Developing a new class of materials resistant to radiation, temperature, and corrosion - NOMATEN Center of Excellence initiative

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NOMATEN Centre of Excellence Director

NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK

National Centre for Nuclear Research Poland (NCBJ)

NOMATEN
Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Nuclear Facilities Operations Department — Reaktor MARIA

Materials Physics Department
Materials Research Laboratory

Fundamental Research Department

Nuclear Equipment & Technology Department

Department of Complex Systems — CIS Centrum Informatyczne Świerk

The largest Research Institute in Poland:
- over 1100 Employees,
- The research staff includes about 70 Professors and Associate Professors as well as over 200 PhDs
- PhD School ca. 45 Students

Research achievements:
- over 500 scientific publications, with over 16 000 c/y

Research projects:
- over 100 in 2021 / 2022 funded by H2020, Euratom, NCN, NCBR, FNP, RPO
- success rate for EU projects ca. 30%

Scientific cooperation:
- JRC, CERN, DESY, Grenoble, JParc, FAIR, Julich, ESS, JINR, T2K, XFEL)

Location: Otwock / Świerk district 35 km from Warsaw in south-east

45 people

Radioisotope Production Centre POLATOM

Nuclear Equipment Division (HITEC)

Science and Technology Park (PNT)

Interdisciplinary Division for Energy Analyses

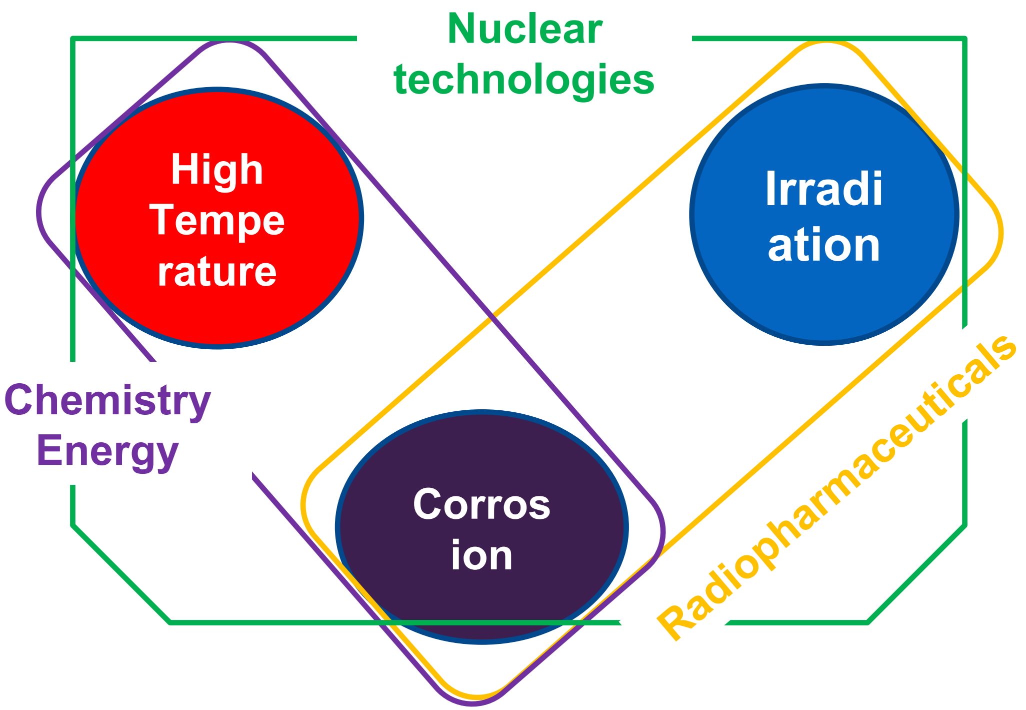
NOMATEN
Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Purpose of the project

- Basic scientific ideas:
  - Research agenda of the NOMATEN CoE is based on:

    (i) ***Development of novel materials for extreme applications***

    (ii) ***Development of novel radiopharmaceuticals for medical applications***
  - Close collaboration with strategic partners (CEA France i VTT Finland). Using and developing complementary infrastructure.
  - Close collaboration with the Polish industry.



Research topics implemented at the CoE are related to the European and Polish long-term planning: Energy, health, and rational use of limited resources.

NOMATEN Research Group Leaders

NOMATEN
Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Functional Properties

Materials Characterization

Radiopharmaceuticals

Materials Design and Manufacturing

Hybrid modelling

In total 35 active scientists

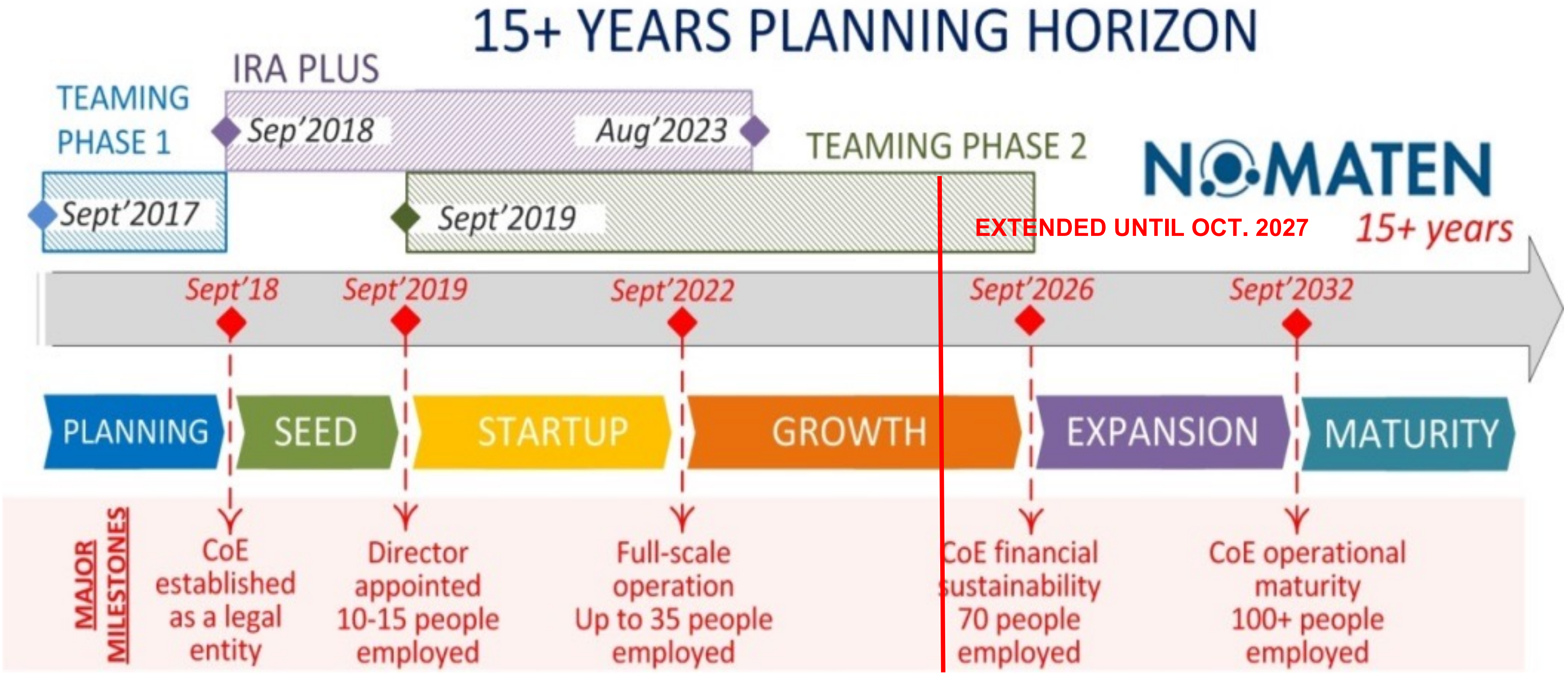
Experiments

Medical

Simulations

NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

NOMATEN Centre of Excellence – growth and capacity building



<u>Launching the Center / Developing the Research Agenda / Basic Operation Procedures and HR Recruitment</u>

…and from 2023 until now the Growth Phase:

<u>Research Activities / Projects / R&D Works / Development of the Infrastrucutre and HR Competencies!</u>

NOMATEN CORE - budget 97.5 MPLN (22.5 Meuro)

Period 01.01.2024 – 30.06.2026
National Information Processing Institute (OPI in Polish)

Science and research
- Research areas

Science for everyone
- Open access
- Conferences
- Publications
- Publishing House

- Doctoral school

Software
- Systems for science and higher education
- Grant systems
- Other systems
- Training
- Security in systems

Artificial intelligence
- AI Lab
- Innovation Centre for Digital Medicine

EU funds for science
- FENG
- KPO
- POIR

Reports and analyses
- Business intelligence
- Sociology of science
- Scientometrics

