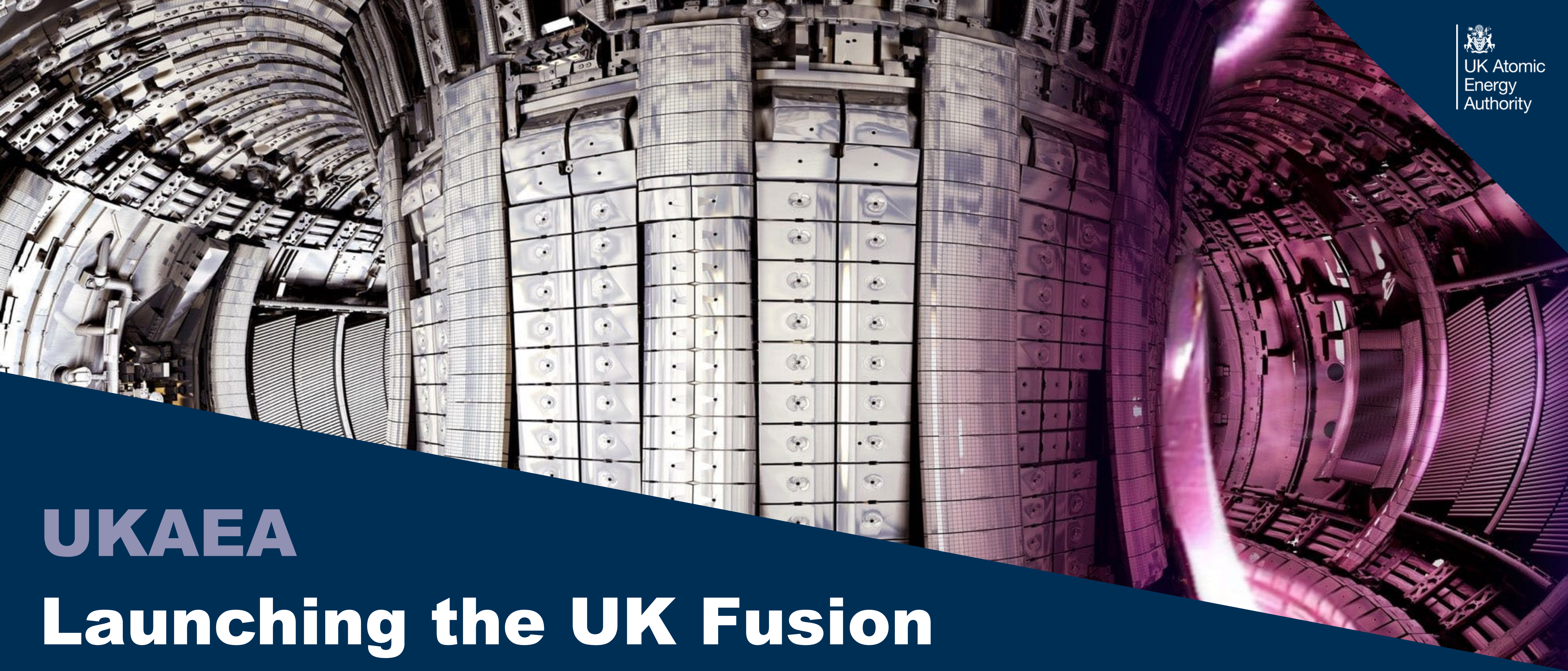


UK Atomic Energy Authority

# UKAEA

# Launching the UK Fusion Materials Roadmap

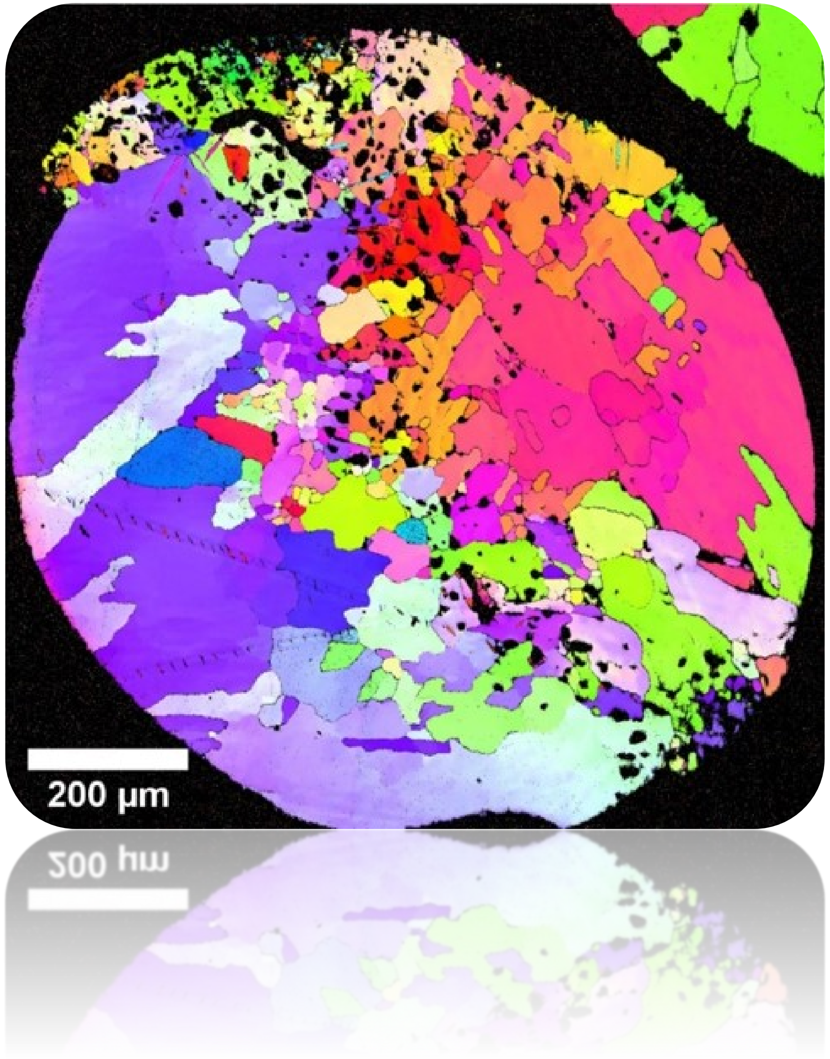
Dr Amanda Quadling, Director of Materials

Nuclear Academics Meeting, Cambridge, 7-8 Aug 2021

# A Roadmap for Fusion Materials

UK Atomic Energy Authority

- ✓ UK has committed to a **LOW CARBON** Energy future and to Fusion – Spherical Tokamak for Energy Production (**STEP**; prototype powerplant scoped for 2040)
- ✓ The fusion reactor environment is possibly the most extreme environment any material will face. We face a sizeable task to address the triple whammy in fusion materials: **TRITIUM, TRANSMUTATION AND DISPLACEMENT**
- ✓ A **PROGRAMMATIC APPROACH** is favoured to ensure timely delivery. Researchers and funders need to reference a common path / plan..



