UK Fusion research and new facilities at UKAEA-CCFE

Martin O'Brien

HiRadMat Workshop, CERN, 10-12 July 2019

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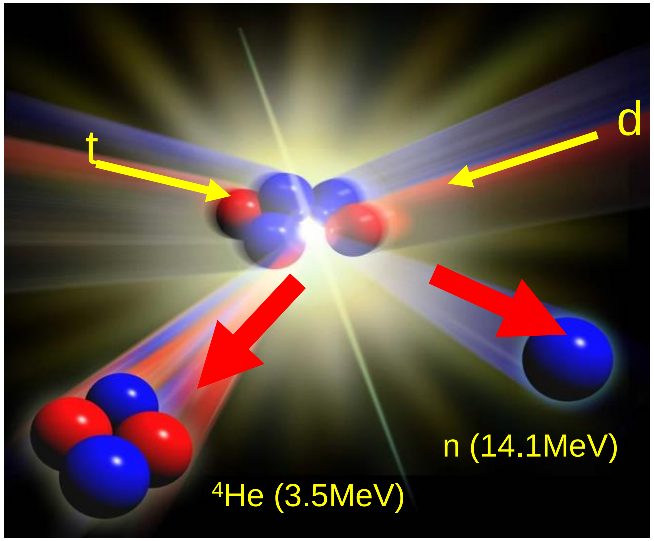
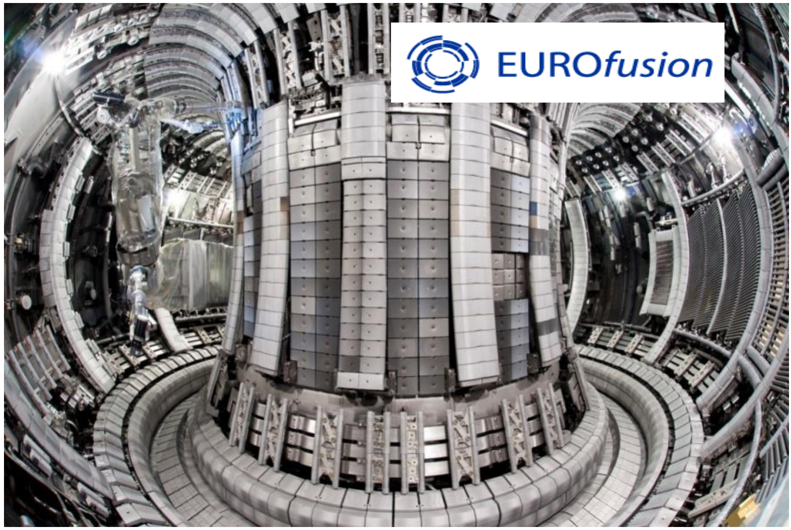
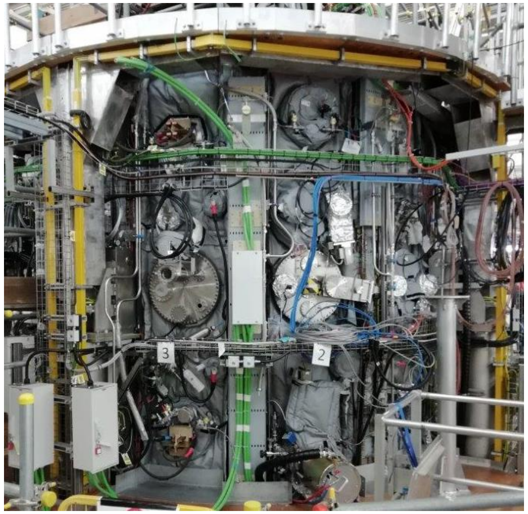
UKAEA's role is to help bring fusion to commercialisation as part of the international fusion R&D programme



JET



MAST-U

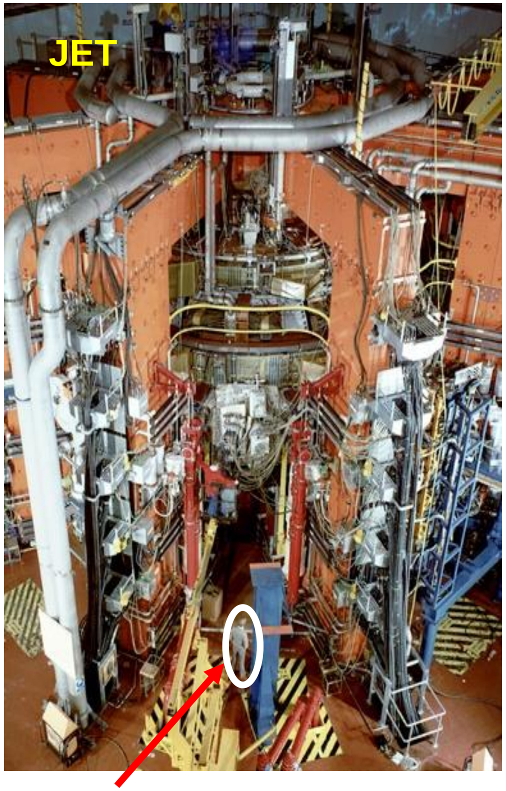


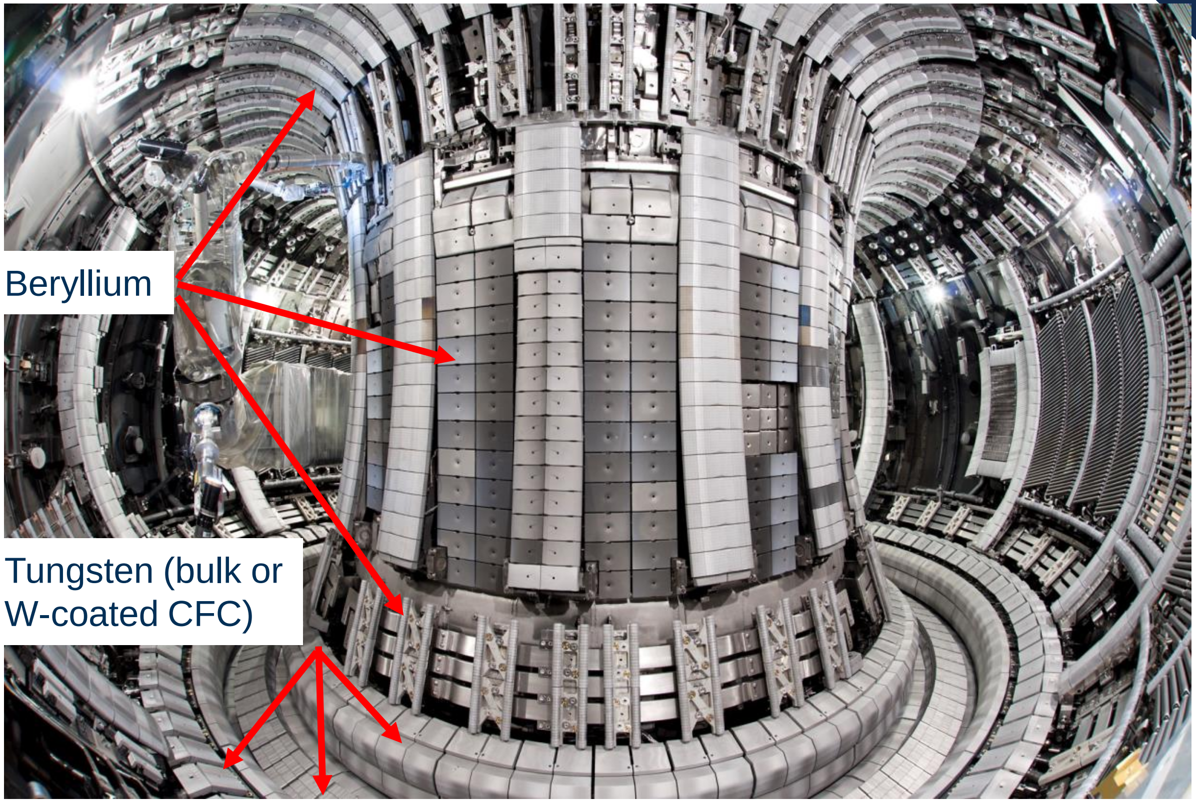
We:

- Operate JET for the EUROfusion consortium
- Are responsible for UK fusion research as part of the collective EUROfusion programme: fusion plasma physics, focused on the MAST-U experiment, plus a wide range of technology and materials R&D