Human–computer interaction

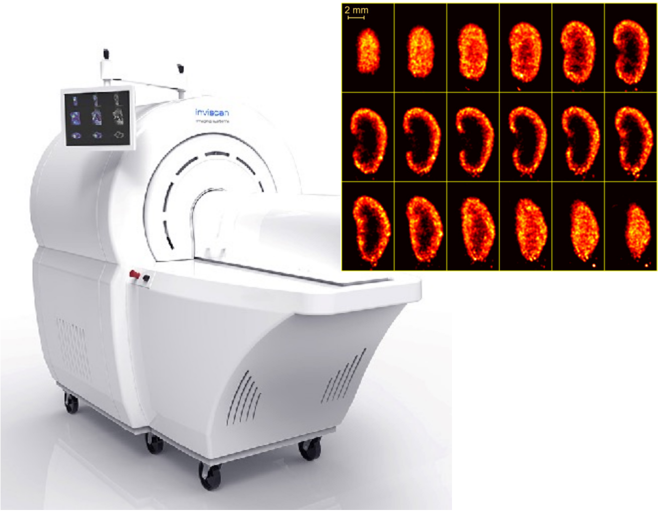
E-learning

OPI is a modern center for information technologies and artificial intelligence.
It supports the implementation of government policy in science and higher education and assists in shaping an innovative, knowledge-driven economy.

NOMATEN CORE = addressing societal needs = about 20 different small/medium-sized infrastructures, but the three most important ones are…


SCC of material in PWR conditions – to be used to test / approve materials for our future NPPs.

Development of materials by using AI tools requires power – we are building a dedicated cluster for this.



SPECT-PET-CT system for intravital (in vivo) molecular imaging of small laboratory animals – development of a new radiopharmaceuticals

What did we build already in the frame of the NOMATEN Center of Excellence?

From nano to micro scale characterization in-situ at HT

Nanoindentation

- **Berkovich, Vickers, Cube Corner and Conical** indenters
- **HT measurements** with diamond (up to 450°C) and cBN (up to 750°C) indenter Measurements under **controlled argon atmosphere**
- Coupled **Atomic Force Microscope**
- Optical microscope (up to 40x mag.)
- Convers range forces from 0.1 mN to 20 N
- Load or depth-controlled mode
- **Single forces or Load Partial Unload**

SEM/FIB/EDS/EBSD

SEM microscope Helios 5 UX DualBeam (Thermo Fisher Scientific)

The Extreme High Resolution (XHR) Field Emission Scanning Electron Microscope (FE SEM) equipped with:

- FIB (Focused Ion Beam) technology
- EDS (Energy Dispersive X-ray Spectroscopy)
- EBSD (Electron Backscatter Diffraction)

XRD (GID + HT)

Bruker D8 ADVANCE with DAVINCI

- equipped with a sealed Cu X-Ray tube, TWIN-TWIN optics and LYNXEYE XE-T strip detector
- Cu radiation, $\lambda_{K\alpha 1}$ = 1.540562 Å
- Energy Resolution < 380 eV at 8 keV
- B-B/GID geometries

High-temperature stage - Anton Paar HTK 1200 N

- temperature up to 1200°C
- operates Under Vacuum or Selected Gas Environment
- specimen Stage with Rotation (Rocking)

Multipurpose TEM

TEM JEOL F-200 with STEM, HAADF, EDS, BEI, BF and ABF detectors Equipped with in-situ tensile and HT annealing up to 1000 ºC holders & PIPS II, electropolishing ….

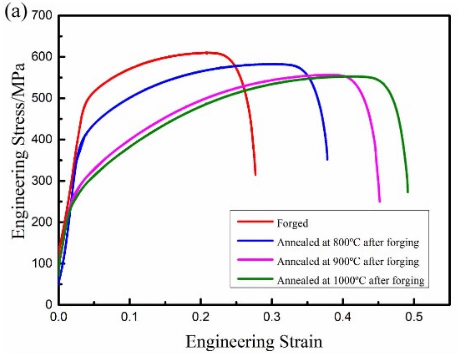
Roadmap of materials development and manufacturing

Almost any chemical composition suggested by the numerical groups is possible to be manufactured!

Arc Melting
max. 3500 ºC,
200 g

HT Annealing
max. 1400 ºC,
10^{-6}

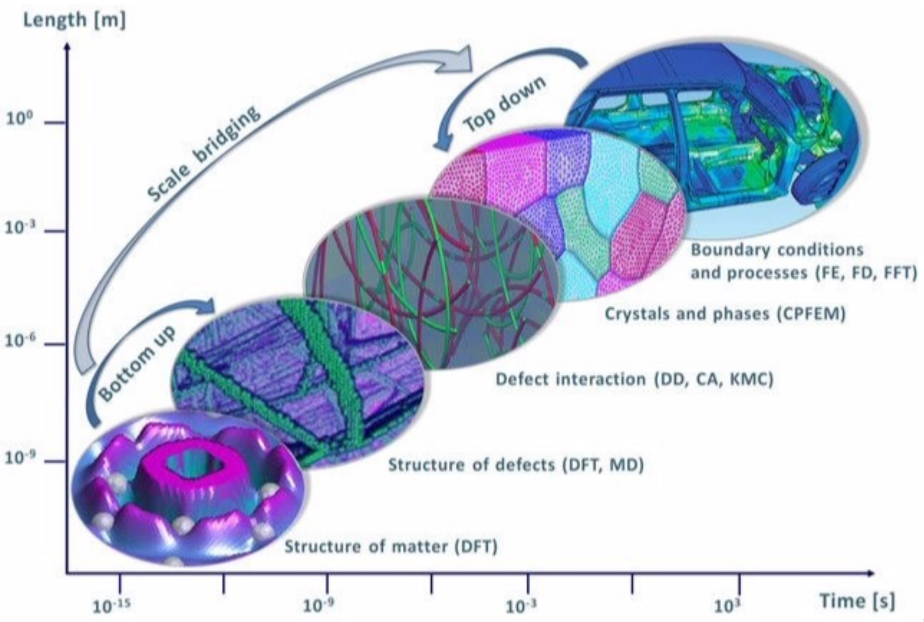
Small scale samples
(tensile with DIC)



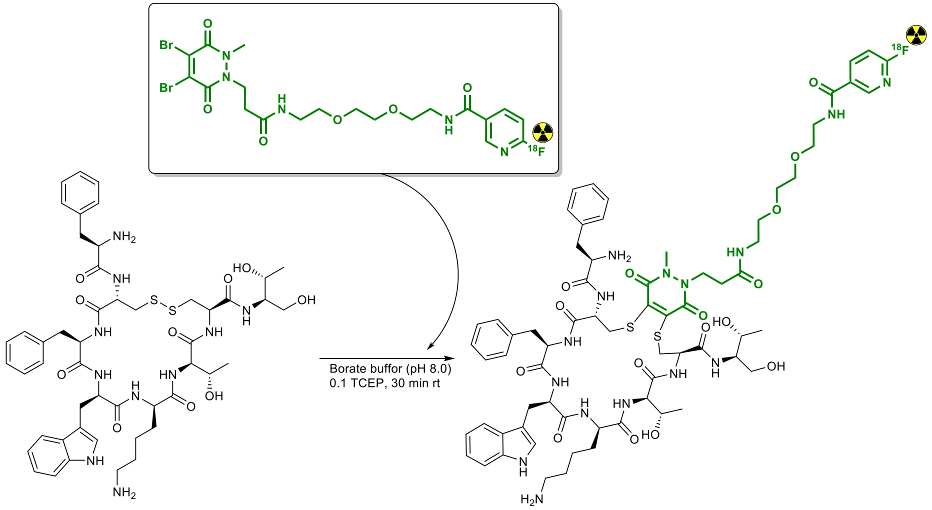
Alloys with improved mechanical, corrosion and radiation damage properties

Multiscale modelling

Multi-scale modeling of materials' behavior allows a better understanding of the physical phenomena responsible for their degradation under extreme conditions.
Simulation and analysis of large sets of data is used to design materials .



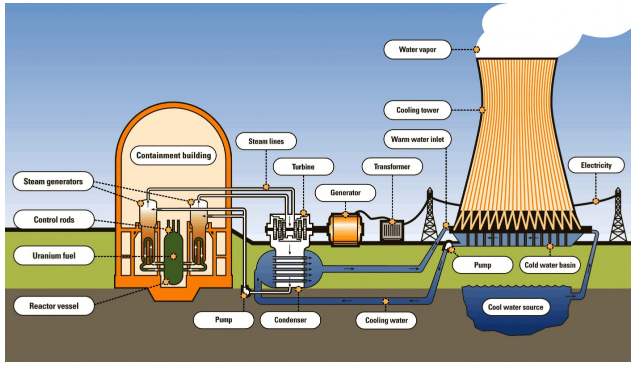
Radiopharmaceuticals development



Development of new radiopharmaceuticals for the diagnosis and therapy of civilization diseases, especially cancer.
The work involves obtaining new medical radioisotopes, labeling biomolecules with them, and in vitro and in vivo preclinical evaluation of their potential use in nuclear medicine.

