UK Atomic Energy Authority

UKAEA

Materials Research Facility

Dr Valentine Kanyanta

Nuclear Academics Meeting – 6th-7th September 2023

UKRI Engineering and Physical Sciences Research Council

NNUF National Nuclear User Facility

HENRY ROYCE INSTITUTE

Fusion Grant 2022/27 EP/W006839/1

MRF is part of the National Nuclear Users Facility (NNUF) and the Sir Henry Royce Institute for Advanced Materials

Introduction to UKAEA

UK Atomic Energy Authority

UKAEA mission is to lead the delivery of sustainable fusion energy and maximise the scientific and economic benefit.

- Be a world leader in fusion research and development
- Enable the delivery of sustainable fusion power plants
- Drive economic growth and high-tech jobs in the UK
- Create places that accelerate innovation and develop skilled people for industry to thrive.

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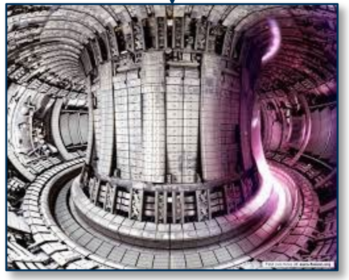
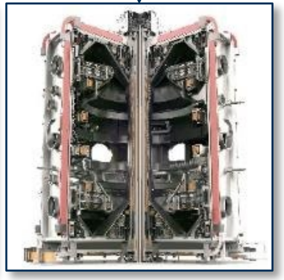


JET



MAST-U

RACE

H3AT

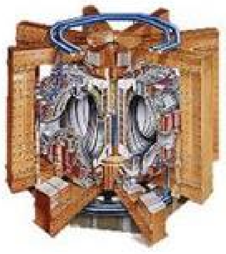
FTF

MRF

STEP

Enabling Delivery of Fusion Energy

…from science experiments to power plants…



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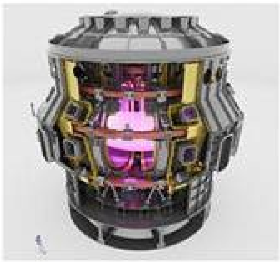
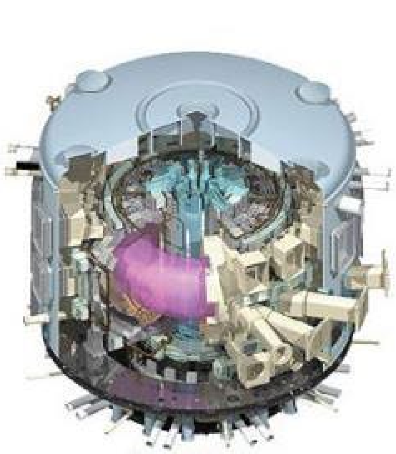
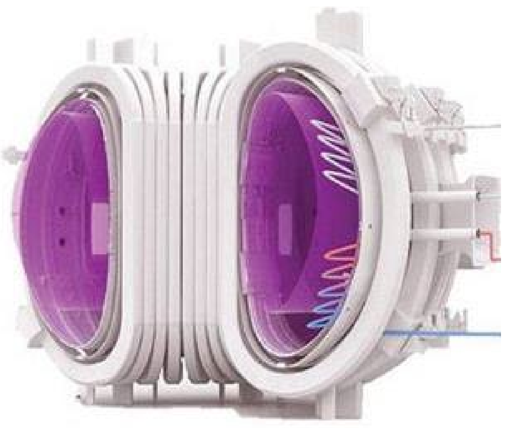


JT-60SA



ITER (2035)



DEMO (2050s)

STEP (2040s)

Fusion energy is in accelerated delivery mode:

- Transitioning from science experiments to delivering fusion power plants
- Increased interest from private sector (over $6B in investments raised)
- 30+ private fusion start-ups
- Increased mobilisation of fusion industry & supply chain

Credits:
Top images from https://fusionforenergy
Bottom image from UKAEA (STEP)

Solving Materials Challenges Critical to the Success of Fusion!

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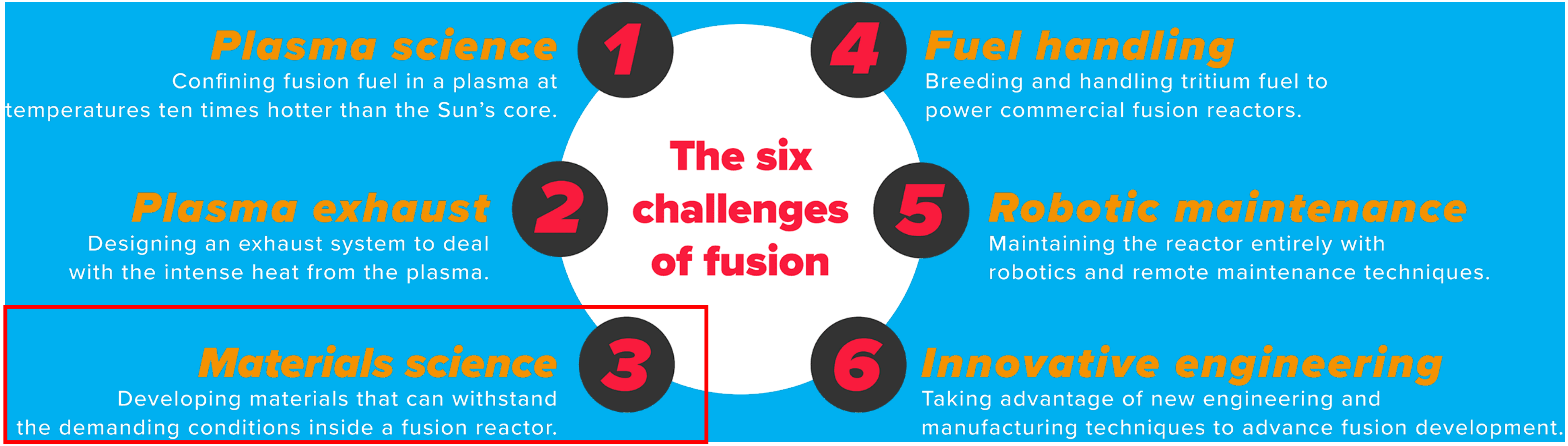

Research challenges - Culham Centre for Fusion Energy (ukaea.uk)

