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An Overview of Work Contributing to Fusion Codes and Standards at the University of Manchester.

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Dalton Research Institute

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- Largest and most advanced nuclear research capability in UK academia
- >80 academic staff across multiple departments
- Many more postdoctoral researchers, PhDs and experimental staff
- A range of activities:
  - World-leading research
    - Fuel & fuel cladding, reactors, recycling, environment & waste, decommissioning, nuclear & society, fusion power, health & medical
  - Fostering interdisciplinary collaboration
  - Partnerships with academia, industry, regulators, and government
  - Engagement with the wider public through school activities, community outreach and the media

Key Fusion Capabilities

nm → m

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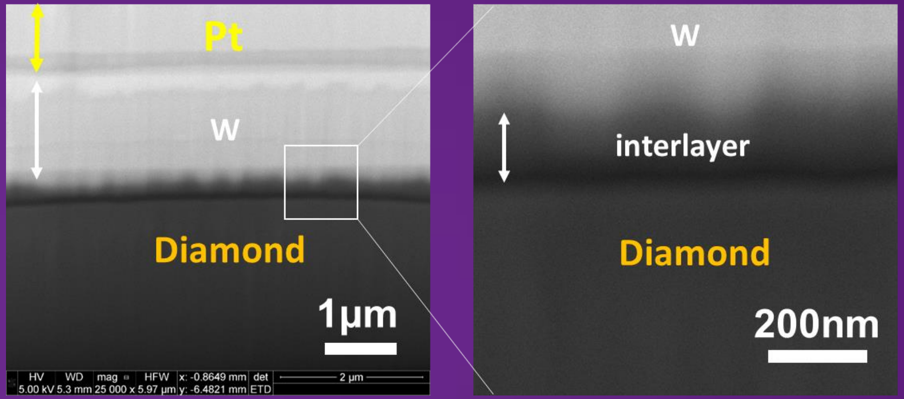
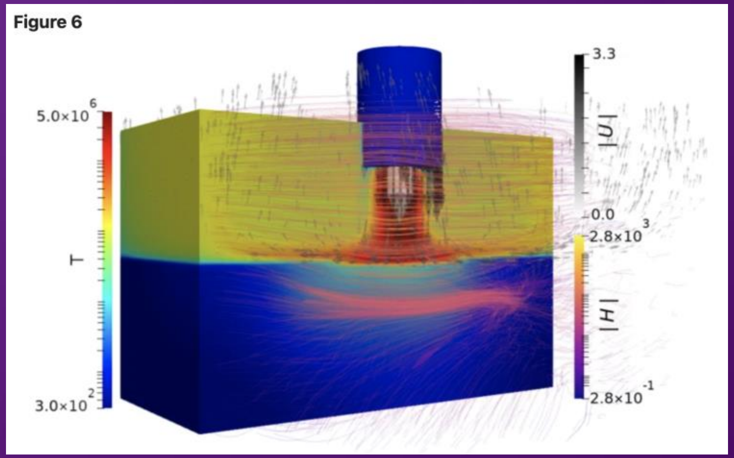
- Fusion Materials
  - Divertor
  - Blanket
  - Structural
  - Novel and established
- Irradiation Damage
- Fusion Engineering
- Advanced Manufacturing
  - Welding (EB, Laser, TIG)
  - Additive Manufacturing
- Tritium
- Multi-scale modelling
  - Atomic scale to advanced weld modelling
- Policy





Nuclear Materials & Engineering Research Themes

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Fission focus

- Fission fuel and cladding
- Nuclear graphite
- Pressure vessel steels
- Radwaste and storage

Fusion focus

- Divertor materials development: W, diamond, MAX, etc.
- Blanket materials: RAFM, V-alloys, HEAs, etc.
- Tritium materials science
- Digital plant design

Fission and Fusion

- Welding and joining
- Irradiation damage
- In-situ characterisation and testing
- Corrosion and degradation
- Fluid dynamics

Strategic Links

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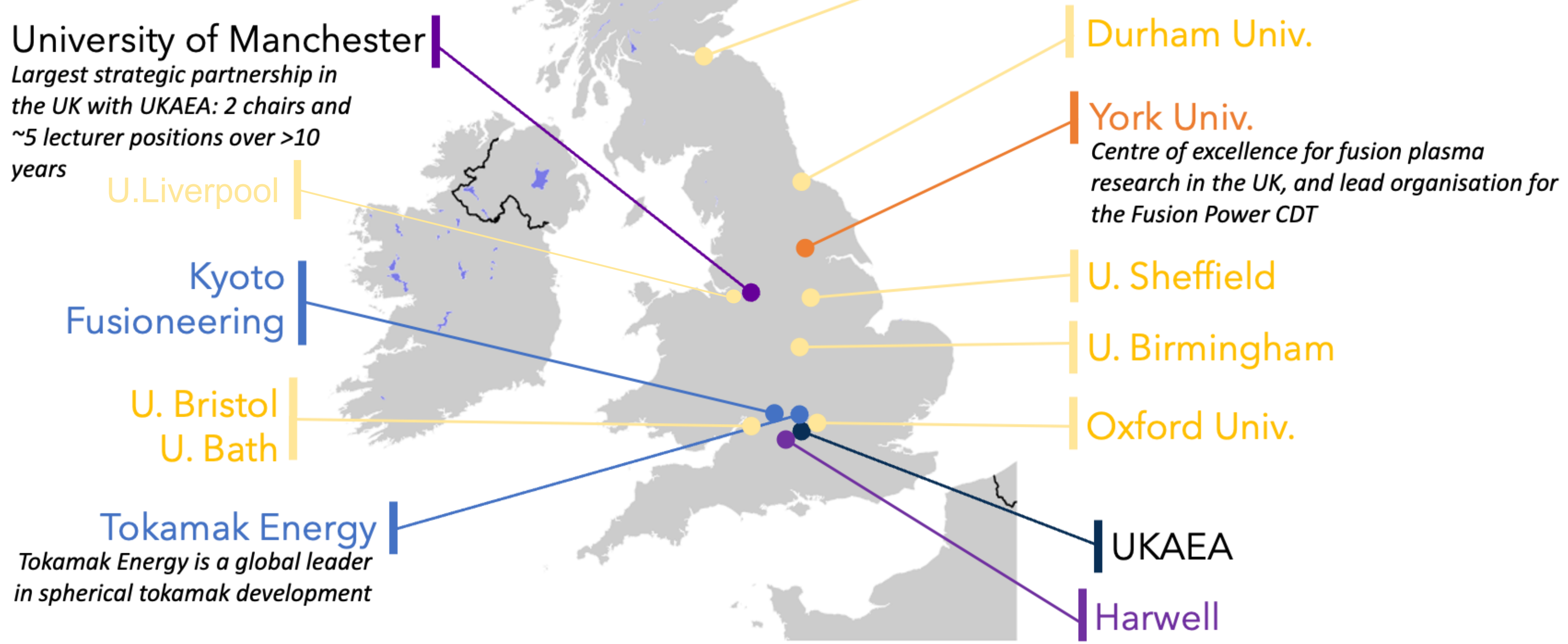
Fusion Research in the UK

In addition to our UK partners, research collaborations occur with global partners

