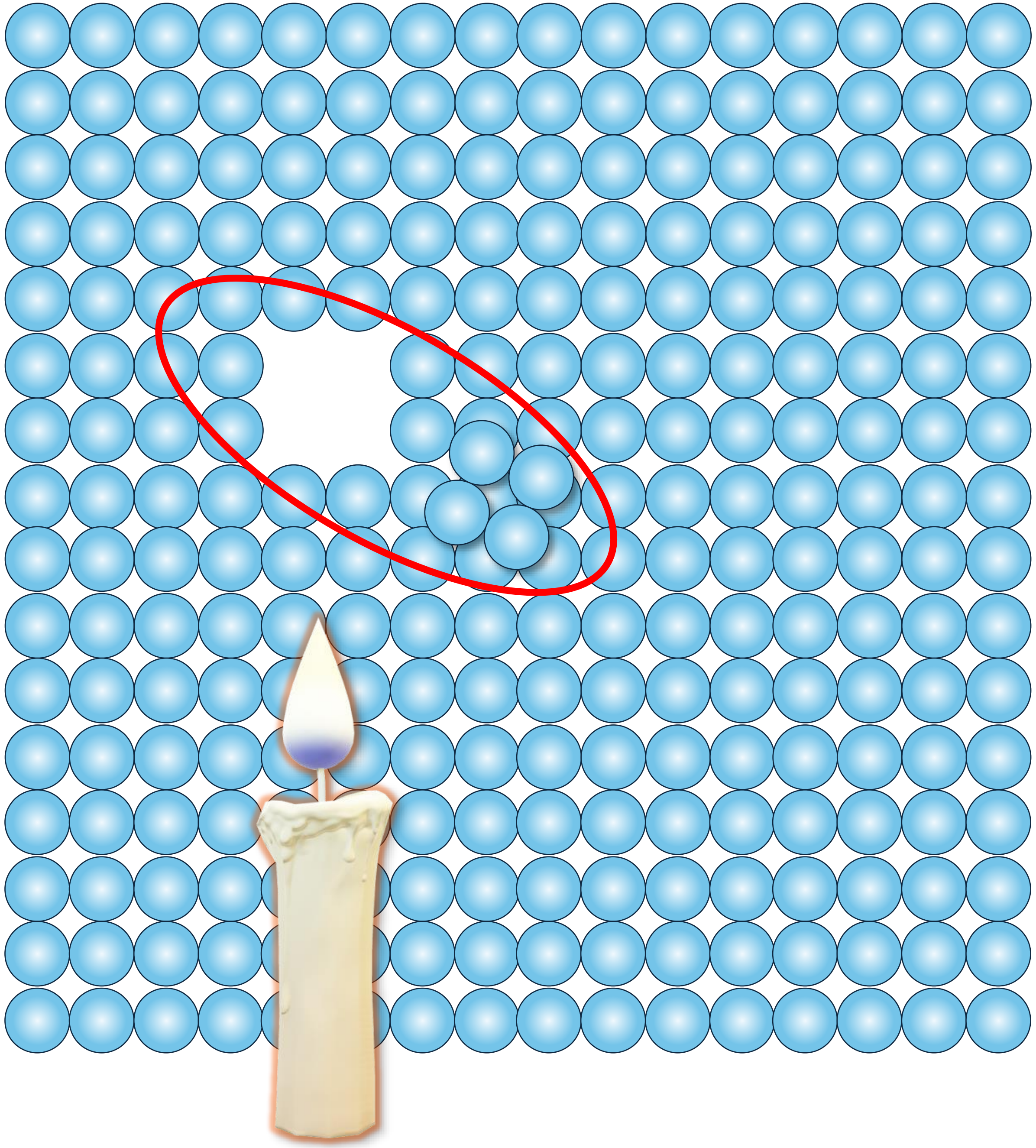
Helium and its consequences

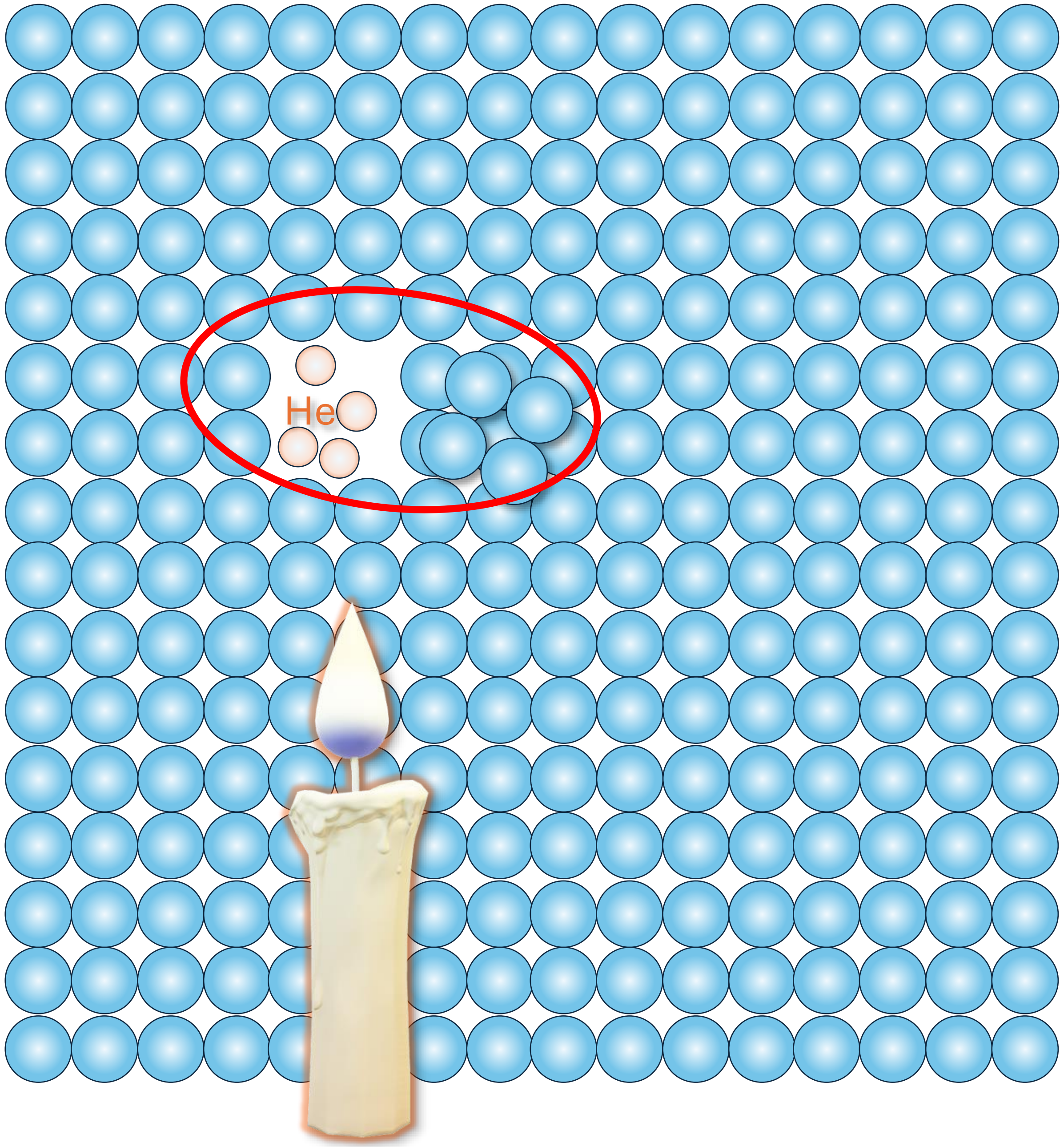
Helium is practically insoluble in metals and tends to accumulate in lattice defects. It significantly increases the binding energy of a vacancy in a (helium)-vacancy cluster.

The accumulation of helium in the lattice significantly alters the behavior of the material in a radiation environment, leading to accelerated growth of volumetric defects and the formation of helium bubbles. → embrittlement, hardening, volumetric swelling…

Helium can be introduced into materials more realistically - via transmutation - or less realistically - by ion implantation it using accelerators. Although the second approach has certain drawbacks, it also offers significant advantages.

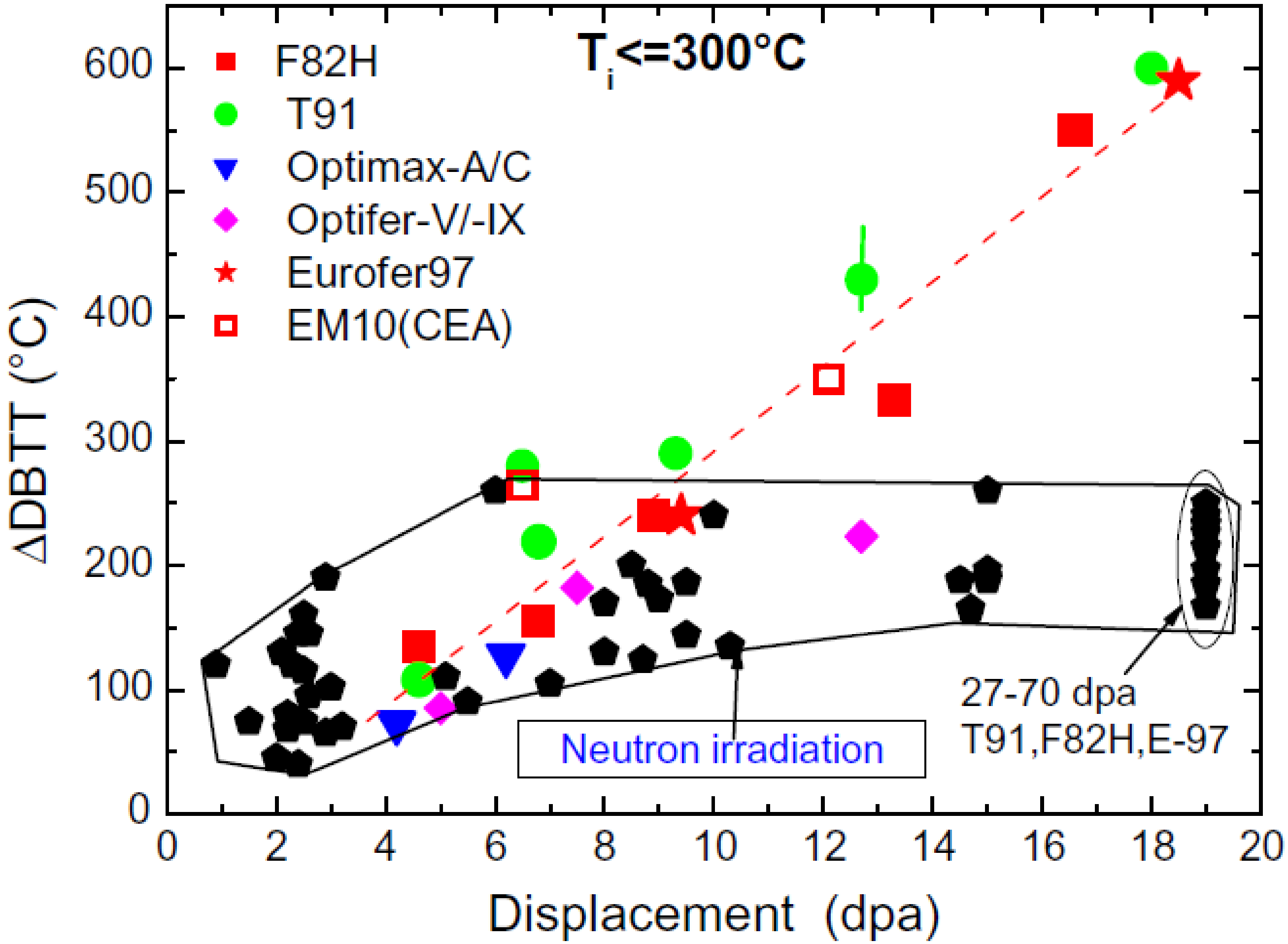
Helium and its consequences





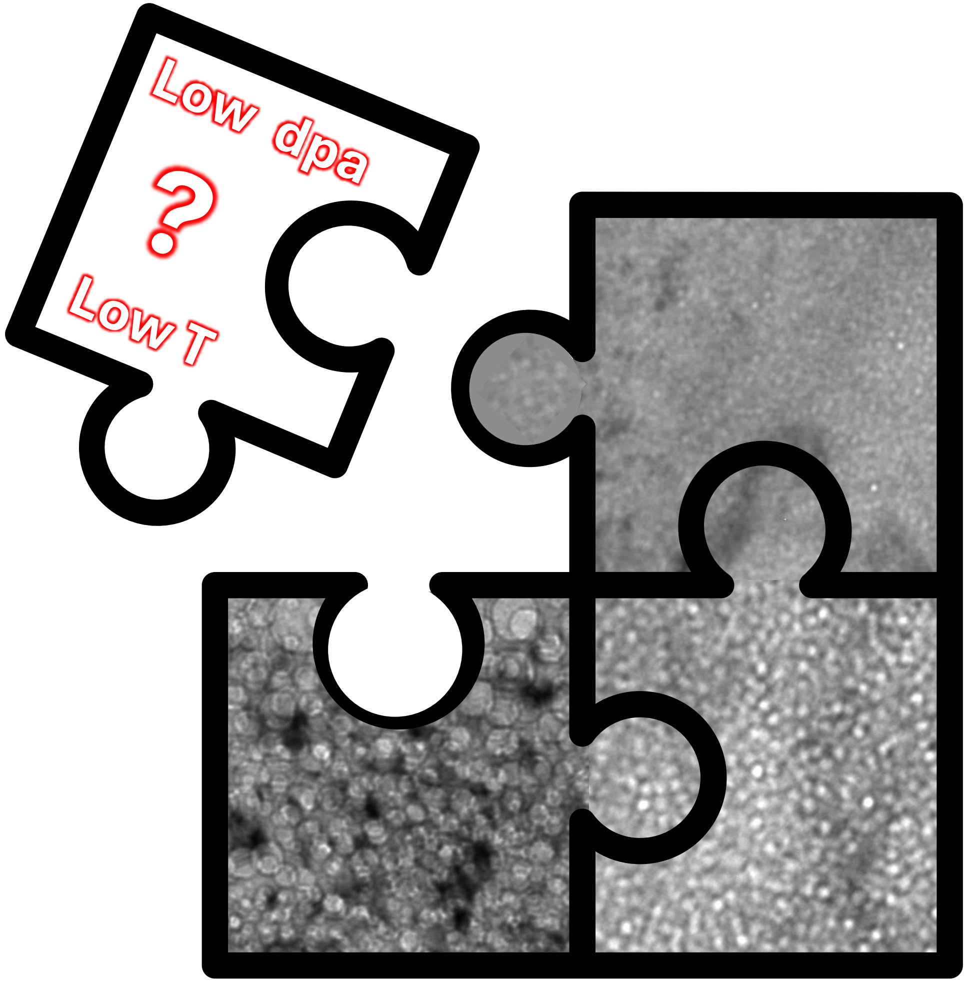
Radiation embrittlement accelerated by He

Y. Dai, G.R. Odette and T. Yamamoto, 2012

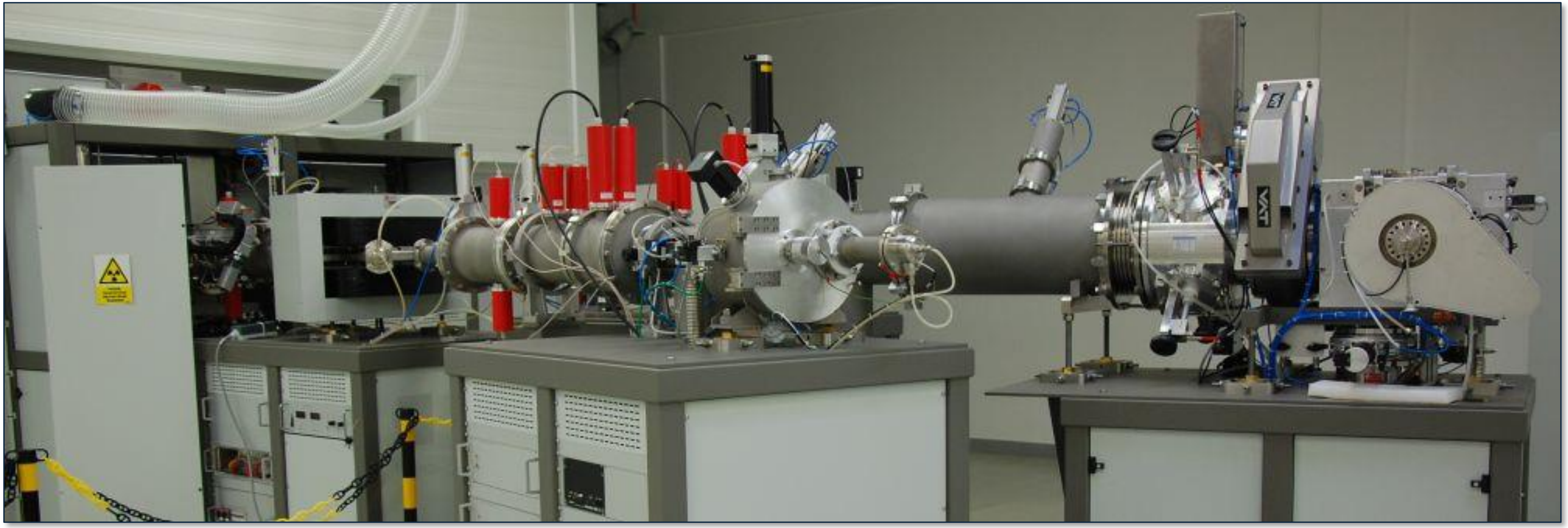


Samples irradiated in a spallation neutron source with high helium production exhibit a significantly higher degree of embrittlement compared to samples irradiated with neutrons alone.

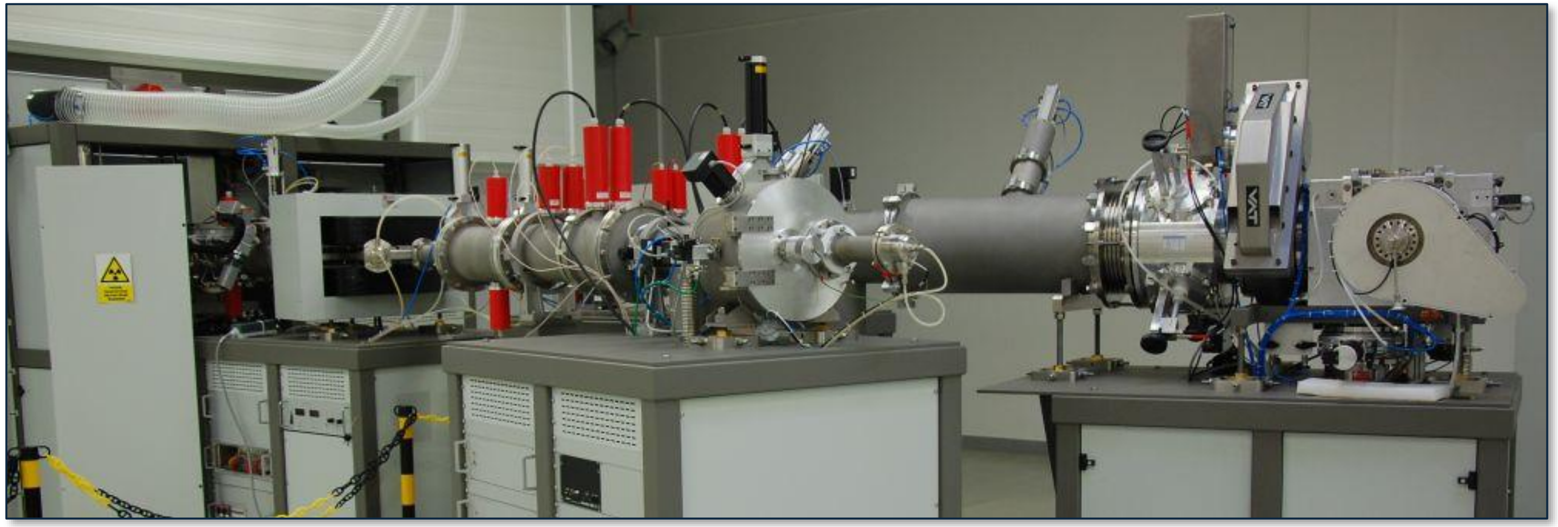
A case study



He ion implantation experiment



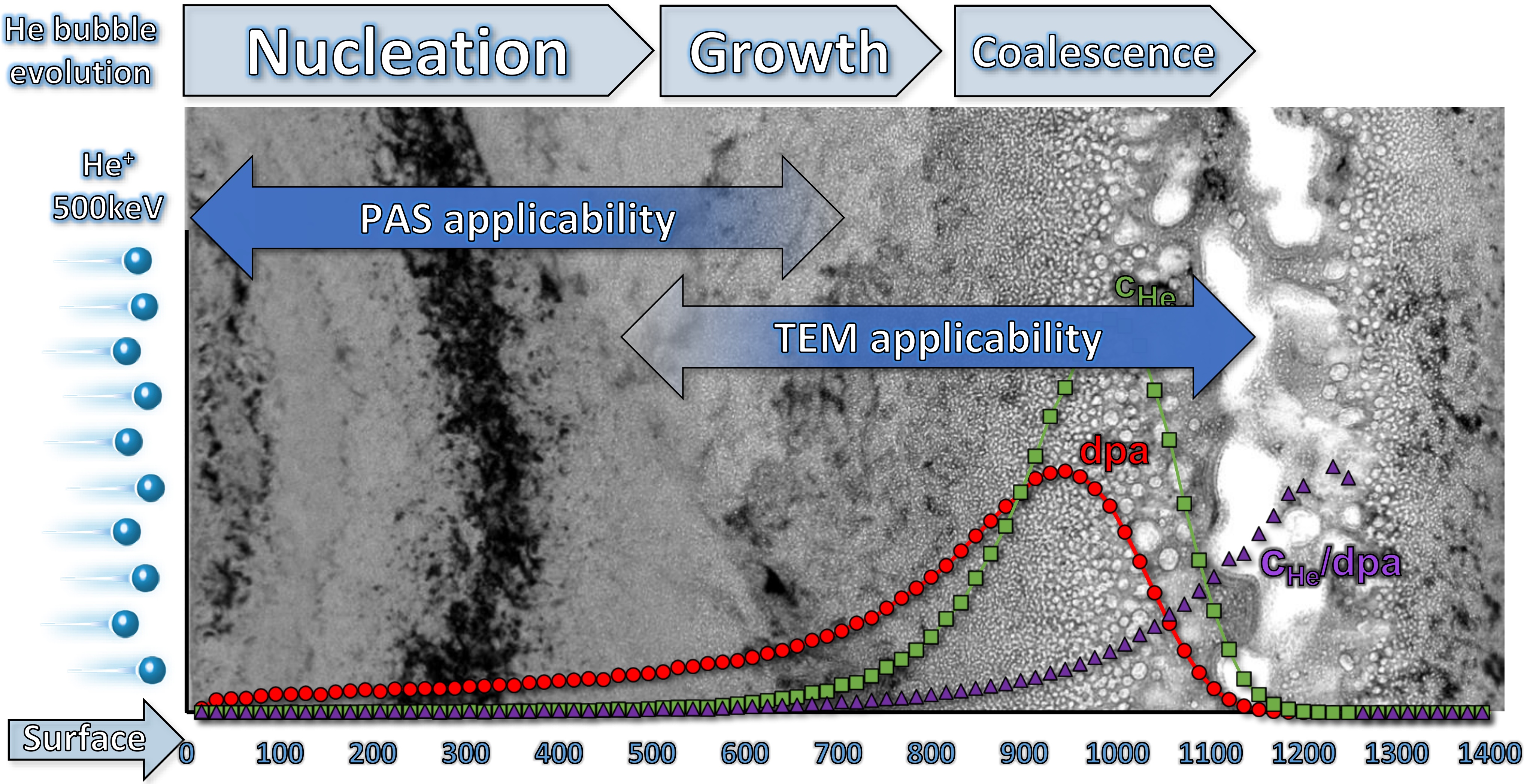
Objective: Characterizing the early-stage radiation damage in Fe/Cr alloys



Note: Introducing a near-surface damage -> slow positron beams are required to investigate this area

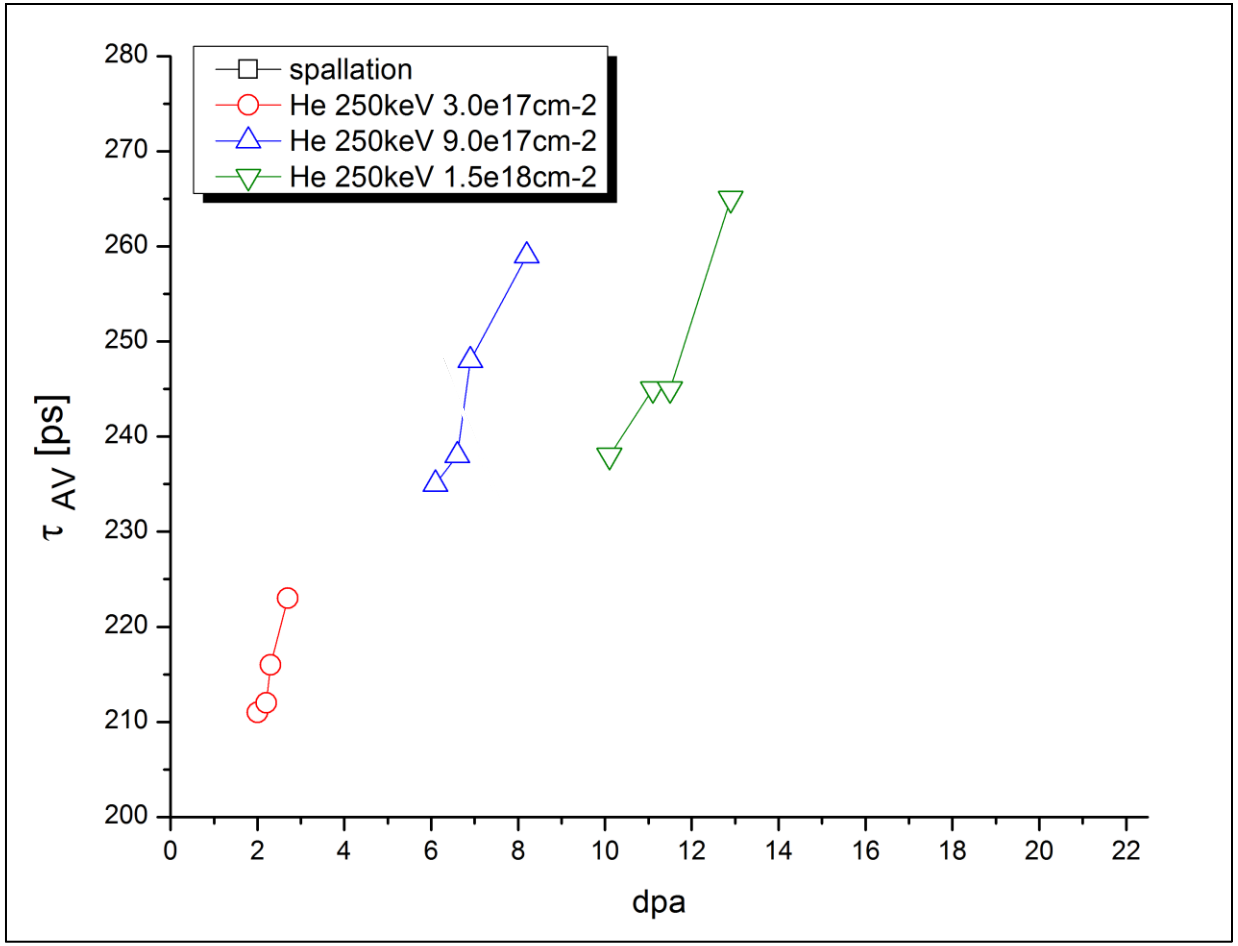
+ availability of research accelerators
+ samples are not radiactive after irradiation
+ non-uniform damage distribution

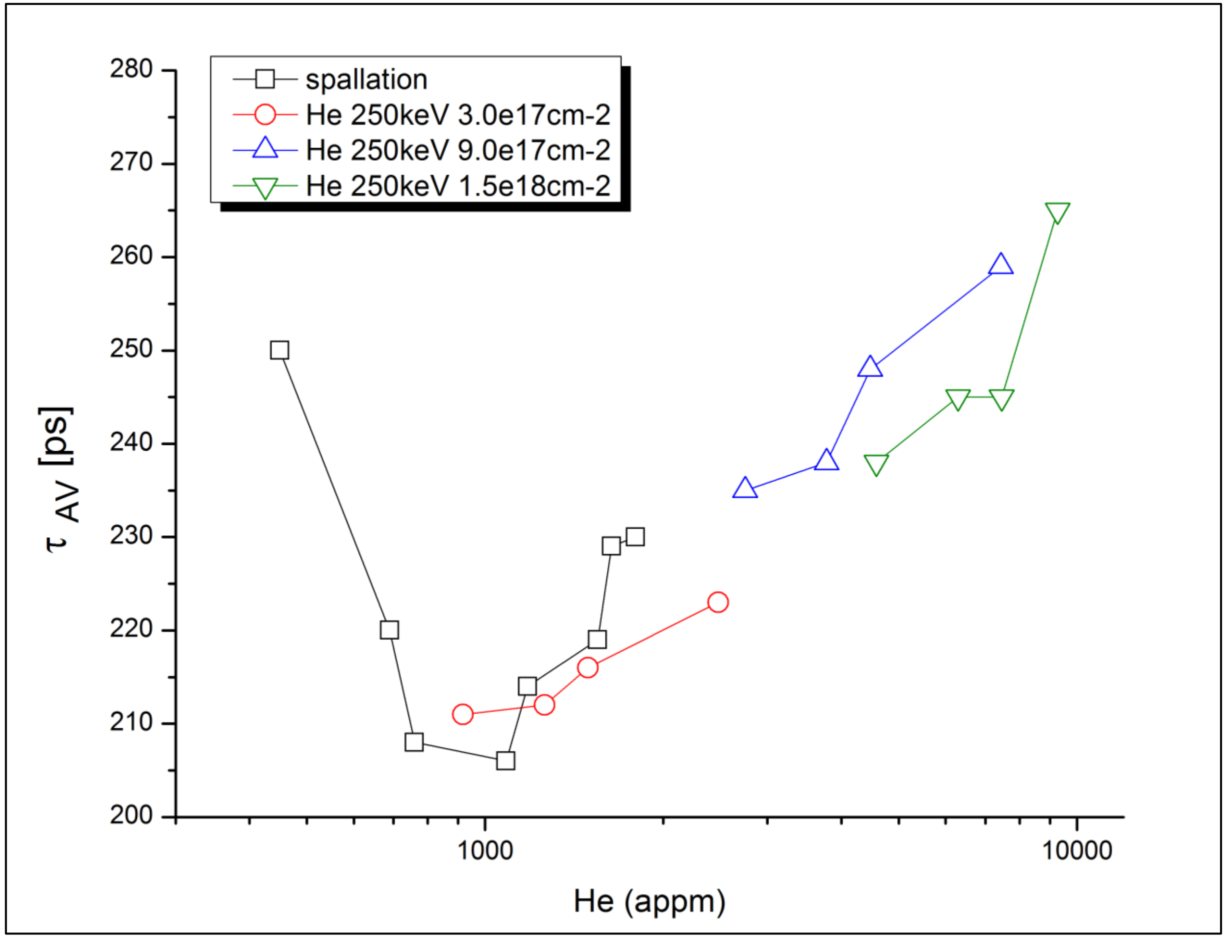
- low displacement damage levels
- “unrealistic” He concentration (He/dpa ratio)
- non-uniform damage distribution

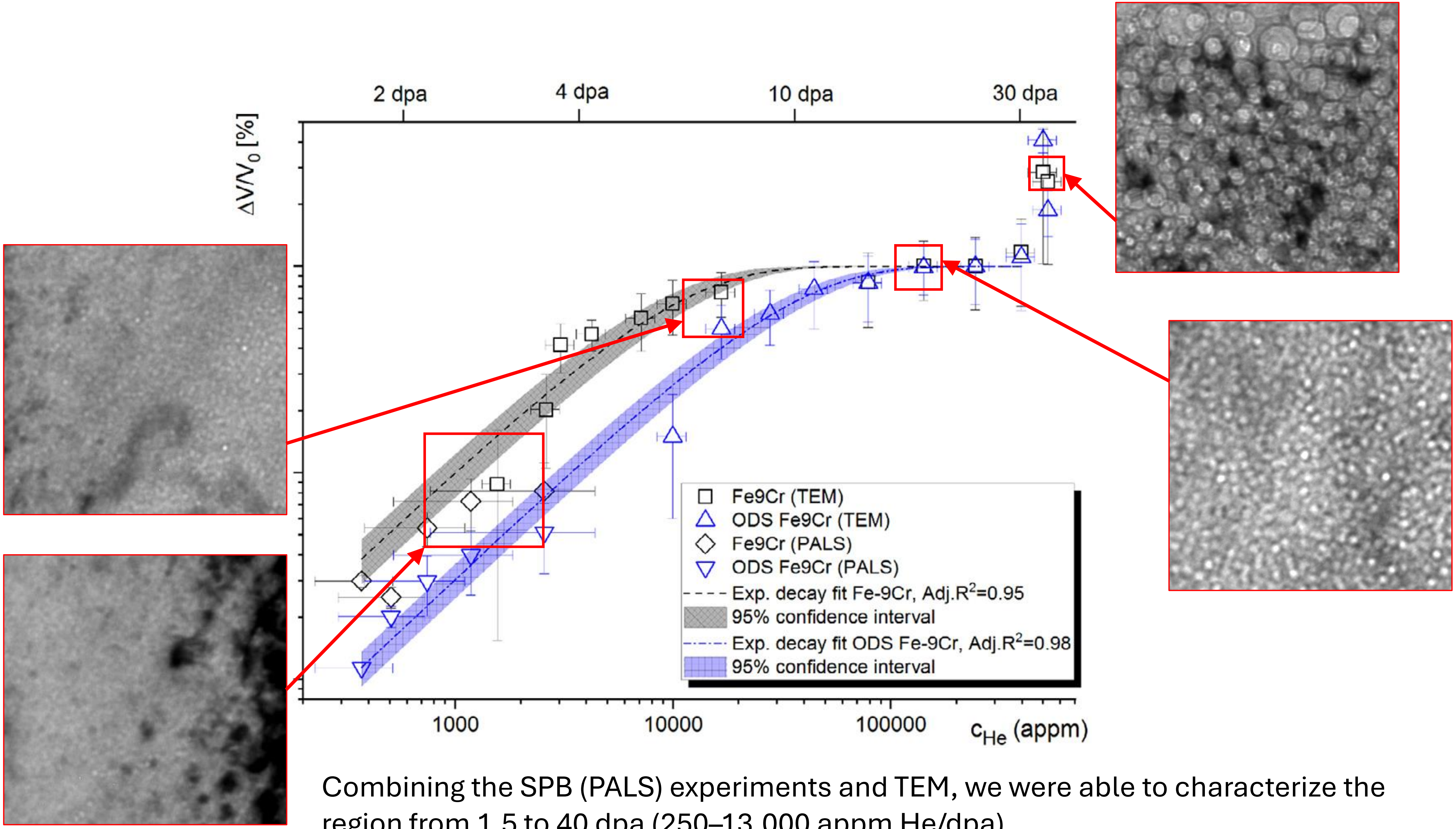


A suitable analytical tool should be depth-sensitive or capable of analyzing micro-samples taken across the thickness.

Why not look at dpa when He production rate (He concentratio) varies?







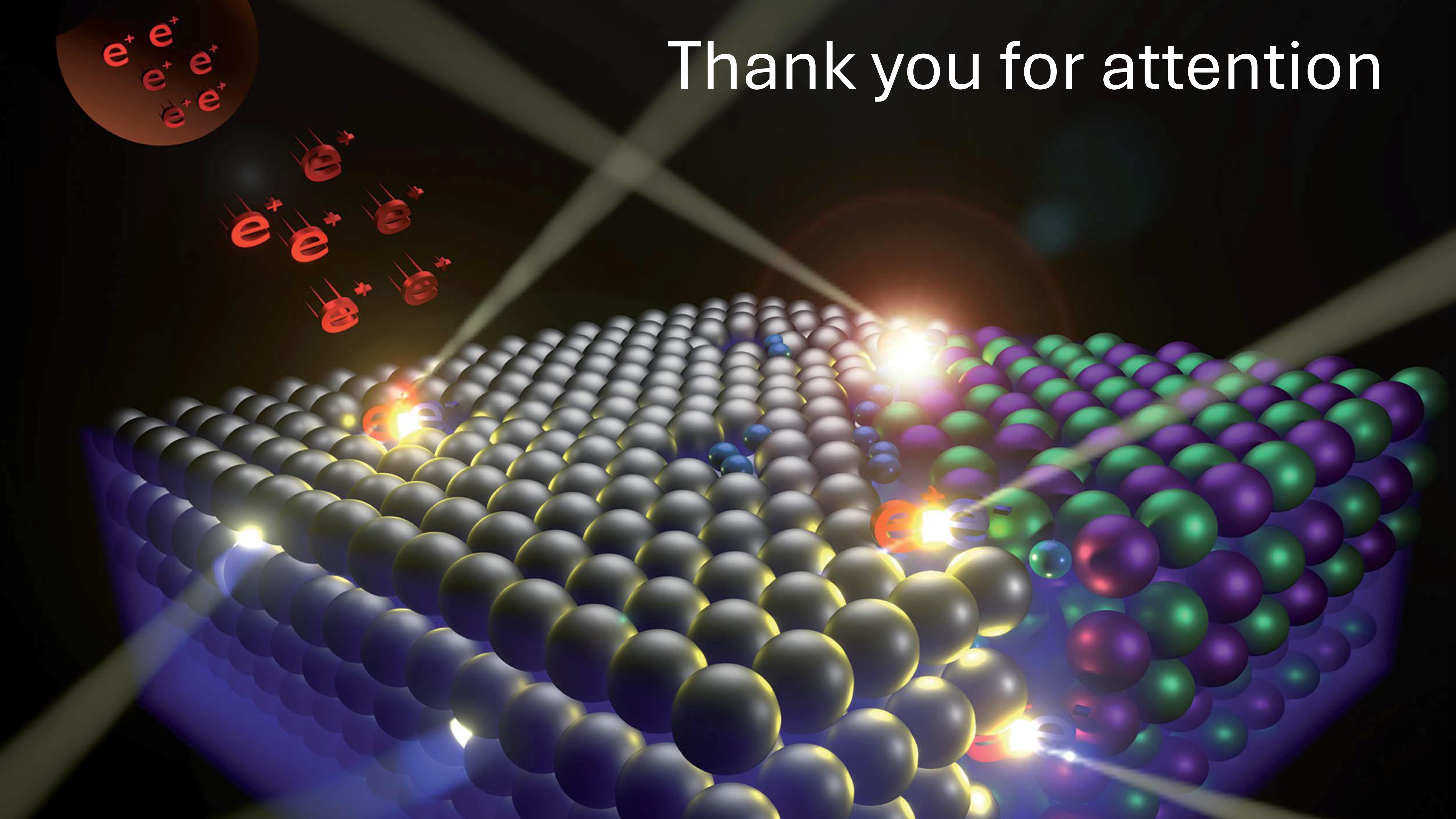
Combining the SPB (PALS) experiments and TEM, we were able to characterize the region from 1.5 to 40 dpa (250–13,000 appm He/dpa).

V. Krsjak et al, Journal of Materials Science & Technology, Volume 105, 2022, Pages 172-181,

Summary:

- Positron is a unique probe for material characterization and various techniques based on positron annihilation have been established in the material research
- PAS techniques offer new insight into the processes of nucleation and growth of helium bubbles.
- Combination of positron annihilation spectroscopy and transmission electron microscopy has a potential for significant improvement of the understanding of the microstructural evolution of radiation-induced cavities.

Thank you for attention



MBN – Magnetic Barkhausen Noise

11.02.2025

Jarmila Degmová

STU FEI
SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE
FAKULTA ELEKTROTECHNIKY A INFORMATIKY

Introduction

DT – classical mechanical testing is good solution, but…

(1) components are over-dimensioned using safety factors that allows all produced components to withstand all possible loads.

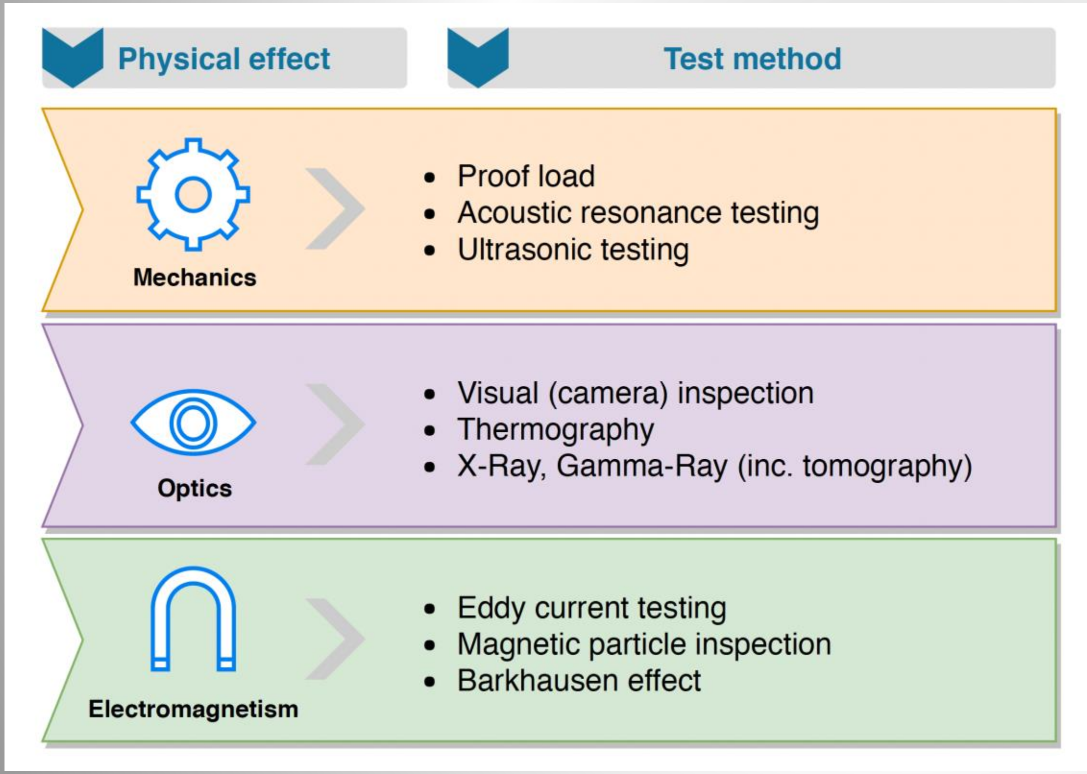
(2) this implies higher production costs as well as higher environmental impact in terms of material and energy consumption.

(3) reusage of the testing samples is not possible

NDT is time and money saving solution

Introduction

There are many methods and techniques, based on different physical effects, that can be used for NDT.



One of these techniques is MBN method which is utilized to assess changes in the surface layer of ferromagnetic materials, especially to monitor changes in hardness and residual stresses.

Introduction

- The BN method functions on the interaction between the external magnetic field and ferromagnetic material.
- Subsequent reorganization of the magnetic domains and the formation of an internal magnetic field are registered by the specialized probe (sensor).
- The magnetization creates an interaction with the material that measures typically from the near surface up to a few hundred microns below the surface. This could be controlled by the magnetizing frequency.
- **BUT**...the magnitude of the registered signal and its parameters depend on many factors.
- **AND...**many of them are non-correlated, while others share a strong correlation.

Introduction

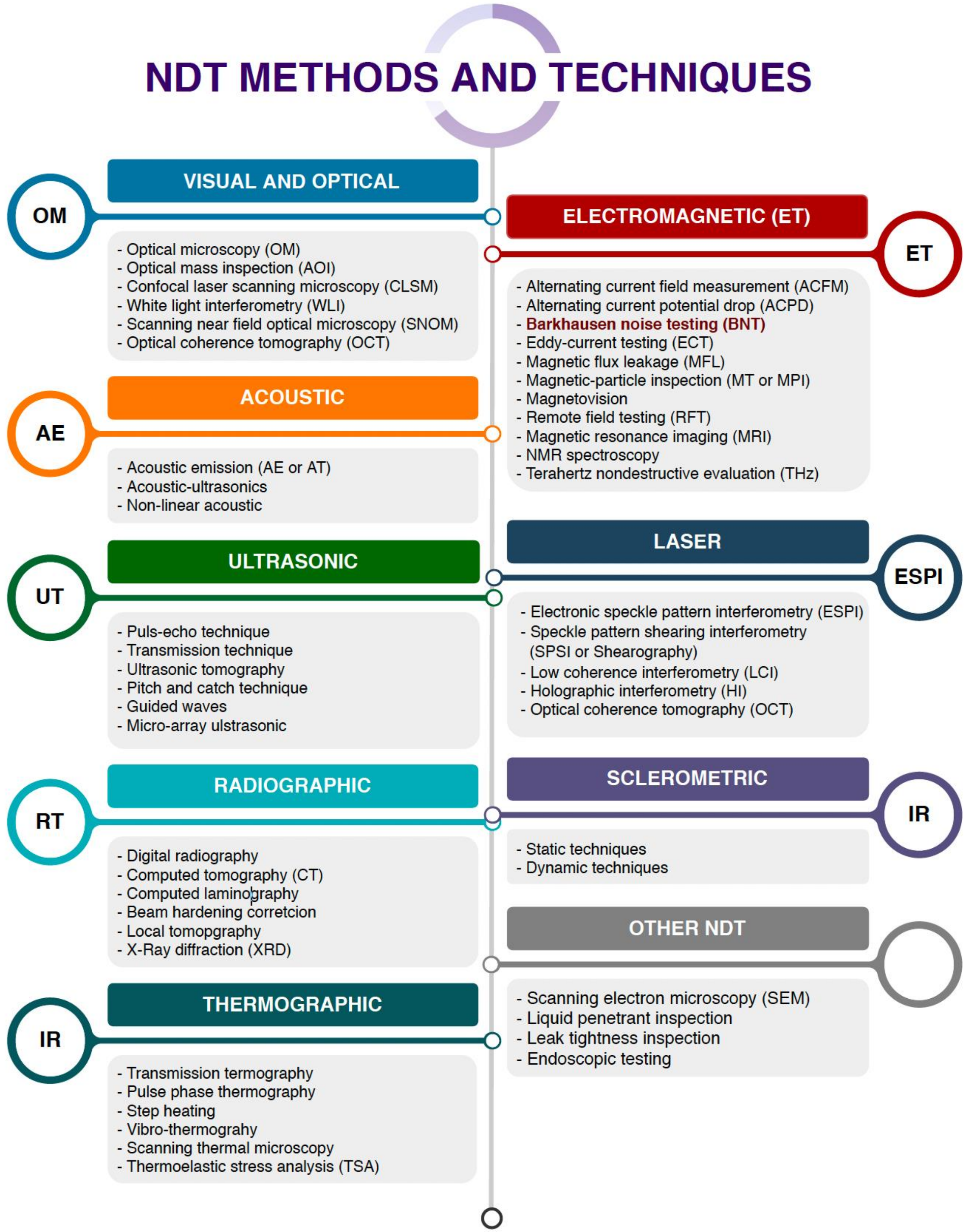
- The advantages of this technique are
  - It is NDT,
  - possibility to test different parts and shapes
  - portable equipment
  - different scanning depth
  - correlation with other techniques
  - works with irradiated materials as well.

Introduction

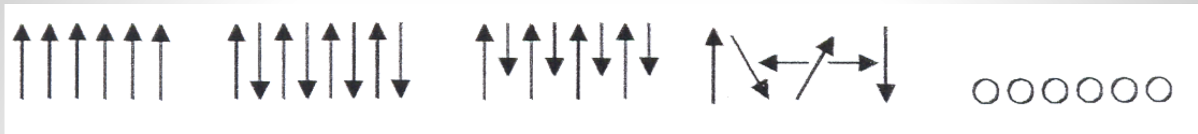
- The limitations of this technique are
  - the sensitivity of the physical condition of the sensor,
  - part integrity (e.g., micro-structure or surface topography)
  - the presence of an oxide on the surface
  - the sensor employs a ferritic material to magnetize the tested surface. This material could wear down, especially if the measurement is dynamic, which may influence the BNT signal.

Introduction

The BNT method is classified as an electromagnetic method of NDT

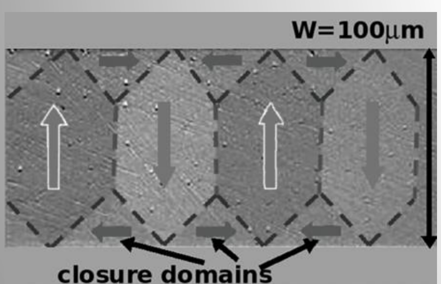


Principle of Barkhausen noise method

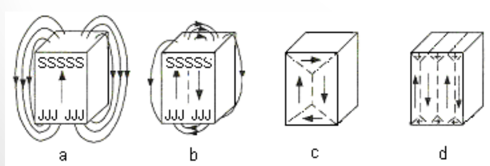


Arrangement of magnetic moments in domains (**ferromagnets**, antiferromagnets, ferrimagnets) and in substances without magnetic moments (paramagnetics at H = 0, diamagnetics)

- In a ferromagnetic material, the inner magnetic field forms domains with preferred orientations relative to the local crystal orientation.



Magnetic domains by Kerr effect



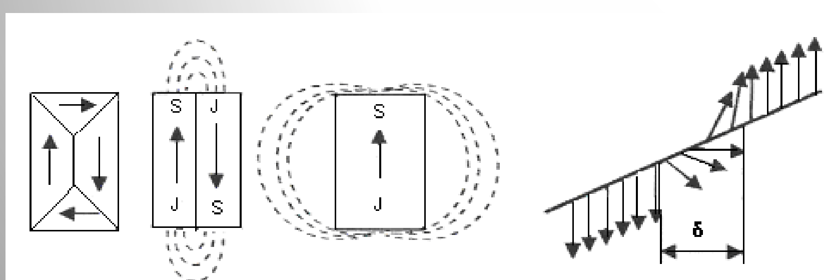
The spontaneous magnetization vectors are arranged in such a way that one can speak of a closed magnetic flux. From the energy point of view, the such arrangement of domains is characterized by practically complete suppression of magnetostatic energy.

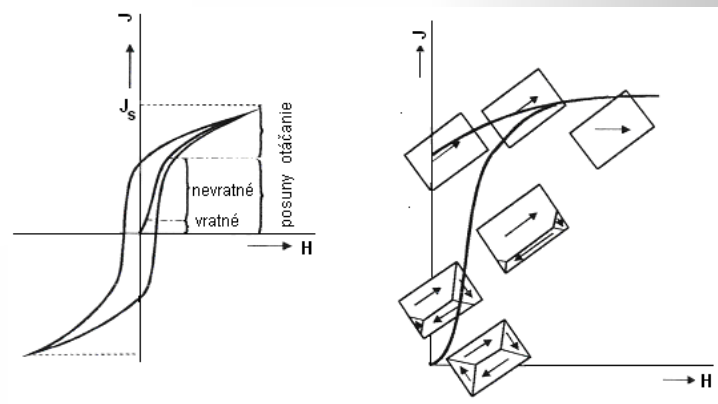
- In a demagnetized material, the domains cancel each other out without forming a long-range internal magnetic field.

Principle of Barkhausen noise method

- When subjected to an increasing external magnetic field, the domains that line up with the external field grow at the cost of the other orientations.

- The material becomes magnetized, and the inner magnetic field grows considerably stronger in comparison to the imposed external field.





The orientation of the magnetic moments in neighboring domains differs from each other by 90° or 180°

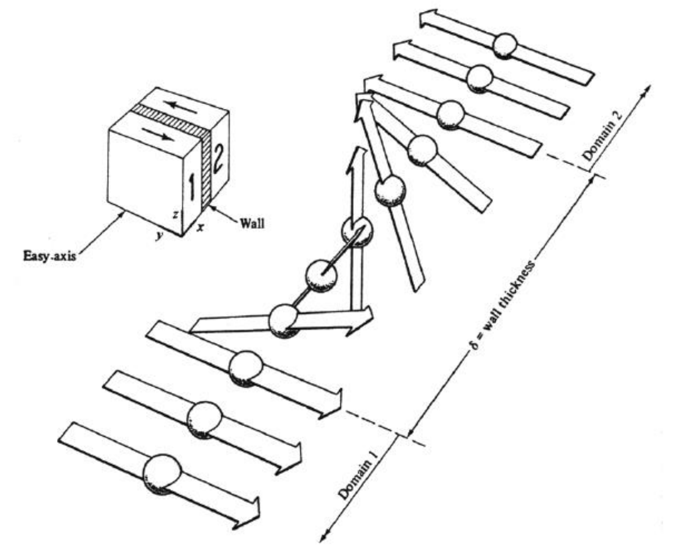
Principle of Barkhausen noise method

- During the process of **magnetization**, when the preferred orientations of the domains grow, the entities known as **Bloch walls** between the domains move.

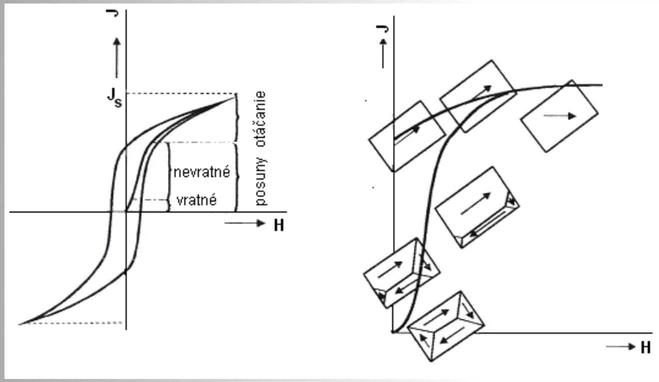
- The domains are separated by a space called the Bloch wall.

- In these inter-domain walls, the direction of the spin magnetic moments gradually changes, and therefore it is necessary to understand them as spatial, not planar, formations.

- The thickness of the wall is determined by the effort to reduce the energy hidden in it.



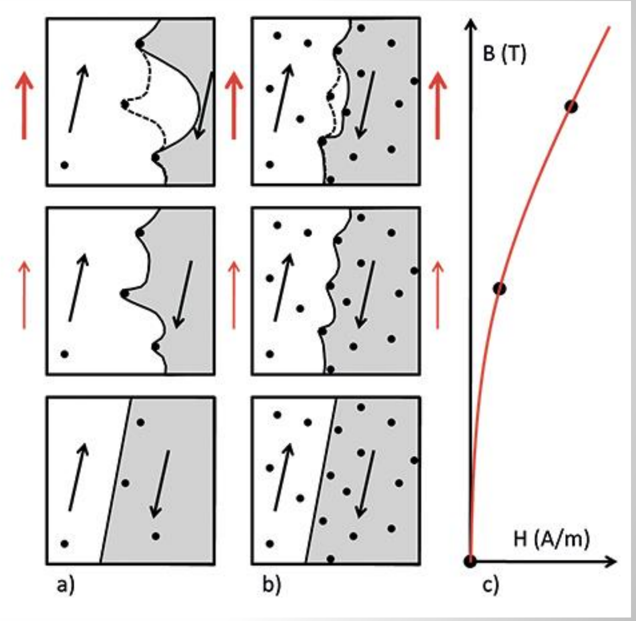
Principle of Barkhausen noise method



- We start from a domain structure arranged in such a way that the resulting magnetization is zero.
- The external magnetic field is the cause of two basic events:
  - the movement of the domain walls and
  - the rotation of the vectors of the spontaneous magnetization of the domains.
- The movement of the walls enlarges the domains aligned with the external field.
- Of the mentioned mechanisms, the one that is less energy demanding is always carried out.
- Walls mostly move in weak fields and in stronger ones there is rotation. This process is shown by the initial magnetization curve.

Principle of Barkhausen noise method

- Due to the presence of obstacles in the microstructure, the Bloch walls motion materializes in discrete steps.



Schematic illustration of step-wise motion (jumps) of a 180◦ domain-wall pinned by obstacles due to an increasing external field, H.

- For a material that contains few obstacles, the motion occurs in big steps, making the inner magnetic field expand in big steps.

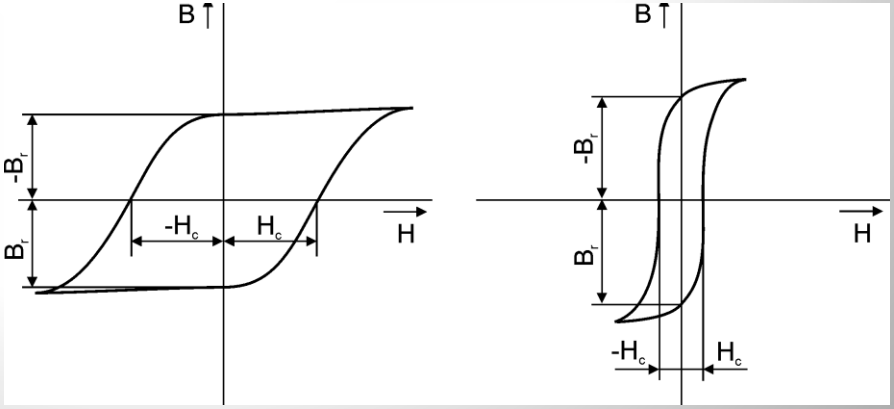
Principle of Barkhausen noise method

- The magnetically soft material is easy to magnetize/demagnetize. Transformer sheet is an example of such a material.

- In a magnetically hard material, which is hard to magnetize/demagnetize, there are numerous obstacles that render the motion of Bloch walls difficult, forcing the magnetization to occur in small steps.

Steel – how it is possible to change the microstructure from soft and ductile to hard and brittle?

Heat treatment



Principle of Barkhausen noise method

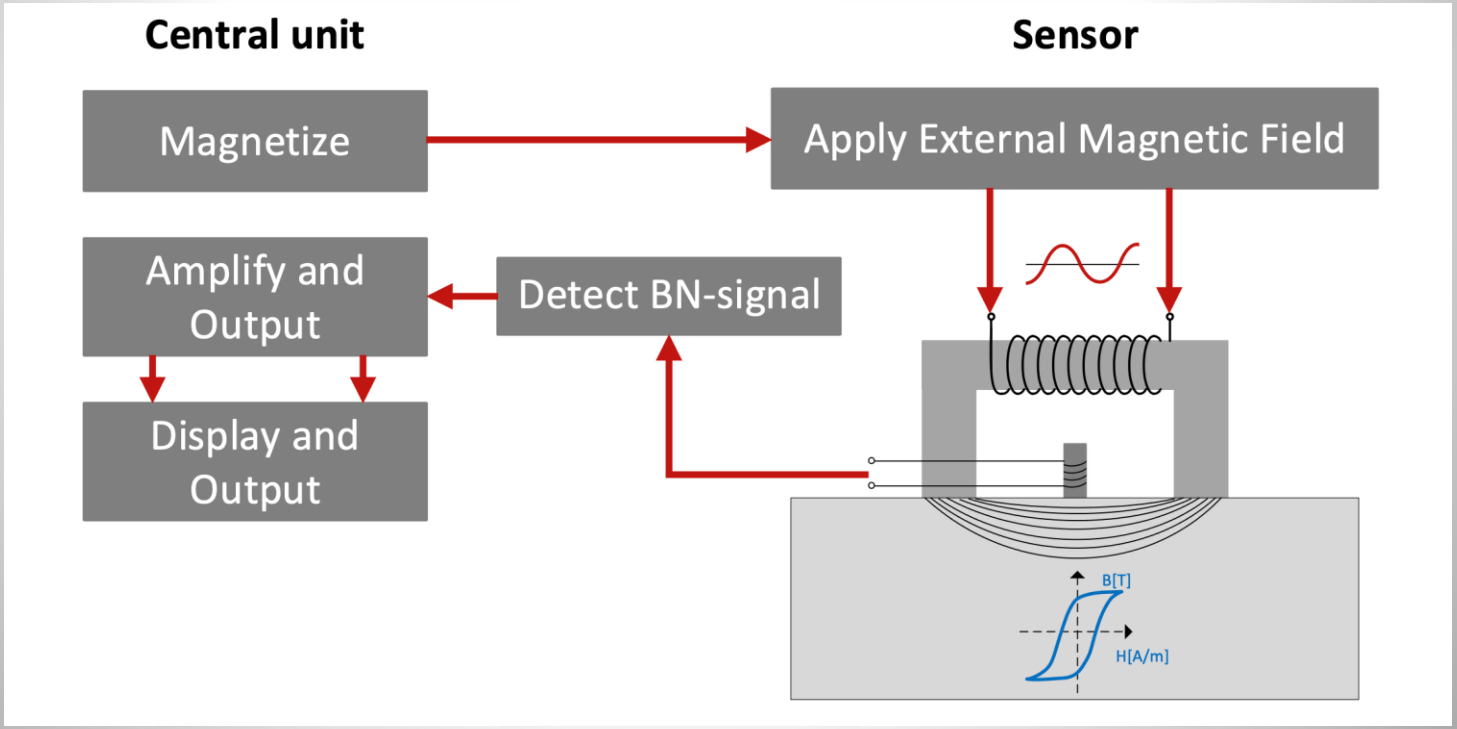
Microstructure vs magnetic vs mechanical properties

- Heat treatment is a fundamental reason behind the success of steel in modern society.
- The different microstructures formed by heat treatments have different mechanical properties because of different obstacles' amounts and strength for plastic deformation.
- In mechanically soft materials, the resistance for dislocation motion is low while it is high in mechanically hard materials.
- Naturally, different microstructures, besides having different mechanical properties, also have different magnetic properties.

How to measure magnetic Barkhausen noise

Into the experimental set-up

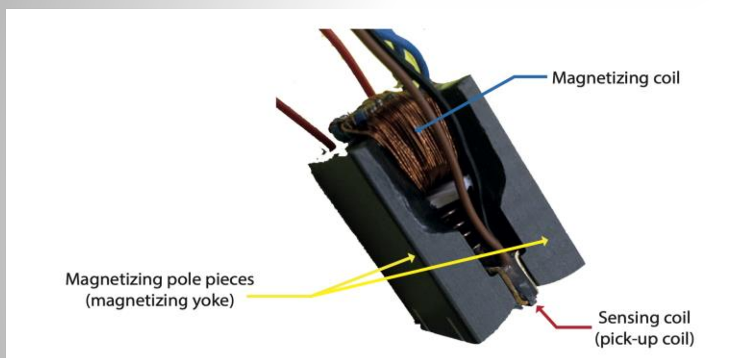
- The basic equipment consists of a measuring device with a sensor and connecting cable to generate and measure BN.

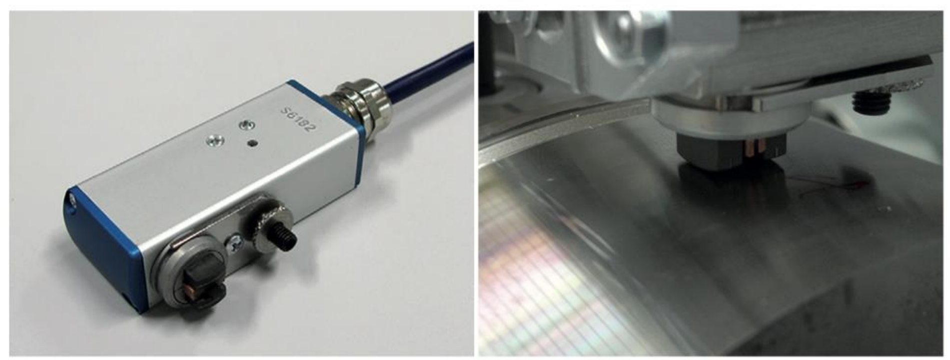


How to measure magnetic Barkhausen noise

Into the experimental set-up

- The BN analyzing instrument requires to both generate the applied magnetic field, to send into the material, and to pick up and …..





(a) Sensor (b) Application

How to measure magnetic Barkhausen noise

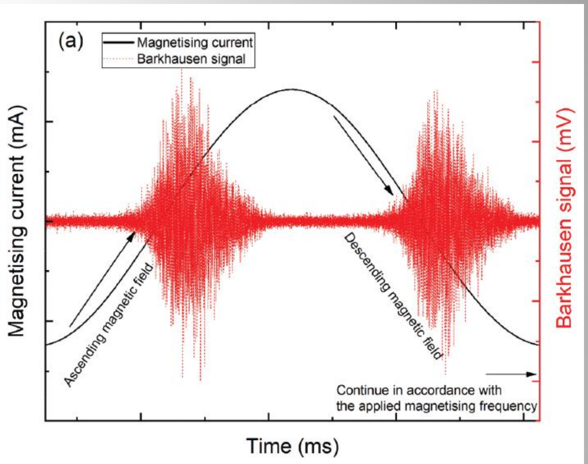
Into the experimental set-up

- present the BN signal generated from the material.

How to measure magnetic Barkhausen noise

Into the measurements parameters

Parameters	Values	Values
Magnetizing frequency	10 Hz	100 Hz
Magnetizing voltage	2 Vpp	1 Vpp
Magnetic offset	0	0
Number of bursts	10	10
Sampling frequency	1 MHz	1 MHz
Signal input scale	5 V	5 V
Magnetizing current input	ON	ON
Magnetizing current input scale	1 A	1 A



In any conductive material, eddy currents arise when the magnetization changes, while the magnetic field induced by them acts against this change.

The greater the magnetization frequency, the more is pronounced their effect and the smaller is the reached depth of the MBN signal in the material.

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \rho \cdot \mu_r \cdot \mu_0}}$$

ρ is conductivity, , μ_r is relative permeability, , μ_0 is permeability of the vacuum.

How to measure magnetic Barkhausen noise

Into the measurements parameters

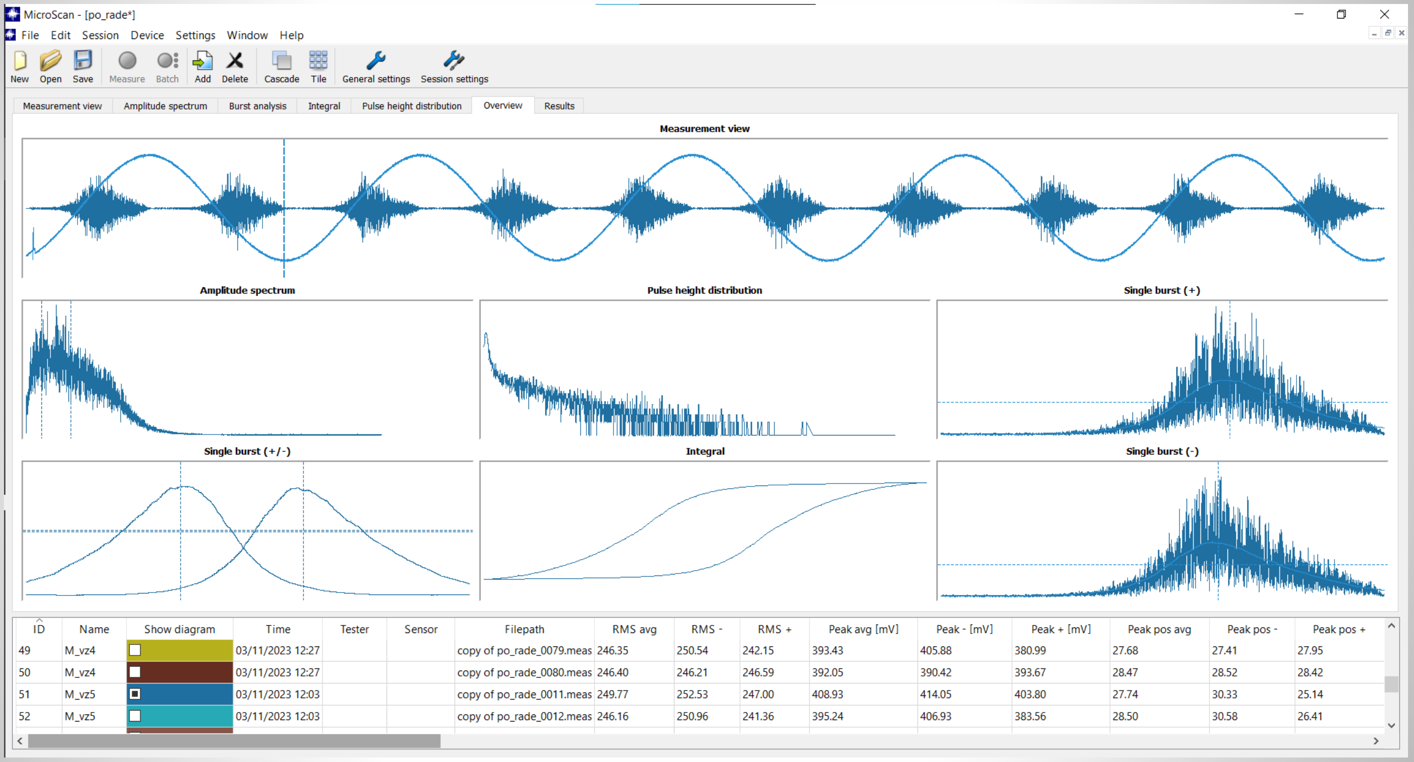
For a low-alloyed hardened and tempered steel component, if we use a magnetizing voltage frequency of 125 Hz, the penetration depth of the applied magnetic field is around 2 mm. For industrial applications, such as grinding burn detection, heat treatment defect detection, analysing frequency range is 70 – 200 kHz. For the same steel component, this range will give an analysing depth around 0,1 mm.

	Material	
	Mild Steel (Annealed)	300M (Hardened and Tempered)
Conductivity	$5*10^6$ Ω·m	10^6 Ω·m (estimated)
Relative Permeability	2000	200
Frequency Range	**Analysing Depth**	
3 – 15 kHz	0.07 mm	0.40 mm
20 – 70 kHz	0.035 mm	0.18 mm
70 – 200 kHz	0.015 mm	0.10 mm

The actual values of analysing depth of measurement may be somewhat (approx. 30%) higher than given in the above table, due to the actual variations in *g(f)*.

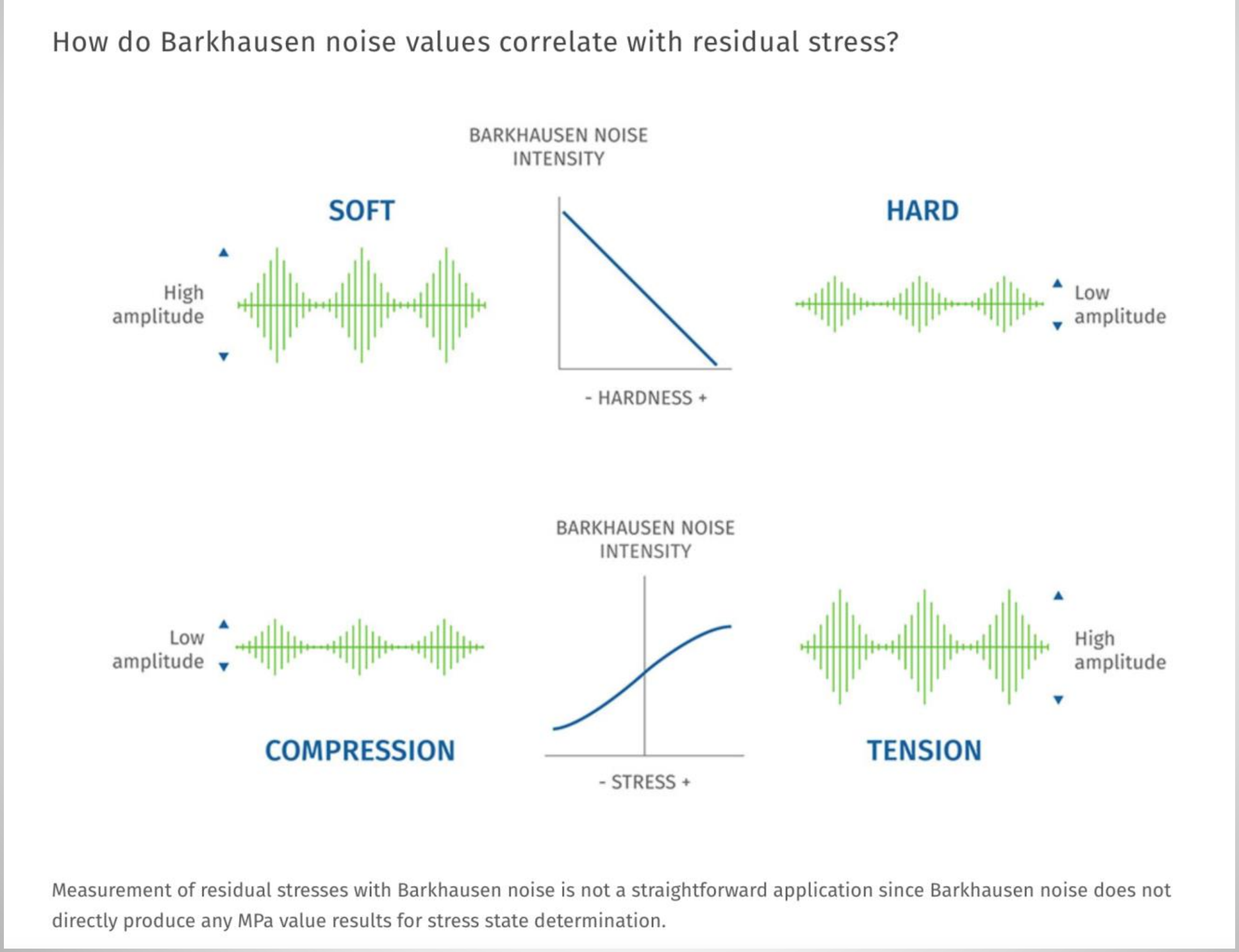
What we measure by magnetic Barkhausen noise

Into the output of the measurements



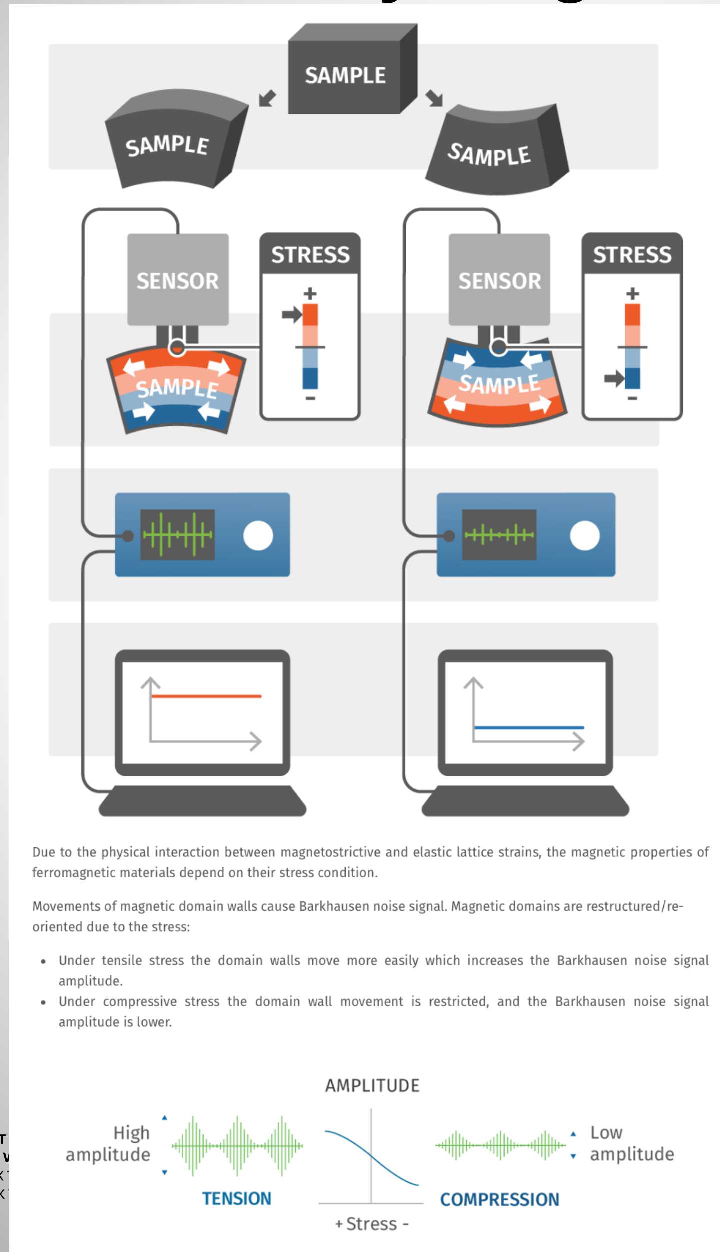
What we measure by magnetic Barkhausen noise

Into the output of the measurements



What we measure by magnetic Barkhausen noise

Correlation with residual stress



Due to the physical interaction between magnetostrictive and elastic lattice strains, the magnetic properties of ferromagnetic materials depend on their stress condition.

Movements of magnetic domain walls cause Barkhausen noise signal. Magnetic domains are restructured/re-oriented due to the stress:

- Under tensile stress the domain walls move more easily which increases the Barkhausen noise signal amplitude.
- Under compressive stress the domain wall movement is restricted, and the Barkhausen noise signal amplitude is lower.

Into the output of the measurements

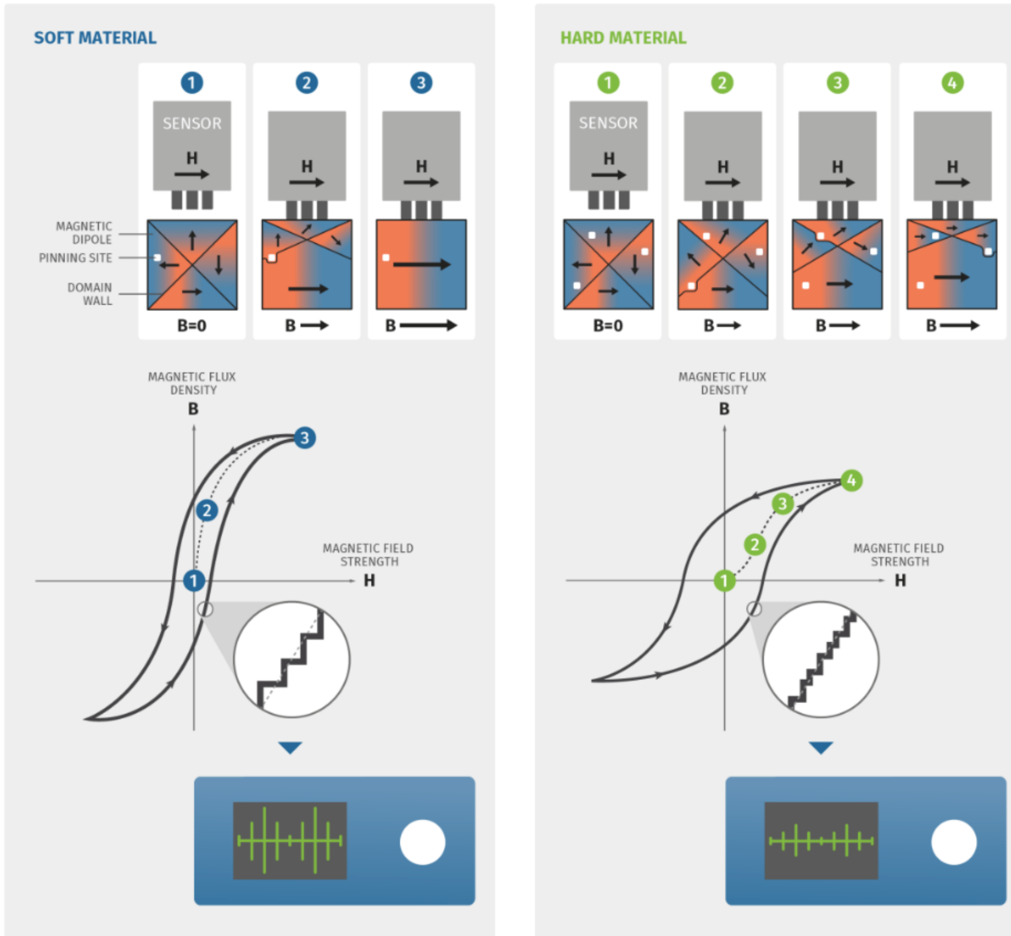
What we ... sen noise

... e measurements

Correlation with hardness

Hardness is related to the number of pinning sites (dislocations, precipitations, or other irregularities) in a material. When a magnetic field is applied to a ferromagnetic material, magnetic domain walls start to move. Domain walls collide with pinning sites in the material structure which impedes the domain wall movement.

In soft materials magnetic domain walls move more easily than in hard materials. This is because in hard materials there are lots of pinning sites and therefore domain wall movements are more restricted. In soft materials domain walls can make bigger jumps.