Examples of Fusion Materials Challenges

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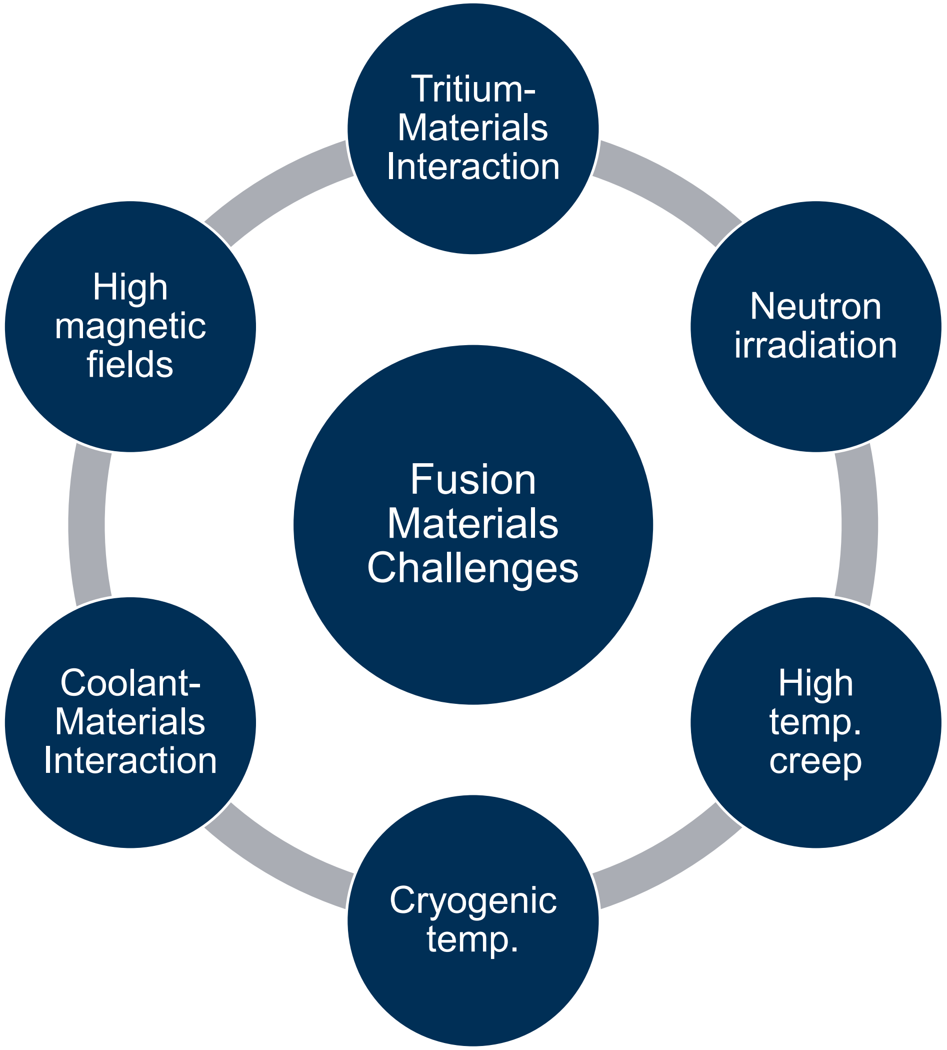
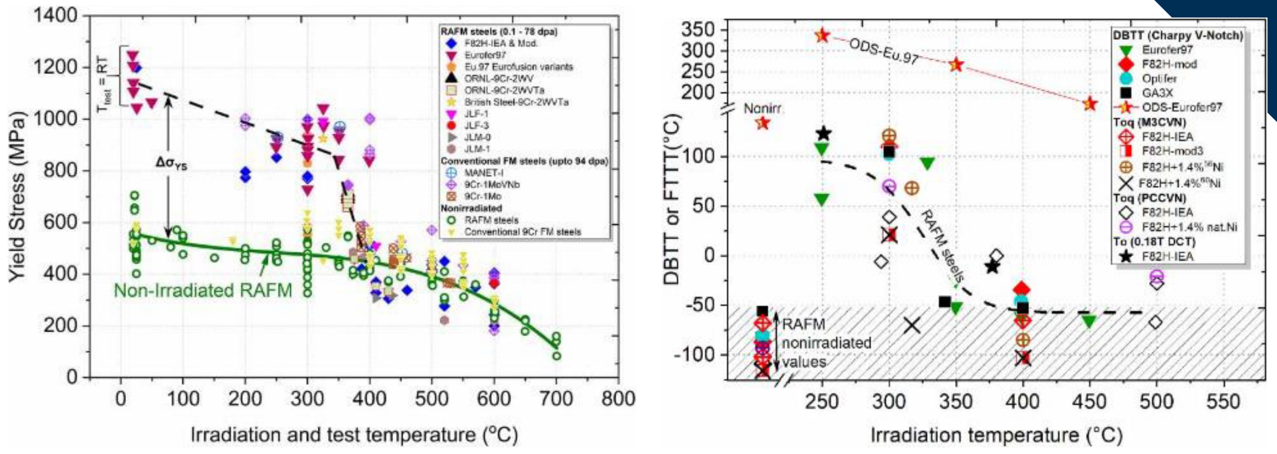
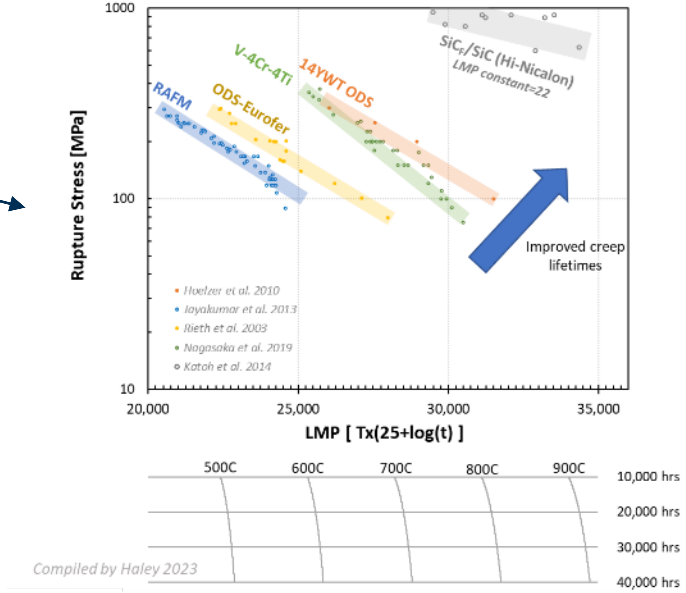
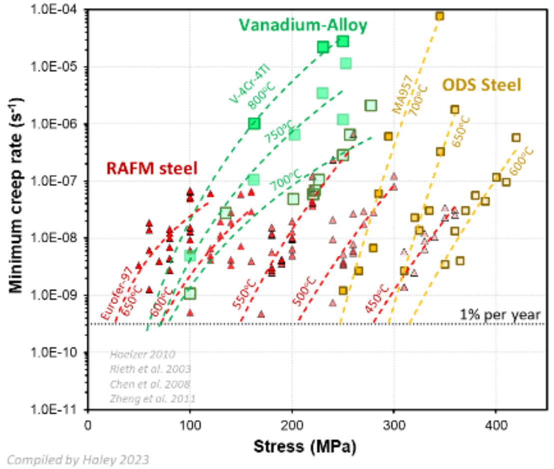




Figures showing effect of irradiation damage on yield strength and ductile brittle transition temperature. Irradiation also results in loss of ductility / fracture toughness (Ref: Bhattacharya et al. J. Phys. Energy (2022))



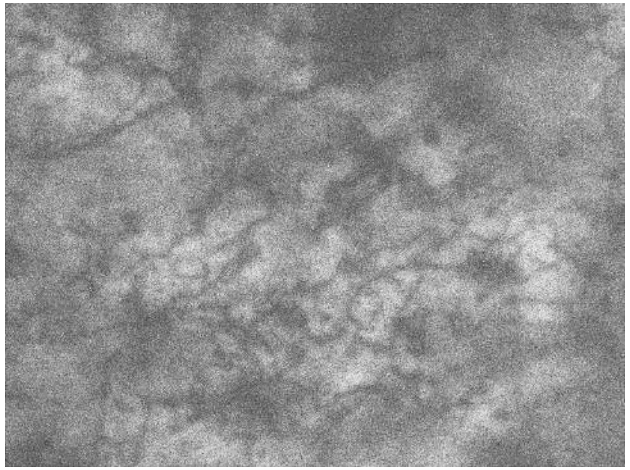


Figures showing rapture stress vs. Larson–Miller parameter and minimum creep rate for different structural materials. [Credit: Dr Jack Haley, UKAEA)