FUSION CDT

FUSION ENGINEERING CDT



Who we work with

NVIDIA OMNIVERSE ENTERPRISE

FuseNet
The European Fusion Education Network

TWI

NUCLEAR AMRC

Tokamak Energy

KYOTO FUSIONEERING

HENRY ROYCE INSTITUTE

UK Atomic Energy Authority

assystem

STAR WARDEN

CVE
CAMBRIDGE VACUUM ENGINEERING

Australian National University

KFE
한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

diamond

UKRI
Science and Technology Facilities Council
ISIS Neutron and Muon Source

Project Elpis

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Dalton Nuclear Institute

DIFFER
Dutch Institute for Fundamental Energy Research

Facilities

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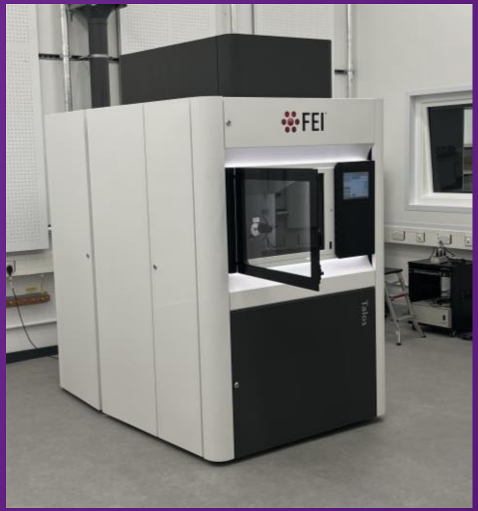
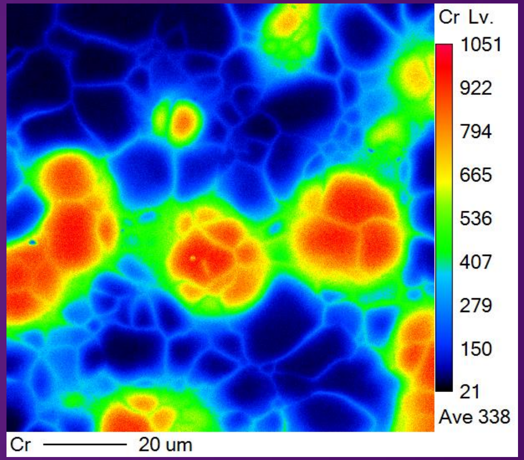
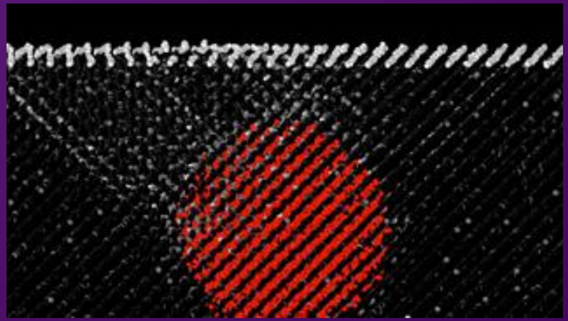
- Manchester Electron Microscopy Centre
    - SEM, TEM, In-Situ (>25 microscopes)
- In situ SEM (TANIST system)
- X-ray Tomography
- XRD, EPMA, NanoSIMS, etc.
- Ion Irradiations – DCF





Facilities

- Welding Capabilities (TIG, Laser, EB)
- Computational simulations across scales from DFT to FEM
- Residual Strain Measurements across scales (atomic to large scale experiments)
- Access to Royce Facilities
  - Manufacture and processing of alloys and coatings
  - Additive manufacturing and associated digital twins
  - Handling active materials



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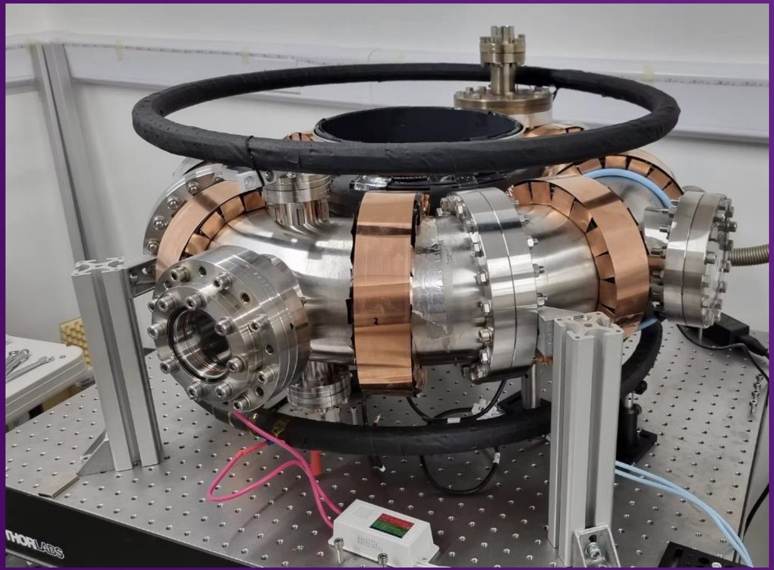
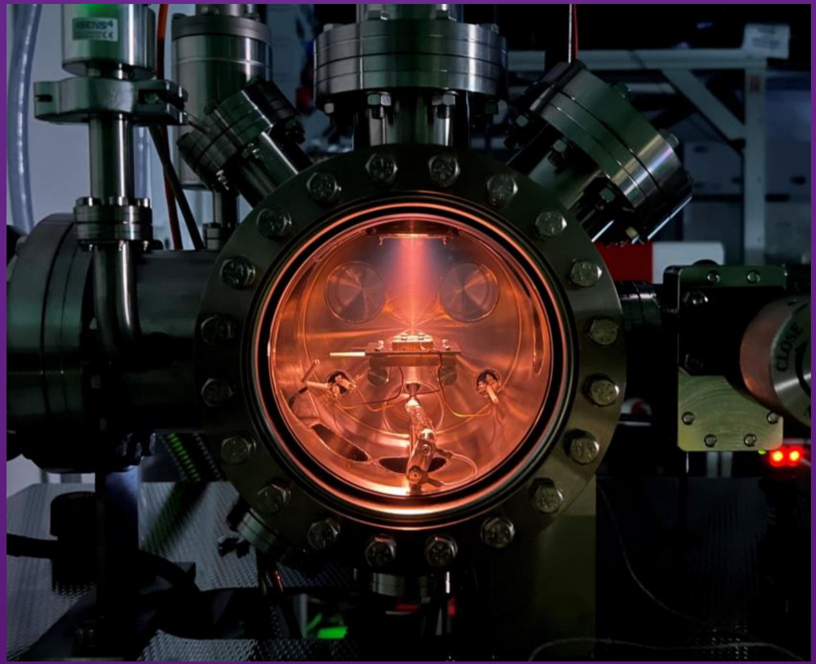
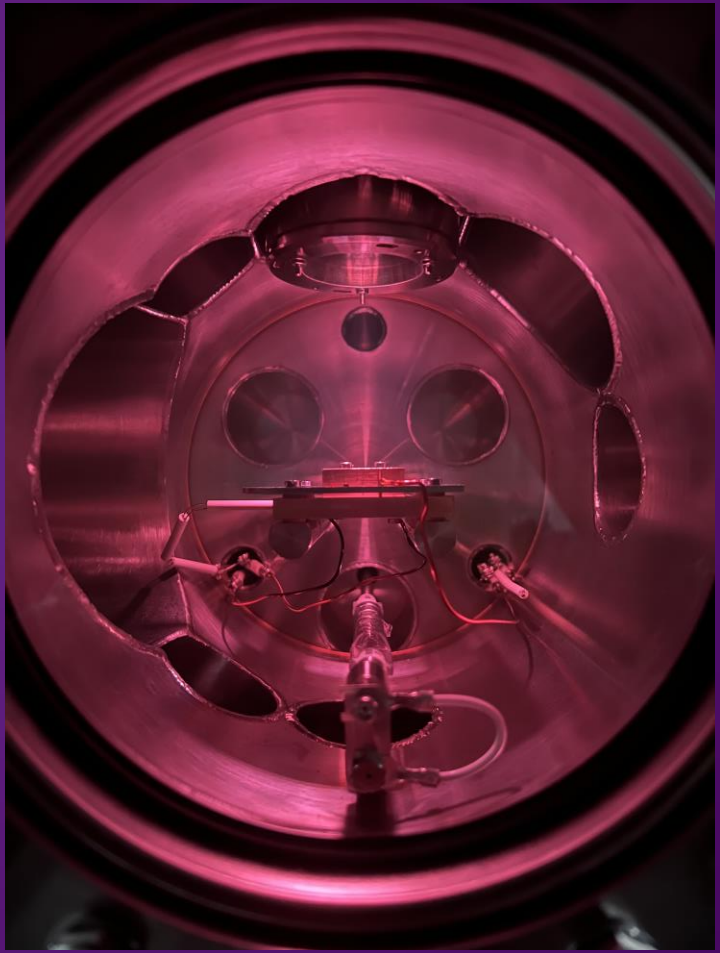
Facilities

- DELPHI-II (Device for Exposure to Low-energy Plasma of Hydrogen Isotopes)
- Minimak







CASE STUDIES

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Understanding the Impact of Helium Irradiation on Stress Relieved Tungsten:

- **Stress relief**:
  - Reduces bubble size.
  - Confirmed by grain structure and drop in hardness.
- **Tungsten deposition**:
  - Forms WOx amorphous layer.
  - Blocks He diffusion and suppresses bubble formation.
- EBSD signal loss in He+W samples confirms oxide formation.