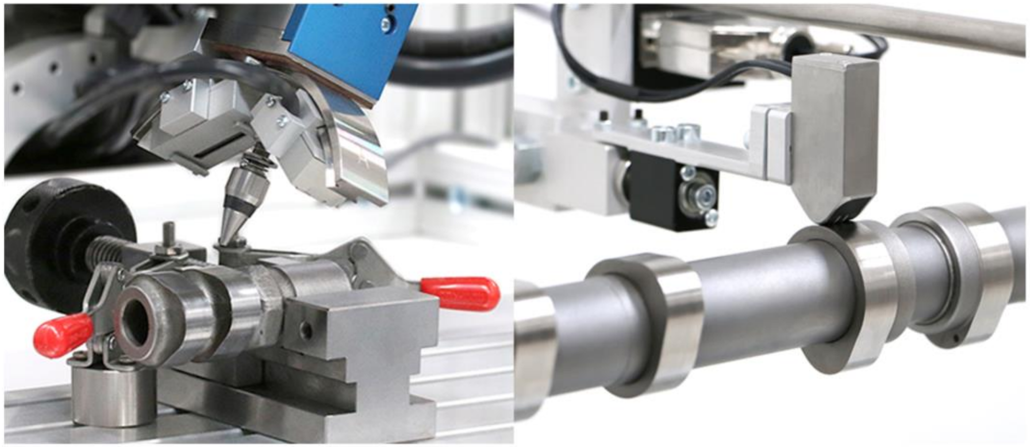


Barkhausen noise signal is caused by the jumps of the domain walls between the pinning sites. In practice, the softer the material, the higher the Barkhausen noise signal amplitude due to the less restricted movement of domain walls, and vice versa for the hard materials.

High hardness leads to low Barkhausen noise activity and low hardness to high Barkhausen noise activity. Barkhausen noise analysis can be easily used to separate soft and hard parts in heat treatment applications, and for detecting grinding burns.

What we measure by magnetic Barkhausen noise

Correlation with X-ray diffraction

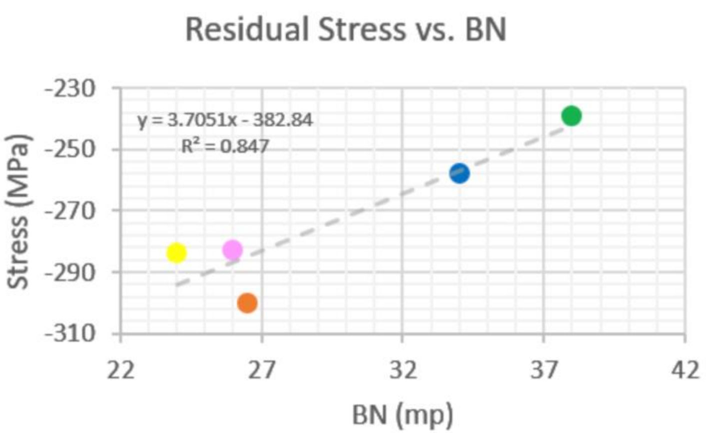


Residual stress measurement on camshaft with X-ray diffraction and Barkhausen noise methods

Barkhausen Noise (BN) testing was implemented, as it is non-destructive and is able to look beyond the surface of the ground lobes.

In order to correlate the two methods, select spots on the lobe were chosen and the BN results and X-Ray diffraction stress depth profiles were compared.

The favorable correlation enables the BN testing to be used at a much more frequent interval to supplement the XRD testing, all while not having to destroy any of the camshafts.



A Correlation Between Barkhausen Noise and X-Ray Diffraction.

What we measure by magnetic Barkhausen noise

Into the output of the measurements

What we look for to compare:

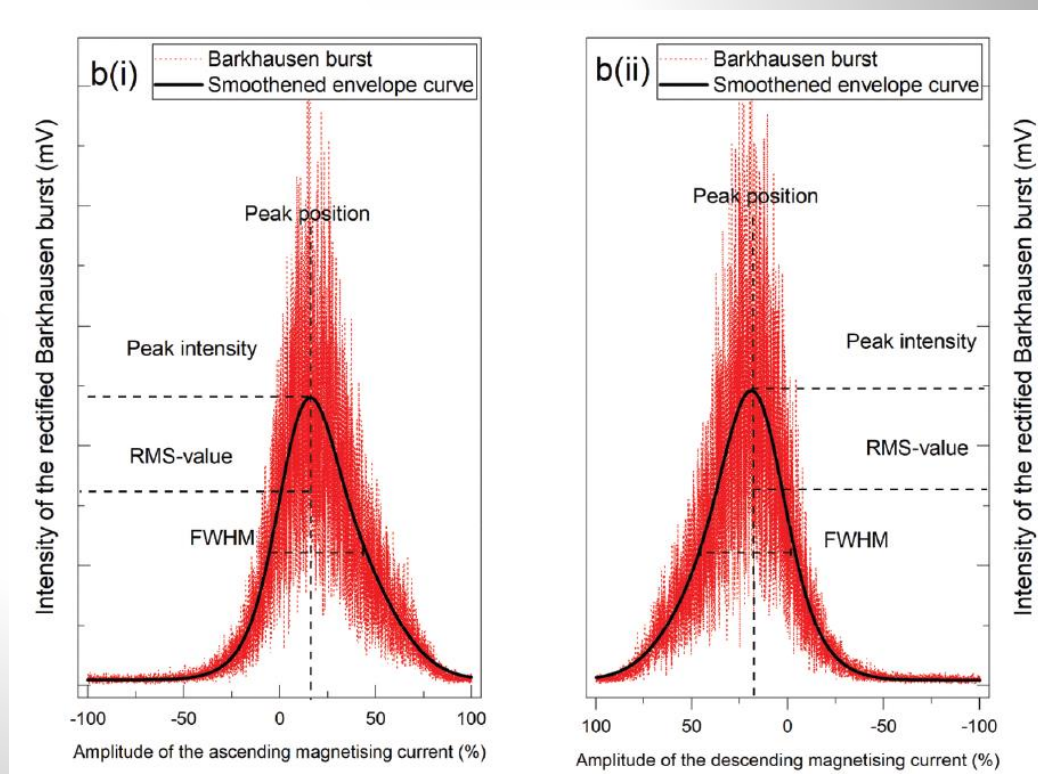
- RMS values

$$RMS = \sqrt{\frac{1}{n}\sum_{i=0}^{n-1} x_i^2}$$

x_i is the amplitude of the signal and n is their number.

- Shape of the envellop

Because we need to compare **reference vs treated material**



How to measure magnetic Barkhausen noise

How to deteriorated our measurement

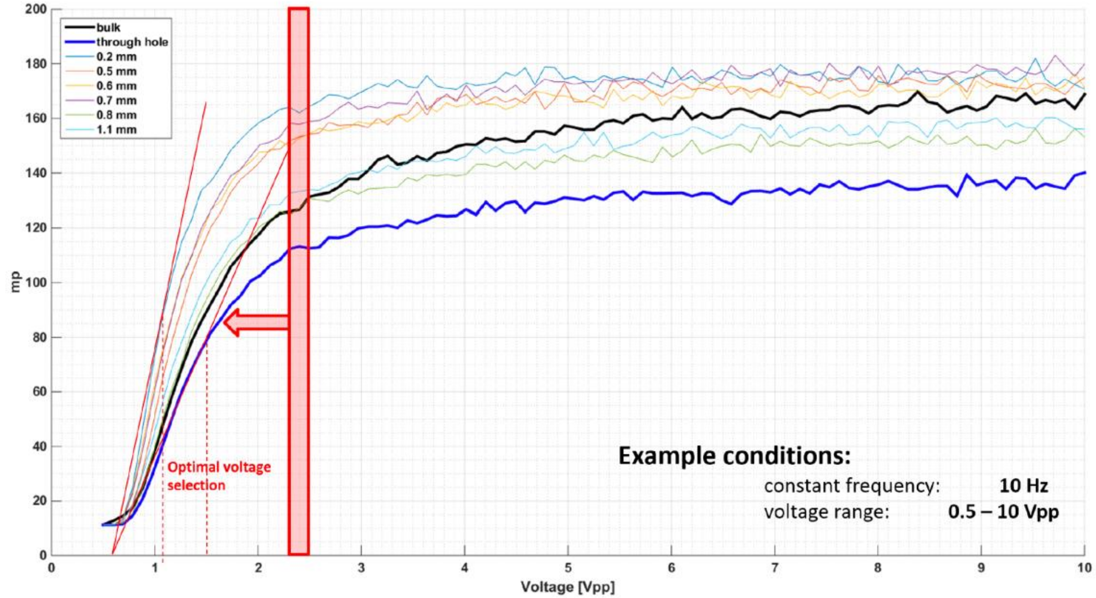
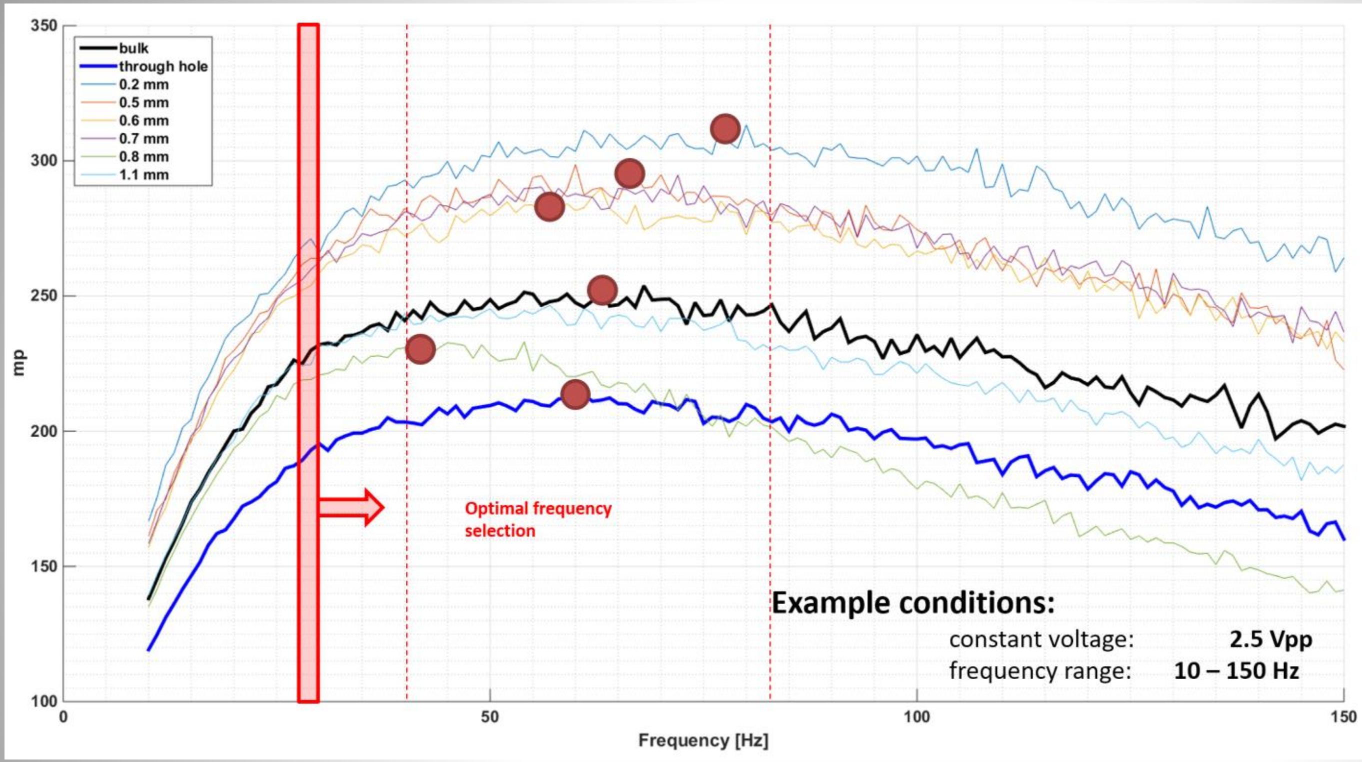


Fig. 2.21: Determination of the optimum measurement voltage by using the voltage sweep curve.

The maximum angle between the tangent line (maximum slope) and voltage sweep curve designates this point of tangency, which, after projection on the ordinate axis, indicates the optimal measurement voltage.

How to measure magnetic Barkhausen noise

How to deteriorated our measurement



The projection of the maximum frequency value point from the frequency sweep curve on the ordinate axis indicates optimal measurement frequency

How to measure magnetic Barkhausen noise

How to deteriorated our measurement

Scanning speed

is the concern of accuracy and is limited to the sampling rate. A higher scanning speed signifies a smaller number of registered points. Optimal scanning speed is determined experimentally. The maximum scanning speed must be below 80 mm/s.

Sensor load

is important for maintaining stable contact between the sensor and measured object. This is especially important for a combination of low frequency and high voltage parameter measurements, in which the excitation of the magnetic field causes sensor vibration, and additionally, loss measurement contact. The standard sensor load is between 10−50N.

Surface preparation

Areas to be tested should be free from dirt, scale, loose rust, weld spatter, grease, oil and any other foreign materials that can affect the test sensitivity. The surface condition greatly influences the measured signal, both in terms of topography as well as material characteristic of the surface such as microstructure and residual stress determined by the heat treatment.

How to measure magnetic Barkhausen noise

How to deteriorated our measurement

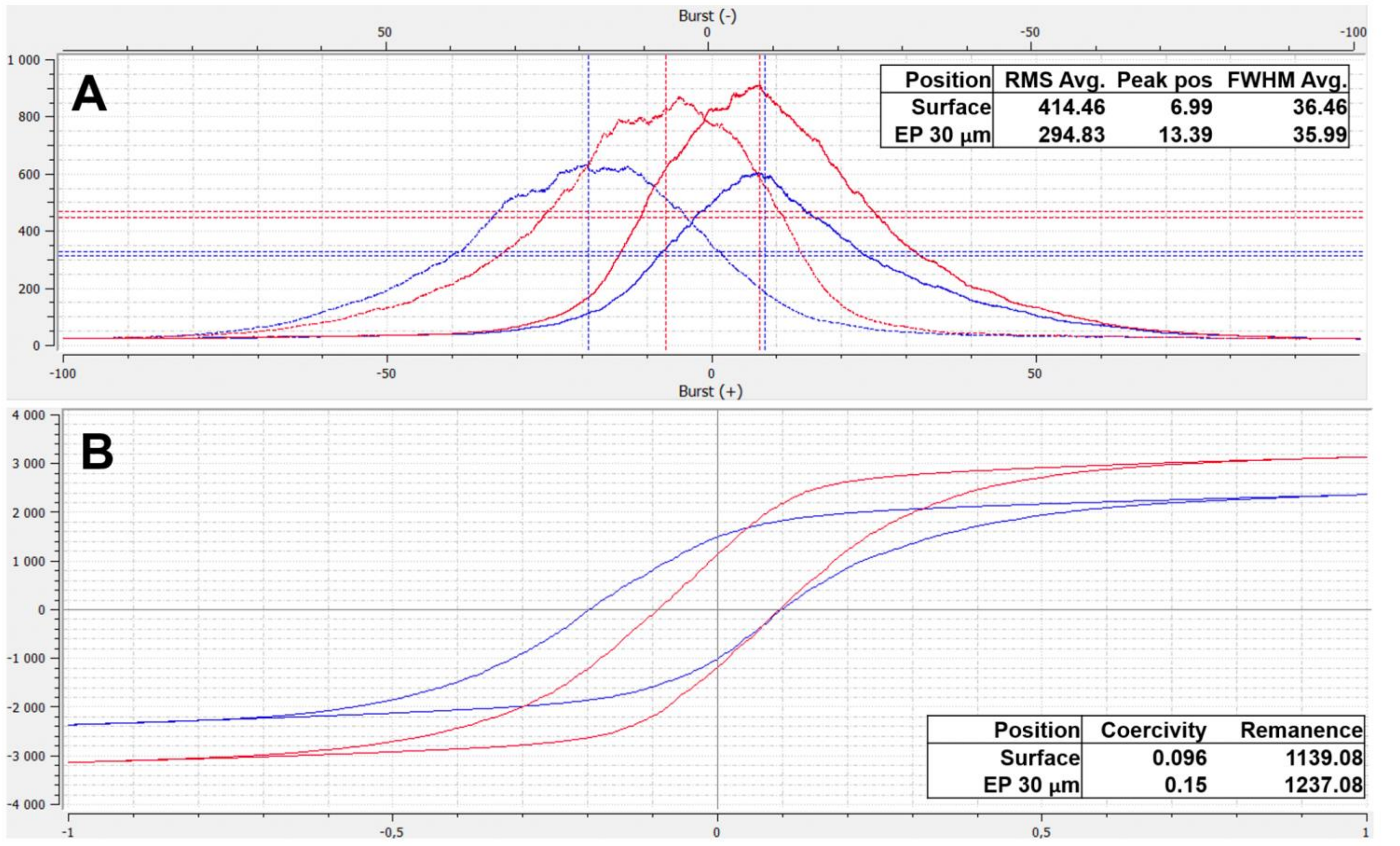
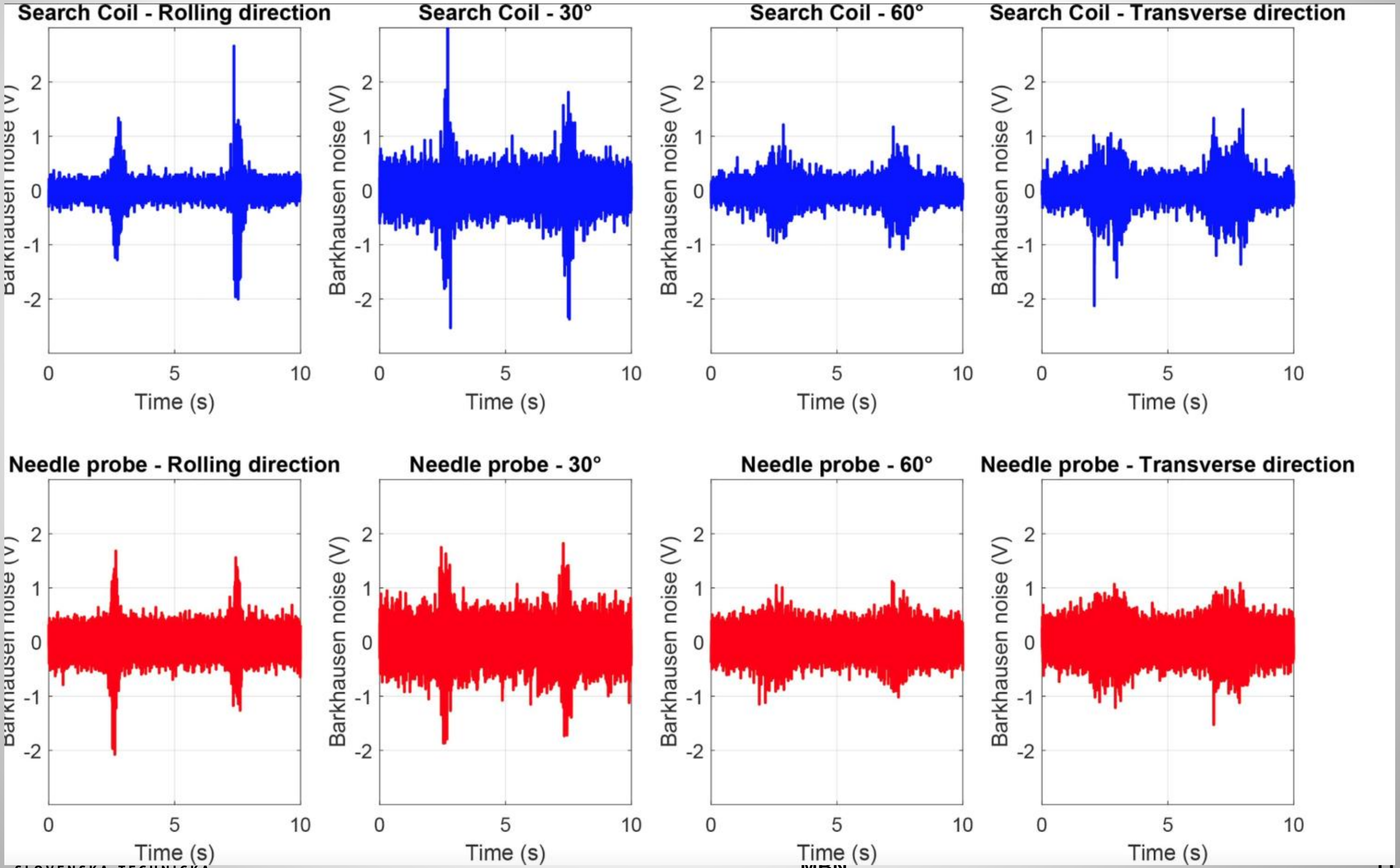


Fig. 2.23: Barkhausen noise signal from an induction hardened steel samples before (red line) and after 30μm electro polishing (blue line) where A: burst analysis, B: integral analysis.

How to measure magnetic Barkhausen noise

How to deteriorated our measurement

Sensor load vs sample size



How to measure magnetic Barkhausen noise

How to deteriorated our measurement

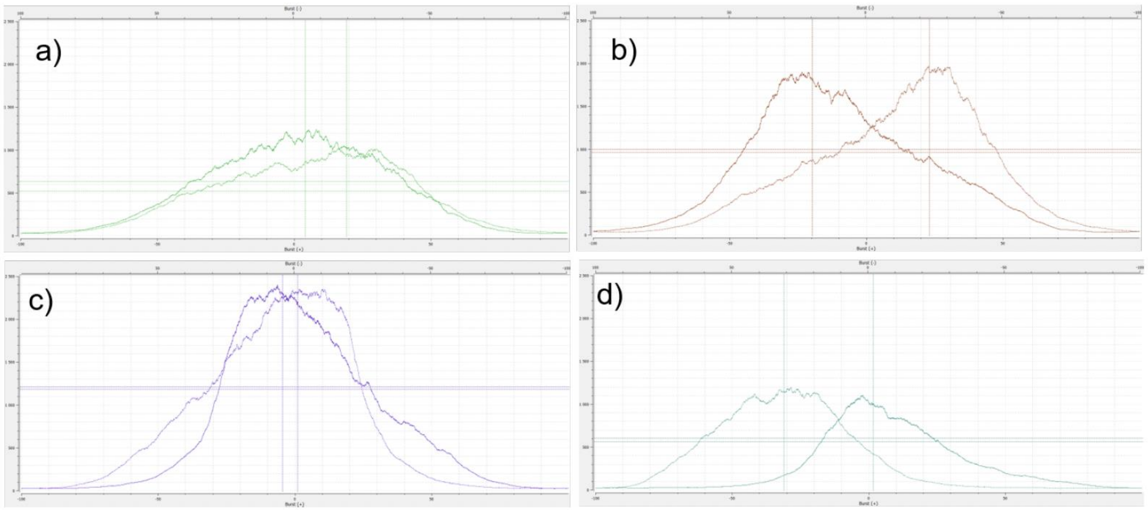


Fig. 2.24: Barkhausen noise signal from different microstructures produced for the same kind of steel but quenched differently: a) as received, b) slow air quenched, c) salt bath quenched, d) water quenched.

Table 2.1: Barkhausen noise signal parameters for different microstuctures (Fig. 2.24).

Sample	RMS avg	dev	Peak avg	dev	Peak pos	dev	FWHM avg	dev
OKV2 EP	617.6	18.2	1105.8	56.2	16.6	2.3	46.9	3.0
OKS2 EP	1346.2	9.5	2342.4	55.6	-3.6	0.7	55.6	2.3
OKL2 EP	1122.6	13.2	1836.0	9.1	-22.2	0.8	58.1	1.1
Ref. EP	748.7	6.9	1073.6	25.4	-7.9	0.1	77.9	2.3

Sensitivity settings

Sensitivity is an absolute quantity, the smallest absolute amount of change that can be detected by a measurement. Possible interference between variables and factors influence the test signal that can be measured:

How to measure magnetic Barkhausen noise

How to deteriorated our measurement

External interference variable

Electromagnetic field: One possible source of faults is strong local electromagnetic fields, for example, those from a PC monitor or transformer. In these cases, care must be taken by maintaining an appropriate distance between the sensor and interference source to ensure that the test signal is not affected.

Grounding: An interference source may be created in the vicinity of strong electromagnetic fields (e.g., the controller of a machine tool).

Residual magnetism: Excessive residual magnetism will prevent the correct formation of Barkhausen pulses with the result that the displayed test signal will be extremely low.

Dirt on the test workpiece: Dirt or other particles will prevent the correct and repeatable creation of contact between the sensor and test workpiece.

Dirt on the sensor: A repeat check of the aerial signal during the test should produce the same signal value.

How to measure magnetic Barkhausen noise

How to deteriorated our measurement

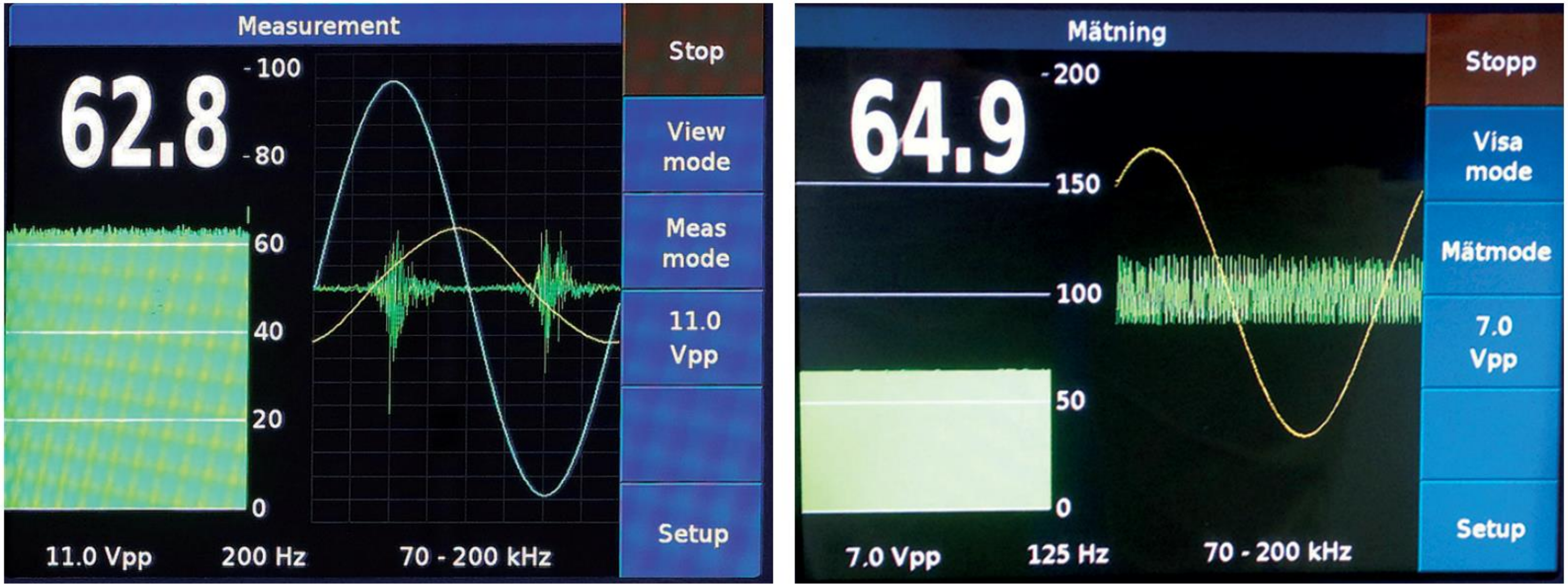


Fig. 2.25: Example screen from oscilloscope for (a) good (correct) Barkhausen signal and (b) bad (incorrect) Barkhausen signal.

Case Study

- “RPV (reactor pressure vessel) **Model Steels**” - represented by **12 ferritic steels** with the parametric variation of alloying elements.
- The aim - understanding the role and influence of selected alloying elements as **Si, Mn and Ni** and their possible **synergistic effect** on the behaviour of RPV steels during the operation of NPP.
- The set of RPV Model Steels was subsequently irradiated in the High Flux Reactor -LYRA irradiation facility (Petten, the Netherlands) in a joint NRG-JRC irradiation experiment to the nominal fast neutron fluence (E>1 MeV) of **1.11×10^{20} n.cm^{-2}.**
- The focus - **magnetic Barkhausen noise (MBN) characterization** and possible correlation with data from **other experimental techniques**.

Materials – RPV model steels

Twelve reactor pressure vessel (RPV) model steels with parametric variation of alloying elements Ni, Si and Mn

Model Steel	C	Si	Mn	Cr	Ni	Mo	V	Cu	S	P
MS - A	0.11	0.28	0.43	2.22	0.02	0.71	0.1	0.09	0.008	0.01
MS - B	0.11	0.26	0.38	2.19	0.99	0.7	0.1	0.1	0.008	0.01
MS - C	0.12	0.24	0.38	2.13	2	0.69	0.1	0.1	0.008	0.01
MS - D	0.11	0.23	0.83	2.13	2	0.68	0.1	0.09	0.008	0.009
MS - E	0.12	0.33	0.77	2.16	1.02	0.7	0.1	0.1	0.008	0.009
MS - F	0.12	0.33	1.37	2.15	1.02	0.7	0.1	0.1	0.008	0.01
MS - G	0.11	0.32	1.36	2.06	1.99	0.69	0.1	0.1	0.008	0.009
MS - H	0.12	0.51	1.31	2.07	2	0.69	0.1	0.1	0.008	0.01
MS - K	0.17	0.35	0.78	0.1	0.58	0.64	-	0.07	0.005	0.009
MS - L	0.18	0.35	0.77	0.08	0.96	0.63	-	0.05	0.005	0.01
MS - M	0.16	0.37	0.74	0.09	1.9	0.61	-	0.05	0.005	0.01
MS - N	0.16	0.33	1.27	0.07	1.97	0.63	-	0.06	0.005	0.01

(WWERs)

(PWRs)

Case study

Different alloying elements each have their effect on the properties of steel:

Manganese increases strength at high temperatures by eliminating the formation of iron sulfides, and it also improves hardenability, ductility and wear resistance;

Nickel increases strength, impact strength and toughness, while also improving resistance to oxidization and corrosion; silicon improves strength, elasticity, acid resistance and results in larger grain sizes, thereby, leading to more excellent magnetic permeability.

Silicon is used as a deoxidizing agent in the production of steel, it is almost always found in some percentage of all grades of steel.

Irradiation experiment

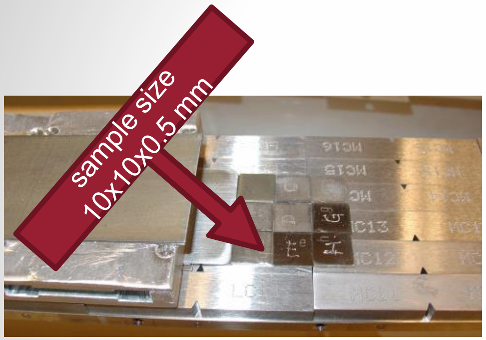
The irradiation experiment at the HFR reactor Petten (Netherlands) ran for 16 cycles (~467 full power days at a nominal reactor power level of 45 MW) to achieve a nominal fast neutron fluence (E>1 MeV) of

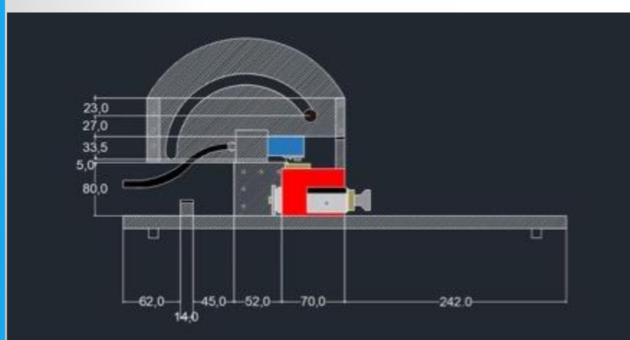
1.11×10^{20} n.cm^{-2} at an average temperature of **286 °C**.

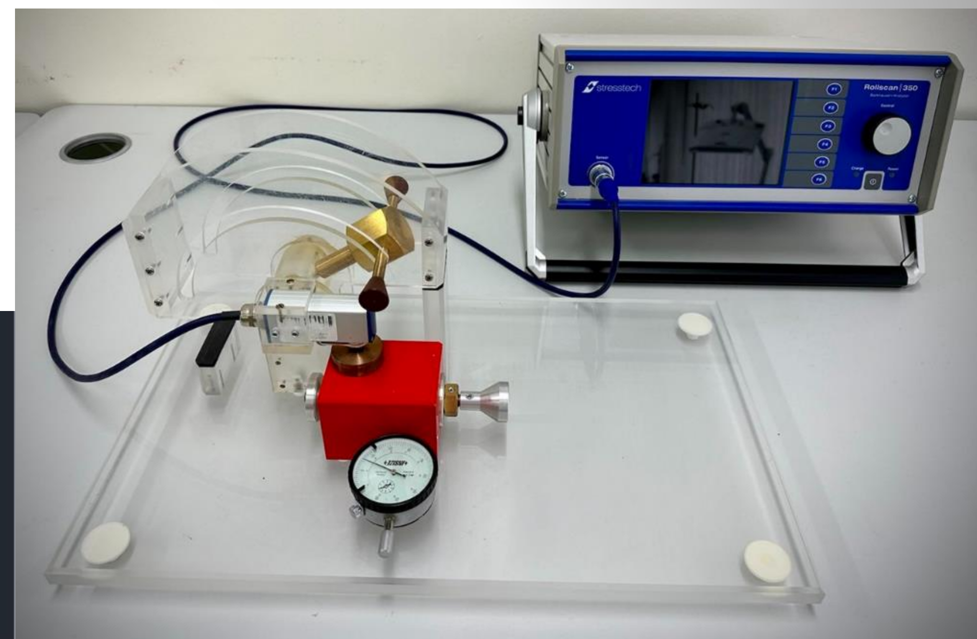
The received fluence corresponds to ~**89 effective full power years** of a PWR reactor operation and to displacement damage **~0.18 dpa**.

MBN characterization

A typical pair of WWER-1000 model steel samples







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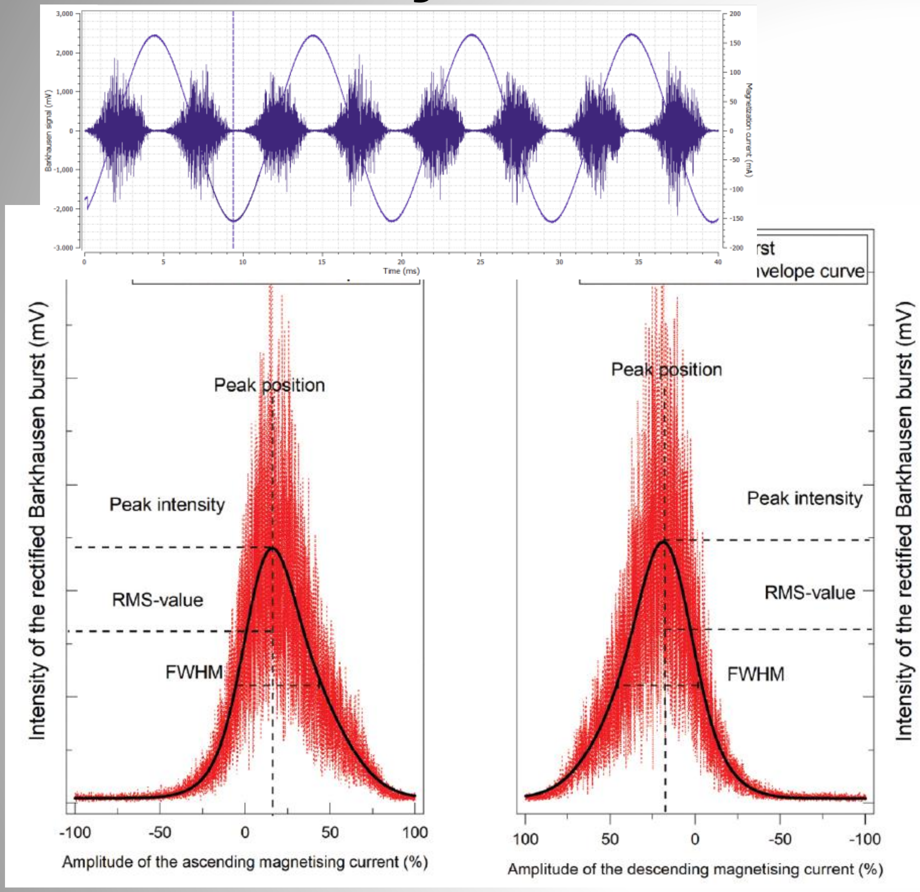
FAKULTA ELEKTROTECHNIKY
A INFORMATIKY

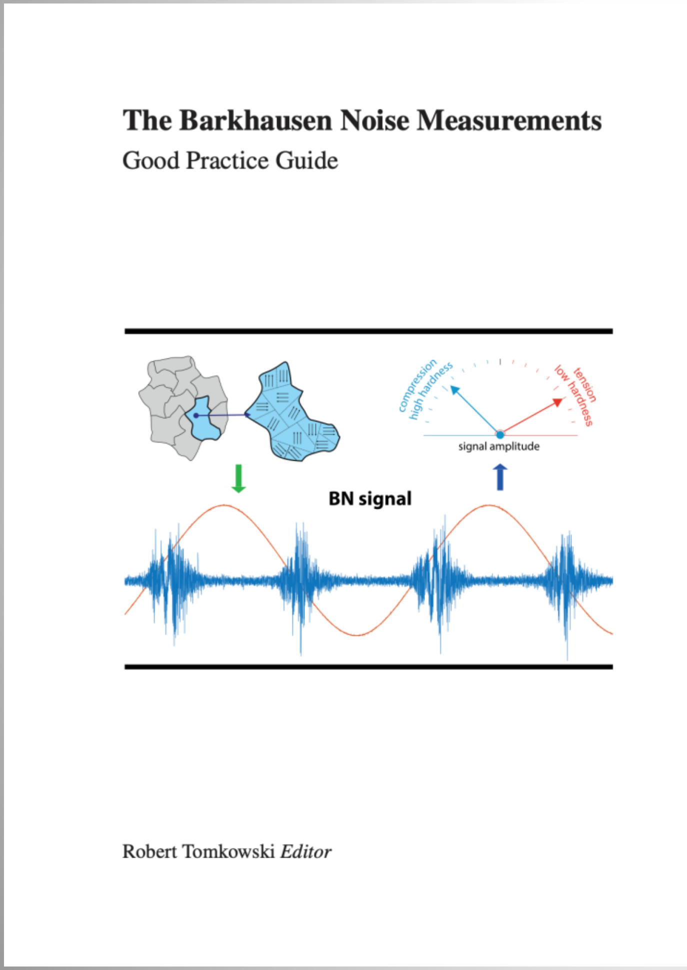
Case study



- The RMS values are taken as an average from 5 measurements.
- The Peak avg. is the maximum value of the smoothed envelope.
- The envelope is the curve connecting the maximum (minimum) values of the output signal MBN in one burst of pulses.
- If the top 15 % of the smoothed envelope is fitted using a parabola. The position of the maximum of this parabola gives the Peak Position value.
- The FWHM corresponds to the value of the full width at half maximum of the smoothed envelope of the Barkhausen signal.
- During measurements, these parameters are given as average values (avg), which means the average value between the value of the given parameter in the positive (+) and negative (-) directions of the spectrum axis

Thank you…

References



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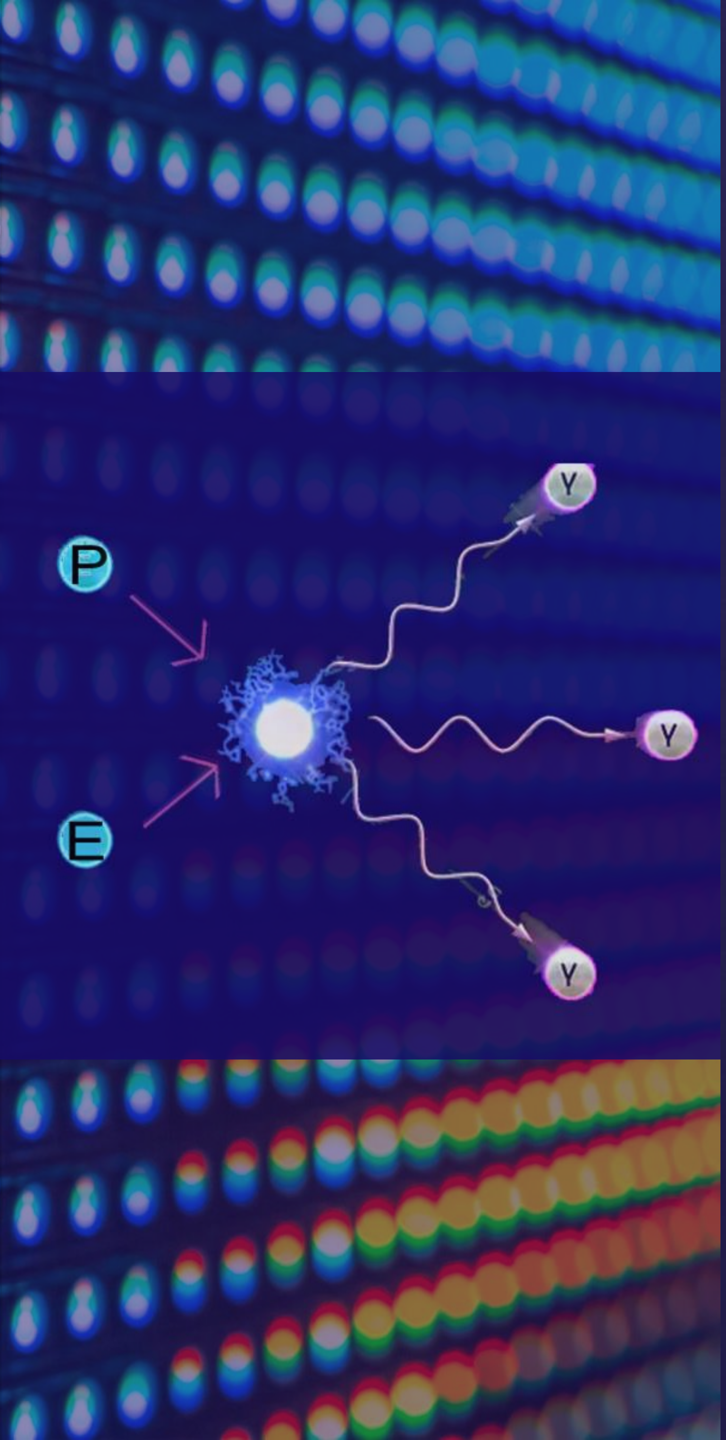
https://kte.website.tuke.sk/slovak/subjects/ZIM/Kapitola%2013%20-%20Magneticke%20materialy.pdf

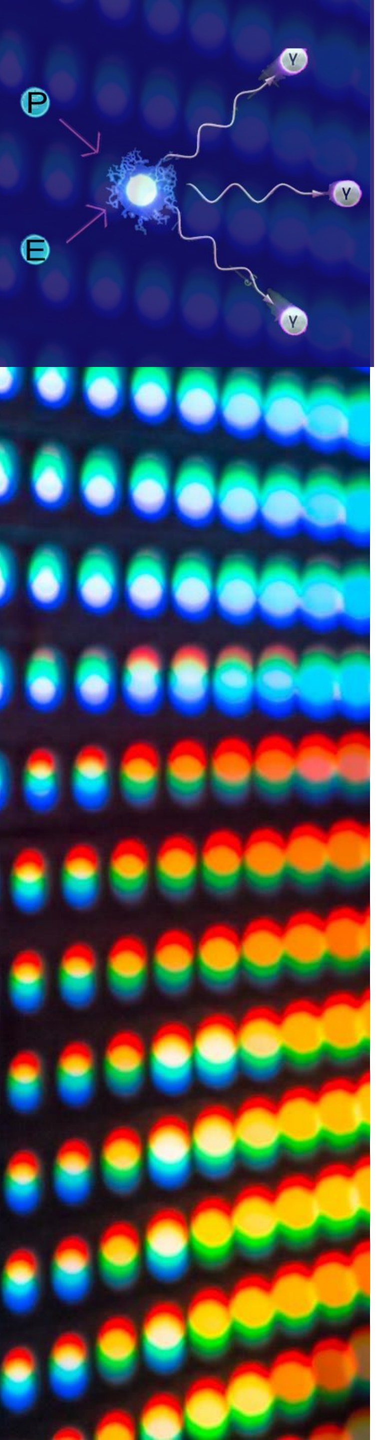
https://www.stresstech.com



Positron annihilation lifetime spectroscopy and spectrum fitting

Jana Simeg Veternikova
INPE FEI STUBA

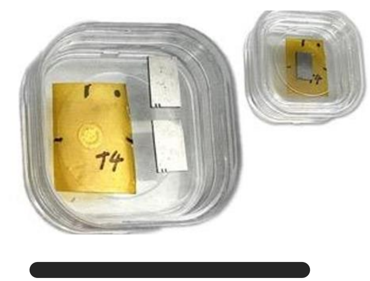
November 2024



Positron annihilation lifetime spectroscopy (PALS)

Advantages:

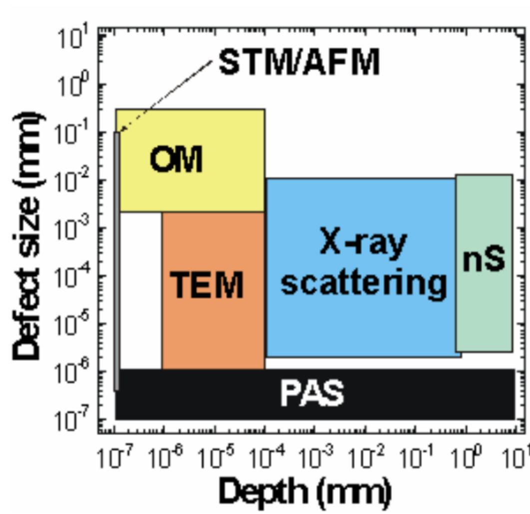
- Non-destructive techniques
- Sub-sized samples
- The most sensitive for vacancy defects
- Sensitive to thermal, radiation, mechanical, corrosion stress and material ageing

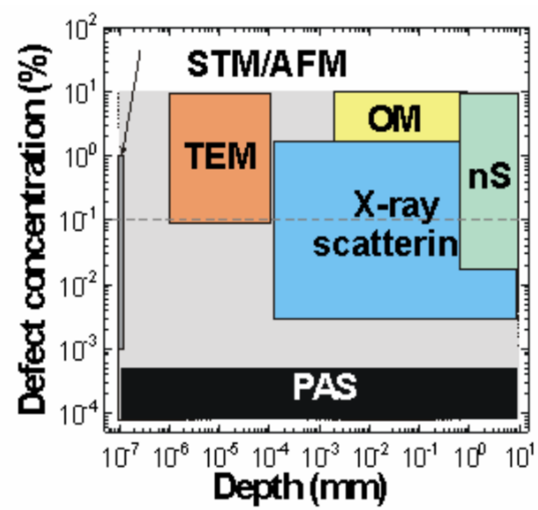


5 cm

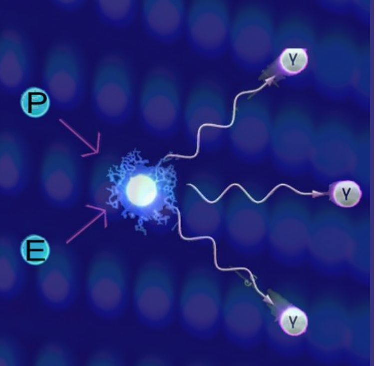
Disadvantages:

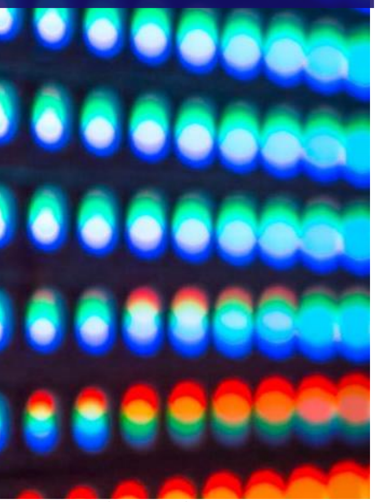
- Need comparative states or methods
- Require Mirror-like polished samples
- Laboratory methods

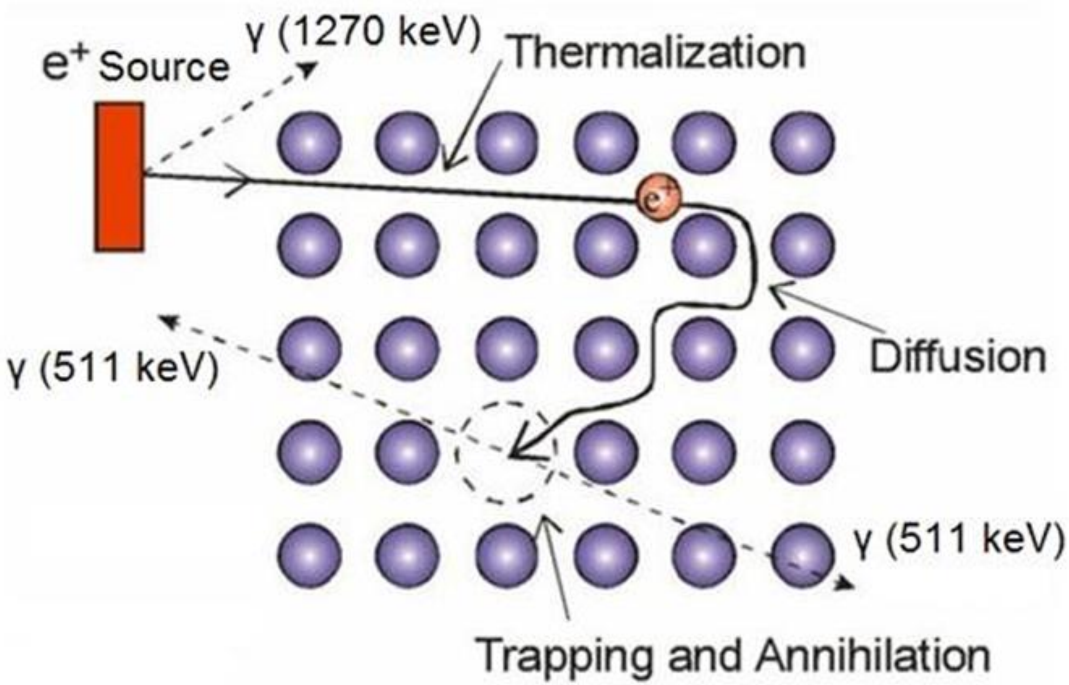


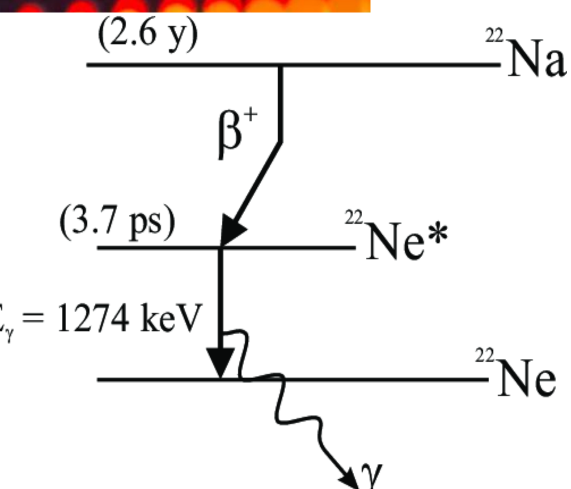


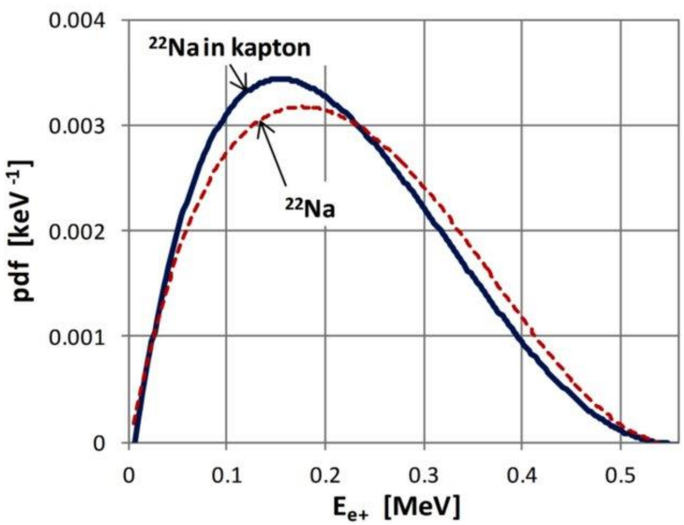
PALS principle

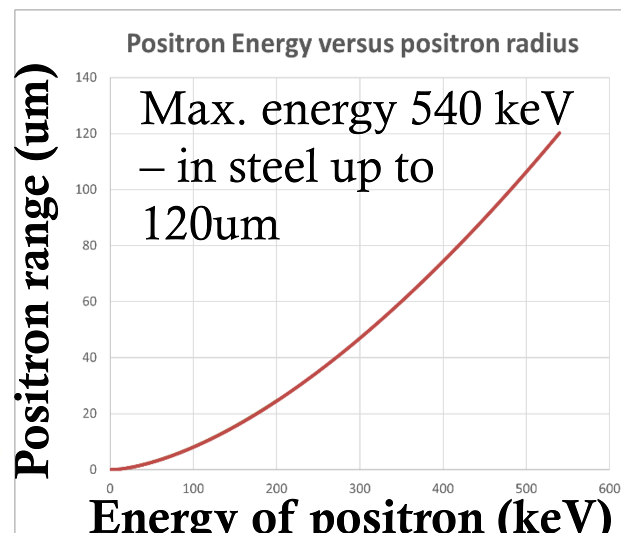


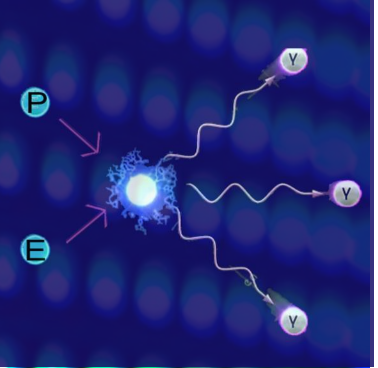


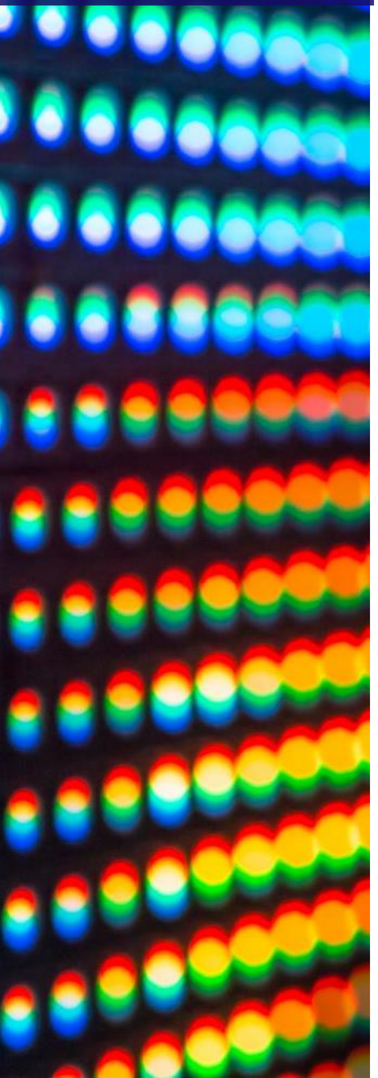




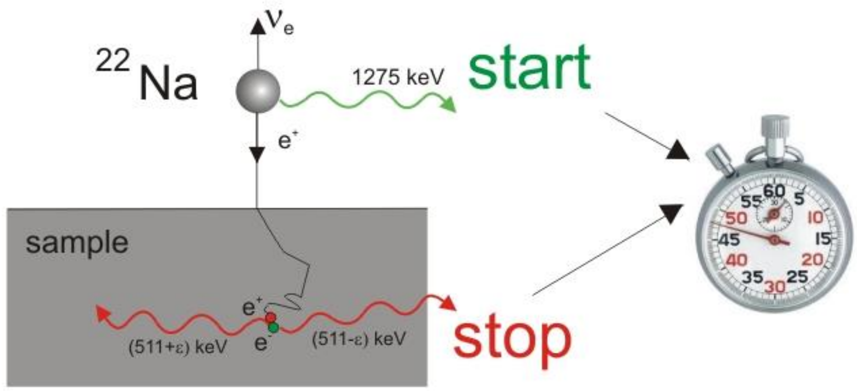


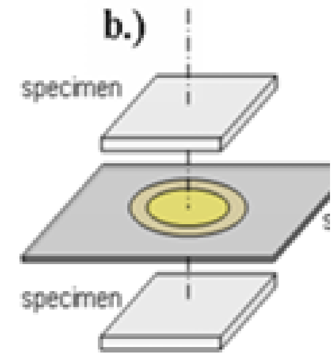


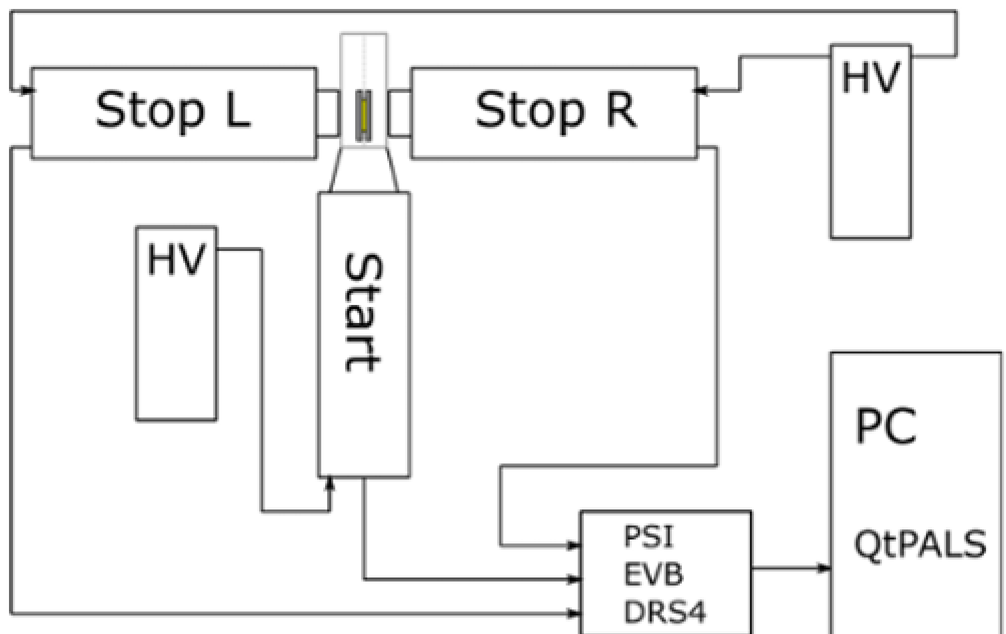


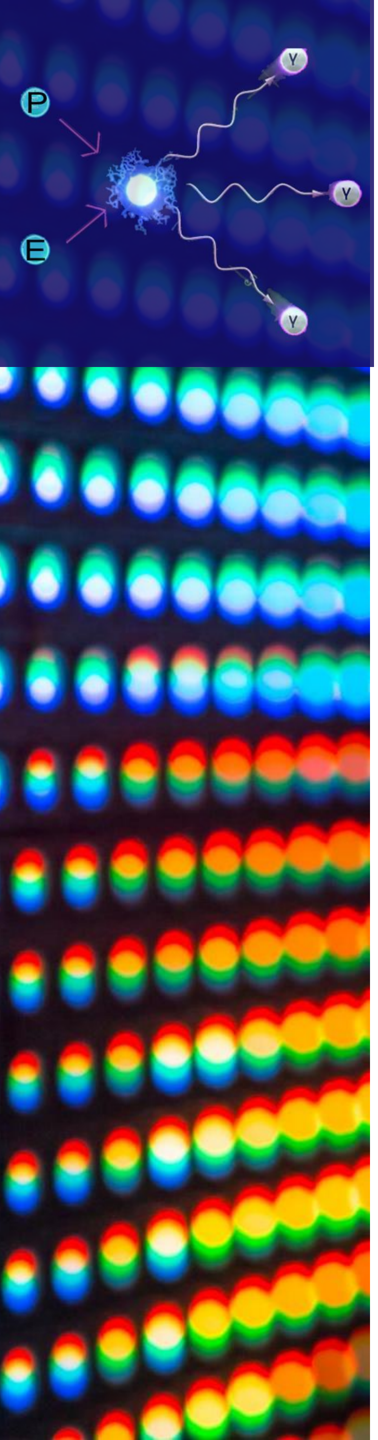


PALS measurement apparatuses

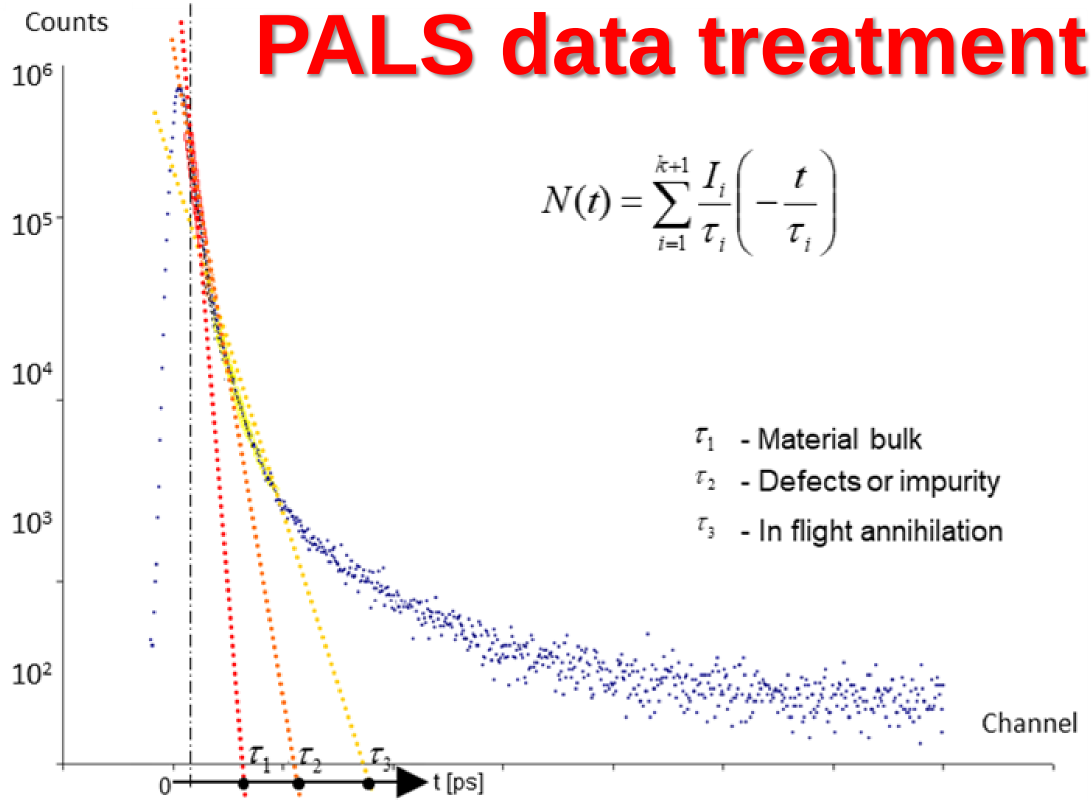




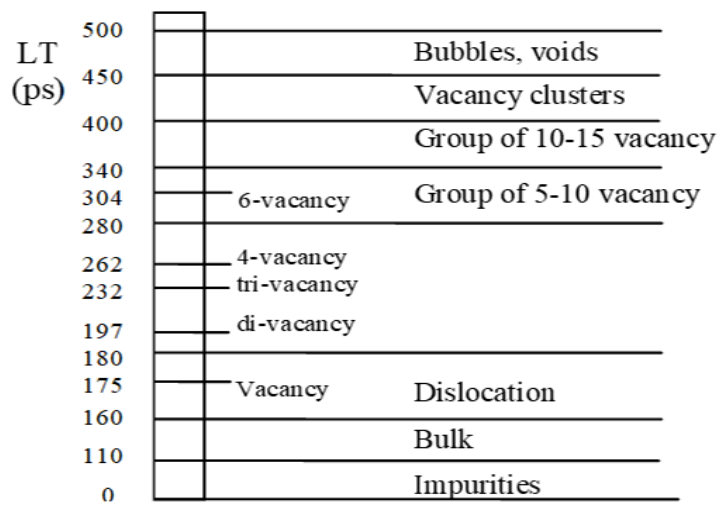


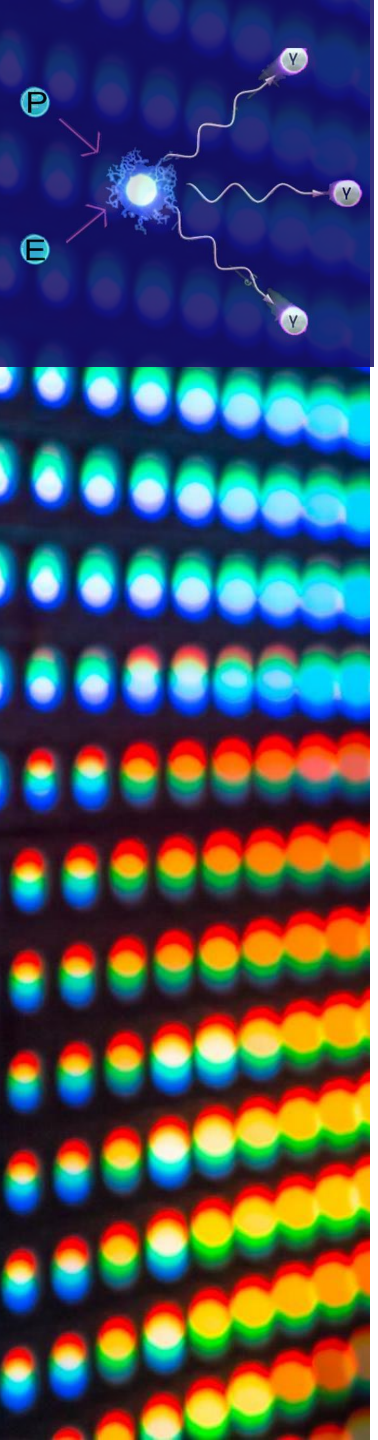


PALS data treatment

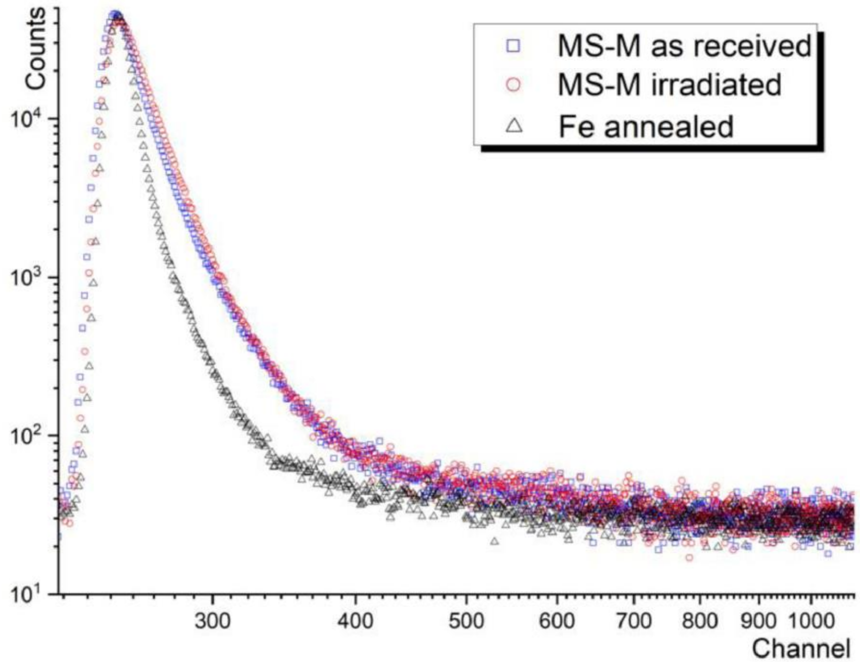


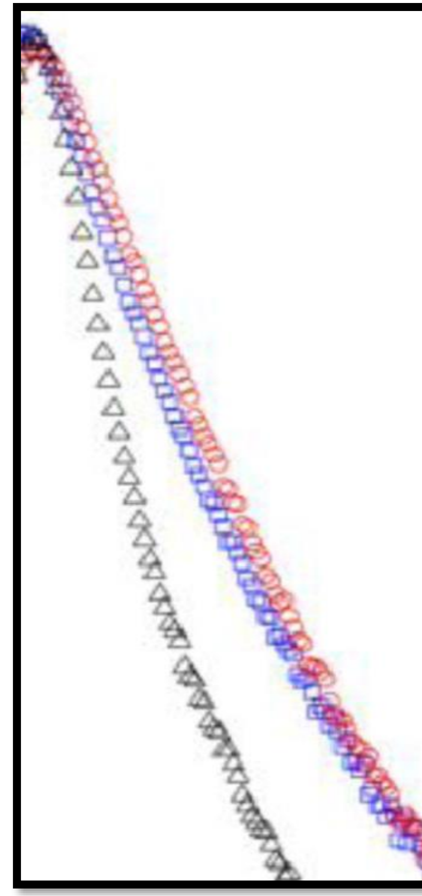
$$N(t)=\sum_{i=1}^{k+1}\frac{I_i}{\tau_i}\left(-\frac{t}{\tau_i}\right)$$

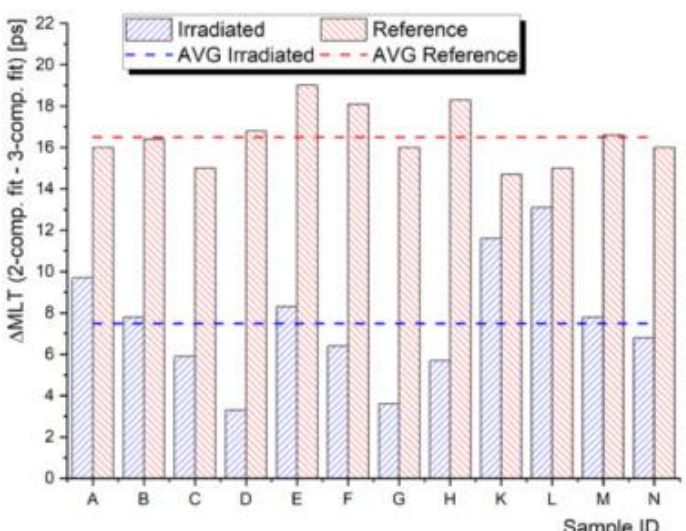


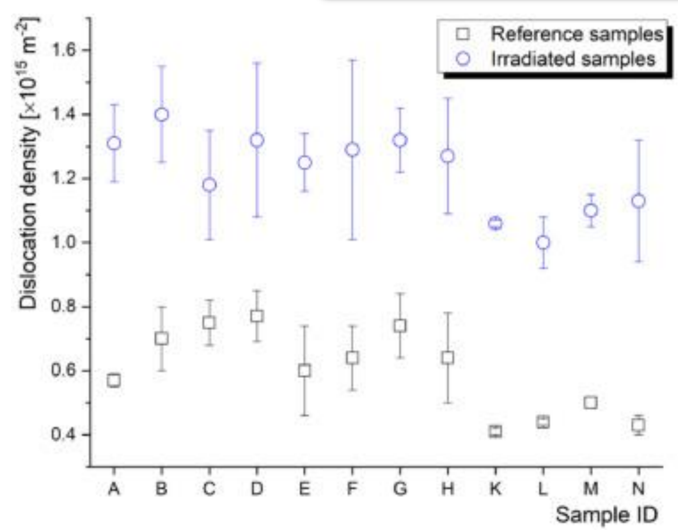


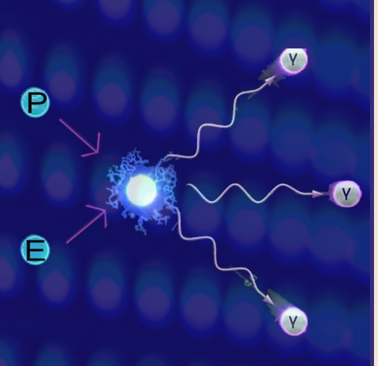
PALS measurement of radiation damage

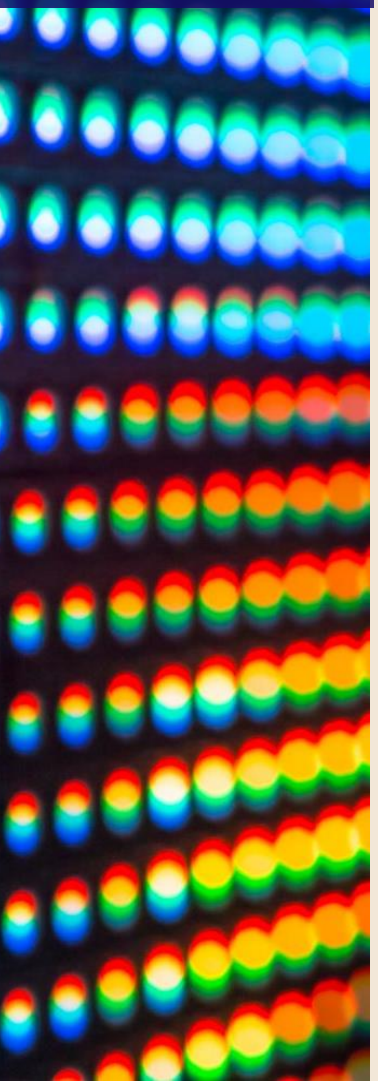












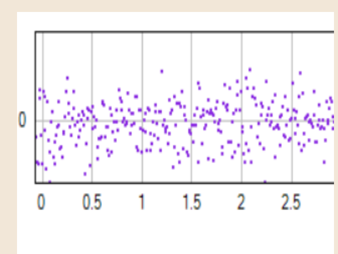
Fitting process

1. Loading Data:
2. Defining the Model
3. Selecting Regions
4. Setting Parameters
5. Performing the Fit
6. Evaluating Fit Quality

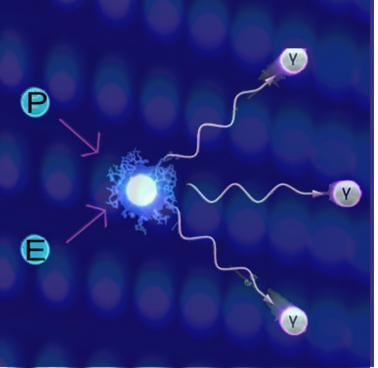
Again, the whole process

Not good fit

- FV=(0.9;1.5)
- LT -0.220 ns approx.80%
- LT2-0.384 ns approx. 20%

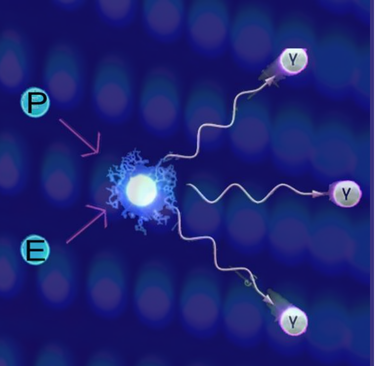


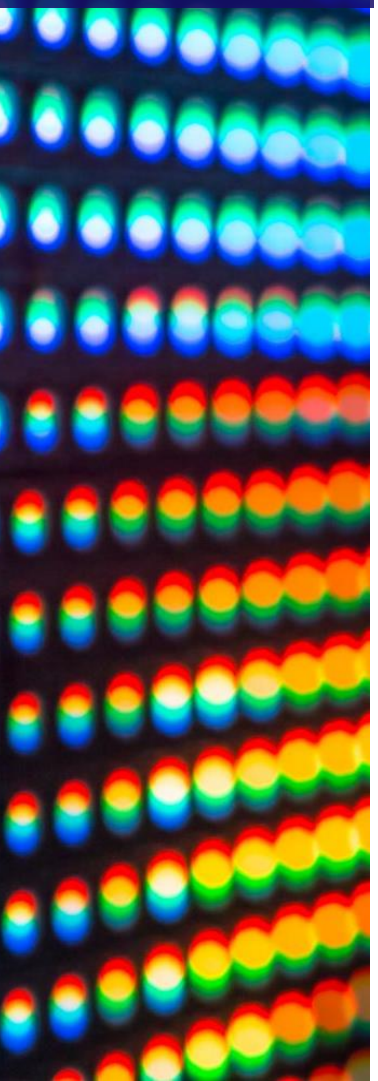
Ok



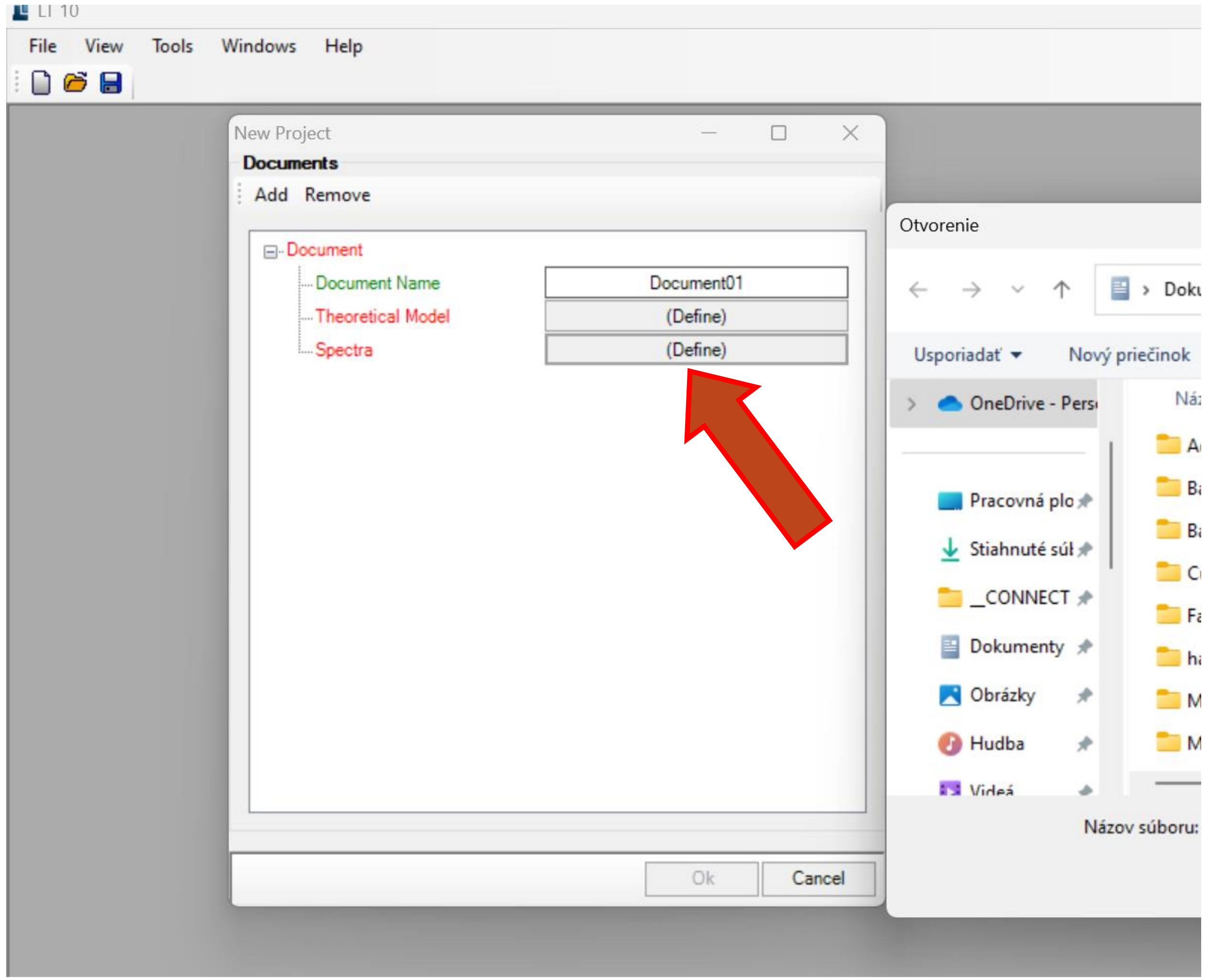
LT10 for Windows (autor J. Kansy)

Save the data in LT10 always before running the fit process !!!