Role of the Materials Research Facility (MRF)

See the damage

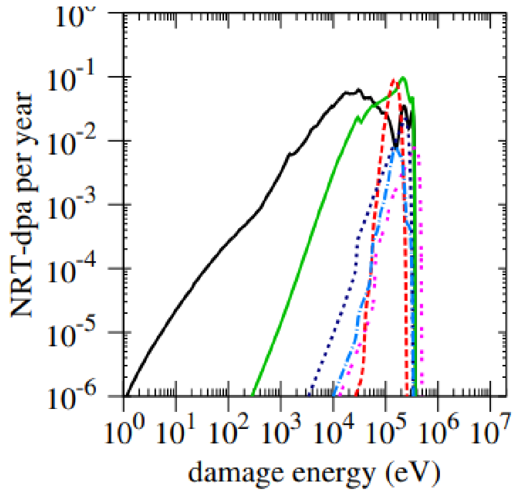
Interrogating materials to nanometer and atomic resolution



Bright-field STEM image showing native dislocations in bainitic RPV steel (credit: Dr Jack Haley, UKAEA).

Understand the damage

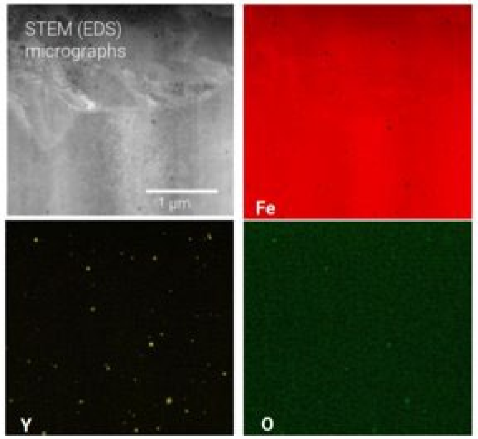
Understanding nature of damage through modelling and experiments; and impact on material properties



"dpa-spectra" for different reaction channels in pure 56Fe irradiated in a typical neutron spectrum for the first wall of a demonstration fusion power plant (Ref: DOI: 10.1016/j.jnucmat.2018.03.032)

Do something about it

Design better materials; provide engineering assurance



Yttria diameter (type)	Average	Range	Min	Max
Feret (nm)	**27.89**	85.68	9.01	94.69
Equivalent circle (nm)	**18.62**	69.5	6.22	75.72

ODS steel (Fe-14Cr-2W-0.3Ti-0.3Y2O3) engineered for better high temperature properties and improved resistance to radiation damage

Where MRF sits in Relation to UK National Capabilities

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Universities, UK

~ 150 MBq

UKAEA – MRF, UK

Medium activity, structural

3.75 TBq (Co^{60})

NNL,UK

Most active, fuel cycle

Non-Active

RR State 1 (manual handling)

RR State 2 (robotic handling)

Hot Cell

MRF partners:

NNUF National Nuclear User Facility

UKRI Engineering and Physical Sciences Research Council

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MRF Current & Future Capabilities

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Sample Preparation & Microstructure Analysis

Tescan AMBER X PFIB

Ga FIB equipped with EBSD Detector and Cryo Vacuum Transfer System

Differential Scanning Calorimetry

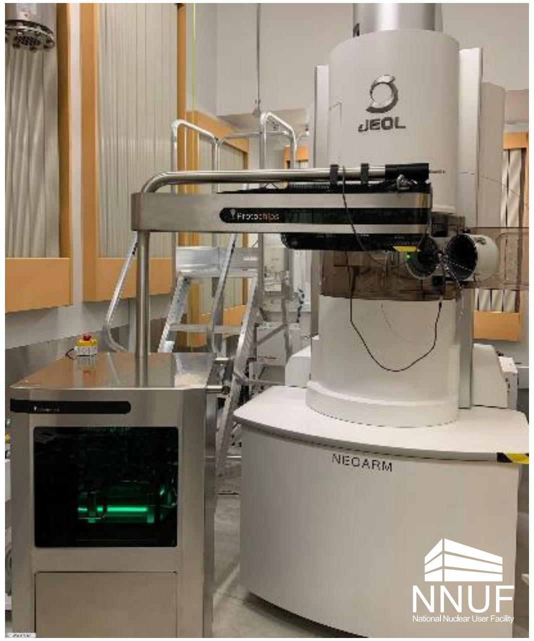
Other instruments:

Sample preparation:

- Hot-cell (high-active) & glovebox (low-active) sample prep
- Precision Ion-beam Polishing
- Sputter Coater
- 2023: Hot-cell EDM/micro-milling/laser cutting

Microstructure analysis:

- SEM (+ EDS, EBSD, TKD, WDS)
- CSLM with Raman Spectroscopy
- Atom Force Microscope
- X-ray Diffractometer
- 2023: DSC-MS
- 2023: XRD s-stage (HT)



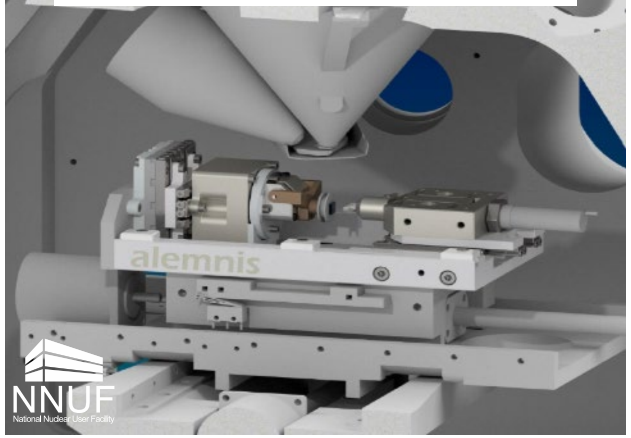
200 kV NEOARM TEM with Gas Cell System (Protochips)

MRF Current & Future Capabilities

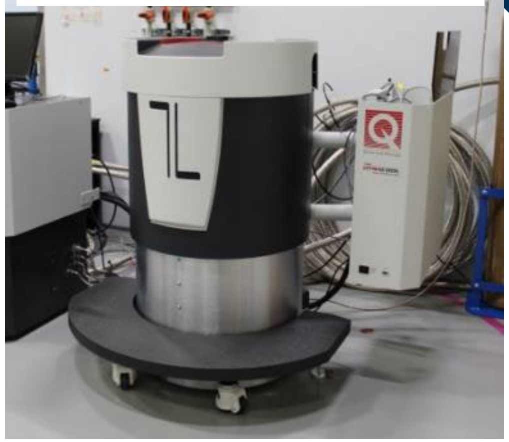
Mechanical & Thermo-Physical Properties Testing

- Tensile properties (Nano- & instrumented indentation, 5kN &10kN static load frames, SEM In-situ testing with hot stage)
- Fatigue (15kN dynamic load frame, 20kHz ultrasonic fatigue rig)
- Creep
- Fracture (small punch test, mini-CT, SENB)
- Physical Property Measurement System (14T/1.8K-1000K)
- Laserflash Analysis (LT/HT)
- Dilatometry (LT/HT)
- DIC (non-contact) strain measurements