Summary:

- Stress relief reduces defect density, limiting He trapping.
- Surface deposition can prevent bubble growth.
- GISAXS and TEM jointly validate observations.

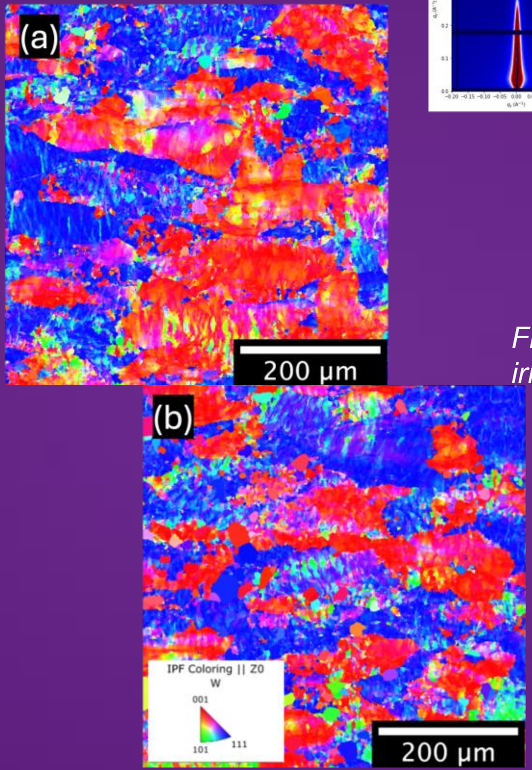

Fig 1: EBSD maps of as (a) received tungsten and (b) stress relieved tungsten

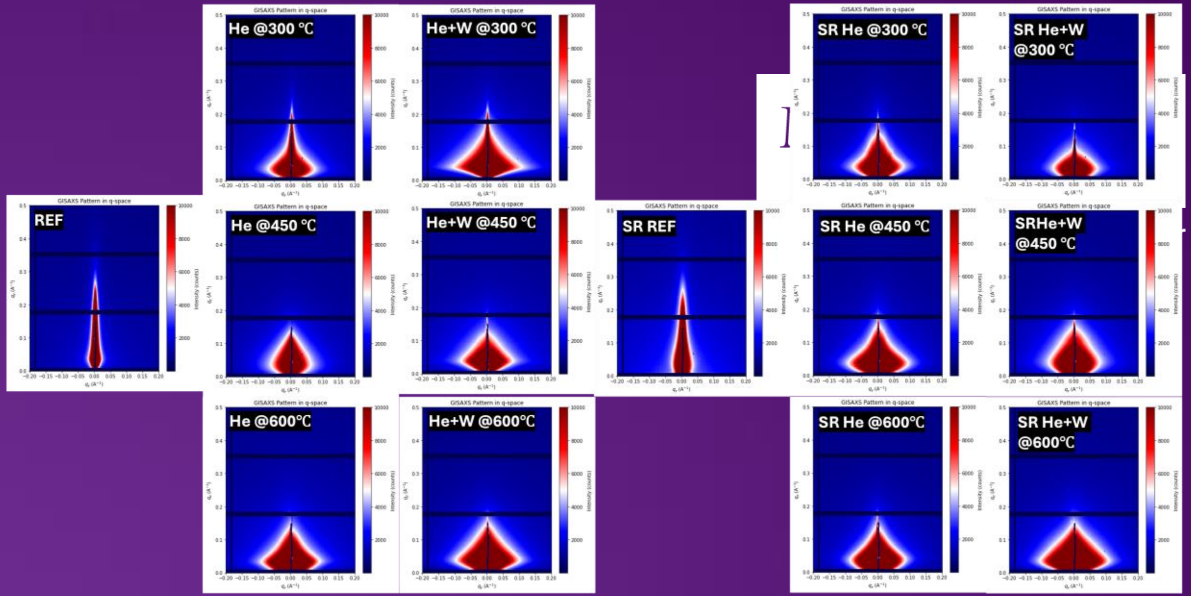

Fig2: GISAXS Patterns Comparison at different helium and tungsten deposition irradiation temperatures and

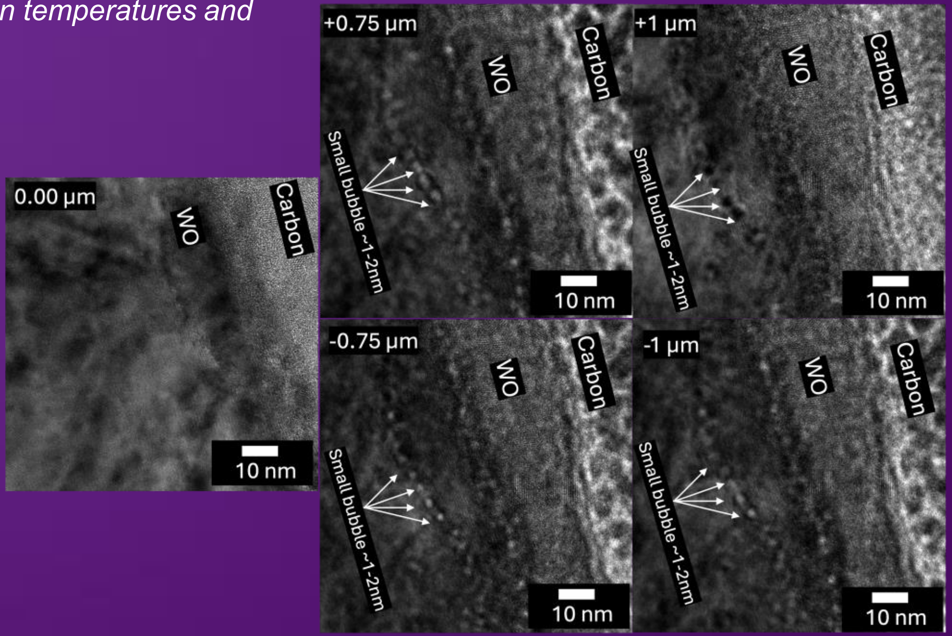

Fig3: TEM results of a Stress relieved helium irradiated and tungsten deposited sample at 600℃.

Credit: Nour Hammoud

PFMs: W-Diamond Composite

W-Diamond Composite

- Melting point: 3687 K
- Low fuel retention
- High sputtering threshold: 260 eV

- Melting point: 3950 K
- Good thermal stability
- Low hydrogen diffusivity
- Thermal conductivity: 2200 W/mK

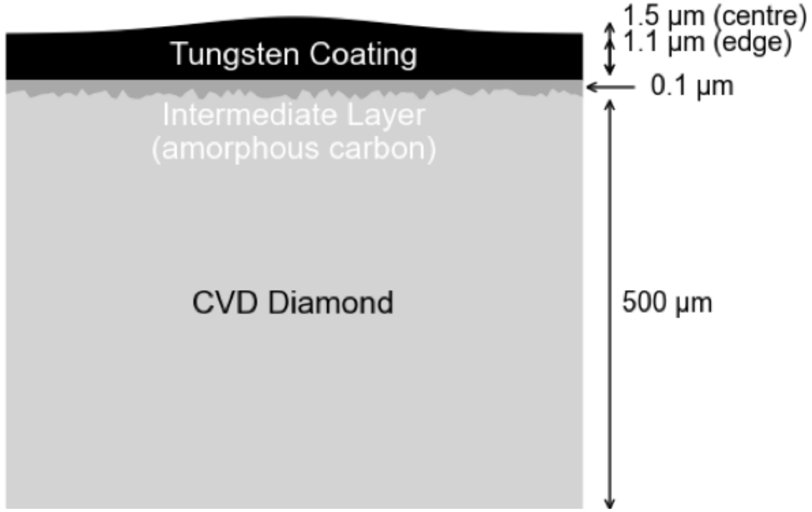

Fig.1: Schematic of the W-Diamond composite.

Background

A recent study ranked Diamond (1st) and Tungsten (3rd) as top candidates for PFM in nuclear fusion applications, following screening over thermal properties, sputtering, and hydrogen isotope inventory [1].