# A seven month group effort..

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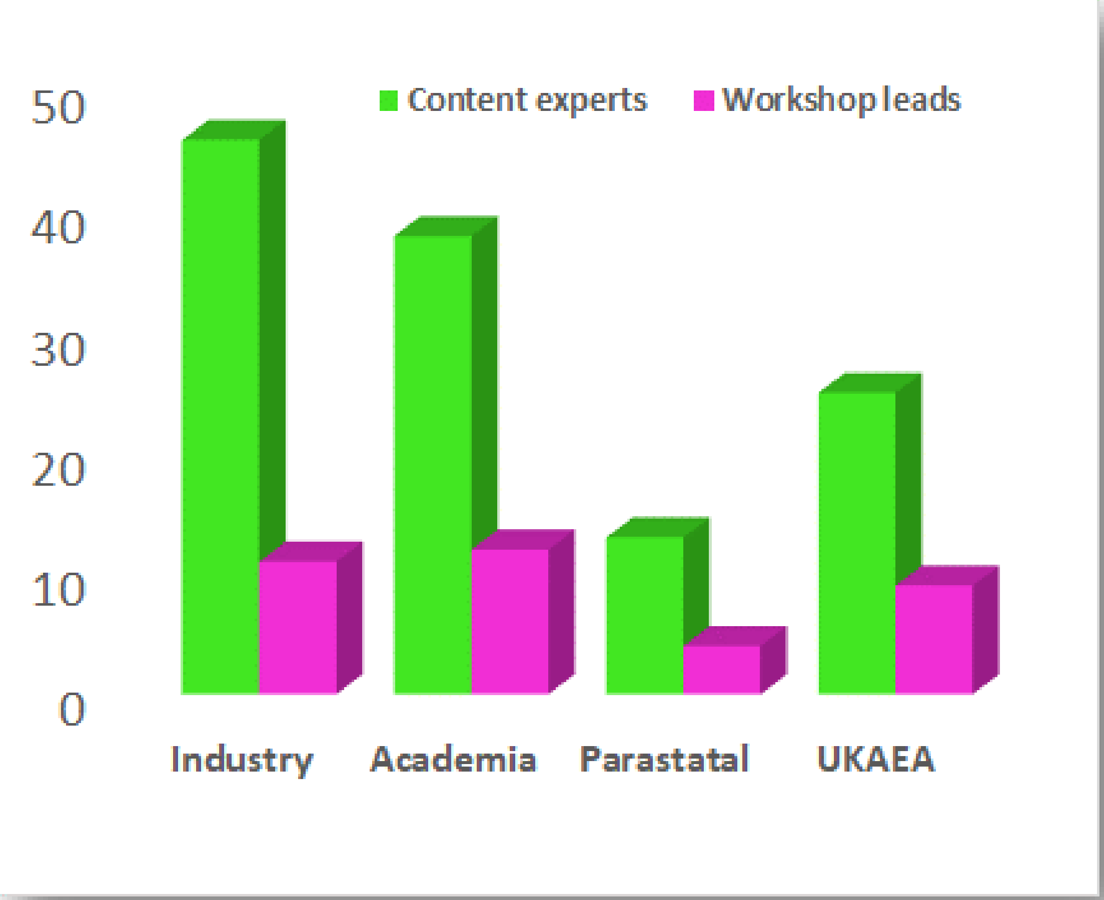
- ✓ Henry Royce Institute sponsored 4 workshops, facilitated by IfM.
- ✓ UKAEA ran two further consultations and a survey.
- ✓ A national editorial team worked to finish final document.




HENRY ROYCE INSTITUTE

UNIVERSITY OF CAMBRIDGE Department of Engineering

IfM Engage

# Roadmap team within Materials Division at UKAEA

UK Atomic Energy Authority

**Director of Materials**
Dr Amanda Quadling

**Head of MRF**
**Materials Testing**
Due end 2021

**Head of Programme – Neutron Materials Interactions**
**Modelling, Nuclear Data and Experiment**
Dr Mark Gilbert

**Head of Programme – Materials Science and Engineer**
**Materials development and routes to qualification**
Dr Jim Pickles