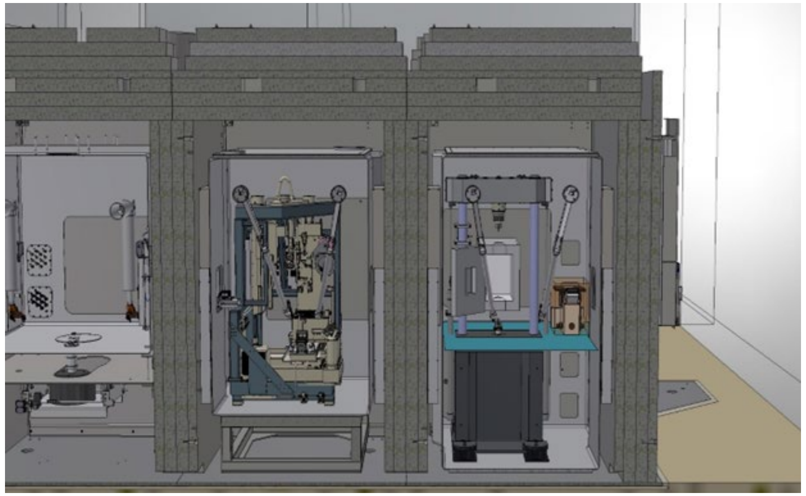
In-situ Mechanical Testing System



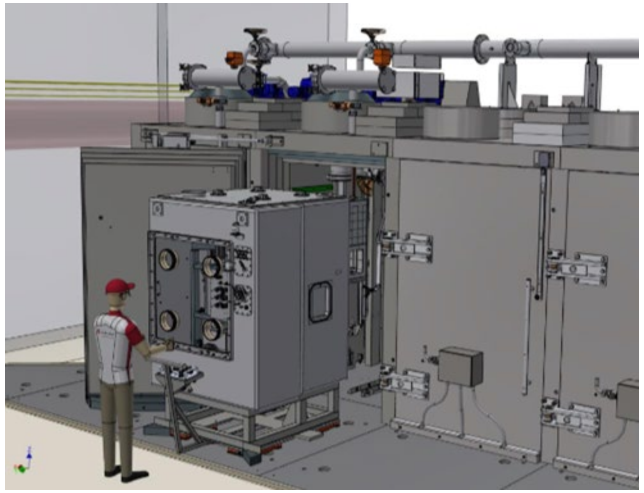
Physical properties measurement system (PPMS)



10kN static load frame



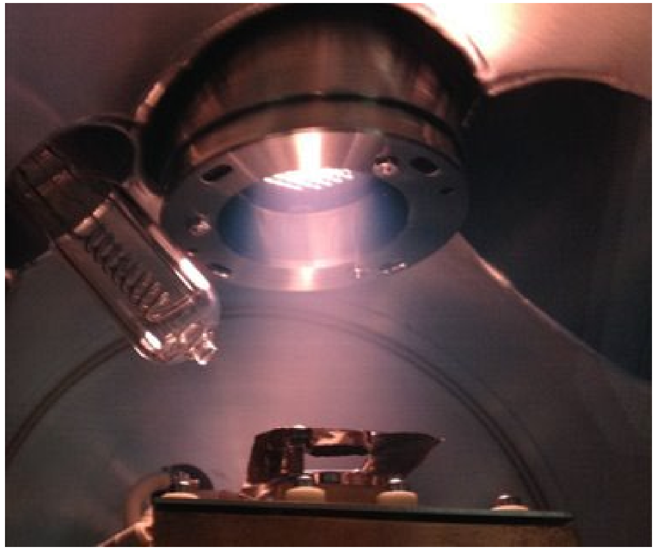
Two new hot cells equipped with a fabrication and mechanical test equipment



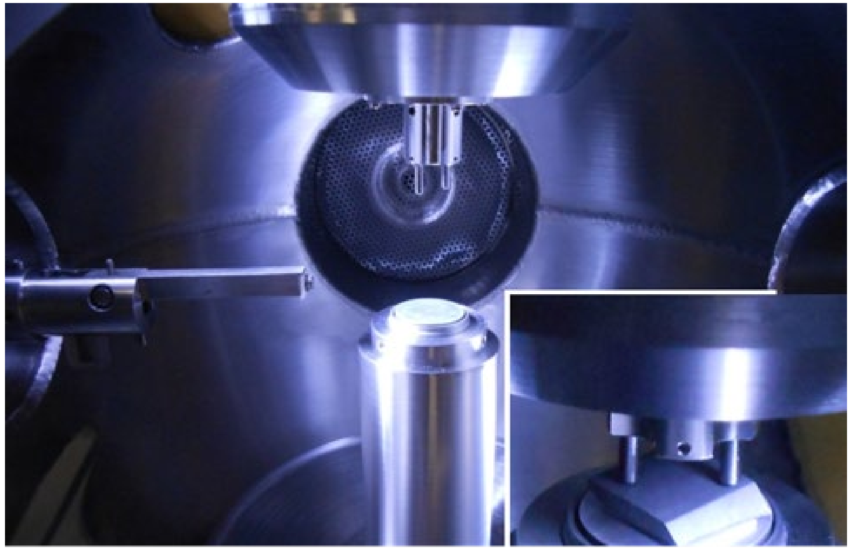
Future proof design with removable containment box

MRF Current & Future Capabilities

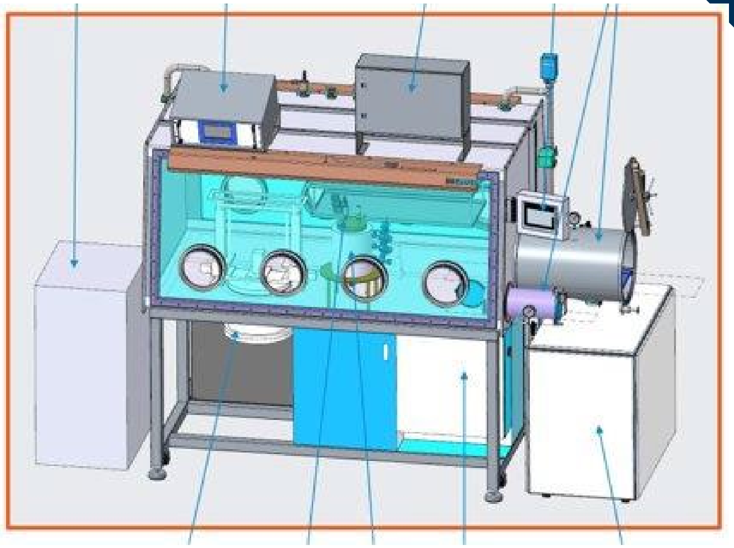
Materials interaction with environment (i.e., tritium, plasma and coolants)



Hydrogen isotope implantation



Thermal Desorption Spectroscopy



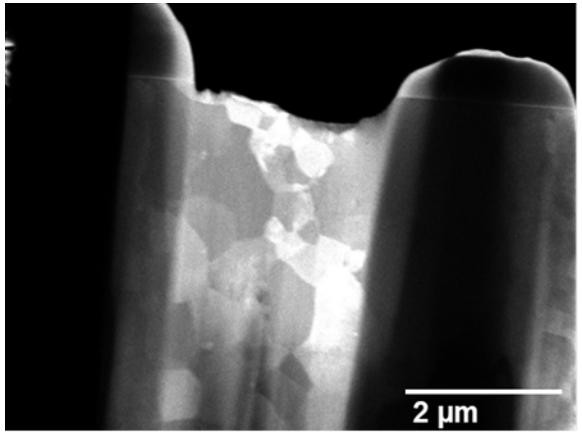
MRF installing capability for Lithium corrosion testing of materials at 200-750^{o}C under controlled atmosphere inside a glovebox