Aims

Combine the best properties of two materials: sputtering resistance from tungsten and thermal properties from diamond. Study PMI of the composite.

Plasma Irradiation

Plasma conditions		Target	
D	He	W-diamond	Diamond
30~35 eV 380~663 K 2×10^{24}~ 3×10^{26} m^{-2}	35 eV 1000~1700 K 3×10^{23}~ 5×10^{25} m^{-2}	10.1x10.1x0.5 mm	
		Coating: 1.4 μm	None
D damage		Delamination (> 1×10^{25} m^{-2})	Erosion
He damage		Deformation	Sputtering

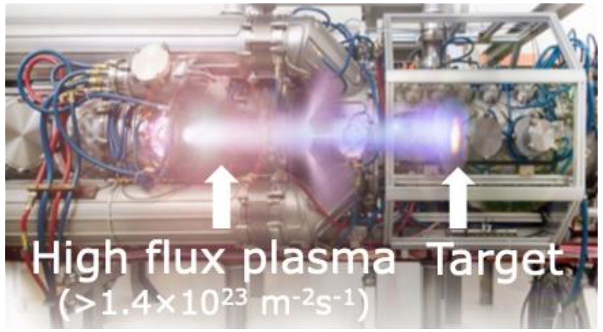

Fig.2: Magnum-PSI facility (DIFFER).

Results

- D chemical erosion on diamond.
- A 1.4 μm W coating can prohibit D erosion before its delamination /saturation after 1×10^{25} m^{-2}.
- Both materials exhibit excellent resistance to He Plasma.

Outlook: 1. Study D mobility in the composite. 2. Prevent delamination with thicker W coatings. 3. High-dpa ion irradiation experiments. 4. Diffusion bonding and multi-layer structure.

Credit: Shaokai Tang

[1] A. Fedrigucci, et al., PRX Energy, 3(4), 043002 (2024)

Production and Measurement of Low-Activation HEAs in Bulk Quantities

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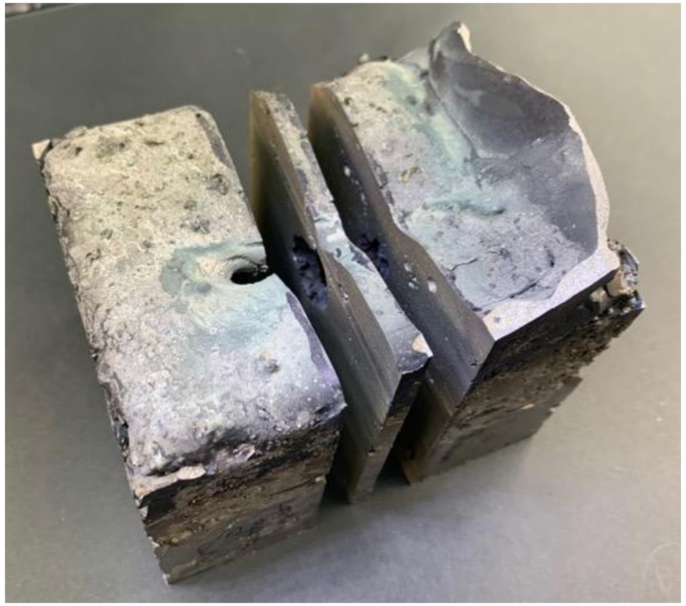
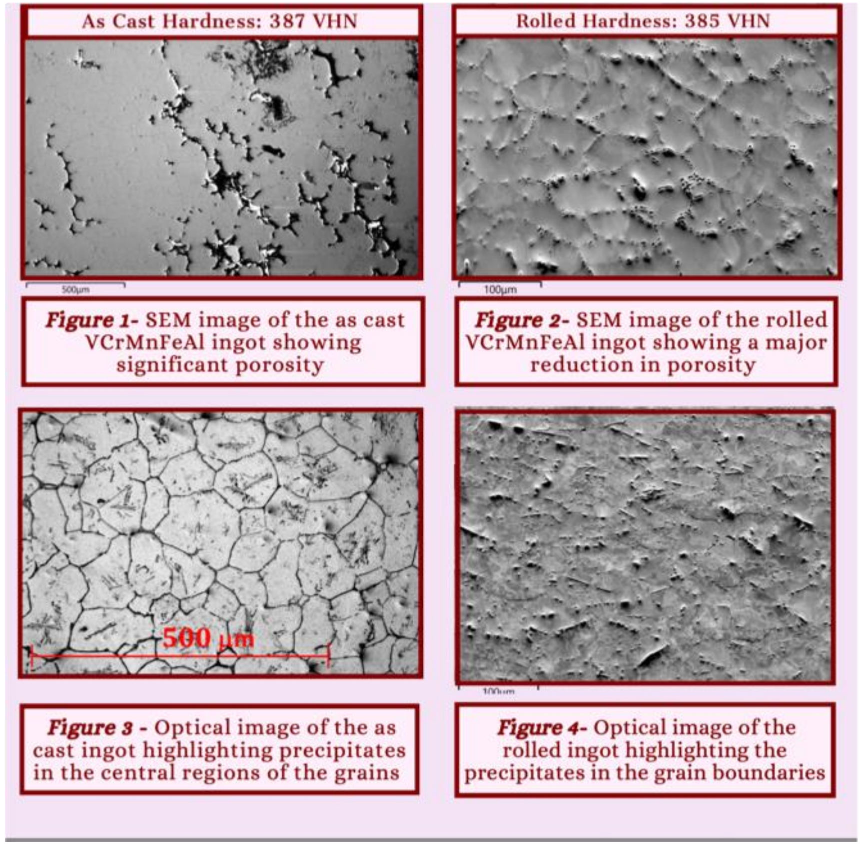
- Alloys in V-Cr-Fe-Mn-Al system have already been assessed in small quantities (references below).
- Ongoing work is scaling-up alloys for bulk properties (e.g., high-temperature tensile testing).



As-cast ingot (a few kgs in weight)



P.J. Barron et al., Scripta Materialia 176 (2020) 12-16.
P.J. Barron et al., Materials Science and Technology 38 (2022) 926-939.
A.W. Carruthers et al., Journal of Alloys and Compounds 888 (2021) 161525.

Credit: Sim Bhaker, Ed Pickering

Tungsten Welds using EBW and TIG

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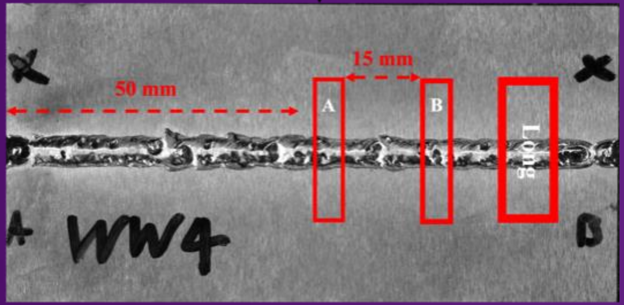


Figure 1: Crack-free 2.5 mm EB butt-weld (2_5WW1), showing the 2G welding setup and EDM extraction locations.

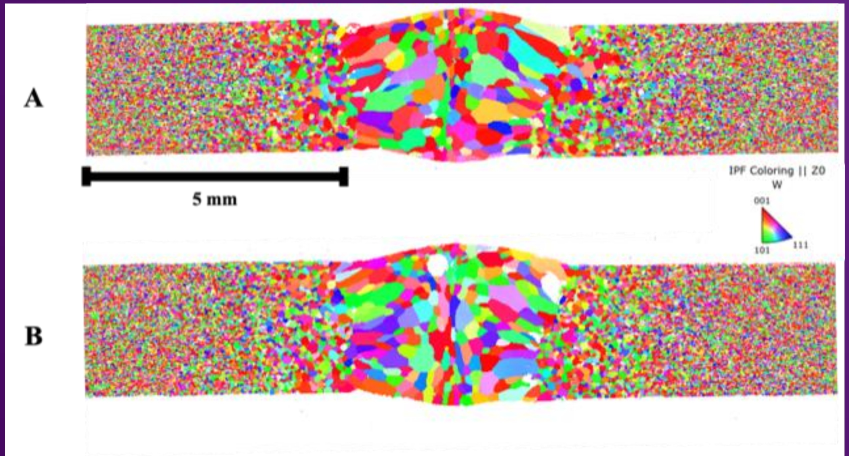
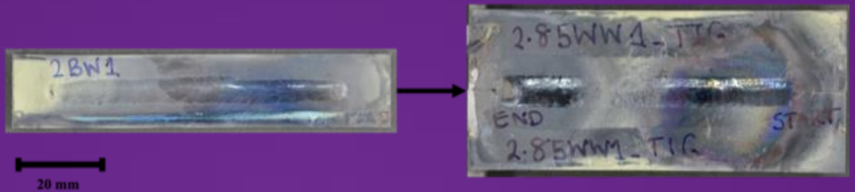


Figure 2: EBSD orientation map IPF Z pole figure in the z direction coming out of the page with a step size of 5µm of two cross sections from weld 2_5WW1.