See the damage

Understand the damage

Survive the damage

Nuclear Data and Waste

**Lead – Materials For Fusion**
*(low TRL)*
Dr Dave Bowden

**Lead – Materials for STEP**
*(high TRL)*
Dr Chris Hardie

Metallurgy

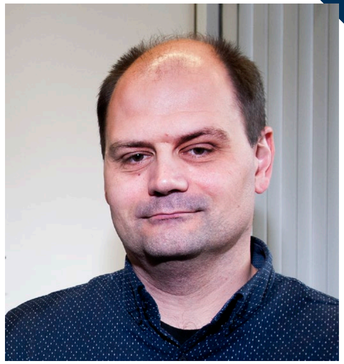
Irradiation campaigns

# Editorial team

**Dr David Armstrong (Oxford University)**

**Dr Amy Gandy (University of Sheffield)**

**Dr Sandy Knowles (University of Birmingham)**



**Dr Karl Whittle (University of Liverpool)**

**Dr Andrew Bowfield (Henry Royce Institute)**
Business Development Manager: Nuclear Materials

**Dr Steven Jones (NAMRC)**
CTO / Lead High-Value Manufacturing Catapult's Joining Technology

**Dr Jon Hyde (National Nuclear Labs)**
Jon is Senior Fellow in Materials and Head of R&D

**Jack Astbury (Tokamak Energy)**
Reactor Technology Manager

# Materials as enabler across the Fusion Roadmap

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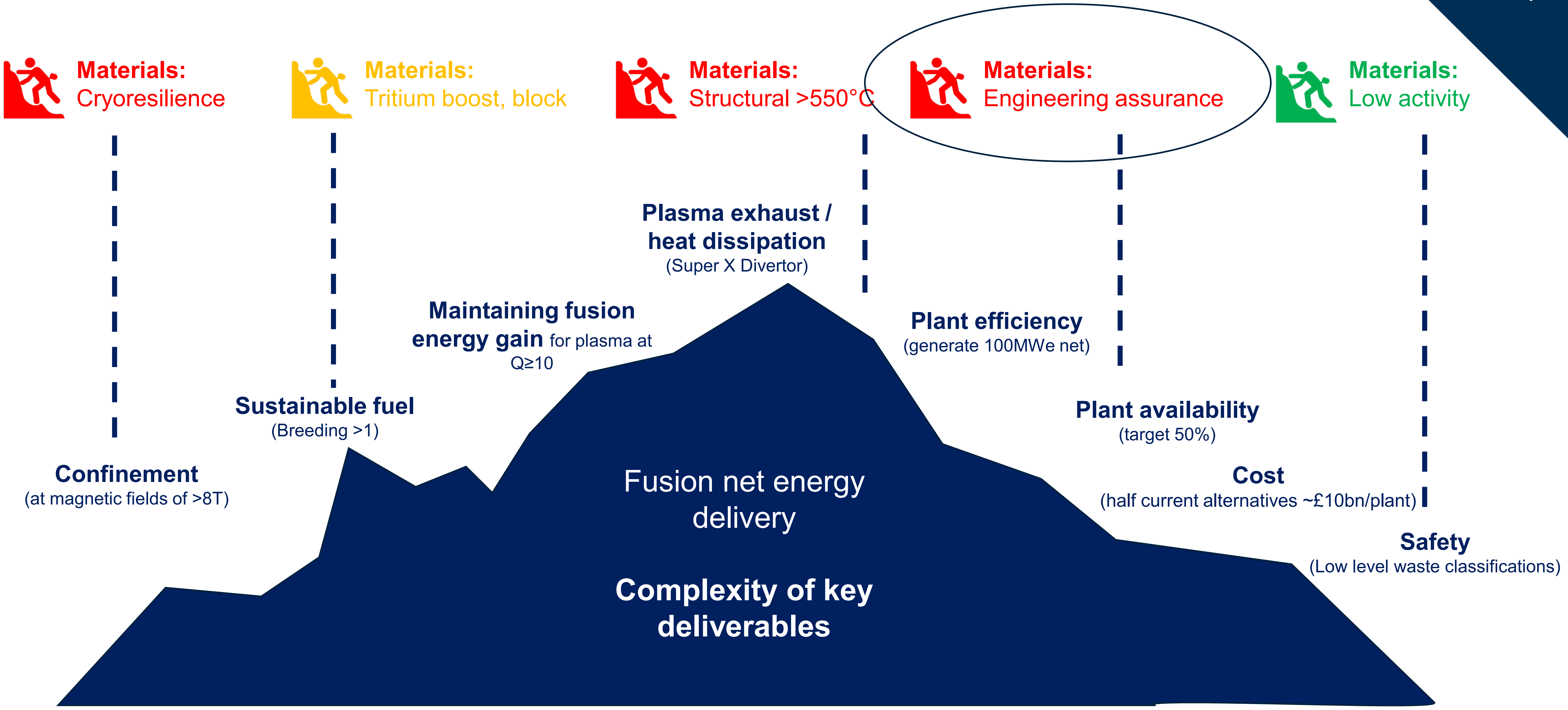