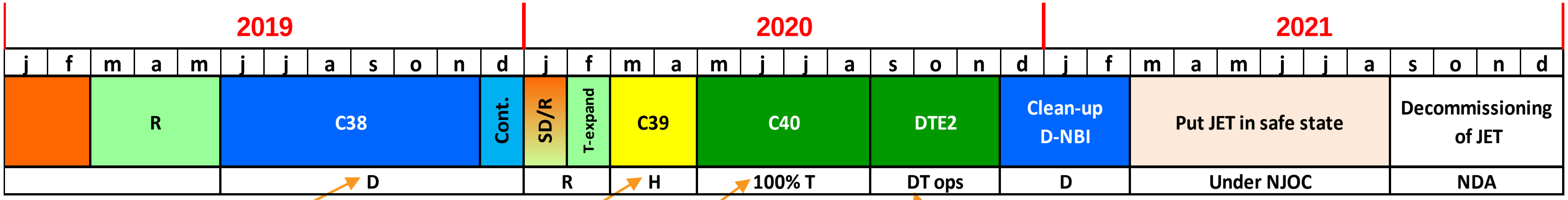
And we contribute to related science & technology fields

JET now has an all-metal wall (used to be carbon)
We are preparing for major deuterium-tritium campaign *(may be later than 2020 if the extension to 2024 now under discussion is approved)*





JET Schedule until 2020, with Tritium and DT in 2020



2019: j f m a m j j a s o n d
2020: j f m a m j j a s o n d
2021: j f m a m j j a s o n d

	R	C38	Cont.	SD/R	T-expand	C39	C40	DTE2	Clean-up D-NBI	Put JET in safe state	Decommissioning of JET
		D		R		H	100% T	DT ops	D	Under NJOC	NDA

Deuterium *Hydrogen* *Tritium* *Deuterium + Tritium*

Where has Fusion R&D got to?

Plasma conditions in JET are routinely those needed for fusion (> 100 M°C). With D-T fuel fusion output power was nearly as high as the heating input power (next D-T run should improve this and sustain it for longer).

But JET plasma is too small for net power out – so we need ITER which will give $P_{out} >> P_{in}$

There are candidate choices and designs for power station technologies and materials – but they need development and testing on ITER and other facilities.

How material properties change under sustained irradiation is one of the most important research topics.

Next steps to Fusion Power Plants – EU approach

ITER is the most important step.

Testing power station grade plasmas and candidate technologies

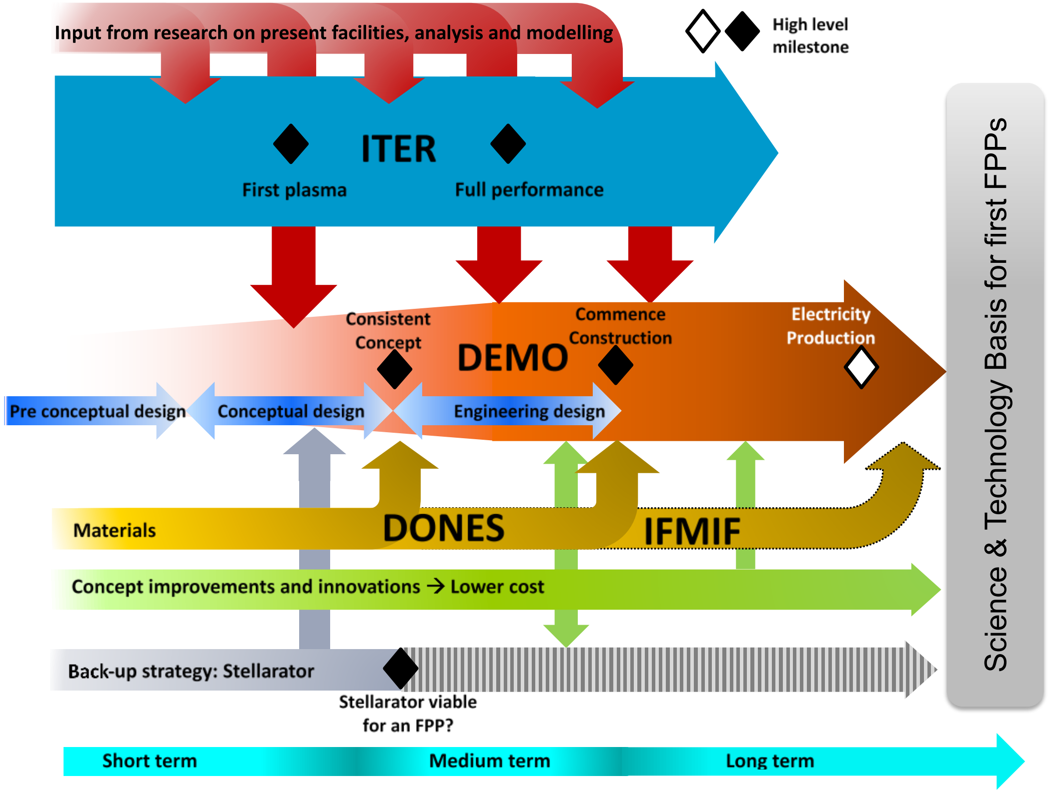
DEMO designed in parallel (now in pre-conceptual design phase)

much higher fusion power

more limited diagnostics

much higher exhaust powers and neutron fluence → bigger materials challenges

power to the grid – not high availability but with a level of reliability.



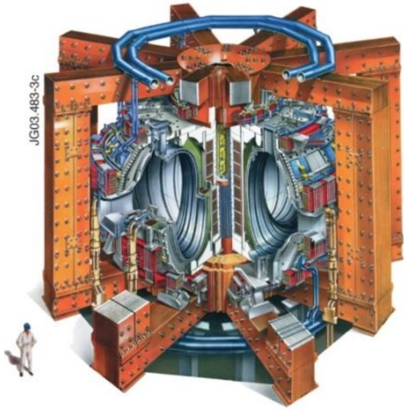
EU has a fusion roadmap centred around ITER

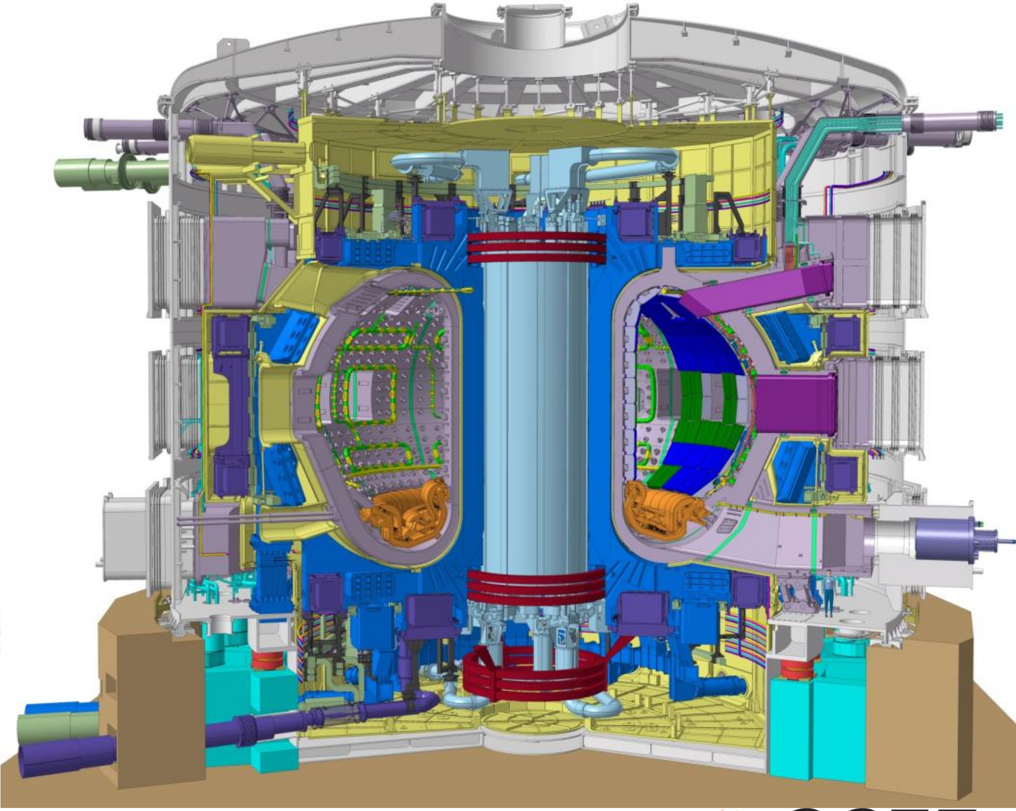
ITER

International **T**hermonuclear **E**xperimental **R**eactor
EU, China, India, Japan, Korea, Russia, US. Being built in France.
Operational in 2020s.