(a)



(b)

Figure 3: TIG Welding (a) sample setup showing an image of the weld after welding (b) Resulting welds produced, with the bead-on-plate weld (2BW1) and the TIG buttweld (2.85WW1_TIG).

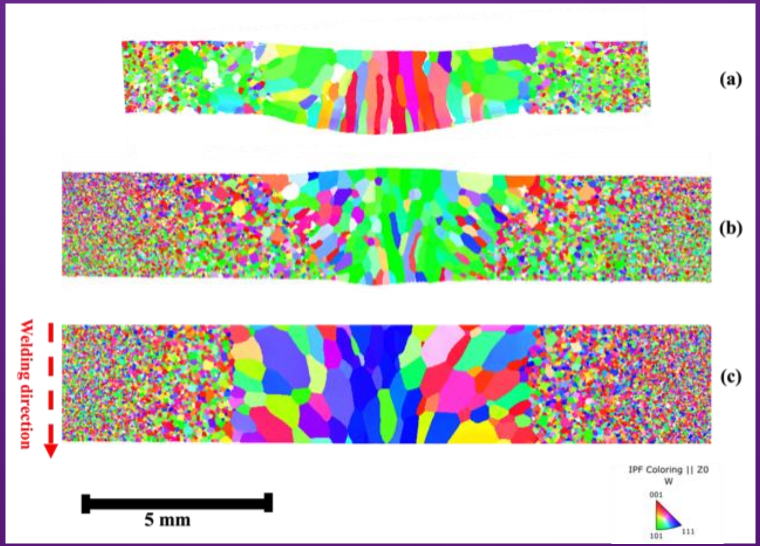


Figure 4: EBSD orientation map IPF Z pole figure in the z direction coming out of the page with a step size of 5 µm (a) cross-section of 2BW1 (b) Cross section at midpoint of 2.85WW1_TIG (c) Longitudinal map at the midpoint of 2.85WW1_TIG.

- Tungsten bead-on-plate welds and butt welds have been produced using electron beam welding and tungsten inert gas welding.
- For electron beam welding (EBW), the plates were preheated to 750 °C and then welded in the 2G position, as illustrated in Figure 1. The EBSD maps are shown in Figure 2, where large columnar grains are visible in the weld pool compared to finer grains in the heat-affected zones (HAZ).
- For tungsten inert gas (TIG) welds, the welding was not conducted in a vacuum but using a shielding gas of 99.99% helium, as depicted in Figure 3.
- Tungsten trioxide was produced as a by-product, as indicated by the yellow powder surrounding the welds.
- EBSD maps for the inert gas welds are presented in Figure 4, where the grains in the weld pool are even larger than those of the electron beam. Sagging in the weld pool is also observed due to the welding setup in 1G and the influence of gravity on the molten pool.

Credit: Toluwanimi Ajayi

Dual-laser Systems in Tungsten Manufacturing

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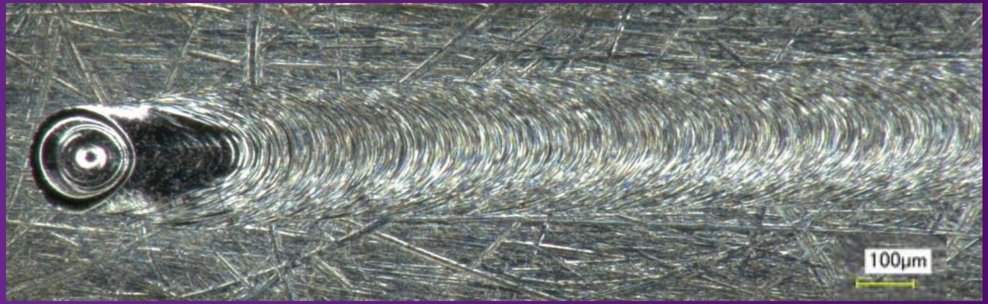
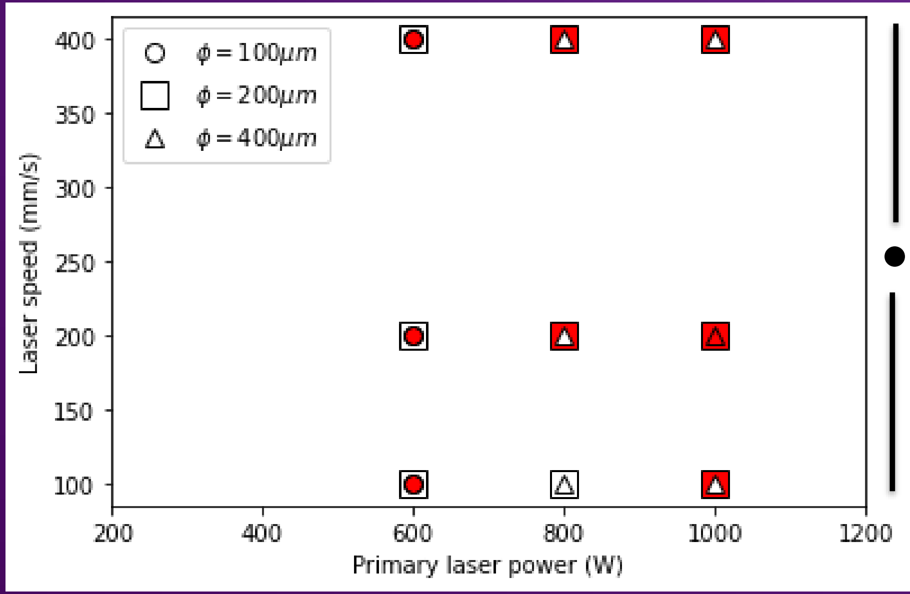
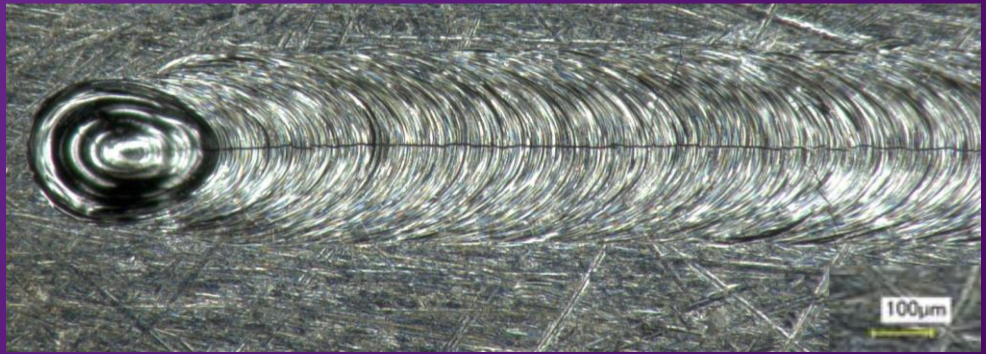
- Collaboration with the University of the Bundeswehr, Munich
- Secondary laser beam used to post-heat the material to prevent cracking
- Further microscopy and mechanical analysis in progress
- Applications to welding and additive manufacturing techniques



600W (500W) primary (secondary) laser power with 100 (500) micron beam diameter, 400 mm/s scan speed and 0.5ms time delay



Appearance of cracking with variation in primary laser power, diameter and scan speed. The beam diameters are indicated by the shapes in the legend and the red shading indicates that the sample cracked.