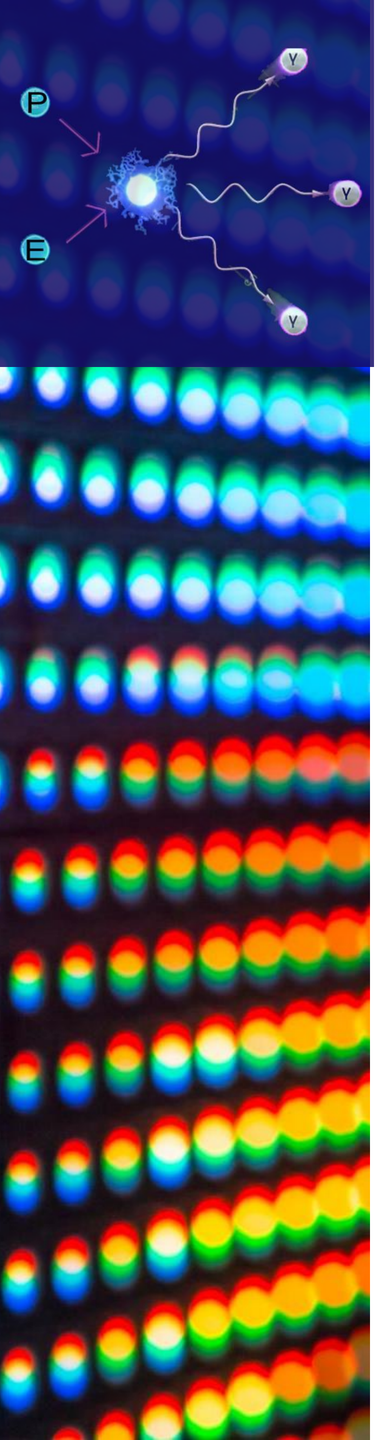


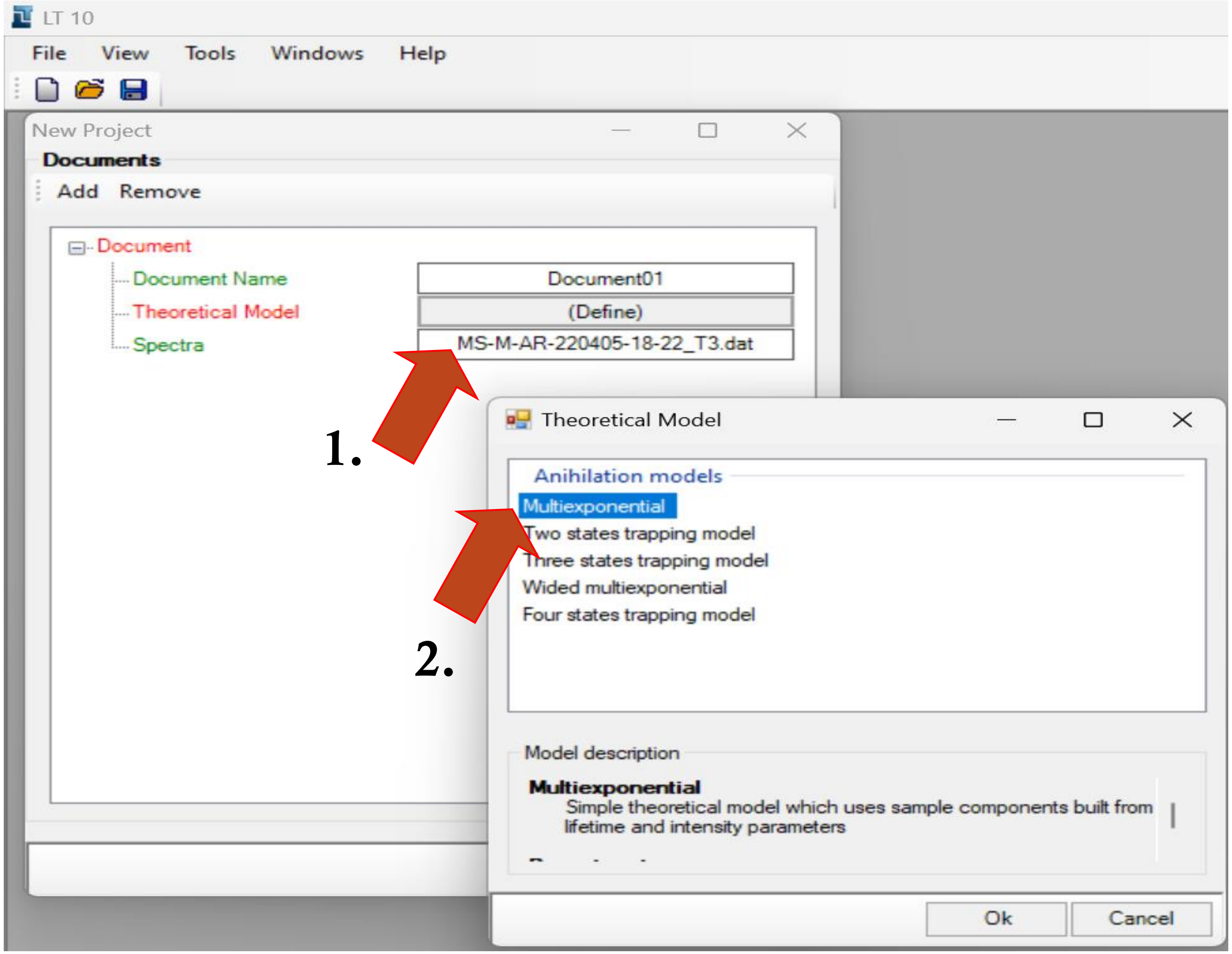
1.Loading Data:



Find and open the spectra (/DESKTOP/ENEN PAS/ *.dat) .

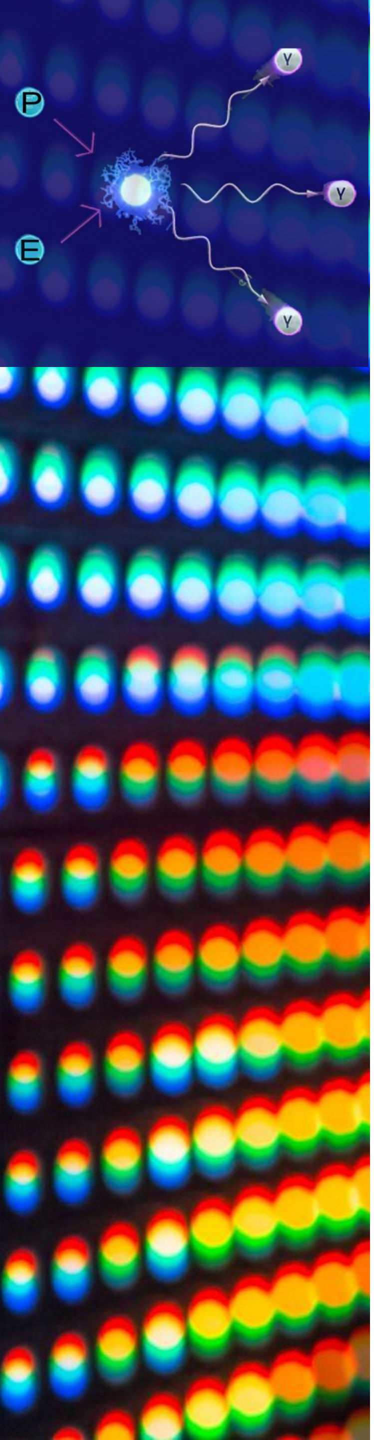
2. Defining the Model:



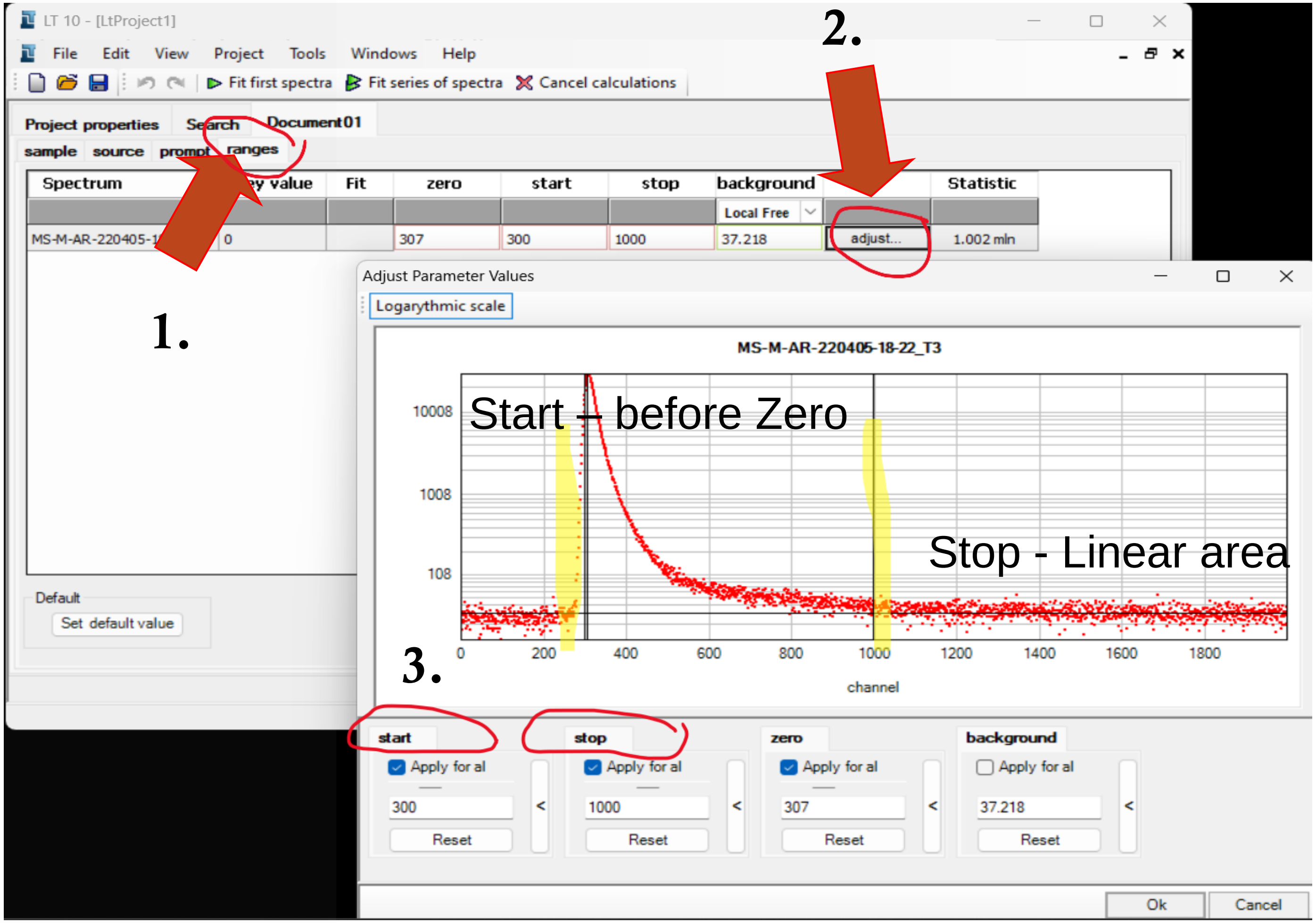


Multiexponential model – for 3 LT components –

Standard trapping model

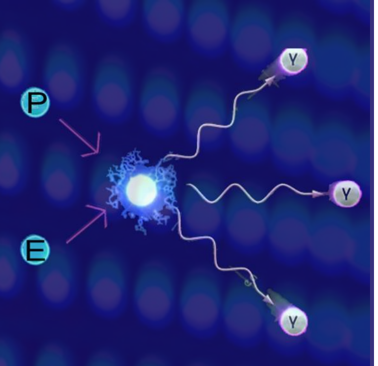


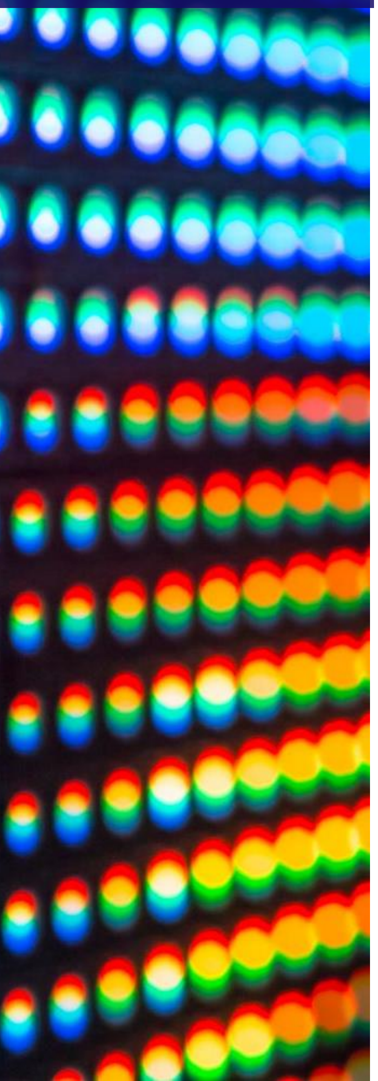
3. Selecting Regions of Interest:



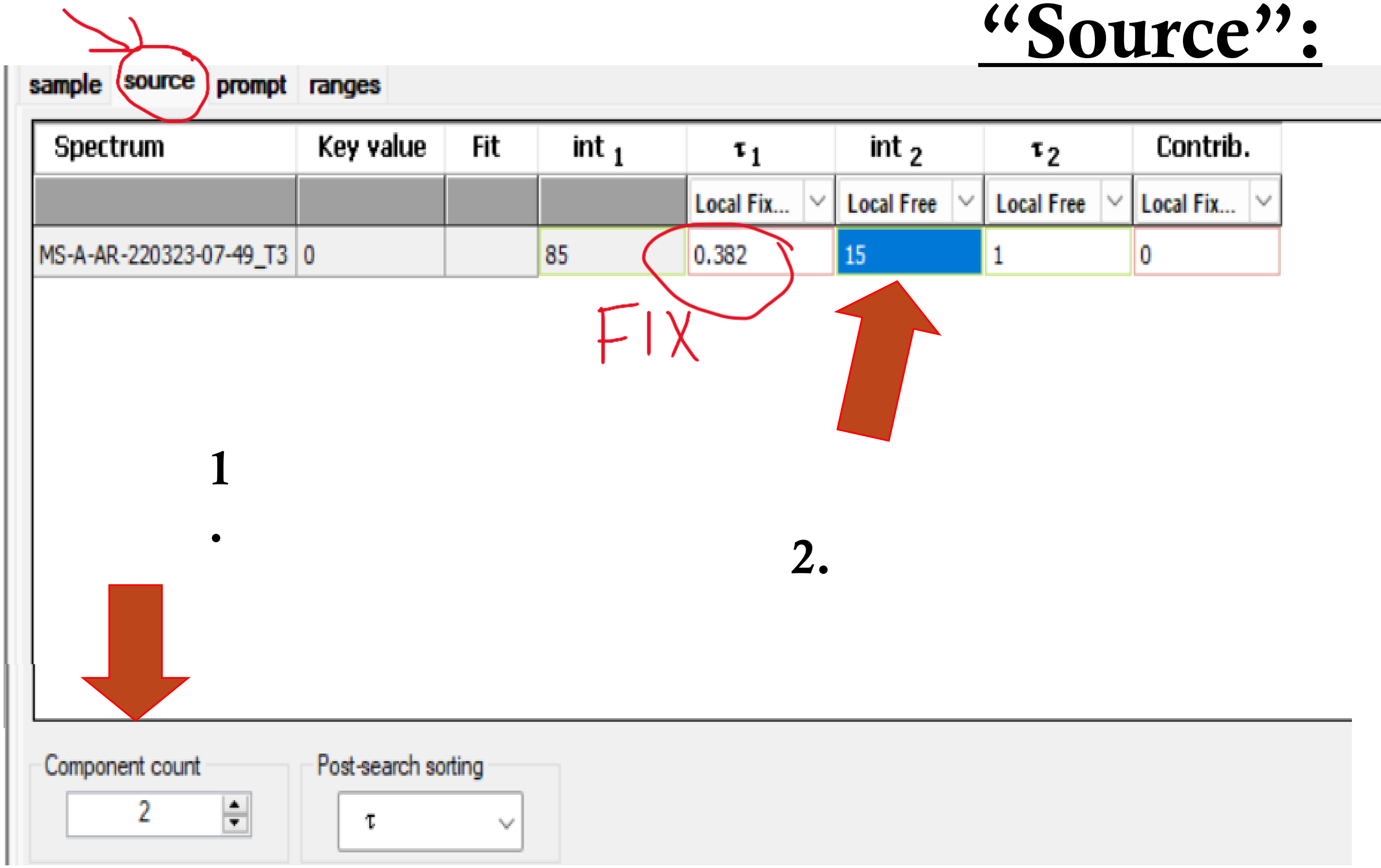
Selecting the spectra:

- START left side near of the peak (5-10 points from ZERO)
- STOP – on linear part of the function



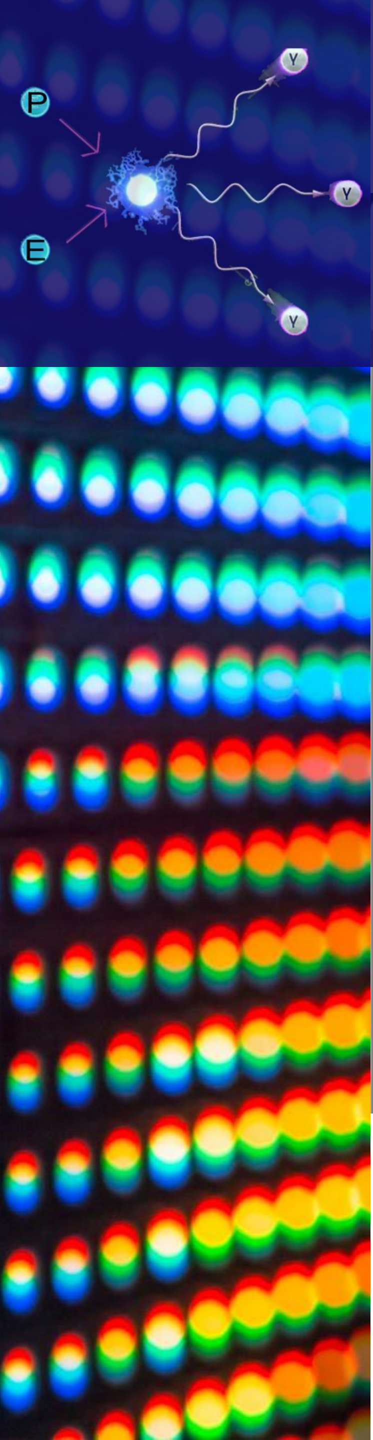


4. Defining the Setting Parameters "Source":

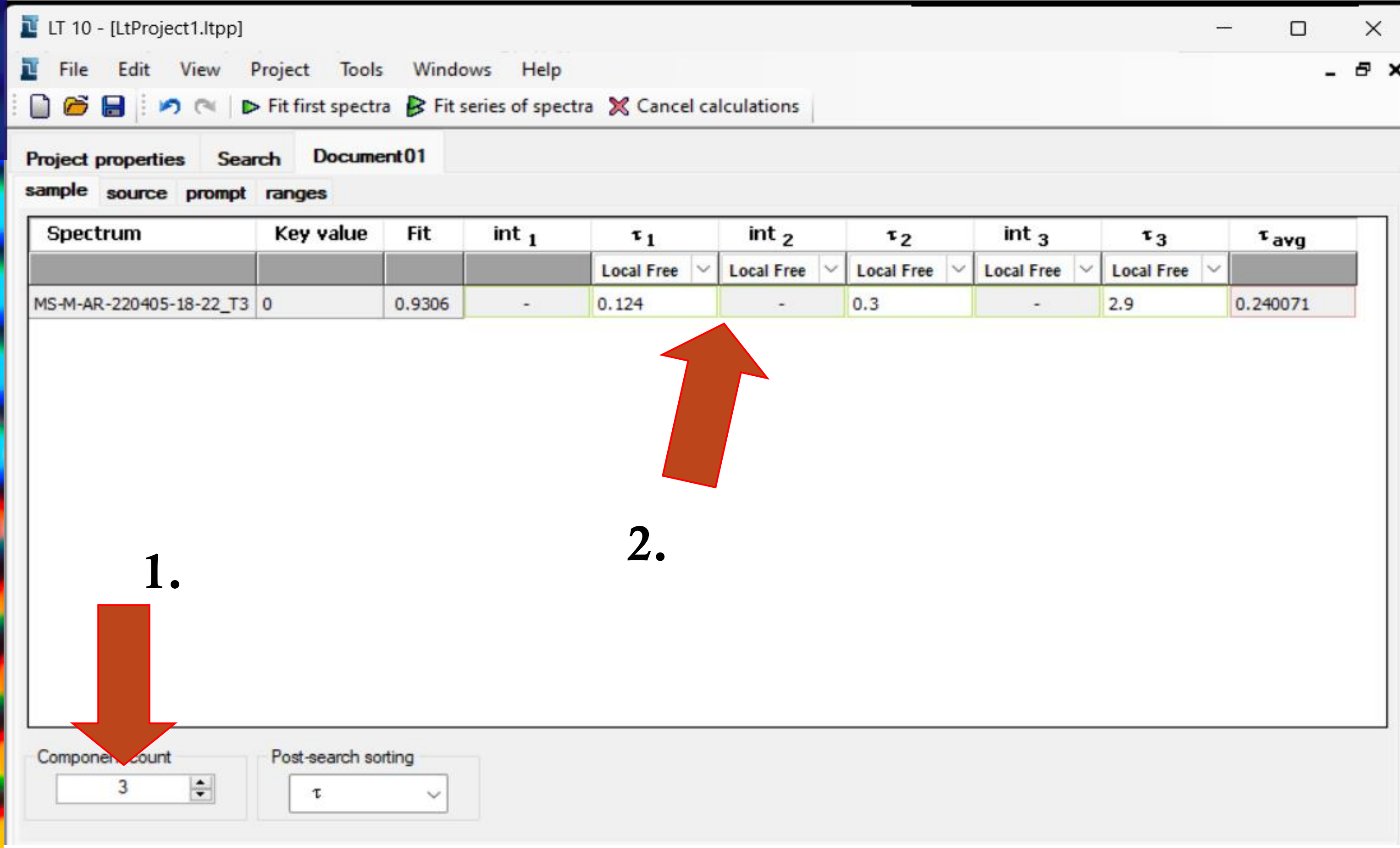


Defining the source:

1. **FIX!!** Annihilation in Na22-source a+ Kapton foil (**0.382 ns with 20-23%**)
2. In-fligh annihilation betwwn the positron source and sample (**over 1 ns with 1-3%**)



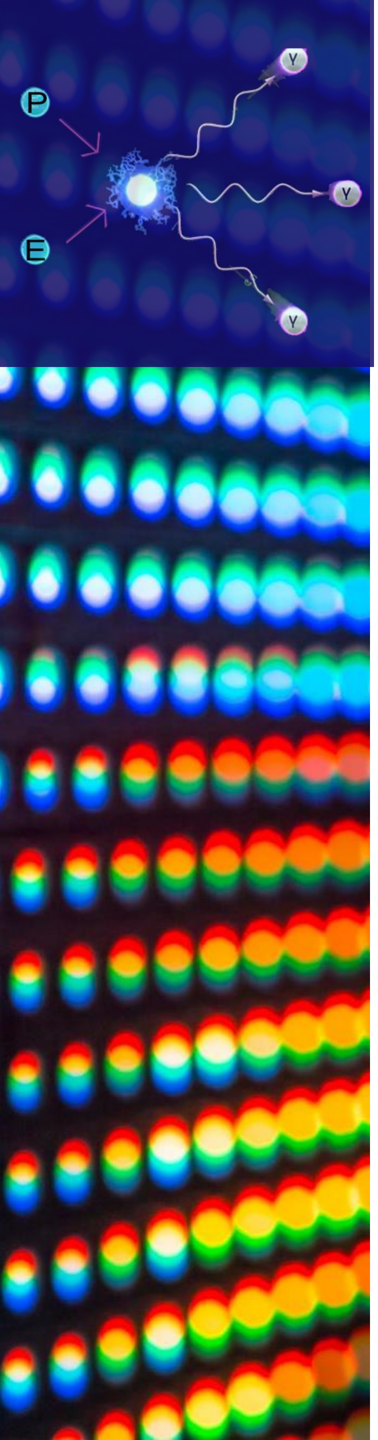
5. Defining Setting Parameters “Lifetimes“:

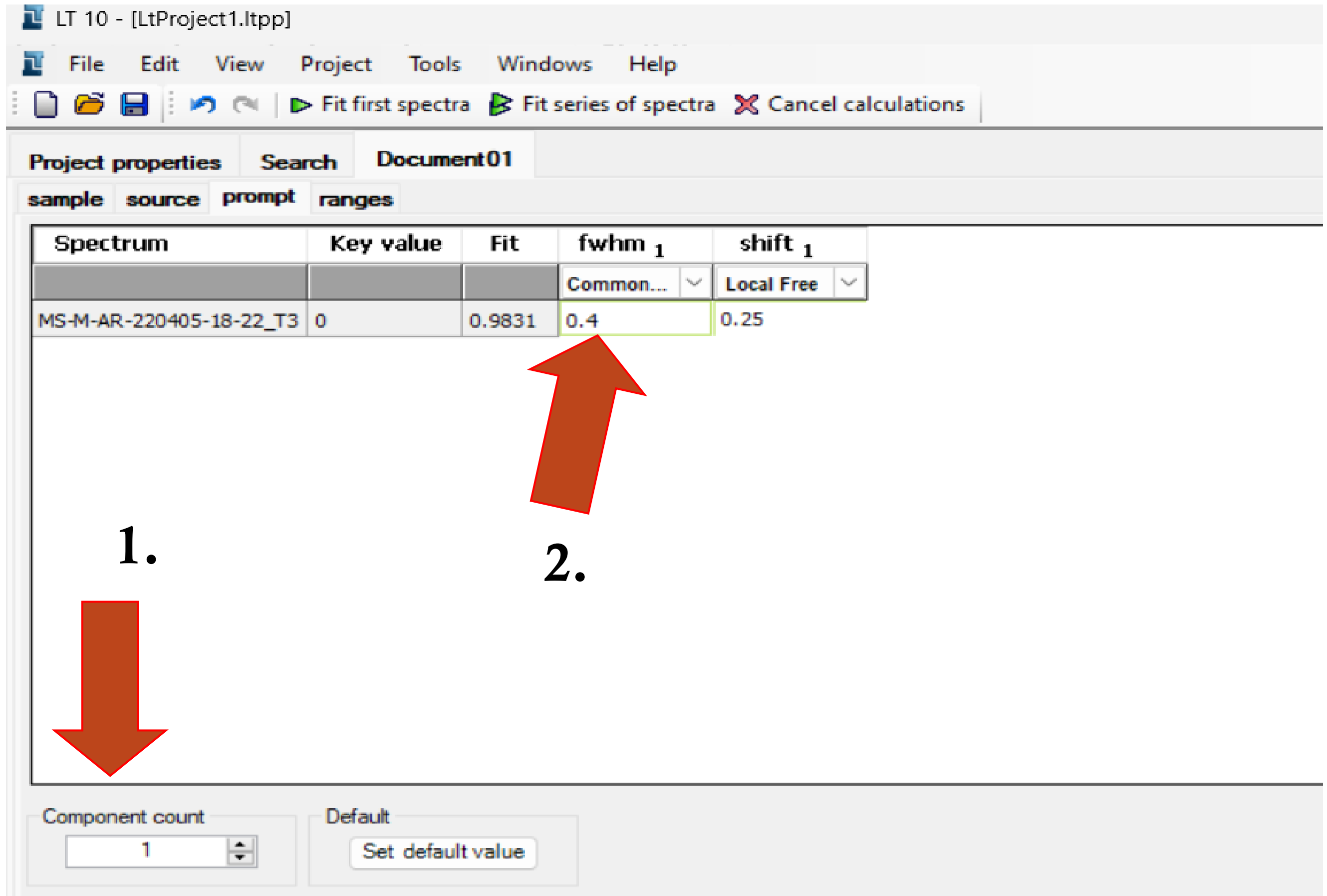


Lifetimes components approximately:

1. **0.11 ns – pure Fe (can be fixed)**
2. **0.150 ns - dislocations**
3. **0.195 ns - monovacancy**

5. Defining Setting Parameters “Gaussian function“:

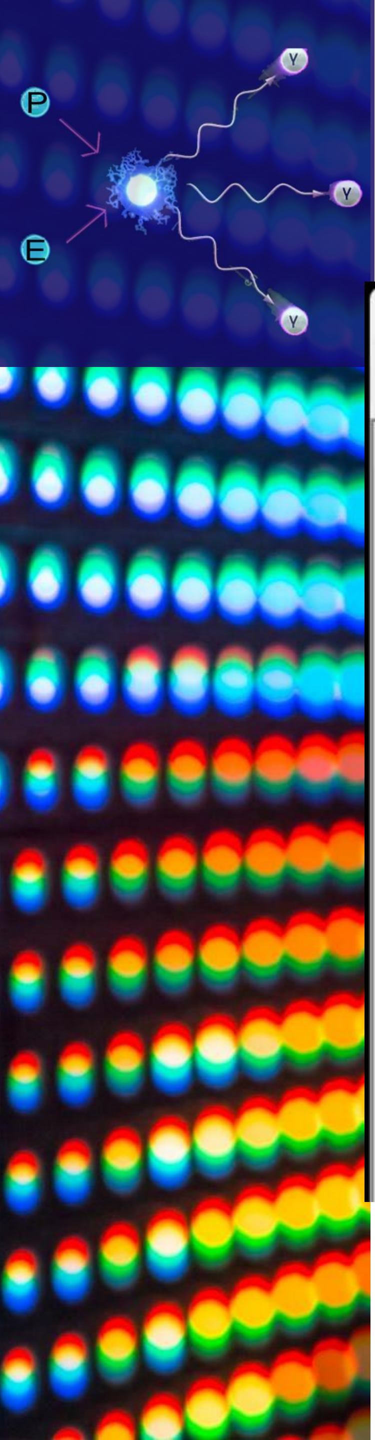


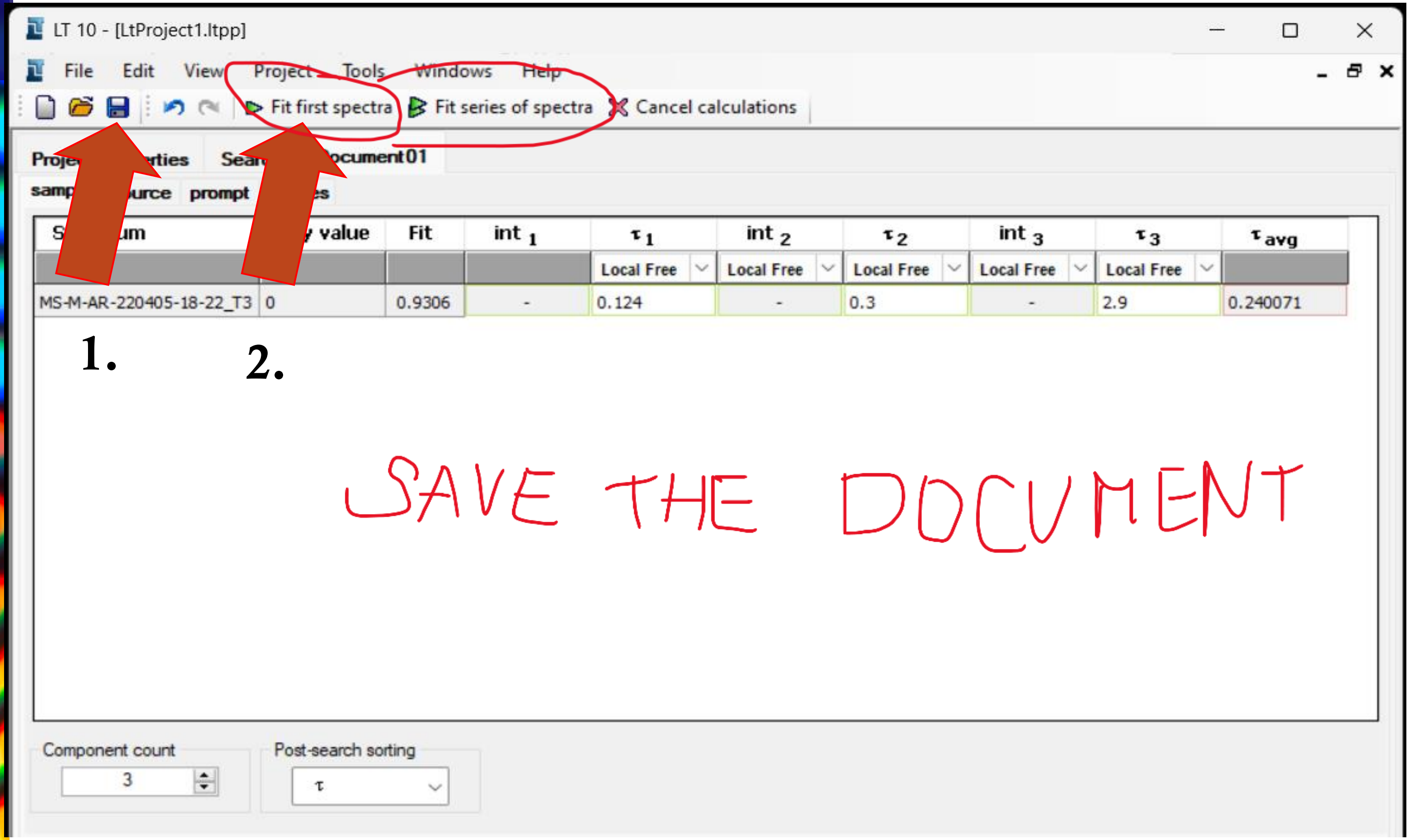


Selecting of the spectera describing Gaussian:

- One Gaussian is ideal
- For problem with fitting – we can use 2 Gaussians

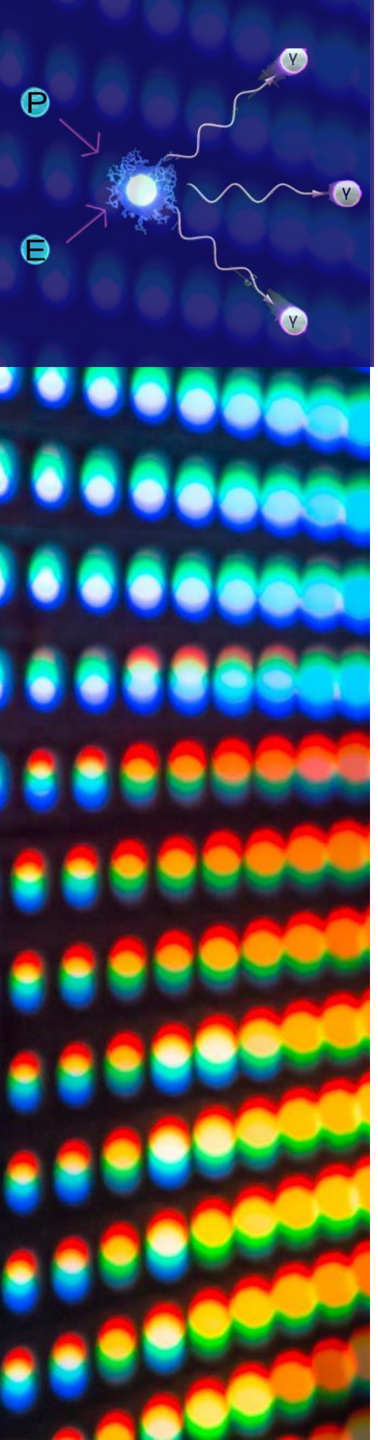
6. Performing the Fit for sample:

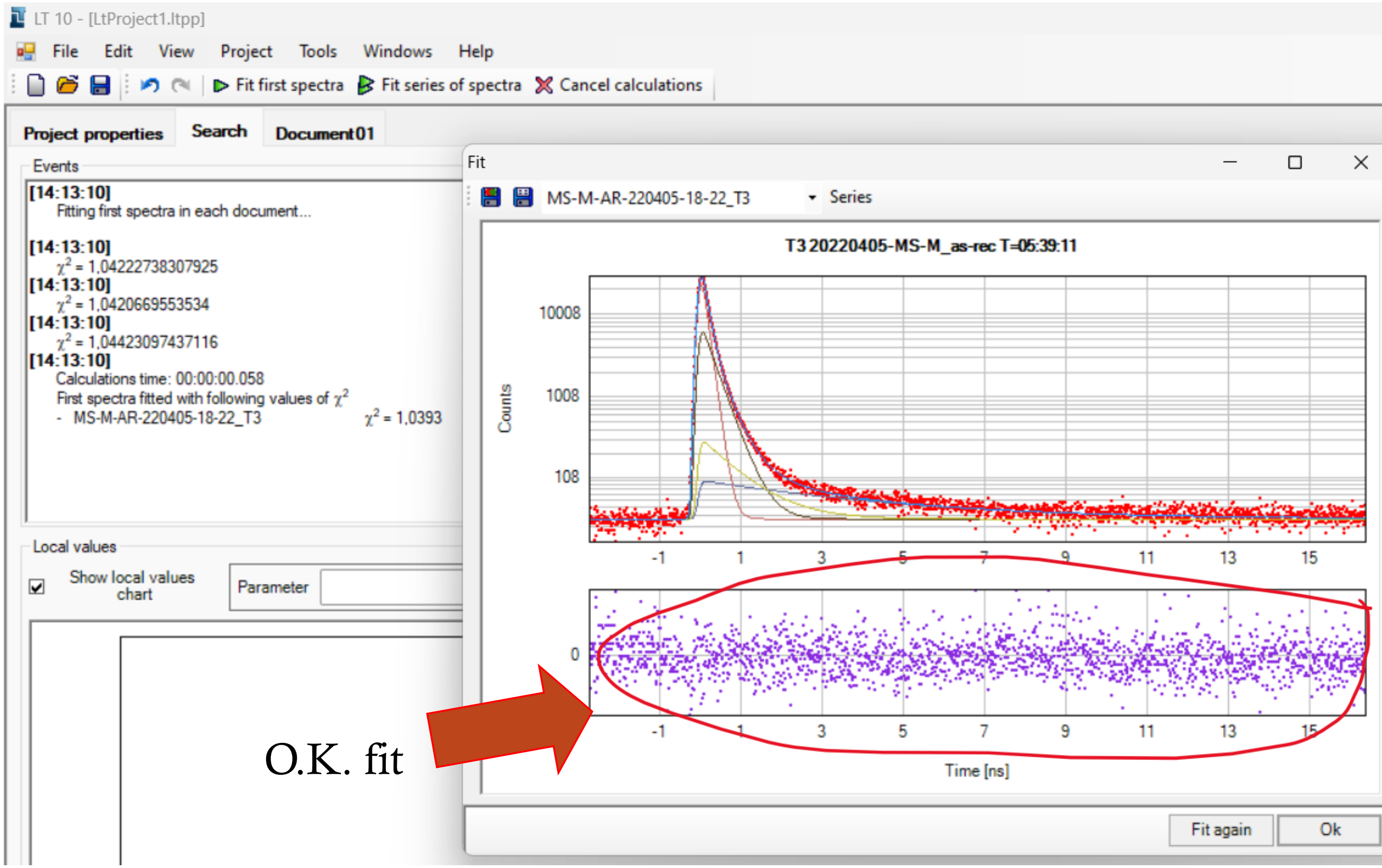




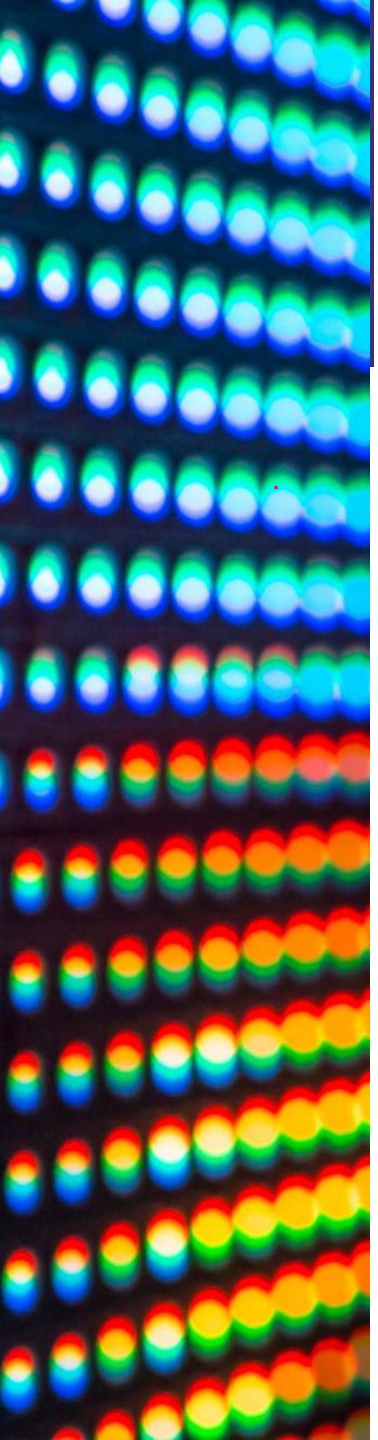
Start of fitting process

7. Evaluating Fit :



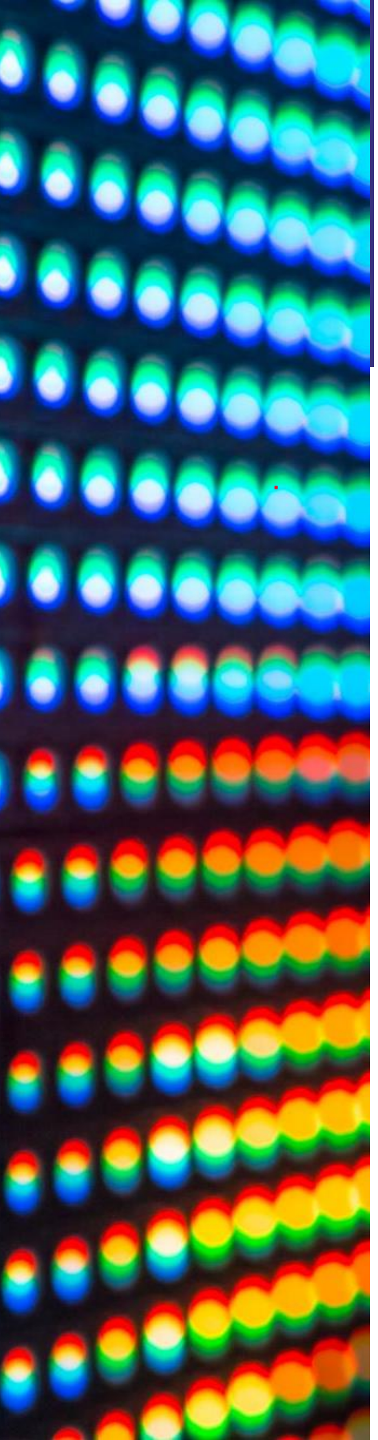


Start of fitting process



7. Evaluating Fit :

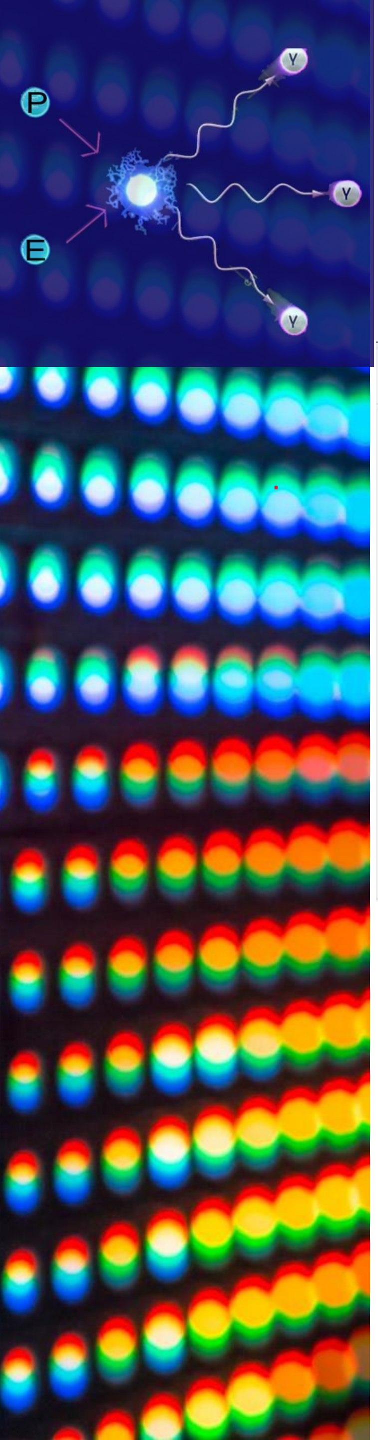
We need more iterations or to modify parameters and fitting area of the spectra – BACK to **STEP 3.**

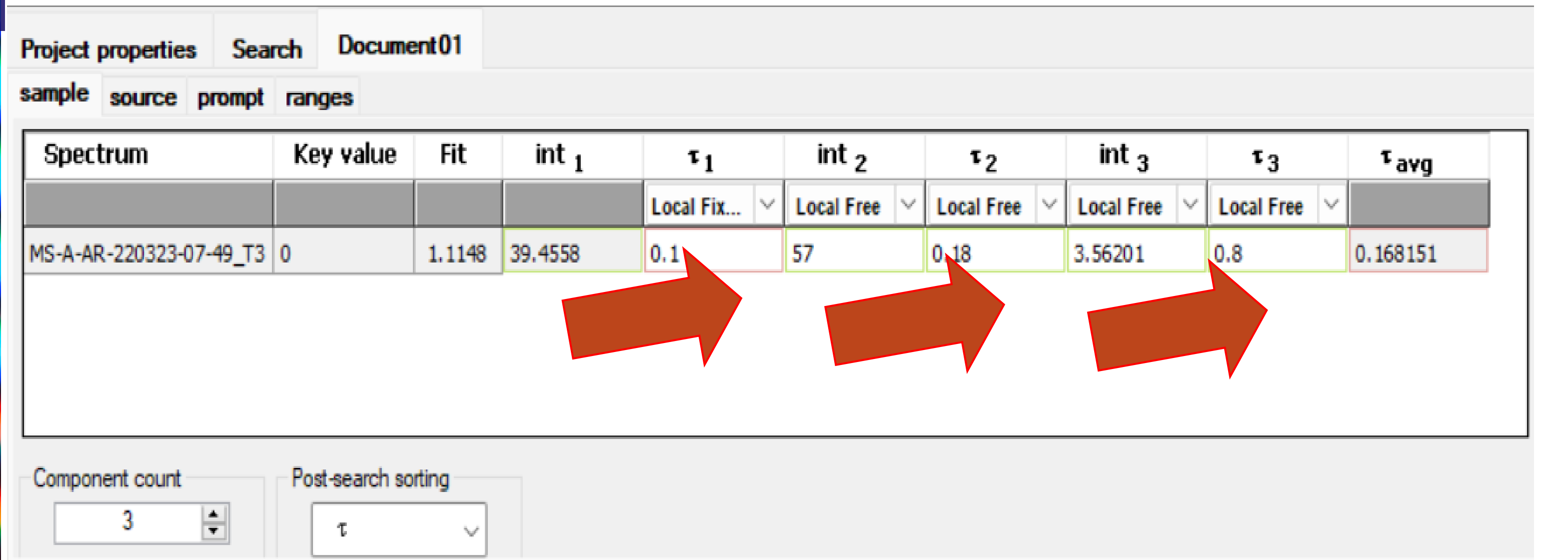


7. Evaluating Fit :

We need more iterations or to modify parameters and fitting area of the spectra – BACK to **STEP 3.**

8. Results treatment:

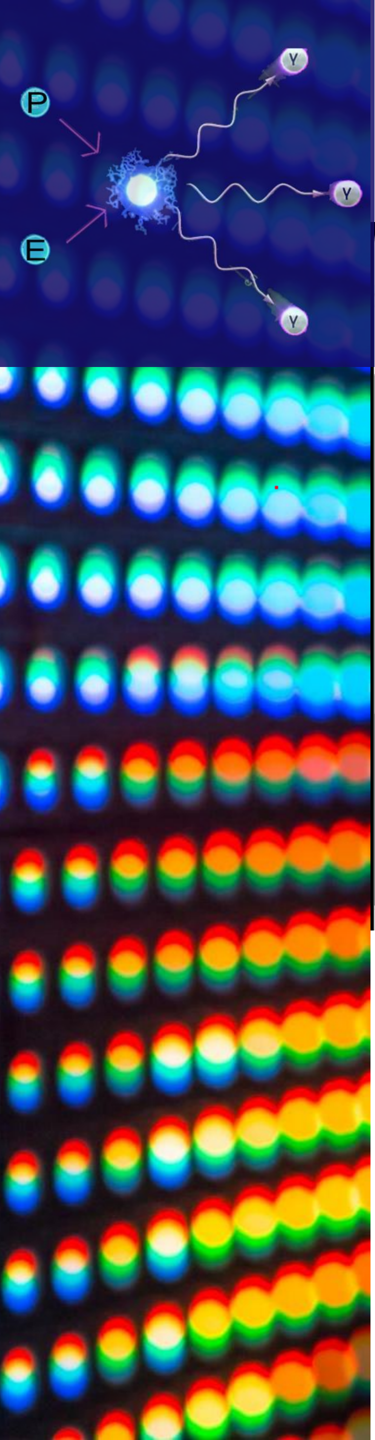




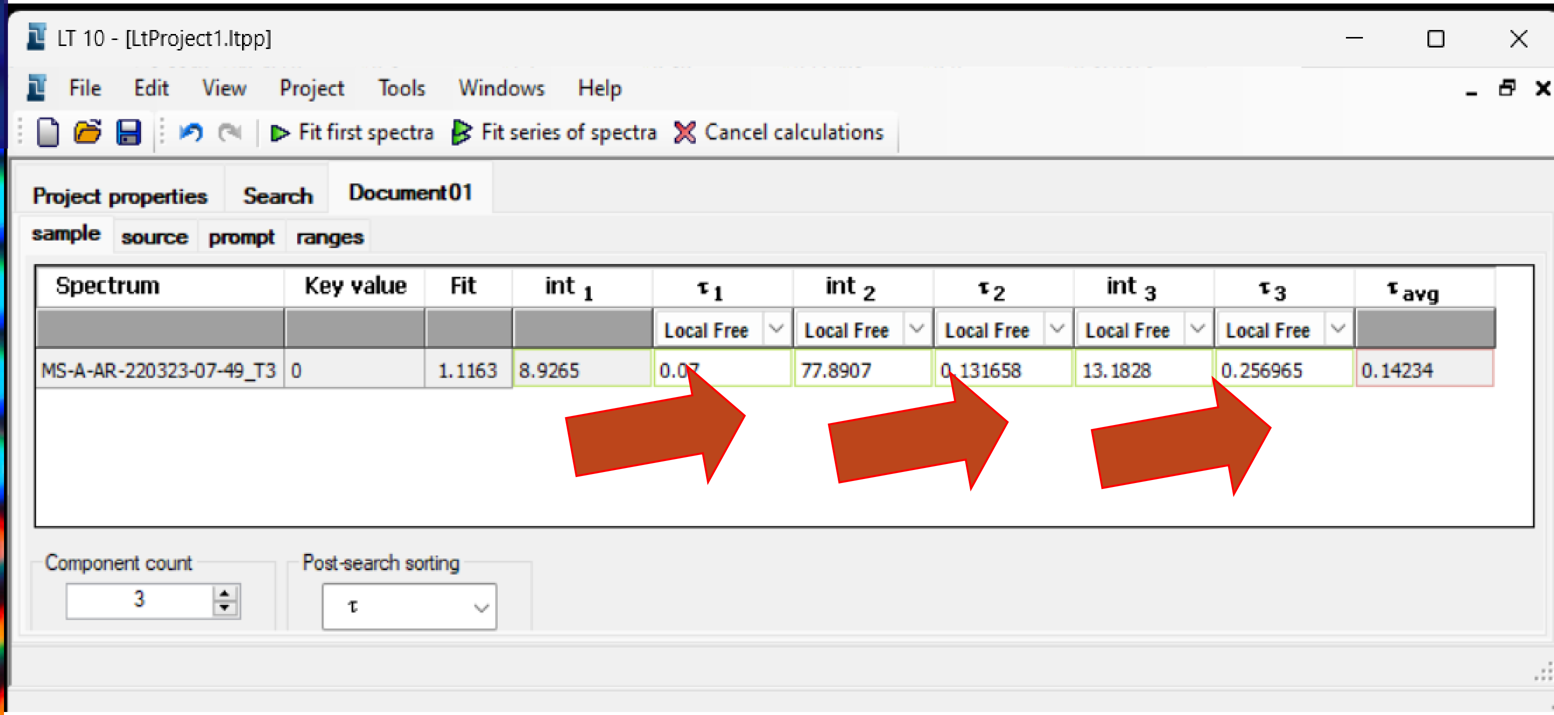
1ST lietime: 100 ps – pure iron – bulk structure - 39%

2nd lifetime: 180 ps - defects (vacancies+dislocations) - 57%

3rd lietime: 800 ps - in-flight annihilation not compansate by source



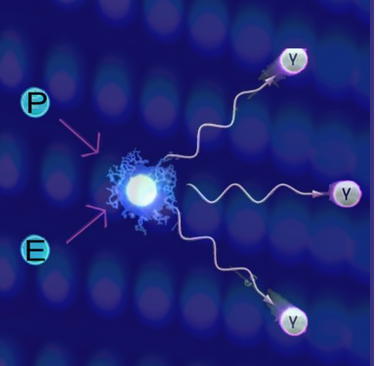
8. Results treatment:

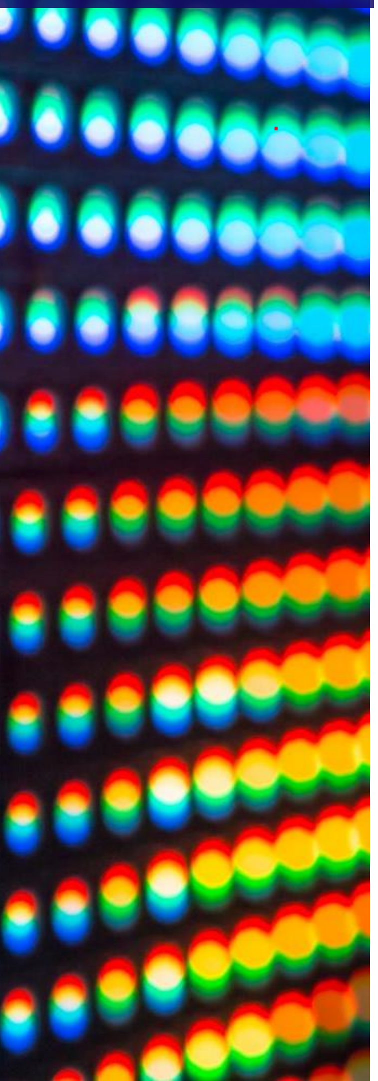


1^{ST} lietime: 70 ps – reduced bulk structure - 9%

2^{nd} lifetime: 130 ps - defects (dislocations) - 77%

3rd lietime: 255 ps - defects (vacancy cluster) - 13%





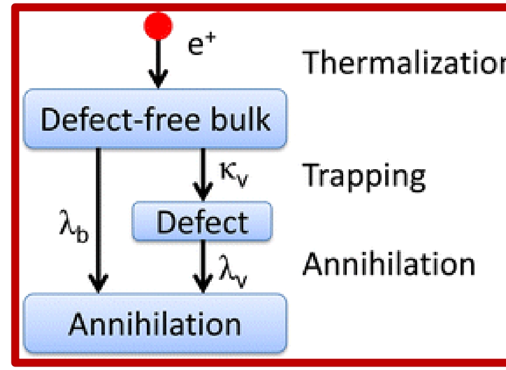
9. Calculations:

Mean lifetime:

MLT = $(LT_1 * I_1) + (LT_2 * I_2) + (LT_3 * I_3)$ ±2 [ps]

Average LT:

$T_{AV} = (LT_B * I_B + (LT_D * I_D)$



Equations:

$$\tau_1 = \frac{1}{(\lambda_b + \kappa)} \qquad I_1 = 1 - I_2$$

$$\tau_2 = \frac{1}{\lambda_d} \qquad I_2 = \frac{\kappa}{(\lambda_b - \lambda_d + \kappa)}$$

Defect concentration:

$$\kappa(T) = \frac{1}{\tau_b}\frac{\tau_{av}(T) - \tau_b}{\tau_d - \tau_{av}(T)} \qquad \kappa_i = \mu_i \cdot C_i$$

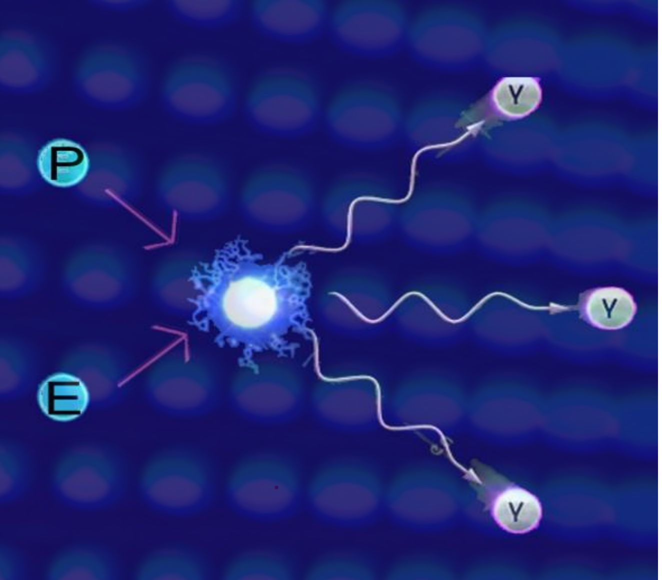
κ – trapping rate (s-1) - r**ate at which positrons are captured**

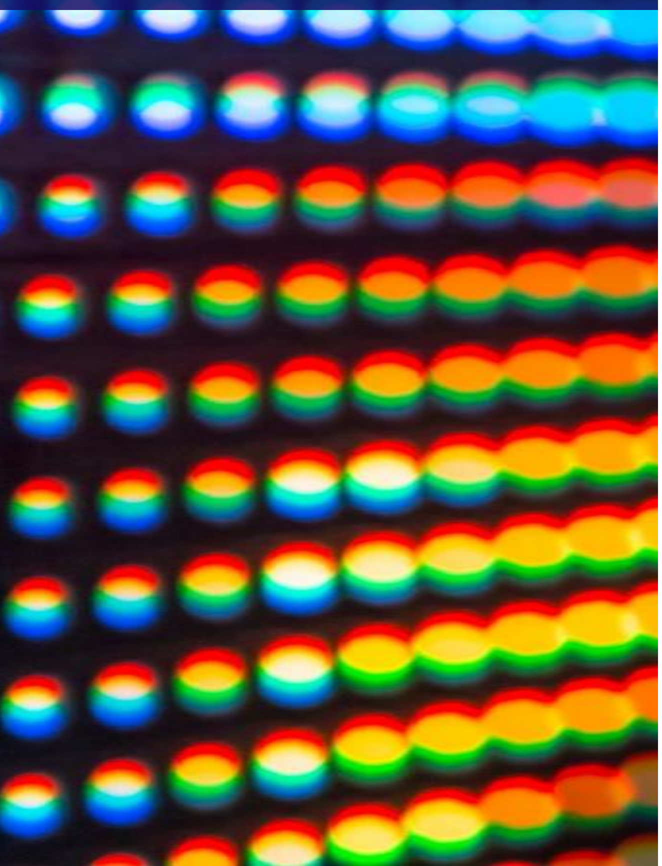
λb – annihilation rates in the bulk,

λd - annihilation rates in the defect

μ - Specific trapping rate depending on the type of a defect

Ci - defect concentration



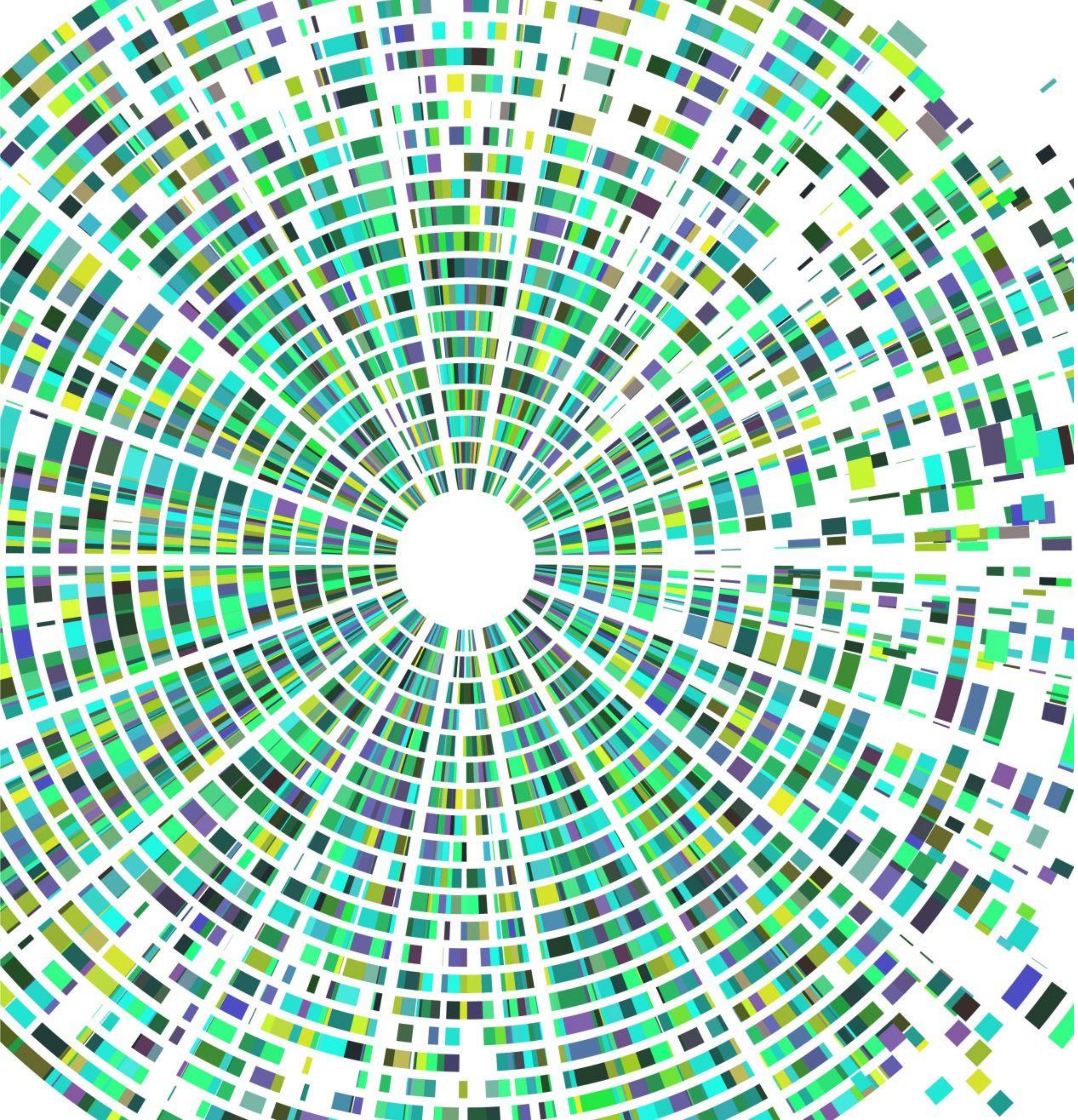


Thank you for attention.

References:

[1] J. Čížek, I. Procházka, J. Kočík, E. Keilová, Positron lifetime study of reactor pressure vessel steels, Physica Status Solidi A Appl Res. 178 (2000) 651–662. https://doi.org/10.1002/1521-396X(200004)178:2<651::AID-PSSA651>3.0.CO;2-O

[2] J. Jiang, Y.C. Wu, X.B. Liu, R.S. Wang, Y. Nagai, K. Inoue, Y. Shimizu, T. Toyama, Microstructural evolution of RPV steels under proton and ion irradiation studied by positron annihilation spectroscopy, Journal of Nuclear Materials 458 (2015) 326–334. https://doi.org/10.1016/j.jnucmat.2014.12.113.



Wednesday’s presentations

DELISA-LTO Workshop II on application of non-destructive testing methods

Ageing management as a key aspect of components structural integrity at the LTO stage

10-14 February 2025, Manor House Kočovce, Slovakia

WP3 Leader – Oleksii Shugailo (SSTC NRS)

DELISA LTO
Description of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

Funded by the European Union

Introduction

Oleksii Shugailo (*WP 3 Leader*)

- SE "State Scientific Technical Center on Nuclear and Radiation Safety" (SSTC NRS)
- Head of the Nuclear Installations Long Term Operational Department
- Field of activity – Ageing Management, Long Term Operation, Structural integrity and reliability of SSC, etc.

  - Tel/Fax. +380 44 422 49 53
  - fax. +380 44 452 89 90
  - E-mail: ap_shugaylo@sstc.ua

SSTC NRS at a glance

- is a state-owned commercial enterprise
- has 250 highly qualified employees
- main tasks:
  - ✓ improve NRS regulation system;
  - ✓ substantiate regulatory decisions in licensing;
  - ✓ ensure oversight function of regulation;
  - ✓ introduce and implement advanced methodologies into regulatory and safety assurance practices

- SSTC has wide international activity and cooperation with European TSOs (involved into international programs/projects etc.)

Content

- *Part I - LTO and Ageing Management – general aspects, importance*

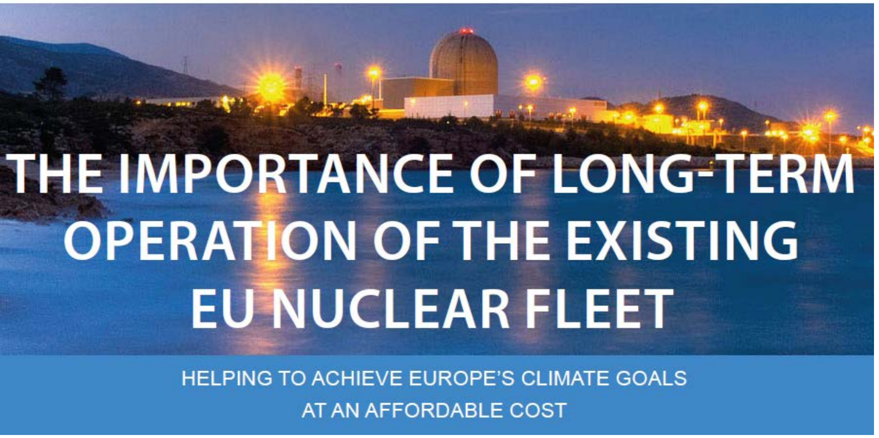
- *Part II - DELISA-LTO – simulation and structural integrity*

Content

- <u>Part I</u> - *LTO and Ageing Management – general aspects, importance*
  - ✓*Long-Term Operation – main features*
  - ✓*Regulatory approaches to LTO in different countries*
  - ✓*Ageing Management as a basis for successful LTO*
  - ✓*Time Limited Ageing Analysis (+examples)*
  - ✓*Impact of Ageing on potential failures/violations*

Funded by the European Union

LTO and Ageing Management importance



FORATOM paper highlights:

- Nuclear Industry will play a significant role if the world with decreasing carbon emission by 2050
- **LTO** is unarguably economically advantageous compared to construction of new units
- **LTO** requires a much lower capital investment cost
- **LTO** leads to low investment risks and lower consumer costs

From a technical point of view, the LTO provides a great advantage thanks to

> ***"…timely implementation of reasonably practicable safety improvements to existing nuclear installations***"

which brings older generation reactors to a level of modern nuclear safety standardse

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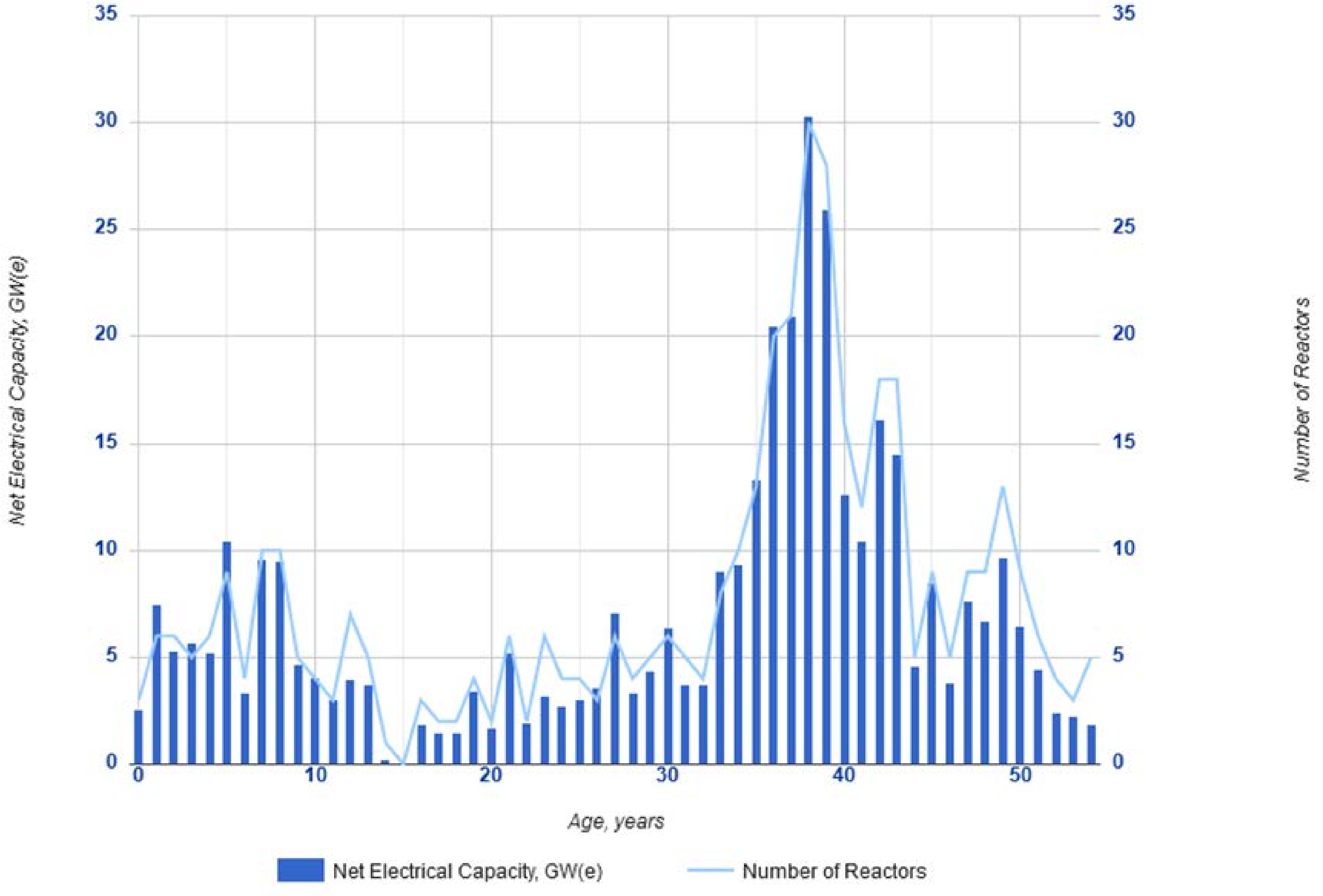
LTO and Ageing Management importance

Units Age Distribution



World statistics, IAEA, [Online, cit. January 2023] <https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx>

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Long-Term Operation – main features

- LTO justification is based on:
  - ✓*Conformity with national and international safety standards* (e.g. IAEA safety standards, WENRA safety levels, US NRC guidance etc.)
  - ✓*Comprehensive Structural Integrity Analysis*
  - ✓*Ageing Management procedures implementation*

- ***LTO up to 60 years is a common practice*** in a significant number of countries with established nuclear programmes

- ***LTO up to 60++ is a common challenge but may be possible*** *(requires huge scope of analytical and experimental activities)*

Long-Term Operation – main features

- ***LTO condition (main)*** → Plant Safety Level should not be less than required by regulations, rules and standards in force
- ***LTO mechanism (there are 2 options):***

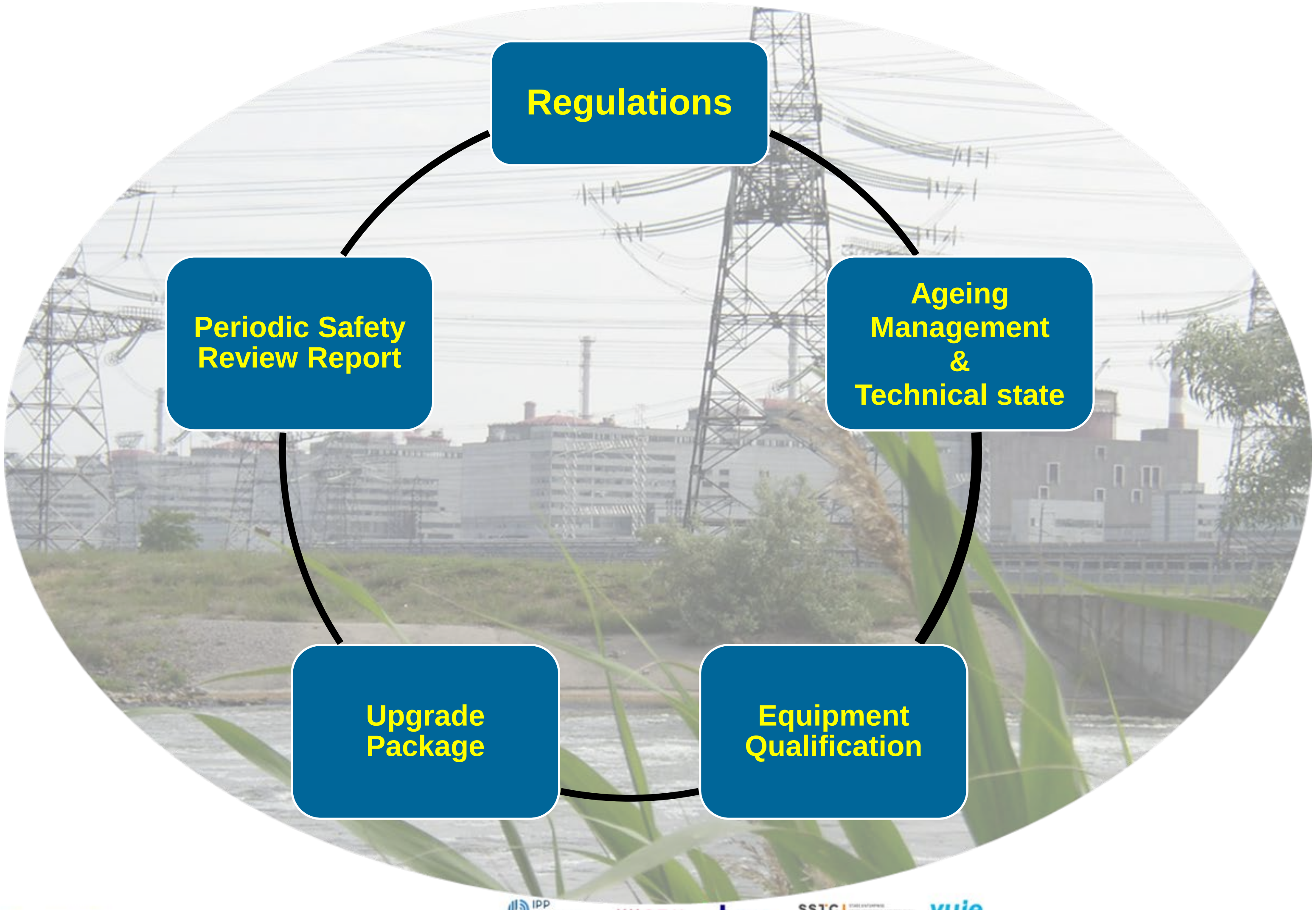
I Changes to the License for operation of nuclear installation (License renewal)

II Periodic Safety Review – in case if Licence does not set a limit for service life

Regulatory approaches to LTO in different countries

	Licence renewal	Periodic safety review (PSR)	Comment
Belgium		Yes	In Belgium, service life (operating licence) for NPPs is set by law at 40 years. Utilities have to conduct a PSR for their operating NPPs every ten years and have to submit the PSR report to the federal regulator for nuclear control for review and approval. In the case of Tihange 1, there will be the possibility of a one-off extension of ten years of the operating licence, under the condition that the results of the next PSR for this reactor are approved by the federal regulator.
Finland		Yes	According to the Nuclear Energy Act, the operating licences are granted for a fixed term. The licence conditions may by changed during its period of validity by the government. The licence can also be revoked if the licensee is failing to comply with the licence conditions and the nuclear regulator (STUK) is given power to monitor the operation of the plants and take any measures required to ensure public safety.
France		Yes	In France, the operating licence for a nuclear reactor does not set a limit for service life. However, article 29 of the Transparency and Nuclear Safety Act (13 June 2006) requires that the operator of a nuclear reactor performs a safety review of the facility every ten years.
United States	Yes		The US Atomic Energy Act of 1954 allows the Nuclear Regulatory Commission (NRC) to issue licences for commercial power reactors to operate for up to 40 years. The NRC regulations allow the renewal of these licences for an additional period of 20 years if the reactor satisfies safety and environmental criteria. Although the licensing process does not require PSRs, the US nuclear plants undergo constant reviews and inspections and the NRC can revoke the licence or take any other actions to ensure public safety.

Key aspects of successful LTO



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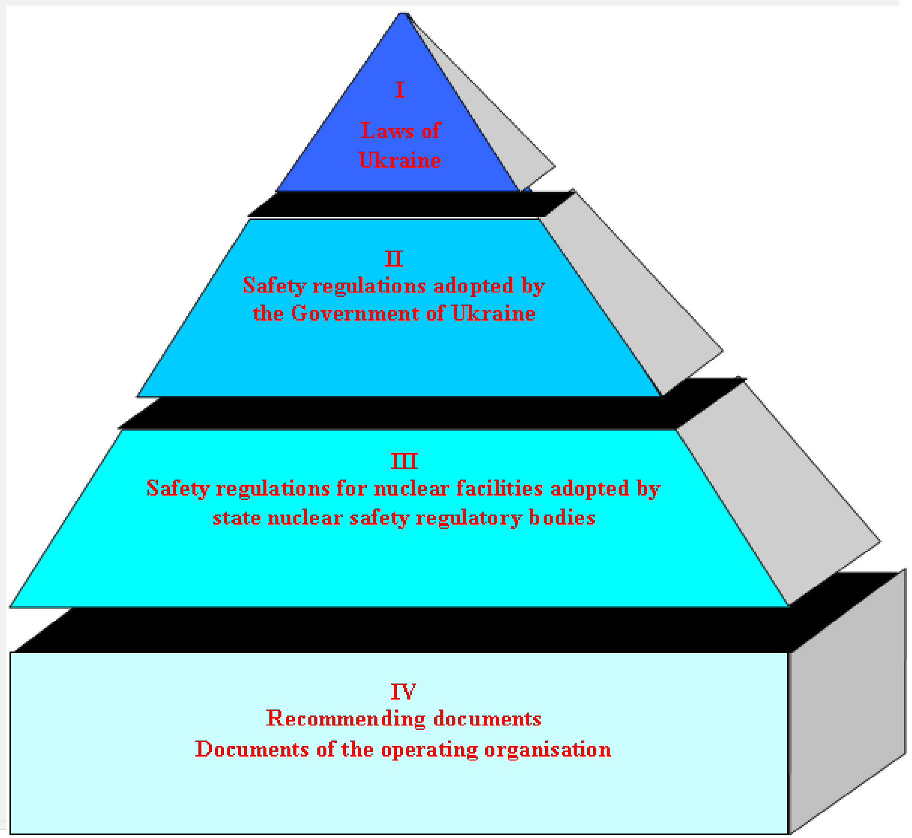
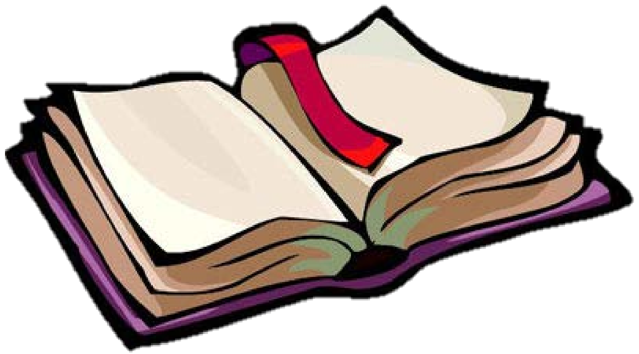
Regulation Structure



- ✓ A hierarchic approach in developing and revising regulatory documents is one of the basic principles of regulatory and legislative control in any country
- ✓ This principle is implemented in a hierarchic pyramid representing regulatory documents on NRS at several levels



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Ageing Management is a basis for successful LTO

Ageing – the process by which the physical characteristics of a system, structure or components change with time or use.