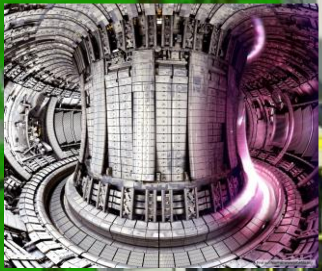
JET and other experiments are providing key operational input
UKAEA and UK industry are providing a range of specialist services

Total Fusion Power	500MW (700MW)
Q — Fusion power/aux. heating power	10
Average Neutron Wall loading	0.57MW/m^2(0.8MW/m^2)
Plasma inductive burn time	≥ 1000 s.
Plasma major radius	6.2 metres
Plasma minor radius	2.0 metres
Plasma current (Ip)	15 MA (17.4 MA)
Toroidal field @ 6.2 m radius	5.3 T
Plasma Volume	837m^3
Plasma Surface	678m^2
Installed Aux. Heating/Current Drive power	73 MW (100 MW)





Fusion needs integrated solutions

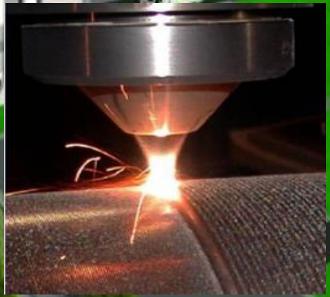


Plasma Science

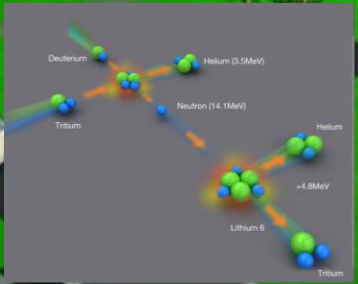
Robotics

Exhaust and High Heat Flux

Materials Science



Fusion Technology



Tritium Technology

The R&D focus is shifting to materials and technologies needed for DEMO, while maintaining a strong plasma physics focus to optimise the burning plasma in ITER.

In Europe (and China and South Korea) there are major activities focusing on designing a DEMO reactor to put power on the grid – with many R&D strands. The UK and other countries contribute to a collective European programme under EUROfusion.

The UK Government has recognised this shift, funding new materials, robotics, tritium and technology facilities for fusion and other applications.

New Facilities at Culham will contribute to many of the remaining R&D challenges.

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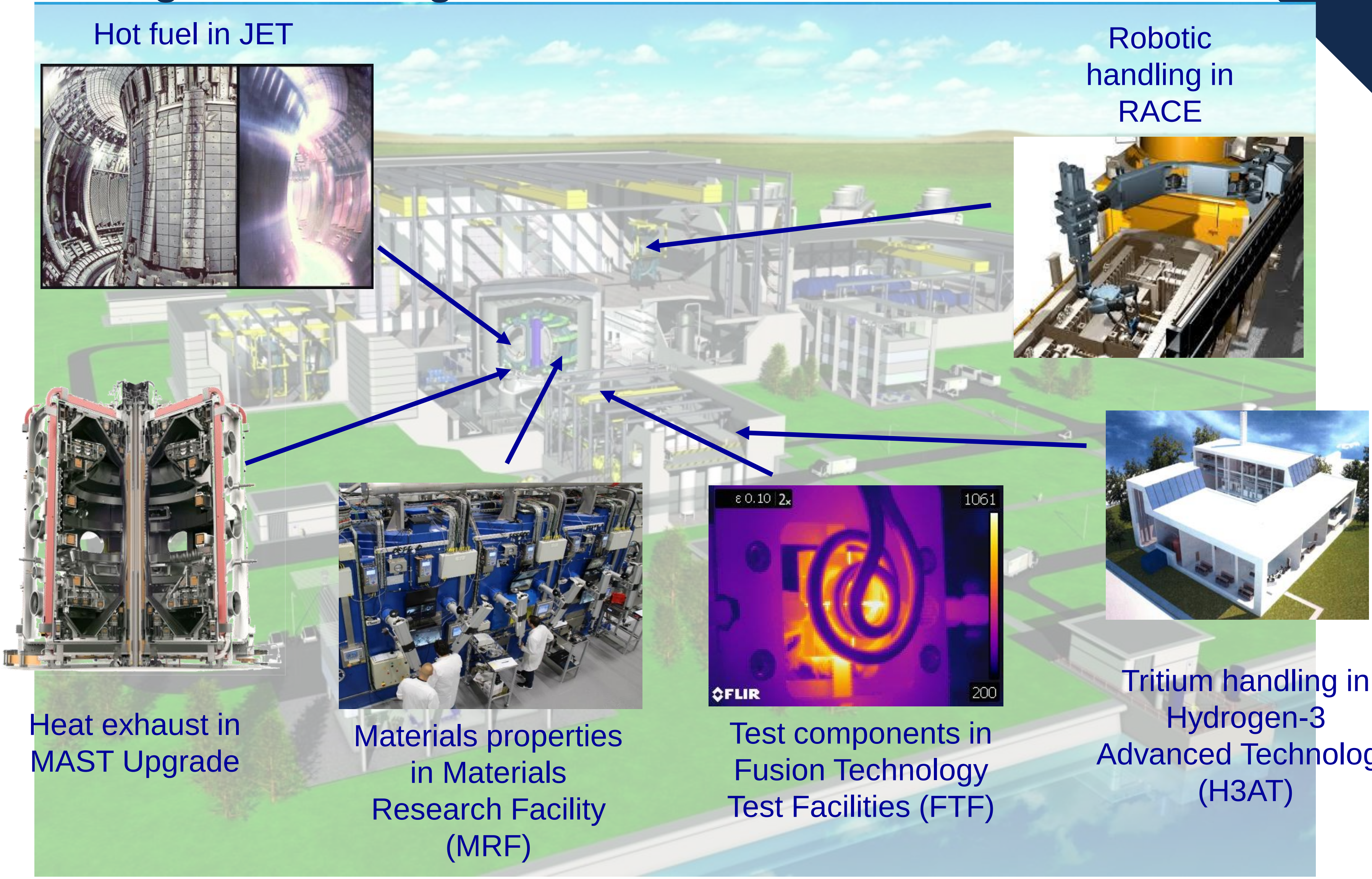


Hot fuel in JET

Robotic handling in RACE

Heat exhaust in MAST Upgrade

Materials properties in Materials Research Facility (MRF)

Test components in Fusion Technology Test Facilities (FTF)

Tritium handling in Hydrogen-3 Advanced Technology (H3AT)

Commissioning of MAST-Upgrade is nearly complete, first plasmas this year

£50M rebuild for longer, higher performance plasma. Particular emphasis on reducing heat loads on plasma facing surfaces and on testing the "spherical tokamak", a more compact approach than the conventional tokamak.