600W (500W) primary (secondary) laser power with 100 (500) micron beam diameter, 200 mm/s scan speed and 1ms time delay

Credit: Charlotte Brown

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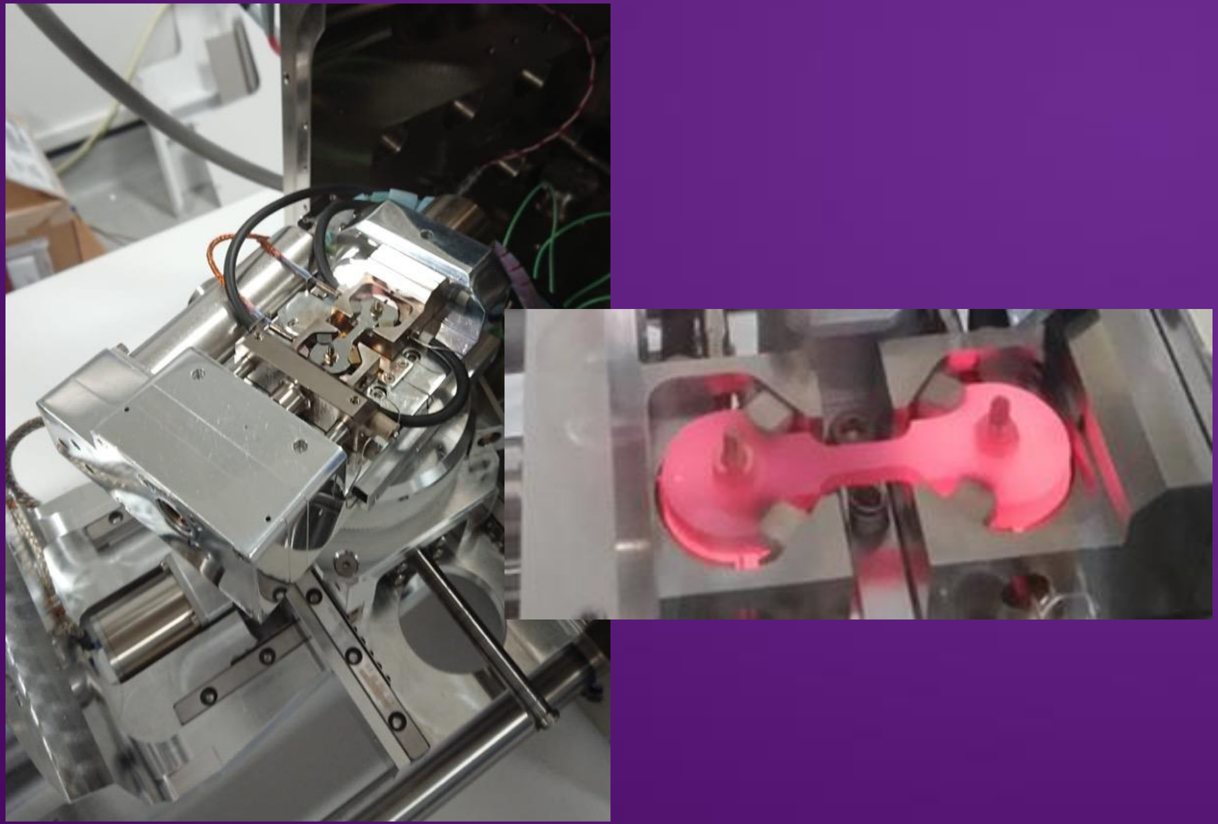
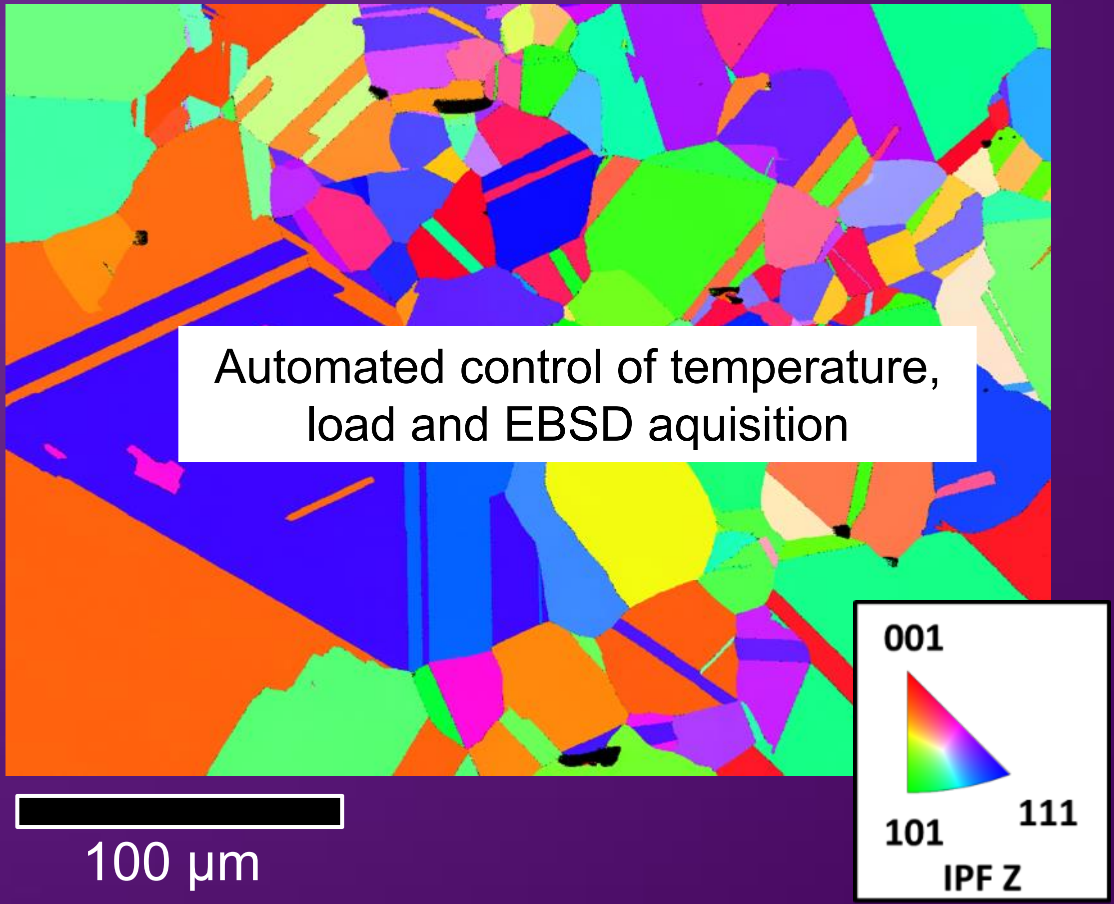
Focus: In-Situ Capabilities

Credit: Jack Donoghue and Albert Smith
‘TANIST’ system (Tescan and NewTec In-Situ Testing system)





Focus: In-Situ Capabilities

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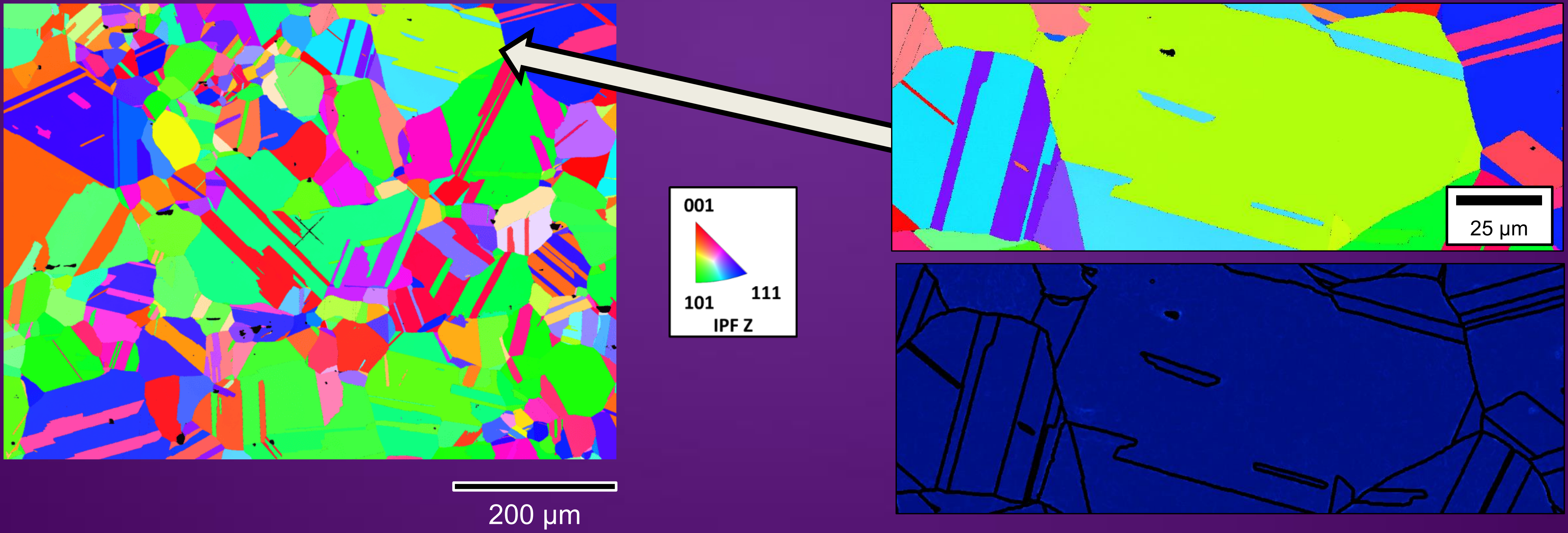
- In-situ EBSD (load and temperature)