The process may involve one or a combination of several ageing mechanisms.

Ageing effects due to degradation may lead to the functional degradation of structures or components

Ageing management – technical and operational measures taken to keep degradation as well as ageing and wear within acceptable limits

Stages of AM implementation: *design, construction, commissioning, operation (i.e. long term), suspended operation, decommisioning*

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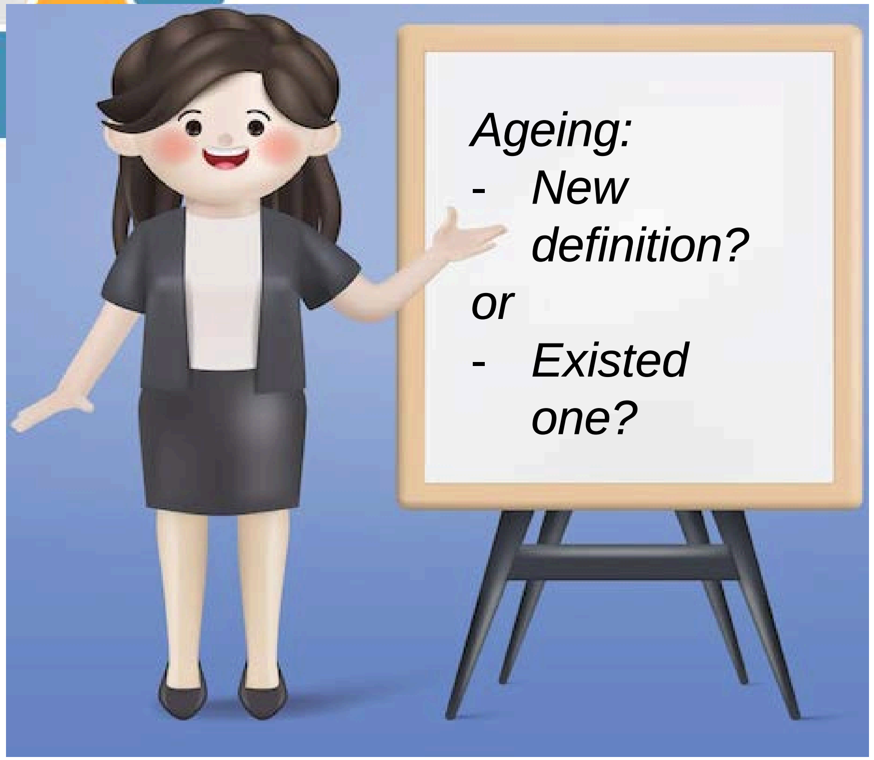
Ageing Management – Historical background (1/2)



The term "*Ageing management*" started to be used about since 1995 despite of presence of AM elements at NPPs since beginning of their operation, for example:

- ✓ *Operational monitoring*
- ✓ *Repair and technical maintenance*
- ✓ *Refurbishment and replacement of equipment*
- ✓ *Change of operational modes etc.*

However, specific Ageing Management Program as well as database for its implementation were absent

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Ageing Management – Historical background 2/2

Ageing management – for what?

- Assure required safety level
(commissioning - operation-life extension)
- Maximal operational efficiency

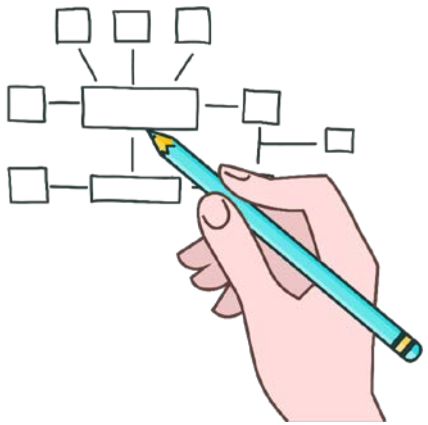
Safety aspects
timely detection of defects to keep power unit components within permissible limits of degradation (guarantee of their integrity and serviceability)

Economic aspects
implementation of appropriate technical and economic measures to prevent and avoid failure as a consequence of ageing

Ageing Management – main attributes

- ✓ AM process shall be organized on a systematic basis
- ✓ Appropriate department/structure shall be established at the Utility for systematic ageing management (the department should be adequately equipped and authorized).

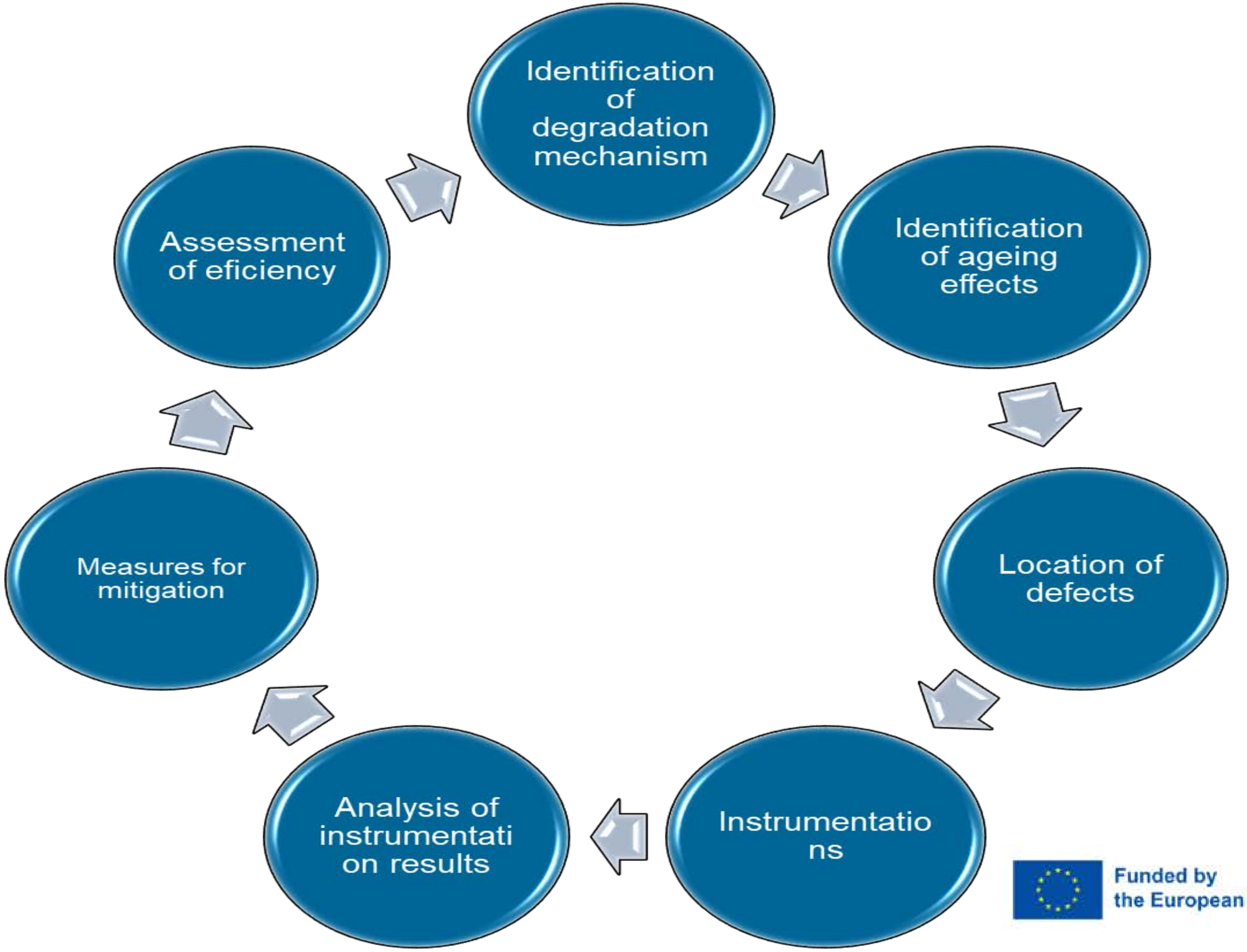
- ✓ There are two types of ageing:
  - ✓ *physical* ageing leading to degradation
  - ✓ *obsolescence* (resulting from the development of knowledge and technologies and changes in international and national requirements and standards)



Ageing Management – main attributes

The Utility shall apply the approach to Ageing management based on:

- ✓ understanding the ageing effects
- ✓ predicting the degradation
- ✓ proactively reacting on the failures



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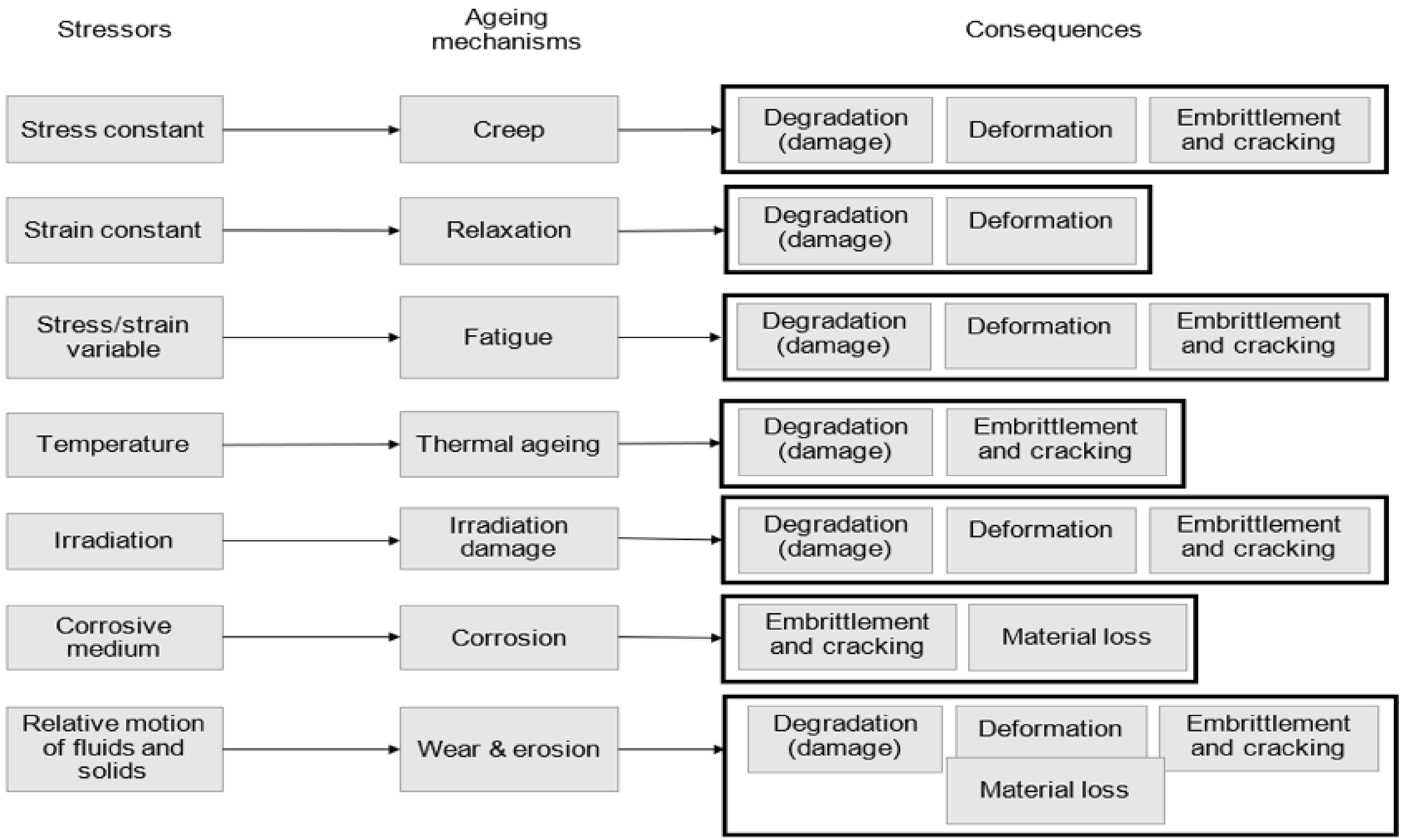
Systematization of ageing effects



The most significant factors influencing LTO for equipment and piping components include:

- ✓ *various degradation mechanisms*

that lead to

- ✓ *ageing effects* and, as a result, to potential
- ✓ *failures and malfunctions*

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Time Limited Ageing Analysis

- Time Limited Ageing Analysis (TLAA)
- Time Limited Assumptions (TLA)
- Residual Life Assumptions (RLA)

Assessment of identified ageing effect (due to time-dependent degradation) of certain plant-specific safety analysis that are based on an explicitly specified length of plant life (10, 30, 40 and more ….)

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Time Limited Ageing Analysis – part of LTO

- ✓TLAA shall be performed for the dominant ageing mechanism
- ✓Justifying period of functions performing by structure or component
- ✓ TLAA shall demonstrate that TSP values will not exceed the criteria over the period considered in the analysis
- ✓TLAA shall apply conservative methods and methodologies agreed upon with the Regulator
- ✓Software tools shall be used in compliance with the Utility’s established procedure

Time Limited Ageing Analysis – part of LTO

TLLA refers to calculations and analyses that (6 criteria of TLAA application):

- ✓ Involve SSCs within the scope of the licence for LTO
- ✓ Consider the effects of ageing degradation
- ✓ Involve time–limited assumptions
- ✓ Were determined to be relevant to safety
- ✓ Involve conclusions to the capability of the SSCs to perform its functions over the defined time
- ✓ Are contained or incorporated by reference in the CLB

Typical TLAAs

№ п/п	Позначення TLAA	Назва TLAA (англійською)	Назва TLAA (українською)
I TLAA для механічних компонентів			
1	TLAA 101	Low-cycle Fatigue Usage	Малоциклова втома
2	TLAA 102	RPV Neutron Embrittlement	Радіаційне окрихчення КР
3	TLAA 103	Crack Growth Analyses	Аналіз росту тріщин
4	TLAA 104	Corrosion Allowances	Припуски на корозію
5	TLAA 106	Environmentally Assisted Fatigue	Втомне пошкодження внаслідок впливу довкілля
6	TLAA 107	High-cycle Fatigue for Steam Generator Tubes	Високоциклічна втома для трубок парогенератора
7	TLAA 108	Fatigue of Cranes	Втома кранів
8	TLAA 109	PWR RPV Internals Swelling	Розпухання ВКП реакторів типу PWR
9	TLAA 110	Thermal Ageing of Cast Austenitic Stainless Steels	Термічне старіння аустенітних нержавіючих сталей
10	TLAA 112	Main Circulation Pump Flywheel	Аналіз старіння маховика головного циркуляційного насосу
11	TLAA 113	Thermal Stratification	Теплова стратифікація
12	TLAA 115	Fatigue and Thermal Ageing Analysis of Manufacturing Flaws	Аналіз втоми та термічного старіння заводських дефектів
II TLAA для електричних компонентів та інформаційних і керуючих систем (ІКС)			
13	TLAA 201	Environmental Qualification of Electrical and I&C Components	Кваліфікація електричних кабелів та обладнання ІКС на умови навколишнього середовища
III TLAA для будівель та споруд			
14	TLAA 301	Concrete Containment Tendon Prestress	Переднапружений стан арматури бетону контайнменту
15	TLAA 303	Cumulative Fatigue Damage of Containment Liners and Penetrations	Накопичена втомна пошкоджуваність облицювання контайнменту та гермопроходок
16	TLAA 304	Foundation Settlement Due to Soil Movement	Осідання фундаменту внаслідок зсуву ґрунту

TLAA acceptance criteria

A TLAA is acceptable if it meets one of the following cases

- ✓ The analysis remains valid for the intended period of operation
- ✓ The analysis has been projected to the end of the intended period of operation
- ✓ The effects of ageing on the intended function(s) of the structure or component will be adequately managed for the intended period of operation

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Examples of TLAAs
TLAA 102 – Neutron Embrittlement

Fatigue (low cycle and high cycle)

Crack growth analyses

Thermal ageing

Mechanical equipment

Corrosion allowances

Neutron embrittlement

Environmentally assisted fatigue

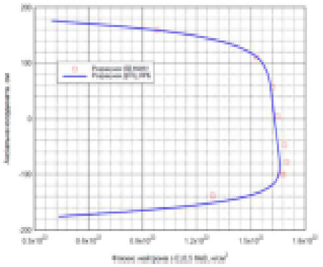
Brittle fracture resistance

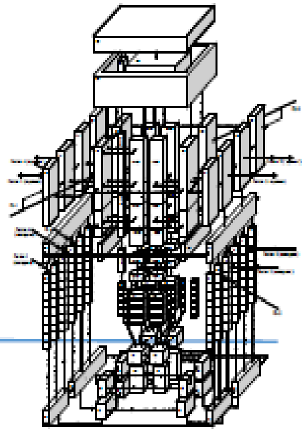
TLAA considered consequence of radiation imbrittelment of reactor vessel materials, and specifies how such mechanism of degradation affect on the results of analysis for further operation

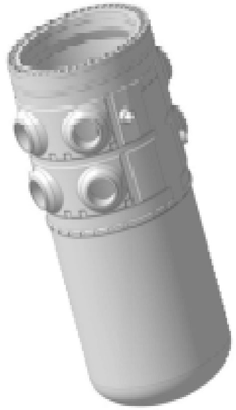
- Ukrainian experience:

✓*such TLAA is mandatory for RPV for each safety reassessment (each 10 years)*

✓*results of this TLAA define possibility of LTO for whole Unit*







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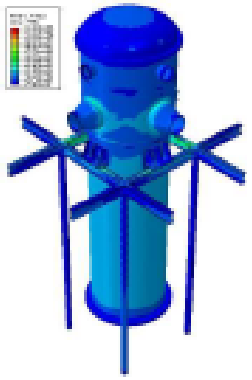
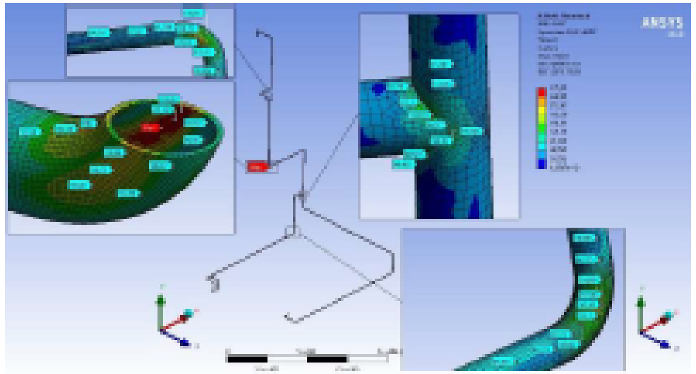
Examples of TLAAs
TLAA 101 – Low Cycle Fatigue Usage

Fatigue → TLAA estimates current fatigue of material and allows to make prediction about moment of time when cracks appears, estimates usage factor *[a]<1*

- Ukrainian experience:
  - ✓ *This TLAA is mandatory in framework of LTO preparation*
  - ✓ *Performs for the safety important equipment and pipes*



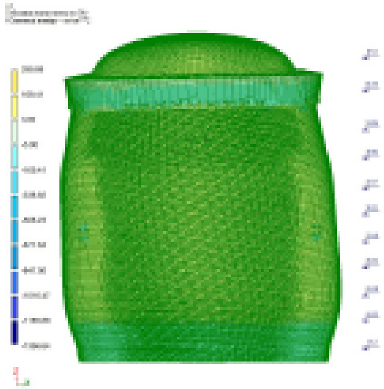


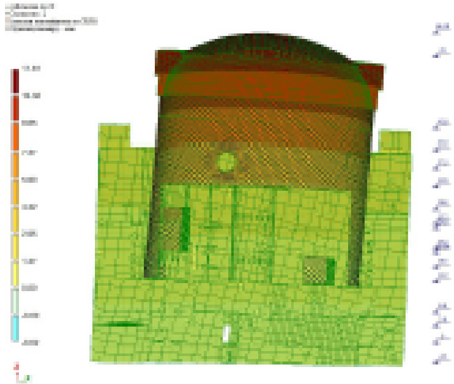
Examples of TLAAs
TLAA 301 - Concrete containment tendon prestress

Relaxation of tendons, prestressed containment system

→ TLAA estimates potential loses of prestressed elements in order to estimate time for replacing or refurbishments measures

- Ukrainian experience:
  - ✓ *This TLAA is mandatory in framework of design operation and LTO preparation*
  - ✓ *Performs for the containment*



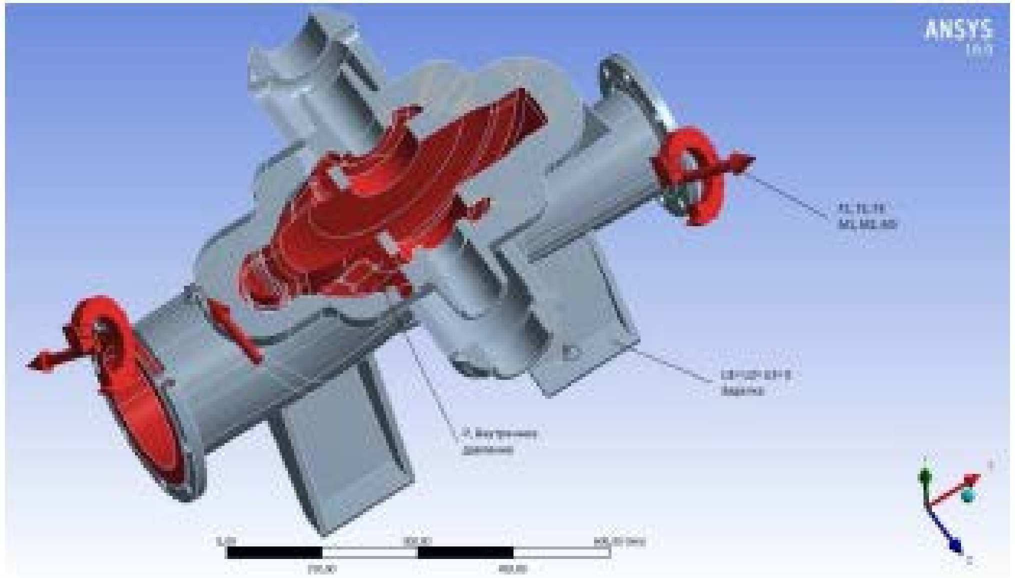


Examples of TLAAs
TLAA 104 Corrosion Allowances

Loss of materials → TLAA estimates level of loses/wear of material and impacts of the defect on further operation

Ukrainian experience (typical TLAA):

- ✓ *Estimation of impact of wall thinning of equipment and pipelines on safe operation*
- ✓ *Prediction of thinning for further operation*
- ✓ *Preventive measures (changing of operating conditions/replacement etc.)*



Impact of Ageing on potential failures/violation

Effectiveness of AM → Operating experience and analysis of operational events that occurred

Ukrainian research → Investigation of Ukrainian NPP operational events that occurred during 2010-2019 (150 reactor years) and were caused by equipment agenting effects

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Impact of Ageing on potential failures/violation

Operational events were initially selected from the database using codes of their causes and using a contextual word search

Events that resulted from the following causes were selected:

- *Corrosion, erosion (code 5.1.1.1),*
- *Wear (code 5.1.1.2),*
- *Metal fatigue, weld defect, internal material defect (code 5.1.1.3),*
- *Exceedance of allowed load (code 5.1.1.4),*
- *Exhaustion of service life (code 5.1.1.6),*
- *Deformation, misalignment, displacement, incorrect movement, disconnection, weakening of connection (code 5.1.1.9),*
- *Loosening of fastening to the foundation or civil structures, destruction of the foundation or civil structures (code 5.1.1.10)*

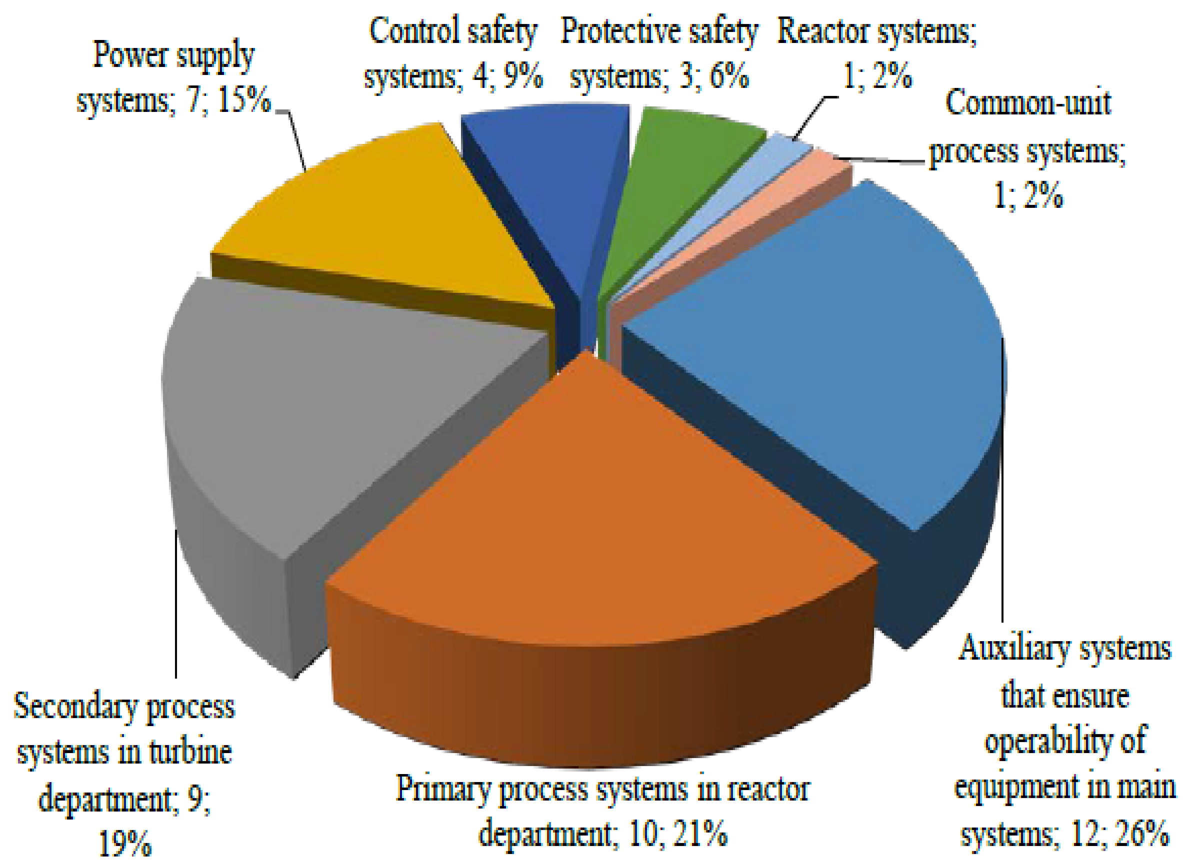
Examples from the data base

No.	Date of event	System	Event	Abnormal occurrence	Code of cause	Description of causes (direct and root)		Stressor	Ageing/degradation mechanism	Consequences	Corrective measures
		3.BA Coolant circulation	Discontinuity in weld No. YB20W connecting primary "c								

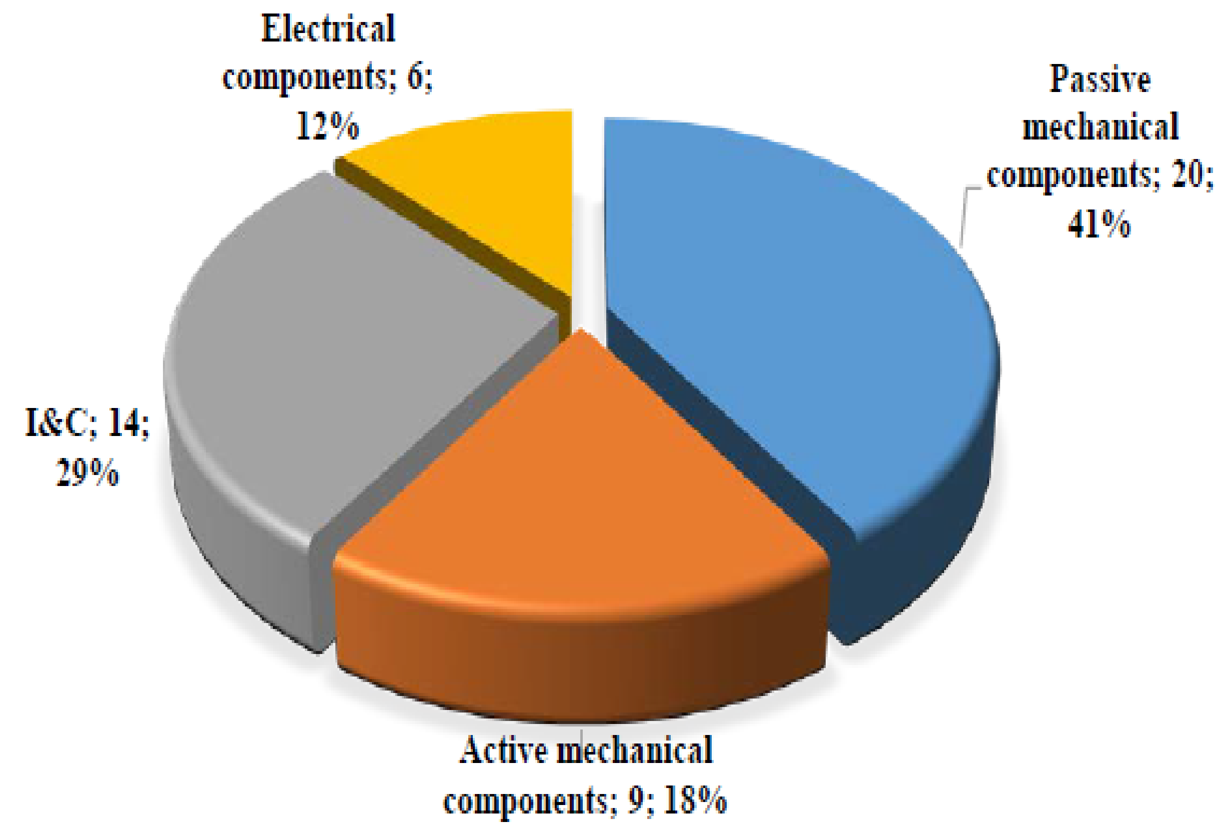
No.	Date of event	System	Event	Abnormal occurrence	Code of cause	Description of causes (direct and root)		Stressor	Ageing/degradation mechanism	Consequences	Corrective measures
											Measure code: 9.10
					5.1.2.1	Damage to the weld from a short circuit at the output of the electric heater to the through pipe (nozzle).		Temperature effect	Thermal ageing	Degradation/ damage	Replace defective PRZ EH tube No. 16. Measure code: 9.2. Inspect the electrical outputs of PRZ EH tubes at Units 1,2,3. Measure code: 9.12. Request the method for restoring (repairing) lead insulators (sealants) of electric heaters from the manufacturer. Measure code: 9.10.
											Contact Energoatom with a proposal on the need to develop an industry program for stage-by-stage replacement of PRZ EH tubes. Measure code: 9.12. Contact the manufacturer (supplier) for information on the criteria showing the PRZ EH condition in which operation of PRZ EH tubes is allowed and in which their operation should be stopped. Measure code: 9.10. Enter information on PRZ EH as an independent piece of equipment into the Ukrainian reliability database. Measure code: 9.12. After receiving a response from the manufacturer, decide on the procedure for the life inspection of PRZ

No.	Date of event	System	Event	Abnormal occurrence	Code of cause	Description of causes (direct and root)		Stressor	Ageing/degradation mechanism	Consequences	Corrective measures
											EHs to extend their service life or replace them. Measure code: 9.10.
3	3 November 2010 19:10	3.GO Overpressure protection system. 4.2.33 Safety valve, membrane.	Failure of equipment important to Ukrainian NPP safety in pre-commissioning testing at Unit 5 caused by a penetration defect in the base metal of the input nozzle of the YP21S02 electrically-driven shut-off valve.	Penetration defect in the base metal of the input nozzle of the YP21S02 valve	5.1.1.3	Damage of the electrically-driven shut-off valve nozzle caused by metal fatigue.		Change of stresses/ strains	Fatigue	Degradation/ damage	
					5.2.1.3	The root cause was design drawbacks of the 5YP21S02 valve.					Send a request to Sempell AG on the extension of technique No. 05.ER.TK.4673 (agreed with the manufacturer and adopted in maintenance of the 5YP21S02 defective region) for strengthening of the nozzles. Measure code: 9.1

Distributions of fails and violations

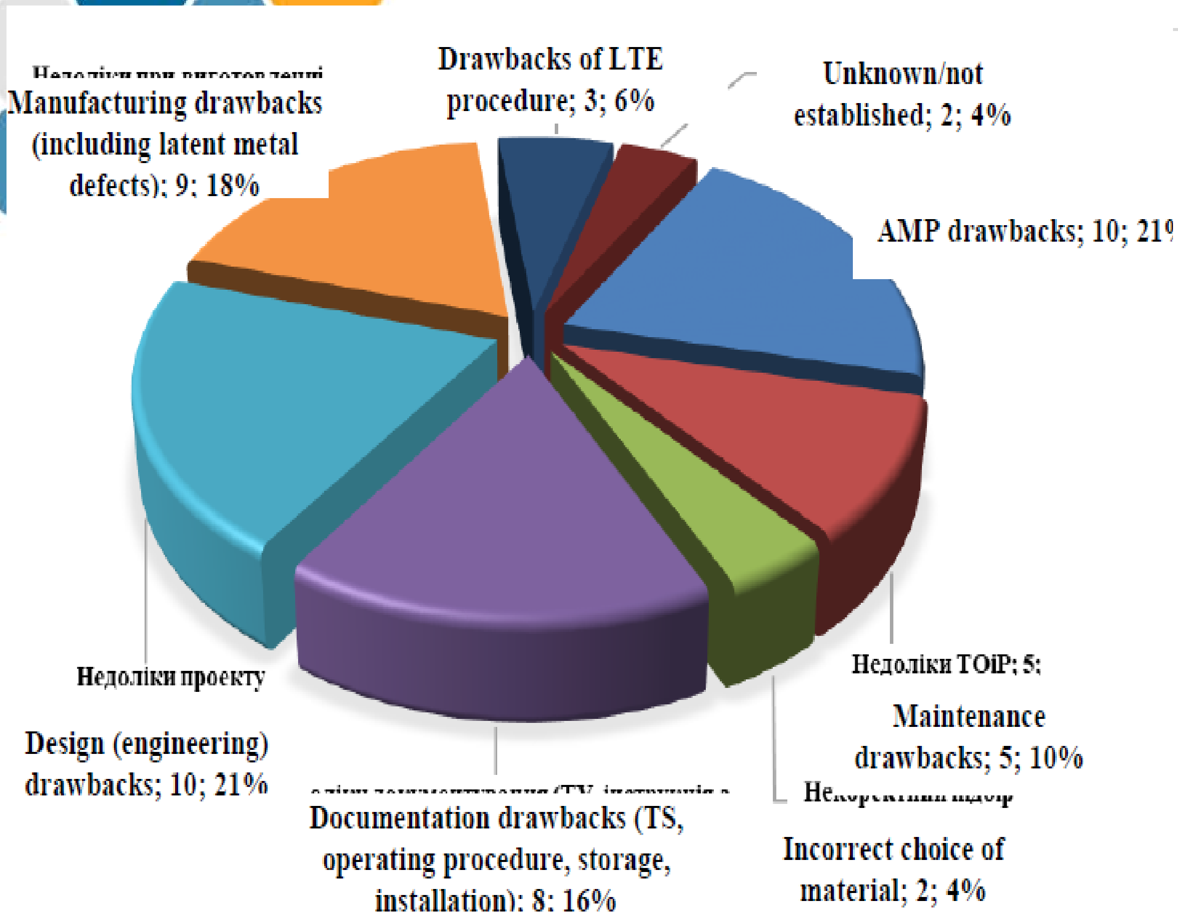


Distribution according to failed of affected **systems**

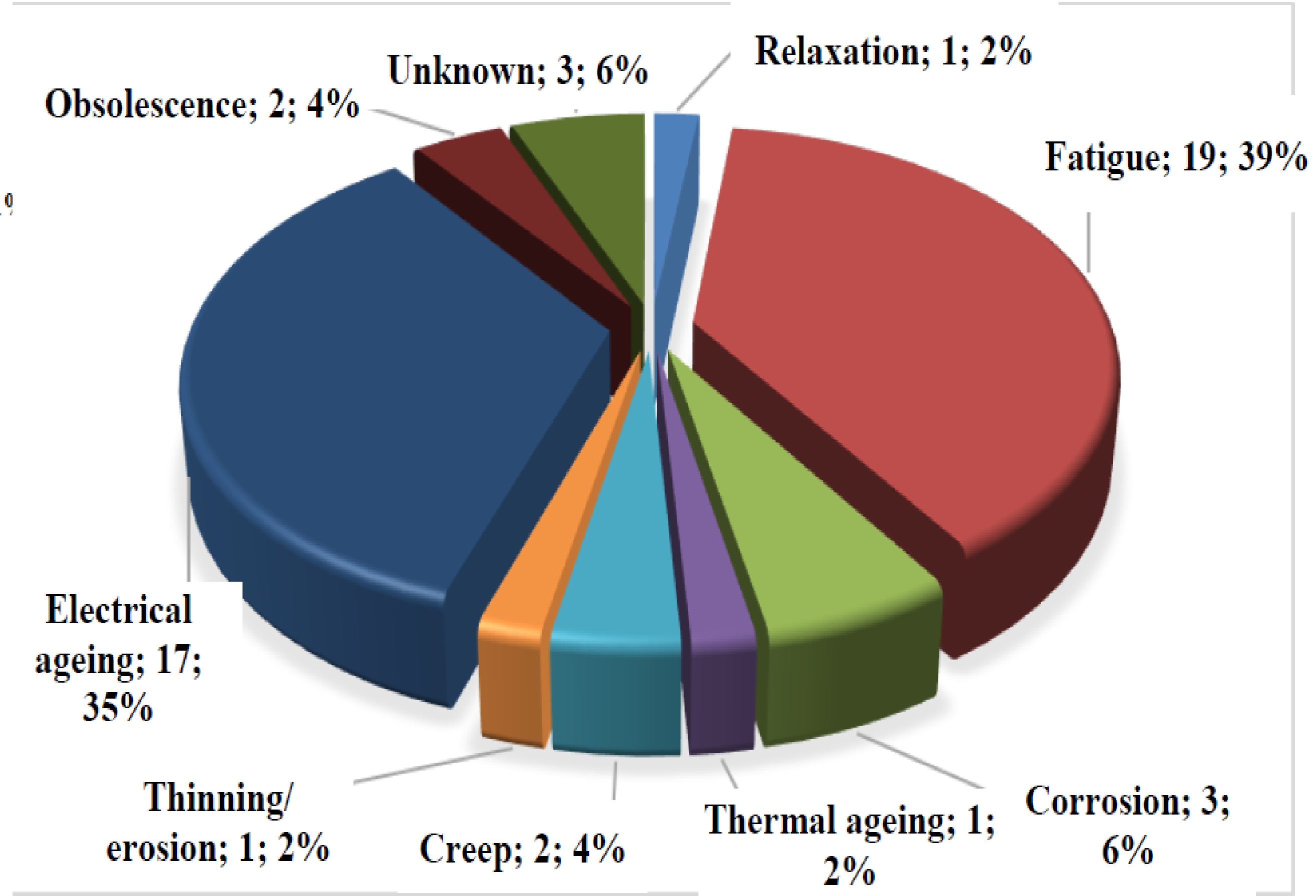


Distribution according to failed of affected **components**

Distributions of fails and violations



Distribution according to root **causes**



Distribution according to degradation mechanisms
that caused events for failed of affected components

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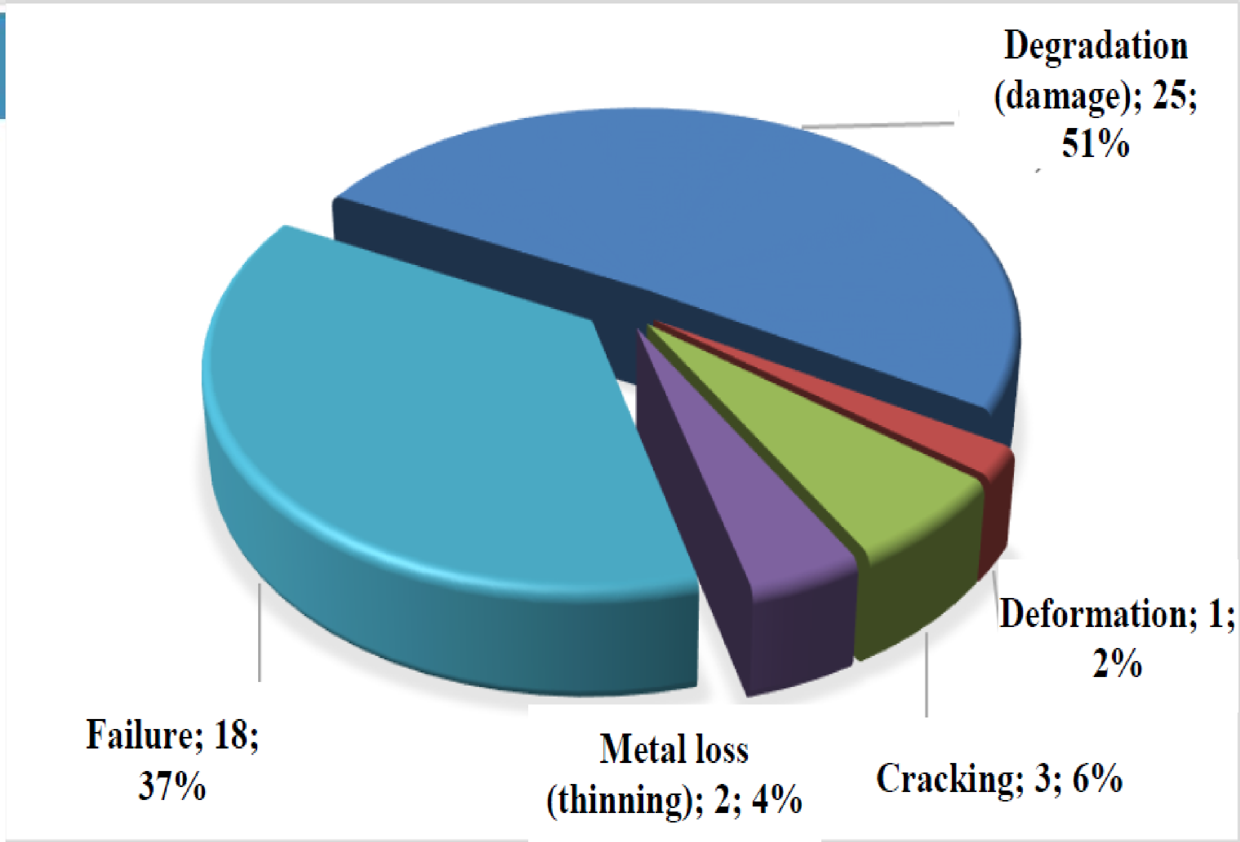
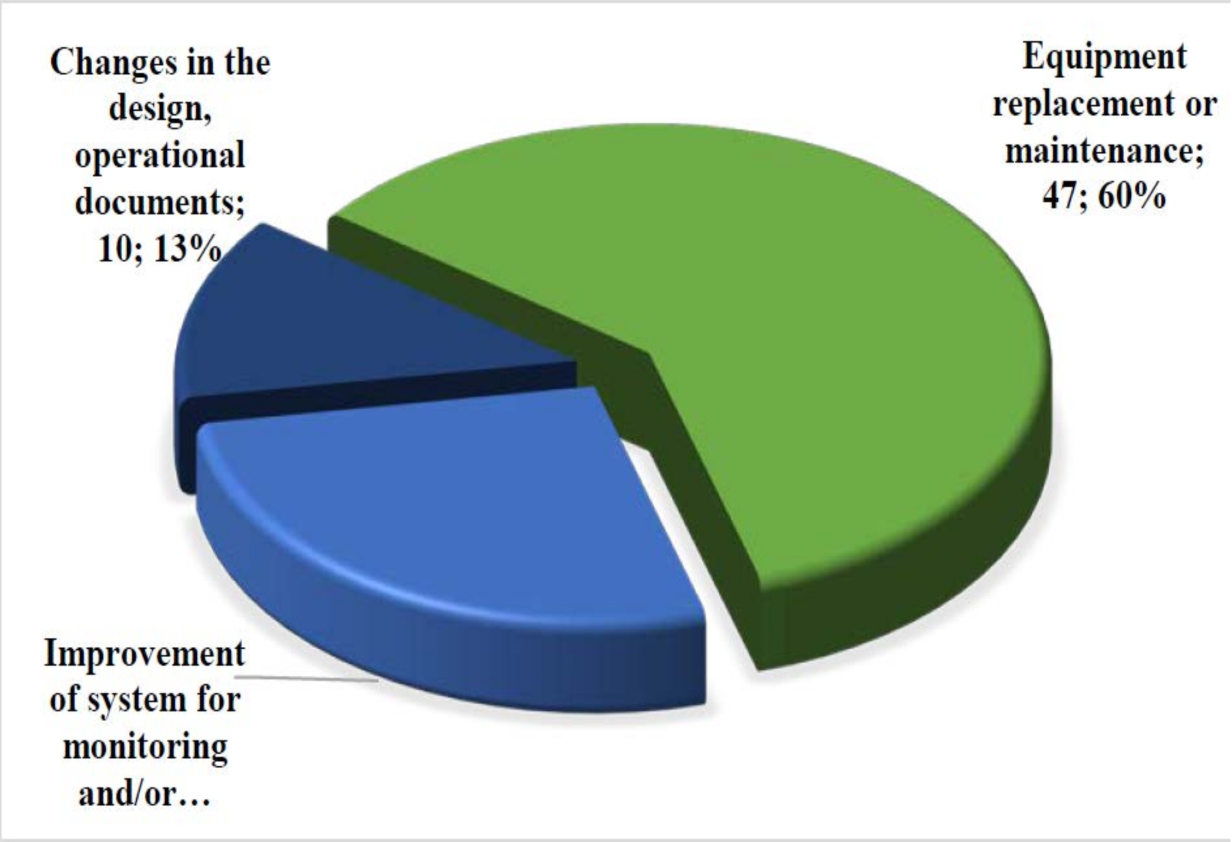
Distributions of fails and violations



Distribution according to ***event cosequences***



Distribution according to ***corrective measures***

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Distribution of Events Based on Ukrainian and International Experience

No.	Analysis area	International results [16]	National results [17]
1	**Number of events by systems**		
	– Reactor systems	**36 %**	**2 %**
	– Power supply systems	**21 %**	**15 %**
	– Auxiliary systems	**13 %**	**26 %**
2	**Failed components**		
	– Passive components	**38 %**	**41 %**
	– Active components	**34 %**	**18 %**
	– Electrical components	**16 %**	**12 %**
	– Components of instrumentation and control system	**9 %**	**29 %**

Distribution of Events Based on Ukrainian and International Experience

No.	Analysis area	International results [16]	National results [17]
3	**Event causes**		
	– Mechanical failure is the main direct cause of ageing-related events	+	+
4	**Root causes**		
	– Drawbacks of maintenance or oversight	**48.7 %**	**10 %**
	– Design drawbacks	**26.5 %**	**21 %**
	– AMP drawbacks	**22.1 %**	**21 %**
5	**Major ageing mechanisms**		
	– Corrosion	**33.6 %**	**6 %**
	– Fatigue	**24.8 %**	**39 %**
	– Electrical ageing	**13.3 %**	**35 %**
	– Wear	**13.3 %**	**2 %**
	– Thermal ageing	**11.5 %**	**2 %**
6	**Major consequences**		
	– Embrittlement and cracking of components	**31.9 %**	**6 %**
	– Loss of material	**26.5 %**	**4 %**
	– Degradation (damage)	-	**51 %**
	– Failure	-	**37 %**
7	**Main corrective measures**		
	– Equipment replacement or maintenance	+	+
	– Improvement of instrumentation and (or) control system	+	+
	– Introduction of change to the design and operational documents	+	+
	– Changes in AMP	+	-
8	**Number of events considered**	**113**	**49**

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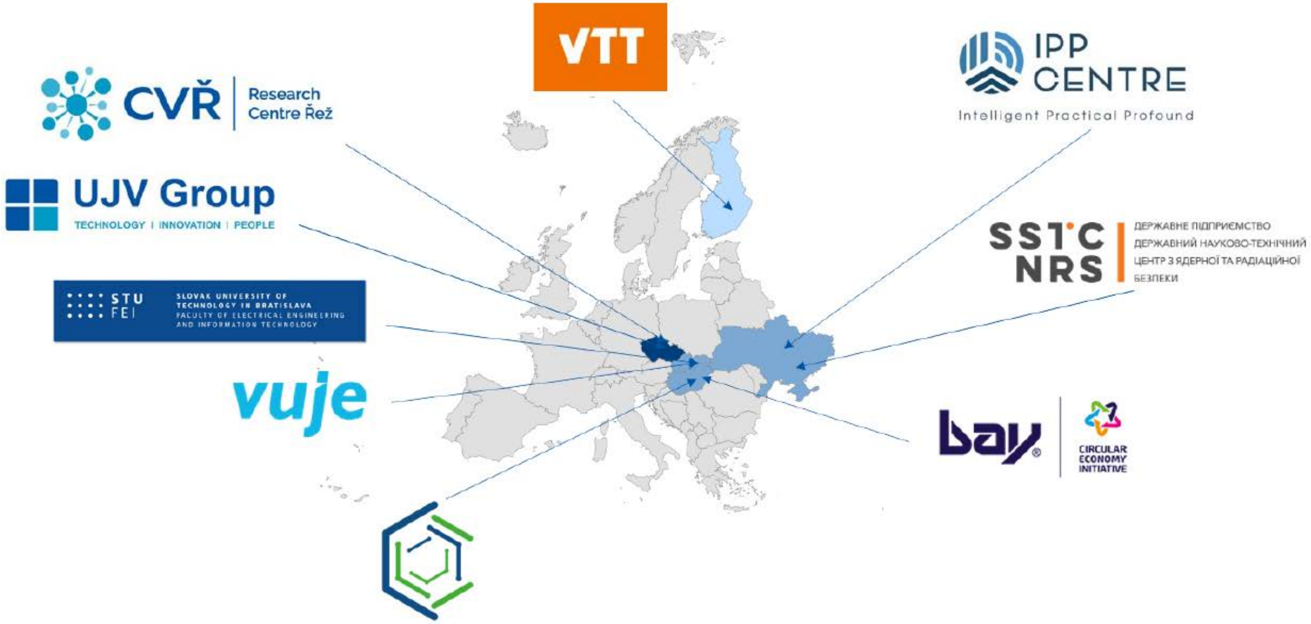
Part II - DELISA-LTO – simulation&modelling, structural integrity

DELISA-LTO project overview

Supported under: HORIZON-EURATOM-2021-NRT-01-01
Total budget & ECcontribution: 3,276,263.06 €
Coordinator: CVŘ(Centrum výzkumu Řež, s.r.o.)



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DELISA-LTO ambitions

Swelling, fatigue degradation, thermal ageing, corrosion damage, and other degradation processes

Swelling
a part of structure that has become bigger because of neutron impact and gamma heating

Thermal aging
refers to long-term, irreversible changes in the structure, composition, and morphology of materials exposed to temperatures that they are typically likely to encounter in service.

Swelling:
Survey and benchmark calculations perform in order to define:
- clearance between core barrel and baffle plate
- evaluate a time of contact between barrel and baffle,
- contact stresses and heat dissipation conditions.

Thermal ageing:
- Main attention focused on the experimental data analyses
- Thermal ageing predictive models performing.

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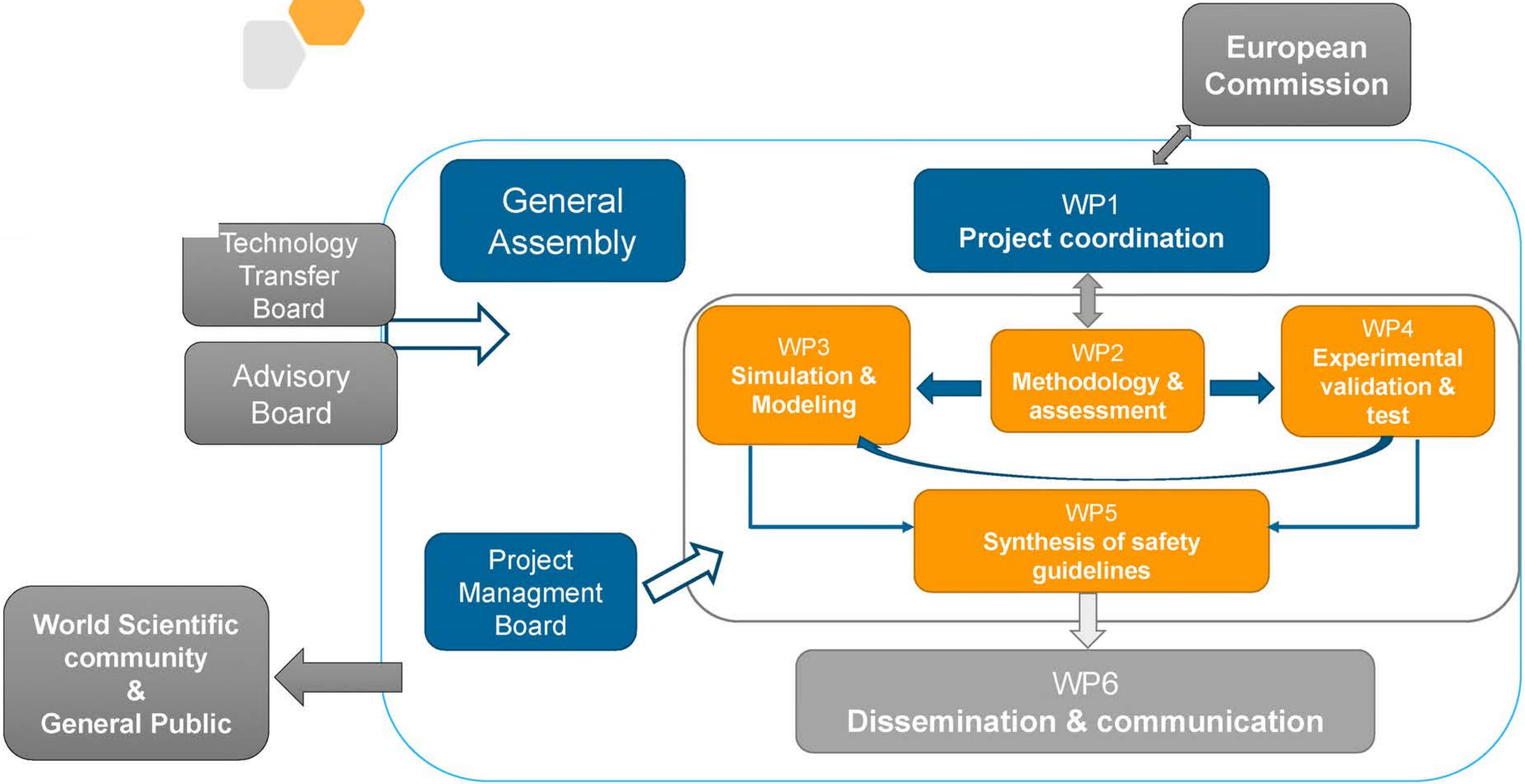

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DELISA-LTO main goals

- To develop a tool for assessment of the NPP's life-time prolongation

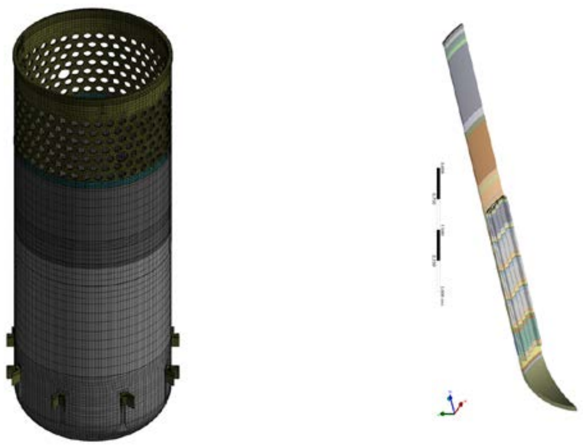
- To provide the international benchmark on modelling of swelling

- To provide the set of recommendations for the future LTO related assessments based on the main project outputs

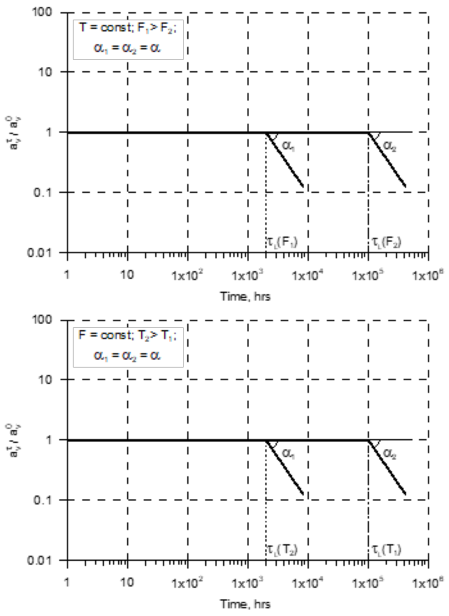
- To harmonize the national methodologies and techniques in order to obtain the generally acceptable set of recommendations for the assessment of the **swelling** and **thermal ageing** from the LTO point of view

Simulation and modelling

- *Simulation and modelling is one of the most important part of any designing or safety justification process*
- *Allow to understand and predict a behavior of elements and components under different operational conditions*
- *Addresses analytical and numerical simulations of –* ***swelling and thermal ageing***



Reactor internals



$$a = \begin{cases} a_o, & \tau < \tau_0 \\ A \cdot \tau^{-q}, & \tau \geq \tau_0 \end{cases}$$

The goals of WP3 are:

- ✓ Analysis of normative approaches, current practice and experience of RPV internals swelling evaluation
- ✓ Developing, testing and validating of models of RPV internals for swelling evaluation (simplified approach, 2D model)
- ✓ Benchmark for swelling evaluation
- ✓ Modeling of thermal ageing

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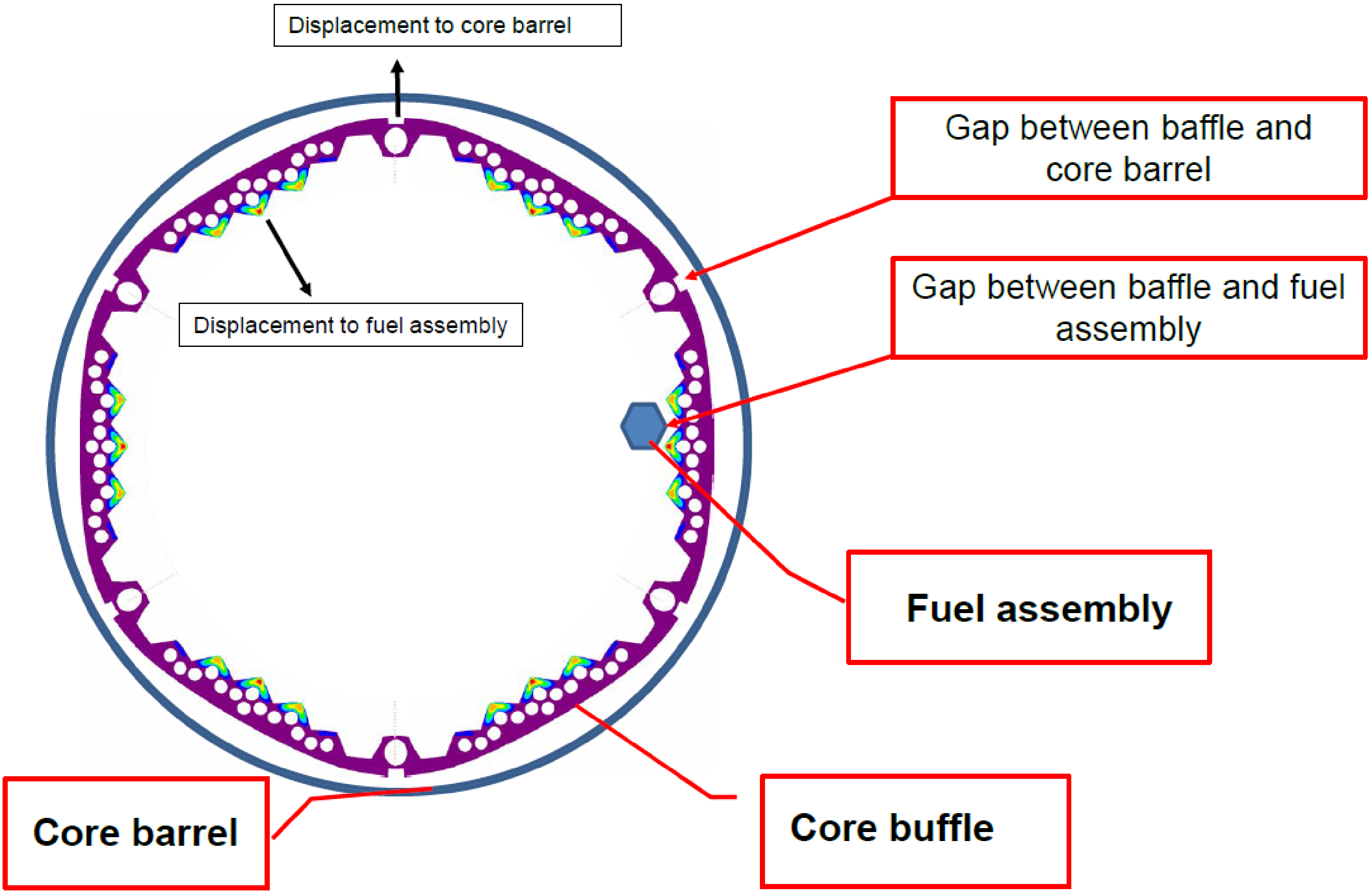
Swelling



Swelling is:

- the main limiting factor from the reactor internals LTO point of view
- one of the Time Limited Ageing Analyses that shall be evaluated for the purpose of LTO justification

Unfortunately presently the experimental data for highly embritteled reactor internals with 08Kh18N10T exist in a very limited scope and verification of calculations is complicated and can be prepared based only on current analytical research results

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Work progress of WP 3

Tasks	Titles	STATUS
Task 3.1	Normative approaches, current practice and experience of RPV internals calculations (swelling evaluation) for LTO justification	Completed
Task 3.2	Developing and testing models of RPV internals for swelling evaluation	Completed
Task 3.3	Benchmark of swelling evaluation	Completed
Task 3.4	Thermal Ageing Evaluation and impacts on LTO	
	- Part I – State of the art on Thermal Ageing Evaluation	Completed
	- Part II – Report on Thermal Ageing	Ongoing

**Deliverable submitted after the due date. All delays happened due to overload of participants and spent time for agreement of structure and content of the report among the participants. Delay was agreed with project coordinator.*

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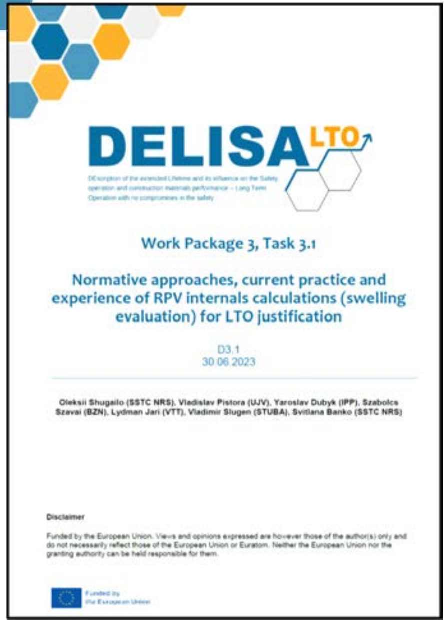
Main results for comparison of normative approach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Work Package 3, Task 3.1

Normative approaches, current practice and experience of RPV internals calculations (swelling evaluation) for LTO justification

D3.1
30.06.2023

Oleksii Shugailo (SSTC NRS), Vladislav Pistora (UJV), Yaroslav Dubyk (IPP), Szabolcs Szavai (BZN), Lydman Jari (VTT), Vladimir Slugen (STUBA), Svitlana Banko (SSTC NRS)

Disclaimer

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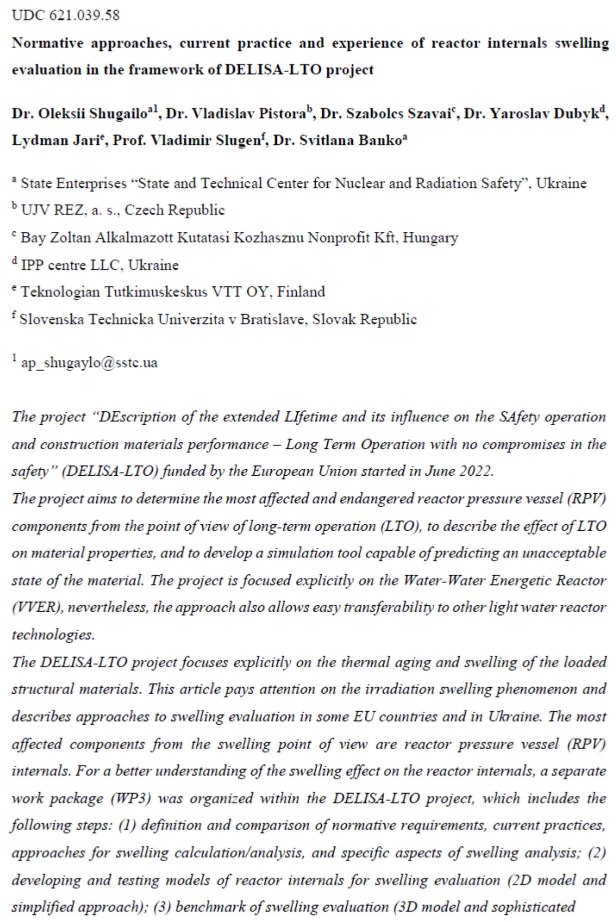
***Report** D3.1 is completed*

The main conclusions of the survey:

- Swelling is one of most important issues and leads to formal limitation of LTO
- The requirements for swelling evaluation are similar in all participating countries
- The main issue concerning the swelling evaluation of RVI lies in the empirical mathematical model of irradiation induced swelling/creep of 08Kh18N10T steel and lack of the failure criteria for the irradiated components
- Initial data for benchmark calculations have been prepared


UDC 621.039.58

Normative approaches, current practice and experience of reactor internals swelling evaluation in the framework of DELISA-LTO project

Dr. Oleksii Shugailo[a1], Dr. Vladislav Pistora[b], Dr. Szabolcs Szavai[c], Dr. Yaroslav Dubyk[d], Lydman Jari[e], Prof. Vladimir Slugen[f], Dr. Svitlana Banko[a]

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The project “DEscription of the extended LIfetime and its influence on the SAfety operation and construction materials performance – Long Term Operation with no compromises in the safety” (DELISA-LTO) funded by the European Union started in June 2022.
The project aims to determine the most affected and endangered reactor pressure vessel (RPV) components from the point of view of long-term operation (LTO), to describe the effect of LTO on material properties, and to develop a simulation tool capable of predicting an unacceptable state of the material. The project is focused explicitly on the Water-Water Energetic Reactor (VVER), nevertheless, the approach also allows easy transferability to other light water reactor technologies.
The DELISA-LTO project focuses explicitly on the thermal aging and swelling of the loaded structural materials. This article pays attention on the irradiation swelling phenomenon and describes approaches to swelling evaluation in some EU countries and in Ukraine. The most affected components from the swelling point of view are reactor pressure vessel (RPV) internals. For a better understanding of the swelling effect on the reactor internals, a separate work package (WP3) was organized within the DELISA-LTO project, which includes the following steps: (1) definition and comparison of normative requirements, current practices, approaches for swelling calculation/analysis, and specific aspects of swelling analysis; (2) developing and testing models of reactor internals for swelling evaluation (2D model and simplified approach); (3) benchmark of swelling evaluation (3D model and sophisticated

*- **Article** – published in the Journal “Problems of strength”*

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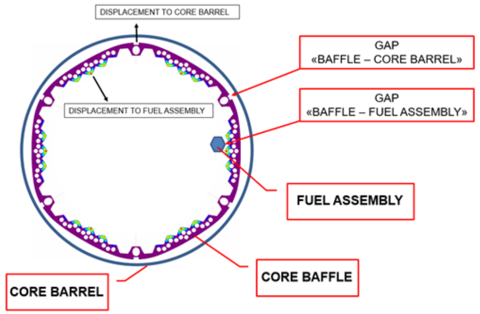
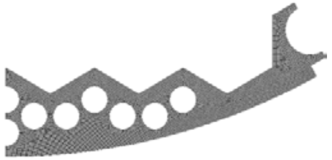
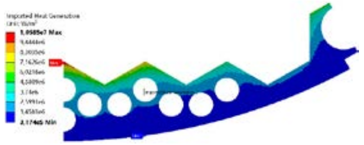
Main results for simplified model

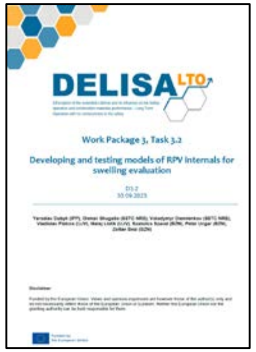


1) Researching of the impact of swelling on the exhausting of gaps between "*buffle-fuel assembly*" and "*buffle-core barrel*"





2) Developing of simplified buffle model (2D)



***Report** D3.2 is completed*

Parameter		IPP	SSTC	UJV	BZN
FEM code		ANSYS	ANSYS	Abaqus	MSC.Marc
Model type		2D Plane strain generalised	3D 1 mm height coupled upper surface	2D Plane strain generalised	2D Plane strain generalised
Element type		quadratic	quadratic	quadratic	quadratic
Time steps for 1 campaign		100	10	2	10
Max. temperature	°C	385,0	386,0	385,6	385,4
Max. von Mises stress	MPa	287,8	200,1	251,8	220,5
Min. axial stress	MPa	-153,7	-153,8	-162,8	-155,4
Max. axial stress	MPa	159,4	119,9	146,2	130,2
Max. vol. swelling strain	%	5,97	6,22	6,20	6,13
Max. equiv. creep strain	%	2,35	2,36	2,46	2,37

3) Using different software (ANSYS, ABAQUS and MSC.MARC)

4) **Conclusions**:

- ✓ Simplified 2D model has been developed and validated;
- ✓ All participants provided comprehensive and technically well-founded results for the 2D simplified benchmark for swelling evaluation;
- ✓ Good accordance was achieved between the benchmark results and basis for benchmark with 3D has been created
- ✓ Most of the 3D effects of core baffle geometry, loading and boundary conditions will be considered within T3.3

Article – completed

DELISA LTO
Description of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

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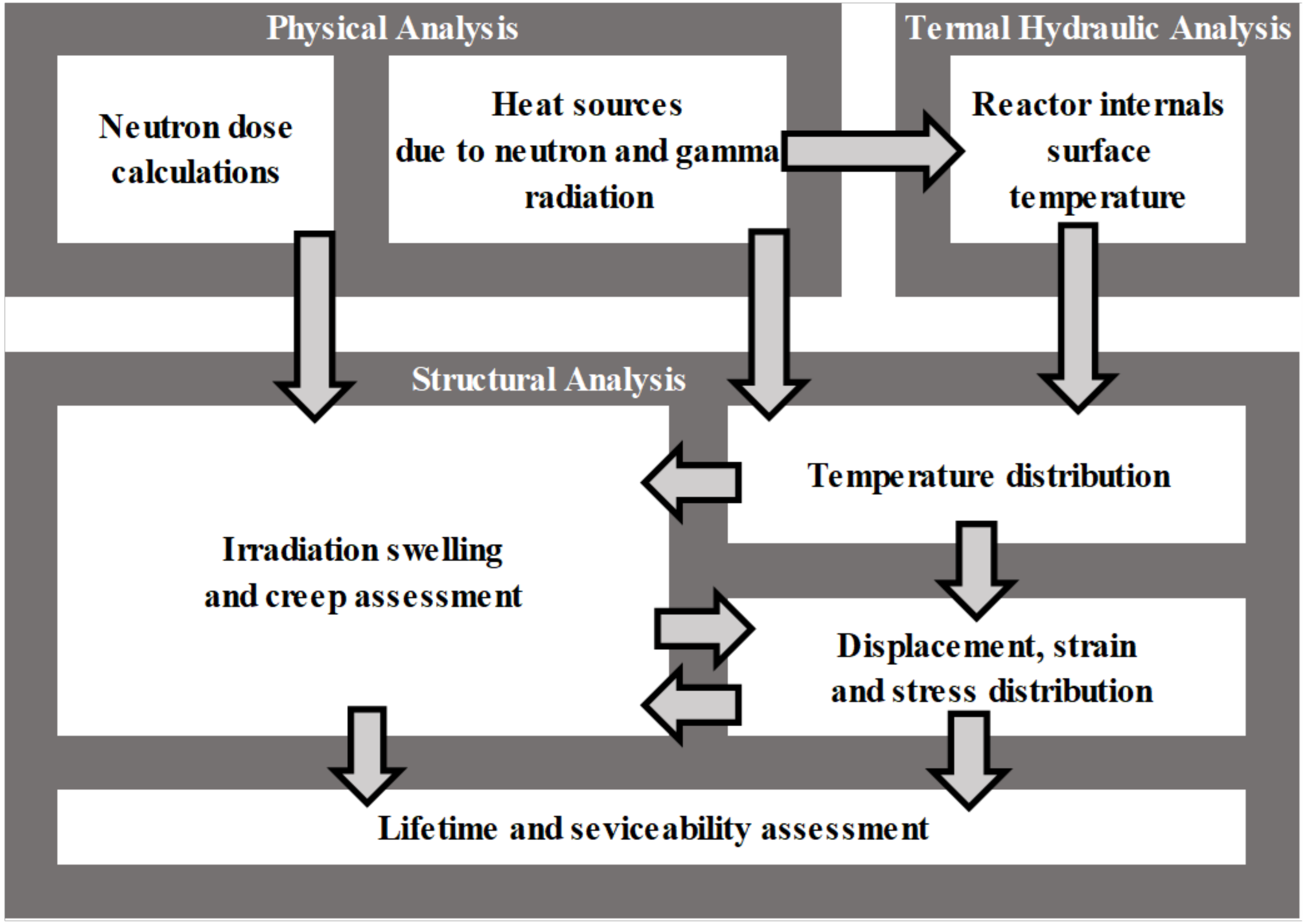
Main results of the benchmark

Motivation of DELISA-LTO swelling benchmark:

1. Conducting the benchmark analysis, encompassing:
   - ✓ mechanical evaluations that account for stress-dependent irradiation swelling
   - ✓ creep behavior
   - ✓ plasticity impact
2. Analysis of the obtained results
3. Determination of areas of uncertainty
4. Conducting of sensitivity study
5. Formulation of optimal practices and recommendations



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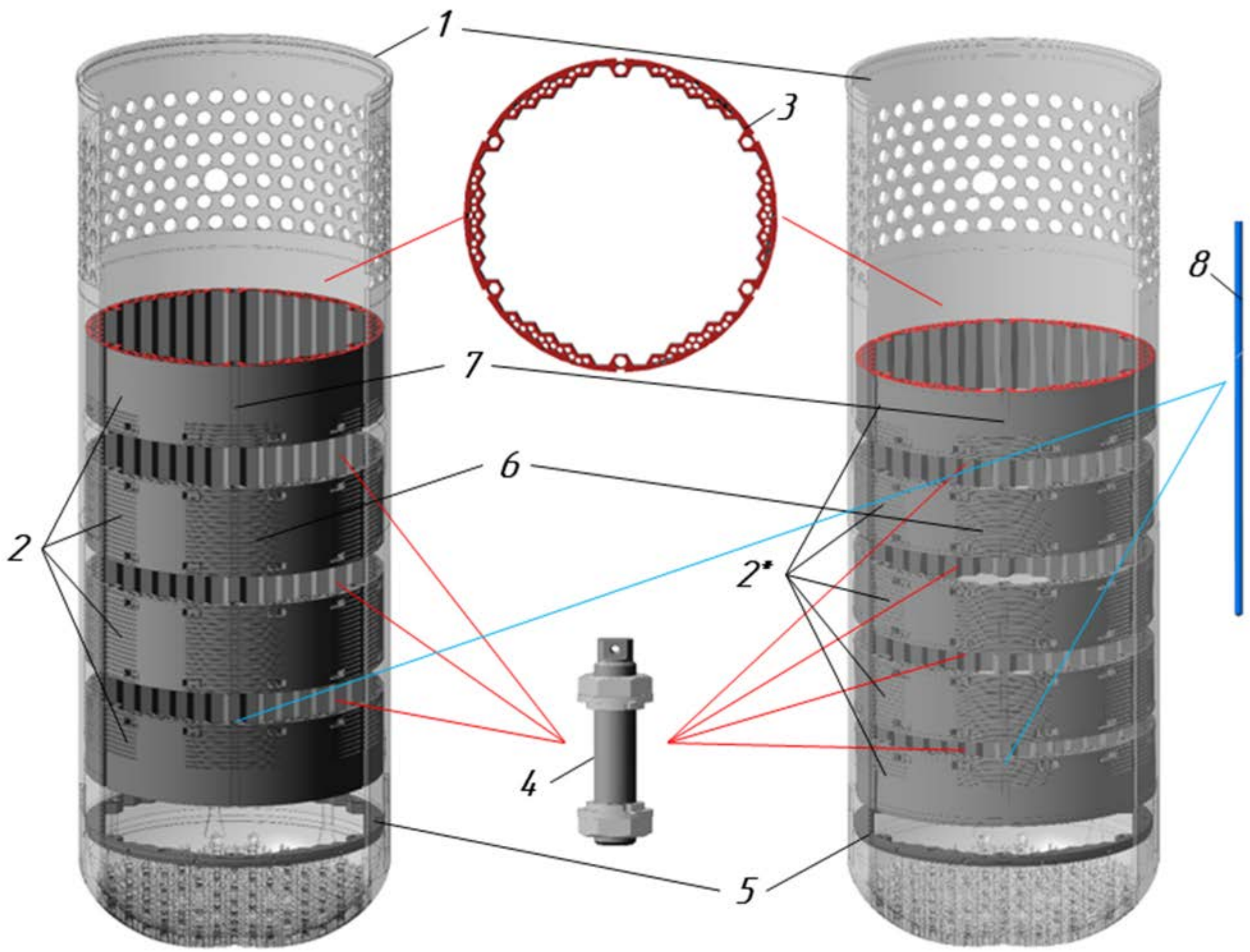
Main results of the benchmark

1 - Core Barrel
2,2* – Baffle rings (4 or 5)
4 – Pins (Bolts)
5 – Facet belt
3 – Baffle cross-section
6 – Cooling ribs
7 – Vertical cooling groove
8 - Tube

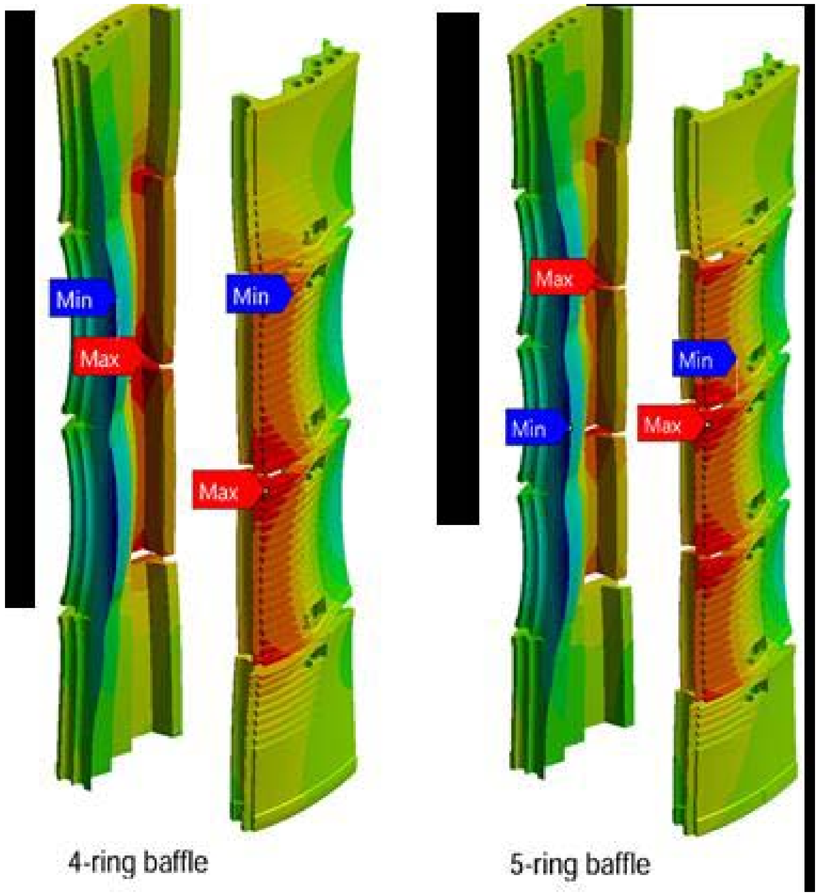


Benchmark conclusions

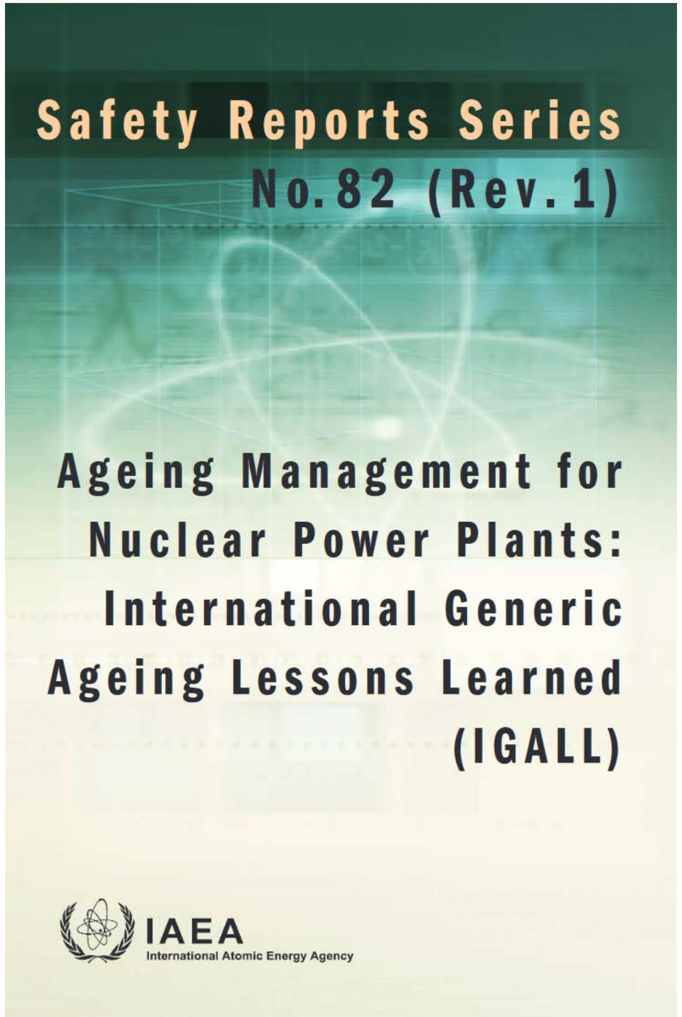
Swelling is the main limiting factor for LTO operation of PVI.