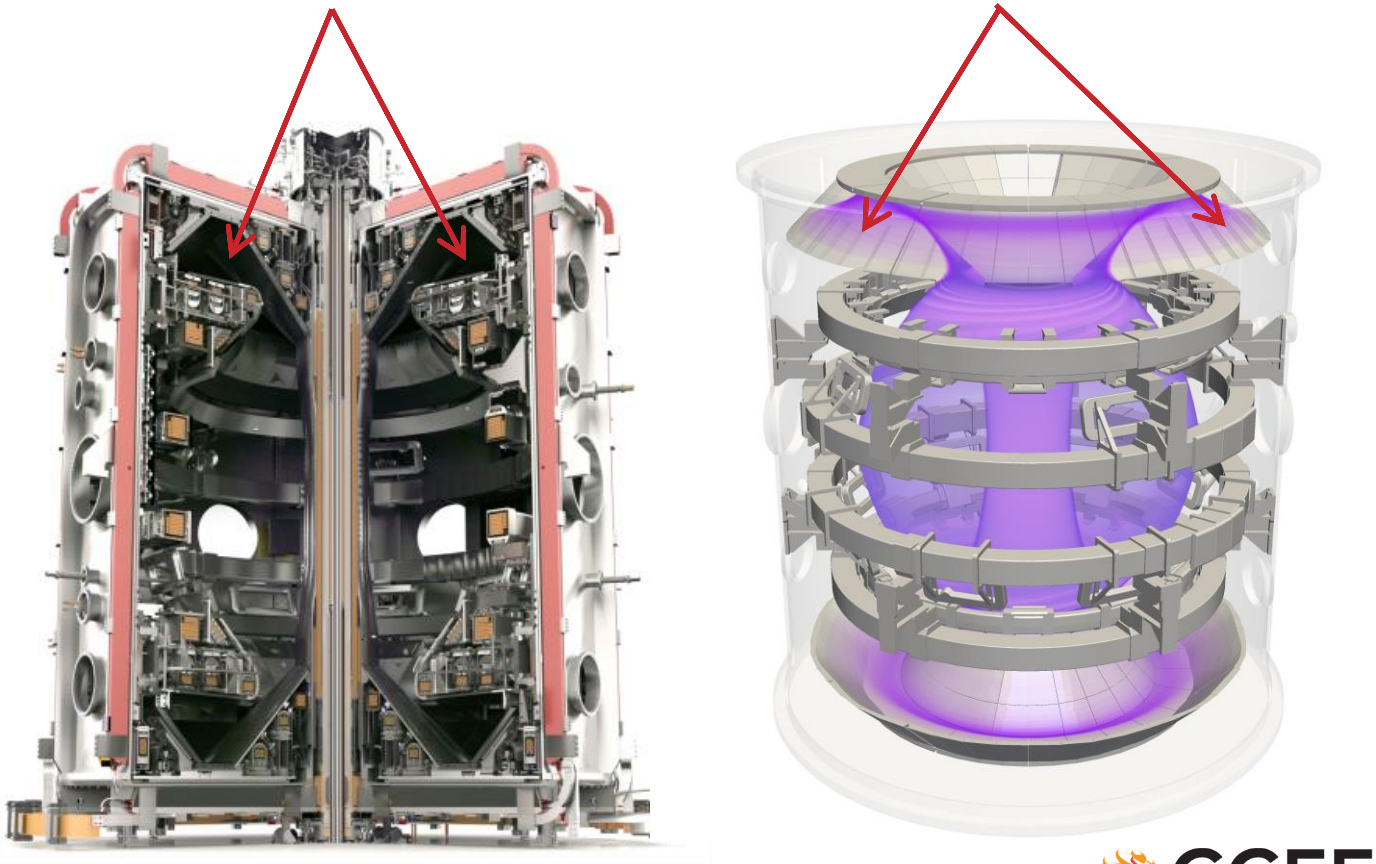
Increased Field
Improved confinement

New Solenoid
Greater I_p, pulse duration

19 New Coils
Improved shaping

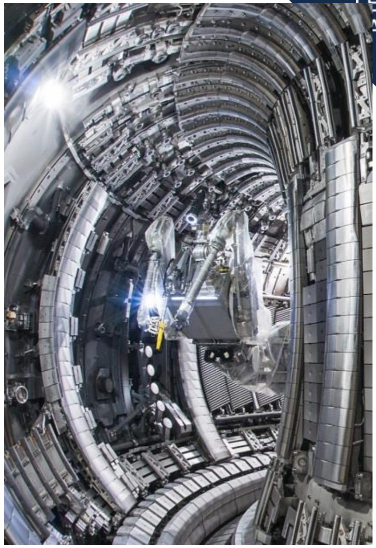
Super-X Divertor
Improved power handling

Off-Axis NBI
Improved profile control

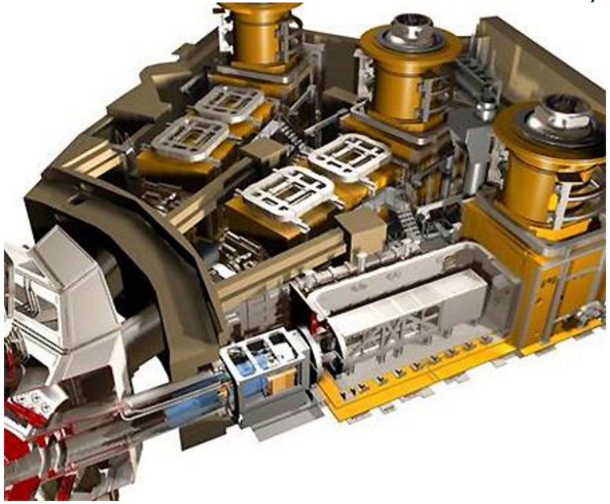


The exhaust heat will be spread at the top and bottom of MAST-U

RACE (Remote Applications for Challenging Environments)



JET Remote Handling
30,000+ hours operational experience



Remote handling is critical to ITER:

RACE is a partner in the Neutral Beam RHS project, in the development of the Divertor RHS, and in the Cask & Plug contract (Remote Handling of transport containers)

RACE is involved in many other fields, e.g. designing the European Spallation Source (ESS) hot cell for handling highly radioactive targets

UKAEA’s Special Techniques Group (STG)

Highly skilled material joining facility using vacuum furnace brazing, EB welding and diffusion bonding equipment

Not only for fusion – we do work for other big science facilities

- Diffusion Bonding
  - Proprietary methods of aluminium diffusion bonding a wide range of materials including metals, ceramic and optical materials
  - Advantages over vacuum brazing for certain combinations particularly optical assemblies

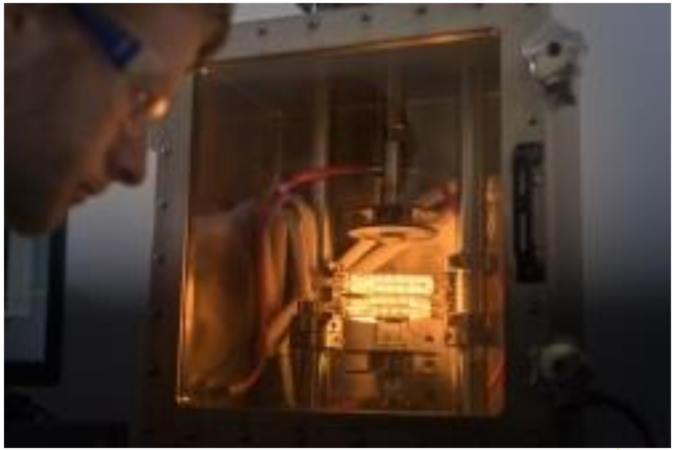
- Bespoke UHV Optical viewport manufacture – Fused silica, Crystal quartz, BK7, sapphire and diamond, all metal sealed

- Vacuum brazing
  - Support for feasibility tasks and development of prototype assemblies
  - Single items or batch brazing capability
  - High quality repeatable brazes without the presence of oxide or flux

£86M announced in December 2017 for National Fusion Technology Platform at Culham

Two new centres of excellence to open in 2021, for UKAEA, industry and universities.

Hydrogen-3 Advanced Technology (H3AT) will research how to process and store tritium, prototyping ITER systems



Fusion Technology Facilities (FTF) will carry out thermal, mechanical, electromagnetic and hydraulic tests on prototype components under conditions experienced inside fusion reactors (heat fluxes, magnetic fields).

Our other new facility is for processing and testing irradiated material – to be covered later.

Some Fusion Materials Issues

DEMO and power plant: need materials that survive and function in high neutron flux, and at high temperature (thermodynamic efficiency). And we need materials that minimise the long-term radioactive waste burden.

Plasma-facing materials must withstand high heat and particle flux, transients, erosion, when neutron-damaged, and retain properties like good thermal conductivity

Functional materials can degrade (insulators, windows, breeding materials, fibres, cables)

Structural materials can become brittle – 14MeV neutrons more energetic than fission neutrons → H and He from transmutation reactions → **He embrittlement** is a major concern.

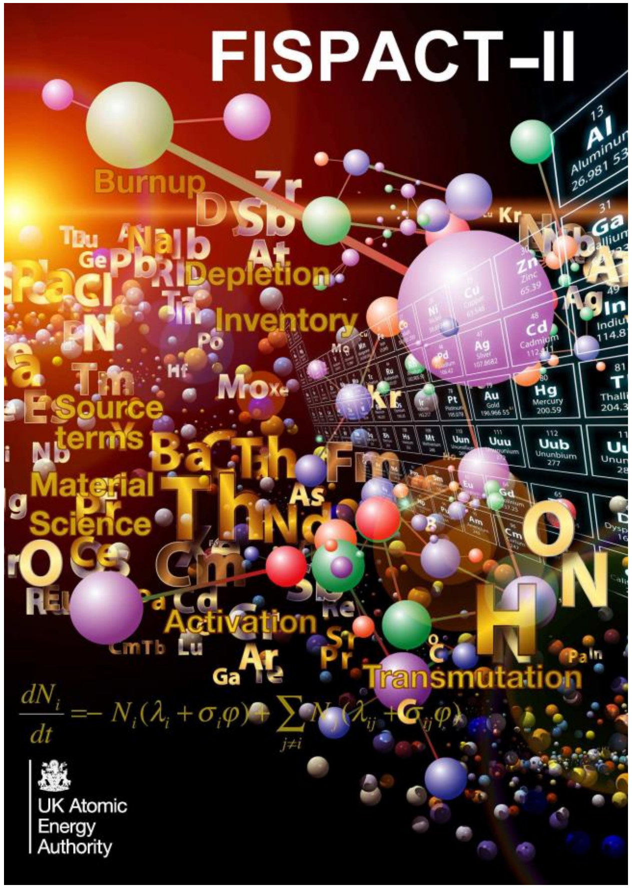
Novel materials show promise – e.g. dispersion-strengthened steels, high entropy alloys.