- Deuterium ion implantation capabilities are available at UKAEA.
- Plans to upgrade capability to tritium (initially will be limited to tritium inventories of 40GBq, increasing significantly once the new H3AT facility is available).
- Also development of Lithium corrosion rig underway (operational from Q2 2023)

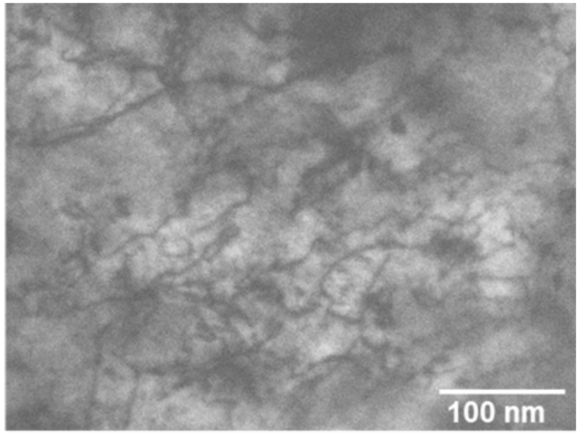
How We Use Capability to Solve Fusion Materials Challenges

See the damage – high resolution microscopy

Examination of native dislocations and precipitates in bainitic RPV steel (Dr Jack Haley, UKAEA)

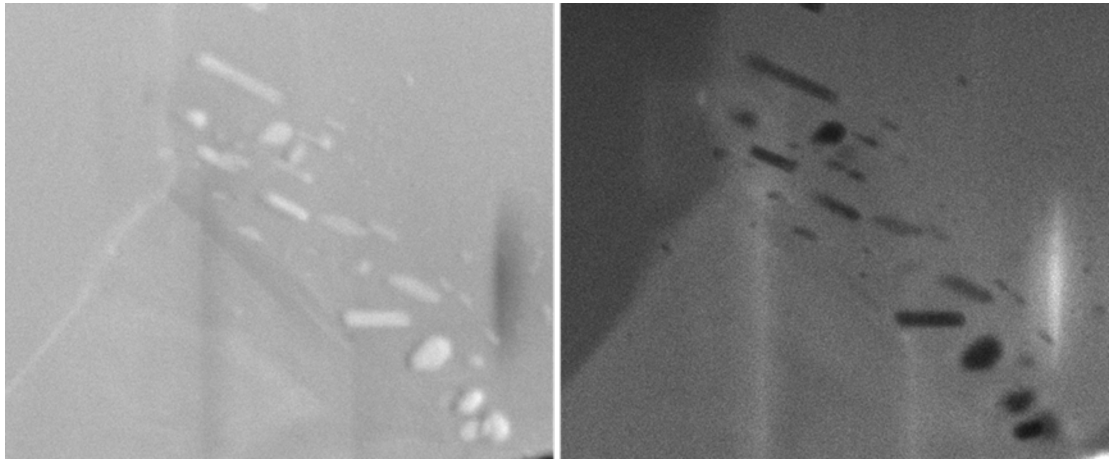


Above: Bright-field STEM image showing grain structure of bainitic RPV steel.



Above: Bright-field STEM image showing native dislocations in bainitic RPV steel.

Examination of helium bubbles in $Be_{12}Ti$ in implanted with He^{+} at 900°C (Dr Slava Kuksenko, UKAEA)

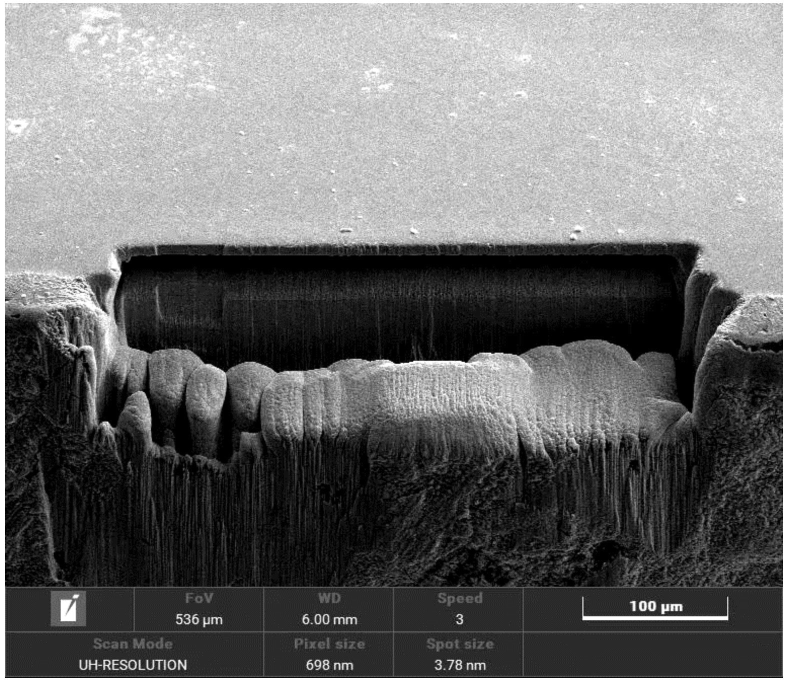


Above: Bright-field (left) and HAADF (right) STEM images showing helium bubbles in He^{+} implanted $Be_{12}Ti$

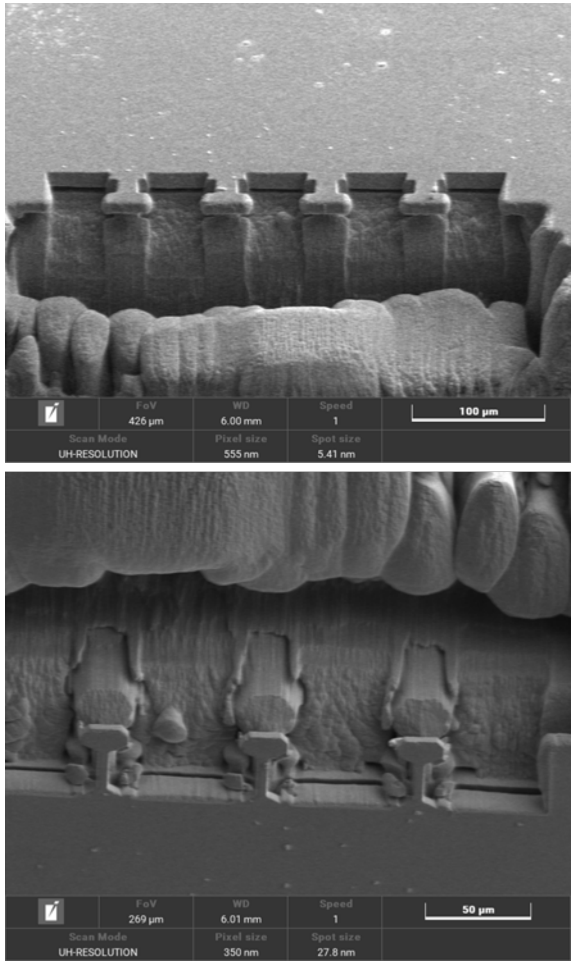
How We Use Capability to Solve Fusion Materials Challenges