Why are we doing this?

We need clean and stable energy source.

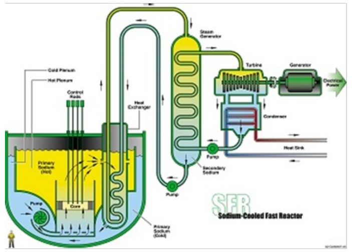


Gen II-III PWR-type reactors'

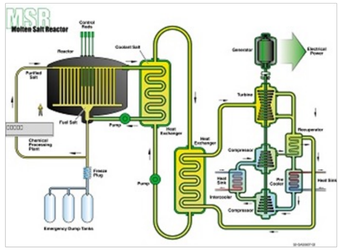
Nuclear is ideal for dealing with climate change, because it is the only carbon-free, scalable energy source that's available 24 hours a day. The problems with today's reactors, such as the risk of accidents, can be solved through innovation.

Bill Gates

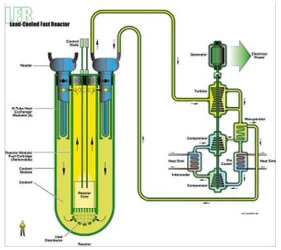
Gen IV Nuclear reactors – increased efficiency up to 45 - 50%



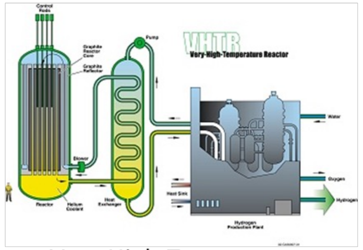
Sodium-Cooled Fast Reactor



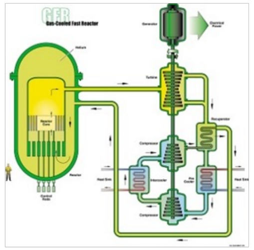
Molten Salt Reactor



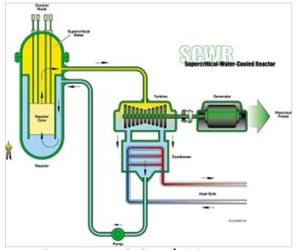
Lead-cooled fast reactor



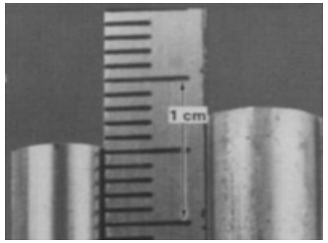
Very-High-Temperature Reactor



Gas-cooled Fast Reactor



Supercritical-Water-Cooled Reactor



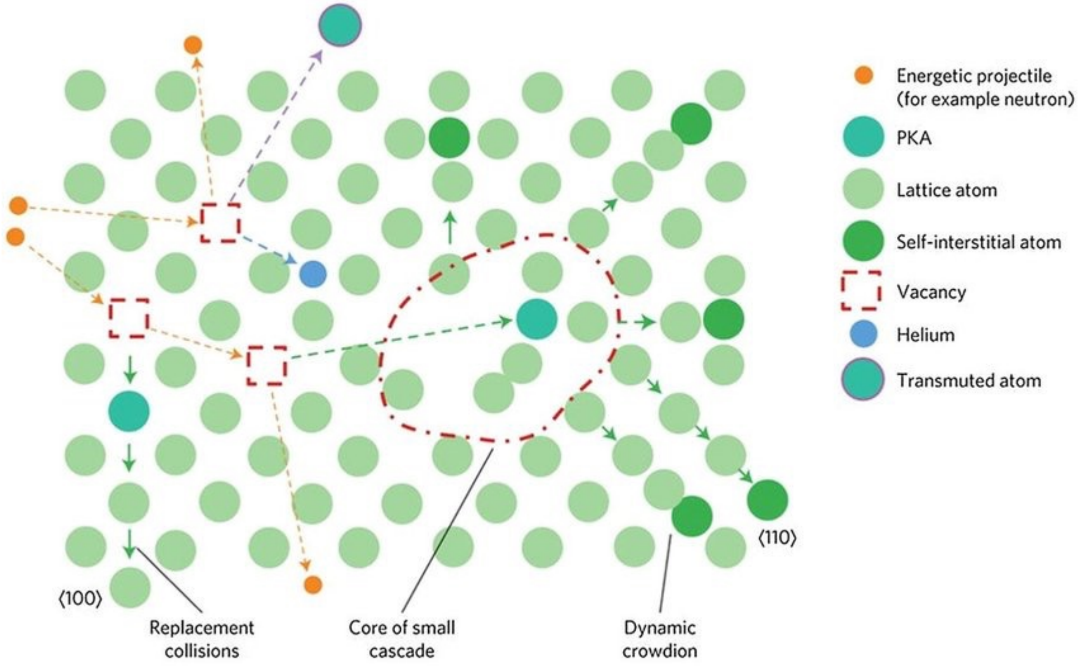
Swelling
He embrittlement
Failure

Extreme conditions
Temperatures greater than 400°C
Radiation damage above 50 dpa
High-stress levels

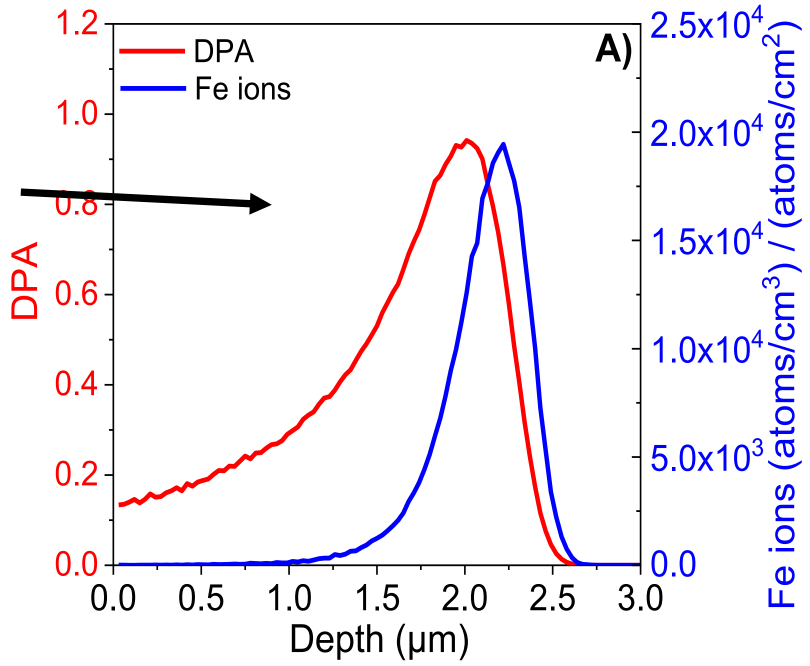
Conventional materials such as stainless steels

What is ion irradiation?

Shooting energetic ions into the material



Radiation damage profile



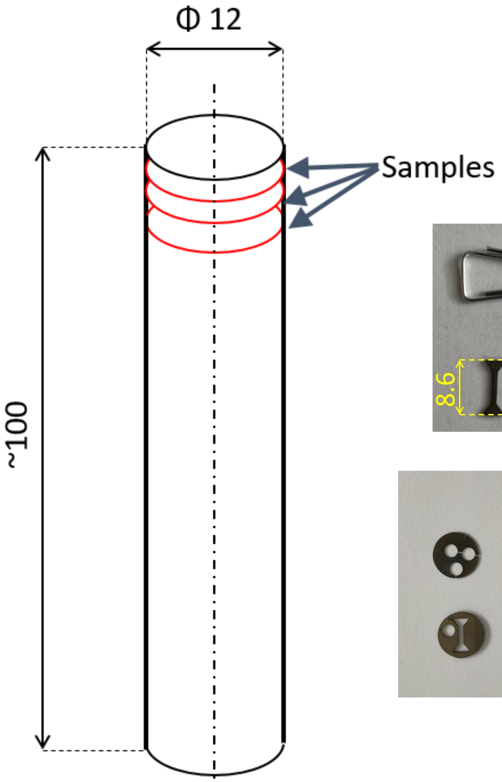
Benefits (in comparison to neutrons): fast, controllable, cheap

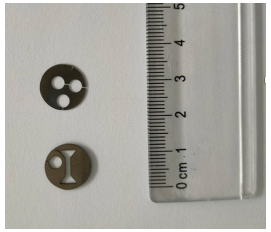
Research examples

REF-HEA1 - (CrFeMnNi family):