Based on the benchmark results obtained for the temperatures, stresses, swelling and creep strains and displacements it can be concluded:

- The maximum temperature 384 °C is reached in the 3rd ring (zone with maximum internal heat source)
- The maximum volumetric swelling strain (about 9% after 80th campaign) is reached in the 3rd ring (due to maximum temperature and dpa in the vicinity)
- The maximum equivalent creep strain (about 3% after 80th campaign) is reached in the 3rd ring



Thermal ageing



Safety Report Series No.82

- TLAA110 Thermal Ageing of Cast Austenitic Stainless Steels
- TLAA116 Thermal Ageing of Low Alloy Steels

✓ The project investigates archived NPP materials exposed to operational conditions for up to 30 years and

✓ Those with accelerated thermal ageing under laboratory conditions with the degradation effect equivalent to operation conditions for 60 years

✓ *The works for thermal ageing research are under preparing ….*

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Conclusions

- LTO is unarguably economically advantageous compared to other power sources and provides a great advantage
- Ageing Management as a basis for successful LTO nad based on Time Limited Ageing Analysis
- There are a lot of degradation mechanisms that lead to different ageing effects but ***swelling*** and ***thermal ageing*** need to be investigated more detail
- DELISA-LTO deals with and these phenomena under evaluation right now

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Thank you for attention!

DELISA LTO

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Thermal ageing in NPP and its effect on Long-term operation

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DELISA-LTO

Workshop on Application of non-destructive testing (NDT) methods in characterisation of long-term treated NPP design materials

12.02.2025, Kočovce / Online

DELISA LTO
DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

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Contents

Introduction

- Thermal ageing
- WWER-440 and WWER-1000 design

Monitoring of the thermal ageing degradation for WWER Units in Ukraine and thermal ageing effect on LTO

- Reactor Pressure Vessel
- Components and piping of primary and secondary circuits

Intro. Thermal ageing

Mechanisms of thermal ageing (literature background)

In some materials a diffusion-controlled precipitation mechanism is active even at service temperatures. This process called thermal aging leads to a loss of ductility, deformability and toughness. The significant parameters responsible for these processes are:

– temperature;

– material state (microstructure, type of steel);

– time.

The conditions required for thermal aging include having an "unstable" material (with a quenched structure in particular) in which the atoms are able to rearrange themselves by diffusion. The rate of diffusion is higher for bainitic low-alloy steels or ferritic and martensitic (body-centered cubic) stainless steels than for austenitic steels or alloys (face-centered cubic structure).

Intro. Thermal ageing

Mechanisms of thermal ageing (literature background)

The two main phenomena causing thermal aging are:

– intergranular segregation of phosphorus in martensitic and bainitic steels

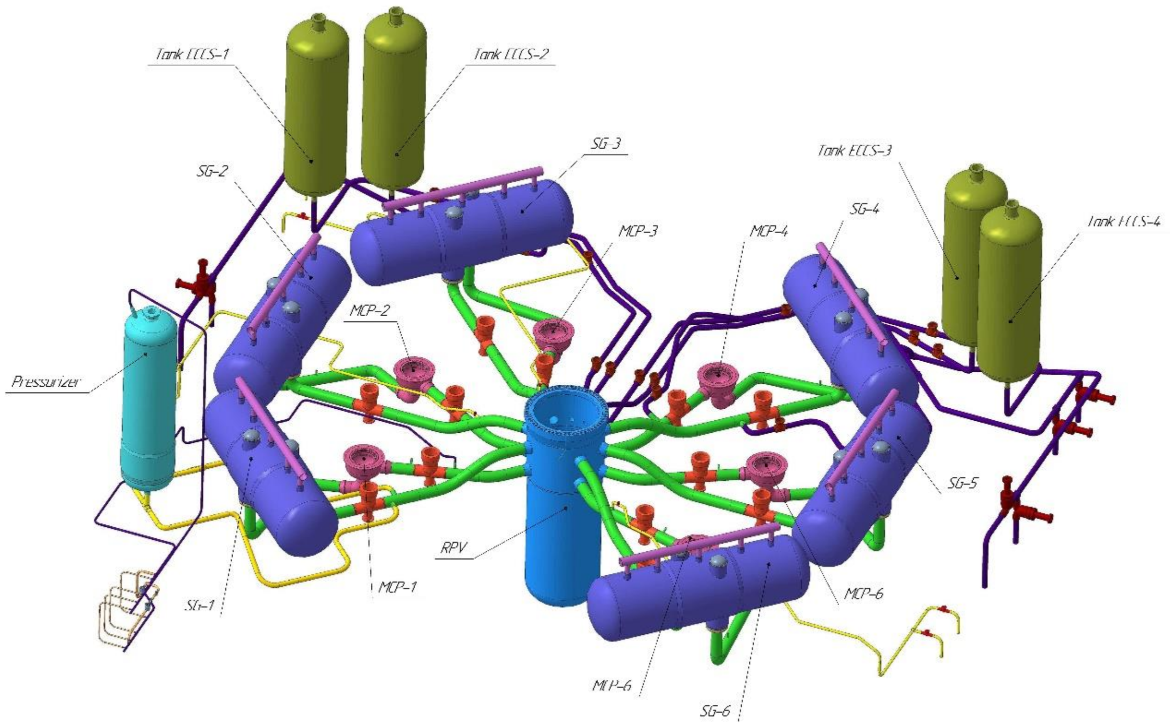
– "unmixing" of chromium from its solid solution in the ferrite of duplex austenitic-ferritic stainless steels and in martensitic stainless steels

RPV materials and low alloy steels. Number of processes could lead to the embrittlement these steels subjected to long-term service at elevated temperatures. These processes include: formation of hardening phases, such as copper-rich precipitates; segregation of phosphorus to grain boundaries leading to a lower intergranular fracture stress; and segregation of impurities to dislocations leading to strain aging.

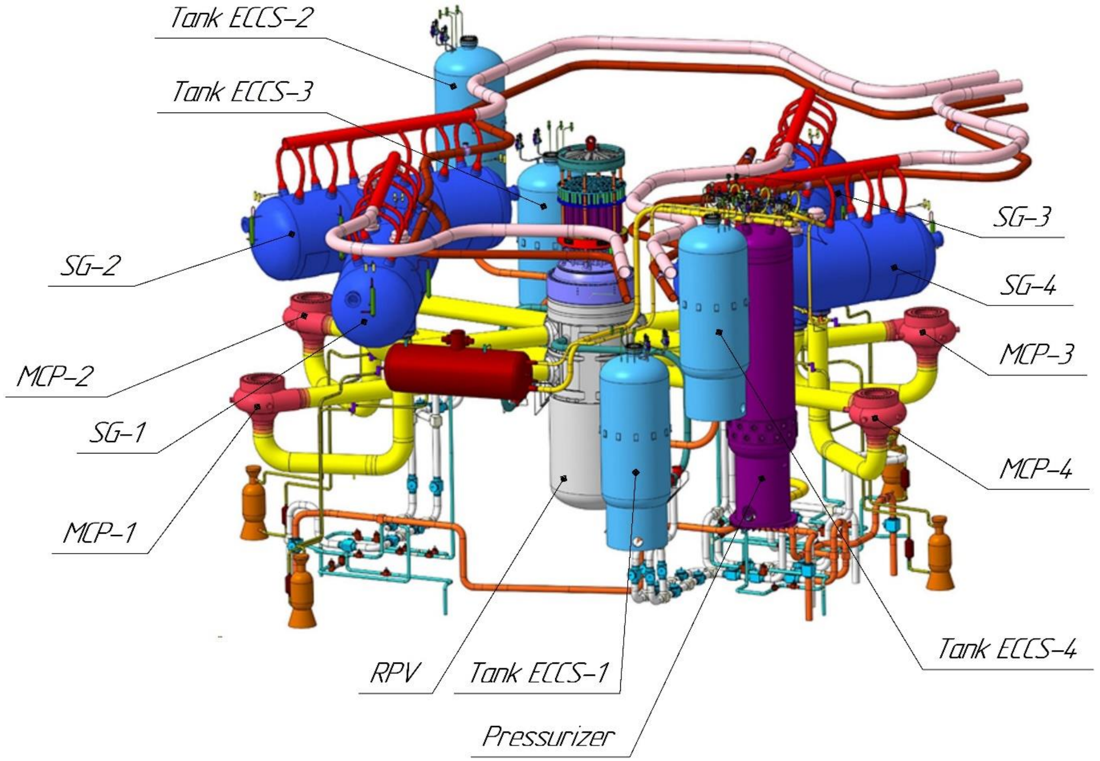
Thermal ageing of cast stainless can lead to precipitation of additional phases in the ferrite, e.g. formation of Cr-rich α–prime, phase by spinoidal decomposition; nucleation and growth of α -prime; precipitation of a Ni- and Si-rich phase, and growth of existing carbides at the ferrite/austenitic phase boundaries

Intro. Design of WWER NPP

Primary system layout of a WWER-440
(model V-230)



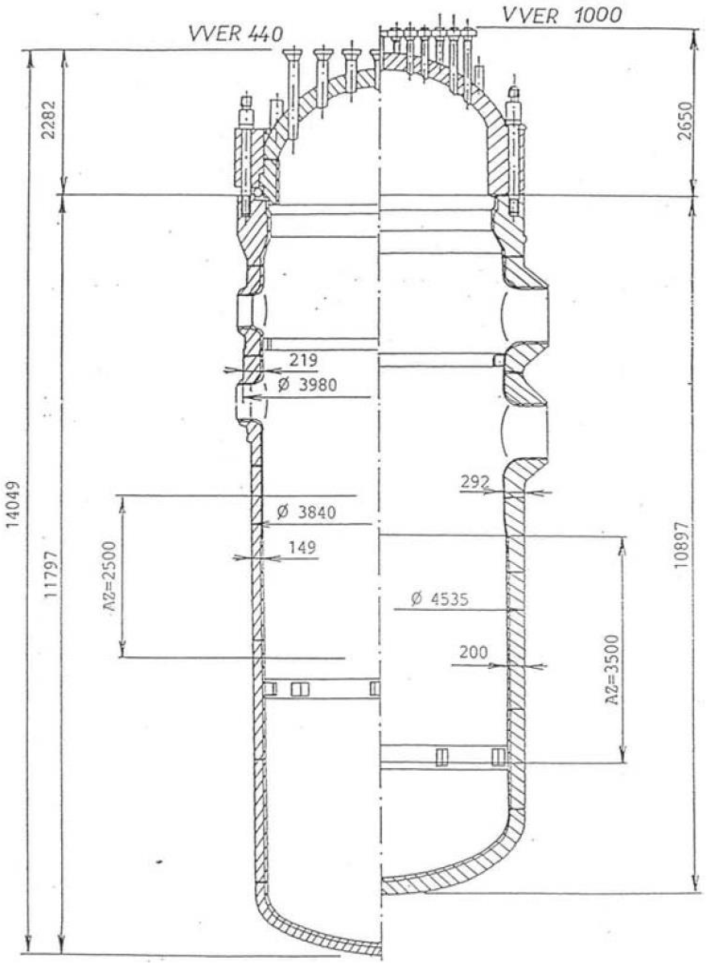
Primary system layout of a WWER-440
(model V-320)



Intro. Design of WWER NPP

WWER design parameters

Reactor	WWER-440		WWER-1000
	V-230	V-213	V-320
Mass (t)	215		320
Length (m)	11.800		11.000
Outer diameter (m)			
in cylindrical ring	3.840		4.535
in nozzle ring	3.980		4.660
Wall thickness without cladding (m)			
in cylindrical part	0.140		0.193
in nozzle ring	0.190		0.185
Working pressure (MPa)	12.26		17.65
Design pressure (MPa)	13.7		19.7
Hydrotest pressure (MPa)	17.1	19.2	24.6
Operating wall temperature (°C)	265		288
Design wall temperature (°C)	325		350
Design vessel lifetime (y)	30	40	40



Thermal ageing of the WWER RPV

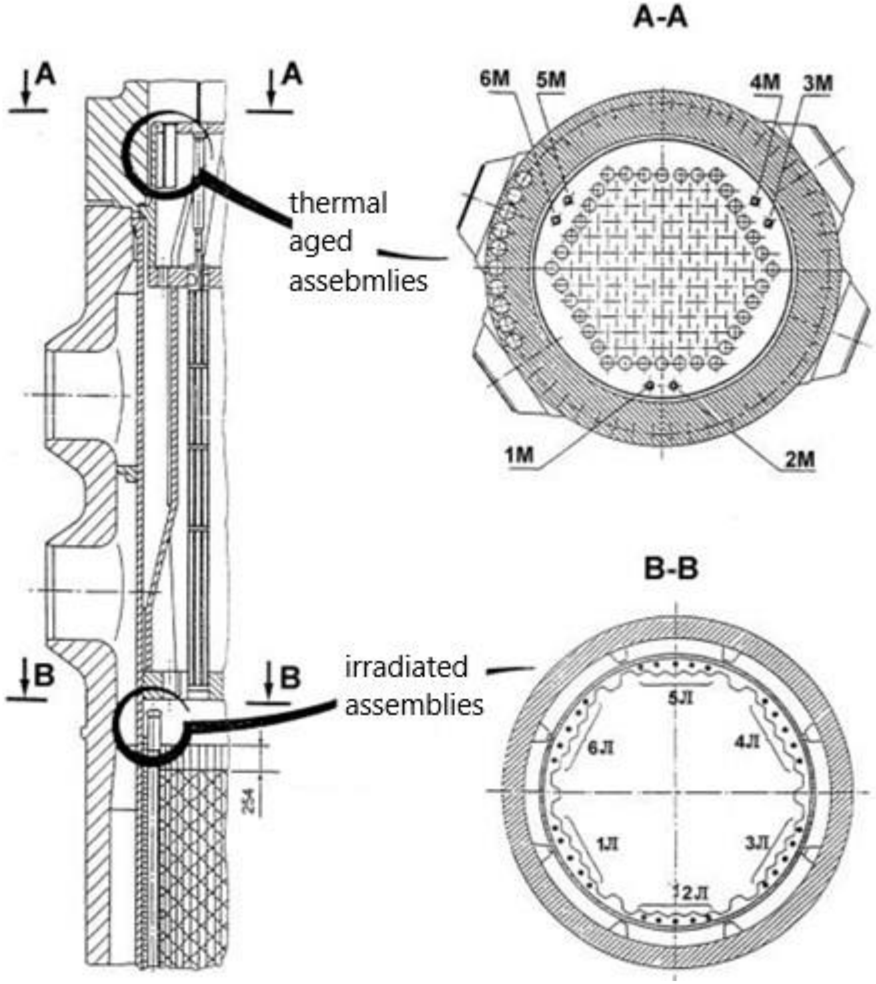
Monitoring of the RPV ageing

- Thermal ageing (embrittlement)
- Radiation embrittlement

WWER-1000 surveillance assemblies

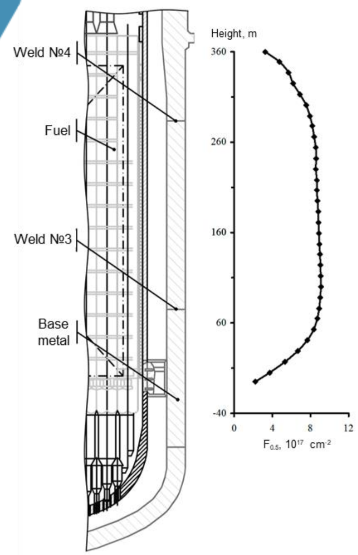
WWER-440 surveillance capsules

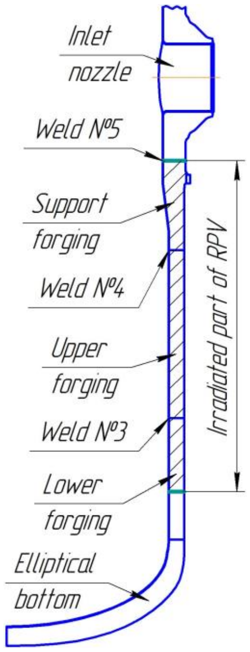
WWER-1000 surveillance assembly for thermal ageing monitoring

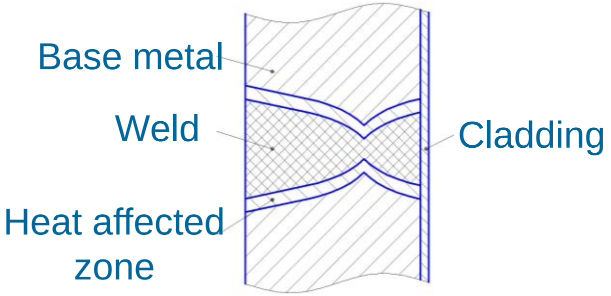


Thermal ageing of the WWER RPV

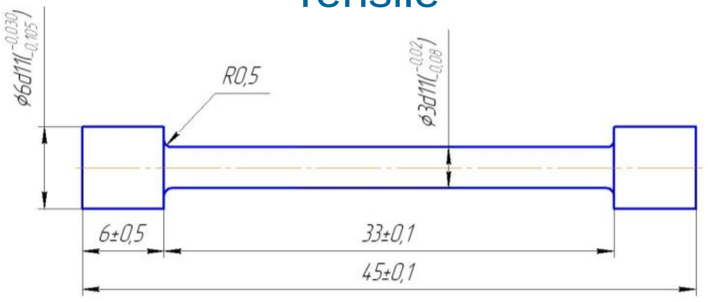
Monitoring of the RPV ageing



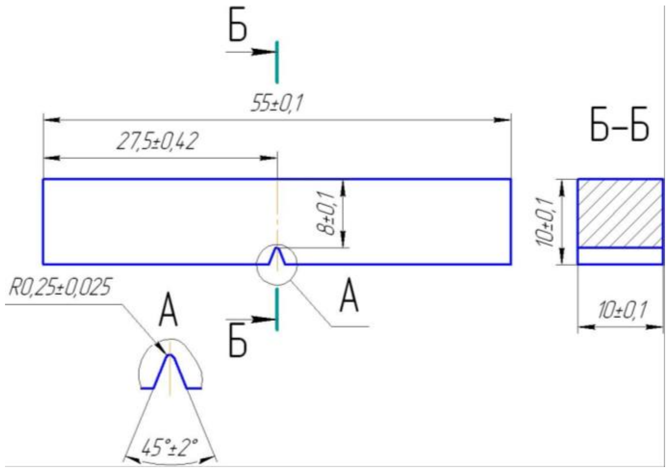




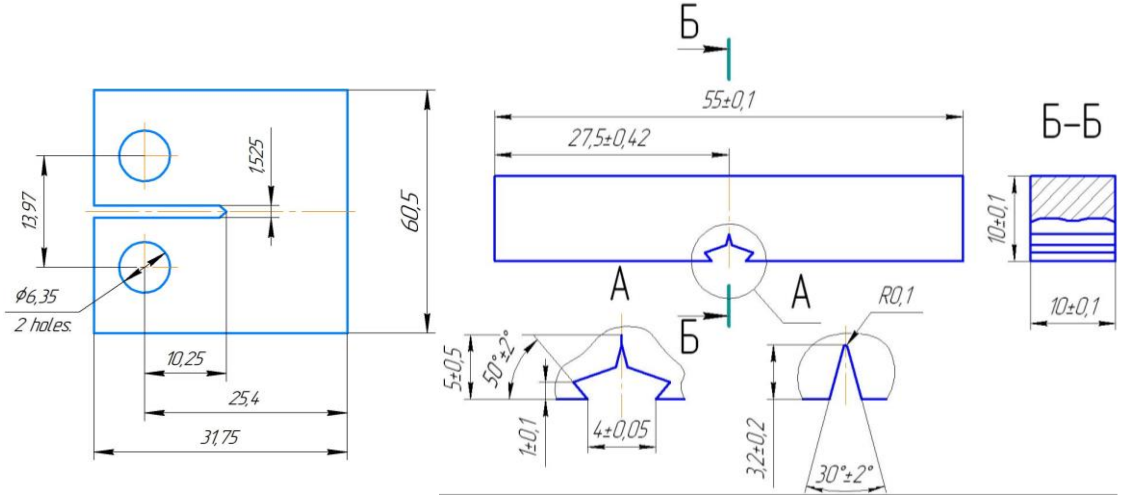
Tensile



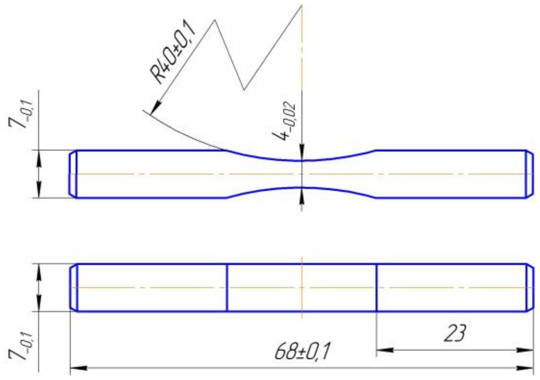
Charpy



Fracture Toughness



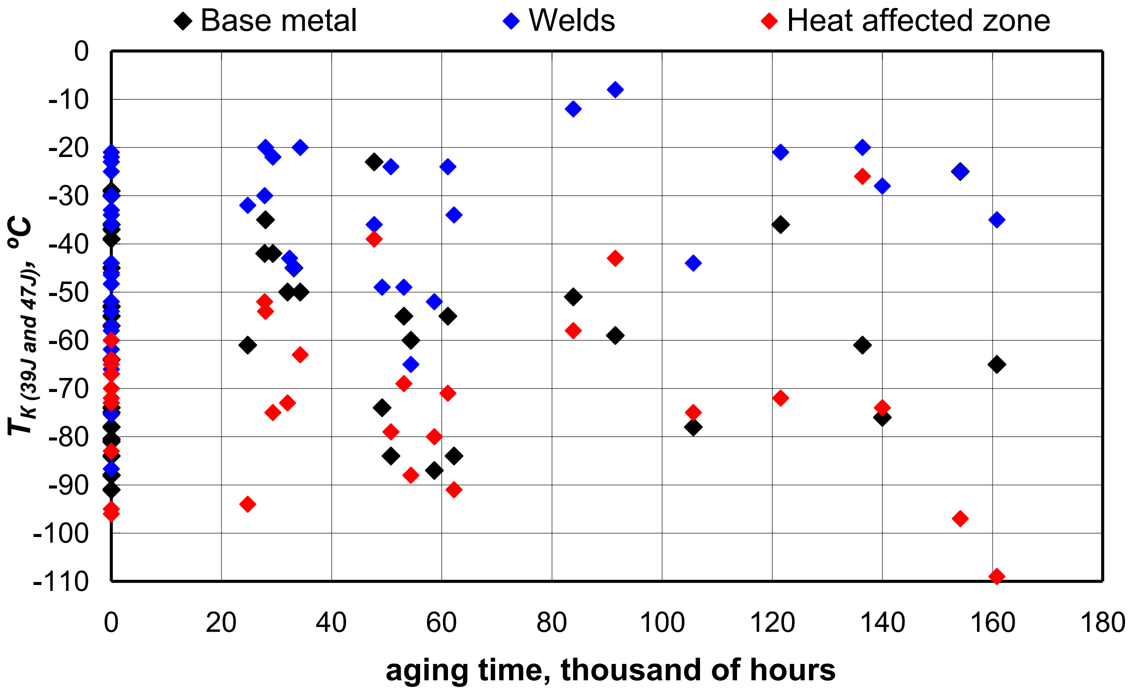
Low cycle fatigue



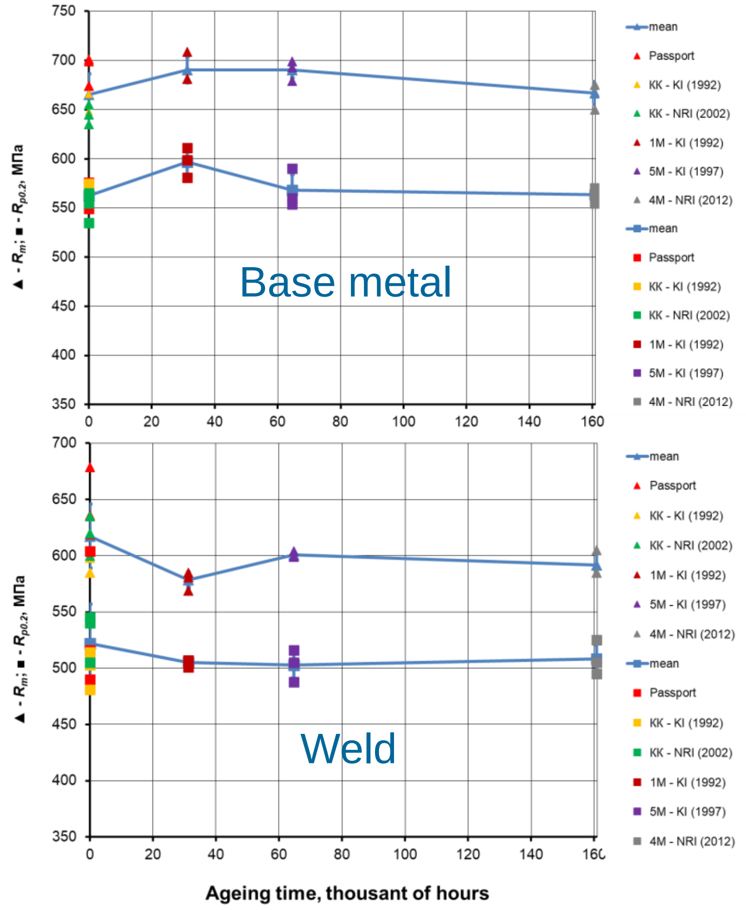
Thermal ageing of the WWER RPV

Results for WER-1000 RPVs

CTB (transition temperature)



Yield and Ultimate stresses of a one RVP



Thermal embrittlement is obtained mainly because that the initial and aged data are characterized by the scatters

Ageing of the WWER RPV

RPV lifetime assessment

The crack initiation criteria, all along the crack tip is based on the following

$$K_I(Loads, Temperature, Time) \leq K_{IC}(Temperature, Neutron\,Fluence)$$

K_I - Stress Intensity Factor along crack tip

K_{IC} - Fracture Toughness (FT) of the material

$\Delta T_{ka} \geq 0$

(criterion #1)

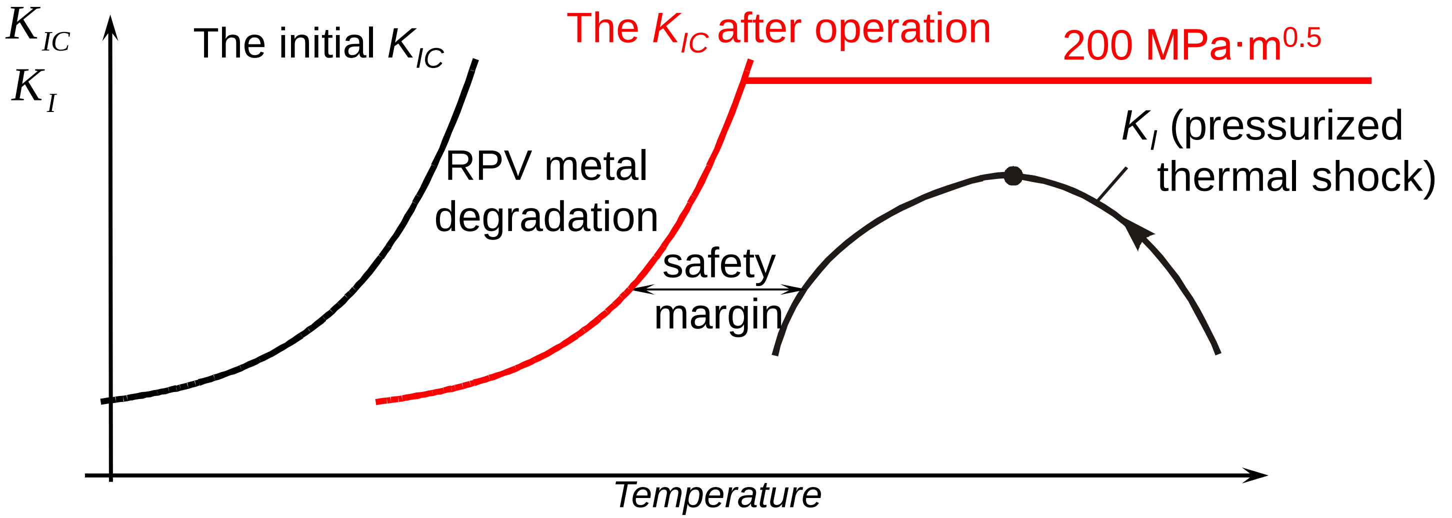
$K_I \leq 200\,MPa\sqrt{m}$

(criterion #2)

$J_{1mm,cladding} \leq 150\,kJ/m^2$

(criterion #3)

RPV metal is subjected to the neutron embrittlement and thermal embrittlement which leads to the K_{IC} decreasing



Thermal ageing of the WWER RPV

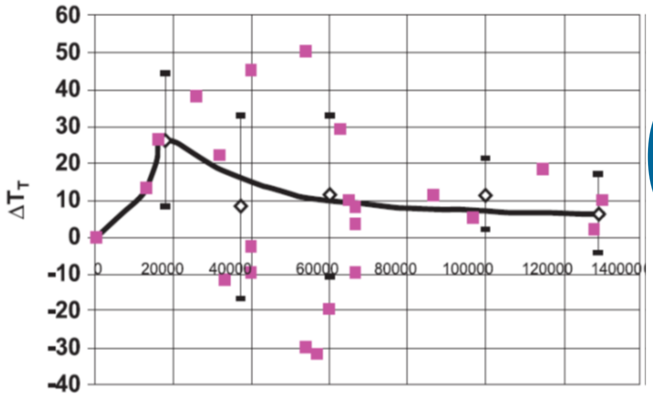
Approaches for RPV thermal ageing

Thermal embrittlement

RPV zone	ΔT_T, ºC			
	SOU NAEK 087:2023	PNAE G-7-002-86	MRKR-CKhR-2004	VERLIFE
Base material	0	0	30	30 $t \geq 1\times10^5$ hours
Weld	[illegible]	0	[illegible]	–

NO IMPACT ON LTO

Russian TSNIINMASH (ЦНИИТМАШ) data



Time of ageing, hours

[illegible]mpiri[illegible] formu[illegible] for [illegible]he[illegible] embrittlement

$$\Delta T_T = 4[illegible].982 - 46.[illegible]66[1 - e^{-0.000185\cdot t}]$$

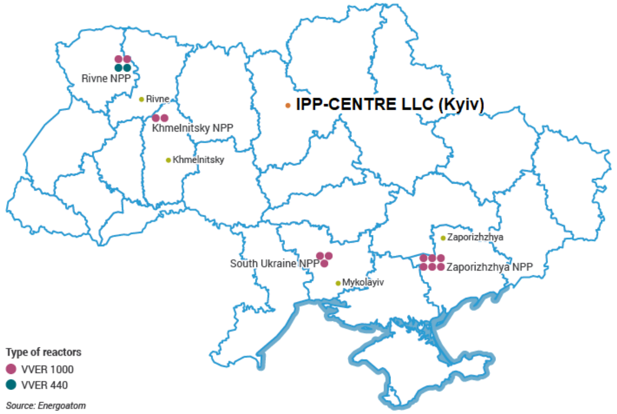
3.6°C for 60 years

Hardening (change in Yield and Ultimate stress) is not considered for LTO

LTO status of Ukrainian WWER Units

Zaporizhua NPP

South-Ukrainian NPP



Rivne NPP

Khmelnytskiy NPP

Service Lifetime of Ukrainian NPPs

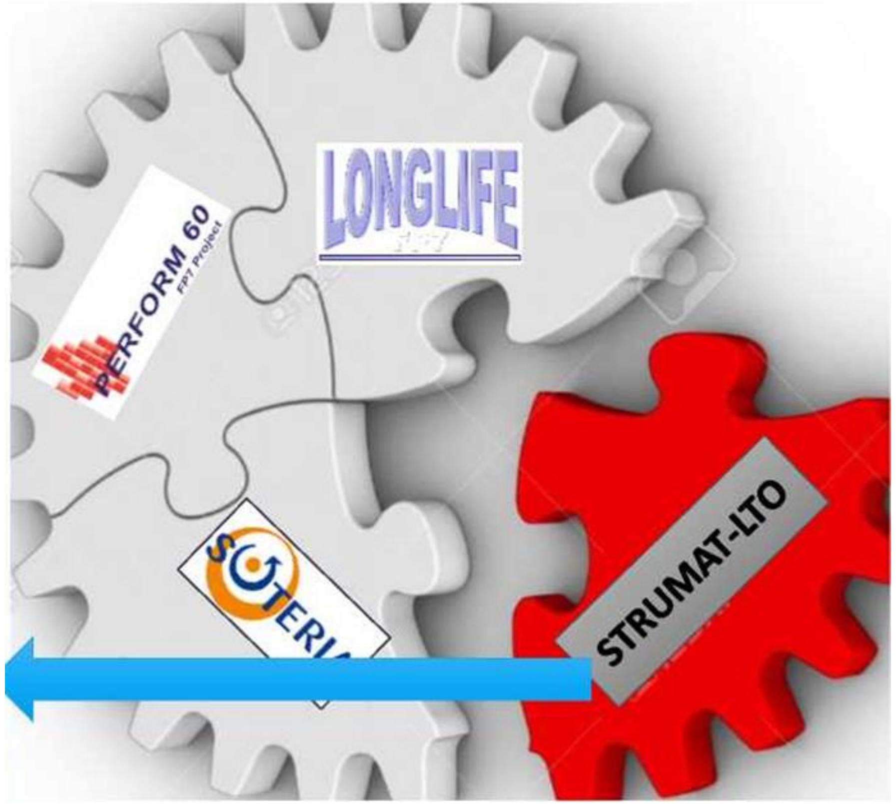
NPP	Unit #	Electric Power, MW	Type	Operation started	End of design life	Extended till
KhNPP	1	1000	V-320	22.12.1987	22.12.1987	The service life has been extended till 31.12.2029 New works are underway
	2	1000	V-320	07.08.2004	07.09.2035	—
RNPP	1	440	V-213	22.12.1980	22.12.2010	The service life has been extended till 22.12.2030
	2	440	V-213	22.12.1981	22.12.2011	The service life has been extended till 22.12.2031
	3	1000	V-320	21.12.1986	11.12.2017	The service life has been extended till 11.12.2037
	4	1000	V-320	10.10.2004	07.06.2035	—
SUNPP	1	1000	V-302	31.12.1982	02.12.2013	The service life has been extended till 02.12.2033
	2	1000	V-338	09.01.1985	12.05.2015	The service life has been extended till 31.12.2025 New works are underway
	3	1000	V-320	20.09.1989	10.02.2020	The service life has been extended till 10.02.2050
ZNPP	1	1000	V-320	10.12.1984	23.12.2015	The service life has been extended till 23.12.2025 New works were planned until 2022…
	2	1000	V-320	22.07.1985	19.02.2016	The service life has been extended till 19.02.2026 New works were planned until 2022…
	3	1000	V-320	10.12.1986	05.03.2017	The service life has been extended till 05.03.2027
	4	1000	V-320	18.12.1987	04.04.2018	The service life has been extended till 04.04.2028
	5	1000	V-320	14.08.1989	27.05.2020	The service life has been extended till 27.05.2030
	6	1000	V-320	19.10.1995	21.10.2026	The works were planned in 2022…

Irradiation embrittlement of the RPV

STRUMAT-LTO project is aimed to address these remaining gaps and open issues in RPV embrittlement research to support safe long-term operation of European NPPs, including the scenario of LTO > 60 years.

Former works & Open issues

1. Flux effect on embrittlement mechanisms
2. Initial microstructure, heterogeneities
3. Prediction models for radiation effects in RPV materials
4. High fluence behavior and Synergetic effects of nickel, manganese and silicon (Ni-Mn-Si) at high fluences
5. Validity of Embrittlement Trend Equations (ETE) for LTO beyond 60 years
6. Lack of surveillance material and moving towards miniature specimens for surveillance testing



Irradiation embrittlement of the RPV

STRUMAT-LTO Results

Expected impact areas

Quantitative PIE data on hardening and embrittlement behavior of PWR and VVER-1000 RPV steels at fluences resembling beyond 60 years of reactor operation to fill the existing data gaps

Comprehensive understanding on the synergetic effects as well as individual role of Ni, Mn and Si on RPV embrittlement at high fluences for low Cu RPV steels

Validated ETEs and a proposal to improve ETEs for better prediction of RPV embrittlement to support RPV LTO beyond 60 years

Improved understanding on the applicability of MC method at high fluences, especially in view of scatter in transition region

Improved understanding on the applicability of small specimen methods for fracture toughness evaluation and generation of more PIE data from available test specimens

Knowledge transfer to younger generations in RPV-LTO research topic

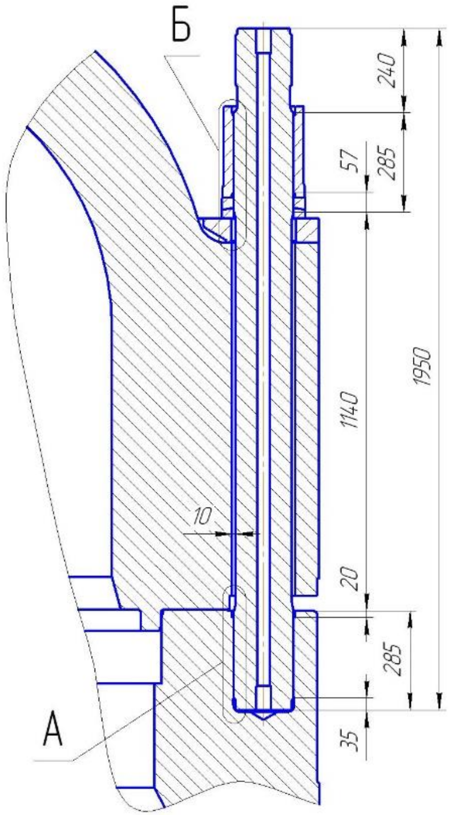
Overall impact of the project is maximized to pave way for safe LTO of European NPPs by conducting

- 2 End User Group meetings,
- 2 Dissemination Workshops,
- 4 Scientific Advisory Board meetings,
- Several international journal and conference publications,
- interaction with other Consortia working in the field (FRACTESUS, ENTENTE and DELISA-LTO)

www.strumat-lto.eu

Thermal ageing for replacement parts of primary circuit

WWER-1000 reactor main junction



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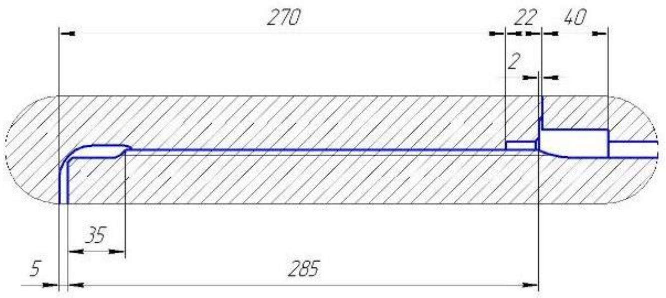

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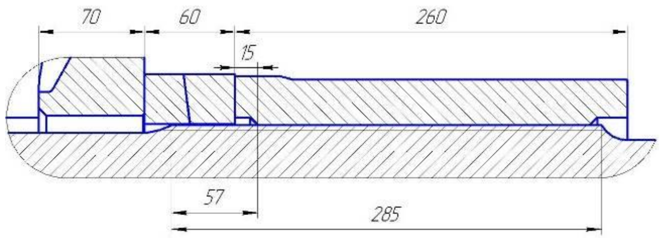
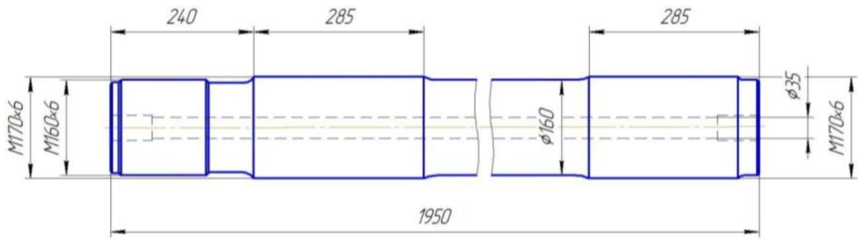
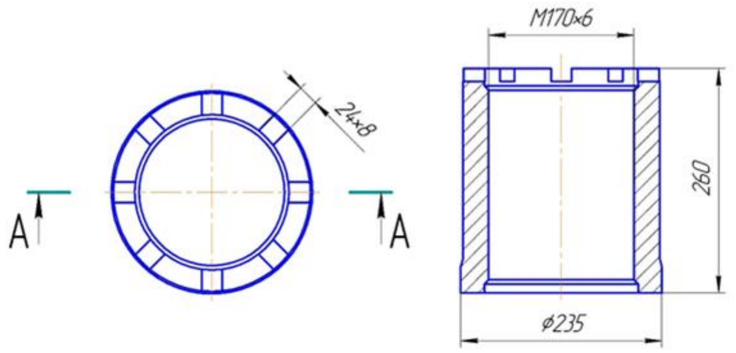


Reactor stud



Reactor nut

A-A



Workshop II, 10-14 February 2025, Kočovce, Slovakia

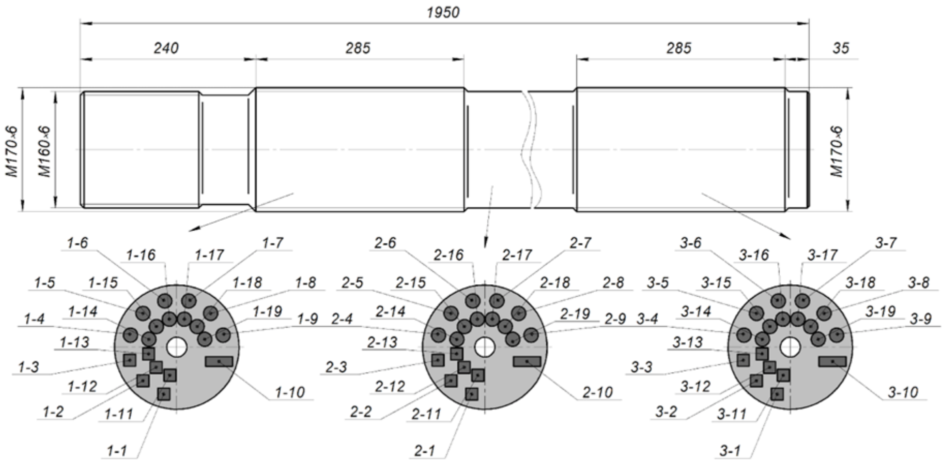
DELISA LTO
DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

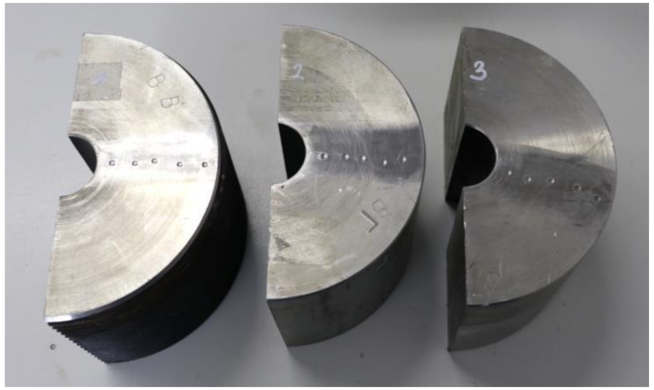
Funded by the European Union

Monitoring of the thermal ageing for replacement parts of primary circuit

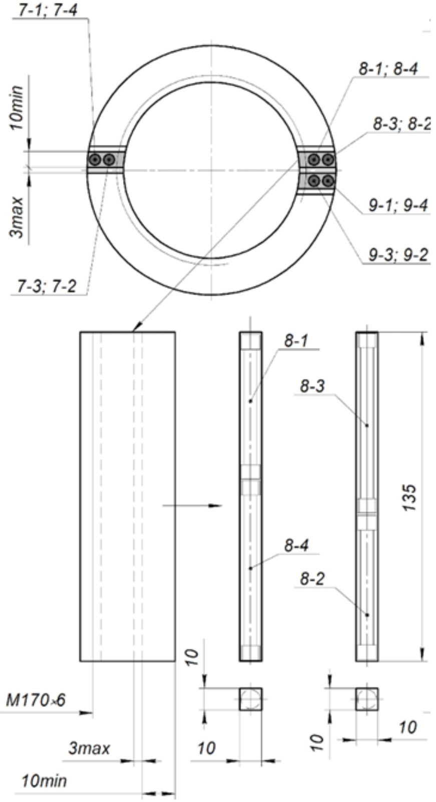
Experimental studies

Stud

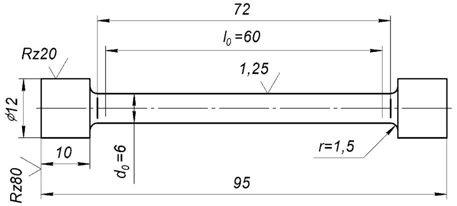




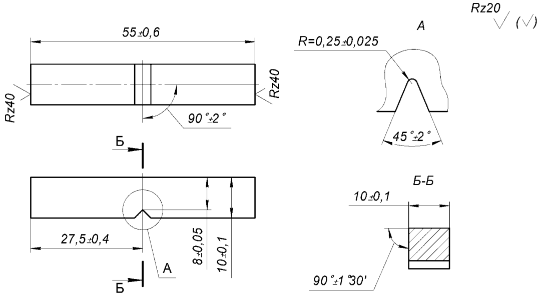
Nut



Tensile



Charpy



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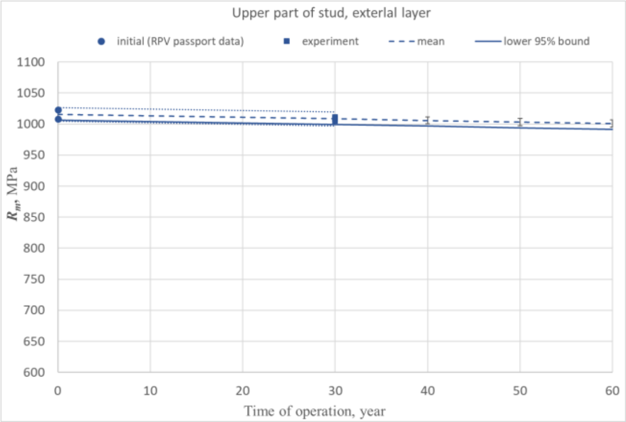
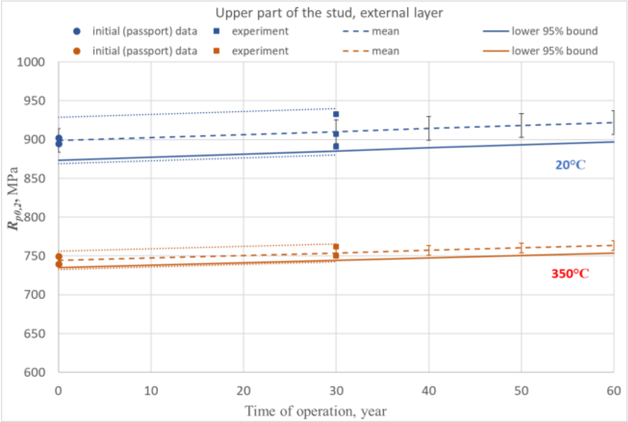
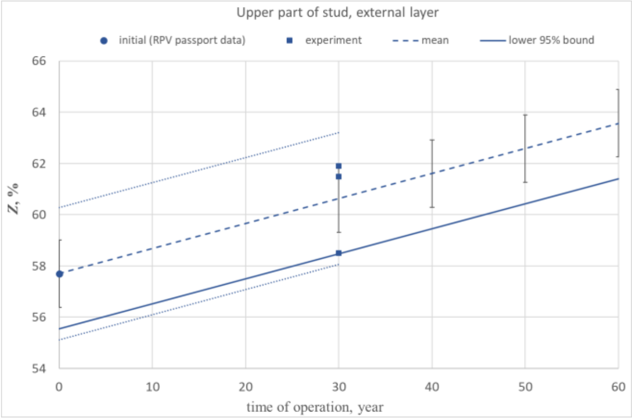
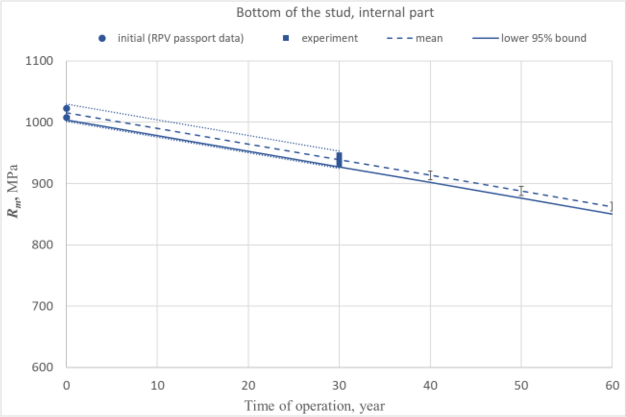
Monitoring of the thermal ageing for replacement parts of primary circuit

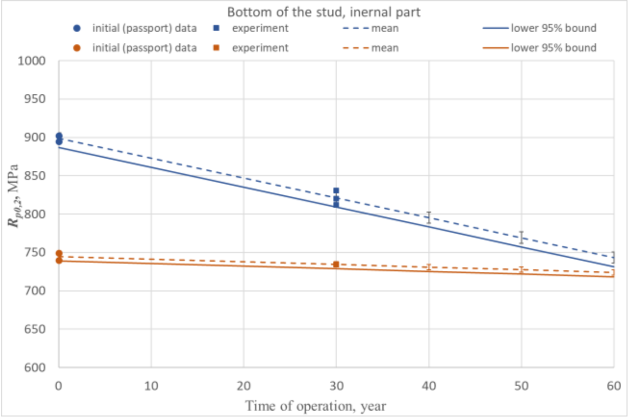
Results

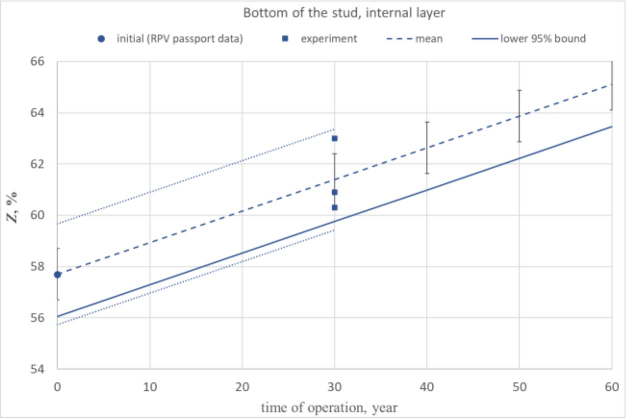












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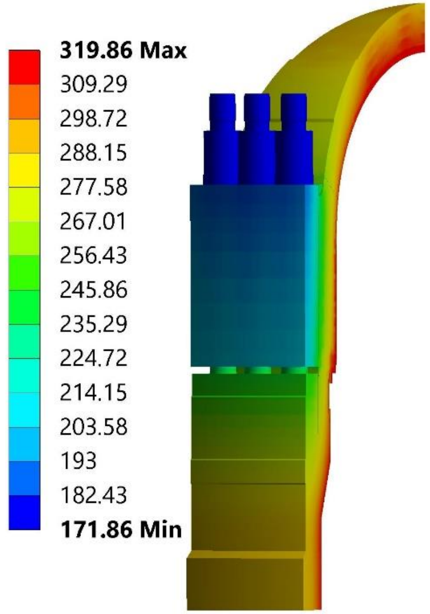
Thermal ageing of WWER-1000 reactor main junction parts

Impact on LTO



Results for the cyclic strength stud

Part of the stud	Fatigue damage for 30 years of operation, a_{30}		Fatigue damage for 50 years of operation, a_{50}	
	Initial data are taken into account	Reassessment with ageing consideration	Initial data are taken into account	Reassessment with ageing consideration
Lower thread turn of the upper part of stud (junction with nut)	1.48E-01	1.48E-01	2.96E-01	3.54E-01
Smooth part of the stud	5.26E-05	5.26E-05	1.05E-04	2.02E-04
Upper thread turn of the lower part of stud (junction with reactor flange)	1.92E-02	1.92E-02	3.84E-02	4.54E-02

Thermal ageing effects is not affected on the static strength and seismic resistance up to 60 years of LTO

Funded by the European Union

Thermal ageing for components and piping of primary circuit

Hardness measurements followed by mechanical properties recalculation

SOU-N NAEK 133:2023

Material	Restriction	Mech. propert.	Equation
Ст3сп5, 10, 15, 20, 20К, 22К, 15Л, 20Л, 25Л, 15ГС, 16ГС *	HB>140	$R_{p0,2}$	3,4 HB -175
	HB<140	$R_{p0,2}$	2,15 HB
	no restrict.	R_m	$8,8\times10^{-4}$ HB^2 + 2,66HB + 103
		A_5	$3,0\times10^4 / (2R_m + R_{p0,2})$
		Z	$1,9\times10^5 / (R_m + R_{p0,2} + 2000)$
16ГНМА, 16ГНМ, 10ХСНД, 12МХ, 12ХМ, 15ХМ, 20ХМ, 20ХМА, 10Х2М, 10ХН1М, 12Х1МФ, 15Х1М1Ф, 12Х2МФА, 18Х2МФА, 15Х3НМФА, 15Х3НМФА-А, 36Х2Н2МФА, 38ХН3МФА*	HB>200	R_m	3,4 HB - 90
		$R_{p0,2}$	3,6 HB - 240
	HB<200	R_m	2,5 HB + 90
		$R_{p0,2}$	2,4 HB
	no restrict.	A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$
08Х18Н9, 09Х18Н9, 10Х18Н9, 12Х18Н9, 08Х18Н10, 12Х18Н9Т, 06Х18Н10Т, 08Х18Н10Т, 08Х18Н10Т-ВД, 08Х18Н10ТЛ, 12Х18Н10Т, 08Х18Н12Т, 12Х18Н12Т, 08Х16Н11М3, 10Х18Н9ТЛ, 08Х18Н12ТФ, 12Х18Н9ТЛ	no restrict.	R_m	1.9HB + 250
		$R_{p0,2}$	1,7 HB
		A_5	$7,5\times10^4 / (2R_m + R_{p0,2})$
		Z	$1,8\times10^5 / (R_m + R_{p0,2} + 2000)$
Austenitic welds	no restrict.	R_m	1,9HB + 250
		$R_{p0,2}$	2,2 HB
		A_5	$6,8\times10^4 / (2 R_m + R_{p0,2})$
		Z	$1,8\times10^5 / (R_m + R_{p0,2} + 2000)$
15Х2МФА, 15Х2МФА-А, 15Х2НМФА-А, 15Х2НМФА	no restrict.	R_m	3,5 HB - 105
		$R_{p0,2}$	3,8 HB - 290
		A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$
10ГН2МФА	no restrict.	R_m	2,2 HB + 180
		$R_{p0,2}$	2,45 HB
		A_5	$4,2\times10^4 / (2 R_m + R_{p0,2})$
		Z	$2,3\times10^5 / (R_m + R_{p0,2} + 2000)$

Mechanical property	Formula error, %	
	Base material	Welds
Ultimate stress, R_m	±10	±15
Yield stress, $R_{p0,2}$	±15	±20
Elongation, A_5	±20	±20
Reduction of Area, Z	±30	±30

+

Hardness data scatter

+

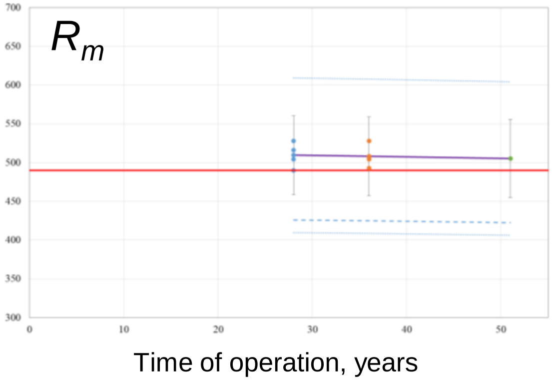
Error of hardness measurement device

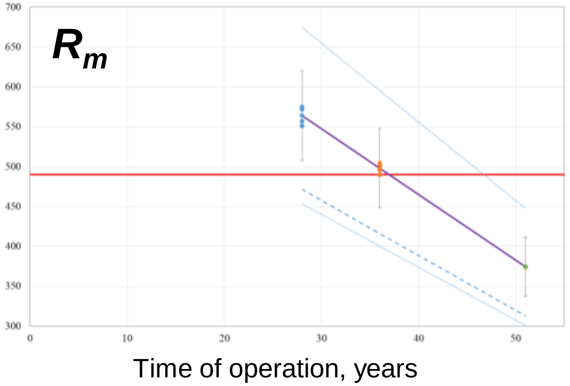
= **large uncertainty**

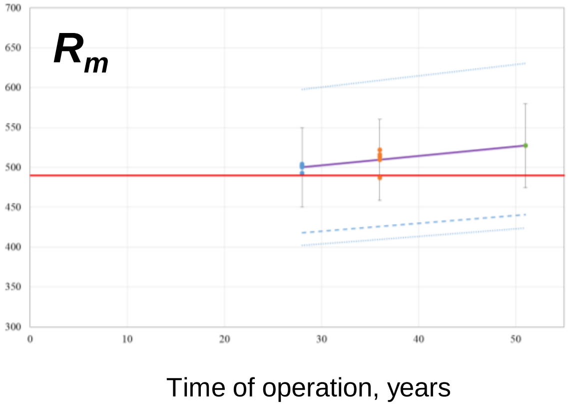
Thermal ageing for components and piping of primary circuit

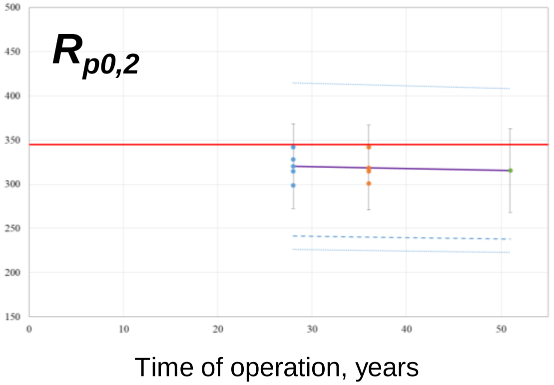
Hardness measurements followed by mechanical properties recalculation

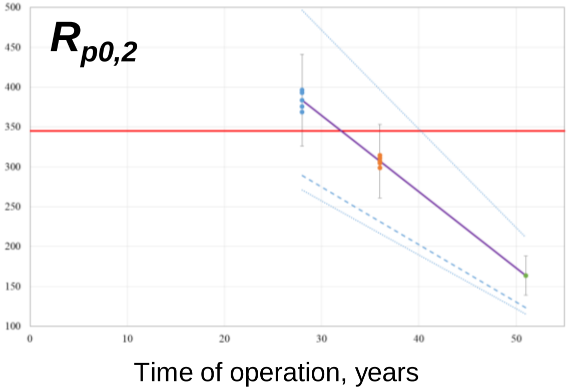
Selected representative results

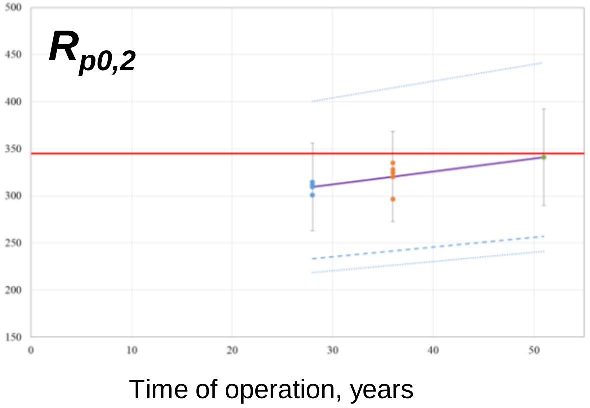








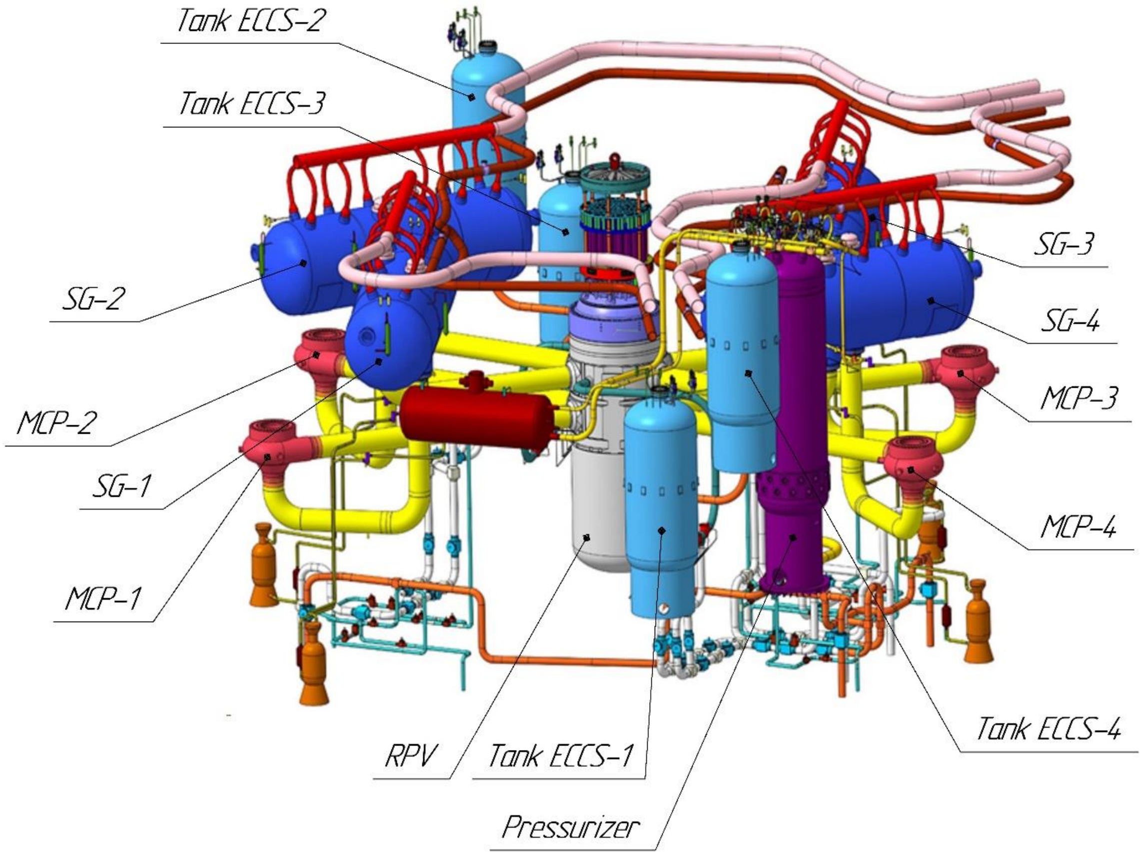




Thermal ageing of components and piping of primary circuit

100 000 / 200 000 hours monitoring program

- **Main coolant pipeline** (BM, WM)
- 10GN2MFA+cladding
- **Pressurizer surge line** (BM, WM)
  10GN2MFA+cladding
- **ECCS pipeline** (passive unite) (WM)
  10GN2MFA+08Kh18N10T
- **ECCS pipeline** (active unite) (WM)
  10GN2MFA+08Kh18N10T
- **Pressurizer injection and cooling pipeline**
  (WM) 08Kh18N10T
- **Steam-gas mixture discharge pipeline** (WM)
  08Kh18N10T
- **Steam pipeline** (BM, WM) 16GS
- **Feed water pipeline** (BM, WM) steel 20



Thermal ageing for components and piping of primary circuit

100 000 / 200 000 hours monitoring program. Methods of control

- **Control of metal structure using the method of impressions ("replicas"):**
  - general structure of metal;
  - determination of the metal phase composition and excess phases;
  - determination of the microdefects presence;
  - assessment of the degree of metal contamination with non-metallic inclusions;
  - assessment of the banding of the ferrite-pearlite structure;
  - grain orientation and size assessment;
- **Control of mechanical properties by direct methods** (if it possible):

- tensile strength	R_m	
- yield strength	$R_{p0,2}$	standard specimens or
- elongation	A_5	micro specimens < 3 mm thickness
- relative narrowing	Z	
- impact strength	KCV	micro specimens < 2 mm thickness
- hardness	HB/HRC	

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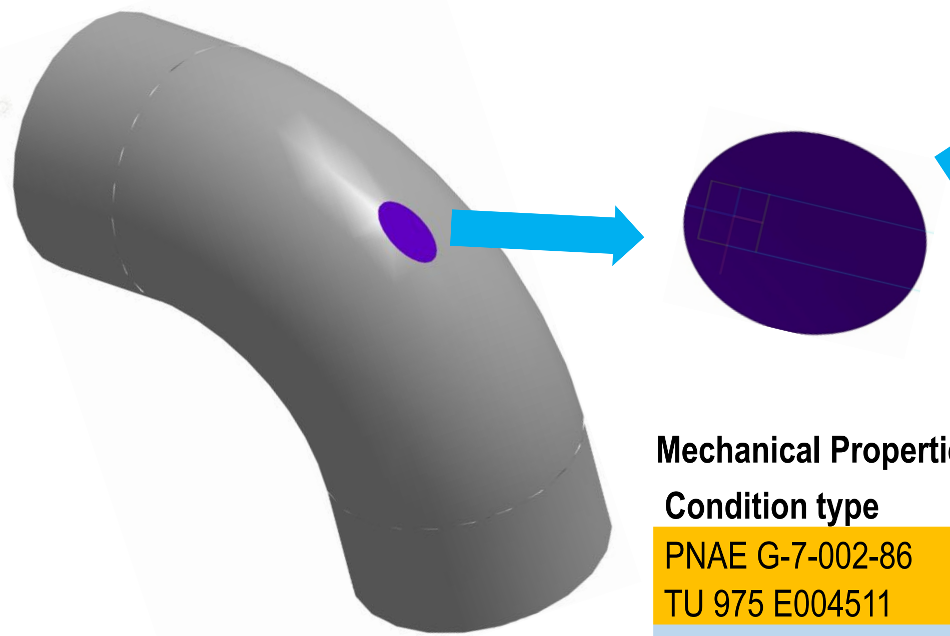
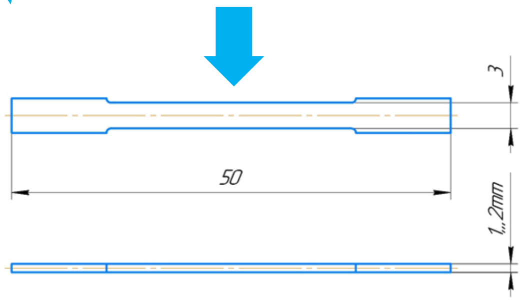
Thermal ageing for components and piping of primary circuit

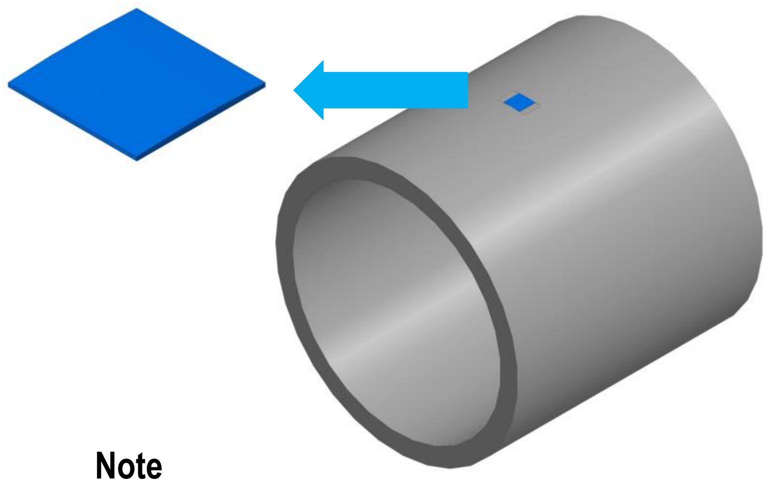
100 000 / 200 000 hours monitoring program

The main aim of the program is monitoring the mechanical properties and structure SSC metal of after **100 and 200 thousand hours** of operation



60mm×60mm× 3.5mm plates





Mechanical Properties of MCP at 350 °C

Condition type	Rm, kgf/mm²	R0.2, kgf/mm²	A5, %	Z, %
PNAE G-7-002-86	>50	>30	>14	>50
TU 975 E004511	>50	>30	>14	>50
Passport data	52,3	31,9	25,3	71,8
Initial state*	52,5	39	26,5	71
Unit #1 after 100 000 h*	55,6	40,4	22,5	72,0

Note

After 100 thousand hours of operation, a tendency towards h hardening and reduction of plasticity is observed

DELISA LTO

DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

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Thermal ageing study within DELISA-LTO

Experimental matrix

DELISA-LTO – WP2/WP4 Experimental matrix				Experimental Technique	A1 - Impact testing							A2 - Tensile Testing					A3 - Static Fracture Toughness									A4 - Hardness								A5 - SPT			A6 - Scanning Electron Microscopy					A7 - Optical Microscopy					A8 - TEM			A9 - Other methods							
				Available / Participating Laboratory	CVR	IPP		EK-CER	UJV		VTT	IPP	EK-CER	UJV	VTT	BZN	IPP		EK-CER	UJV		VTT		BZN		CVR	IPP	STUBA	EK-CER	UJV	VUJE	VTT	BZN	IPP	UJV	VUJE	CVR	STUBA	EK-CER	VUJE	VTT	CVR	STUBA	EK-CER	VUJE	VTT	CVR	STUBA	VTT	STUBA			VUJE		CVR		
Material No.		Material (description, *provider, operational temperature*)	Material Type	Material state / Specimen geometry	M	ST	M	ST	ST	M	M	ST	ST	ST	ST	ST	ST	M	ST	ST	M	ST	M	ST	M	ST	ST	M	ST	ST	ST	ST	ST	M	M	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1		**Main circulation piping - 08Ch18N12T** - NPP V1 – initial state *(VUJE)* - *Top = 294 °C*	BM	As received	■	■	-	-	■	■	■	■	-	■	■	■	■	■	-	■	■	■	-	■	■	■	■	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 2165 hours)	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	■	-	-	■	■	■	-	-	-	-	-	-	■	-	■	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	■	■	■
2		**Pressurizer surge line - 08Ch18N10T** - NPP EBO3 – initial state *(VUJE)* - Top = 276 °C	BM	As received	■	-	-	-	■	■	■	-	-	■	■	■	-	-	-	■	■		■	■	■	■	-	■	-	■	■	■	■	-	■	■	-	■	-	■	■	-	■	-	■	■	-	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 1085 hours)	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	■	-	-	■	■	■	-	-	-	-	-	-	■	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	■
3	3a	**Main circulation piping - 08Ch18N12T+WM** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 294 °C	BM	As received	■	-	-	-	■	■	■	-	-	■	■	■	-	-	-	■	■	■	-	-	-	■	-	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 2474 hours)	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	■	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	■	■	■
	3b		WM	As received	-	■	-	-	■	■	■	■	-	■	■	■	■	■	-	■	■	■	-	-	-	■	■	■	-	■	■	■	■	■	■	■	■	■	-	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	■	■	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-
	3c		HAZ	As received	-	■	-	-	■	■	■	N/A					-	-	-	-	■	■	-	-	-	■	■	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	-	■	■	■	■	■	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	■	-	-	-	-	-						-	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-	-	-	■	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-
4	4a	**Main circulation piping – triple T-junction - 08Ch18N12T+WM** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 294 °C	BM	As received	-	-	-	■	-	-	-	-	■	-	-	■	-	-	■	-	-	-	-	-	-	-	-	■	■	■	■	-	■	-	■	■	-	■	■	■	-	-	■	■	■	-	-	■	-	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	-	-	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
	4b		WM	As received	-	-	-	■	-	-	-	-	■	-	-	■	-	-	■	-	-	-	-	-	-	-	-	■	■	■	■	-	■	-	■	■	-	■	■	■	-	-	■	■	■	-	-	■	-	■	■	■	■	■	-	-	-
				Thermal Aged (450 °C / 2474 hours)	-	-	-	■	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
	4c		HAZ	As received	-	-	-	-	-	-	-	N/A					-	-	-	-	-	-	-	-	-	-	-	■	-	-	■	-	■	-	■	■	-	■	-	■	-	-	■	-	■	-	-	■	-	■	■	■	■	■	-	-	-
5		**Pressurizer surge line - 08Ch18N10T** - NPP V1 – after 28 years in operation *(VUJE)* - Top = 276 °C	BM	As received	■	■	-	-	-	-	-	■	-	■	■	■	■	■	-	■	■		■	-	-	-	■	■	-	■	■	■	■	■	■	■	-	■	-	■	■	-	■	-	■	■	-	■	■	■	■	■	■	■	■	■
				Thermal Aged (450 °C / 1240 hours)	■	■	-	-	-	-	-	■	-	-	-	■	■	■	-	-	■	-	-	-	-	-	■	-	-	■	-	-	■	■	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	■
6		**WWER-1000 - Reactor flange fastening parts** after 30 years in operation *(IPP-C)* - Top = 240 - 305 °C	BM	As received	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	-	-	■	■	-	-	■	-	-	■	■	■	-	■	-	-	-	-	■	-	-	-	-	■	-	■	■	-	-	■	■	-
				Thermal Aged (450 °C / 252-3465 hours)	-	■	-	-	-	-	-	■	-	-	-	-	■	■	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	-
7		**WWER-1000 - Steam generator collector with HE tubes** - 08Ch18N10T - operated *(IPP-C)*	BM	As received	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■	-	-	■	-	-	■	-	■	-	■	-	-	-	-	■	-	-	-	-	■	-	■	■	■	■	■	-	-	-
8		**WWER-1000 - Main circulation piping** - 10GN2MFA+SS cladding - NPP V1 – initial state *(IPP-C)* - Top = 290 °C	BM	As received	-	■	-	■	■	■	-	■	■	■	-	■	■	■	■	■	■	-	-	■	■	-	■	■	■	■	■	-	■	■	■	■	-	■	■	-	-	-	■	■	-	-	-	■	-	■	■	■	■	■	■	■	-
				Thermal Aged (450 °C / 3994 hours)	-	■	-	■	-	-	-	■	■	-	-	-	■	■	■	-	-	-	-	-	-	-	■	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	■	■	-
9	9a	**WWER-440 - Capsules** of the thermal specimens used in Paks NPP (2 pcs), 08Ch18N10T - 24 years in operation *(EK-CER)* - Top = 278 °C	BM	As received								-	■	-	-	-	N/A									-	-	-	■	-	-	-	-	-	■	■	-	-	■	-	-	-	-	■	-	-	-	■	-	■	■	■	-	-	-	-	-
				Thermal Aged (450 °C / 1510 hours)								-	■	-	-	-										-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
	9b	**WWER-440 - Capsules** of the thermal specimens used in Paks NPP (2 pcs), 08Ch18N10T - 32 years in operation *(EK-CER)* - Top = 278 °C	BM	As received								-	■	-	-	-	N/A									-	-	■	■	-	-	-	-	-	■	■	-	-	■	-	-	-	-	■	-	-	-	■	-	■	■	■	-	-	-	-	-
				Thermal Aged (450 °C / 1174 hours)								-	■	-	-	-										-	-	-	■	-	-	-	-	-	-	-	-	-	■	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
10		**WWER-440 - Main circulation pump** - Guide wheel - 10H18N9TL - 27 years in operation *(EK-CER)*	BM	As received	-	-	-	-	-	-	-	-	■	-	-	-	-	-	■	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-	-	-	-	■	■	-	-	-	■	■	-	-	-	■	-	■	■	■	-	-	-	-	-

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DEscription of the extended Lifetime and its influence on the Safety operation and construction materials performance – Long Term Operation with no compromises in the safety

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DELISA-LTO Workshop II

Application of non-destructive testing (NDT) methods in characterization of long-term treated NPP design materials

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Eddy Current Testing in the Nuclear Industry

Ing. Michal Benák, PhD.

(02/2025)

Layout

- Eddy currents (EC) - background
- Eddy currents principle
- Important EC parameters (skin effect, EC penetration depth, etc.)
- Impedance plane
- Probes & instruments for ET
- Steam generator inspection
- Software for eddy current testing
- ET acquisition and data analysis

Introduction

- Eddy current testing is one of the most extensively used non-destructive techniques for inspecting electrically conductive materials at very high speeds that does not require any contact between the test piece and the sensor.
- This presentation includes an overview of the fundamentals and parameters of eddy current testing in the nuclear industry.
- It also describes the state-of-the-art modern techniques.
- After this presentation, specific practical demonstrations (collection and analysis) of eddy current methods will be carried out.

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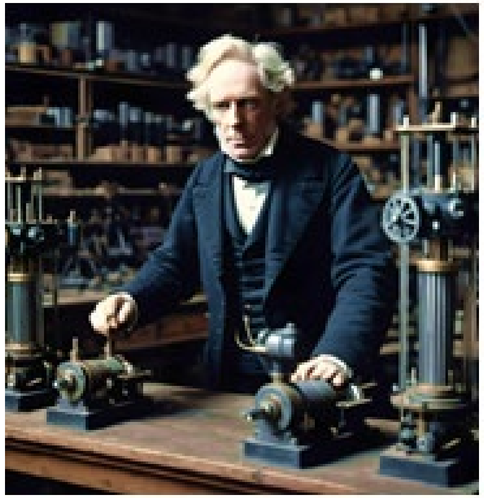
EC - History and Development

- By the end of the 18th century, scientists had noticed many electrical phenomena and many magnetic phenomena, but most believed that these were distinct forces. Then in July 1820, Danish natural philosopher Hans Christian Oersted published a pamphlet that showed clearly that they were in fact closely related. H. Ch. Oersted's discovery: "A magnetic field exists around a coil carrying current proportional to the number of turns in the coil and the current" [1].
- Eddy current testing has its origins with Michael Faraday's discovery of electromagnetic induction in 1831 [1].