# Generic requirements – materials in fusion

UK Atomic Energy Authority

Resource 1

**TO DEVELOP EACH NEW FUSION MATERIAL (OR MATERIAL FAMILY), WE NEED TO:**

| | |
|---|---|
| **Determine performance under irradiation** | Characterise the impact of neutron dose on prioritised mechanical properties (creep, toughness, and particularly DBTT in bcc options). Qualify the impact due to displacement damage (typically short timescale experiments) vs that due to transmutation / compositional effects (longer timescale experiments or experiments with gas implantation and varying starter compositions). Where proxies are used for neutrons, qualify outcomes accordingly. |
| | Determine the synergistic effect of other loads applied simultaneous with irradiation (mechanical, thermal, magnetic, electrical, cryogenic)? Stress combinations and stress cycling data adds value. |
| **Demonstrate microstructural and chemical link/s to irradiation resilience** | Determine how crystallography – as well as the interfaces / grain size/ distribution/ density and size of precipitates (ODS, nanostructured steels) - impact defect structure, scaling and propagation. |
| | Evaluate the dependency between chemical bond energies and defect structure and propagation (density functional theory has indicated the latter is dependent to some extent, on the former). |
| **Explore likely temporal evolution of bulk properties under operating conditions** | Establish whether there is a hysteresis characteristic over multiple irradiations or potential for new degradation mechanisms over time (for example, in fission there is concern about late blooming phases or late onset embrittlement) |
| | Describe and understand evidence for damage recovery / annealing / saturation relative to time, dose and temperature. Qualify for irradiation source. Do some microstructural elements improve resilience over time, under dose? Does dose over time obviate optimised microstructures? |
| **Understand the fuel interface** | Determine whether, and to what extent, the material – post irradiation – retains deuterium and tritium. Establish the trapping mechanism or link to degradation phenomenon. |
| | Determine the route to, and rate of, permeation of fuel (useful for safety and fuel budget perspectives). |
| **Develop safer variants** | Evaluate the potential to 'swop out' elements within the compositional space, for those less prone to long half lives, while maintaining microstructural benefits established to this point, especially for mechanical properties (ie. develop low activation variants). |
| | Evaluate impact of microstructure on spallation and delamination under plasma conditions to improve waste control / safety. |

# DIRECTION OF TRAVEL: Irradiation - Summary

Resource 2

UK Atomic Energy Authority

**Experiments for nuclear data**

- Integral cross section data → Differential cross section data
- Neutronics benchmarking
- Uncertainty quantification

**Experiments to enhance breeder materials**

- Development of compact neutron source experiments → Full breeder mock ups
- Optimisation of neutron transfer, amplifier materials → Development of tritium extraction microstructures

**Experiments to underpin and validate damage modelling and to down select materials**

- Ion / proton experiments for bulk material properties
- Dual beam with /without gas implantation for bulk material properties
- Materials test reactor experiments on fabricated materials
- (IFMIF DONES) / ITER for fusion neutron spectra → Prototype plants