Superconducting magnets need substantial shielding. Use of HTS?

Many links with fission and accelerator communities, to mutual benefit.

Activation and radiation transport calculations are very important: FISPACT-II

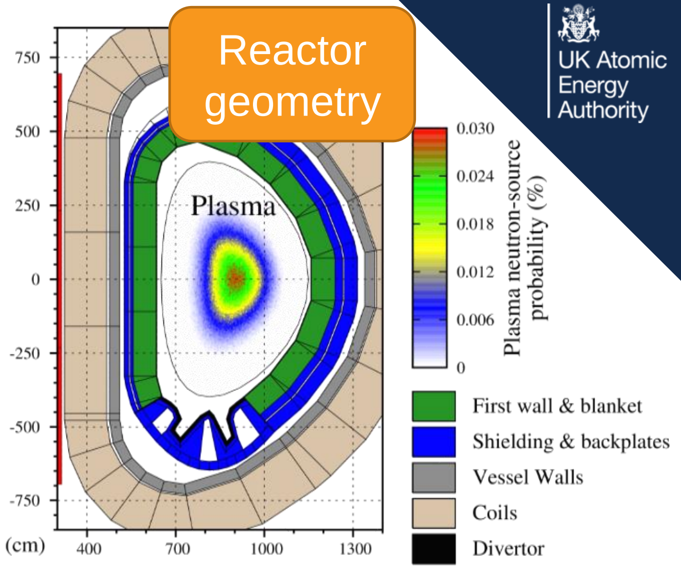
- Multiphysics platform for predicting inventory changes under both neutron and charged-particle interactions
- Calculates activation, transmutation, burn-up, dpa, gas production, gamma spectra, etc.
- Employs up-to-date international nuclear data libraries with nuclear reaction data, radioactive decay data, fission yield data
- Covers energies much higher than fusion (e.g. includes proton-induced cross sections up to 1 GeV for 2095 targets) → collaborations with accelerator nuclear data community.



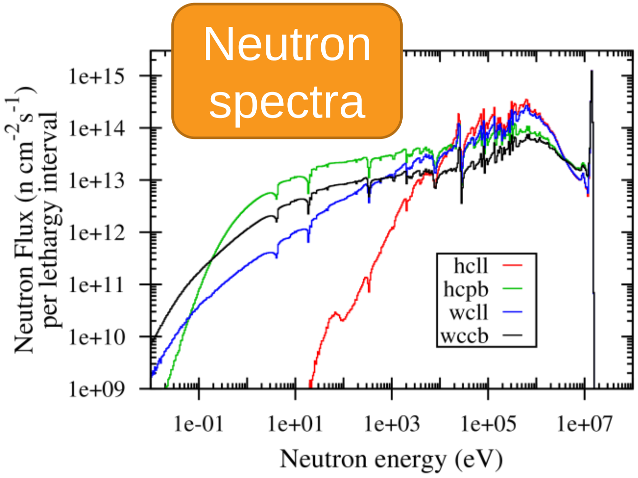
FISPACT-II:
Inventory rate equation solver developed at UKAEA

Review paper on FISPACT-II: Nuclear Data sheets: special edition on "Nuclear Reaction Data" (volume 139 [2017] pp. 77-137

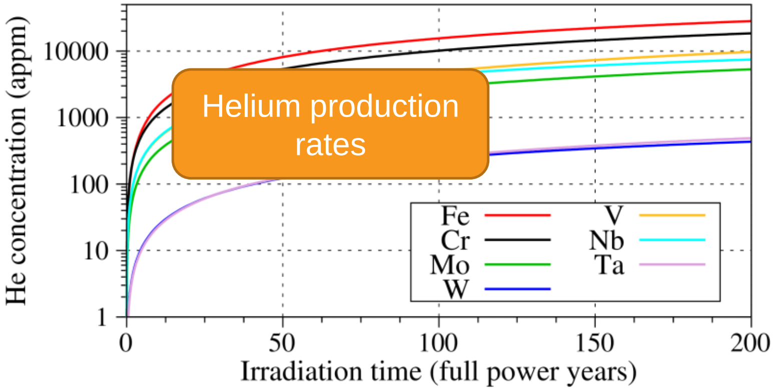
Integrated modelling of DEMO – e.g. He embrittlement


Reactor geometry

Neutron transport Simulations (MCNP)


Neutron spectra

Inventory calculations (FISPACT-II)


Helium production rates

embrittlement modelling

≈ operational lifetimes

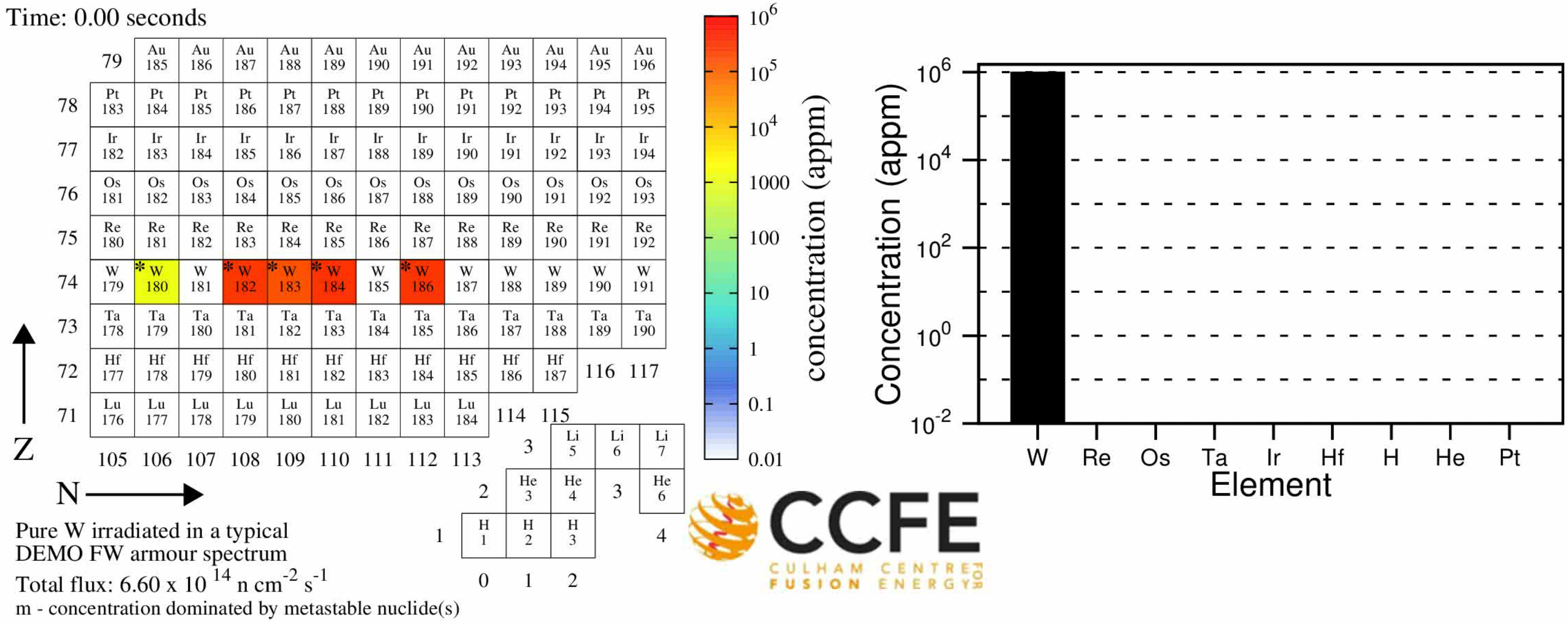
Design feedback

Critical helium embrittlement lifetimes (full power years)	HCLL	HCPB	WCLL	WCCB
Iron	9	6	8	7
Tungsten	100+	100+	100+	100+
Molybdenum	58	63	59	62