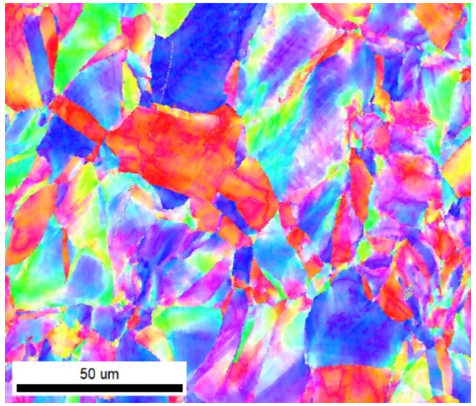
BAR IN70-1 (380 mm from the hot side) with chemical composition (in %wt.):

39.7% **Fe** + 14.2% **Cr** + 33.6% **Ni** + 12.5% **Mn**

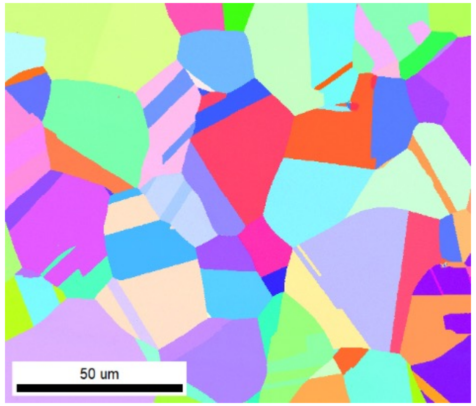


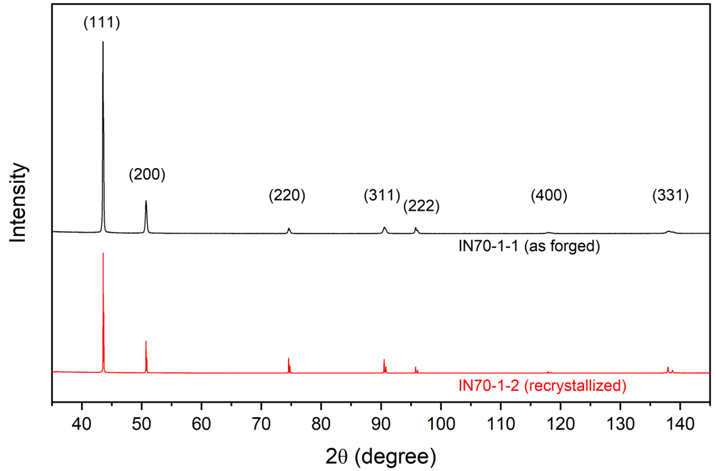


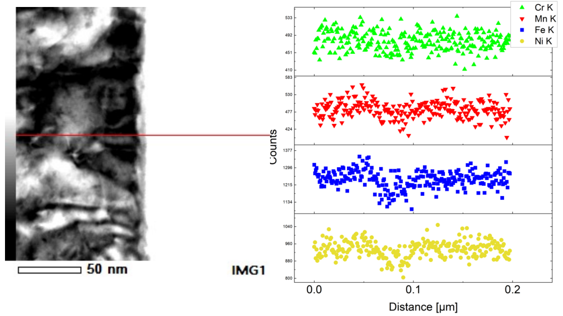
IN70-1-1 (as forged)



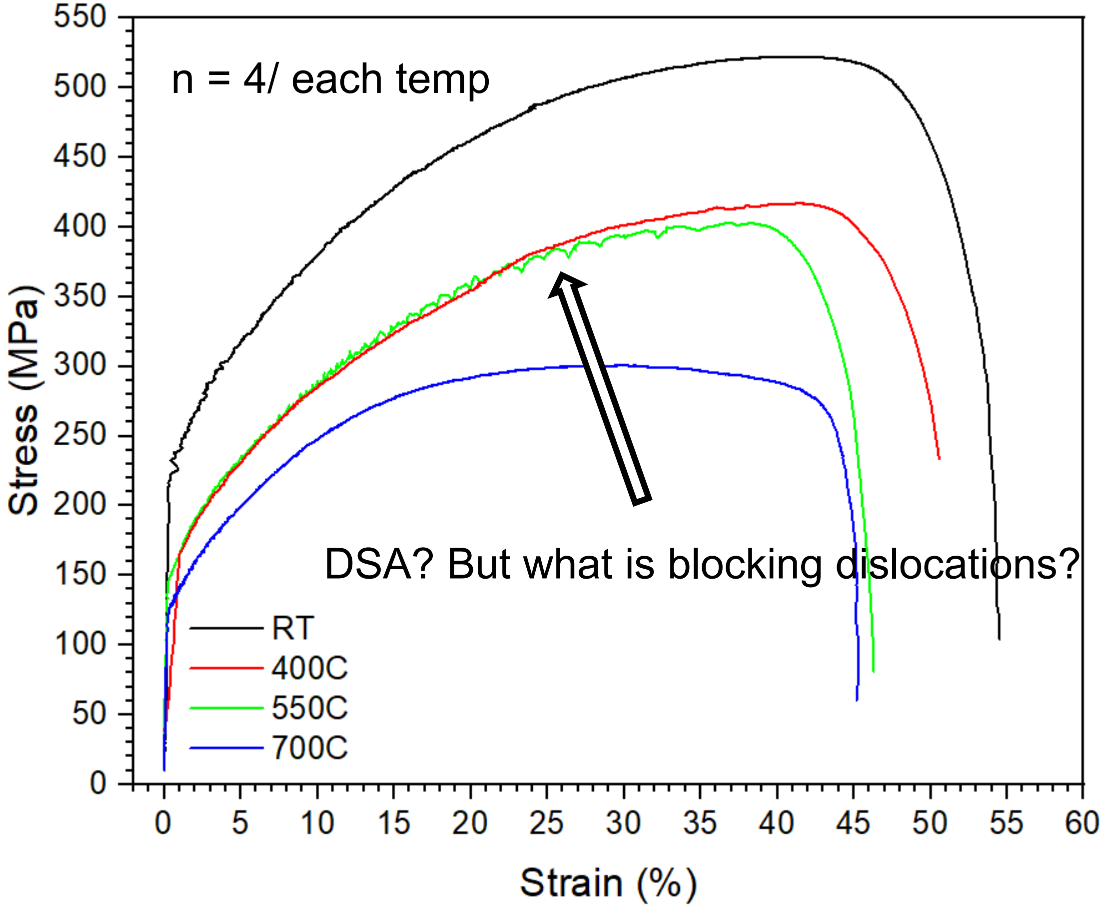
IN70-1-2 (recrystallized)