H. Ch. Oersted's & Michael Faraday's [1]

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Eddy currents

- The eddy current method is a non-destructive test method that has a number of possible applications, is based on the principle of **electromagnetic induction**. If we place an electrically conductive object in an alternating magnetic field, the so-called eddy currents that are concentrated at the surface of the object (**skin effect**).
- In technical practice, eddy currents are mostly undesirable because they act against the direction of the exciting field and thus cause energy losses in electrical machines. An accompanying phenomenon is the generation of heat, which can have other negative effects on the operation of the electrical machine. The basic elementary means for testing are as follows:
    - AC source
    - Coil
    - Device

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Eddy currents

- The alternating current from the source creates a alternating magnetic field in the coil. This field, with the same frequency as the current in the coil, induces eddy currents in the test object.

- These eddy currents - their flux - in turn have a reverse influence on the coil. Changes in the flow of eddy currents in different parts of the material will cause changes in the voltage on the coil, which in itself represents a variable when testing with the eddy current method.

- Before proceeding to the interpretation of the technique of this inspection method , it is necessary to deal with some electrical and electromagnetic principles and the interpretation of some phenomena.

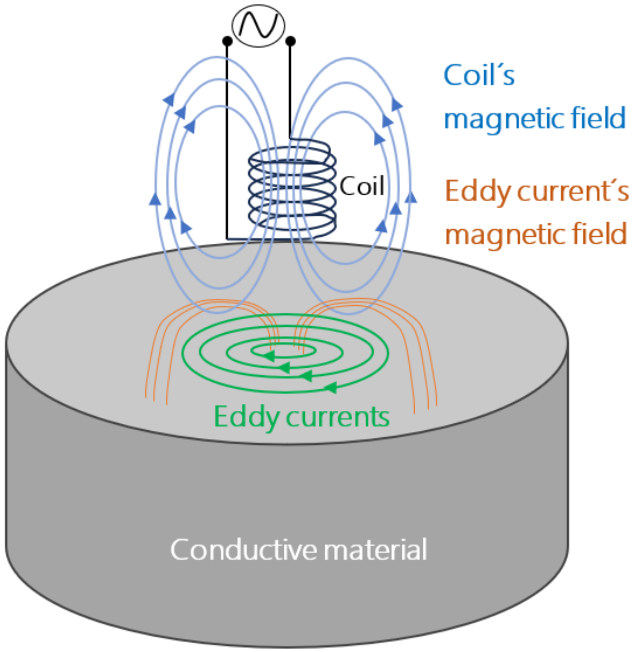
Factors effecting of the EC

The factors which affect eddy currents are:

- Electric current & conductivity σ
- Permeability μ
- Magnetism & electric current
- Electromagnetic induction
- Resistance of alternating current in a circuit with a coil – impedance (Z)
- Proximity (Lift off/fill factor)
- Geometry
- Probe Handling
- Discontinuities (Defects)

Eddy currents

- Eddy currents are induced electrical currents that flow in a circular path.
- An eddy current is a current set up in a conductor in response to a changing magnetic field. They flow in closed loops in a plane perpendicular to the magnetic field. By **Lenz law**, the current swirls in such a way as to create a magnetic field opposing the change; for this to occur in a conductor, electrons swirl in a plane **perpendicular** to the magnetic field.
- Because of the tendency of eddy currents to oppose, eddy currents cause a loss of energy.
- The existence of eddy currents leads to the creation of a eddy current´s magnetic field, and this field acts against the coil´s magnet field !



A coil with a flowing current on the surface of the conductive material

Note: The direction of the magnetic field produced by an electric current is always *perpendicular* to the direction of the current that produces the field.

Eddy currents

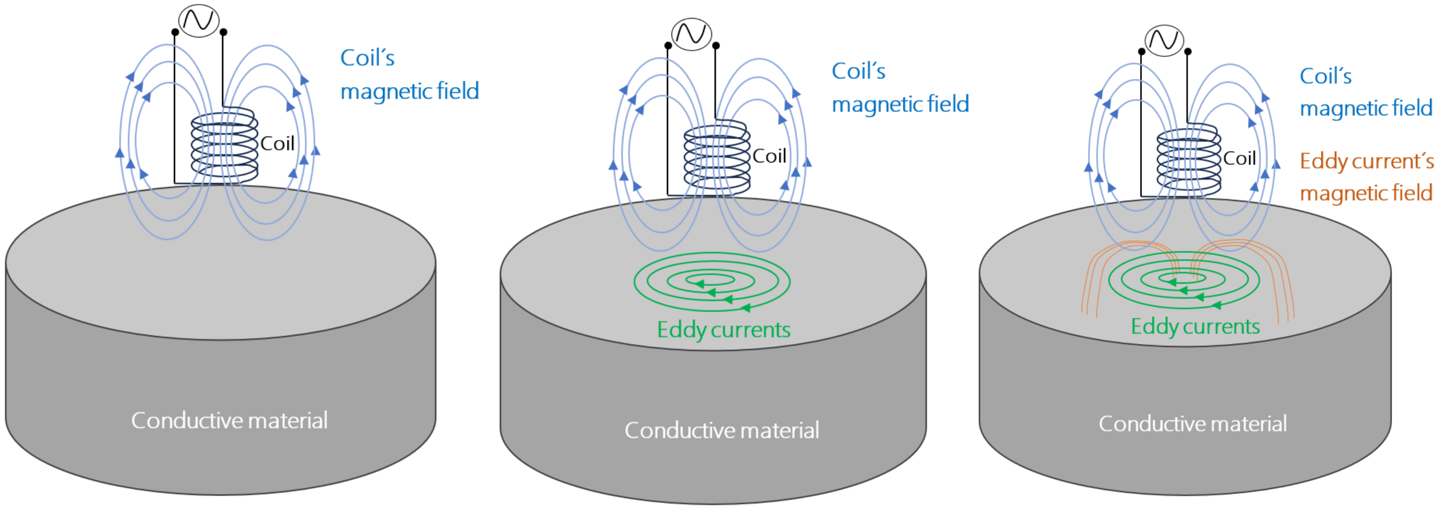
Most important!

If there is a material defect, for example a crack, in an electrically conductive object under the sensing coil:

- this defect will act as an obstacle - resistance to the flow of eddy currents and will cause a change in the paths of eddy currents and thus a change in the secondary magnetic field, which in turn will cause a change in the induced voltage in the sensing coil.
- The voltage in the sensing coil will also change if the sensor is placed next to a material that differs in electrical conductivity or magnetic permeability (e.g. due to chemical composition or processing temperature).
- The change in voltage consists not only in a change in size - amplitude, but also in a change in phase - a shift of the sinusoid on the time axis.

Eddy currents

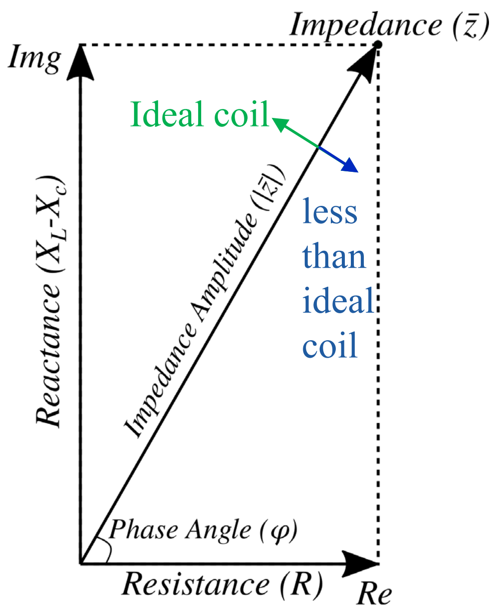
- The alternating current flowing through the coil at a chosen frequency generates a magnetic field around the coil.
- When the coil is placed close to an electrically conductive material, eddy current is induced in the material.
- If a flaw in the conductive material disturbs the eddy current circulation , the magnetic coupling with the probe is changed and a defect signal can be read by measuring the coil impedance variation.



Eddy current on the test piece
(Primary and secondary magnetic field)

Eddy currents – impedance ($\bar{z}$)

- Impedance ($\bar{Z}$) is a complex quantity that has 2 dimensions: amplitude and phase delay or real (*R*) and imaginary (X_L) component parts.
- ($\bar{Z}$), is the total opposition that a circuit presents to alternating current. Impedance is measured in ohms [Ω] and may include resistance (*R*), inductive reactance (X_L), and capacitive reactance (X_c). Capacitive reactance is usually not present in eddy current testing, so this term is not included in the equation.
- The total impedance is not simply the algebraic sum of resistance and inductive reactance. Since the inductive reactance is 90° out of phase with the resistance and, therefore, their maximum values occur at different times, vector addition must be used to calculate impedance. This is illustrated in the image to the right. (X_L) depends on the frequency of the current in the coil.



Phase relationships in a real alternating current electrical circuit

$$|\bar{z}| = \sqrt{R^2 + (X_L^2 - X_C^2)}$$

$\bar{z}$ – impedance [Ω];
R - ohmic resistance [Ω];
X_L - inductive reactance [Ω];
Xc – capacitive reactance [Ω].

$$X_L = 2.\pi.f.L$$

X_L - inductive reactance [Ω];
f - frequency [Hz];
L – induction [H].

The phase impedance leads the current (R) by an angle:

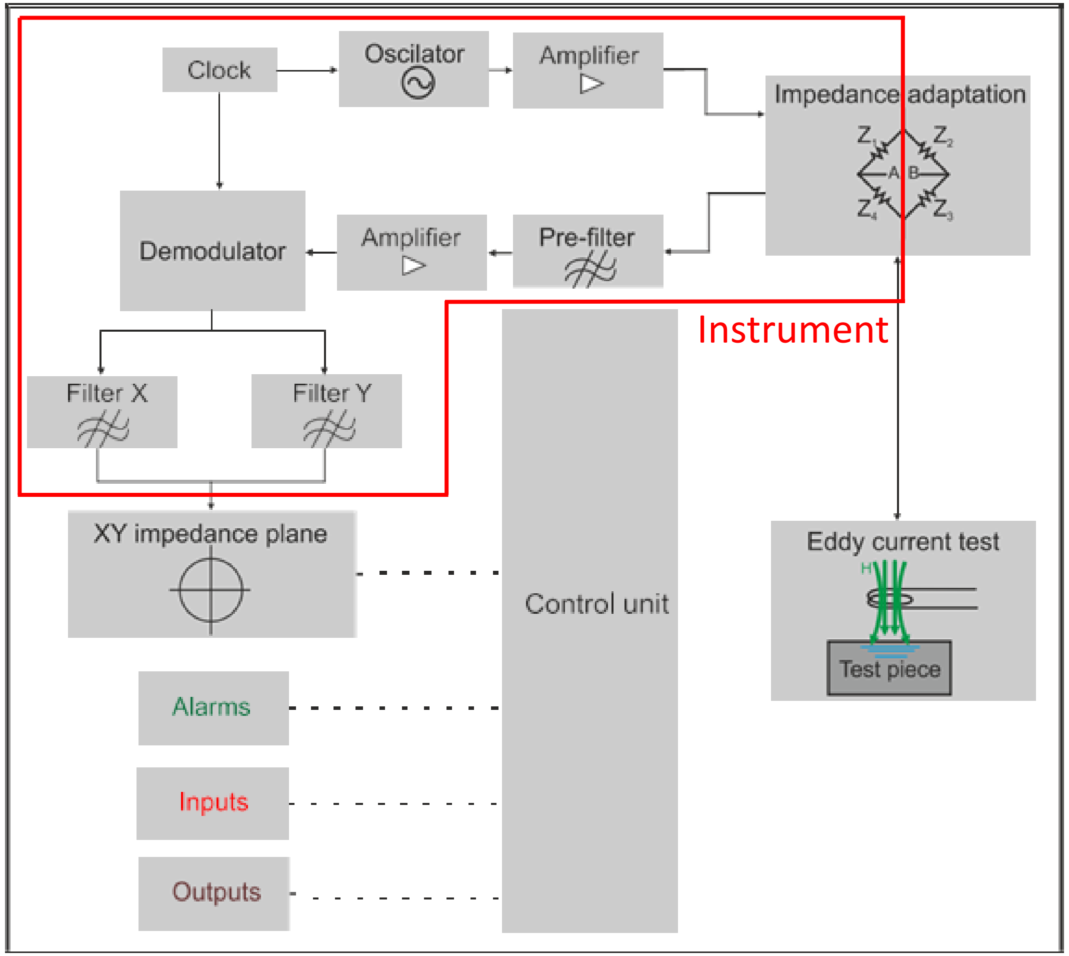
$$tg\varphi = \frac{X_L}{R}\ [°]$$

Note: the larger X_L is than R, the closer it is to the ideal coil

Eddy current system

- Figure presents a block diagram of analog eddy current equipment. It includes a single tone **generator** which energizes the test coil sensor. Phase, frequency and amplitude can be adjusted to optimum parameters for the test pieces. When a crack occurs, the coil impedance experiences a change.

- The defect signal modulates the tone from the oscillator. A quadrature amplitude demodulator extracts the defect signal caused by the impedance variation. The demodulator outputs are X-axis and Y-axis signals. Each component represents the real and imaginary parts of the impedance respectively. These signals can be filtered and analyzed [2].



Block diagram of an analog EC system [2]

Note: the oscillator generates a current of the required intensity and frequency

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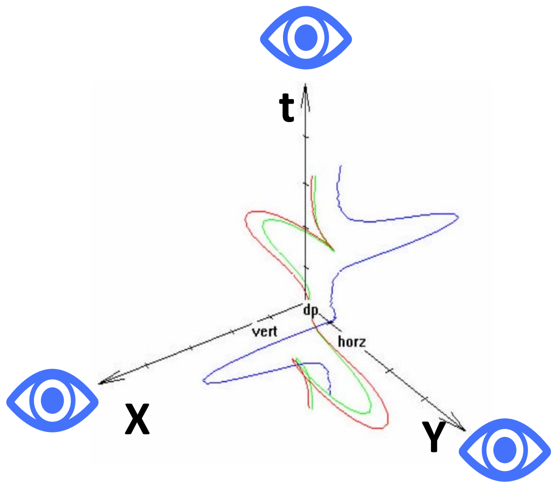
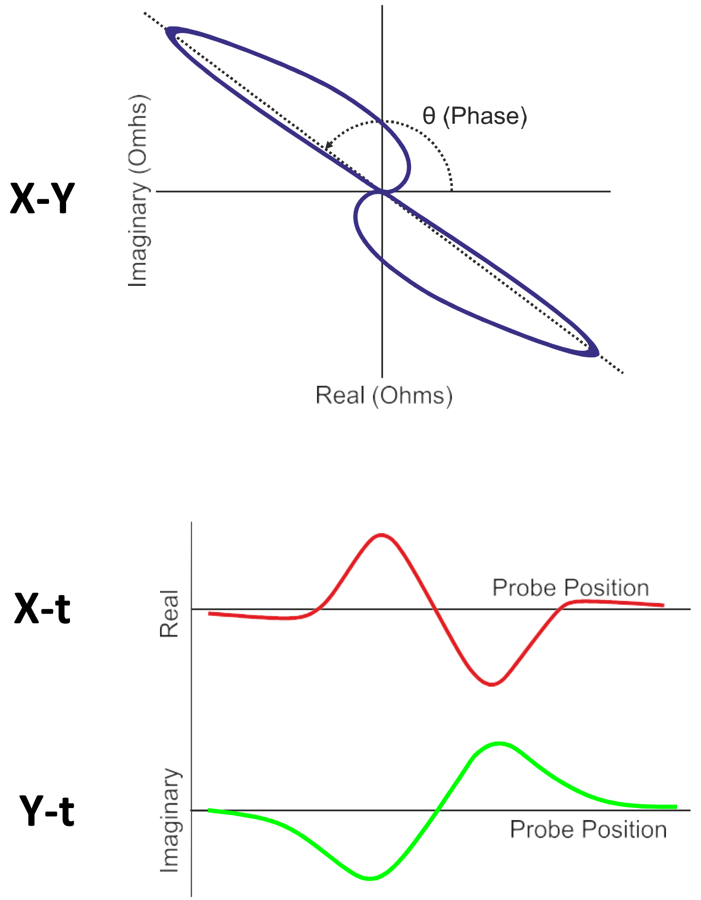
Eddy current – impedance plane

- The signal from the probe comes the EC device, is amplified and demodulated, i.e. "removed" of the working frequency. This creates a point that deviates in the X-Y axes. The resulting signal is projected onto the device screen in three basic views. X-t, Y-t, X-Y (t...time) [2].





Typical loop of a complex impedance plane of a differential Bobbin probe inside a tube affected by a flaw. (b) Real and imaginary part of impedance change vs. time [2].

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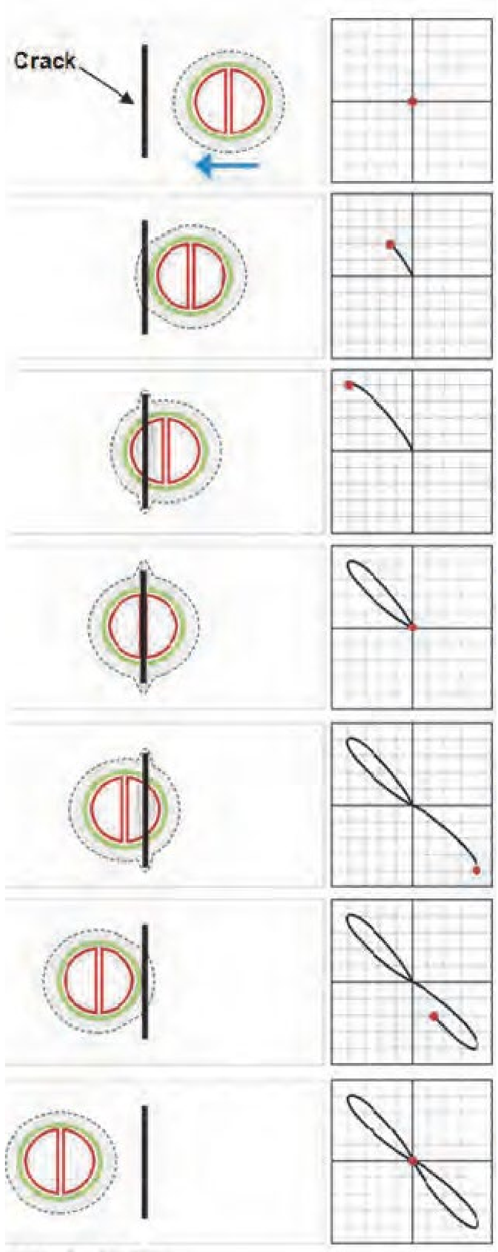
Eddy current testing

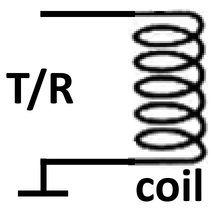
- As the probe moves the crack the path of the EC changes and they flow around or below the crack. This change is picked up by Receiver Coil 1 and as a result, the signal on the impedance plane moves upward.
- As the probe moves further, the current distortion effect causes a maximum response in Receiver Coil 1 and the signal response on the impedance plane reaches a maximum.
- When the cracks is located at the center of the coils, the currents flow mostly around the crack and distortion is at its maximum. However, at this location both Receiver Coils are „sensing" the same field and because they are wired in difference, the resultant signal is zero (null point)
- As the probe moves past the crack, Receiver Coil 2 now „senses" the distortion of the currents and as a result, the signal on the impedance plane moves downward.
- The signal response will return to the null point and the double-loop is complete [3].

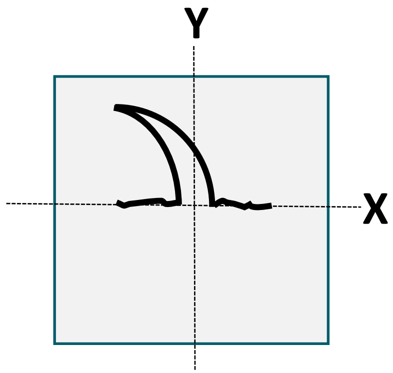


Bolt hole eddy current signal responses from a crack [3]

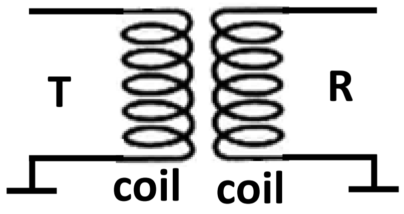
Eddy current testing- coils connection

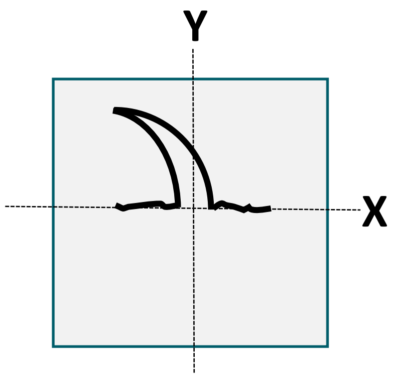
ABS



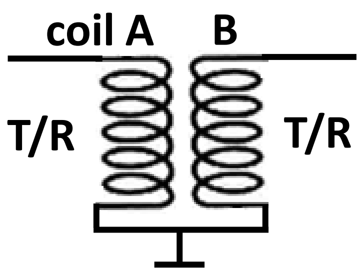


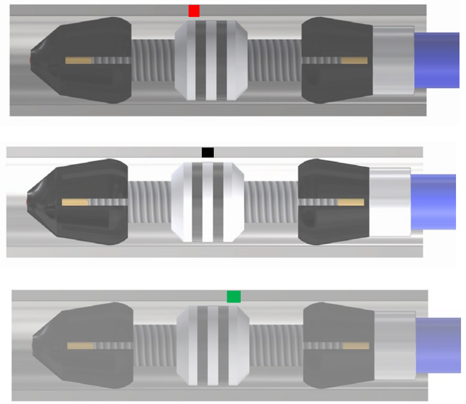
D-P

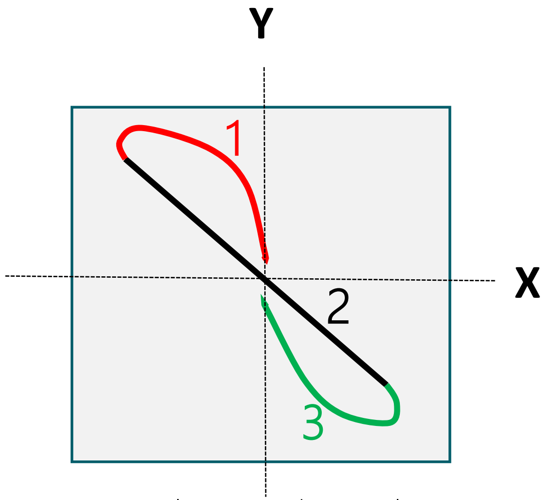




DIFF







Complex impedance plane

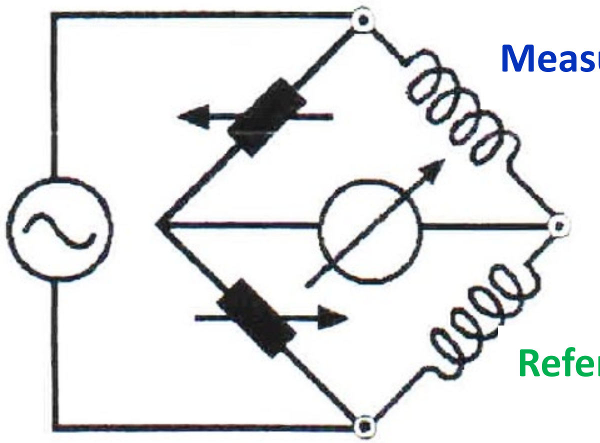
1 - Indication passes through coil A

2 - Indication is between coils A+B, both coils are affected

3 - Indication passes through coil B

Probes connecting

- The EC device basically senses the change in impedance on the coils.
- The connection of the probes in the EC device is "bridged".
- Differential probe - the coils are connected into a bridge opposite each other.
- Reference probe – one coil is from the measuring probe and the other is from the probe. This way an absolute signal is created which is needed for long defects and SLG.



Sensor „bridge“ connections

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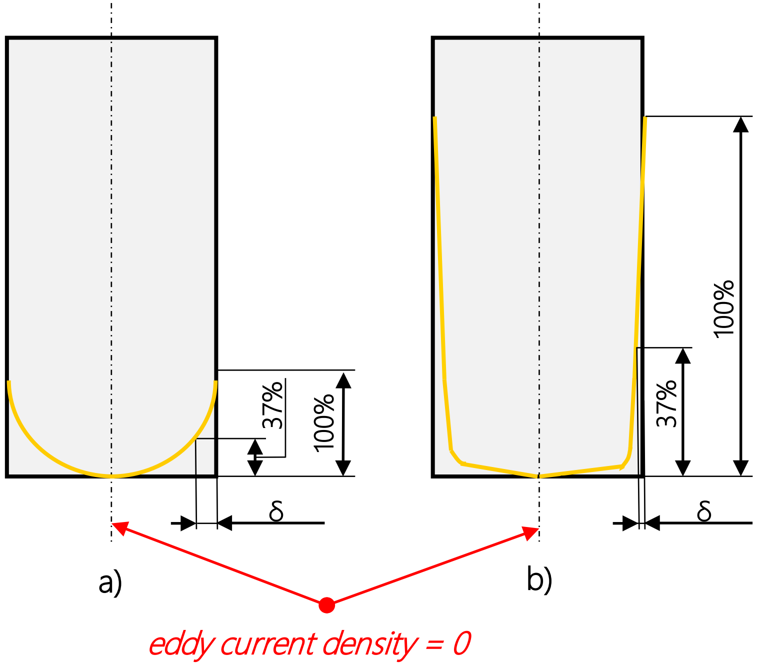
Eddy current penetration depth

- Eddy currents are not distributed uniformly in the test object. We will first explain the distribution of demanding currents when the test object is in the coil (the so-called through-hole sensor, details will be given later). In the conductor axis, their density is zero, on the conductor surface it is the largest.
- This distribution depends mainly on the frequency of the exciting electromagnetic field (corresponds to the frequency of the exciting current).
- The higher the frequency, the higher the density of the more demanding currents, and the higher the currents will penetrate to a shallower depth. This phenomenon is called the *skin effect*.

Eddy current penetration depth

- The standard depth of eddy current penetration is the depth below the surface of the material at which the eddy current density reaches **37%** of the eddy current density at the surface.

- If the frequency increases by 4x, the standard penetration depth drops by half. The figure shows a comparison of the standard penetration depth at different frequencies. However, the conductivity (specific electrical conductivity) of the material in which the EC are generated has exactly the same effect as the frequency. The figure can therefore also be interpreted as follows: on the left is the distribution of EC and the corresponding value δ for a material with low conductivity (e.g. titanium) and on the right is the eddy current profile for a material with high conductivity (e.g. copper), both at the same frequency.



Comparison of standard penetration depth
a) low frequency (material Ti), b) high frequency (material Cu)

- Standard penetration depth:

$$\delta = \frac{500}{\sqrt{f.\sigma.\mu_r}}$$

δ- standard penetration depth [mm]; *f*- working frequency [Hz];
μ_r- relative permeability; σ - electrical conductivity

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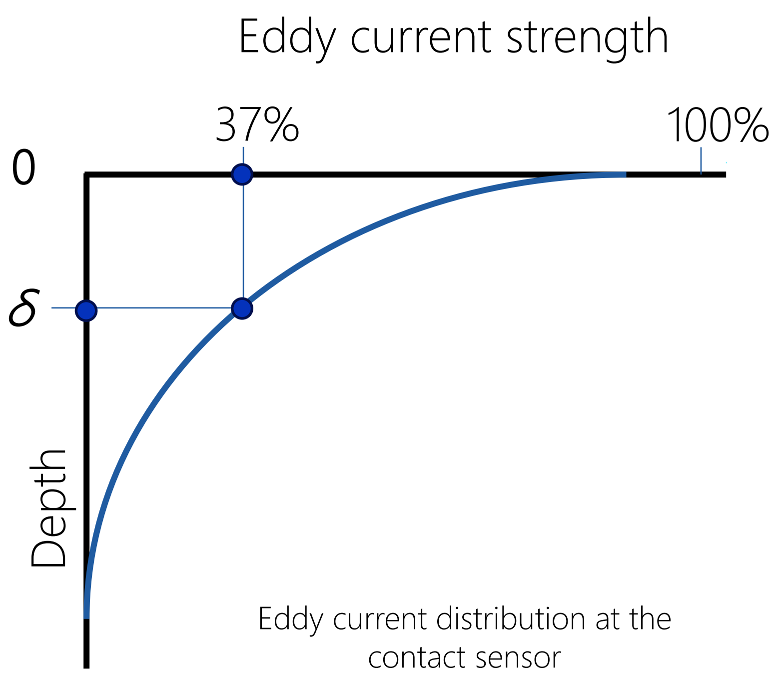
Eddy current penetration depth

- The standard eddy current penetration depth is not a threshold value below which eddy currents no longer exist. The distribution of eddy currents follows logarithmic laws. At a depth of 2δ, the eddy current density is 37% of 37% (can also be written as 0.37 0.37, i.e. 0.372), i.e. 13.69% of the value at the surface. At further depths, the pattern is as follows:

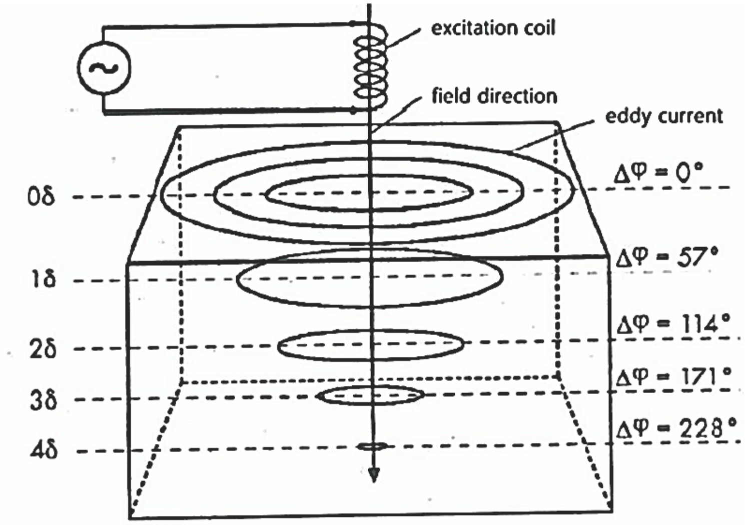
Surface	Depth			Percentage
	0δ		0.37^0	~100%
	1δ	0.37	0.37^1	~37%
	2δ	0.37x0.37	0.37^2	~13.7%
	3δ	0.37x0.37x0.37	0.37^3	~5.07%
	4δ	0.37x0.37x0.37x0.37	0.37^4	~1.87%
Generally	**nδ**		0.37^n	



Eddy current distribution at the contact sensor

Eddy current penetration depth

- Furthermore, the deeper the eddy currents penetrate the surface, the greater their phase lag with respect to the eddy currents on the surface. At a depth of δ, the phase lag with respect to the surface is exactly 1 rad, at a depth of 2δ, it is 2rad, etc. An angle of 1 radian corresponds to approximately 57° (180°/π). Here, a linear relationship applies, so that the phase lag, for example, at a depth of 0.75δ is 0.75 rad, or approximately 43°. This fact is shown in figure.



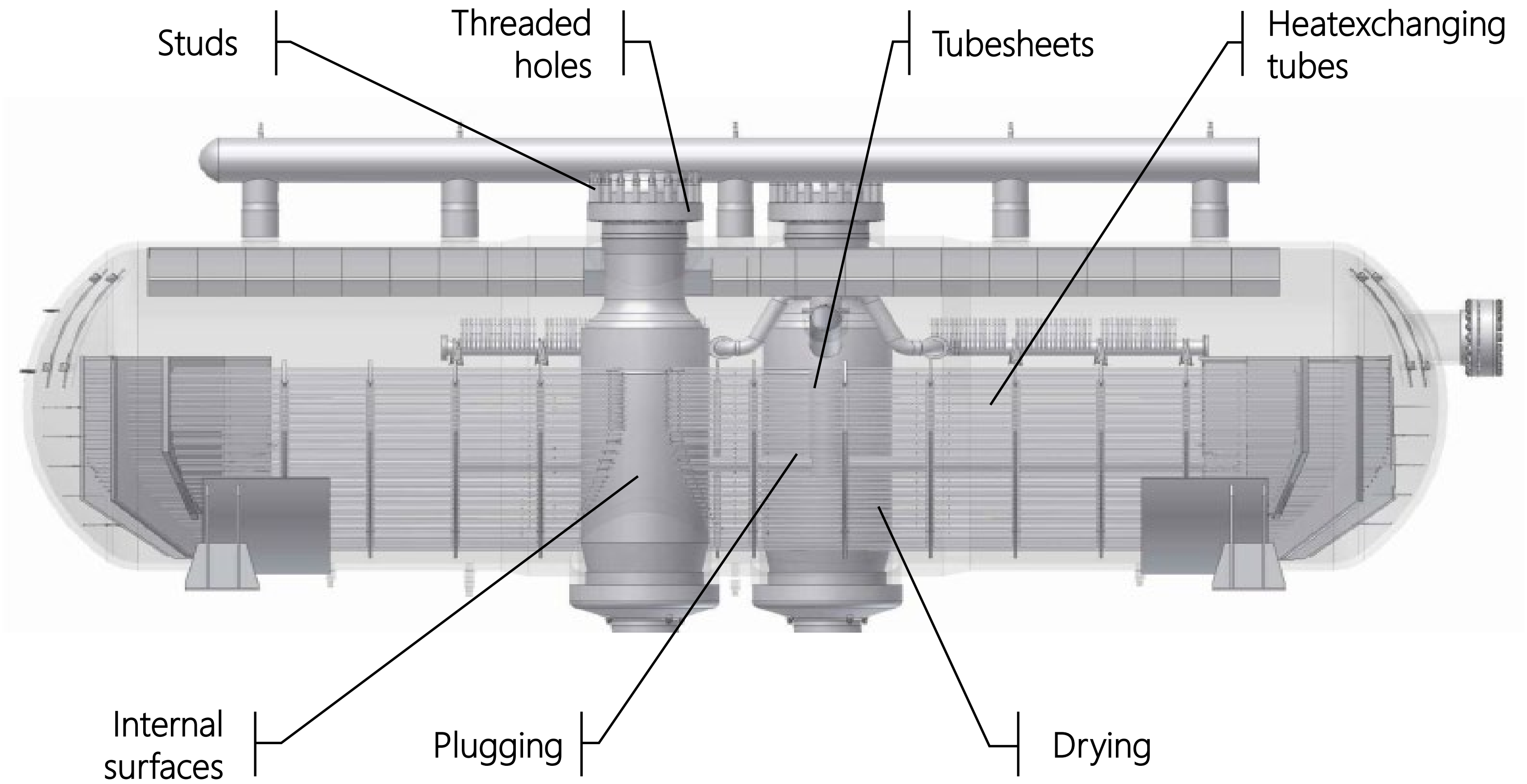
Phase delay of eddy currents relative to the surface at different depths

Eddy current instrument

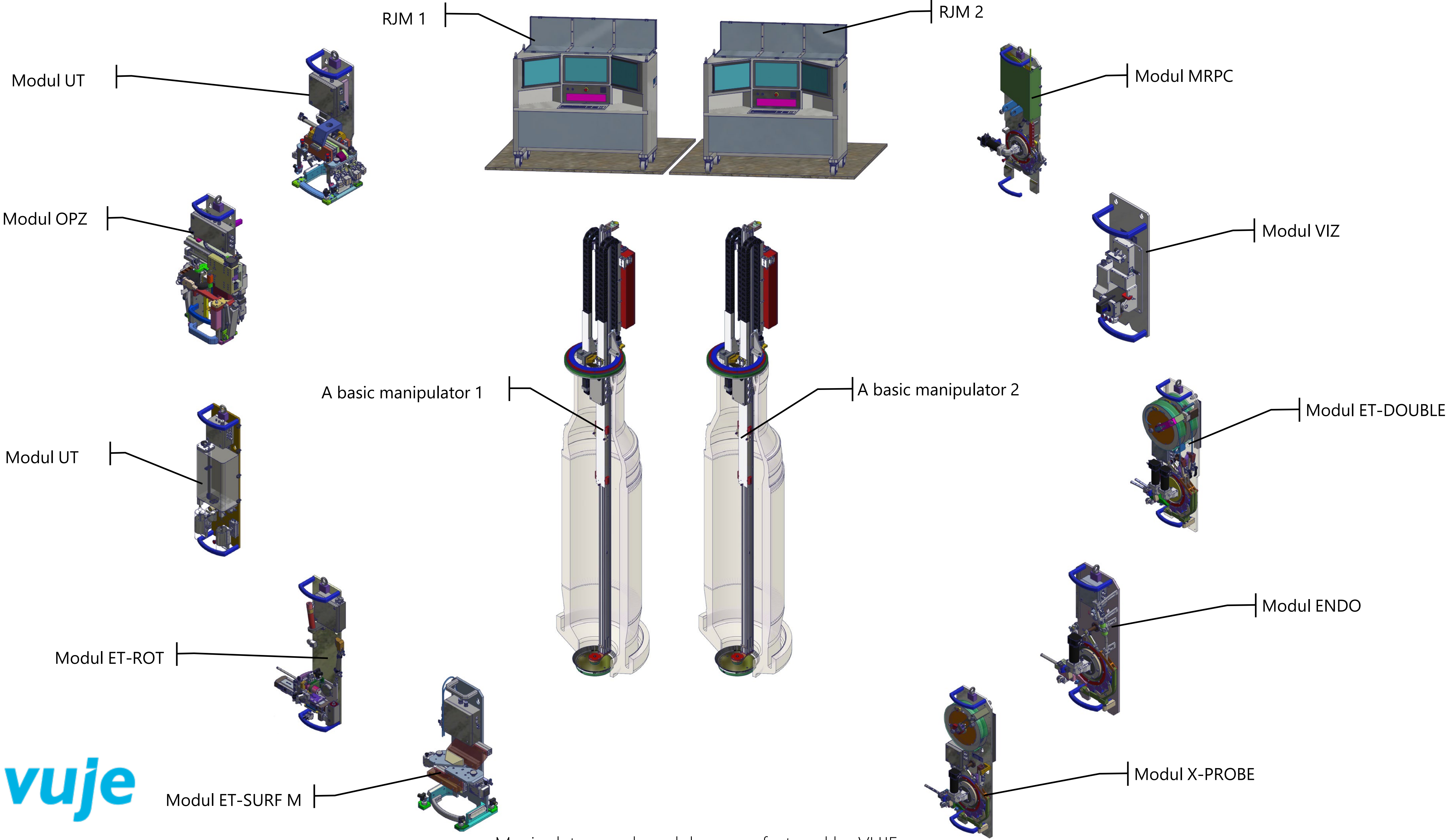
- ZETEC, Inc.: The MIZ-85iD leverages the architecture of our industry-leading MIZ-80iD eddy current instrument into a modular, instrument-only system. It’s a small, rugged and lightweight unit that can be utilized in a variety of inspection environments. All configurations of the MIZ-85iD are completely sealed to provide protection from environmental and radiological contamination. This protection ensures the unit’s integrity in electronic performance and allows the unit to be serviced throughout the life of the product [4].

MIZ-85iD [4]

SGT inspection



Steam generator



Manipulators and modules manufactured by VUJE, a.s.

Eddy current probes and standards

- The eddy current method works on the basis of comparison.
- The eddy current signal from the calibration defects is compared with the detected indication.
- The calibration standard usually has several artificially produced defects.
- The parameters of the artificially produced defects are described in standards (e.g. ASTM, ASME code...) or are produced depending on the sensitivity criteria of the test.
- The calibration standard must be made of the same material as the tested component.
- When producing artificial defects, emphasis must be placed on accuracy.

Calibration standards

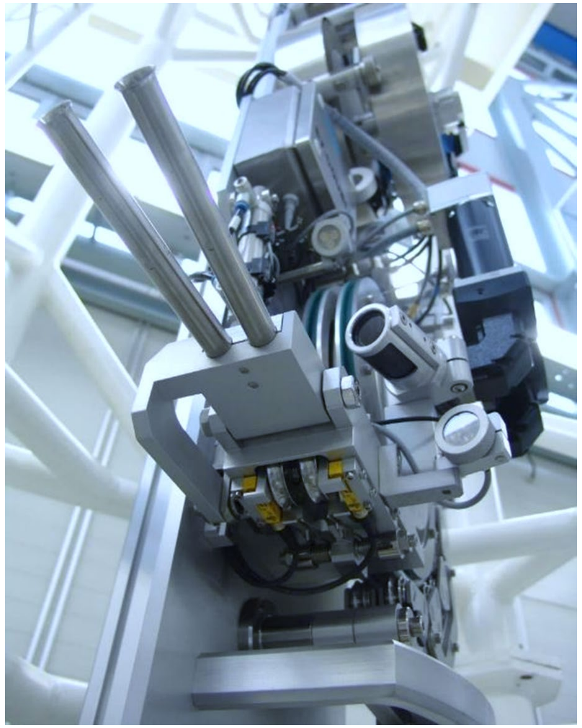
Expected damage of the SGT

Expected damage are:

- Stress corrosion cracking
- Pitting corrosion
- Intergranular corrosion
- Vibration damage
- External deposits – corrosive environment
- Damage in the area of the collector pipe outlet

EC inspection of SGTs

- Fully automated remote-controlled system was developed primarily for EC inspection of heat exchanging tubes with standard Bobbin probe (single or double pusher). System consists of manipulator, exchangeable inspection modules, control unit and EC measuring unit.
- Whether you are testing an entire tube or searching for indications in tube bends we have the probes to meet your needs.
- Basic parameters affecting probe characteristics: grounding design, wire diameter, number of turns, fill factor, centering, overall mechanical design.



Bobbin probe & module

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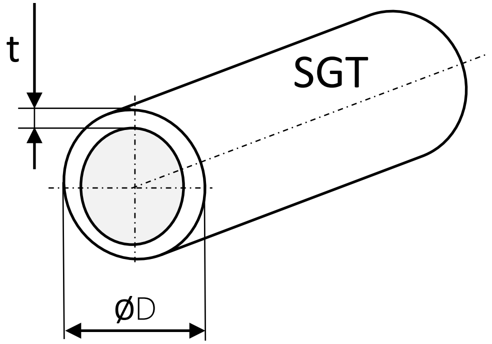
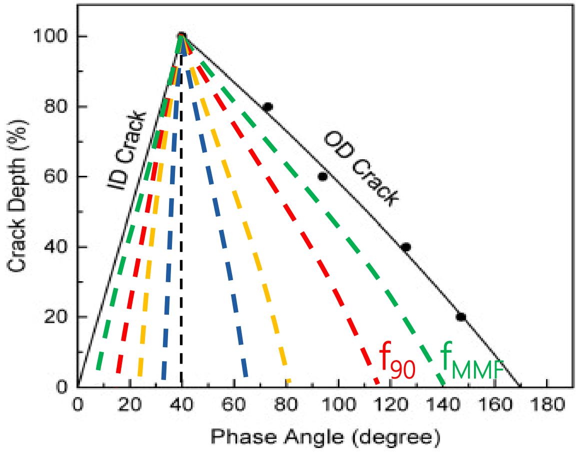
Standard frequency for internal passage sensor

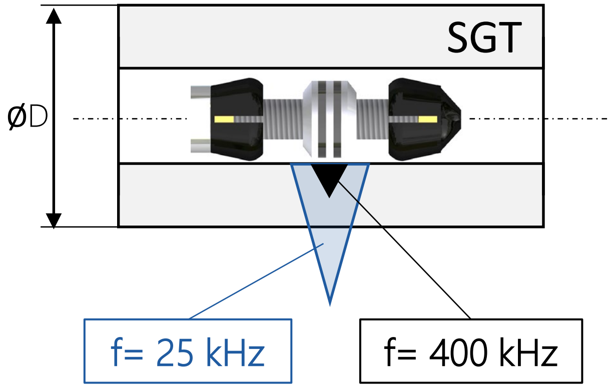
- 1st step calculation f_{90} (standard frequency for internal passage sensor);
- 2nd create calibration curve;
- 3rd performing a inspection SGT.

		$2 \times f_{MTF}$	- Dent (DNT) - Internal surface
$f_{90} \times 1$ to 2	=	f_{MTF}	- MMF - Quantification indication
		$f_{MTF} : 2$	- Detection
		$f_{MTF} : 4$ (8)	- Permeability (PV) - Localization





Curve of dependence of the phase angle of indications on the depth of the defect



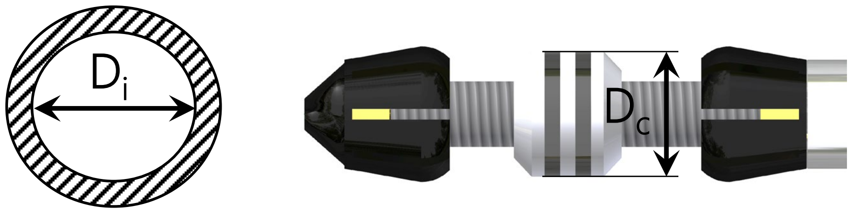
$$f_{90} = \frac{300}{\sigma.\mu_r.t^2} \text{ [kHz]}$$

f_{90} - standard frequency [kHz];
σ - conductivity [MS/m];
μ_r - relative permeability;
t - wall thickness [mm]

Fill factor for internal and external flow sensor

Fill factor:

- never greater than 1,
- The ideal factor is 0.90 (possible with clean straight pipes),
- The filling factor should fall below 0.8.



External pass-through coil

$$\eta = \frac{D_o^2}{D_c^2}$$

D_o - external diameter of the SGT [mm];
D_c- coil diameter [mm].

Internal pass-through coil

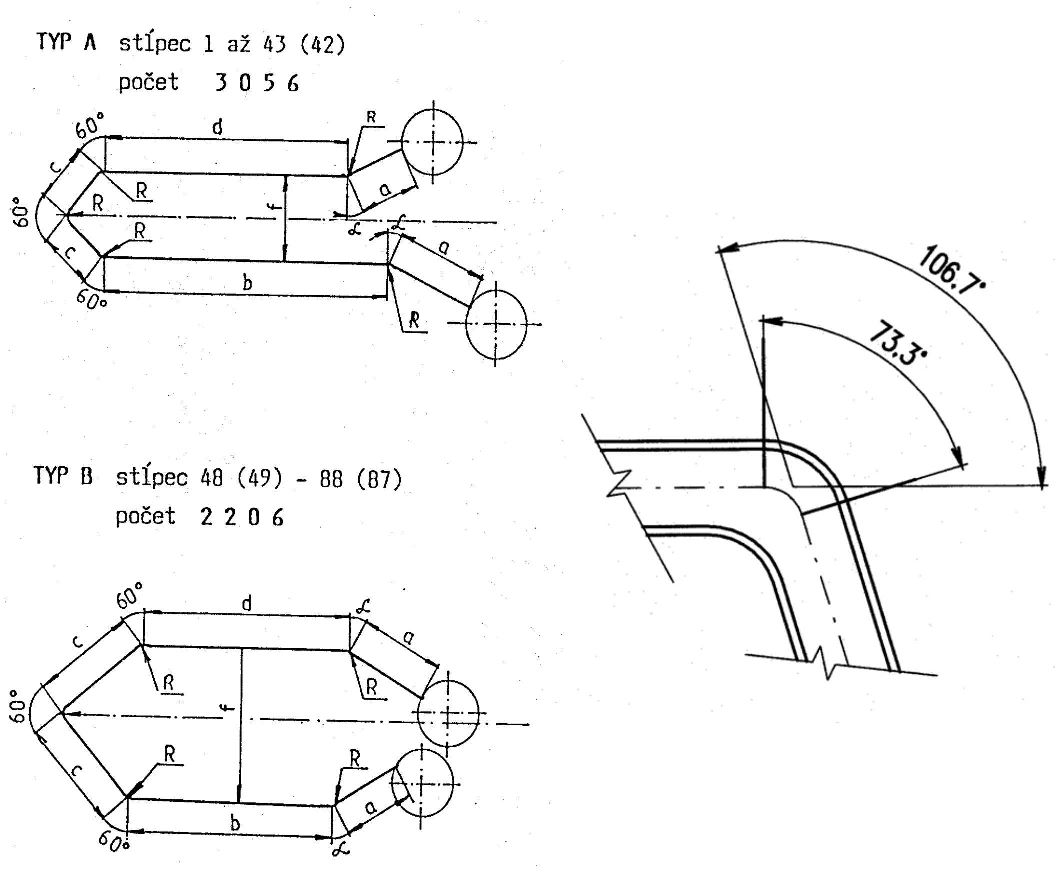
$$\eta = \frac{D_c^2}{D_i^2}$$

D_i - internal diameter of the SGT [mm];
D_c- coil diameter [mm].

Effect of bends on the fill factor

- When calculating the fill factor for a bobbin probe, the bends (bent tubes have an oval cross-section with a reduced radius at the bend point) of the heat exchange tube (SGT) must also be taken into account, due to the probe's passability when testing SGTs because the probe must create the required recording length of the object under inspection. In addition to bends, it is also necessary to take into account sludge (SLG) on the inner surface of the pipes (SLGs reduce the inner diameter and thus the passability of the probes).

- Angle value depends on tube column and it is in range from 4°to 73.3° (worst case).

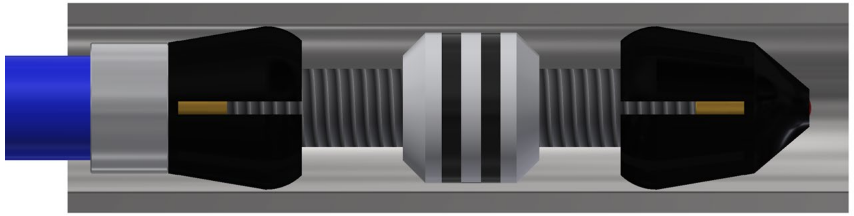


SGTs with bends

Effect of bends on the fill factor

- Inspection of the straight tubes and tubes with bends. Our tubing bobbin probes are built for flexibility, allowing for optimal navigation through tubing u-bends, while maintaining high data quality.

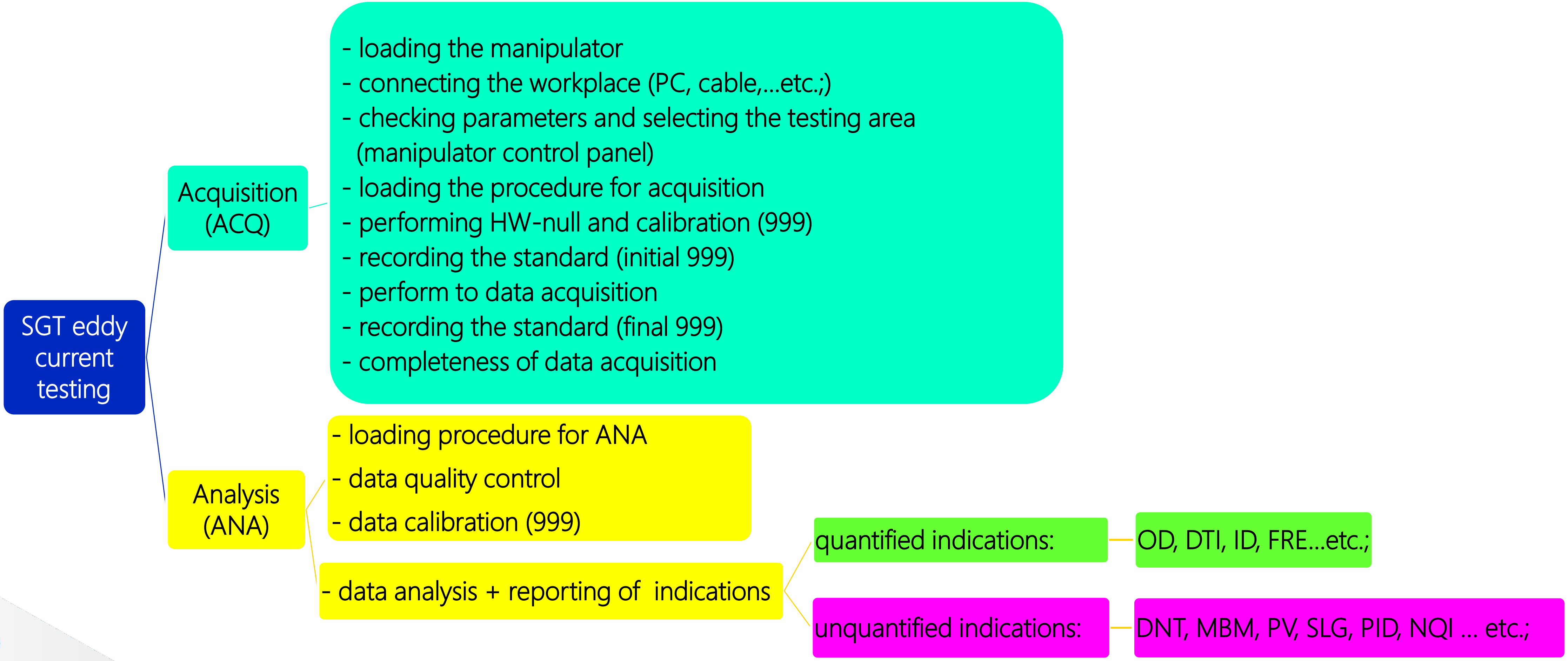
Probe for inspection condenser tubes



For inspection of the straight tubes (Bobbin probe)

For inspection of the tubes with bends

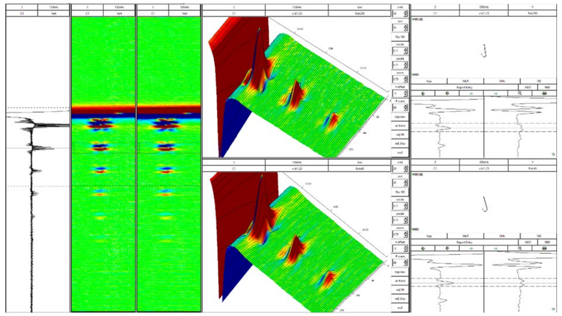
ET acquisition and data analysis



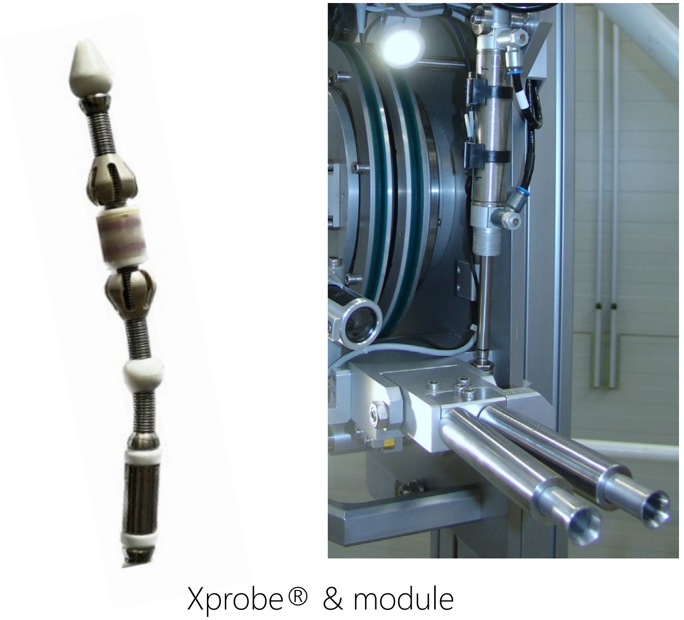
ECT diagram for SGT inspection

EC inspection of SGTs in tubesheets

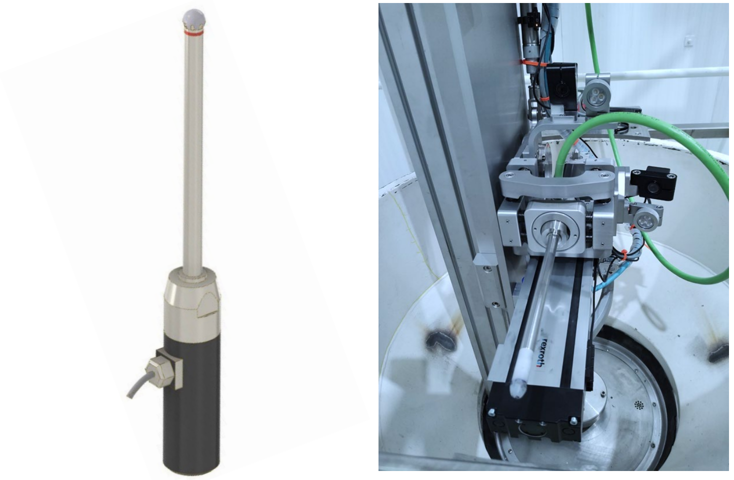
- Fully automatized remote-controlled system is designed for inspection of steam generator collector tubesheet for crack detection.
- Special exchangeable modules enables inspection with motorized rotating probes, MRPC or array probes.
- EC inspection of tubes with a rotary probe
- EC inspection of tubes with a rotary probe in the rolling area



MRPC technique (C-Scan)



Xprobe® & module



MRPC & module

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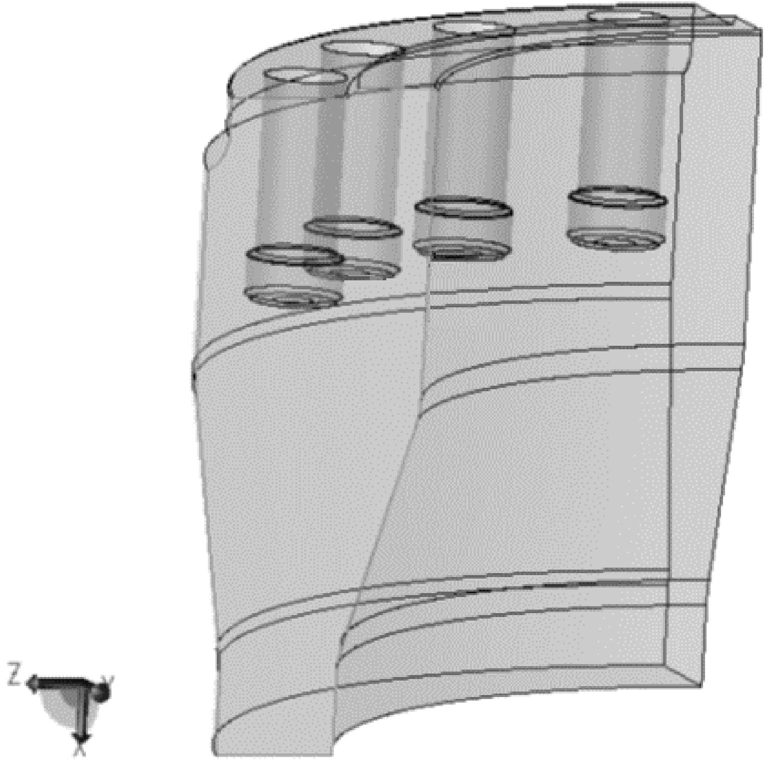
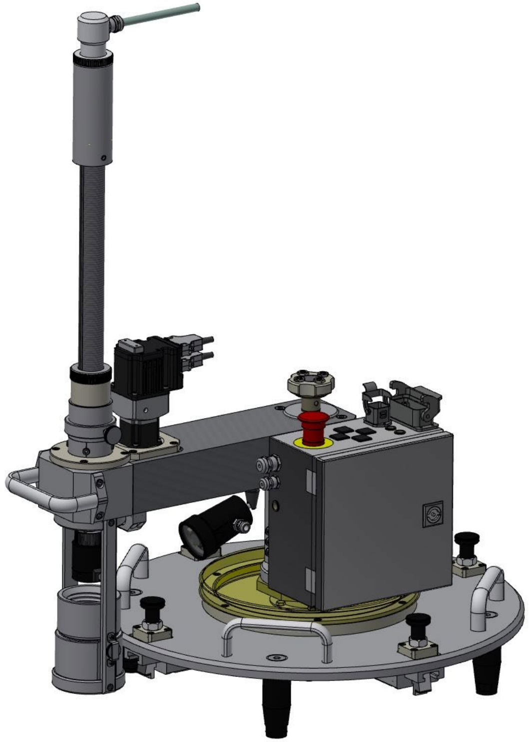
Eddy current probes and standards

EC probe



Flange

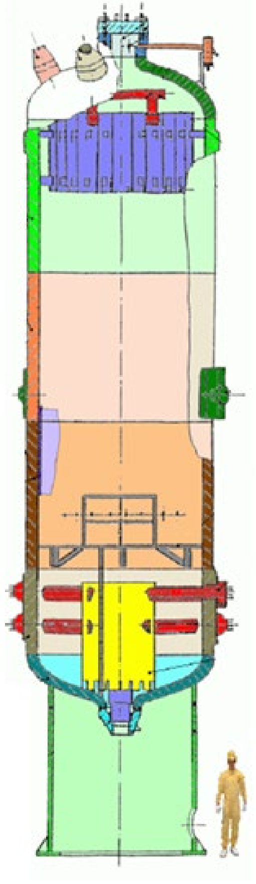


DIZAP manipulator with EC probe

vuje

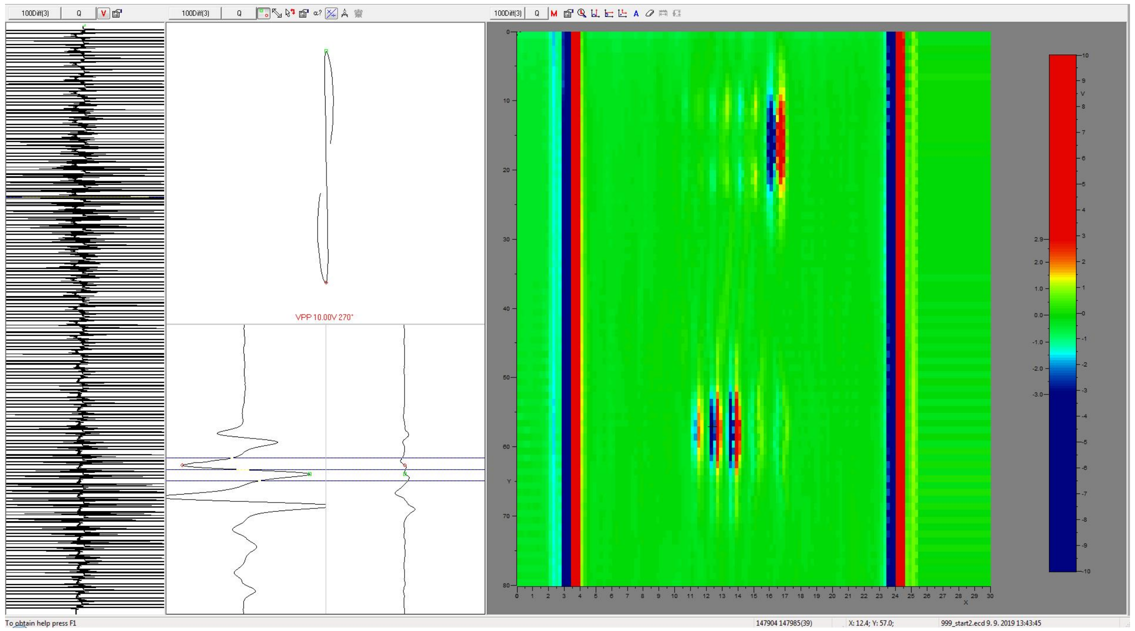
Eddy current probes and standards

- Inspection of stainless steel cladding Pressurizer (PZR)



PZR

PZR manipulator & EC probe

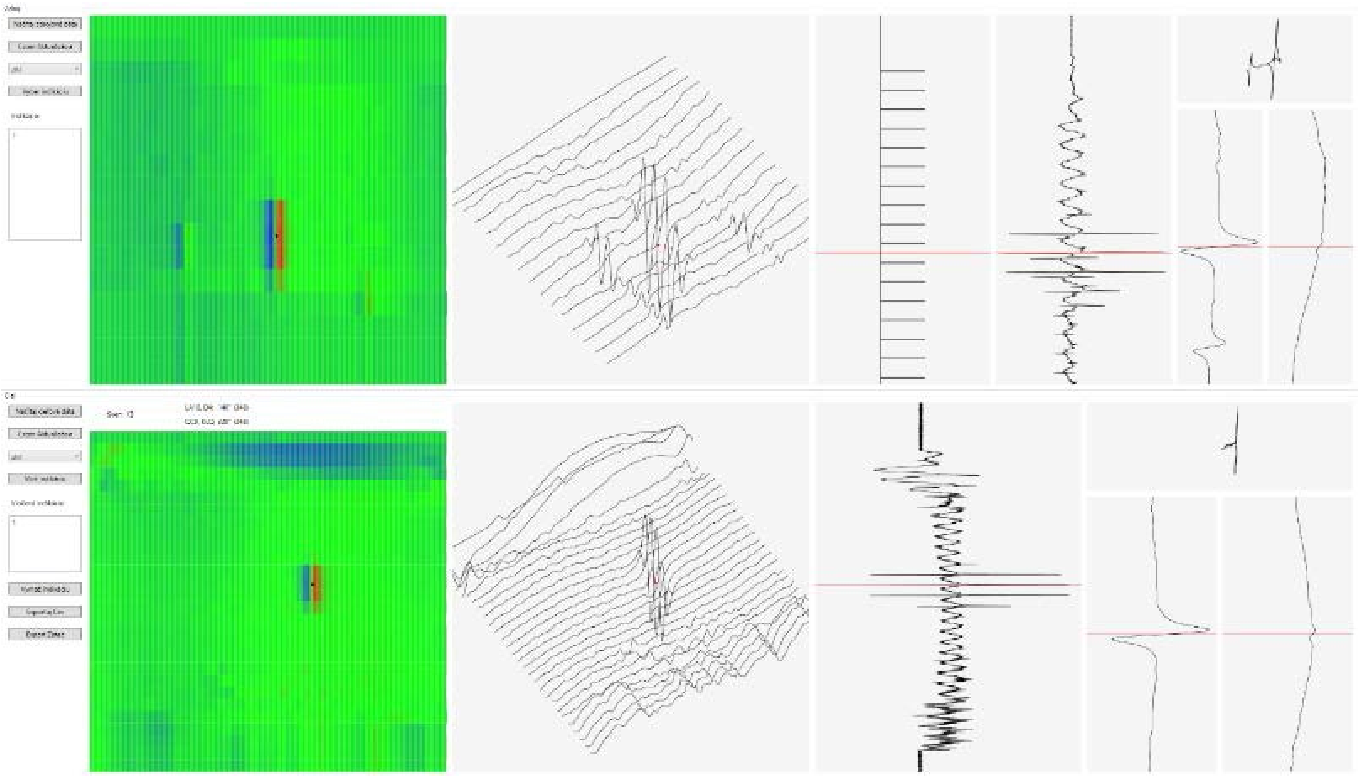


Data from inspection of the surface PZR

vuje

COREC software

- Corec software is used to create training and qualification data (blind tests). This software allows to inject a real defect signal into a any part of the signal from a defect-free material.
- Data created by this software have a realistic appearance (the inserted signal is fully connected to the real data signal).
- Therefore, there is no need to produce large amounts of test blocks (mock-ups) for qualification purposes.

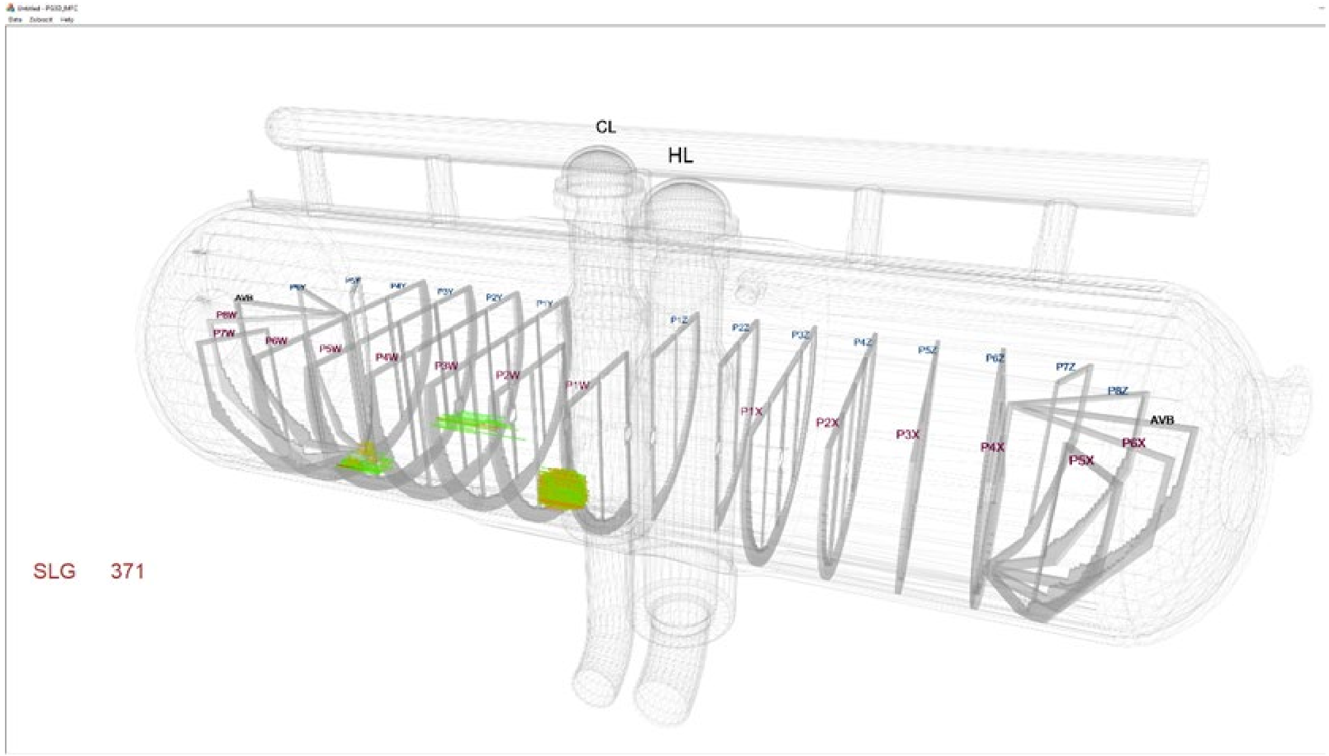


SW COREC (VUJE, a.s.) display application threaded holes

vuje

Sludge-Vision 3D software

- Use of SLUDGE-Vision 3D software (VUJE, a.s.) for amplitude mapping of deposites (sludge) on steam generator tubes (SGTs).
- Sludge (SLG) data from the real SGT inspection is input into the aforementioned SW, then an SLG map is created in a specific part of the PG.
- SLG occurs on the outer surface of the SGT (the surface of the SGT from the secondary side of the steam generator). The sludges creates the conditions for the creation of defects from the outer side of the SGT.



SW Sludge-Vission 3D (VUJE, a.s.)

CIVA software

SW CIVA [5]

CIVA software

- From the numerical point of view, the crack signature is modeled in CIVA by employing an integral-equation based approach in conjunction with the Method of Moments (MoM). In particular, inside CIVA two methods are developed, the so called Volume Integral Method (VIM) and the Boundary Element Method (BEM) [5].

- CIVA software allows simulating a large variety of probes used to induce eddy current inside the piece or as receivers. Different kinds of probe coils can be used, each being driven by a variable current. In CIVA software allows to define probes that work in the absolute and differential mode and in separated emission and reception [5].

- Moreover, coils array are also used to enhance the collected information during the acquisition process. Moreover, different kinds of coils can be used in order to collect information on different aspects of the electromagnetic field induced by the tested object. In particular, 2D-symmetrical coils with and without ferrite core can be modeled. Moreover, in case of non-ferrite core coils, 2D-symmetrical and non-symmetrical 3D-coils can be modeled without restriction on coils orientations [5].

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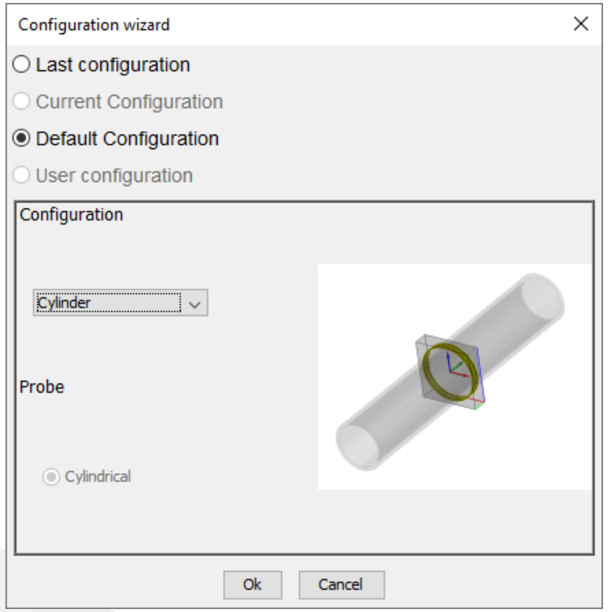
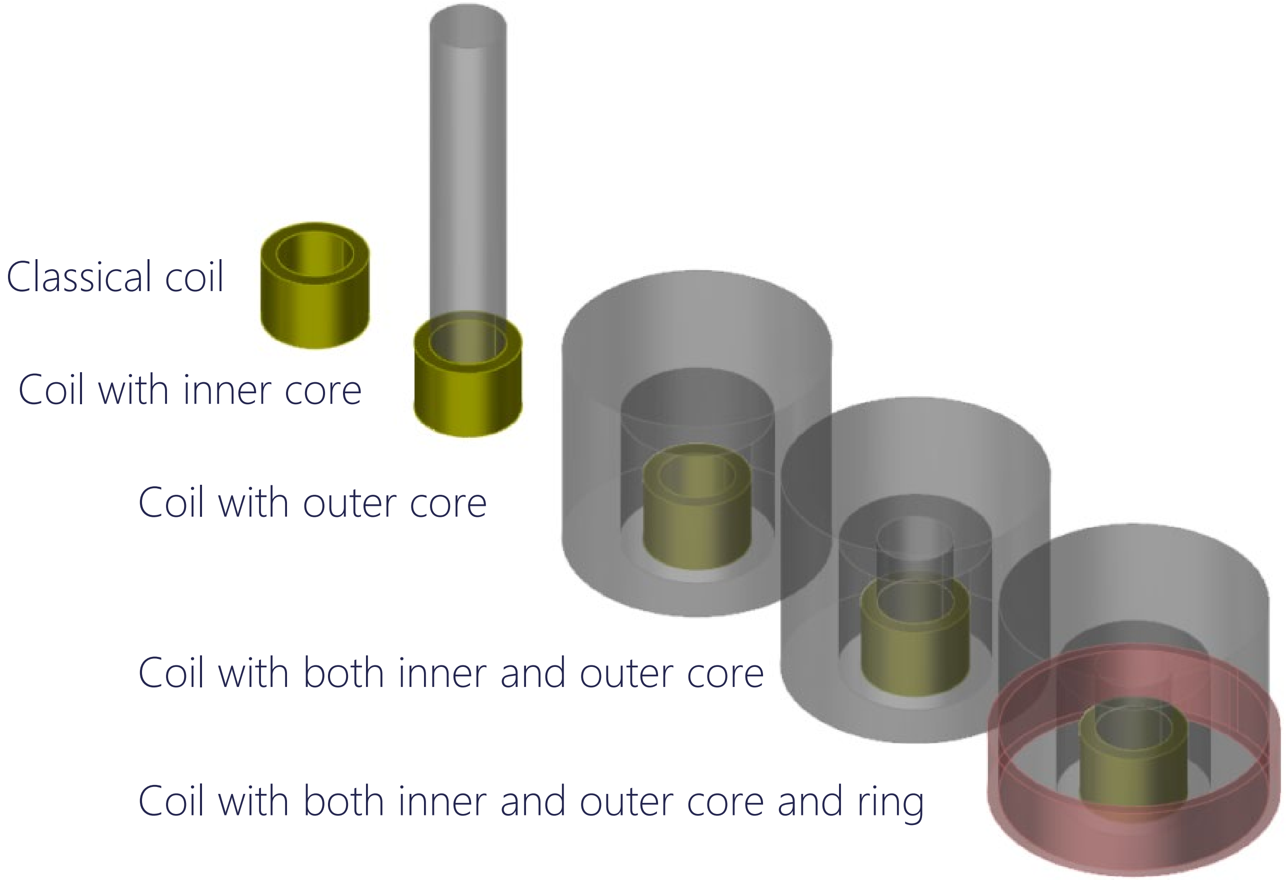
Field computation

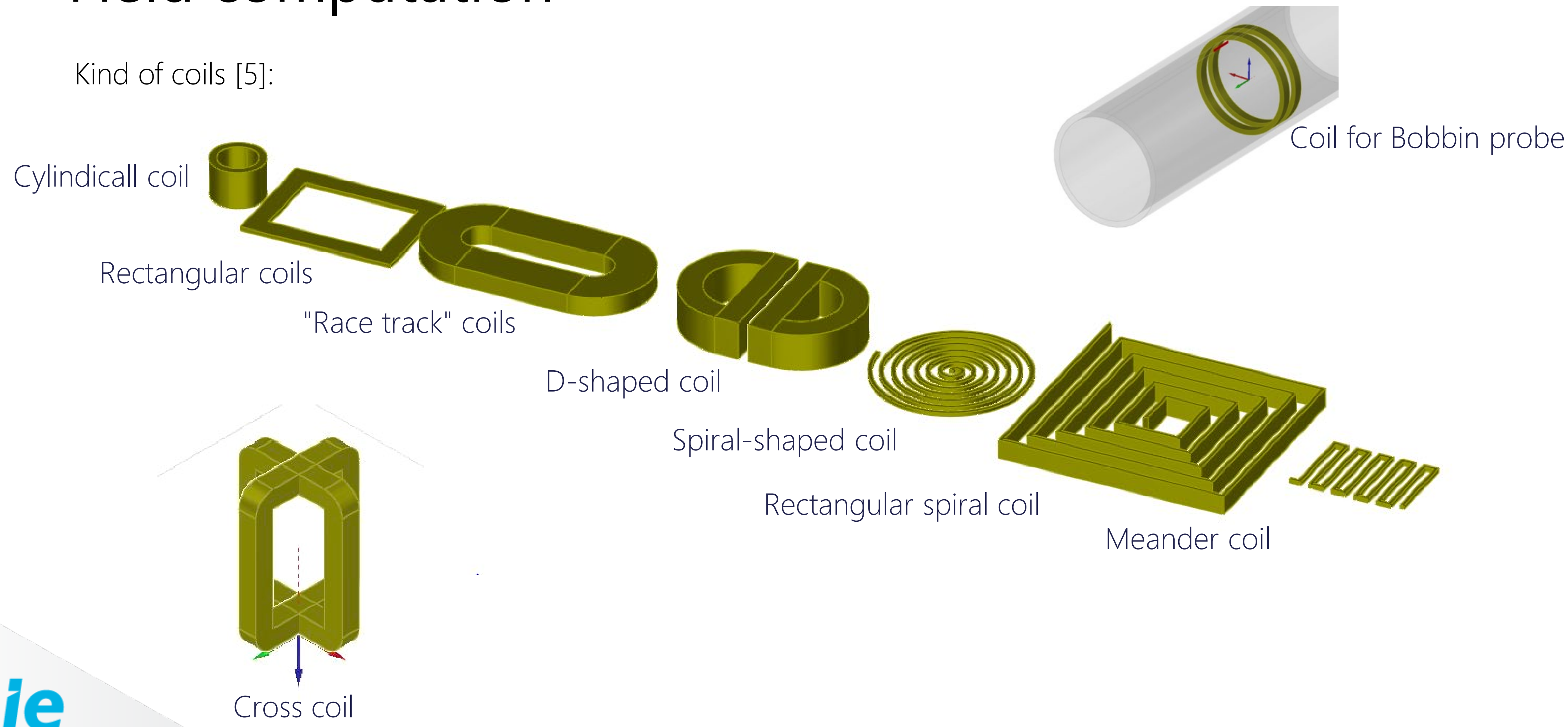
- Probe – geometric parameters (external and internal diameter), number of turns, shape of the core, number of coils, core type … [5]





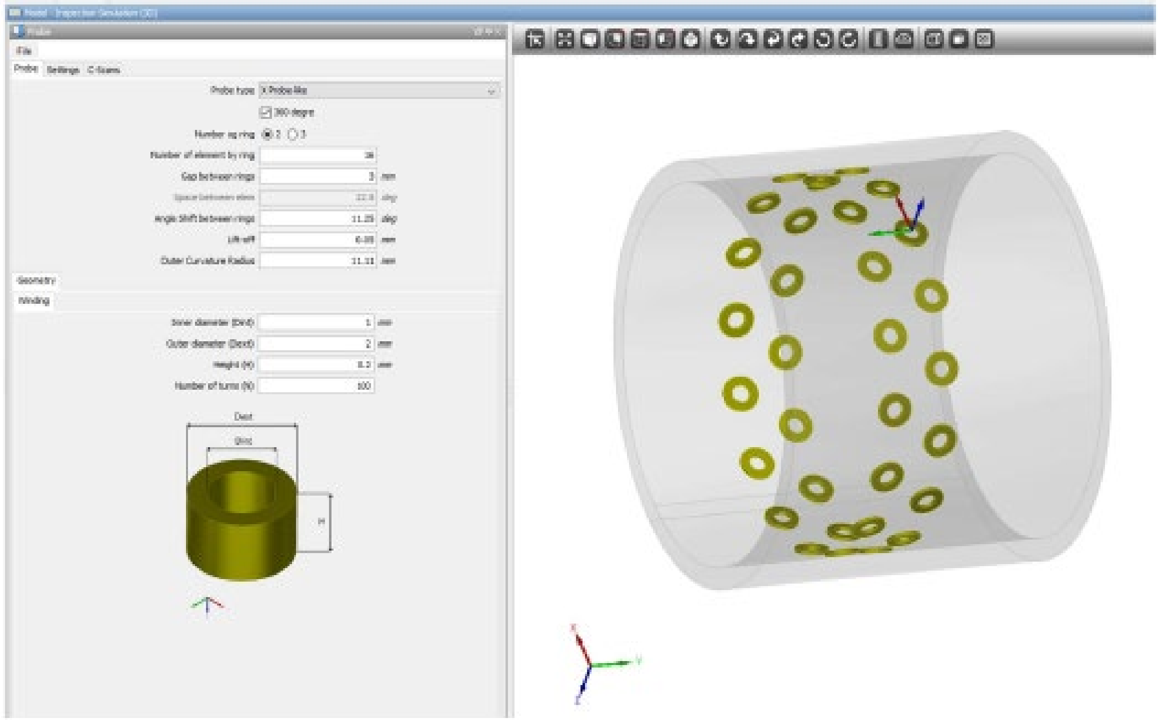
Field computation

Kind of coils [5]:



Define the coil properties

- The X-probe like probe is working in a separate transmit-receive mode. This kind of probe can be used for the detection of both circumferential flaws and longitudinal flaws. Depending on the type of flaw to be detected, different patterns can be used. In CIVA, 3 predefined patterns are available under the "Settings" tab [5].
- Two axial patterns with transmission coil and reception on different rings are useful for longitudinal flaws detection and a transverse pattern with transmission coil and reception coil on the same ring which is useful for circumferential flaws detection [5].