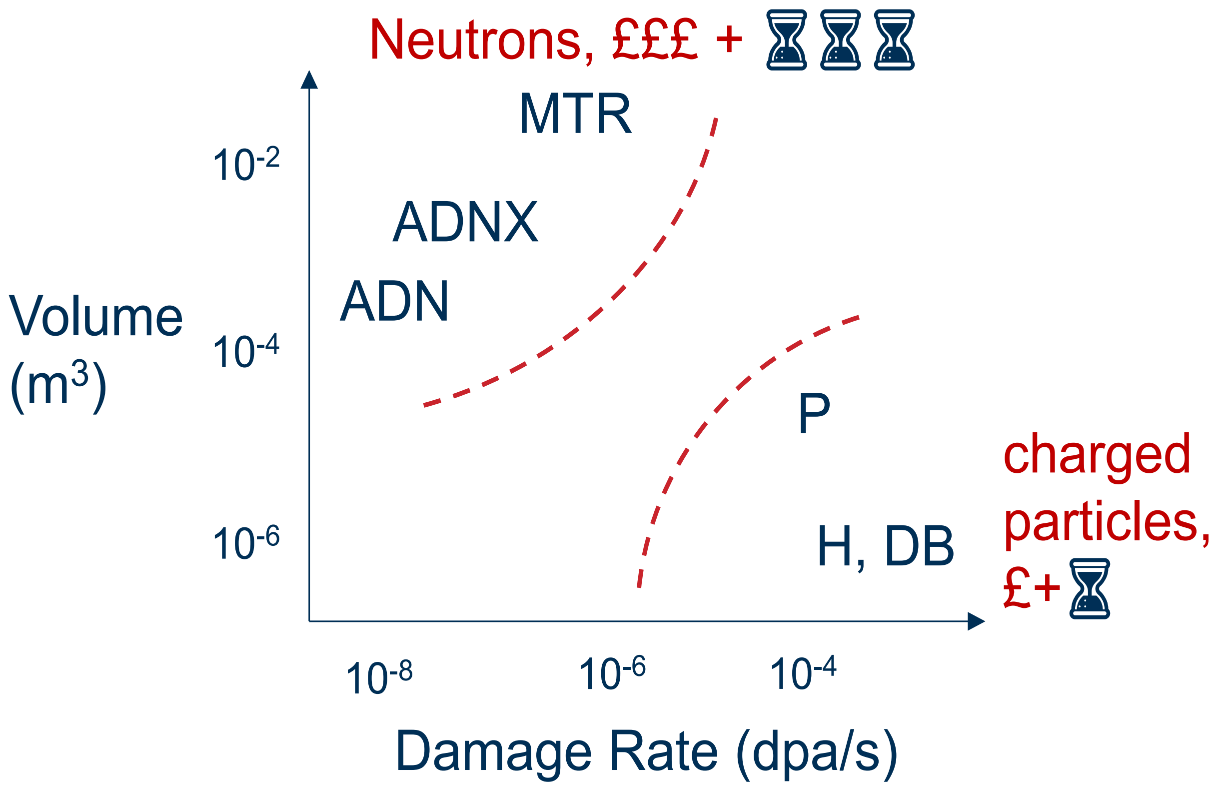
**Experiments to provide engineering assurance on components and joins**

- Mechanical property testing for failure mode analysis
- Testing of complex materials / joins
- Temporal evolution of damage
- Combinatorial load analysis → Proof testing to failure

# Use of irradiation sources

Resource 3

UK Atomic Energy Authority




*   Neutron energy spectra not DT fusion
**   Transmutation gas production by doping can cause artifacts
***   Extremely high cost