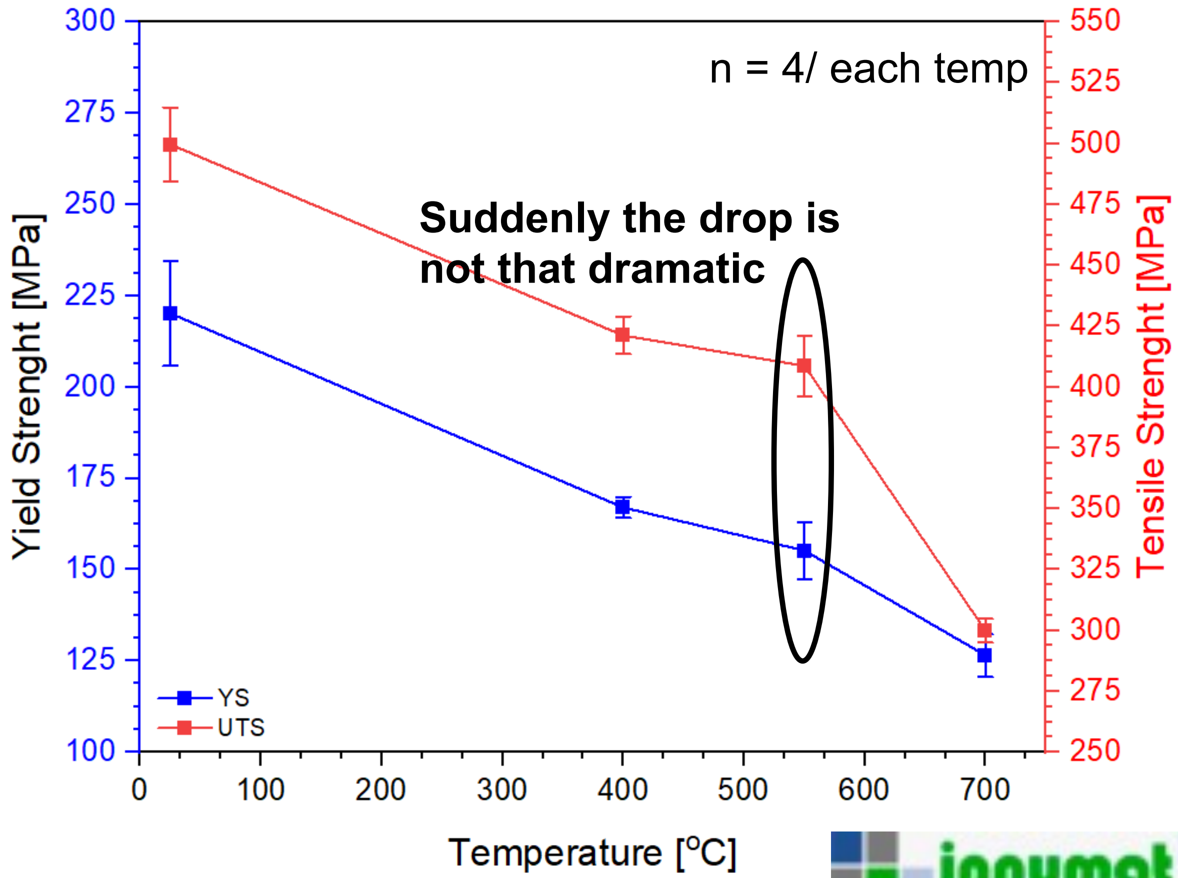






Mechanical properties vs temperature





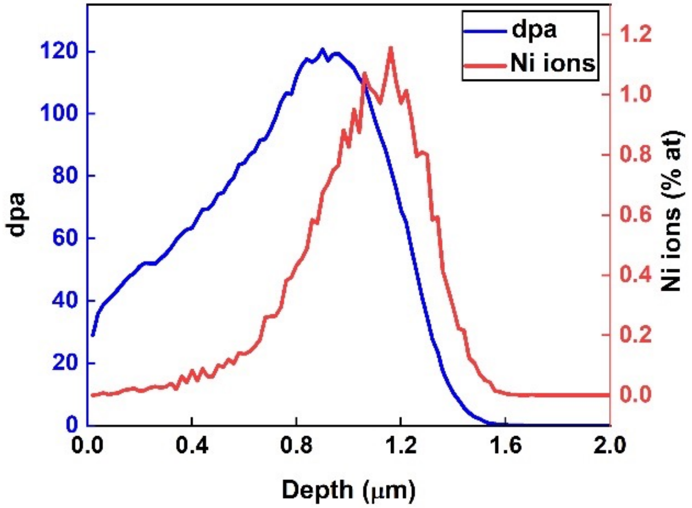
42% difference between the values of YS at RT and 40% for UTS at abovementioned temperatures

What would happen if you mix two material design concepts: HEA and ODS…

Radiation damage resistance of ODS-HEA

Family	Manufacturing technique	Material	Nominal Chemical Composition	Irradiation Temperatures
MEAs	Arc melting, homogenization, and quenching	NiCoFe	Equiatomic	580°C
		NiCoCr	Equiatomic	700°C
ODS-MEAs	Mechanical alloying, spark plasma sintering, and annealing	ODS-NiCoFe	NiCoFe-1.2Ti-1.5Y_2O_3	580°C, 700°C
		ODS-NiCoCr	NiCoCr-1.2Hf-1.5Y_2O_3	700°C
		ODS-NiCoFeCr	NiCoFe-1.2Ti-1.5Y_2O_3	580°C

Irradiation profiles using SRIM calculations

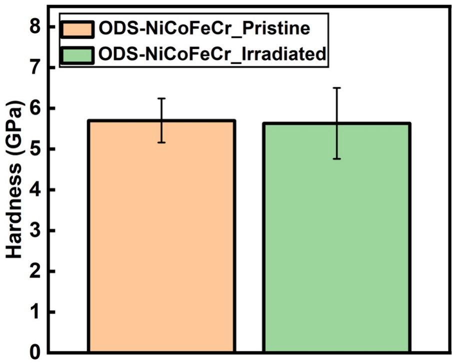


Mimicking the end lifetime of the material in the nuclear reactor environment

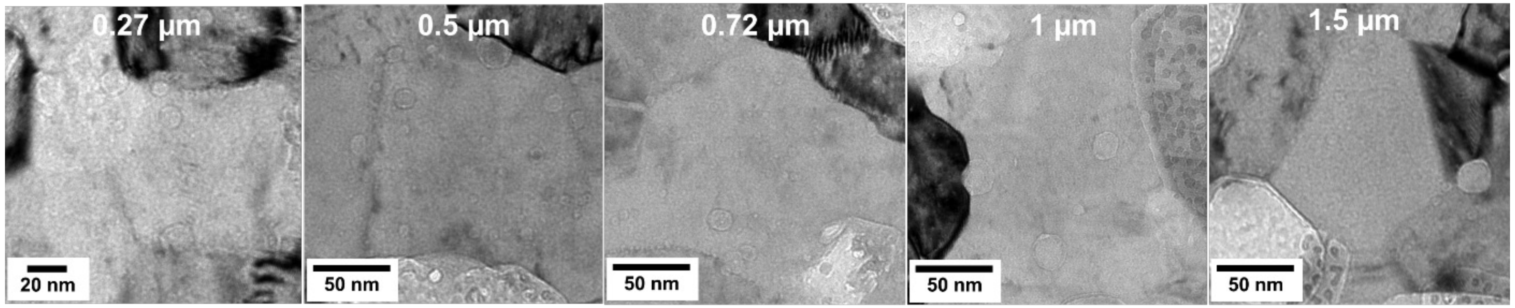
Irradiation conditions - Ni^{2+} , 3 MeV, 5 x $10^{16}$$cm^{-2}$ at 580 ^{o}C

Irradiation effects in the ODS-NiCoFeCr at 580℃

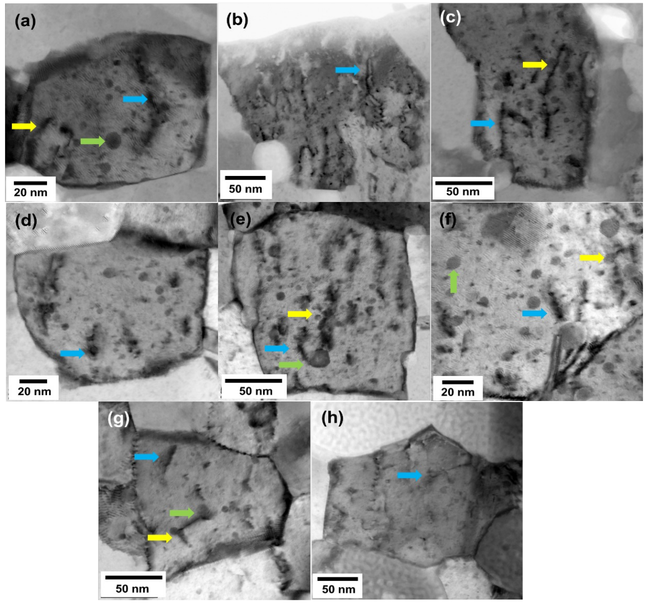
No significant irradiation hardening



No significant void formation

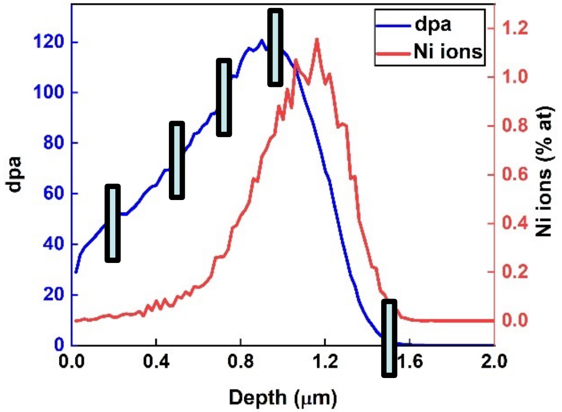


STEM-BF studies



Dislocations, Nanoprecipitates, Dislocation pinning at the precipitates

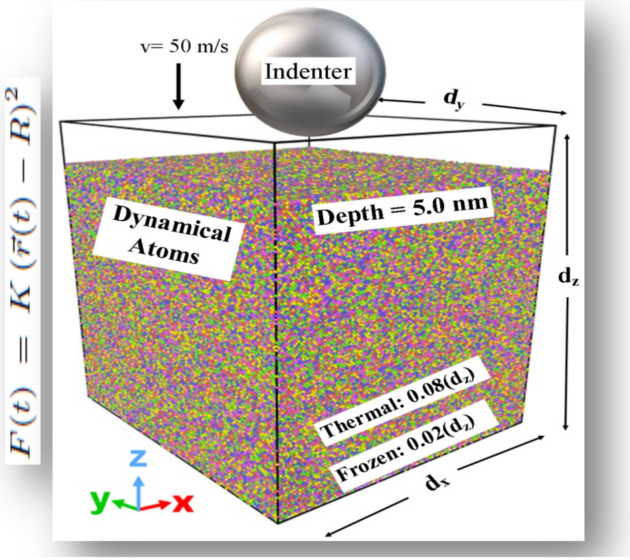
Region of examination	Distance of the grain from the surface (µm)	Dislocation density (x10^{14} m^{-2})	Mean dislocation length (nm)
Irradiated	0.3	11.1	234
	0.4	9.3	142
	0.5	8.5	64
	0.7	6.0	69
	0.9	11.2	72
	1	7.7	60
	1.5	7.3	64
Pristine	3.5	4.6	89