DEMO designs with 4 different blankets for heat exchange & tritium breeding

FISPACT-II simulation of tungsten transmutation

→ chemical composition changes as W becomes contaminated with transmutants → we need to understand how thermal and other properties change with time



Pure W irradiated in a typical DEMO FW armour spectrum

Total flux: 6.60 x 10^{14} n cm^{-2} s^{-1}

m - concentration dominated by metastable nuclide(s)

Materials modelling – a multiscale problem

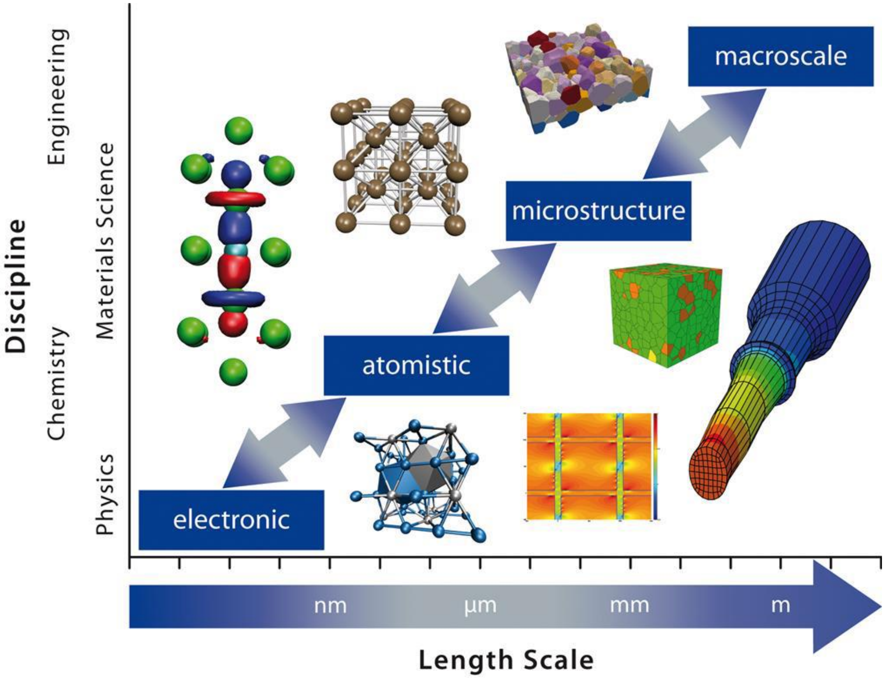
At Culham we concentrate on tungsten and steels and on the smallest scales – but now have theories to determine how nano-scale effects give macro-scale consequences.

Electronic

- Density Functional Theory for interatomic potentials etc
- Magnetic effects (fundamental for steels)

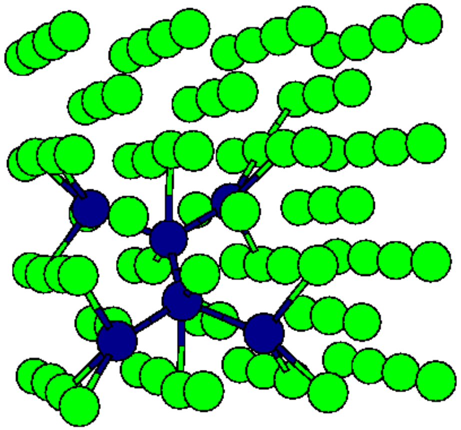
Atomistic

- Molecular dynamics etc
- Dislocation behaviour (determines macroscopic properties)
- Effect of defects, impurities, dispersants (why do tiny levels of oxides give better radiation resistance?)

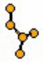


Experimental comparisons vital. Validating models for fusion materials is hampered by not having a 14 MeV neutron source – but comparison with as many other radiation options as possible strengthens faith in the models (fission neutrons, wide range of ion beams).

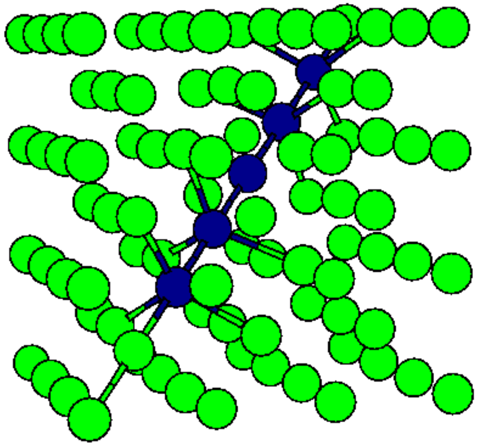
Brownian motion of defects. Magnetic metals differ qualitatively from non-magnetic metals → radiation damage develops differently.



110 dumbbell



Thermal migration of a 110 dumbbell. Occurs in Fe and ferritic steels.



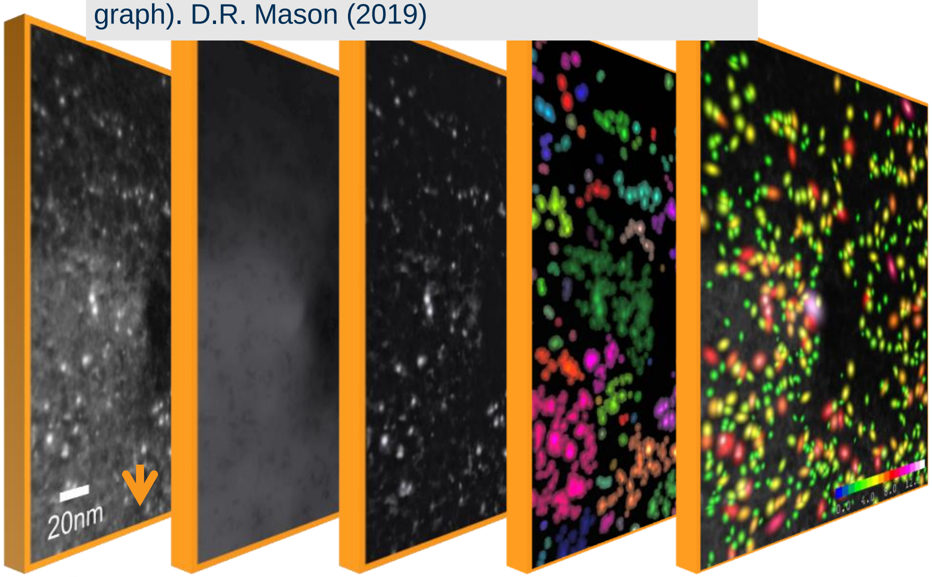
111 crowdion

Thermal migration of a linear 111 type defect. Occurs in non-magnetic transition metals (tungsten, vanadium, molybdenum).

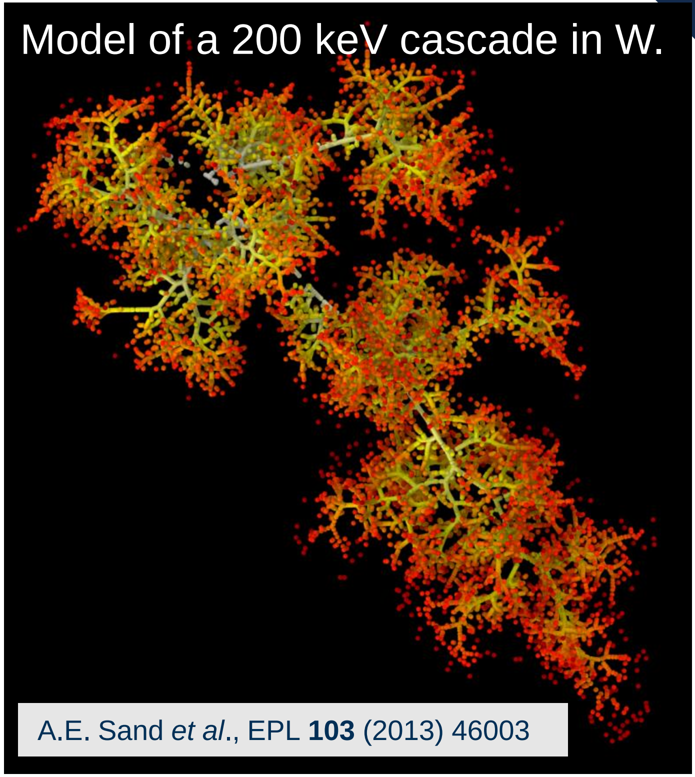
DFT energies -> potentials -> MD modelling -> transition states -> kMC or RT