Focus: In-Situ Capabilities

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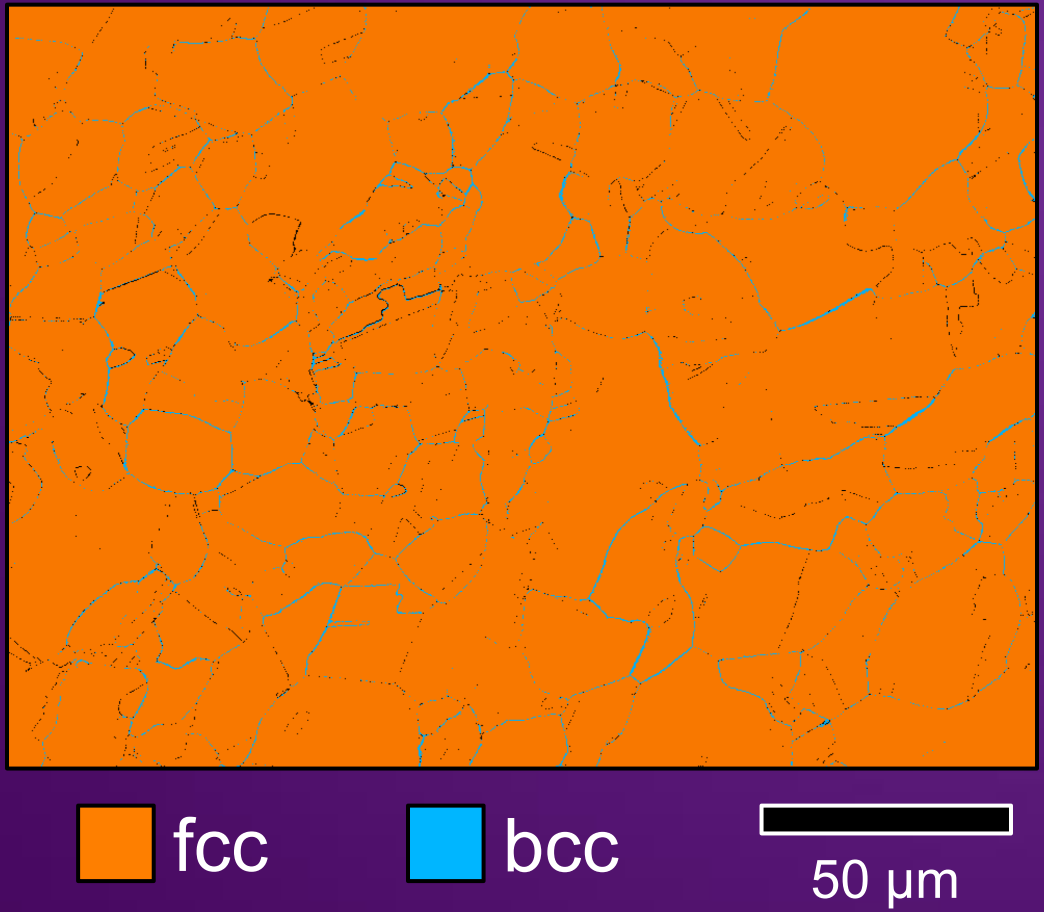
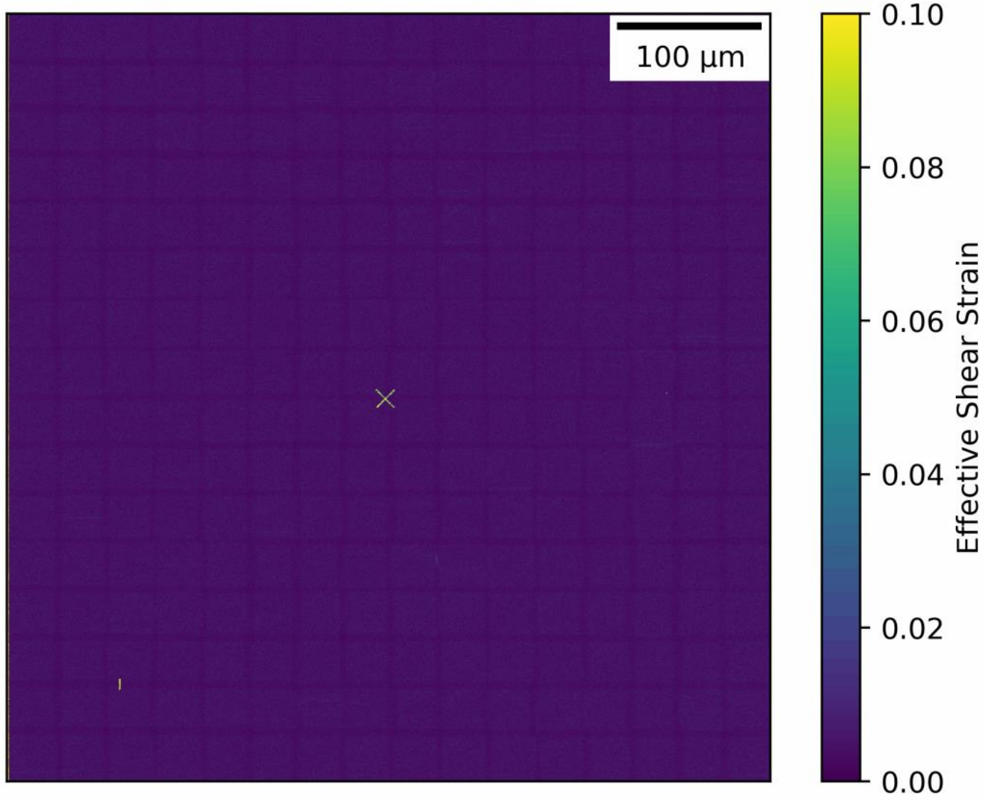
Martensitic transformation