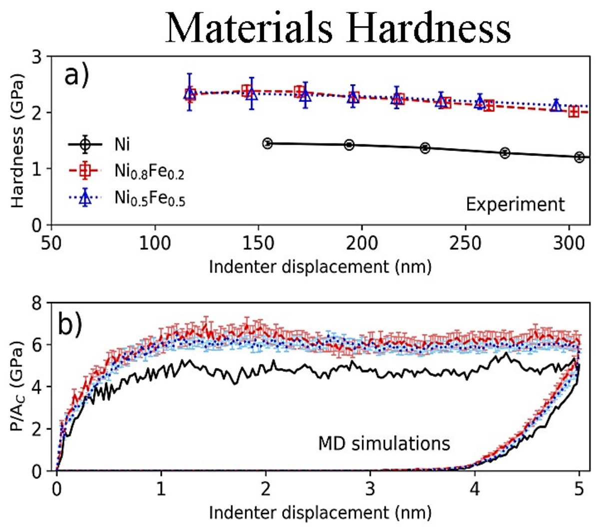


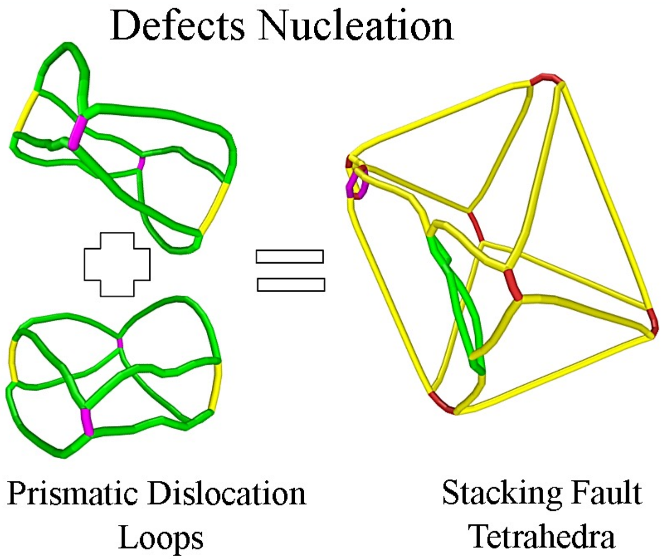
Dislocation length densities are similar order of magnitude

Single phase concentrated solid solution alloys (SP-CSAs)

Samples:
Pure Ni, $Ni_{80}Fe_{20}$,
and $Ni_{50}Fe_{50}$
[100] crystal
orientation
300 K temperature



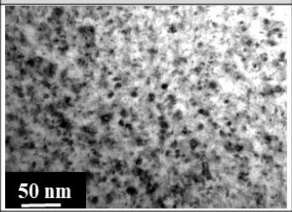
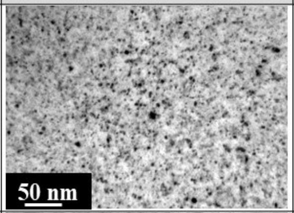
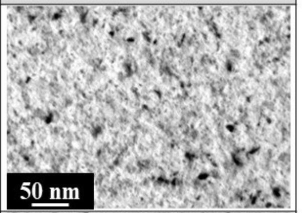
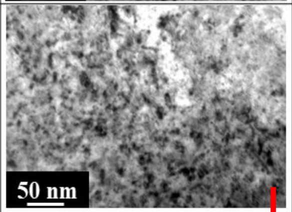
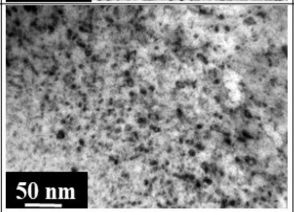
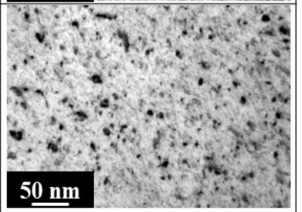




The main strengthening factors are associated to sluggish dislocation diffusion, reduced defect sizes and the nucleation of tetrahedral stacking faults. **Interstitial type prismatic dislocation loops mainly formed by 1/6 <1 1 2> Shockley dislocations are nucleated during the loading proces. Their interaction leads to the formation of pyramidal shaped stacking fault which are mainly created by 1/3 <100> Hirth dislocations** lines. Both types of defects coexist in the same plastic deformation zone.

TEM images of Ni, $NiFe_{23}$, and $NiFe_{62}$ irradiated with the fluence of $4x10^{13}$ ions/cm^2 and $4x10^{15}$ ions/cm^2

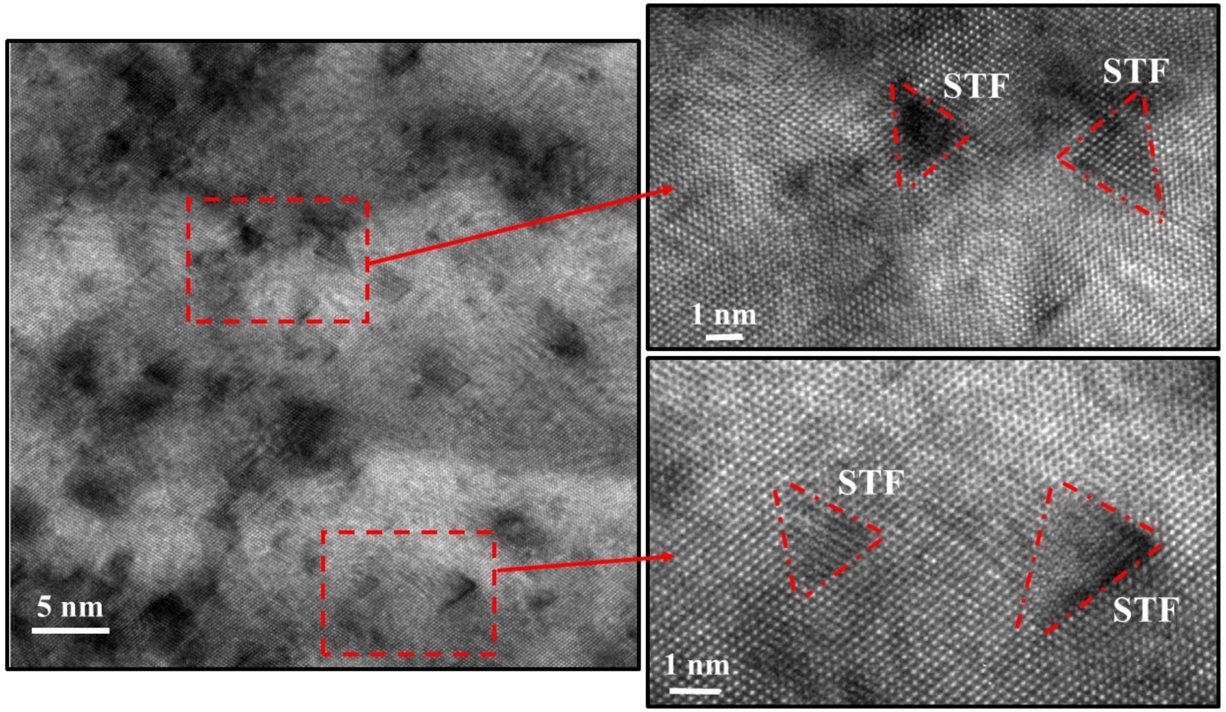
Fe concentration

Material / Fluence $ions/cm^2$	*Ni*	$NiFe_{23}$	$NiFe_{62}$
$4x10^{13}$			
$4x10^{15}$			

Defect size

Pictures taken from the area with the highest defect concentration

HRTEM image of $NiFe_{23}$ irradiated up to the damage level of 20 dpa – STF's mostly dominate in the structure



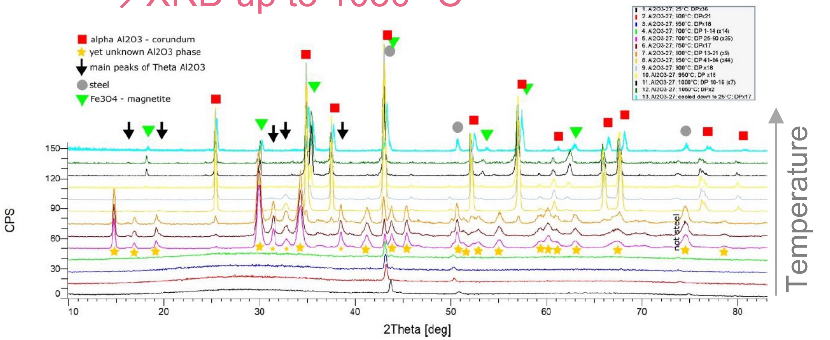
- Defect concentration is decreasing as the iron content increases both at low and high irradiation fluence
- The defect types are changing for different compositions