UK Atomic Energy Authority

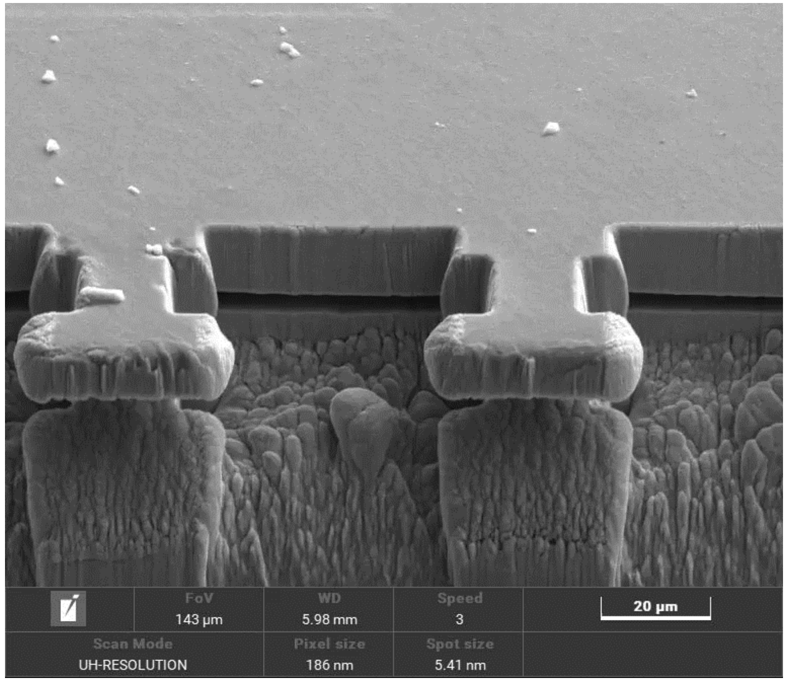
Preparing micromechanical test samples using Plasma FIB



Volume preparation



Rough shaping

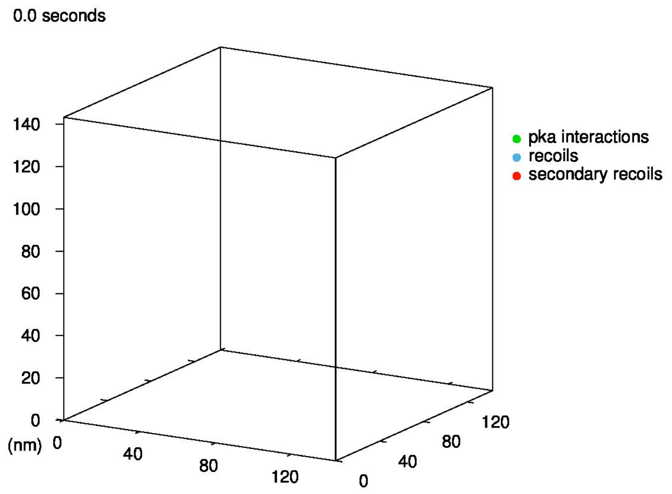


Final shaping

How We Use Capability to Solve Fusion Materials Challenges

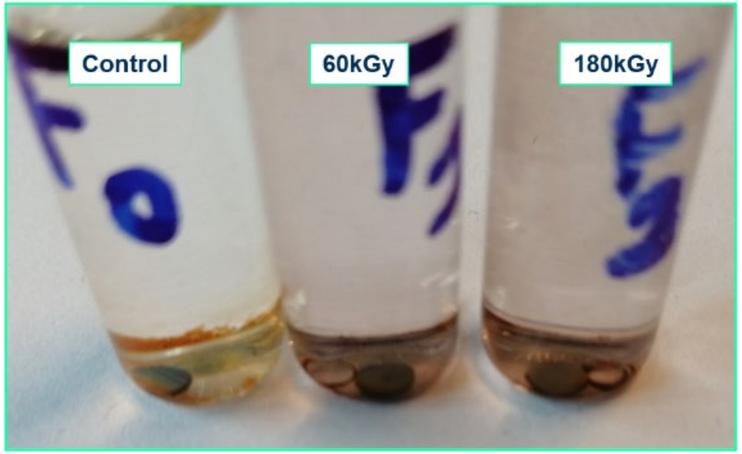
***Understand the damage** – modelling and experimental characterisation of materials-environment interactions (i.e., neutrons, plasma and coolants)*

Modelling of materials interaction with neutrons

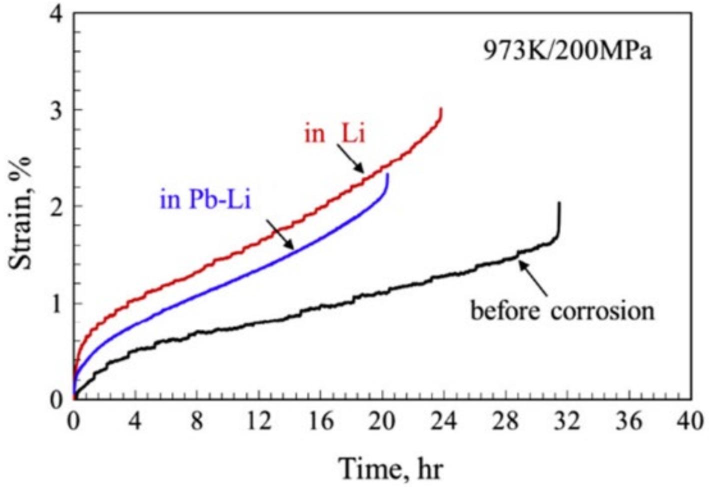


Credit: Dr Mark Gilbert and Dr Joven Lim, UKAEA

Materials interaction with coolants – characterisation of corrosion behaviour



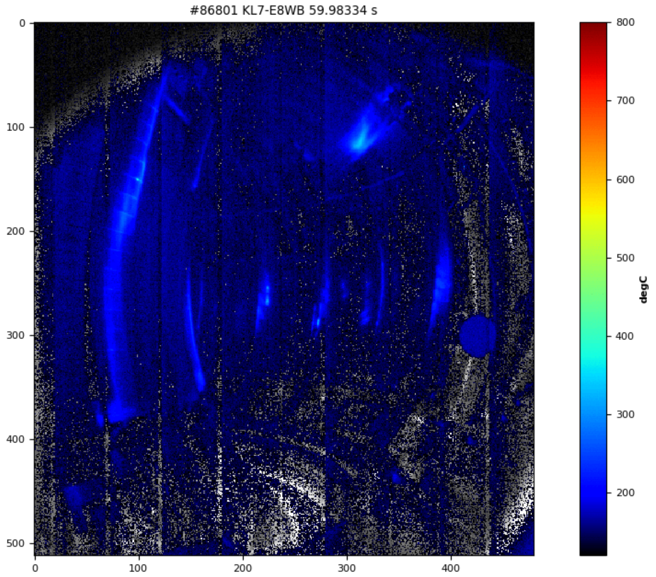
G91 F/M steel exposed to gamma irradiation under controlled water environment at 150 °C. Water clarity is reduced with increase of exposure to gamma radiation due to increasing amount of oxides contaminated the water.