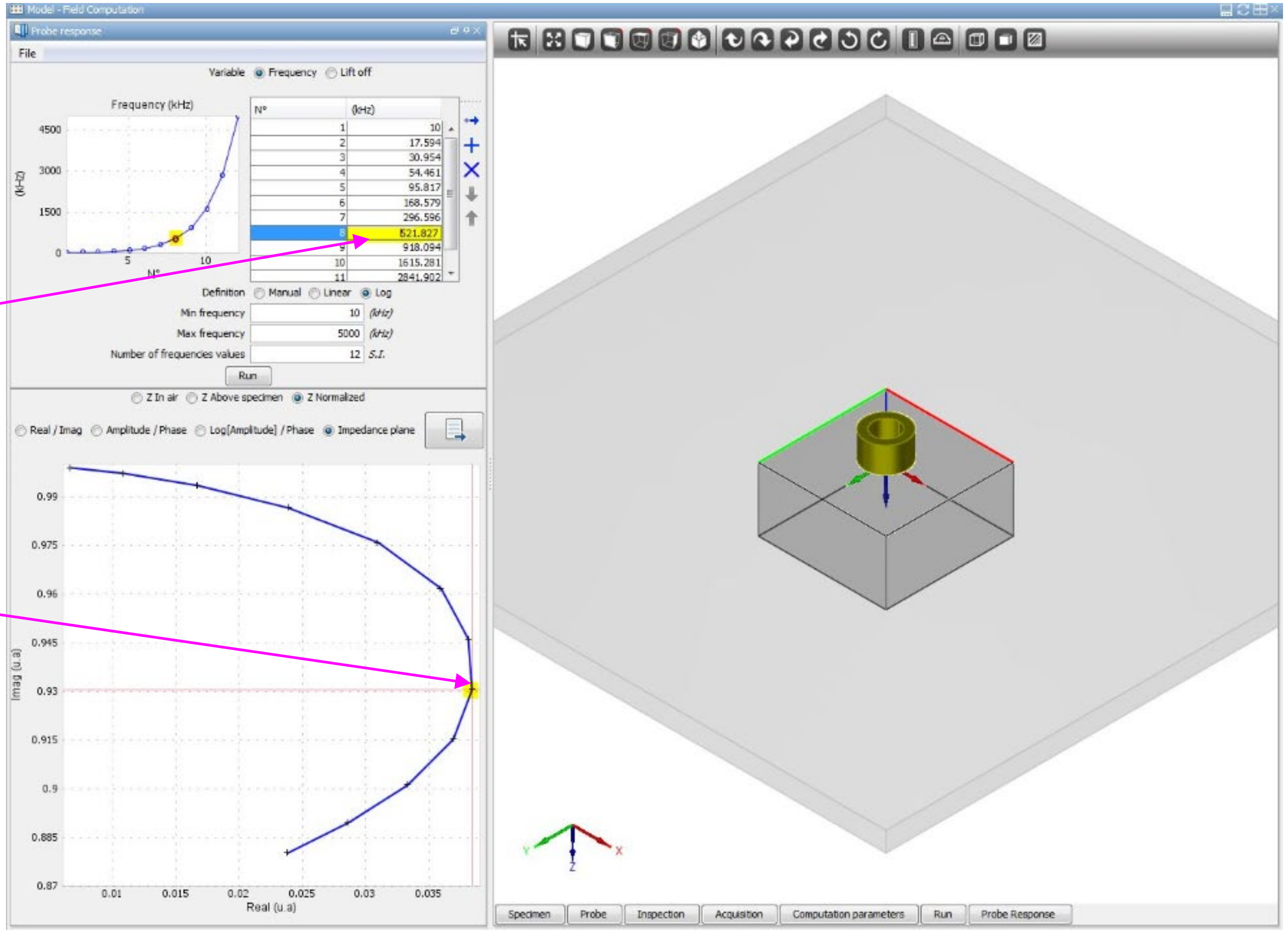
X-probe® parameters [5]

Field computation

Probe response – calculation of the normalized impedance plane and the appropriate frequency

Optimal frequency for testing

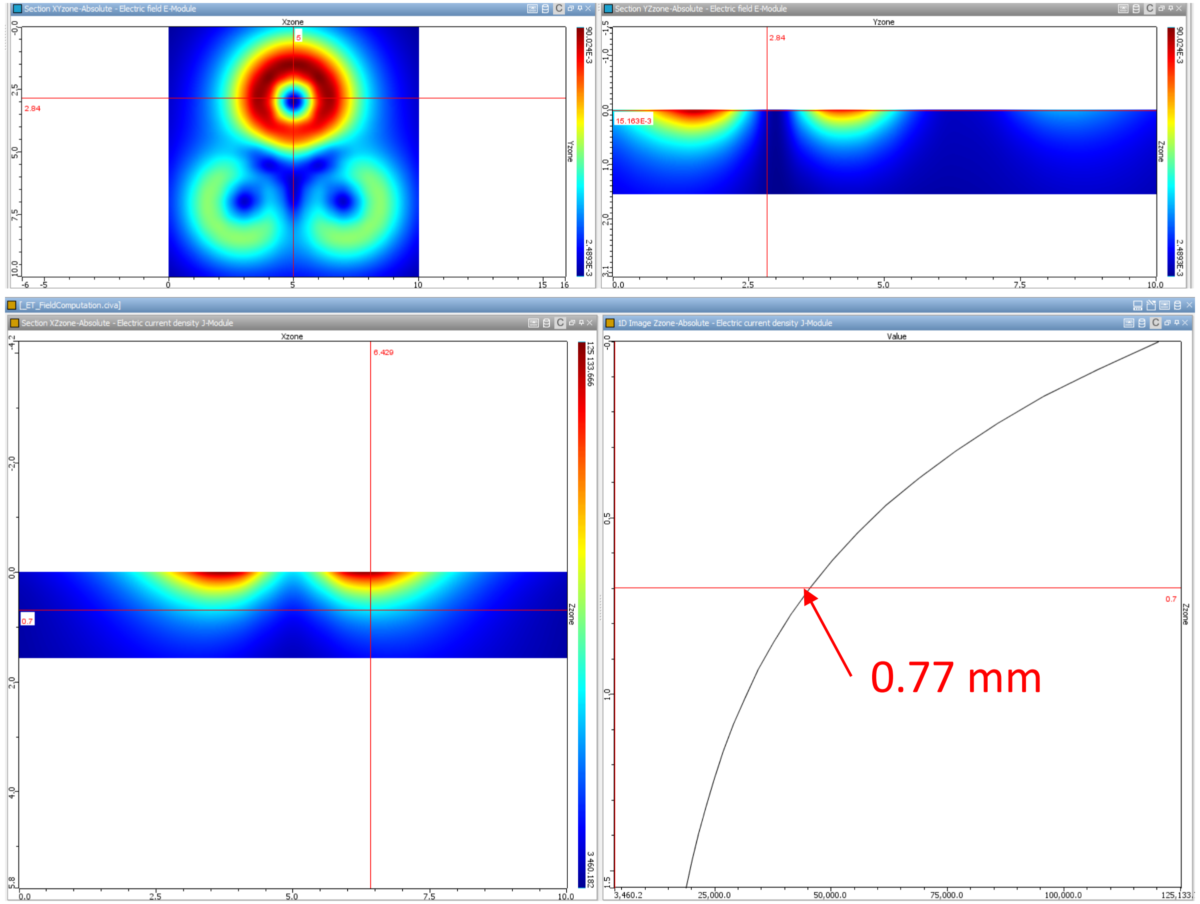
Normalized impedance plane



Probe response

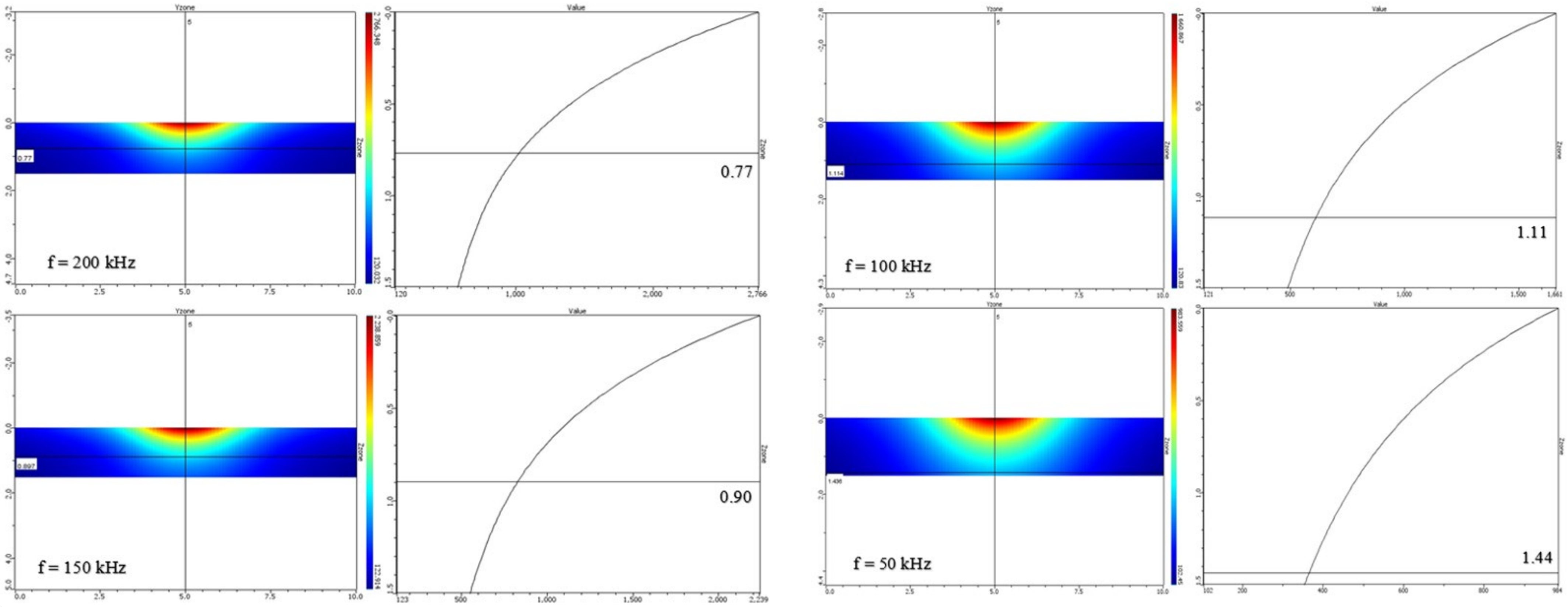
Calculation EC penetration depth in SW CIVA

- Display only the XZ section as well as the "1D image zone" at a position of maximum amplitude [5].
- The skin depth is where the current density is 37% of the maximum current density. In this case, the skin depth is around 0.7 mm [5].



Skin effect [5]

Calculation EC penetration depth in SW CIVA



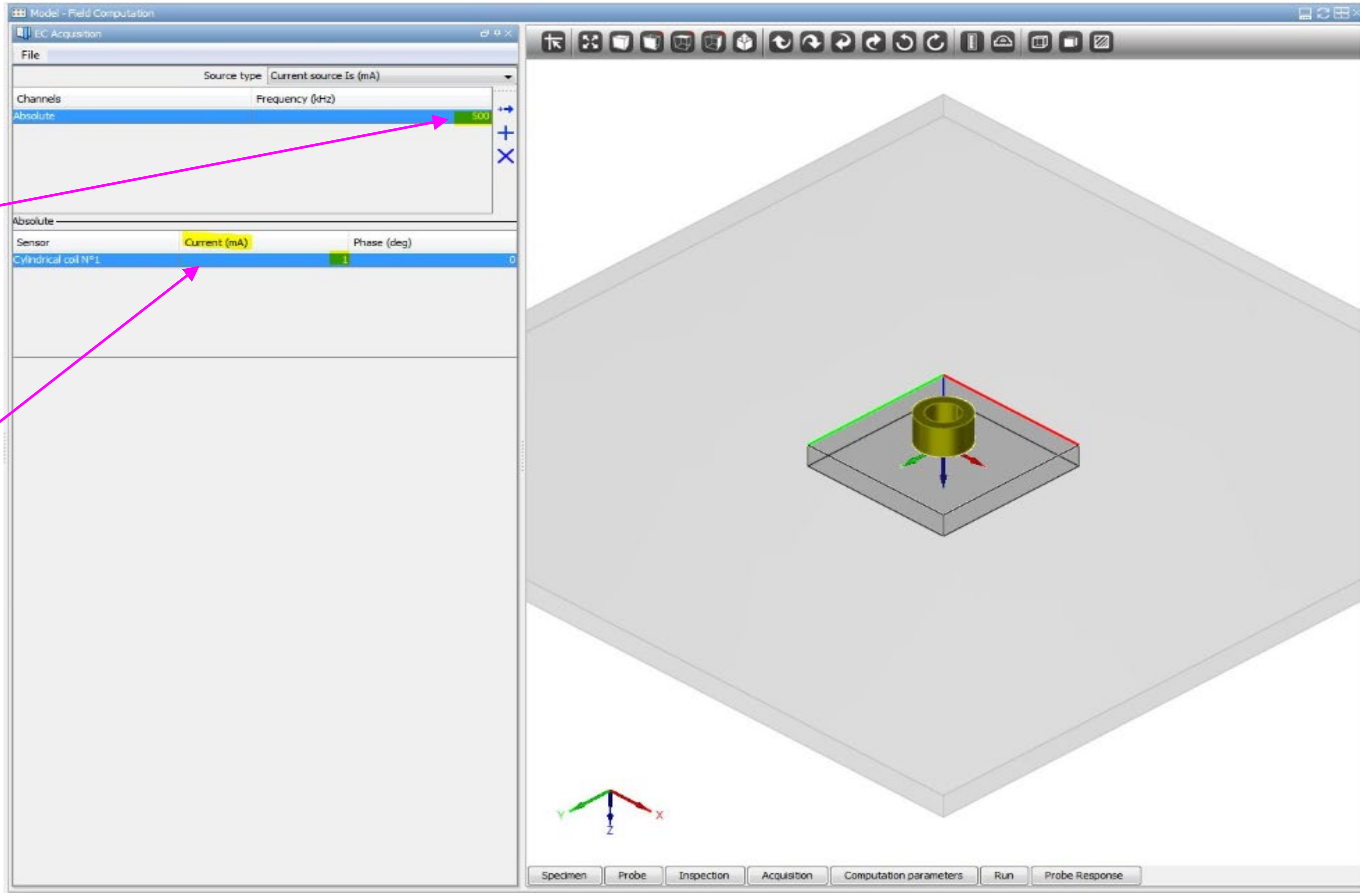
Graphical representation of the density and standard penetration depth of eddy currents

Field computation

- Acquisition – frequency, coil power supply… [5]

Test frequency

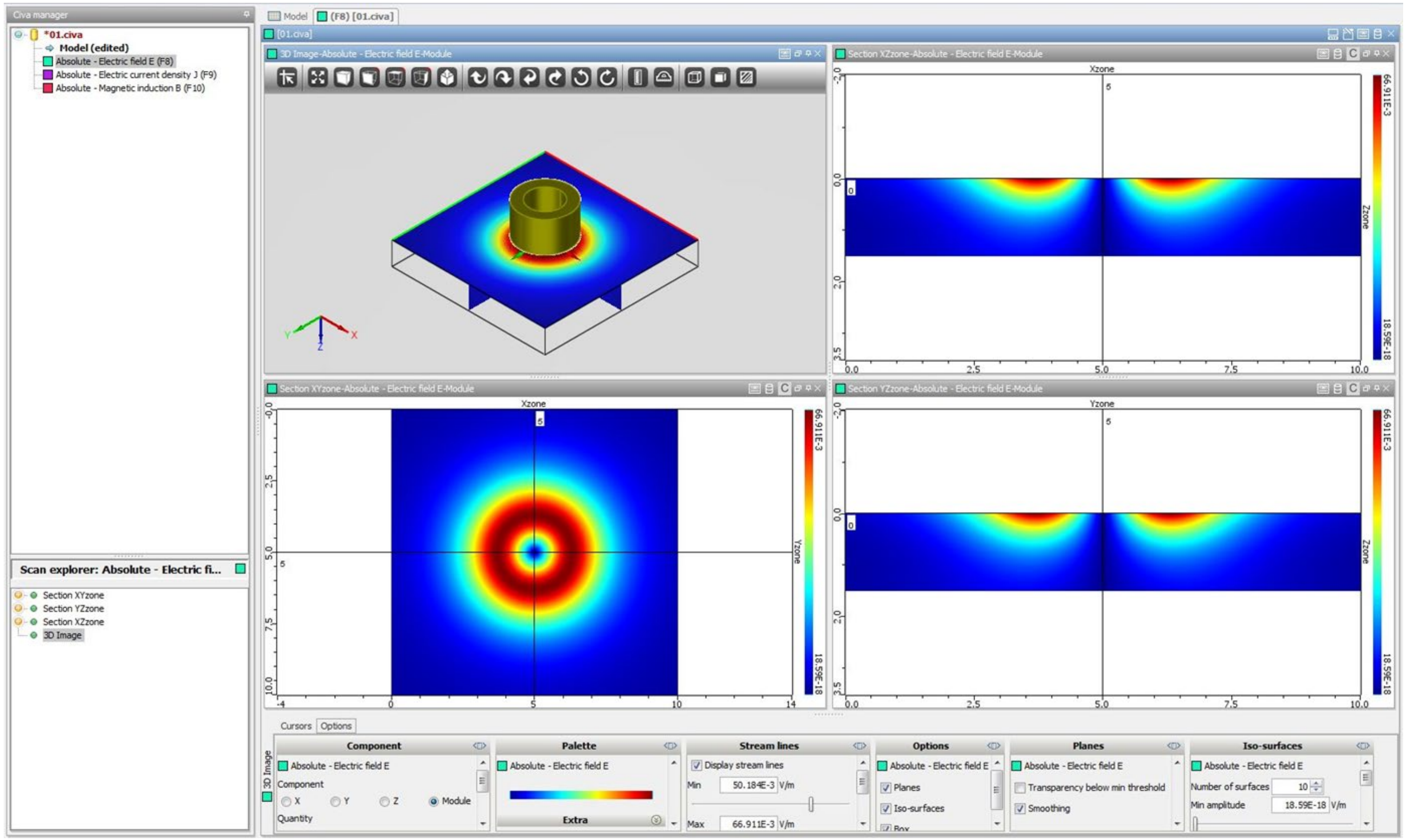
Coil connection method, for example D-P, Diff. etc.



EC Acquisition [5]

Field computation

- Calculation results [5]:



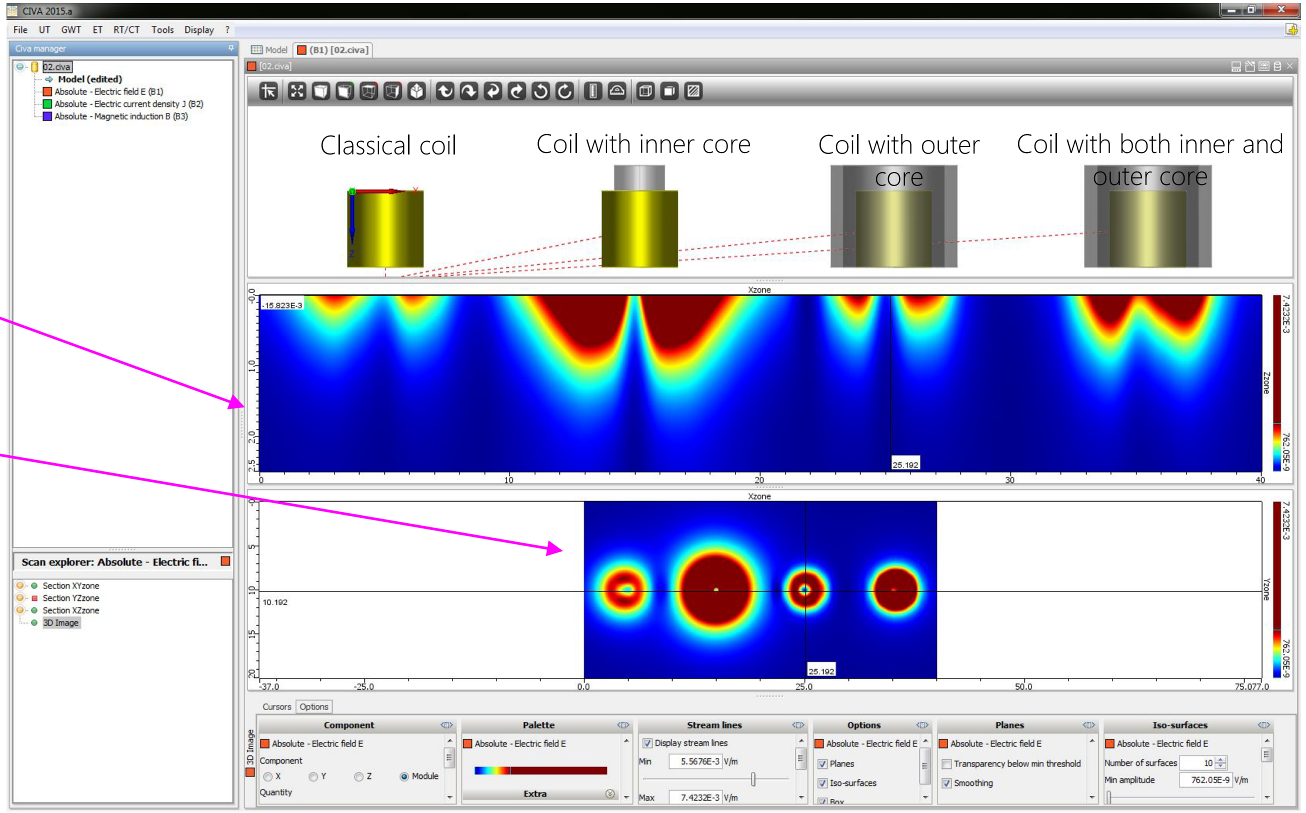
Display results [5]

Field computation

- Same coil and different cores – different penetration depth

Different intensity and depth of eddy current penetration

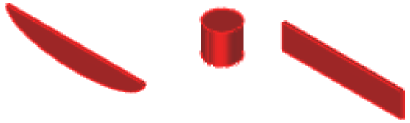
Different coil width

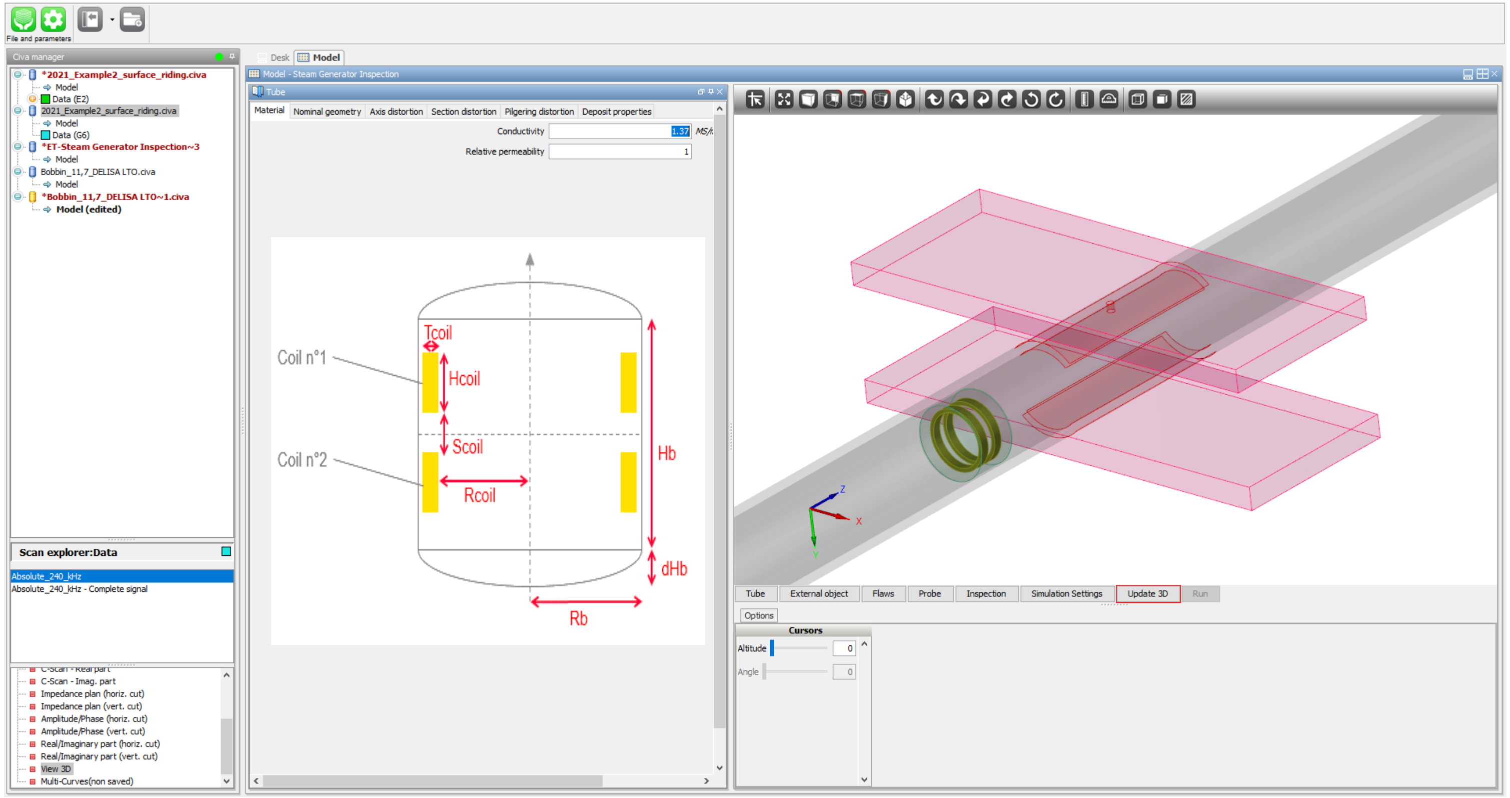


Display results [5]

Steam generator inspection

- To define the relevant input data, you will have to successively open 5 panels:

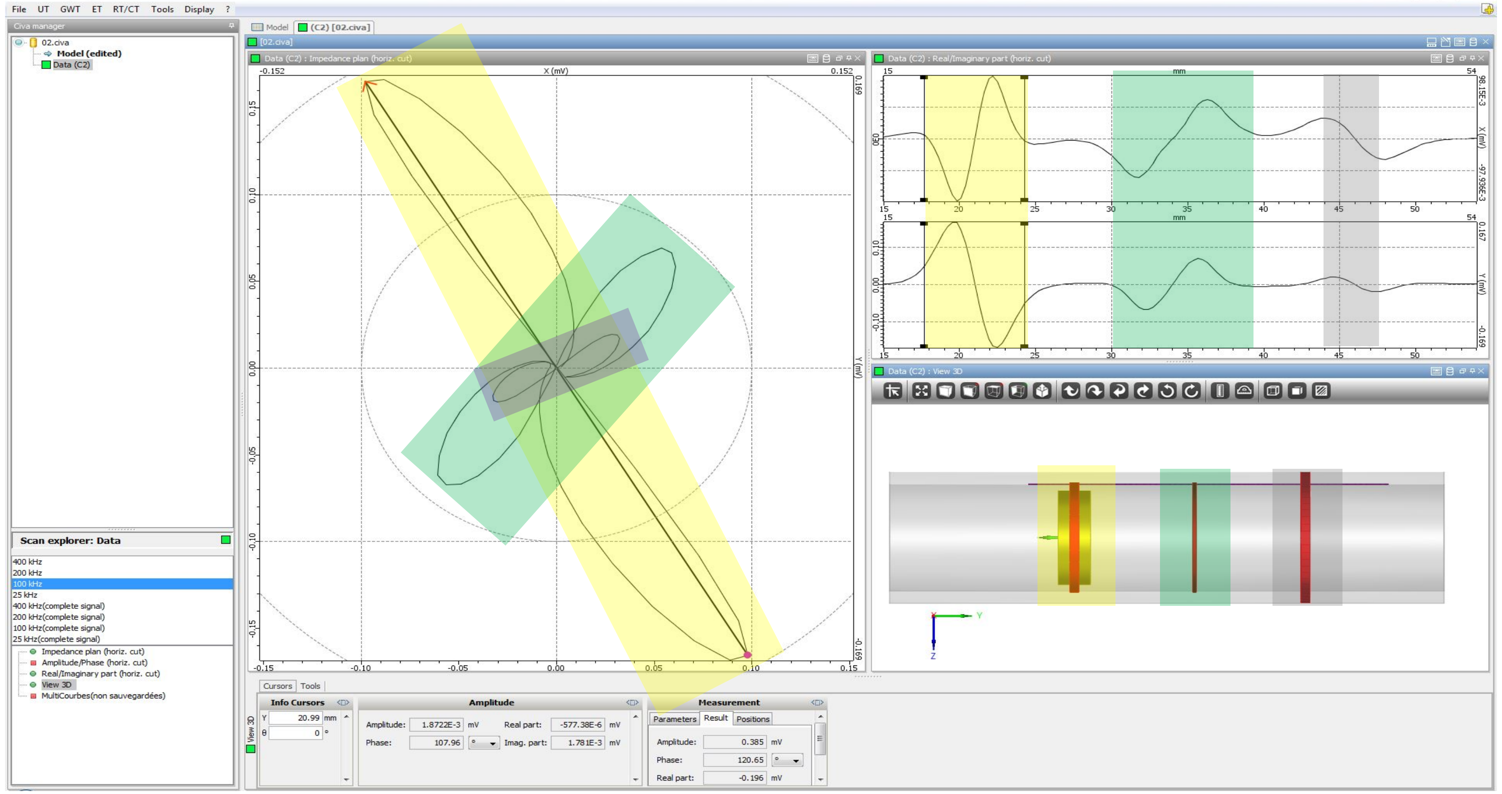
  - Specimen
  - Probe
  - Inspection
  - Flaw 
  - Acquisition



Inserting input data before calculation

Steam generator inspection

- Bobbin technique simulation
- Display of indications at a frequency of 100 kHz



Bobbin technique simulation

Inspection simulation 3D

- Simulation of surface inspection using a cross probe – differential coil connection [5].

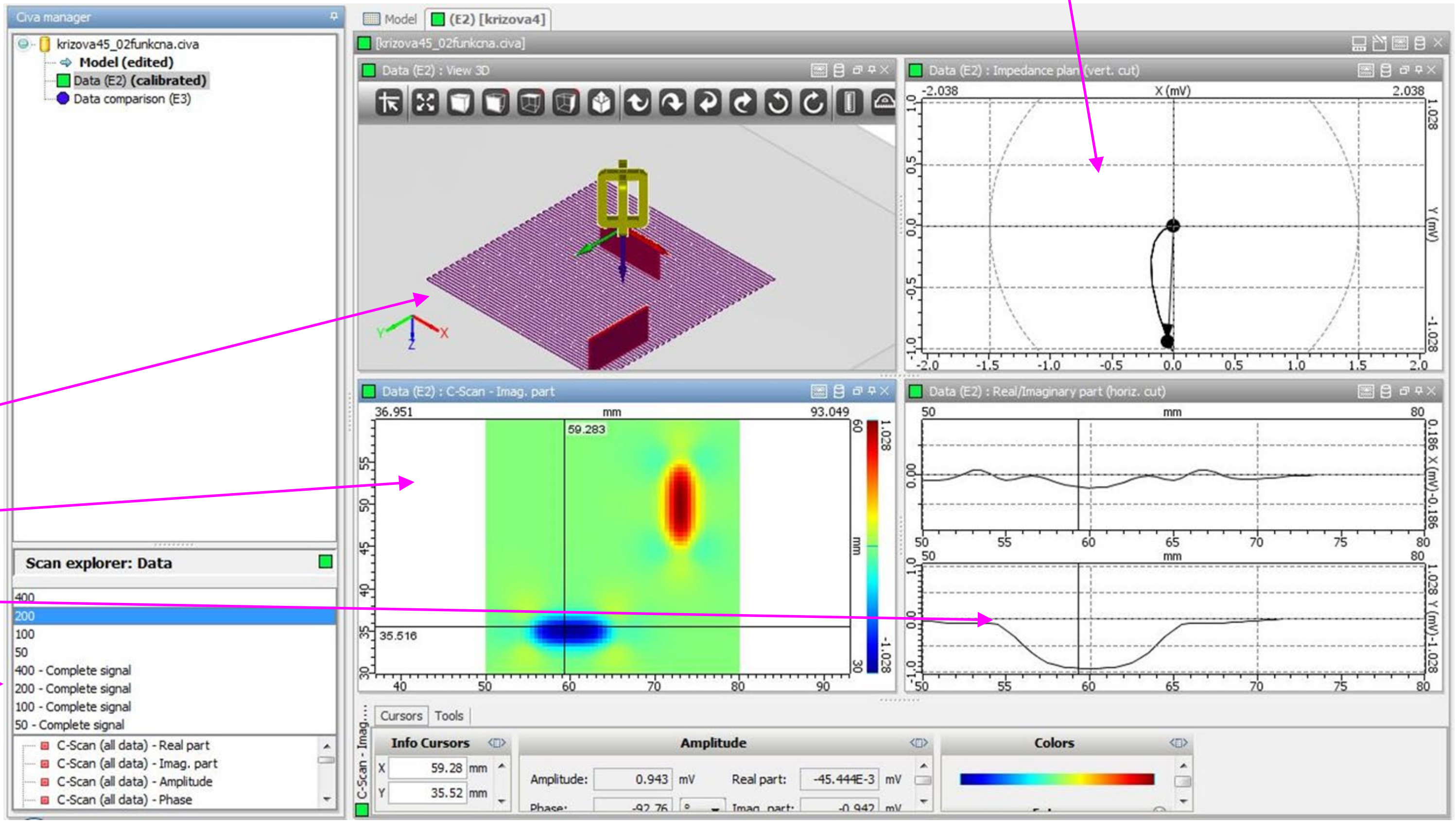
Impedance plan

The meander of testing

C-Scan display

Impedance plan

Frequencies used



Cross probe display [5]

Conclusion

- The presentation provides an overview of the state-of-the-art methods and software for eddy current testing, which is one of the most widely used forms of non-destructive testing in the nuclear industry. The only requirement is that the materials being tested must be electrical conductors where eddy currents can flow.
- Coil probes are the most commonly used type of sensor, and standard coils can be used in a wide variety of applications.
- Although eddy current testing has been in development for several decades, research into the development of new probes, techniques, and instrumentation is currently being conducted by manufacturers and research groups around the world.

vuje

References

- [1] V. Sankar, „Eddy Current Testing (ECT)- Modul 6," Department of Mechanical Engineering, Rajagiri School of Enegineering & Technology (RSET), 01 January 2019. [Online]. Available: https://www.rajagiritech.ac.in/home/mech/Course_Content/Semester%20V/ME%20367%20Non%20Destructive%20Testing/Module%206.pdf. [Cit. 11 February 2025].
- [2] J. G. Martín, J. G. Gil a E. V. Sánchez, „Non-Destructive Techniques Based on Eddy Current Testing," Sensors, zv. 11, 1. vyd.ISSN 1424-8220, pp. 2525-2565, 2011.
- [3] NDT Supply.com, Inc., „CHAPTER 4 EDDY CURRENT INSPECTION METHOD. SECTION I EDDY CURRENT INSPECTION (ET) METHOD," "Oklahoma City AFLCMC/GUEAA, 3001 Staff Drive, Tinker AFB, OK 73145", 18 February 2020. [Online]. Available: https://content.ndtsupply.com/media/Eddy%20Current%20-USAF-Tech-Manual-N-R.pdf. [Cit. 11 February 2025].

References

- [4] Zetec, Inc., „Overwiev, A modular unit for power plant inspections.“ 2022. [Online]. Available: https://www.zetec.com/products/eddy-current/eddy-current-instrumentation/miz-85id/. [Cit. 11 February 2025]
- [5] EXTENDE, „CIVA NDE 2023 - User manual,“ Extende, France, 2023.

Our References

Slovenské elektrárne, a.s., Bohunice NPP, Mochovce NPP

ČEZ, a. s. Dukovany NPP, Temelin NPP

ROSATOM, Kola NPP, Novovoronezh NPP

NAEK Energoatom, Khmelnitsky NPP, Rivne NPP, South-Ukrainian NPP

MVM, Paks NPP

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Thank you for your attention

Do not hesitate to contact us for more information

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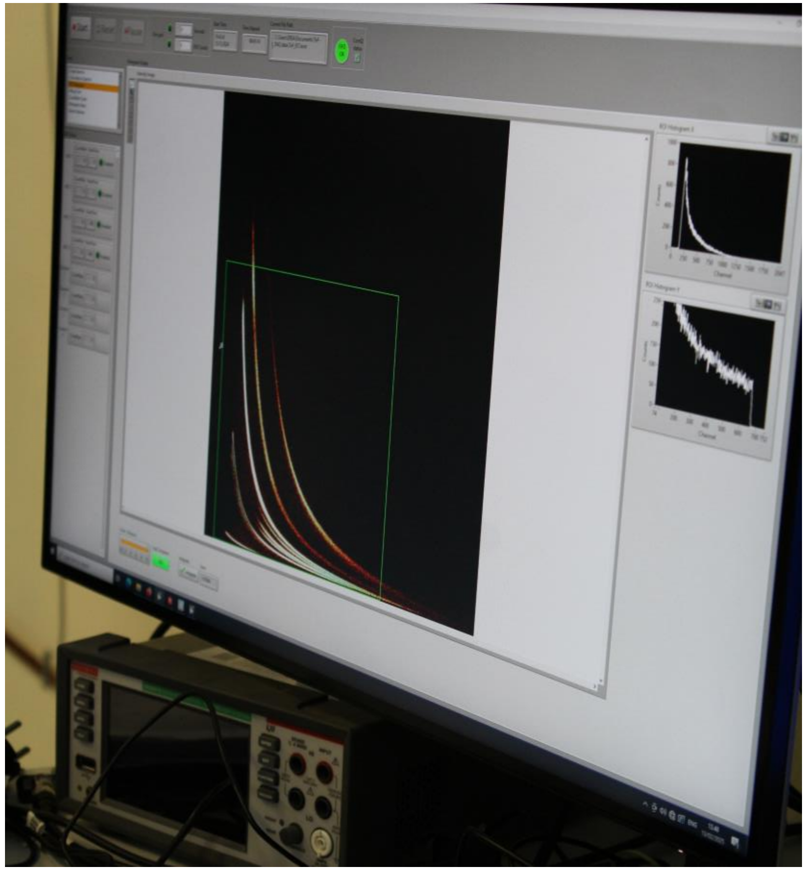
Social activities on Wednesday

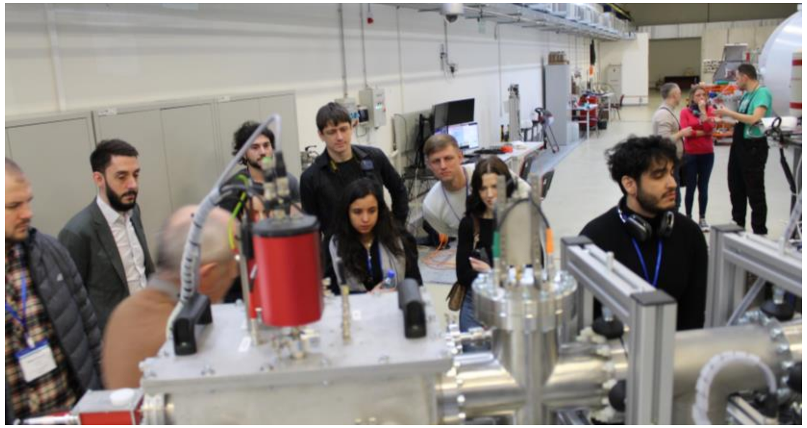
Piešťany SPA with medical mud

THURSDAY'S EXCURSION

Excursion at VUJE

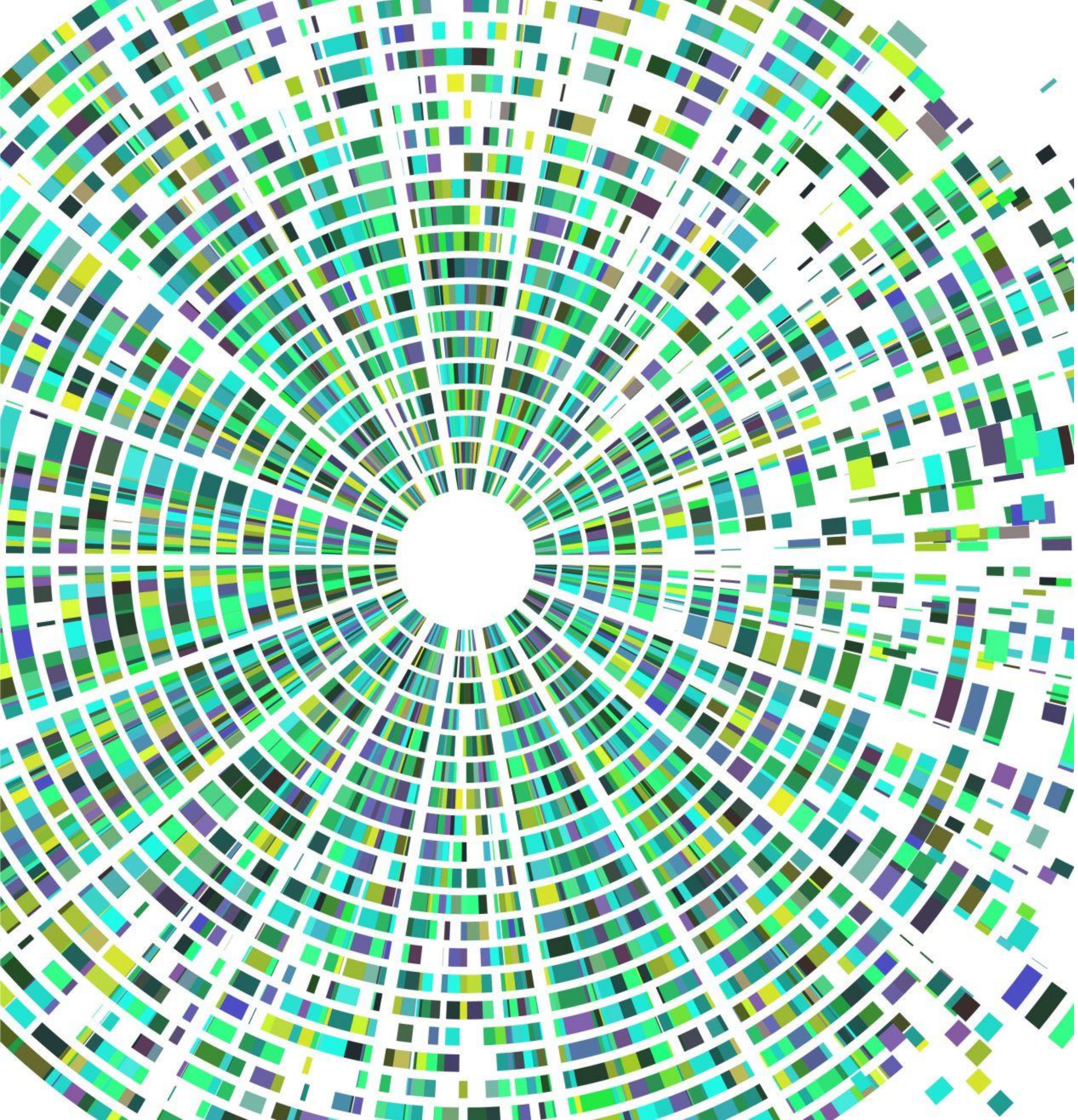







Excursion at MTF STU

Excursion at MTF STU



Friday's presentations

Long Term Operation of NPPs in SR

Fulfilment of legislative requirements for LTO programme in SR

Long Term Operation of NPPs in Slovak Republic

DELISA-LTO Workshop

Ľudovít Kupča | 14 Feb 2025 | Kočovce

Content

Introduction

LTO of NPPs in SE process model

Legislative requirements for LTO programme

IAEA requirements and recommendations for LTO

LTO programme for Bohunice 3,4 (2010-present)

LTO programme for Mochovce 1,2 (2019-present)

Purpose and objective of LTO programme

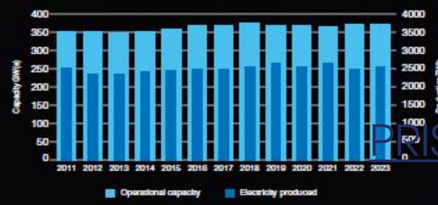
Nuclear Power Status 2023

Reactors in operation
371.5 GW(e) total net capacity
413 reactors
2552.1 TWh electricity produced

Reactors in suspended operation
21.3 GW(e) total net capacity
25 reactors

Reactors under construction
61.1 GW(e) total net capacity
59 reactors

IAEA | Power Reactor Information System PRIS

Capacity utilization


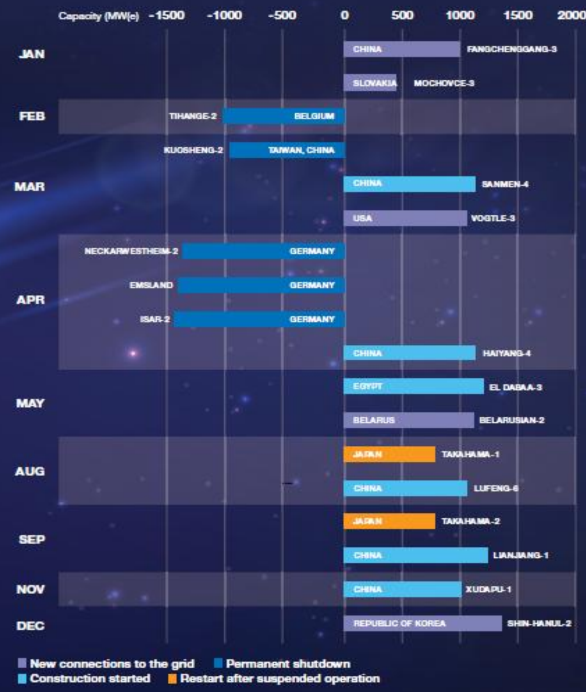
Use of nuclear power for non-electric applications
Utilization by type
2 046 GWh equivalent of heat


Utilization by country


PRIS - Miscellaneous reports - Operational by Age

Age distribution of net operational capacity

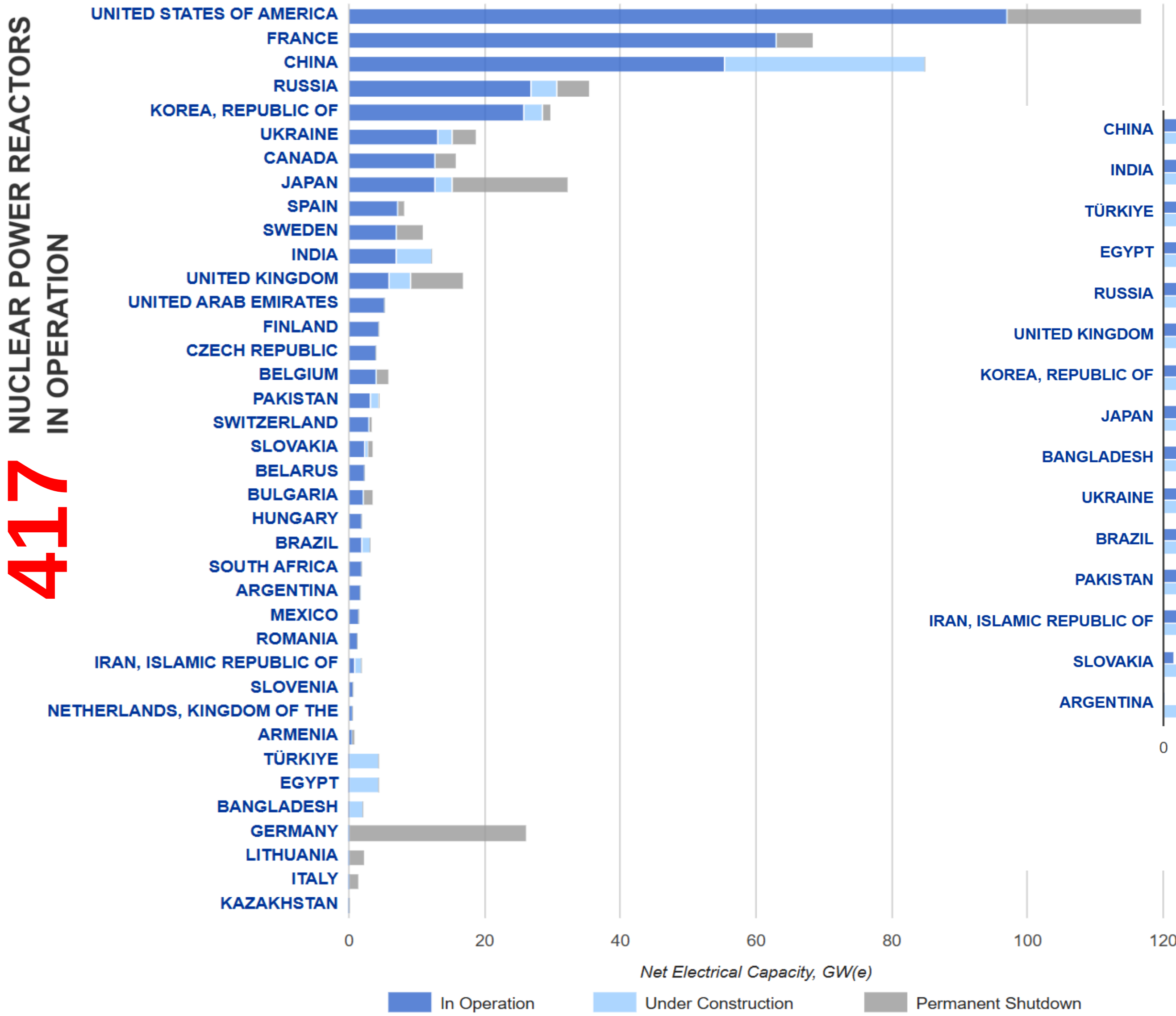

Global nuclear power performance 2023

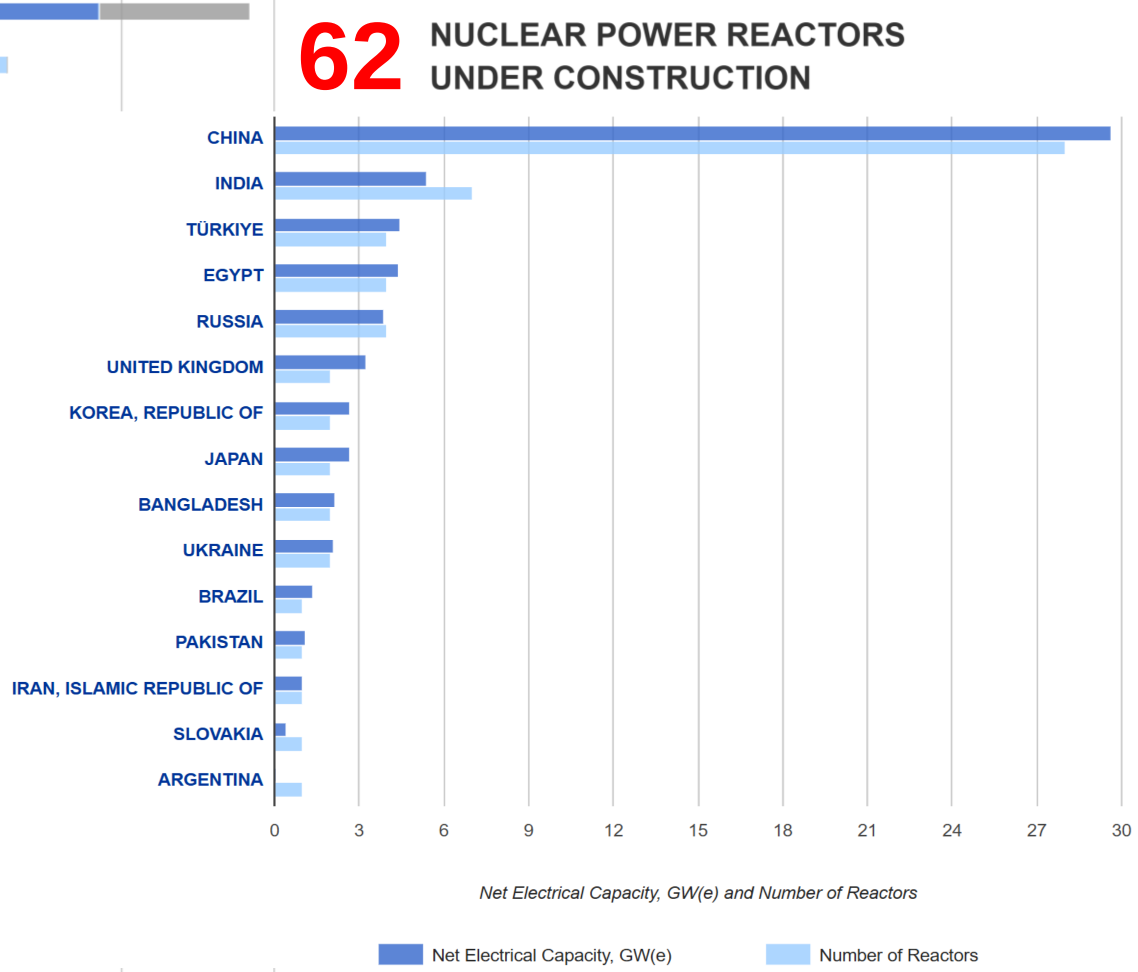

Reactor status changes


Country statistics


[PRIS - Country Statistics]

Plants Worldwide Status





[PRIS - Reactor status reports - Under Construction - By Country]

Construction in Europe vs China

Olkiluoto 3	EPR 1600 MW_e
12 Aug 2005	Construction Start
21 Dec 2021	First Criticality
12 Mar 2022	First Grid Connection
1 May 2023	Commercial Operation
17ys 8m	< Construction - commercial operation >

Flamanville 3	EPR 1630 MW_e
3 Dec 2007	Construction Start
3 Sep 2024	First Criticality
21 Dec 2024	First Grid Connection
N/A	Commercial Operation
17ys	< Construction - commercial operation >

Taishan 1	EPR 1660 MW_e
18 Nov 2009	Construction Start
6 Jun 2018	First Criticality
29 Jun 2018	First Grid Connection
13 Dec 2018	Commercial Operation
9ys 1m	< Construction - commercial operation >

Taishan 2	EPR 1660 MW_e
15 Apr 2010	Construction Start
28 May 2019	First Criticality
23 Jun 2019	First Grid Connection
7 Sep 2019	Commercial Operation
9ys 5m	< Construction - commercial operation >

Construction in Europe vs China

Hinkley Point 1	EPR 1630 MW_e
11 Dec 2018	Construction Start
N/A	First Criticality
N/A	First Grid Connection
N/A	Commercial Operation
?	< Construction - commercial operation >

Hinkley Point 2	EPR 1630 MW_e
12 Dec 2019	Construction Start
N/A	First Criticality
N/A	First Grid Connection
N/A	Commercial Operation
?	< Construction - commercial operation >

Kursk 2-1	VVER-TOI 1200 MW_e
28 Apr 2018	Construction Start
N/A	First Criticality
N/A	First Grid Connection
N/A	Commercial Operation
?	< Construction - commercial operation >

Kursk 2-2	VVER-TOI 1200 MW_e
1 May 2019	Construction Start
N/A	First Criticality
N/A	First Grid Connection
N/A	Commercial Operation
?	< Construction - commercial operation >

Validity of the operating licence
Licence Renewal

SR, CZR	Operating licence without time limitation. LTO approval after 30 years of plant operation. PSR every 10 years.
France	Operating licence without time limitation. PSR every 10 years.
Hungary	Licence renewal for 20 years after 30 years of plant operation. PSR every 10 years.
USA	Licence renewal for 20 years after 40 years of plant operation.
Russia	Extension of operating licence for 15-25 years after 30 years of plant operation, depending on the type of reactor.
Finland	Extension of operating licence for 20 years after 30 years of plant operation.

Regulatory requirements for LTO

NRA SR (UJD)

Submittal of the required LTO licensing documentation pursuant to Decree on PSR.

Operating licence without time limitation.

LTO = 30+30+30 PSR every 10 years.

Note: First PSR completed in 2007 (Final report submitted to NRA on 22 Feb 2007, revised version of the report submitted on 15 July 2008).

On 30 Oct 2008 NRA issued authorization for operation of Bohunice 3,4 plant (Decision No. 275/2008).

This authorization (operating licence) is valid till present days.

US NRC

Licensee shall submit to US NRC licensing documentation together with the request to licence renewal in the timeframe 20-34 years of plant operation; at the latest before reaching 35 years of plant operation - that means **5 years before** reaching **40** years of operation. Submittal of the request to licence renewal for the plant operation together with licensing documentation for another 20 years of operation.

LTO = 40+20+20+...

Reviews, inspections conducted by the NRC throughout 20 years after licence renewal **(LR, Subsequent LR, ...).**

https://www.nrc.gov/reactors/operating/licensing/renewal.html

https://www.nrc.gov/reactors/operating/licensing/renewal/slr/guidance.html

What is Long Term Operation ?

Operation beyond the original timeframe (that has been originally given by the operating licence and/or design) which was set forth on the basis of a safety assessment taking into account the limiting processes and characteristics of the systems, structures and components.

NRA Safety Guide 2/2023 „Ageing Management and Long Term Operation of NPPs“

Objective of LTO programme

Demonstrate capability of plant SSCs to perform their functions throughout the expected period of operation while maintaining all technical and legislative requirements for nuclear, radiation and technical safety.

Planned LTO timeframe for NPPs in SR

In SE we

intend to

operate

nuclear units

for up to

minimum

years

LTO of NPPs in SE process model

Management of Plant Programmes Main activities

1. Methodical management of plant programmes (production programmes).
2. Management and coordination of the Commission for evaluation of in-service inspection programme.
3. Management and coordination of **ageing management programme.**
4. Management and coordination of **LTO licensing programme.**
5. Management and coordination of equipment qualification (EQ preservation) programme.
6. Management and coordination of material compatibility programme.
7. Management and coordination of welding programme.
8. Methodical management and coordination of technological obsolescence programme (on corporate level).
9. Management and coordination of coating (paint) programme.

Management of Plant Programmes with regard to LTO

Management of Plant Programmes Unit is responsible for management and coordination of LTO **licensing** programme = **Fulfilment of legislative requirements = Review of a comprehensive LTO Programme pursuant to requirements of Decree on PSR.**

Our unit **does NOT provide** fulfilment of Plant Asset Management requirements specified in Proposals for a Change of Equipment and/or Investment projects, etc. („LTO Projects"). This is the competence of other SE departments.

JE

Označenie: JE/NA/260.01-20 Číslo kópie:

Vydanie č.: 01 Revízia č.: 00

KLASIFIKÁCIA INFORMÁCIÍ

INTERNÉ

JE/NA/260.01-20

NÁVOD

Program riadenia starnutia Strojovne a základov TG

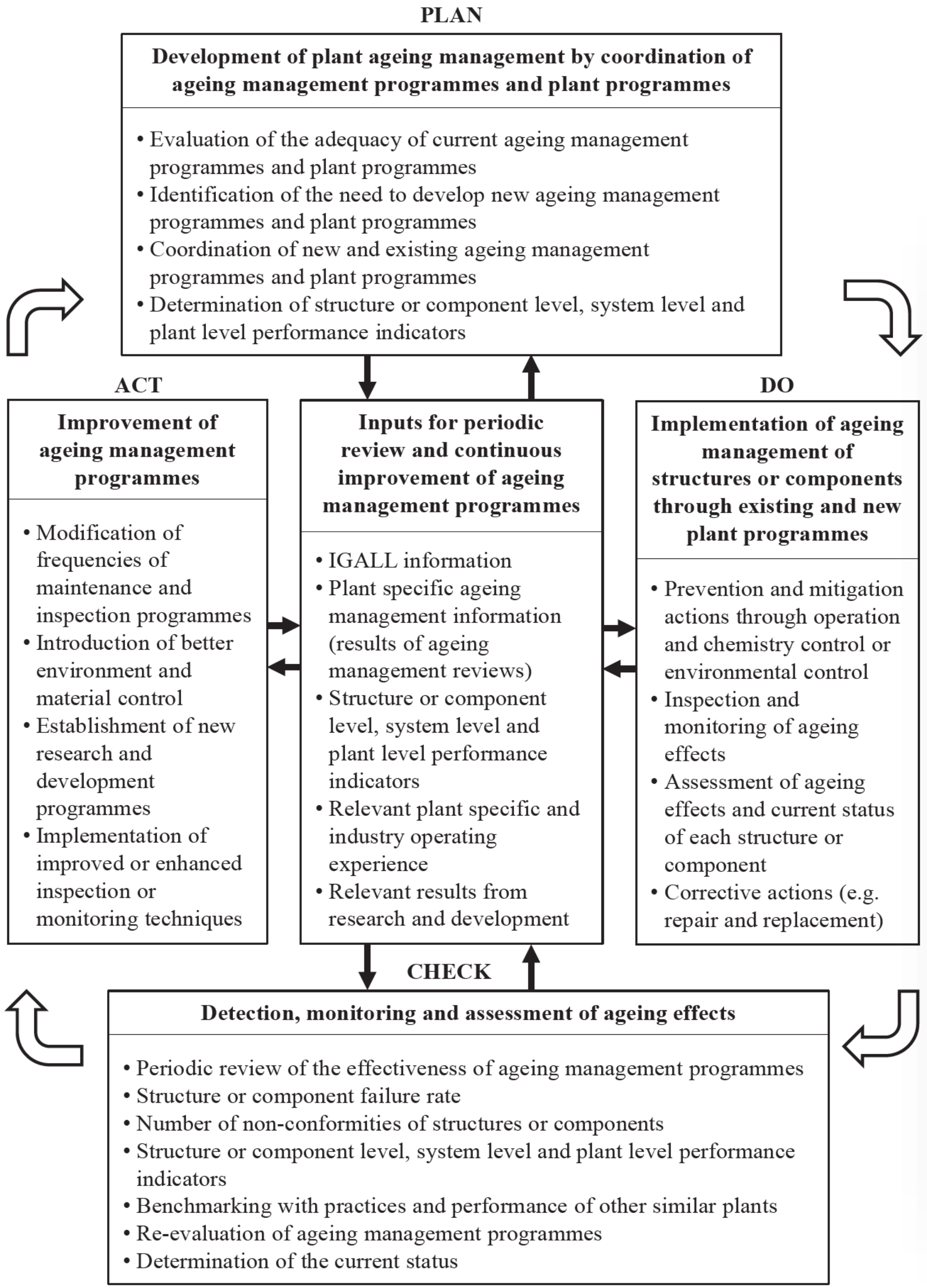
Záväznosť pre:	JE EBO V2, JE EMO1,2, MO34, 20100
Účinnosť od:	15.06.2023

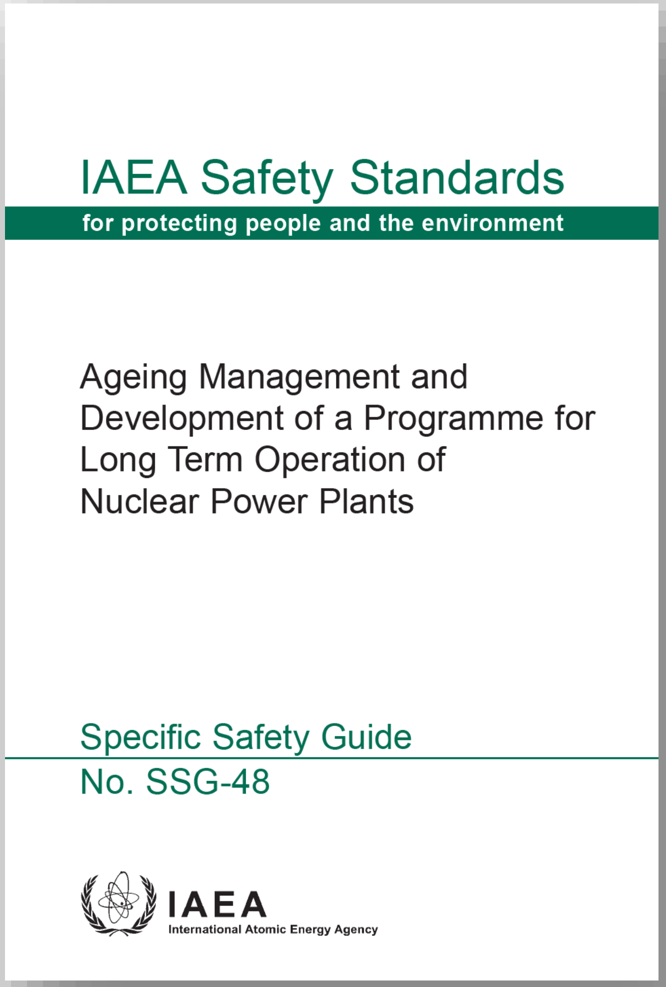
Nahrádza:	JE/NA-344.02-20

Plní požiadavky noriem:					
ISO 9001:2015	X	ISO 14001:2015	X	ISO 45001: 2018	X
8.1, 8.5					

Evidenčné číslo:	

Development, implementation, review, improvement of AMPs





Generic attributes of an effective AMP

Each AMP should be consistent with

the above nine attributes

as should

any other plant programme or process

that is used

to manage the **ageing effects !**

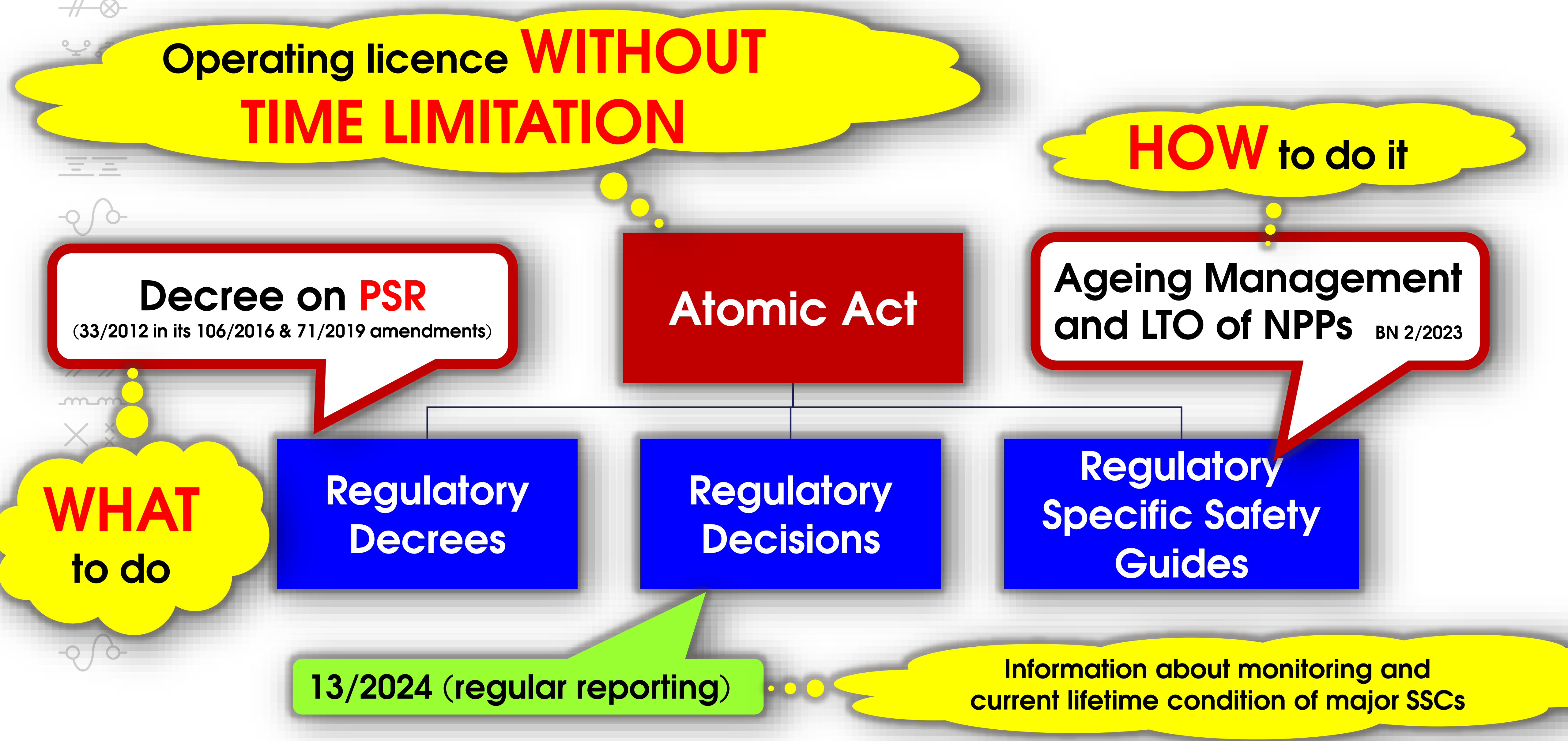
What is Ageing management ?

Ageing management is a dynamic process in which available engineering, research and diagnostic tools are used to determine the current condition of the SSCs, which triggers an adequate and effective response in the form of operating and maintenance actions. These activities ensure that the degradation of the SSCs by ageing and wear is controlled and guided within acceptable limits.

Ageing of SSCs is managed throughout the lifetime of the plant (design, construction, commissioning, operation (including long term and temporarily suspended operation), decommissioning), taking into account the associated methods, engineering practices, costs and personnel exposure involved.

Legislative requirements for LTO

LTO of NPPs – structure of relevant legislation



ZBIERKA ZÁKONOV
SLOVENSKEJ REPUBLIKY

Ročník 2012

Vyhlásené: 3. 2. 2012 Časová verzia predpisu účinná od: 15. 3.2019

Obsah dokumentu je právne záväzný.

33

VYHLÁŠKA
Úradu jadrového dozoru Slovenskej republiky
z 30. januára 2012
o pravidelnom, komplexnom a systematickom hodnotení jadrovej bezpečnosti jadrových zariadení

Úrad jadrového dozoru Slovenskej republiky (ďalej len „úrad") podľa § 23 ods. 2 písm. g) zákona č. 541/2004 Z. z. o mierovom využívaní jadrovej energie (atómový zákon) a o zmene a doplnení niektorých zákonov v znení zákona č. 350/2011 Z. z. (ďalej len „zákon") ustanovuje:

§ 1
Predmet úpravy

Táto vyhláška upravuje intervaly a rozsah vykonania pravidelného, komplexného a systematického hodnotenia jadrovej bezpečnosti jadrových zariadení (ďalej len „periodické hodnotenie").

§ 2
Intervaly a rozsah periodického hodnotenia počas prevádzky

(1) Držiteľ povolenia vykoná prvé periodické hodnotenie aktuálneho stavu jadrového zariadenia ku dňu, v ktorom uplynie osem rokov od nadobudnutia právoplatnosti povolenia na prevádzku jadrového zariadenia bez časového obmedzenia. Každé ďalšie periodické hodnotenie vykoná držiteľ povolenia podľa aktuálneho stavu jadrového zariadenia ku dňu, v ktorom uplynie desať rokov odo dňa, ku ktorému bolo vykonané predchádzajúce periodické hodnotenie.

(2) Ak bolo povolenie na prevádzku časovo alebo technicky ohraničené v súlade s § 8 ods. 1 písm. d) zákona, držiteľ povolenia vykoná prvé periodické hodnotenie aktuálneho stavu jadrového zariadenia ku dňu, od ktorého zostávajú dva roky do ukončenia platnosti povolenia na prevádzku.

(3) Držiteľ povolenia na základe vykonaného periodického hodnotenia preverí súlad aktuálneho stavu jadrového zariadenia so stavom, ktorý je opísaný v predprevádzkovej bezpečnostnej správe platnej ku dňu vykonania periodického hodnotenia. Zistené odchýlky odstráni.

(4) Periodické hodnotenie zahrnujúce ciele a prvky jednotlivých oblastí podľa odseku 5 je zamerané na

a) porovnanie dosiahnutého stavu jadrovej bezpečnosti na jadrovom zariadení so súčasnými požiadavkami na jadrovú bezpečnosť a s dobrou praxou,

b) hodnotenie kumulatívnych efektov starnutia jadrového zariadenia, vplyvu vykonaných i uvažovaných zmien na jadrovom zariadení, prevádzkových skúseností a technického rozvoja na jadrovú bezpečnosť,

ÚRAD JADROVÉHO DOZORU SLOVENSKEJ REPUBLIKY

EDÍCIA
Bezpečnosť jadrových zariadení

2023

BN 2/2023

Riadenie starnutia a dlhodobá prevádzka jadrových elektrární (3. vydanie – revidované a doplnené)

1. **Scope** of the AMP based on **understanding ageing**	• **Structures** (**including structural elements**) **and components** subject to **ageing management.** • Understanding of ageing phenomena (significant **degradation mechanisms,** susceptible sites): ➢ Structure or component **materials,** service conditions, **stressors,** degradation sites, **degradation mechanisms** and **ageing effects.** ➢ Structure or component **condition indicators** and **acceptance criteria.** ➢ Quantitative or qualitative **predictive models** of relevant ageing phenomena.
2. Preventive actions to **minimize** and **control ageing effects**	• Specification of preventive actions. • Determination of service conditions (i.e. environmental conditions and operating conditions) to be maintained and operating practices aimed at precluding potential degradation of the structure or component.
3. **Detection** of **ageing effects**	• Specification of parameters to be monitored or inspected. • Effective technology (inspection, testing and monitoring methods) for detecting ageing effects before failure of the structure or component.
4. **Monitoring** and **trending** of **ageing effects**	• **Condition indicators** and **parameters monitored.** • Data collected to facilitate assessment of structure or component ageing. • Assessment methods (including data analysis and trending).
5. **Mitigation** of **ageing effects**	Operations, maintenance, repair and replacement actions to mitigate detected ageing effects and/or degradation of the structure or component.
6. **Acceptance** criteria	Acceptance criteria against which the need for corrective actions is evaluated.
7. **Corrective** actions	Corrective actions if a structure or component fails to meet the acceptance criteria.
8. **Operating experience** feedback and feedback of **R&D results**	Mechanism that ensures timely feedback of operating experience and research and development results (if applicable) and provides objective evidence that they are taken into account in the AMP.
9. **Quality management**	• Administrative controls that document the implementation of the AMP and actions taken. • Indicators to facilitate evaluation and improvement of the AMP. • Confirmation (verification) process for ensuring that preventive actions are adequate and appropriate and that all corrective actions have been completed and are effective. • Record keeping practices to be followed.

Setting the scope of SSCs for LTO evaluation

At present, there is no prescribed list of SSCs that are subject to periodic replacement or planned refurbishment, and at the same time are not required by regulatory oversight to be included in the scope for ageing management.

Output of SSCs scope setting Phase 1 is :

- ✓ List of SSCs **for their LTO evaluation**
- ✓ List of SSCs **included in the scope for ageing management** that contains
  - ✓ In-scope structures and components, and their parts
  - ✓ In-scope commodity groups of structures and components

Setting the scope of SSCs for LTO evaluation

Only SSCs that are not subject to periodic replacement or planned renewal, nor excluded by the regulatory authority, but identified in the phase of scope setting of SSCs for ageing management, enters the process of identifying AMPs.

The purpose of identifying AMPs is to identify SSCs that are subject to ageing mechanisms and/or that are subject to time limited ageing analyses (TLAAs).

Output of SSCs scope setting Phase 2 is :

- ✓ List of SSCs, for which it is needed to review validity / modify **AMPs** for the scope of ageing management.
- ✓ List of SSCs, for which it is needed to develop **AMP** for the scope of ageing management.
- ✓ List of SSCs, for which it is needed to review validity / modify **TLAA** in the frame of AMP for the scope of ageing management.
- ✓ List of SSCs, for which it is needed to develop **TLAA** for the scope of ageing management.
- ✓ List of SSCs, for which it is needed review validity / modify **other plant programmes** for the scope of ageing management.

Setting the scope of SSCs for LTO evaluation

- The relevant legislation (Atomic Act, Decree on requirements for nuclear safety) categorizes **plant SSCs** into **safety classes** following their importance for nuclear safety, safety function of the system of which they are a part and severity of their potential failure.
- Some criteria for scope setting of SSCs for (their) LTO evaluation may be repeated / overlapped. So the same device can be selected in the scope for LTO evaluation by the use of two (or more) criteria.
- At present, there are no known SSCs that would be required by the requirements of the regulatory authority to be included in scope for LTO. However, the methodology for scope setting of SSCs for (their) LTO evaluation foresees this !