Crystalline/amorphous alumina – applied and fundamental research

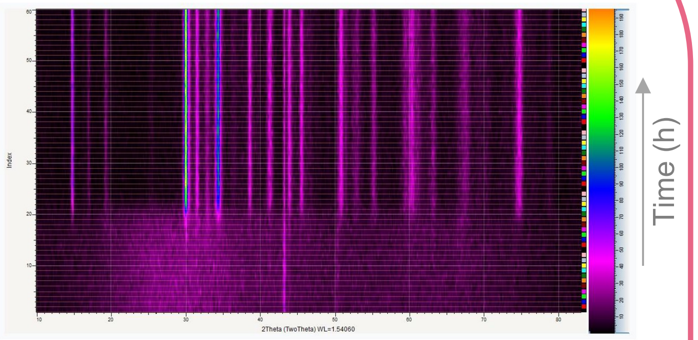
PLD-grown amorphous thin alumina coatings

IIT coatings, GEMMA follow-up, focused on HT in-situ tests

→ XRD up to 1050 °C

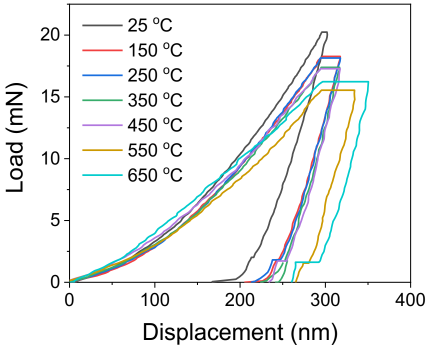


Diffraction patterns (DPs) for equilibrium states (25 – 1050 °C)

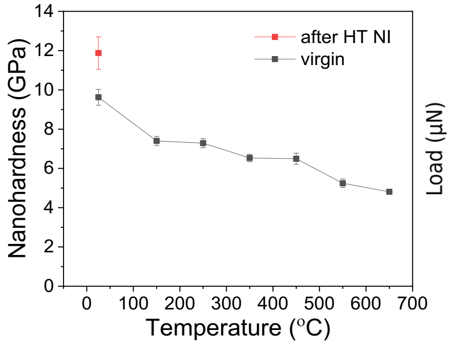


Phase evolution at 700 °C (crystallization)

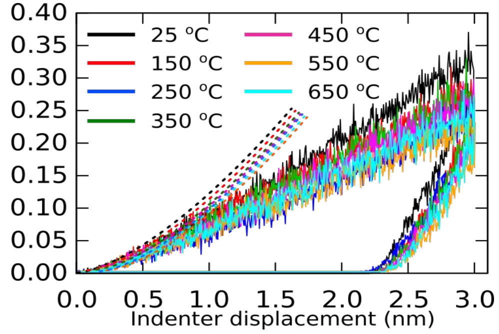
→ Nanoindentation up to 650 °C (experiment & simulations – good agreement)



LD curves

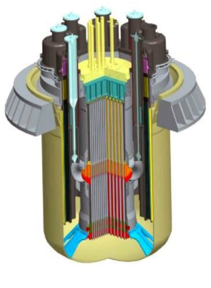


H vs T

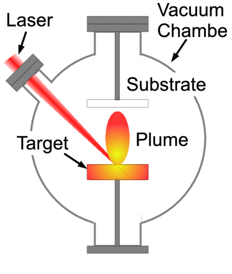


MD simulations

Scientific understanding of the temperature induced evolution of the coating system



ALFRED



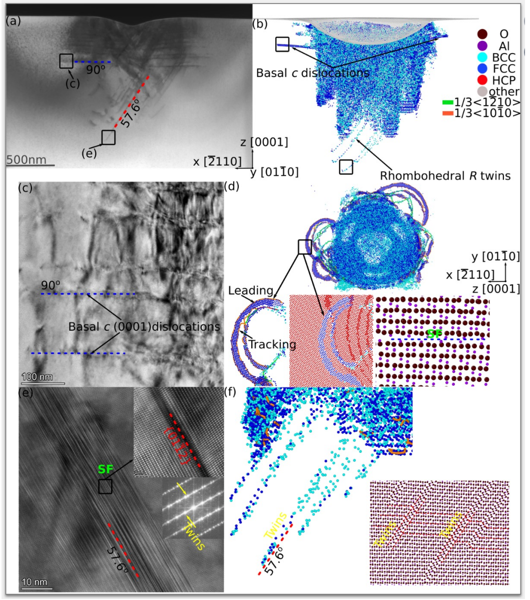
PLD process

- Dedicated for GEN IV reactors
- RT deposition
- Amorphous structure
- Strong interfacial bonding and good mechanical properties
- Corossion resistant in liquid lead
- Promising radiation tolerance

Sapphire

Fundamental research – mechanical behavior - simulations and experimental verification

Cooperation with numerical group



Some industrial successes

Non-Destructive Testing – Expertise works

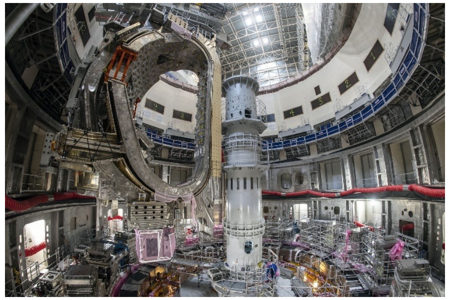
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

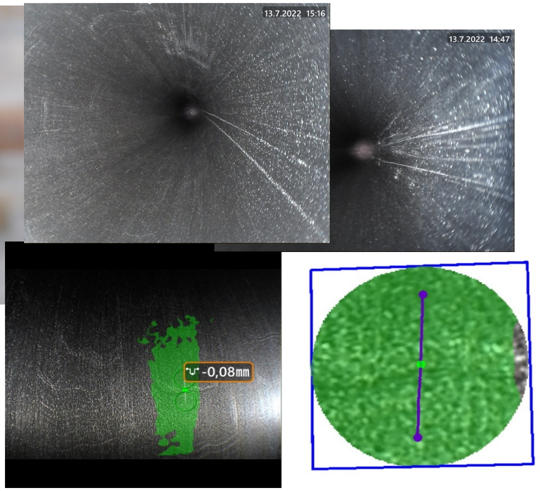
NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

PCA POLSKIE CENTRUM AKREDYTACJI BADANIA AB 025

ilac-MRA

AISI 316L seamless pipes NDT testing for ITER Blanket System components (First wall panels cooling system) – commissioned by ITER's supplier BIMO TECH





Cold drawing effects depth measurements

Analysed by VT Flexible Videoendoscope

Accredited NDT tests realized according to:

X2CrNiMo17-12-2, (AISI 316L) First Wall Panels for ITER Blanket System Specification

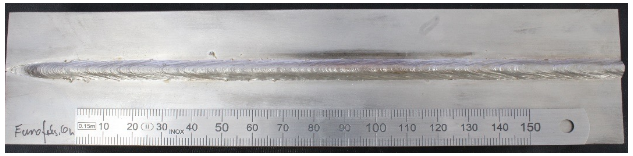
Visual Testing VT *– visual inspection outer / inner surface*
Ultrasound tchickness test UTT *– wall tchickness*
Direct meaurements *– pipes dimensions*

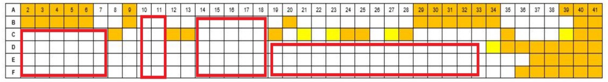
Magnetic Permeability Test according to IEC 60404-15 and ASTM A342M

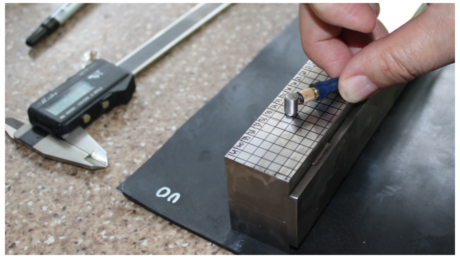
EUROfusion

EUROFER 97 after Electron Beam Welding NDT testing
in cooperation with Karlsruher Institut für Technologie