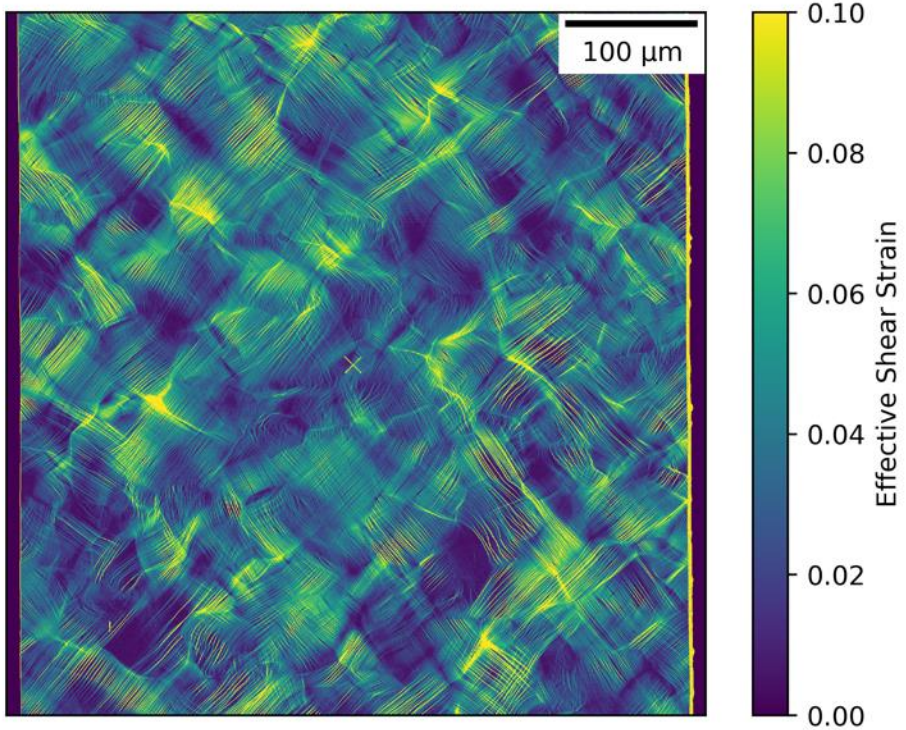
High-resolution DIC



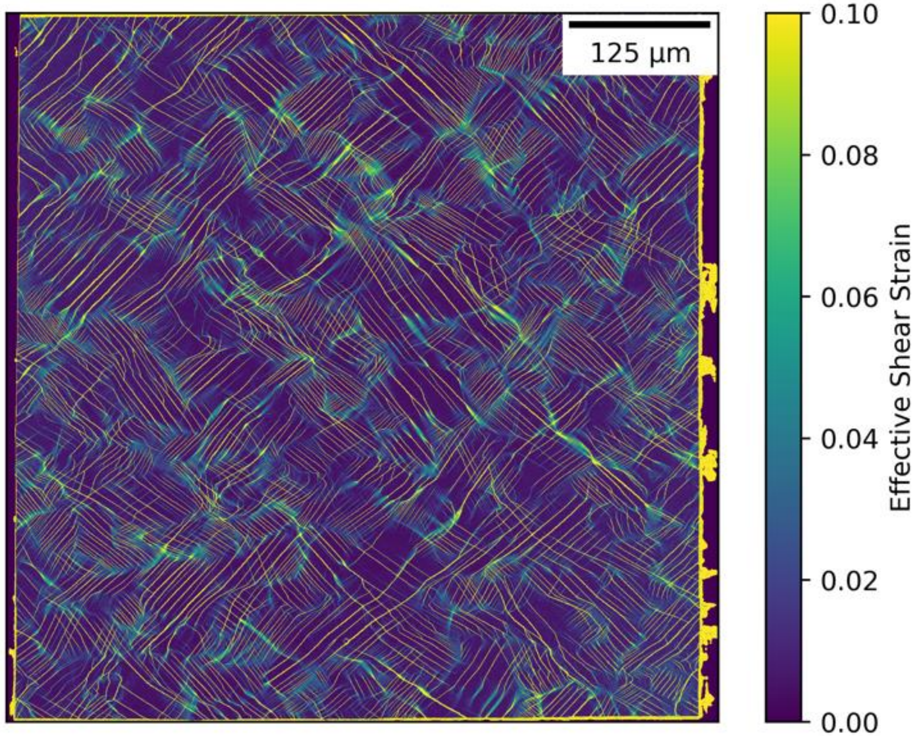
High-Resolution Digital Image Correlation

- To examine underlying slip behaviour in BCC iron
- Non-irradiated versus irradiated (0.66 dpa)

Non-irradiated rm T



Irradiated rm T



Credit: Florence Goodrich, Jack Donoghue, Albert Smith

Electron Beam Welding of Steel

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200 mm thick

- Examined application of novel heat treatments involving re-austenitisation of whole component

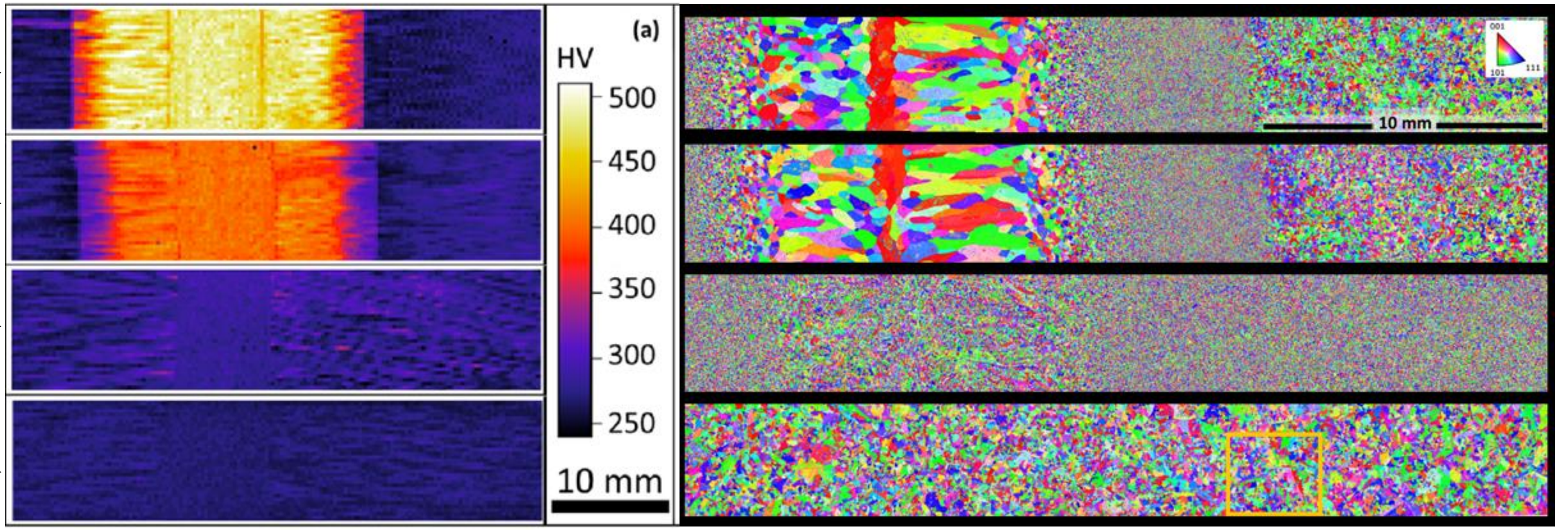
- Can successfully homogenise the hardness and microstructure across the weld, almost making it ‘disappear’!

As-welded

Conventional PWHT

Reaust+quench+ temper

Homogenise+ reaust +quench+temper



Credit: Kirstie Bruce, Mark Taylor

Bruce et al., Metallurgical and Materials Transactions A 56.2 (2025): 655-669.

CODES AND STANDARDS NEEDS

Materials Qualifications Landscape

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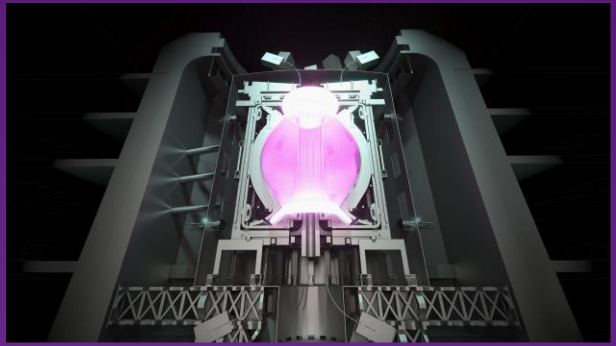
- ASME BPVC only have 6 nuclear qualified materials with 2 being 100 years old; the youngest being 40 years old
- Qualification of new materials takes a significant amount of time and finances as we are qualifying for 40 years
- A shorter lifetime for 5 years full power may be more appropriate for a FOAK fusion device?

Mini-STEP?



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- University based miniature version of the UK’s flagship Spherical Tokamak for Energy Production (STEP programme).
- Built using additive manufacturing techniques.
  - Avenue for training the next generation of scientists and engineers
  - Development of engineering standards and protocols for building a tokamak
  - Demonstration of novel additive manufacturing techniques
  - Test-bed for concepts for the STEP programme and a stimulus for supply chain and economic development in the UK.

Summary

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- Manchester has excellent qualification capabilities to contribute to Fusion Codes and standards
- Strong links with industry and research sector
- Extensive experience in codes and standards space and materials qualification in the wider nuclear sector
- Coordinated effort needed to qualify materials and components
- Lets work together!