National safety classification of SSCs

a) 1	**SKK dôležité pre bezpečnosť, ktoré zabezpečujú integritu tlakovej hranice chladiaceho okruhu reaktora**
BT I	zariadenia tvoriace hranicu chladiaceho okruhu reaktora s výnimkou tých zariadení, ktorých poškodenie možno kompenzovať normálnym systémom doplňovania chladiva
BT II a)	tvoriace hranicu chladiaceho okruhu jadrového reaktora a nepatria do BT 1,

a) 2	**SKK dôležité pre bezpečné odstavenie reaktora a jeho udržiavanie v bezpečných podmienkach odstavenia**
BT II b)	na odstavenie reaktora za stavu abnormálnej prevádzky, ktorý by mohol viesť k havarijným podmienkam, a na odstavenie reaktora s cieľom zmierniť následky havarijných podmienok
BT II c)	na udržanie dostatočného množstva chladiva na chladenie aktívnej zóny reaktora počas havarijných podmienok, pri ktorých nedošlo k porušeniu chladiaceho okruhu reaktora, a po týchto podmienkach
BT II d)	na odvod tepla z AZ pri porušení chladiaceho okruhu reaktora s cieľom obmedziť poškodenie paliva
BT II e)	na odvod zostatkového tepla pri normálnej a abnormálnej prevádzke a pri havarijných podmienkach, keď nedošlo k porušeniu integrity chladiaceho okruhu reaktora
BT III a)	na zabránenie neprípustných prechodových procesov spojených so zmenami reaktivity
BT III b)	na udržanie reaktora v podmienkach bezpečného odstavenia po každom z jeho odstavení

a) 3	**SKK, ktoré sú dôležité pre zabránenie, alebo zmiernenie následkov udalosti, ktorá môže viesť k úniku rádioaktivity**
BT II d)	na odvod tepla z AZ pri porušení chladiaceho okruhu reaktora s cieľom obmedziť poškodenie paliva
BT II f)	na zabránenie únikov rádioaktívnych látok z paliva do okolia
BT II g)	nevyhnutné na obmedzenie únikov rádioaktívnych látok z ožiareného paliva z ochrannej obálky pri havarijných podmienkach a po ich uplynutí
BT II h)	určené na obmedzenie prieniku ionizujúceho žiarenia mimo ochrannej obálky pri havarijných podmienkach a po ich uplynutí
BT II j)	určené na prepravu vyhoretého jadrového paliva

National safety classification of SSCs

a) 3	**SKK, ktoré sú dôležité pre zabránenie, alebo zmiernenie následkov udalosti, ktorá môže viesť k úniku rádioaktivity**
BT II k)	na zabránenie únikov rádioaktívnych látok do životného prostredia.
BT III e)	nevyhnutné na udržanie ožiarenia obyvateľstva a zamestnancov jadrového zariadenia pod stanovenými limitmi v priebehu havarijných podmienok spojených s únikom rádioaktívnych látok a ionizujúceho žiarenia zo zdrojov nachádzajúcich sa mimo ochrannej obálky, ako aj po týchto havarijných podmienkach
BT III g)	na zabránenie rádioaktívnych únikov z ožiareného paliva pri jeho skladovaní na území jadrového zariadenia, pri normálnej a abnormálnej prevádzke
BT III n)	nevyhnutné na obmedzenie výpustov alebo únikov tuhých, kvapalných, alebo plynných rádioaktívnych látok a ionizujúceho žiarenia pod ustanovené limity pri normálnej a abnormálnej prevádzke
BT III m)	určené na prepravu jadrových materiálov a rádioaktívnych odpadov v zásielkach typu B(U), B(M) a C
b)	**SKK ktorých porucha môže zabrániť dostatočnému plneniu bezpečnostných funkcií zariadenia uvedeného v písmene a) 1, 2, 3**
BT II i)	nevyhnutné z hľadiska plnenia bezpečnostných funkcií na dodávku energií, alebo na riadenie ostatných komponentov zaradených do BT I, alebo II a určené na prevádzku v prostredí, ktoré vznikne po havárii so stratou chladiva z chladiaceho okruhu reaktora, alebo po havárii s prasknutím vysokoenergetických potrubí
BT III c)	na udržanie dostatočného množstva chladiva na chladenie AZ pri normálnej a abnormálnej prevádzke
BT III d)	na odvod tepla z bezpečnostných systémov až do prvého akumulačného objemu dostačujúceho z hľadiska plnenia bezpečnostných funkcií – okrem základných systémov odvodu tepla zaradených do BT II. písm. d) a e),
BT III f)	nevyhnutné na udržanie podmienok prostredia vnútri jadrového zariadenia potrebných na prevádzku bezpečnostných systémov a na prístup zamestnancov k plneniu činností dôležitých pre jadrovú bezpečnosť
BT III h)	na odvod zostatkového tepla z ožiareného paliva skladovaného na území jadrového zariadenia
BT III i)	nevyhnutné na udržanie dostatočnej podkritičnosti paliva skladovaného na území jadrového zariadenia
BT III j)	nevyhnutné z hľadiska plnenia bezpečnostných funkcií na dodávku energií, alebo na riadenie ostatných komponentov, ktoré nie sú zaradené do BT II
BT III k)	nevyhnutné z hľadiska plnenia bezpečnostných funkcií na zabezpečenie funkčnej schopnosti ostatných komponentov zaradených do BT I až III, ktoré sa netýkajú systémov a kontroly riadenia, alebo dodávok energií
BT III l)	určené na nakladanie s jadrovými materiálmi, rádioaktívnym odpadom a vyhoretým jadrovým palivom

LTO assessment

The assessment of the plant LTO must be carried out at the latest at the last periodic safety review (PSR) before the expiry of the operating period according to the timeframe originally specified** in the operating licence for the nuclear installation, in the original design, in standards, in the national general binding legislation or estimated from the economic return on investment in the plant design.

Regulatory Safety Guide 1/2020 „Comprehensive PSR"

** In conditions of our company, the original timeframe is **30** years of operation of the nuclear unit **from the proof-of-concept test run at nominal power** (the test run lasts144 hrs).

Obligation to develop and implement LTO programme

To maintain safety and reliability of plant operation in order to ensure its optimal economic use and in accordance with the requirements of the legislation, the licensee is **obliged** to develop and implement a LTO programme.

Regulatory SG 2/2023 „Ageing management and LTO of NPPs"


ÚRAD JADROVÉHO DOZORU SLOVENSKEJ REPUBLIKY

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TLAAs: Review

Time limited ageing analyses (TLAAs) are plant specific ageing analyses based on an explicitly considered operational lifetime or plant design life (where time limited assumptions were included in the original computational analyses when determining the design life of a given structure or component).

During its validity, TLAA must demonstrate safe and reliable operational capability of the analyzed structure or component throughout the planned LTO by demonstrating a sufficient safety margin in remaining lifetime of the analyzed structure or component.


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(3. vydanie – revidované a doplnené)

TLAAs: Content

- technical conditions of a given solution
- description of the models used in computational analysis, measurements, tests,
- operating parameters, loading history
- description of material properties
- description of computational analyses, measurements, tests
- results of calculations, measurements, tests and their evaluation / interpretation
- conditions of TLAA validity with regard to applicable ageing processes
- conclusions, recommendations, proposed actions

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(3. vydanie – revidované a doplnené)

IAEA requirements and recommendations for LTO

Requirements and recommendations

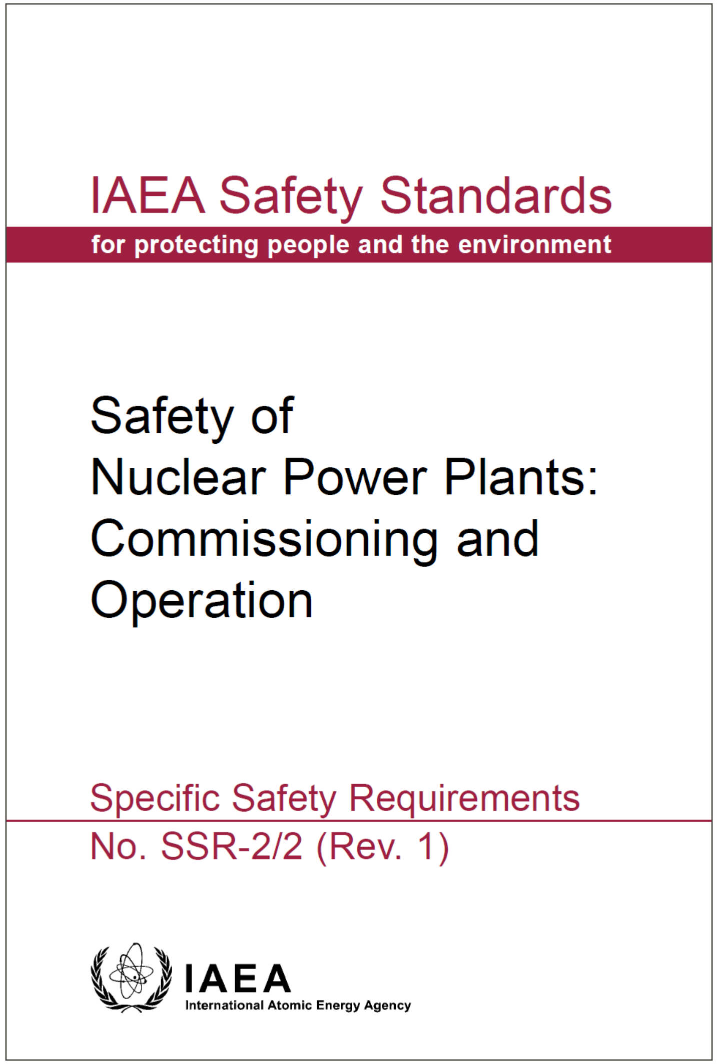
Requirement for LTO programme

Requirement 16: Programme for long term operation

Where applicable, the operating organization shall establish and implement a **comprehensive programme for ensuring the long term safe operation of the plant** beyond a time-frame established in the licence conditions, design limits, safety standards and/or regulations.

4.53.

The justification for LTO shall be prepared on the basis of the results of a safety assessment, with due consideration of the ageing of structures, systems and components. **The justification for LTO shall utilize the results of PSR and shall be submitted to the regulatory body,** as required, for approval on the basis of an analysis of the AMP, to ensure the safety of the plant throughout its extended operating lifetime.



Requirement for LTO programme

4.54.

The comprehensive programme for long term operation shall address :

(a) Preconditions (incl. the current licensing basis, safety upgrading and verification, and operational programmes)

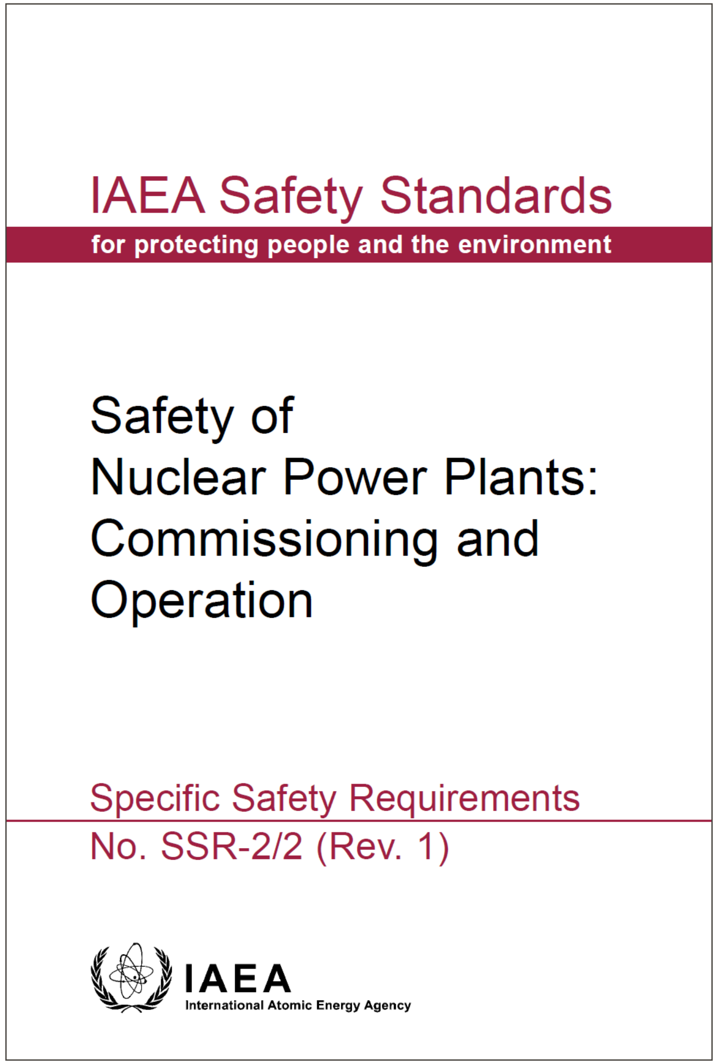
(b) Setting the scope for all structures, systems and components important to safety

(c) Categorization of structures, systems and components with regard to degradation and ageing processes

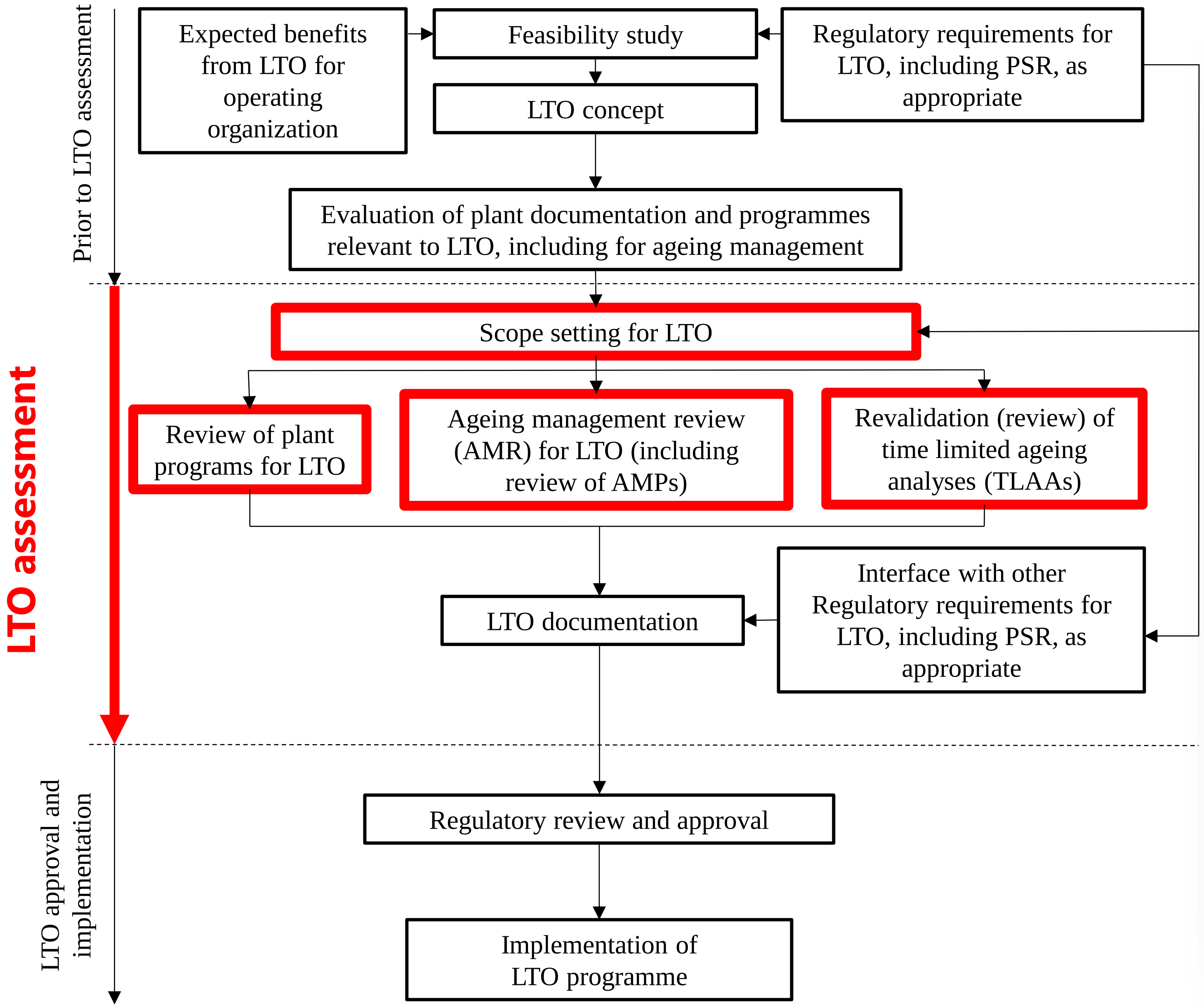
(d) Revalidation of safety analyses made on the basis of time limited assumptions

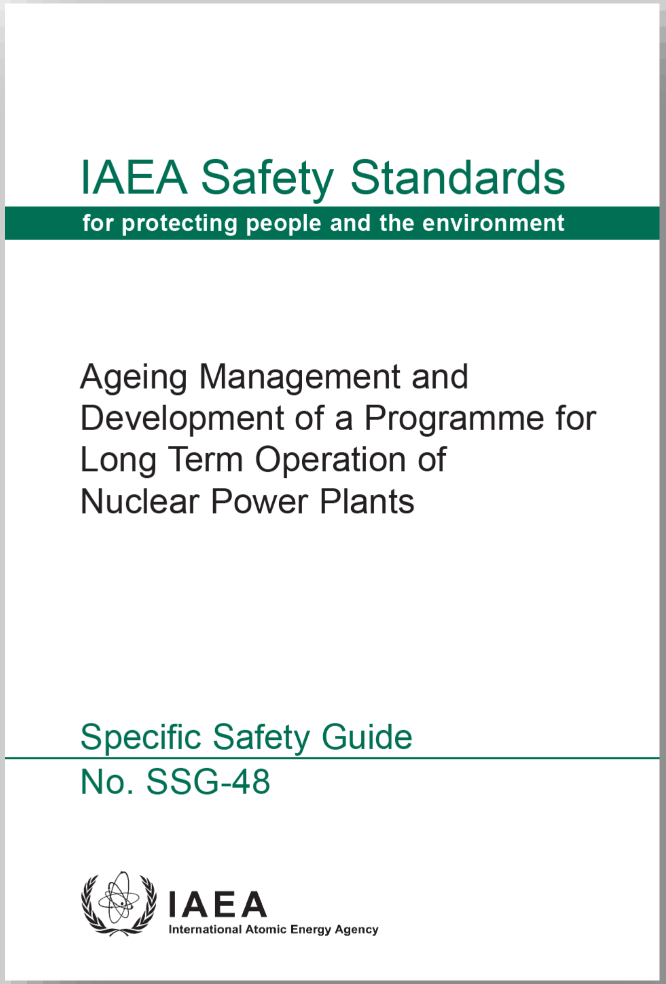
(e) Review of ageing management programmes in accordance with national regulations

(f) The implementation programme for long term operation.



Key activities in review of LTO



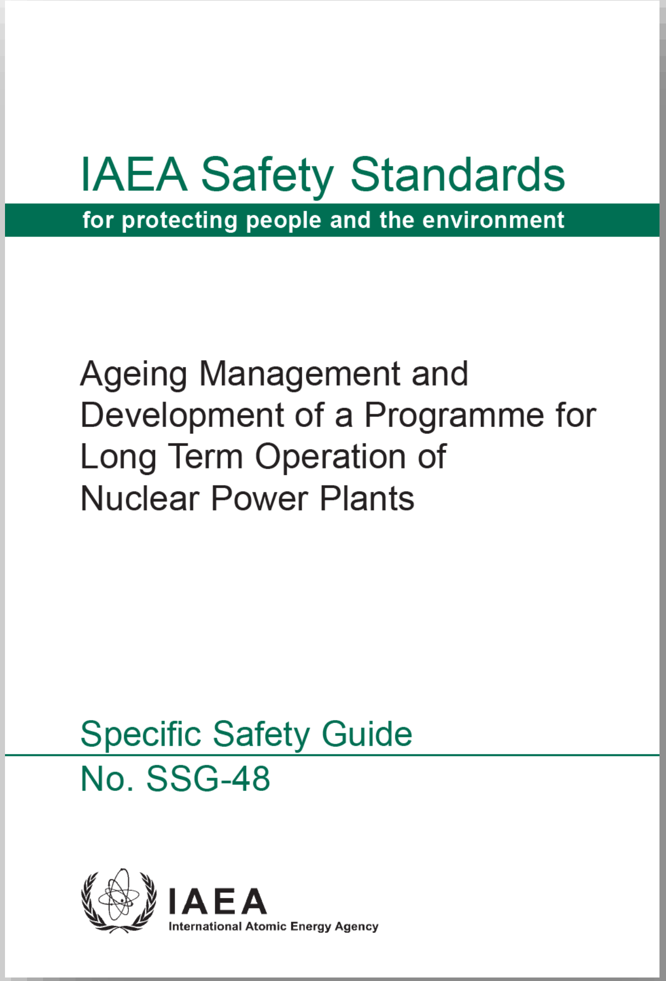


Key activities

- **Scope setting** for LTO evaluation
- Review of management of ageing for SSCs important to safety within the existing **plant programmes*****
- Review of time limited ageing analyses **(TLAAs)**
- Ageing management review **(AMR)**

These activities are **the most** technically and time consuming !

*** Review of **Maintenance, EQ, ISI, SUP, Water chemistry** programmes with regard to LTO.


IAEA Safety Standards
for protecting people and the environment
Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants
Specific Safety Guide
No. SSG-48
IAEA
International Atomic Energy Agency

CENTRUM PRE VEDU A VÝSKUM

Centrum pre vedu a výskum, s.r.o.
935 32 Kalná nad Hronom, časť Mochovce 6
Slovenská republika

PROTOKOL O PREHODNOTENÍ ANALÝZ STARNUTIA S ČASOVO OBMEDZENOU PLATNOSŤOU

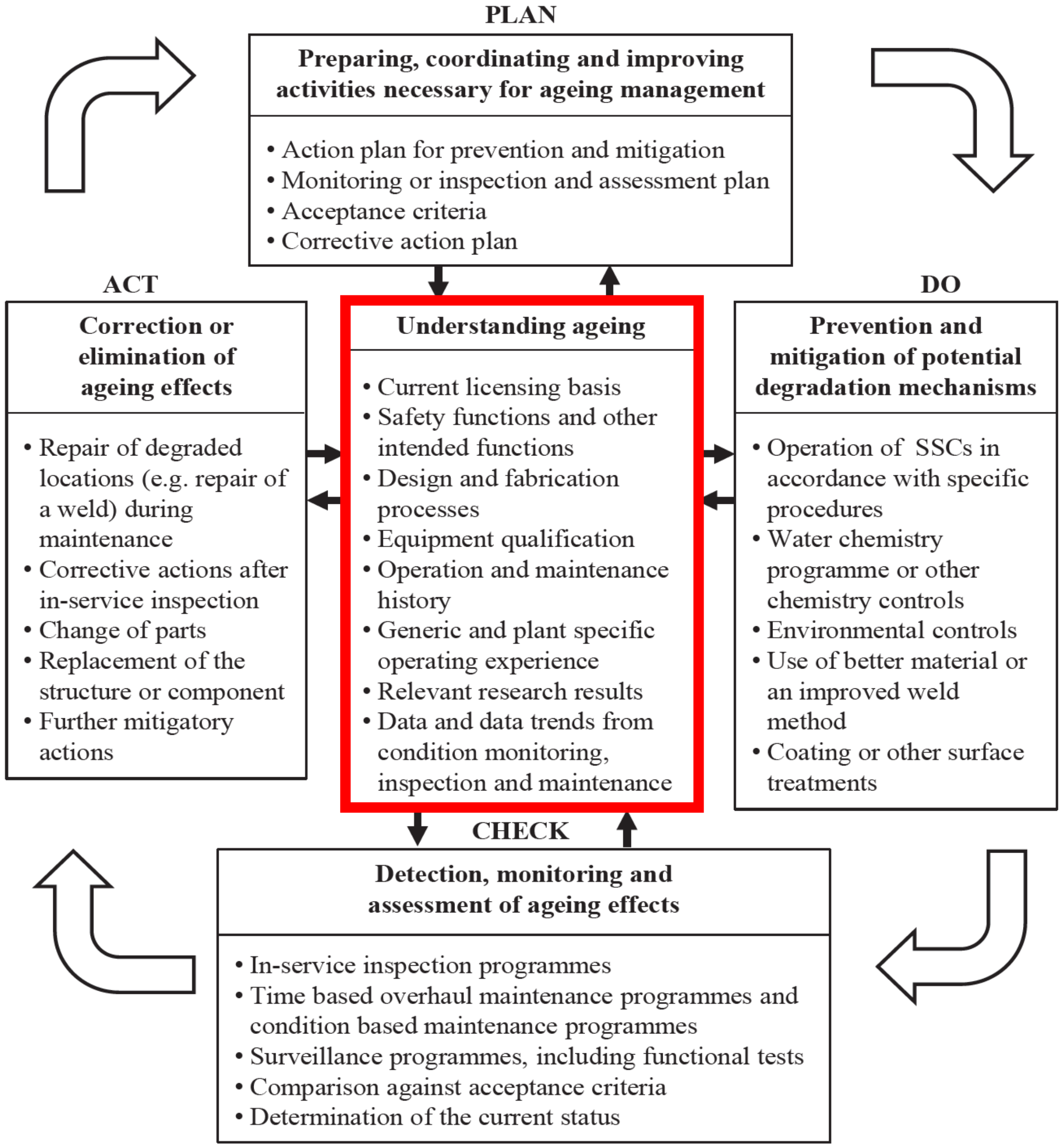
Názov:

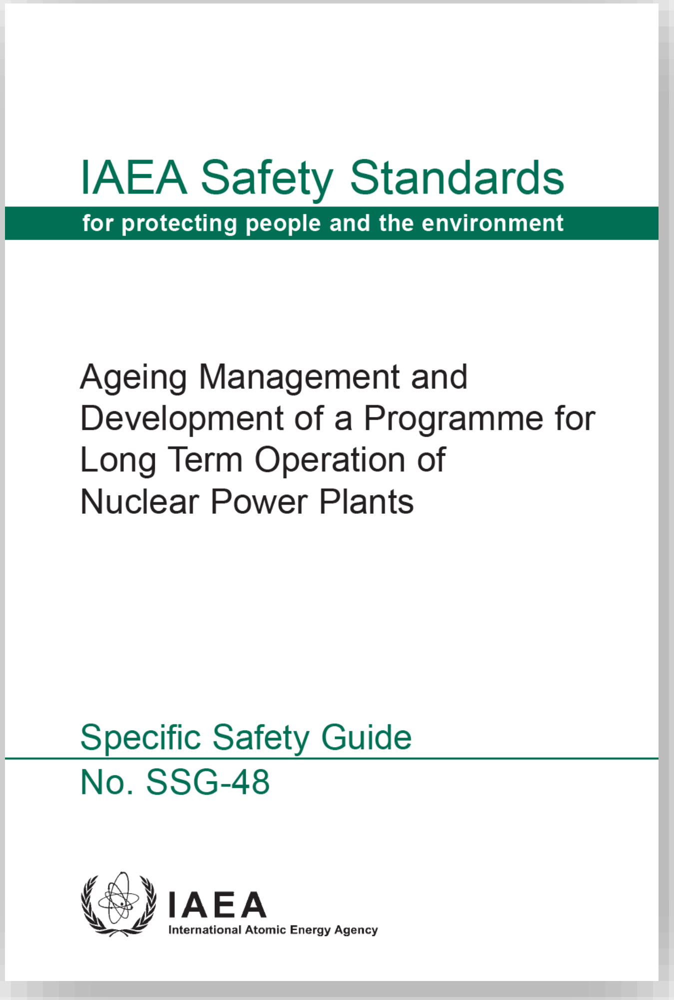
Analýza zmeny materiálových vlastností ťažkého betónu v dôsledku starnutia JE EMO 1,2

Evidenčné číslo protokolu **4600014316/AČOP/STAV/0011/r1**

	Meno:	Organizácia:	Dátum:	Podpis:
Vypracoval:	Prof. Ing. Vladimír Slugeň, DrSc.	*UJFI FEI STU*	*1.3.2023*	
	Doc. Ing. Róbert Hinca, PhD.	*UJFI FEI STU*	1. 3. 23	
	Doc. Ing. Gabriel Farkas, PhD.	*UJFI FEI STU*	1. 3. 23	
	Ing. Július Dekan, PhD.	*UJFI FEI STU*	1. 3. 23	
Overil:	Ing. Miroslav Lipár	*CVV, s.r.o.*	8. 3. 23	
Odsúhlasil:	Ing. Imrich Krajmer	*CVV, s.r.o.*	8. 3. 23	
Schválil:	Ing. Miroslav Miklovič	*CVV, s.r.o.*	10. 3. 23	

Ageing Management Review





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Slovenská republika

PROTOKOL O PREVIERKE RIADENIA STARNUTIA

SO 800/1-01 Budova reaktorov

I. Hlavný výrobný blok JE EMO 1,2

Evidenčné číslo protokolu **4600014316/PRS/STAV/0001/r0**

	Meno	Organizácia	Dátum	Podpis
Vypracoval	Ing. Daniel Beňačka	CVV, s.r.o.	31.12.2021	[signature]
Overil:	Ing. Miroslav Lipár	CVV, s.r.o.	31.12.2021	[signature]
Odsúhlasil:	Ing. Imrich Krajmer	CVV, s.r.o.	31.12.2021	[signature]
Schválil:	Ing. Miroslav Miklovič	CVV, s.r.o.	31.12.2021	[signature]

CENTRUM PRE VEDU A VÝSKUM
PROTOK
Evidenčné číslo protokolu
	Meno
Vypracoval	Ing. Jan V
Overil:	Ing. Miros
Odsúhlasil:	Ing. Imrich
Schválil:	Ing. Miros
Uved

CENTRUM PRE VEDU A VÝSKUM
PROTOK
Evidenčné číslo protokolu
	Meno
Vypracoval	Ing. Marcel
Overil:	Ing. Mirosla
Odsúhlasil:	Ing. Imrich
Schválil:	Ing. Mirosla
Uveden

CENTRUM PRE VEDU A VÝSKUM
PROTOK
Evidenčné číslo protokolu
	Meno
Vypracoval	Ing. Dušan
Overil:	Ing. Mirosla
Odsúhlasil:	Ing. Imrich
Schválil:	Ing. Mirosla

Ageing Management Review

1) Assessment of SC's current physical status

Description / Summary / Information about: current status

1.1 Design requirements

1.2 Data identification of integrity and functional capability

1.3 Data identification of lifetime assessment

1.4 Scope and results of tests / inspections demonstrating functional capability

1.4.1 Tests and inspections applied on SCs

1.4.2 Evaluation of tests and inspections suitability and sufficiency / adequacy

1.4.3 Significant finding affecting SCs functional capability

1.5 Summary of current physical status assessment

2) Identification of potential ageing effects

What are the identified and potential ageing effects applicable for SCs?

2.1 Identification of materials and stressors

2.2 Identification of ageing effects – list of degradation mechanisms / ageing effects from our plant(s) + IGALL;

2.3 Methods for detection of identified ageing effects

2.4 Evaluation of the SCs operation history and maintenance

2.5 Evaluation of operational experience

3) Review of programmes for management of ageing

What are the programmes / activities applied to SCs?; Are they sufficient?

3) Review of plant programmes for management of ageing is carrying out by consistency check against the 9 attributes of an effective AMP.

3.1 Scope of the ageing management programme based on understanding ageing

3.2 Preventive actions to minimize and control ageing effects

3.3 Detection of ageing effects

3.4 Monitoring and trending of ageing effects

3.5 Mitigation of ageing effects

3.6 Acceptance criteria

3.7 Corrective actions

3.8 OPEX feedback and feedback of R&D results

3.9 Quality management

4) Demonstration that ageing effects are managed for LTO

How the ageing effects are managed for LTO period?

Based on the results of review, demonstration that aging effects are adequately managed for planned LTO period consists of:

1) Documentation of identified ageing effects

2) Identification of programmes for managing the ageing affects

3) Description of way / approach how the identified ageing effects are managed by plant programmes / activities – focus on evidence that programmes include one or more activities aimed to detection and mitigation of ageing effects (prevention, mitigation, condition monitoring, performance monitoring activities)

Generic attributes of an effective AMP

Each AMP should be consistent with
the above nine attributes
as should
any other plant programme or process
that is used
to manage the **ageing effects !**

Implementation of LTO programme for Bohunice 3,4

Milestones

Date of issue of a licence for a start of test operation

is considered as start of operation for the purpose of a start of LTO date setting.

https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=546

** Decision issued after submission of PSR final report in 2008

Zoznam správ programu schvaľovania dlhodobej prevádzky

[1] Koncept "Dlhodobej prevádzky JE V2", rev.1, správa VUJE ev.č.V01-5401810/DT/1213.01
[2] Program zabezpečovania kvality a organizačné zabezpečenie DP JE V2, rev.3, správa VUJE ev.č.V01-5401810/RD/QA/PK.04
[3] Program dlhodobej prevádzky JE V2, rev.2, správa VUJE ev.č.V01-5401810/TD/1214.02
[4] Metodika výberu zariadení JE V2 pre program dlhodobej prevádzky, rev.1, správa VUJE ev.č.V01-5401810/TD/1221.01
[5] Zoznam zariadení vybraných pre hodnotenie dlhodobej prevádzky JE V2, rev.1, správa VUJE ev.č.V01-5401810/TD/1222_1223.02_TS
[6] Analýzy s časovo obmedzenou platnosťou - metodický popis, rev.2, správa VUJE ev.č.V01-5401810/TD/1224.02
[7] Návrh prostredia a schematizácia vlastností databázy DP JE V2, správa VUJE, ev.č.V01-5401810/TD/1232.00
[8] Sumarizácia požiadaviek na databázu DP JE V2, správa VUJE ev.č.V01-5401810/TD/1231.00
[9] Štúdia realizovateľnosti pre dlhodobú prevádzku JE V2, rev.3, správa VUJE ev.č.V01-5401810/TD/1212.03
[10] Metodika hodnotenia programov riadenia starnutia, rev.1, správa VUJE ev.č.V01-9000111/6.6/TD/PRS_r00.1
[11] Metóda výberu a revízie analýz s časovo obmedzenou platnosťou, správa VUJE ev.č.V01-9000111/6.6/TD/AČOP_r01.1
[12] Metodika pre revíziu programov starostlivosti pre zariadenia s krátkodobou životnosťou z pohľadu DP JE V2, rev.1, správa VUJE ev.č.V01-9000111/6.6/TD/Prg_rev00.1
[13] Databáza DP JE V2 - Návrh štruktúry databázy, rev.1, správa VUJE ev.č.V01-9000111/6.6/TD/DTB_r00.1
[14] Preskúmanie vplyvu dlhodobej prevádzky jadrového zariadenia na životné prostredie, správa VUJE ev.č.V01-9000111/6.6/TD/ ŽPr_r00.1
[15] Hodnotenie vplyvu dlhodobej prevádzky jadrového zariadenia na životné prostredie, správa VUJE ev.č.V01-9000111/6.6/TD/ ŽPr_II. časť_r01
[16] Preskúmanie vplyvu tvorby rádioaktívnych odpadov v podmienkach dlhodobej prevádzky, správa VUJE ev.č.V01-9000111/6.6/TD/NRaO_r00.1
[17] Posúdenie vhodnosti a úplnosti programov údržby a kvalifikácie, rev.1, správa VUJE ev.č.V01-9000111/6.6/TD/Prg_r00.2/S
[18] Výsledky revízie AČOP, 1.etapa, správa VUJE ev.č.V01-9000111/6.6/TD/AČOP_r00.2
[19] Sumarizácia zistení a návrh nápravných opatrení pre AČOP - 1.etapa riešenia, správa VUJE ev.č.V01-9000111/6.6/TD/AČOP_r00.3
[20] Sumarizácia prác vykonaných v oblasti hodnotenia PRS za rok 2011, správa VUJE ev.č.V01-9000111/6.6/TD/PRS_r00.2
[21] Hodnotenie vybraných zariadení s krátkou dobou životnosti. Hodnotiace listy - Strojné komponenty primárneho okruhu, správy VUJE ev.č.:
V01-9000111/6.6/TD/HL/Stroj/1.1-PO_r01
V01-9000111/6.6/TD/HL/Stroj/2.1-PO_r01
V01-9000111/6.6/TD/HL/Stroj/3.1-PO_r00
[22] Hodnotenie vybraných zariadení s krátkou dobou životnosti. Hodnotiace listy - Strojné komponenty sekundárneho okruhu, správy VUJE ev.č.:
V01-9000111/6.6/TD/HL/Stroj/1.1-SO_r01
V01-9000111/6.6/TD/HL/Stroj/2.1-SO_r01
V01-9000111/6.6/TD/HL/Stroj/3.1-SO_r00
[23] Hodnotenie vybraných zariadení s krátkou dobou životnosti. Hodnotiace listy - Elektrické komponenty, správy VUJE ev.č.:
V01-9000/111/6.6/TD/HL/ELE/1.3_r01
V01-9000/111/6.6/TD/HL/ELE/2.3_r01
V01-9000/111/6.6/TD/HL/ELE/3.3_r00
[24] Hodnotenie vybraných zariadení s krátkou dobou životnosti. Hodnotiace listy - SKR, správy VUJE ev.č.:
V01-9000/111/6.6/TD/HL/SKR/1.2_r01
V01-9000/111/6.6/TD/HL/SKR/2.2_r01
V01-9000/111/6.6/TD/HL/SKR/3.2_r00
[25] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke AČOP - Strojné komponenty, správy VUJE ev.č.:
V01-9000111/6.6/TD/PROT/AČOP_r01/STROJ/1.1
V01-9000111/6.6/TD/PROT/AČOP_r00/STROJ/2.1
[26] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke AČOP - Stavby, správy VUJE ev.č.:
V01-9000111/6.6/TD/PROT/AČOP_r00/Stavba/1.2
V01-9000111/6.6/TD/PROT/AČOP_r00/Stavba/2.2
[27] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke PRS - Strojné komponenty, správy VUJE ev.č.V01-9000111/6.6/TD/PROT/PRS/STROJ_záver
[28] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke PRS - Elektrické komponenty, správy VUJE ev.č.V01-9000111/6.6/TD/PROT/PRS/ELE_záver
[29] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke PRS - SKR, správy VUJE ev.č.V01-9000111/6.6/TD/PROT/PRS/SKR_záver
[30] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke PRS - Elektrické komponenty + SKR, správy VUJE ev.č.V01-9000111/6.6/TD/PROT/PRS/ELE+SKR_záver
[31] Hodnotenie vybraných zariadení s dlhou dobou životnosti. Protokoly o previerke PRS - Stavba, správa VUJE ev.č.V01-9000111/6.6/TD/PROT/PRS/Stavba_záver
[32] Kvalifikácia zariadení JE V2 z hľadiska dlhodobej prevádzky, správa VUJE ev.č.V01-9000111/6.6/TD/RPS II časť_1.etapa/TS2_r00_S
[33] Hodnotenie systému programov prevádzkových kontrol z pohľadu dlhodobej prevádzky JE V2, správa VUJE ev.č.V01-9000111/6.6/TD/RPS II časť_1.etapa/TS3_r00_S
[34] Hodnotenie systému programov diagnostiky z pohľadu dlhodobej prevádzky pre zariadenia s krátkodobou životnosťou JE V2, správa VUJE ev.č.V01-9000111/6.6/TD/RPS II časť_1.etapa/TS4_r00_S
[35] Hodnotenie systému programov údržby zariadení z pohľadu dlhodobej prevádzky JE V2, správa VUJE ev.č.: V01-9000111/6.6/TD/RPS II časť_1.etapa/TS1_r01_S
[36] Monitorovanie chemických režimov z pohľadu DP JE V2, správa VUJE ev.č.V01-9000111/6.6/TD/RPS II časť_1.etapa/TS5_r01_S
[37] Databáza Projektu DP JE V2 - Príručka používateľa, rev.1, správa VUJE ev.č.V01-9000111/6.6/TD/DTB_II.časť_1.et./TS_r01_S
[38] Realizácia databázy Projektu DP - časť I., správa VUJE ev.č.V01-9000111/6.6/TD/DTB_r01.1
[39] Databáza Projektu DP - Používateľská príručka - Správa, správa VUJE ev.č.V01-9000111/6.6/TD/DTB/Správa_III.časť_r00
[40] Sumarizácia zistení a návrh nápravných opatrení - Nálezy a odporúčania pre zariadenia s krátkodobou životnosťou, správa VUJE ev.č.V01-9000111/6.6/TD/RPS IIčasť/SUMÁR_r01/TS1_S
[41] Analýza dopadov DP na BS a odporúčania pre revíziu BS vo vzťahu na DP – revízia bezpečnostnej správy - II. časť, správy VUJE ev.č.V01-9000111/6.6/TD/RevBS_II.časť_r01/ANaOdp.
[42] Sumarizácia zistení, návrh a zapracovanie nápravných opatrení – revízia prevádzkových predpisov - II. časť, správa VUJE ev.č.V01-9000111/6.6/TD/RevPP_II.časť_r01/Sumár
[43] Posúdenie vhodnosti a úplnosti uchovávania vedomostí, správa VUJE ev.č.V01-9000111/6.6/TD/RevSUV/Posúdenie/TS_r01
[44] Dlhodobá prevádzka - sumarizačná správa, správa VUJE ev.č. V01-9000111/6.6/TD_Dokalmp_II.časť_Sumárspr_r00
[45] Záverečné hodnotenie programu DP JE V2, správa VUJE ev.č. V01-9000111/6.6/TD_Dokalmpl_II.časť_Záverspr.1_r00

Implemen… …actions

SLOVENSKÉ ELEKTRÁRNE

ATÓMOVÉ ELEKTRÁRNE BOHUNICE

Materiál na rokovanie porady vedenia SE…
dňa: 18.11.2014

EBO-MATPV-11/2014-33
Akčný plán nápravných opatre…
programu dlhodobej prevádzky J…

Dôvod predloženia: Akčný plán nápravných opatrení programu dlhodobej pre… vyplývajúci z požiadaviek legislatívy ÚJD SR.

Pripomienkuje: A0100, A0200, A0300, A1000, A2000

Vypracoval: Ing. Ľudovít Kupča, PhD. — Vedúci projektového tímu dlhodobej prevádzky
Ing. Dušan Liška — Vedúci pre jadrové technológie
Ing. Ján Borák — Vedúci technického jadrového inžinieringu
Ing. Ľuboslav Jasovský — Vedúci systémovej inžinierskej podpory

Predkladá: Ing. Imr… Manažér j…

Klasifikačný stupeň: interné
Znak hodnoty - lehota ulože…

Elektronická verzia uložená: prístupová cesta

Schválil:
dňa: 18 -11- 2014
Ing. Milan M O L…
riaditeľ SE-EB…

Revízia č. 1
Rozdeľovník: A0000, A0100, A0200, A1000, A2000, A3000, 23100, 23310, 60210, 7…

EBO-MATPV-11/2014-33
Revízia č. 0
RZ: AC5/23100/LK

SLOVENSKÉ ELEKTRÁRNE

ATÓMOVÉ ELEKTRÁRNE BOHUNICE

Jaslovské Bohunice
dňa: 21.10.2024
RZ: AC6/20100/LK

Materiál na rokovanie porady vedenia SE-EBO
dňa: 21.10.2024

EBO-MATPV-10/2024-26
„Hodnotenie plnenia opatrení akčného plánu programu dlhodobej prevádzky JE EBO V2“

Dôvod predloženia:	Predloženie správy o postupe plnenia opatrení akčného plánu programu dlhodobej prevádzky JE EBO V2 Úradu jadrového dozoru SR

Vypracoval: Ing. Ľudovít Kupča, PhD. — špecialista pre dlhodobú prevádzku

Predkladá: Ing. Ján Borák — manažér programov riadenia výroby

Klasifikačný stupeň: interné
Znak hodnoty – Lehota uloženia: 5

Elektronická verzia uložená:
I:\02_Vyroba a riadenie energii\ 31 EBO\Utvar_riaditela_SE_EBO\ PORADA VEDENIA SE-EBO\ MATPV\ 2024

Schválil:
Dňa:
Ing. Peter Farkaš
riaditeľ SE-EBO

Revízia č. 0

EBO-MATPV-10/2024-26
Revízia č. 0
RZ AC6/20100/LK

Strana č. 1
Spracované dňa: 21.10.2024
Lehota uloženia 5

…jadrového dozoru Slovenskej republiky
…kalská 27, P. O. Box 24, 820 07 Bratislava 2
pracovisko Okružná 5, 918 64 Trnava

-1. 12. 2014

Slovenské elektrárne, a. s.
Ing. Jozef Tomek
manažér jadrovej bezpečnosti a radiačnej ochrany
935 39 Mochovce

Naše číslo	Vybavuje/☎	Trnava
7762/2014	Ing. Smrtník/033/5991142	25. 11. 2014

…plánu nápravných opatrení programu dlhodobej prevádzky …ému hodnoteniu programu dlhodobej prevádzky JE V2 …uvažovanej životnosti JE V2.

…SE/2013/086399 zo dňa 13. 11. 2013 zaevidovaným pod číslom …vali Úrad jadrového dozoru SR (ďalej len „úrad“) o Programe …V2 (ďalej aj „PDP V2“) a ako prílohu uvedeného listu ste na úrad …vu PDP V2, rev. 0“.

…ne, a. s., (ďalej len „SE, a. s.“) ako držiteľ povolenia na prevádzku …a 4. blok jadrovej elektrárne Bohunice v Jaslovských Bohuniciach, …radu č. 275/2008, v záujme plnenia povinností podľa § 23 ods. 2 …541/2004 Z. z. o mierovom využívaní jadrovej energie (atómový …není niektorých zákonov v znení neskorších predpisov a podľa § 2 … 7 a § 18 vyhlášky Úradu jadrového dozoru SR č. 33/2012 Z. z. …nom a systematickom hodnotení jadrovej bezpečnosti jadrových …láška“) vykonali hodnotenie prevádzky jadrového zariadenia 3. a 4. …e Bohunice v Jaslovských Bohuniciach (ďalej len „JE V2“) …ktom uvažovanej životnosti. Podľa § 2 ods. 7 a 8 a § 18 ods. 6 …dložili o tomto vykonanom hodnotení úradu správu, ktorá spĺňa …ds. 3 a § 19 vyhlášky.

…s úplnou dokumentáciou PDP V2 oboznámili počas neplánovanej …priestoroch JE V2. Na základe formálneho hodnotenia predloženej …špektori úradu konštatovali, že dokumentácia PDP V2 obsahuje: …nom hodnotení, ktorá spĺňa požadované náležitosti podľa § 18 ods. 3 …itosti podľa § 2 ods. 9 písm. a), c) a d) vyhlášky, …otenie prevádzky jadrového zariadenia JE V2 po dosiahnutí jeho …vanej životnosti, ktoré v súlade s § 18 ods. 6 vyhlášky v primeranej …adavky podľa § 19 vyhlášky.

	Bankové spojenie	IČO	Internet
… 15 30	7000061905/8180	30844185	http://www.ujd.gov.sk

Review of comprehensive LTO programme for Mochovce 1,2

Milestones

Date of issue of a licence for a test operation

is considered as start of operation for the purpose of a start of LTO date setting.

https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=550

Objectives

Comprehensive LTO programme for NPPs in SR is of the company top priorities.

LTO programme is part of the Company's Integrated Policy: point *13) Manage existing production and technical base of NPPs so that it is usable in the long term. Ensure the LTO programme, including managerial, material and human resources for its implementation.*

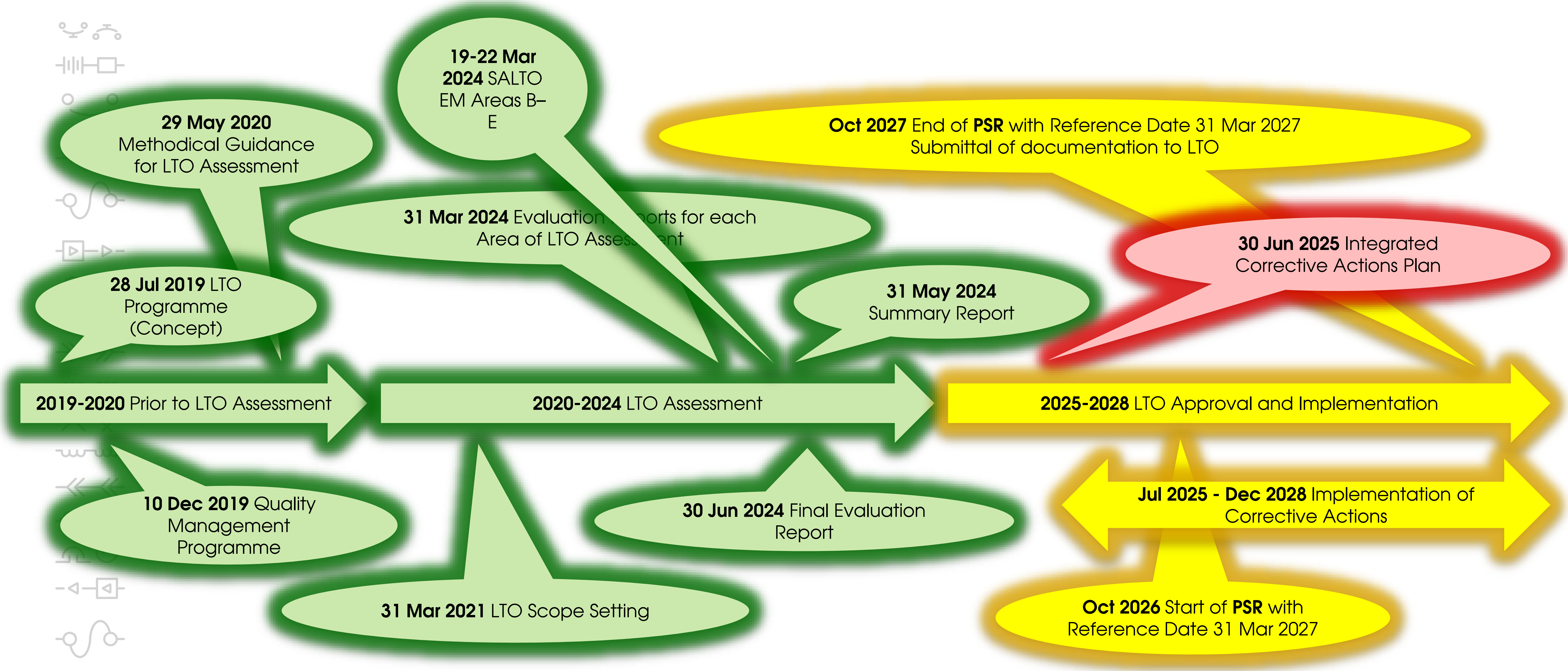
The implementation of the comprehensive LTO programme for Mochovce 1,2 is carried out as **a separate safety assessment** within the legislative framework given by the regulatory decree on PSR.

The objective of the programme is to demonstrate that the plant equipment (SSCs), which are the subject of the programme, will perform the required safety functions throughout the planned operating life of at least **60 years.**

The programme is designed to meet national legislative requirements and international recommendations. At the same time, its implementation will create conditions for plant safe and reliable operation of at least **60 years.**

The generation contribution is expected to be about 220 TWh (2028-2060).

Review of LTO programme for EMO 1,2



What has already been done

Deliverables (documentation produced):

Required by the national legislation in order to maintain the valid operating licence throughout the intended LTO timeframe

No.	Deliverable	Period	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1.	**PRIOR TO LTO ASSESSMENT**	**01/2019-05/2020**	✓									
1.1	Comprehensive LTO programme (conceptual document)	06/2019-12/2019	✓									
1.2	Organizational arrangements for the programme (quality management)	01/2019-12/2019	✓									
1.3	Scope setting for LTO (methodical guidance)	01/2020-05/2020		✓								
1.4	Review of management of ageing for SSCs important to safety within existing plant programmes with regard to LTO (methodical guidance)	01/2020-05/2020		✓								
1.5	Review of time limited ageing analyses with regard to LTO (methodical guidance)	01/2020-05/2020		✓								
1.6	Ageing management review (methodical guidance)	01/2020-05/2020		✓								
1.7	Revision of operating procedures with regard to LTO (methodical guidance)	01/2020-05/2020		✓								
1.8	Assessment of the human resources, competencies and knowledge management system for the LTO programme (methodical guidance)	01/2020-05/2020		✓								
1.9	Verification of the maintenance of safety skills, attitudes and expertise at the nuclear installation, including verification that long term policy objectives for human resources are developed and met (methodical guidance)	01/2020-05/2020		✓								
2.	**LTO ASSESSMENT**	06/2020-12/2024		✓	✓	✓	✓	✓				
2.1	Scope setting for LTO	06/2020-03/2021		✓	✓							
2.2	Review of management of ageing for SSCs important to safety within existing plant programmes with regard to LTO	03/2021-03/2024			✓	✓	✓					
2.3	Review of time limited ageing analyses with regard to LTO	03/2021-03/2024			✓	✓	✓					
2.4	Ageing management review	03/2021-03/2024			✓	✓		✓				
2.5	Revision of operating procedures with regard to LTO	03/2021-12/2023				✓						
2.6	Assessment of the human resources, competencies and knowledge management system for the LTO programme	03/2021-12/2023				✓						
2.7	Verification of the maintenance of safety skills, attitudes and expertise at the nuclear installation, including verification that long term policy objectives for human resources are developed and met	01/2024-06/2024					✓					
2.8	Final evaluation report	01/2024-06/2024						✓				
3.	**LTO APPROVAL AND IMPLEMENTATION**	01/2024-12/2028										
3.1	Summary report	01/2024-05/2024						✓				
3.2	Integrated corrective actions plan	06/2024-**06/2025**										
3.3	**Implementation of corrective actions**	**09/2025-12/2028**										

Ageing Management Review

SCs = structures and components

type of SCs	AMR reports produced	SCs reviewed
Mechanical	125	9 176
ELE / I&C	15	1 435
Civil	28	1 013
TOTAL	168	11 624

Degradation mechanisms have been identified for each SC reviewed.

Main Deliverables

evaluated area	number of produced documents
Review of management of ageing for SSCs important to safety within existing plant programmes	5 Review of M, EQ, ISI, SUP, Ch
Time limited ageing analyses (TLAAs)	41 29 Mech, 1 ELE/I&C, 11 Civil
Ageing management review (AMR)	168 125 Mech, 15 ELE/I&C, 28 Civil
Revision of knowledge retention system	2
Review of operating procedures	4

A total 277 documents were produced (introductory and final summary documents, methodical guidance, evaluation sheets, TLAA and AMR reports) = more than 10 000 pages of text

Corrective actions

evaluated area	245 corrective actions
Review of management of ageing for SSCs important to safety within existing plant programmes	21 Review of M, EQ, ISI, SUP, Ch
TLAAs that are NOT valid for LTO (60 years) = new to be elaborated	70 66 Mech, 4 ELE/I&C
Ageing management review (AMR)	115 82 Mech, 18 ELE/I&C, 15 Civil
Revision of knowledge retention system	1
Study of supporting documentation	38

A total 277 documents were produced (introductory and final summary documents, methodical guidance, evaluation sheets, TLAA and AMR reports) = more than 10 000 pages of text

Recommendations

evaluated area	260 recommendations
Review of management of ageing for SSCs important to safety within existing plant programmes	27 Review of M, EQ, ISI, SUP, Ch
Time limited ageing analyses (TLAAs)	2 2 Mech
Ageing management review (AMR)	159 94 Mech, 7 ELE/I&C, 58 Civil
Revision of knowledge retention system	3
Study of supporting documentation	69

A total 277 documents were produced (introductory and final summary documents, methodical guidance, evaluation sheets, TLAA and AMR reports) = more than 10 000 pages of text

Final result

The preparation, implementation and evaluation of the LTO of Mochovce 1,2 NPP show that the plant has a functional comprehensive LTO programme.

Thank you for your attention

Ďakujem za pozornosť

Long Term Operation of NPPs in Slovak Republic

DELISA-LTO Workshop

Ľudovít Kupča | 14 Feb 2025 | Kočovce

SLOVENSKÉ ELEKTRÁRNE

Questions ?

Long Term Operation of NPPs in Slovak Republic

DELISA-LTO Workshop

Ľudovít Kupča | 14 Feb 2025 | Kočovce

framatome
Intercontrôle

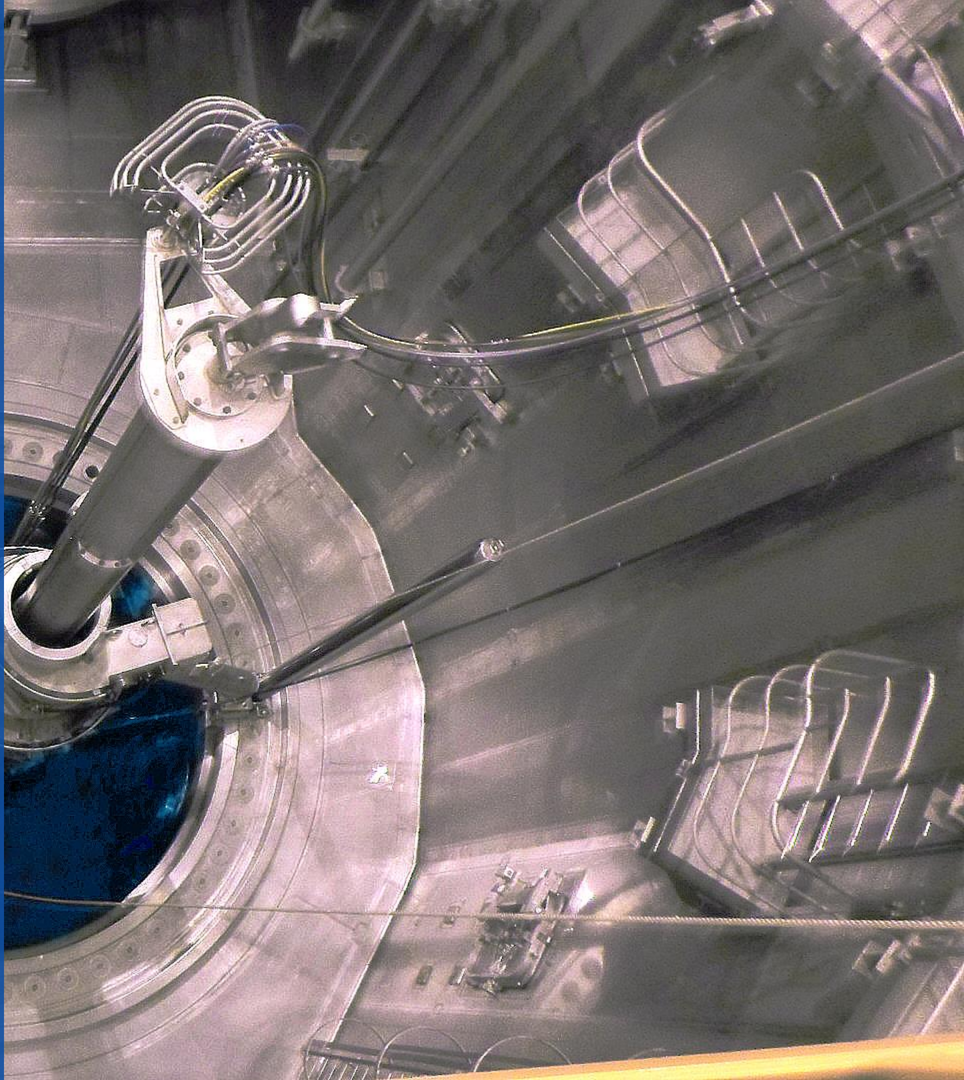
NDT APPLICATIONS IN NUCLEAR FIELD

Alexandre BLEUZE

Senior UT Expert FRAMATOME

14/02/2025

Winter University 2025, Slovakia



Framatome

For over **65 years**, Framatome's teams have been involved in developing safe, competitive, clean, low-carbon nuclear energy worldwide by:

- designing nuclear power plants,
- Supplying and commissioning nuclear steam supply systems,
- designing and manufacturing components and fuel assemblies,
- integrating automation systems,
- and servicing all types of nuclear reactors.

Framatome is the original equipment manufacturer of **84 nuclear power plants** in operation.

- **€4.1** billion revenue in 2023
- **€4.8** billion new orders

framatome

Worldwide presence

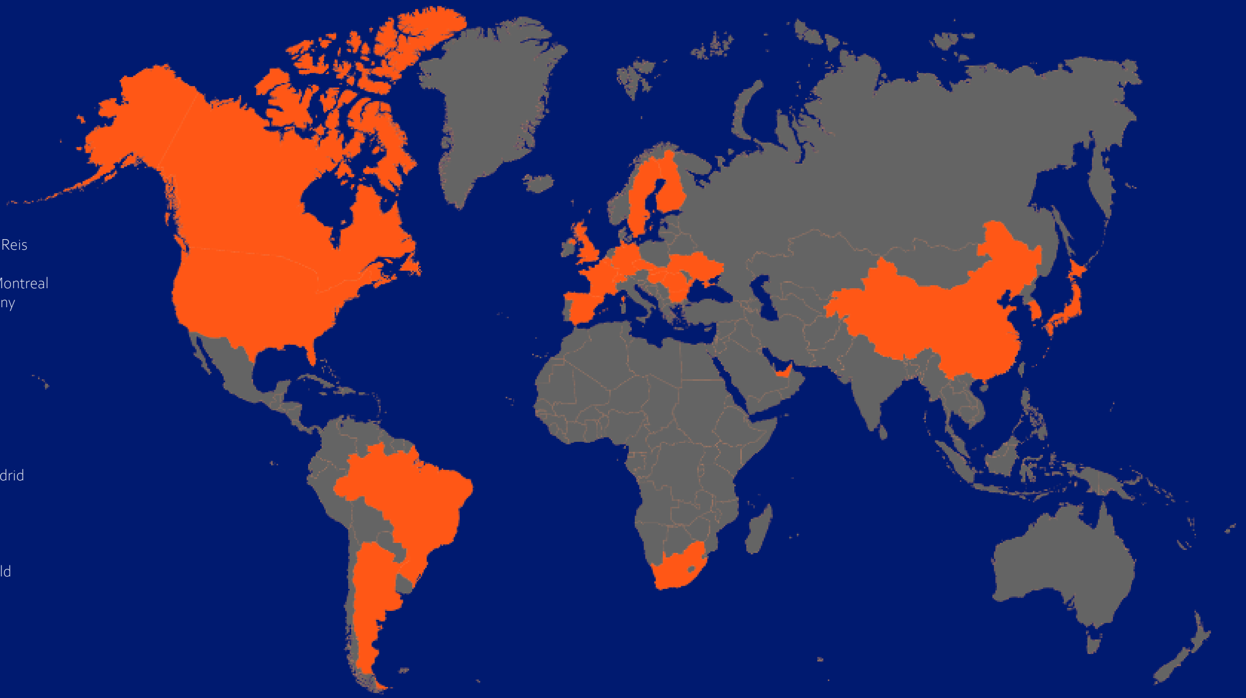
France
- Beaumont
- Chalon-sur-Saône
- Cherbourg
- Frans
- Grenoble
- Jarrie
- Jassus-Riot
- Jeumont
- Le Creusot
- Les Achards
- Lyon
- Marseille
- Massy
- Maubeuge
- Montbard
- Montreuil-Juigné
- Orsan
- Paimboeuf
- Paris
- Romans-sur-Isère
- Rugles
- Rungis
- Saint-Marcel
- Saint-Paul-lez-Durance
- Sully-sur-Loire
- Ugine

Germany
- Erlangen
- Karlstein
- Lingen

USA
- Benicia
- Charlotte
- Christiansburg
- Cranberry Township
- Jacksonville Houston
- Lynchburg
- Mansfield
- Richland

China
- Beijing
- Daya Bay
- Deyang
- Haiyan
- Lianyungang
- Shanghai
- Shenzhen
- Taishan

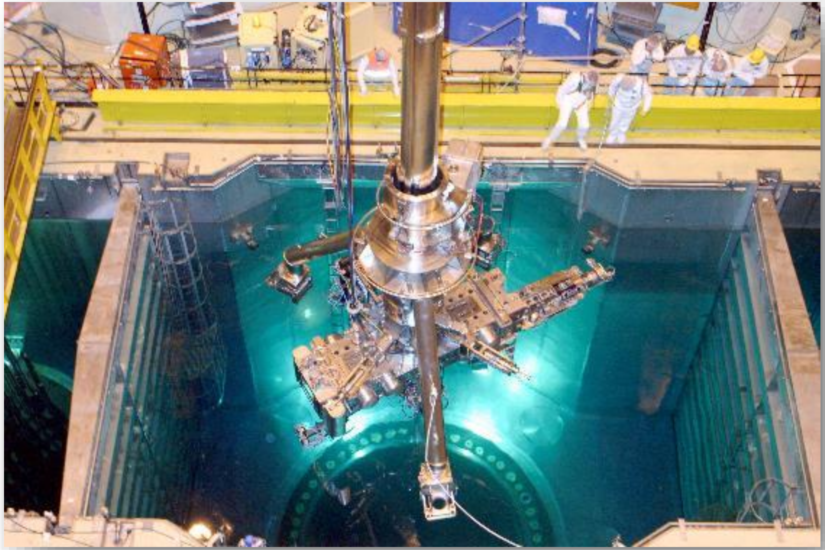
Rest of the world
- Belgium: Brussels
- Brazil: Rio de Janeiro, Angra dos Reis
- Bulgaria: Sofia, Kozloduy
- Canada: Pickering, Kincardine, Montreal
- Czech Republic: Prague, Dukovany
- Finland: Olkiluoto
- Hungary: Budapest, Paks
- Japan: Tokyo
- Romania: Bucarest
- Russia: Moscow
- Slovakia: Bratislava
- South Africa: Cape Town
- South Korea: Seoul, Gwanggyo
- Spain: Zaragoza, Tarragona, Madrid
- Sweden: Helsingborg
- Switzerland: Baden
- Ukraine: Kiev
- United Arab Emirates
- United Kingdom: Bristol, Cranfield



+20,000 employees | +70 sites* | 20 countries

* Locations can have multiple sites

Framatome/Intercontrôle provides safe, reliable, innovative and competitive NDT for nuclear and industrial fields



NDT as Nuclear Services

- Automated Non-Destructive Testing
- Softwares, probes and systems
- Pre-Service and In-Service Inspection

NDT R&D, development and qualification

- Applied R&D,
- Feasibility studies,
- Development (NDE methods, probes, software, tooling and robotics)
- Specific industrial systems
- Integration and Qualification

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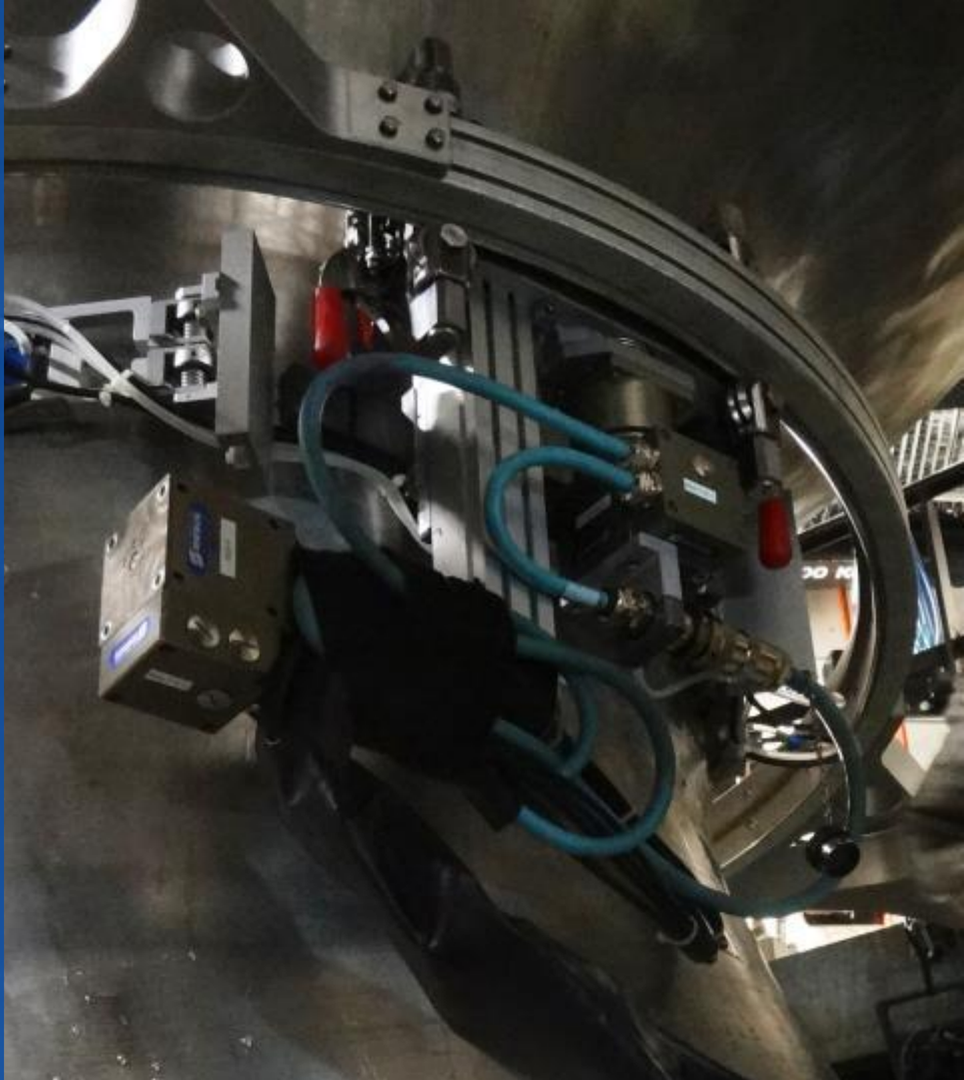
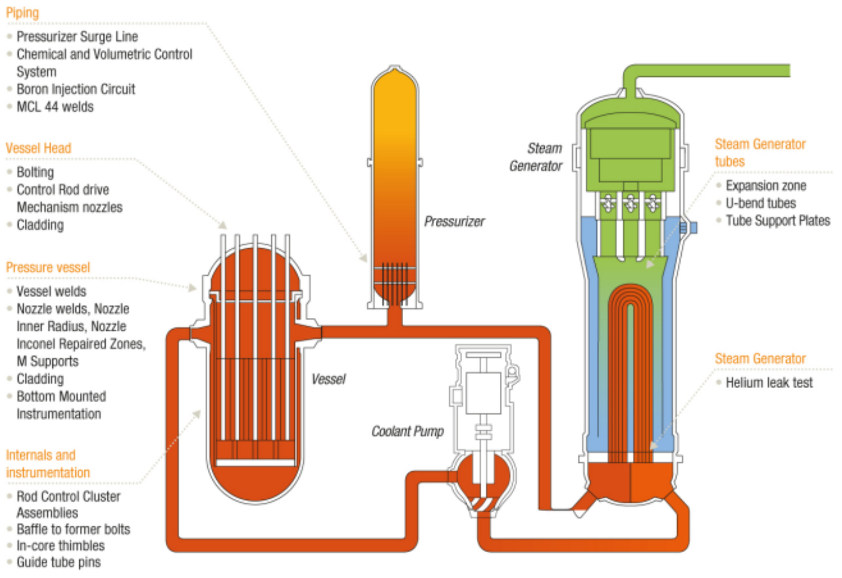
NDT AS NUCLEAR SERVICES



NDT as Nuclear Services

Intercontrôle is specialized in automated non-destructive testing of nuclear reactors primary circuit components



INTERVENTION CAPACITY & CERTIFICATIONS

- >100 inspections per year
- 2 hot workshops (tools storage and maintenance)
- >155 ISO 9712 certified operators

METHODS

- Standard and Phased Array UT
- Standard and multielement ET
- X and gamma RT
- Visual testing
- Penetrant testing
- Thermography
- Leakage Testing

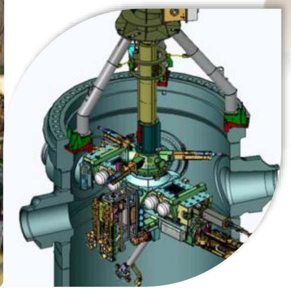
CODES & STANDARDS

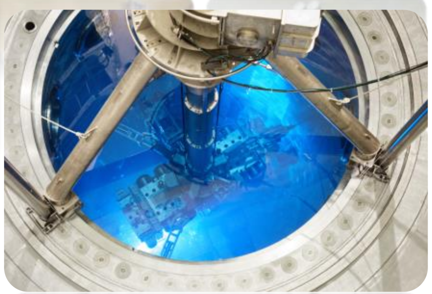
- RCC-M / RSE-M
- ASME
- Specific Customer Request

Reactor Pressure Vessel Inspection

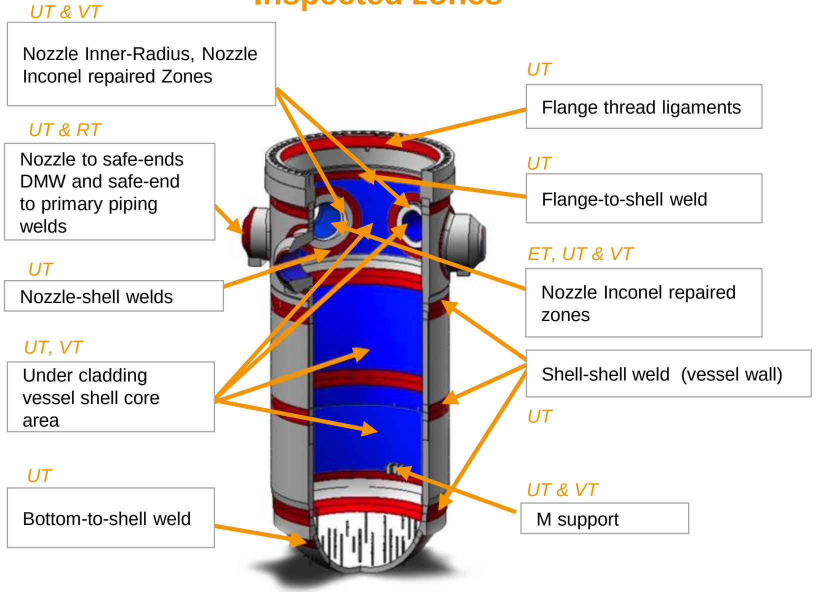
More than 350 RPV inspected worldwide with the In-service Inspection Machine MIS

- 3 hot MIS (MIS7, 8 and MISB)
- 1 cold MIS EPR





Inspected zones



METHODES

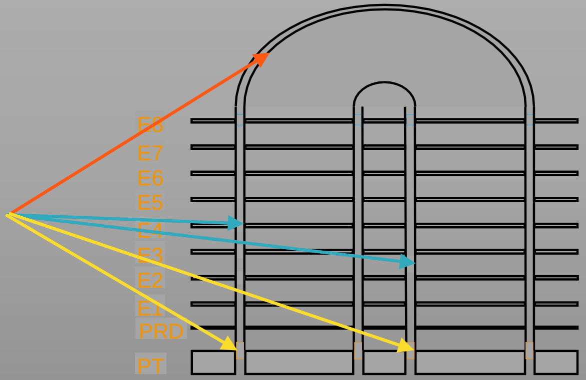
- Ultrasonics (UT)
- X and Gamma Radiography (RT)
- Visual Testing (VT)
- Eddy currents (ET)
- Analysis software (CIVACUVE, CIVAMIS)

Steam Generator (SG) tubes inspection

More than 5 millions tubes inspected worldwide

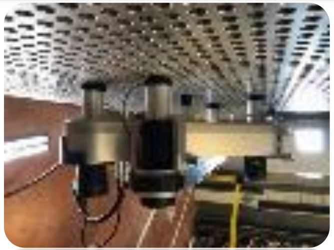
INSPECTION TECHNIQUES

- Bobbin coil for defect detection on full tube length
- Rotating probe for higher sensitivity and defect characterization in specific areas with suspected degradations/flaws
- Mix bobbin / phased-array probe to combine in one path defect detection on full tube length and characterization in specific areas with suspected degradations/flaws



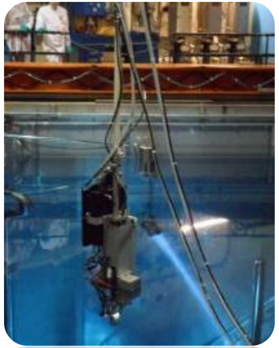
METHODS

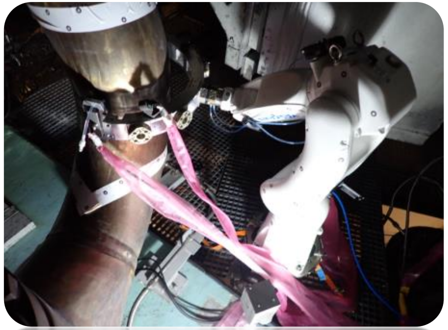
- Multi-frequency Eddy Currents
- Analysis software AÏDA
- Helium leak detection



Primary Circuit Components Inspection

More than 100 inspections per year around the world





RPV INTERNALS

- RPV Head
- RPV Bolting
- Bottom Mounted Instrumentation (BMI)
- Rod Control Cluster Assemblies
- Guide tube pins
- Baffle-to-former bolts
- In-Core thimbles
- EPR Control Rod Drive Mechanism (CRDM)

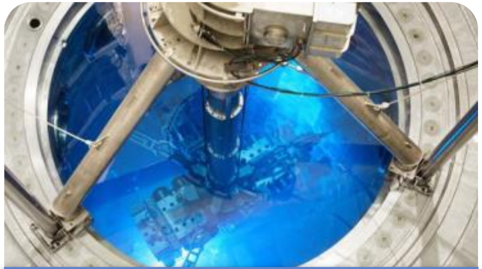
PRIMARY CIRCUIT PIPING

- Pressurizer Surge line
- Chemical and Volumetric Control system
- Boron injection Circuit
- EPR welds of the MCL
- Safety injection Reactor
- Pump casing

METHODS

- **ET, UT, PT, VT, RT**

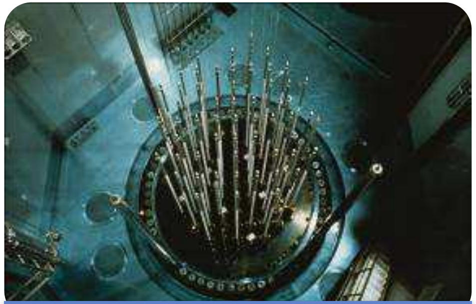
Pre-Service Inspection : EPR FA3 Experience



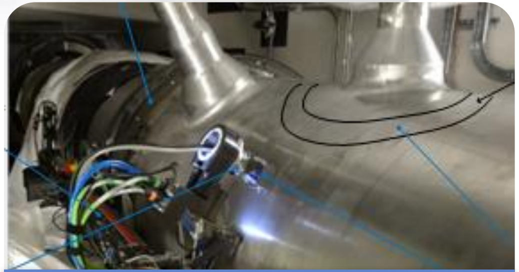
- Reactor Pressure Vessel
- NDE Method : UT / ET / VT / RT
- FA3 PSI in 09/2017

- 44 welds of Main Coolant Line (EPR)
- NDE Method : UT
- FA3 PSI in 02/2017 and 02/2018 (44 welds)

- Bolting (Studs and Nuts)
- NDE Method : ET / PT
- FA3 PSI in 06/2016



- Control Rod Drive Mechanism (EPR)
- NDE Method : UT / ET
- FA3 PSI in 10/2017



- Set-In welds (EPR)
- NDE Method : UT
- FA3 PSI in 10/2017 in Expertise mode

- SG tubes
- NDE Method : ET
- FA3 PSI in 08/2016

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NDT R&D, Development & Qualification

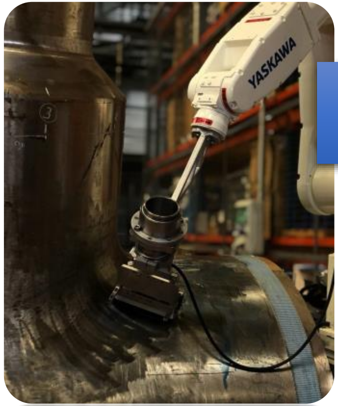
R&D, Development & Qualification

The Technical and Projects Department : more than 85 engineers and technicians

NDE methods development

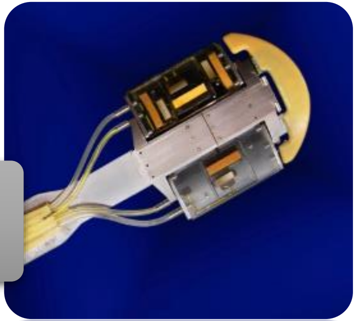
- UT / ET / VT / TT
- UT instead of RT
- TT instead of PT/MT

Systems development and qualification



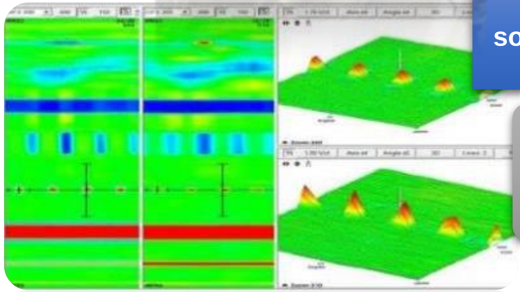
- Feasibility study
- Tooling and robotics
- Integration and qualification
- Project management

Probe design and manufacturing



- Severe environment
- Life extension
- High performance

software development



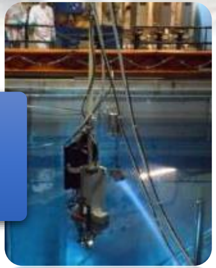
- NDE data analysis
- Signal processing
- Control command

Development et qualification

Examples of development

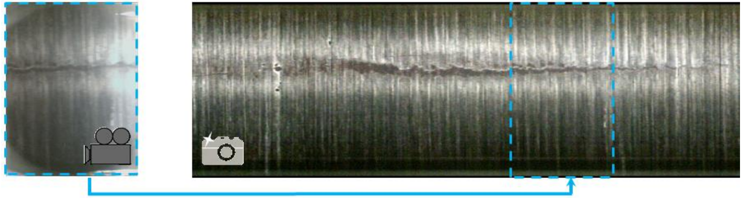
Nuclear reactor nozzle inner-radius defect characterization with a flexible phased-array UT transducer

Nuclear reactor Pressure Vessel Bottom Mounted Instrumentation inspection

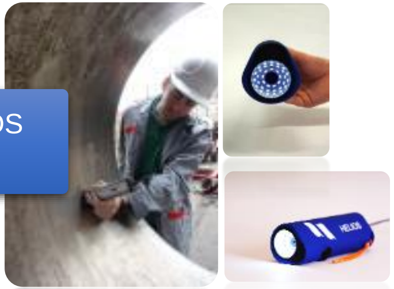


Nuclear reactor Pressure Vessel nozzle Inner-radius inspection

Stitching: image reconstruction software for Tele Visual inspection



TV inspection with HELIOS system



Thermic plant Pelton wheel Inspection with APC (Active Photo thermal Camera)

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Thank you for your attention