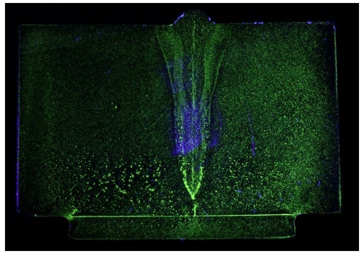
KIT Karlsruher Institut für Technologie







Ultrasound testing UT

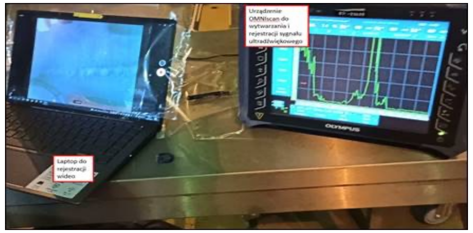


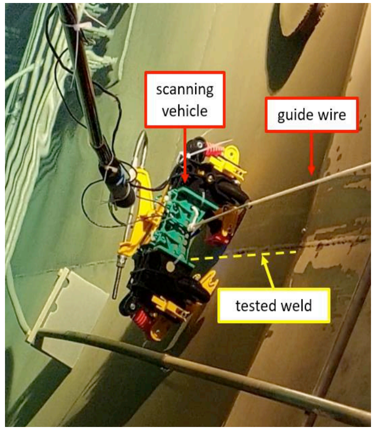
Magnetic particle inspection MT

MARIA Reactor NDT Inspections

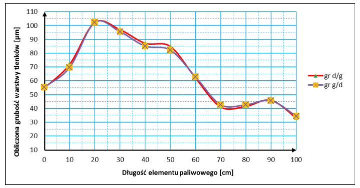
Reaktor MARIA

Welded joints on secondary circuit piping with UT, VT, MT

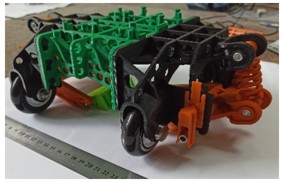




VT, UT reactor pool weld joints inspection

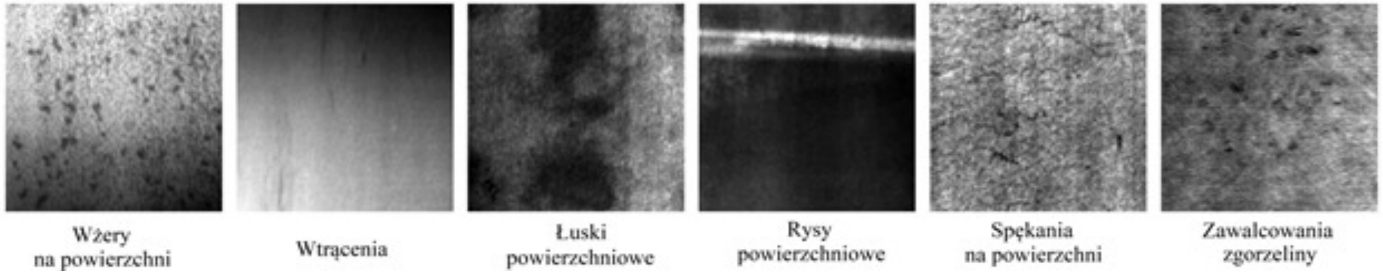


Thickness evaluation of Al_2O_3 layer of the fuel element shells, Eddy Current Testing

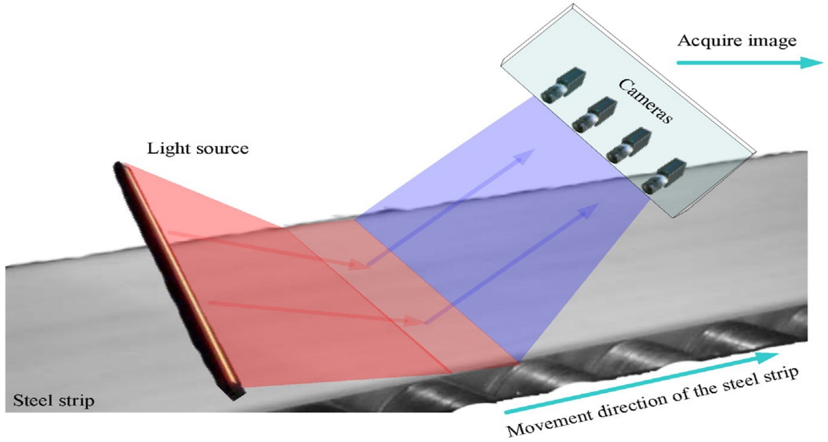


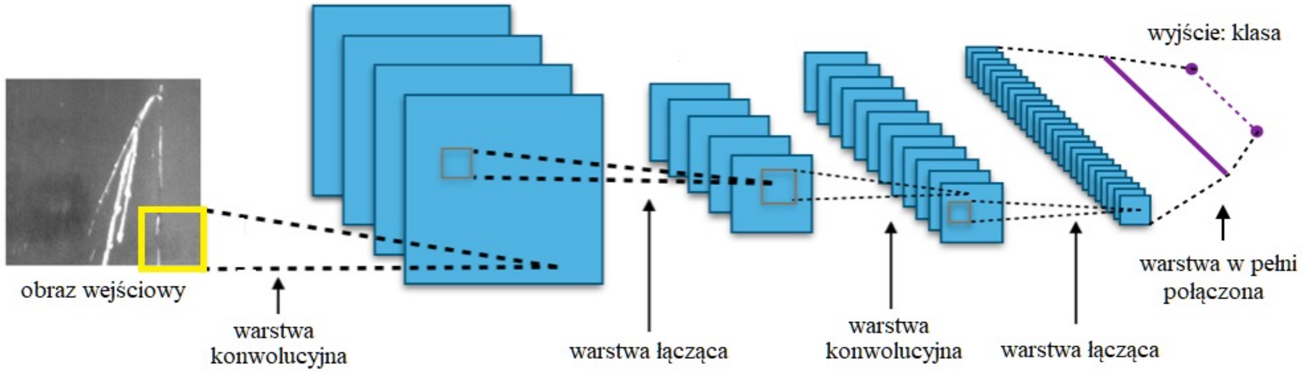
MARIA reactor weld joints UT scanning vehicle designed by Reactor and MRL engineers

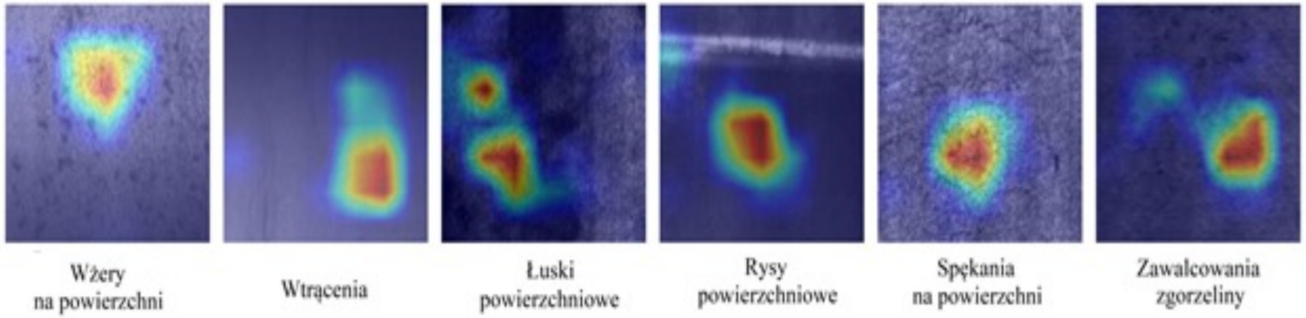
AI Solutions for the Industry – Steel processing

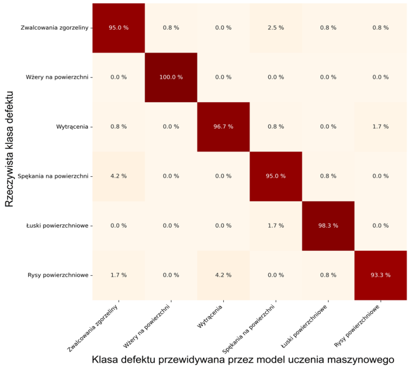


Machine Learning
Identification of defects at during forming









Other applications of Machine Learning (including Deep, Convolutional or Graph Neural Networks):

- *Automatic microstructure classification and segmentation based on LM and SEM images,*
- *Laser welding assesment*
- *Natural language processing (AI for specific applications),*

NOMATEN Centre of Excellence – implementation of science into industry

Nuclear Sector

GOBIERNO DE ESPAÑA – MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CVŘ
Oak Ridge National Laboratory
NOMATEN – Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications
EERA JPNM – European Energy Research Alliance – Joint Programme on Nuclear Materials
Nuclear AMRC
CEN WORKSHOP 64 PHASE 4
Design and Construction Codes for Gen II to IV nuclear facilities
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Tools / 3D Printing / Welding / Turbines / Biomaterials / Automotive

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TOMEX brakes
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EDP Obróbka Stali Sp. z o.o.
BIMO TECH
Narzędziownia Pszenica
Bureau Veritas 1828
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ZF TRW
neapco
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boccard kates – Alliance for success

Thank you for your attention!

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