Production of defects in cascades

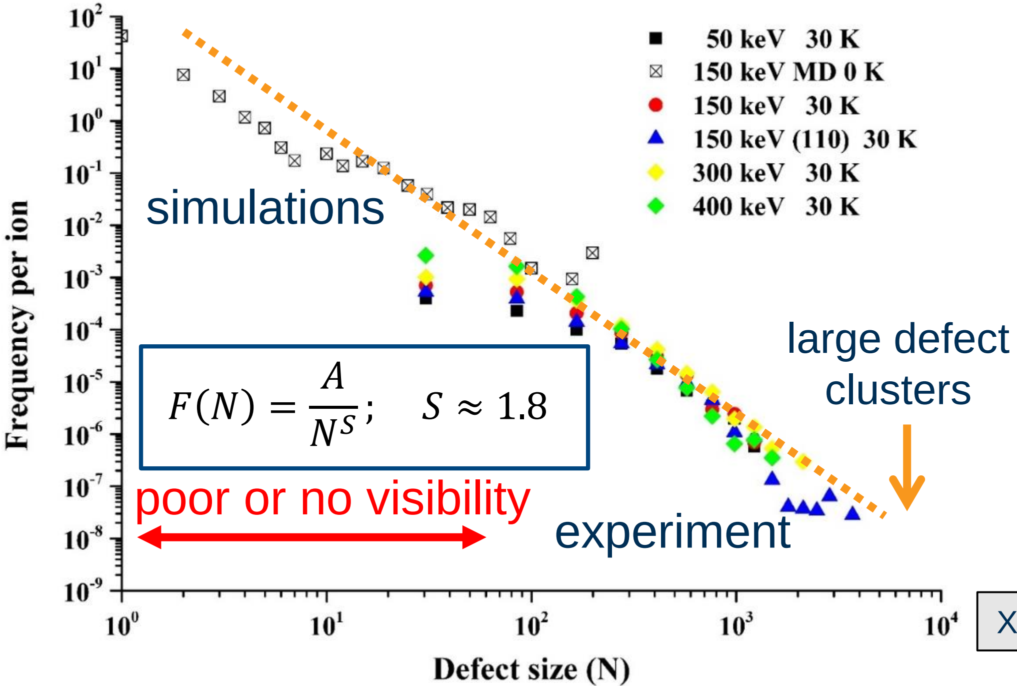
Analysis of micrographs (“experiment” region in the graph). D.R. Mason (2019)



Model of a 200 keV cascade in W.



A.E. Sand *et al*., EPL **103** (2013) 46003



simulations

$$F(N) = \frac{A}{N^{S}}; \quad S \approx 1.8$$

poor or no visibility

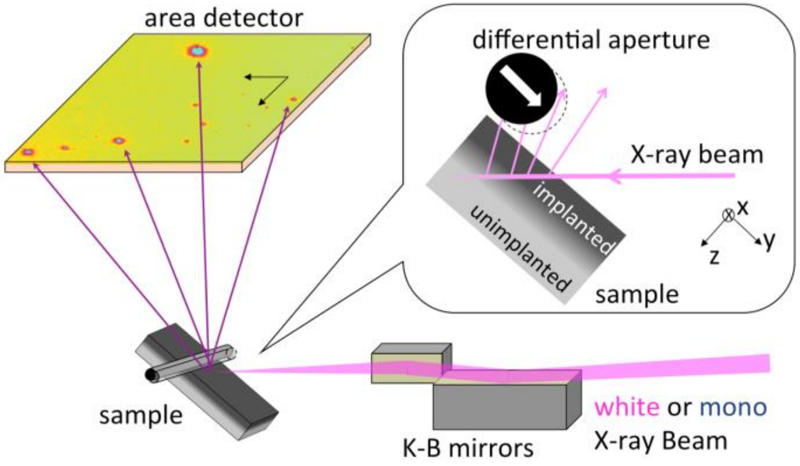
experiment

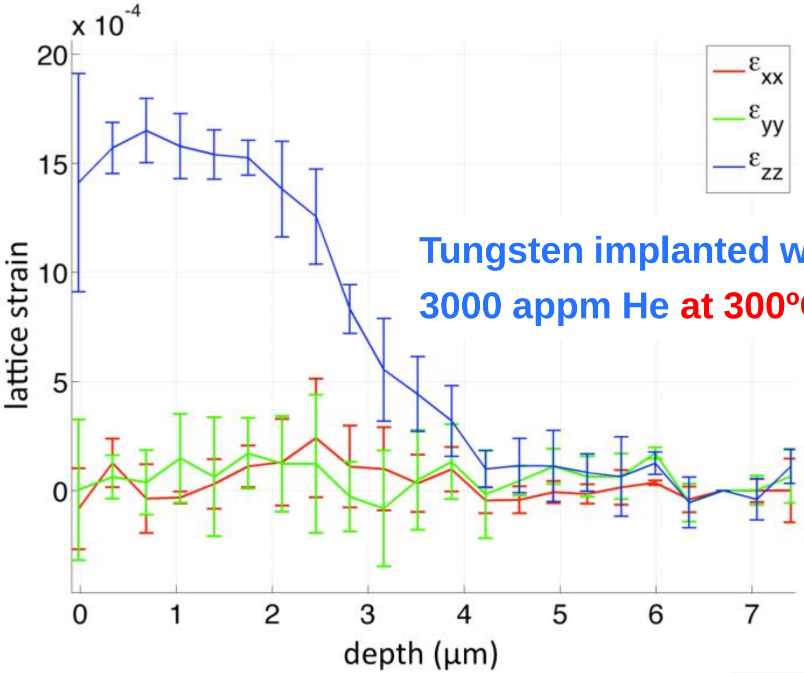
large defect clusters

Analysis of hundreds of collision cascade simulations, and tens of thousand of events observed in electron microscope images show that the distribution of sizes of defect clusters follows a power law – like avalanches and earthquakes.

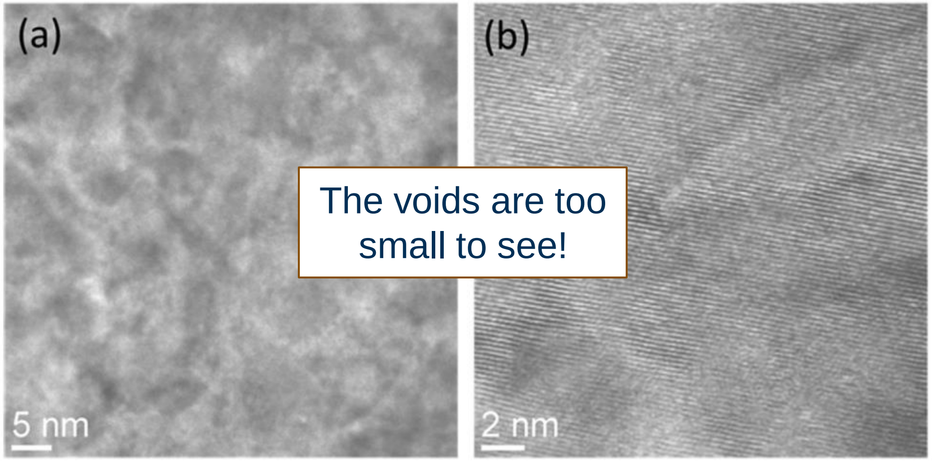
X. Yi *et al*., EPL **110** (2015) 36001

Radiation-induced strains and stresses





Tungsten implanted with 3000 appm He at 300ºC.



The voids are too small to see!

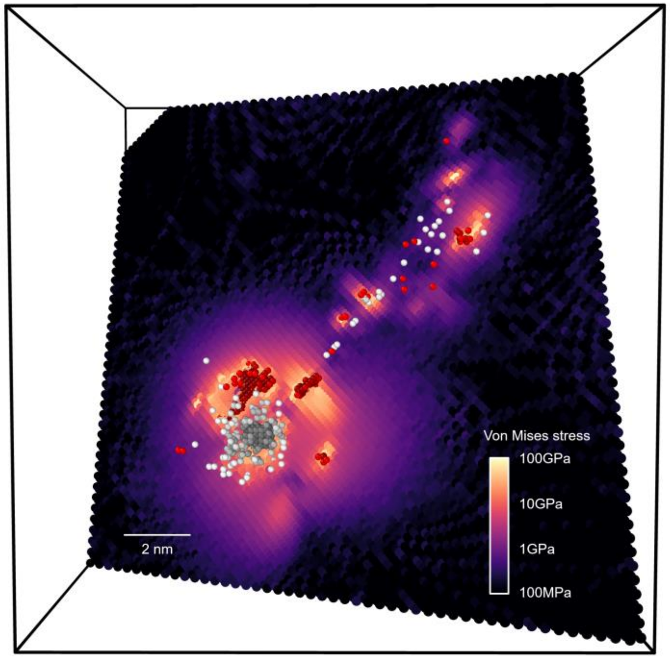
FIG. 4. TEM micrographs of the 3000 appm He implanted pure W. The image was recorded at ∼1 μm underfocus. No Fresnel contrast was observed in a through-focus series indicating no He bubbles are present.