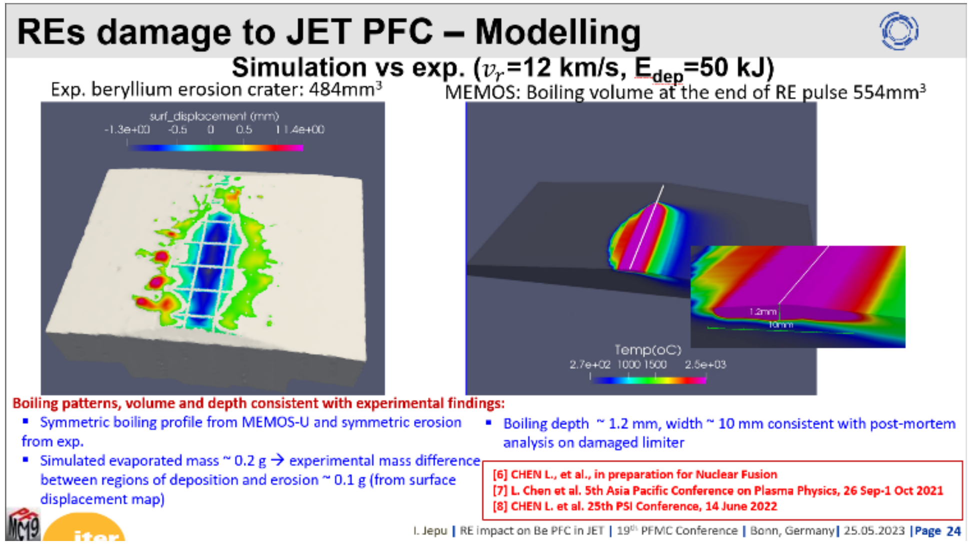
Strain-time curves of 9Cr-ODS Ferritic/Martensitic steels before and after exposure to static Li and PbLi [Courtesy of NIFS, Japan]

How We Use Capability to Solve Fusion Materials Challenges

Understand the damage – materials interaction with plasma



Modelling of temperature profile on plasma facing wall during a pulse



REs damage to JET PFC – Modelling

Simulation vs exp. (v_r=12 km/s, E_{dep}=50 kJ)

Exp. beryllium erosion crater: 484mm³

MEMOS: Boiling volume at the end of RE pulse 554mm³

surf_displacement (mm)

-1.3e+00 -0.5 0 0.5 1.4e+00

1.2mm

10mm

Temp(oC)

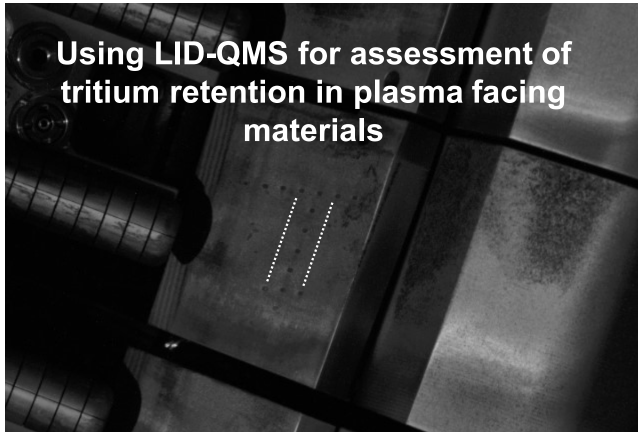
2.7e+02 1000 1500 2.5e+03

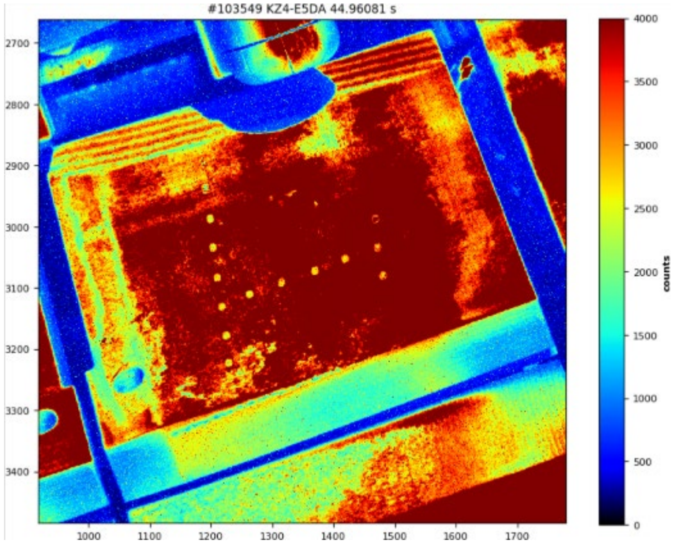
Boiling patterns, volume and depth consistent with experimental findings:

- Symmetric boiling profile from MEMOS-U and symmetric erosion from exp.
- Simulated evaporated mass ~ 0.2 g → experimental mass difference between regions of deposition and erosion ~ 0.1 g (from surface displacement map)
- Boiling depth ~ 1.2 mm, width ~ 10 mm consistent with post-mortem analysis on damaged limiter

[6] CHEN L., et al., in preparation for Nuclear Fusion
[7] L. Chen et al. 5th Asia Pacific Conference on Plasma Physics, 26 Sep-1 Oct 2021
[8] CHEN L. et al. 25th PSI Conference, 14 June 2022