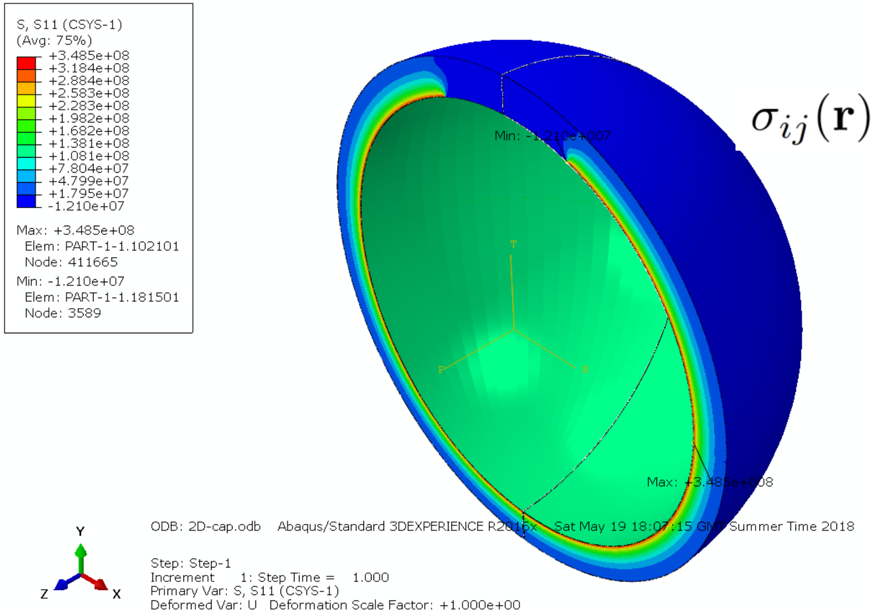
Radiation-induced swelling:

- volume increase due to formation of voids in the bulk and “redeposition”of atoms to the surface or grain boundaries.
- macroscopic strain due to local microscopic distortions from invisible atomic-scale defects.

F. Hofmann *et al*., Acta Mat. **89** (2015) 352

Radiation-induced strains and stresses – linking the micro to the macro





$$\sigma_{ij}(\mathbf{r})n_j = 0$$

$$\frac{\partial\sigma_{ik}(\mathbf{r})}{\partial x_k} + \rho g_i - B\alpha\frac{\partial T}{\partial x_i} - B\frac{\partial}{\partial x_i}\omega_{rel}(\mathbf{r}) = 0.$$

Theoretical models developed recently show how to compute strains and stresses not only on the microscopic scale, for example in the vicinity of defects produced by a cascade, but also on the macroscopic scale of reactor components. The treatment includes effects of gravity, thermal expansion and accumulation of radiation defects (entering in the ω_{rel} strain term, B = Bulk Modulus).

S.L. Dudarev *et al*., Nucl. Fusion **58** (2018) 126002

Materials Research Facility

- testing radioactive materials on a non-licensed site

- New building with hot cells and scientific equipment for universities, industry and UKAEA to do experiments **for fission, fusion and accelerator technology**.
- Process active material for analysis on-site or at universities
- Intermediate between universities (very low activity) and nuclear licensed site (Sellafield). MRF inventory limit ~ 3 TBq

- Not yet fully commissioned – but many users already from universities and other organisations. Some use already for accelerator R&D, more intended (discussions with STFC, CERN, Fermilab, BNL …). And UKAEA is using it for a range of fusion R&D, e.g. assessing plasma damage to Be and W tiles in JET.

Universities

~100 MBq

UKAEA

Medium activity, structural materials

~3 TBq (Co^{60})

NNL

At Sellafield, most active, fuel cycle

Materials Research Facility


Hot cells for processing, up to TBq


Shielded rooms, analysis up to GBq


Glove boxes for T up to 10 µSv/hr

Many of the following are already in use for inactive / low active samples and hazardous materials like Be. They will be gradually brought into use for GBq samples, from this autumn.

Microstructural characterisation: SEM (XRD, EDBS, TKD), Dual-beam FIB, Confocal Laser Scanning Microscopy with Raman, AFM, XRF, XRD for defect identification

Mechanical testing: Nano-indenter, Instrumented indenter, 10kN Universal testing machining, 15kN Dynamic load frame, 5kN in-situ load frame in the SEM, Impulse Excitation testing, DIC, Digital Image Correlation, Electrical Potential Drop, Ultrasonic fatigue testing.

Sample preparation in hot-cells and gloveboxes: Labscale EDM, Precision Ion Polisher, Sputter Coater, Dimple Grinder, Diamond wire saw, Electrolytical polishing

Thermo-physical analysis – Laser Flash Analysis, STA

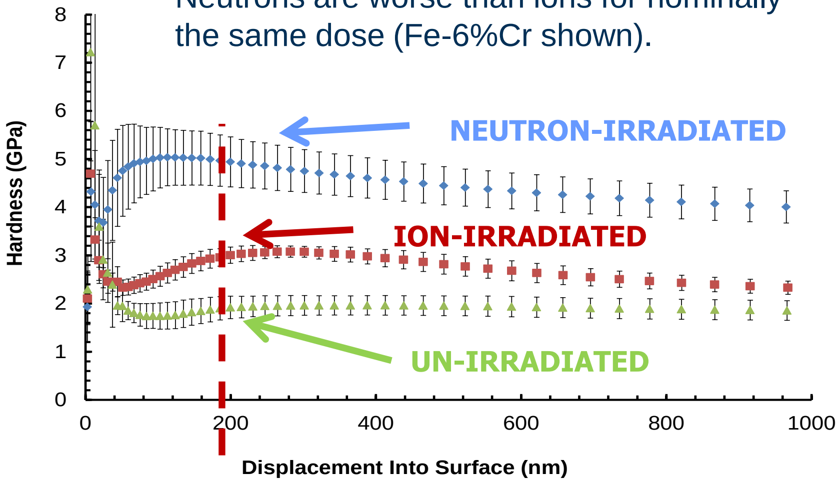
£73M of investment in UK nuclear research facilities over 3 years will be allocated later this year (NNUF Phase 2). We expect well over £10M to expand MRF's nuclear capabilities and range of scientific instruments.

http://www.ccfe.ac.uk/mrf.aspx

NNUF National Nuclear User Facility HENRY ROYCE INSTITUTE EPSRC CCFE CULHAM CENTRE FOR FUSION ENERGY

We need to irradiate materials in many ways to maximise understanding of radiation damage

- Irradiated samples are needed for tests at UKAEA's Materials Research Facility and other laboratories, with the properties measured compared with models.
- Fusion R&D is part of various international initiatives (e.g. under IAEA). And we participate in the accelerator collaboration RADIATE.
- Neutron irradiation (in fission reactors) is presently restricted to < ~ 1MeV, so doesn't reproduce the highest energy part of the fusion spectrum with little H and He generation. And it is time-consuming and expensive.
- Ion beams are cheaper and quicker and of various types, including dual and triple beam irradiation, some with real-time in situ diagnosis. But damage is at the surface and rate of damage is much greater → how useful are they for predicting the effects of neutron damage?



Neutrons are worse than ions for nominally the same dose (Fe-6%Cr shown).

→ Essential role of Modelling

→ A great need for a 14 MeV neutron source → IFMIF/ DONES, talk by Rafael Vila

Main Points

UK Atomic Energy Authority

- The focus of Fusion R&D in Europe and elsewhere is shifting to technology and materials while still improving the plasma to make best use of ITER and optimise DEMO designs.
- With large investment from the UK Government, UKAEA-CCFE has major new facilities for a range of fusion R&D – contributing to the EUROfusion programme and also having applications in related fields.
- Materials science – in particular how irradiation affects properties – is an increasing focus at UKAEA-CCFE, with a strong modelling team and a new Materials Research Facility for analysing properties of irradiated materials.
- Even when we have a fusion-dedicated 14 MeV neutron source (IFMIF-DONES), fusion R&D will have a continuing need for experiments using samples irradiated by both fission reactors and ion beams.