I. Jepu | RE impact on Be PFC in JET | 19th PFMC Conference | Bonn, Germany | 25.05.2023 | Page 24

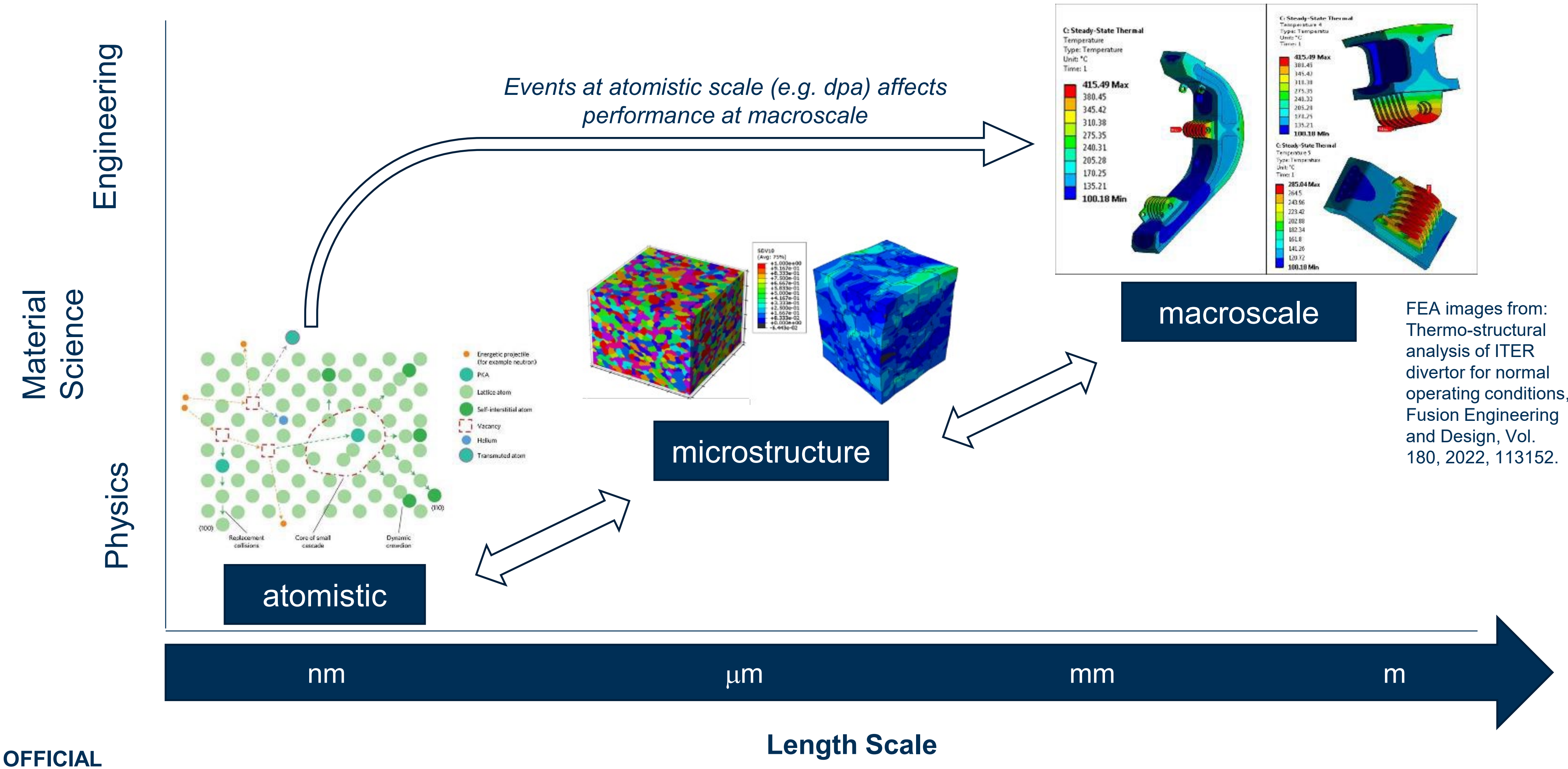




Credit: Dr Yevhen Zayachuk, Dr Anna Widdowson, Dr Ionut Jepu, Dr Robert Kerr, Dr Alvaro Pechero and Dr Paul Coad, UKAEA.

We also Invest in Modelling

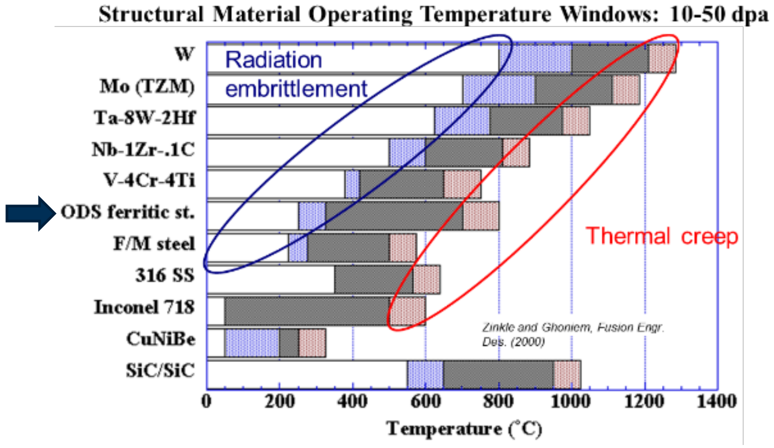
__Understand the damage__ – we also employ multiscale modelling approach, working with other groups at UKAEA and academic partners

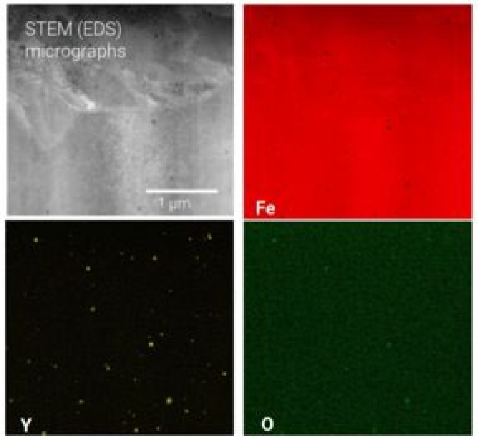


FEA images from: Thermo-structural analysis of ITER divertor for normal operating conditions, Fusion Engineering and Design, Vol. 180, 2022, 113152.

And Developing New Materials

Do something about the damage – developing better materials





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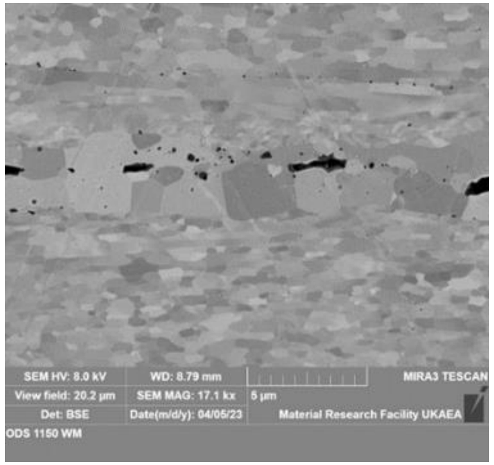
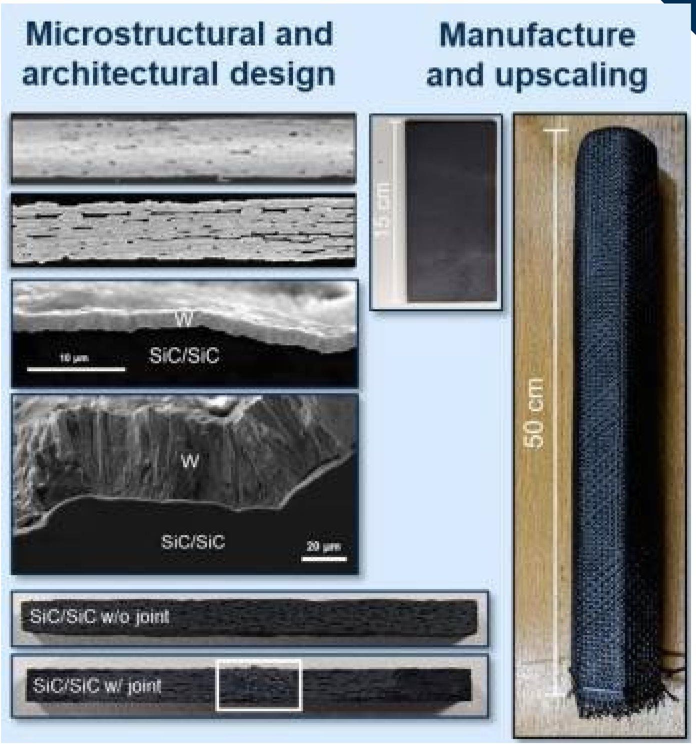
Fe-14Cr-2W-0.3Ti-0.3Y2O3 ODS steel micrograph (left)



Joining techniques and post-weld heat treatments for novel/new materials such as ODS



Development of non-metallic composites (SiC/SiCf) as high temperature structure materials for fusion.

Credit: Dr David Bowden, Dr James Wade-Zhu, Dr Slava Kuksenko, Dr Jack Haley, Dr Alex Leide and Dr Max Rigby-Bell, UKAEA.

Key Contacts

- Materials Director
  Dr Amanda Quadling
  - Head of Material Science & Engineering
    Prof. Amy Gandy
    - Metallics
      Dr David Bowden
    - Non-metallics
      Dr James Wade-Zhu
    - Design by Fundamentals
      Dr Chris Hardie
  - Head of Fusion Material Interfaces
    Dr Mark Gilbert
    - Neutrons
      Dr David Foster
    - Plasma
      Dr Anna Widdowson
    - Coolants
  - Head of Materials Research Facility
    Mr Barry Ward
    - Active Materials Lead
      Dr Andy London
  - Head of Large Projects
    Dr Valentine Kanyanta

Key contact

Thank You

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