**Phenomena**

1 – Displacement Damage
2.1 – Transmutation Gases
2.2 – Transmutation Solids

**Rate**

L – Low (sub dpa)
H – High (10 dpa)
D - Dynamic

**Volume**

S – Small (μm - mm)
B.1 – Big (10s – 100s μm)
B.2 – Big (mm)

| | Radiation Source | Damage Phenomena | Damage Rate | Volume |
|---|---|---|---|---|
| H | Charged Particles (Heavy Ions) | 1 | H | S |
| DB | Dual Beam | 1, 2.1 | H | S |
| P | Protons | 1 | H, D | S, B.1 |
| ADN | Accelerator Driven Neutrons | 1, 2.1*, 2.2* | L | S, B.1, B.2 |
| ADNX | Future Facilities | 1, 2.1*, 2.2* | L | S, B.1, B.2 |
| MTR | Materials Test Reactors | 1, 2.1** | H, D*** | S, B.1, B.2 |

# Local irradiation sources

Resource 4

UK Atomic Energy Authority

High flux ($10^{12}$ n/cm$^2$/s)

Useful UK beams and sources

Low flux ($10^4$ n/cm$^2$/s)

Inertial electrostatic confinement neutron source (fusor style) being explored at **University of Bristol**, taking account of Japanese studies – may use ASTRAL* or microNOVA* type source

**ASP** at AWE (neutron)

Compact neutron source facility ($10^{12}$ n/cm$^2$/s) being scoped for Sellafield for 2025 (**Project STELLAR**) – may use Phoenix* type source

**Phoenix, ASTRAL, microNOVA are commercial systems*

**Birmingham cyclotron** (proton beam) – Additional in-situ corrosion+proton setup imminent: 650°C $H_2O$, molten salt, 1000°C with loading vacuum or $O_2$ atmosphere; stress rig installation Oct 2021

**Birmingham high flux accelerator** driven neutron source – Coming onstream 2022

**Dalton Cumbrian Facility** – Dual beam capability coming onstream H2, 2021 (ion and protons)
For irradiation + Stress: DCF are developing a Deben rig to support the irradiation of thin ~20 µm samples under load, with in-situ DIC to measure creep strains as a function of the irradiation.

**MIAMI** - Surrey Ion Beam Facility (ion beam)

2020 | 2022 | 2024 | 2026 | 2028

**INTERNATIONAL MATERIALS TEST REACTORS include:** HFIR (USA), BOR60 (Russia), ANSTO (Australia), NRG (Netherlands), NCBJ (Poland), BR2 (Belgium), LVR-5 (Czech Republic), KURRI (Japan) etc. **FUSION NEUTRON GENERATORS include**: Frascati (Italy), NG TUD (Germany) and HINEG (China)

Resource 5

# POST IRRADIATION EXAMINATION FACILITIES IN THE UK

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## MRF IN 2021

**Mechanical:**
nanoindenter, small scale tensile tester, ultrasonic fatigue rig, impedance spectroscopy

**Microstructural:**
FIB, SEM, Atom probe

## MRF IN 2023

**Mechanical:**
- dynamic (standard scale) tensile / compression testing

**Thermophysical:**
- DSC, TGA, Laser flash, DIlatometer

**Microstructural:**
- Plasma FIB, TEM

## MRF IN 2025

+ sample archive

## NNL IN 2021

**Highly Active:**
Visual Inspection, measurements, Fuel analysis (fission gas, isotopics), density measurements, thermal properties, LOM, SEM, sample fabrication/ size reduction, electrical resistivity, fracture properties, strength testing, elastic properties, Pycnometry, GasDiffusivity/Permeability

**Medium & Low active:**
Low + medium load strength testing, micro/macro hardness, LOM, SEM (+WD, EBSD), (FEG) TEM (+EELS), FIB (+cryostage), PFIB (+SIMS), Laser flash, Raman, DSC, TGA, elastic properties, Pycnometry, Gas Diffusivity/Permeability, Machining

## NNL IN 2023

**Highly Active:**
- laser Raman (3 λ)
- micro indenter, profilometry
- hydrogen charging
- electrochemistry
- small scale tensile testing
- H analysis

**Medium & Low active:**
- ultramicrotome
- XRD

## NNL IN 2025

**Highly Active:**
- small scale punch testing
- sample archive
- laser flash
- LIBS

**Medium & Low active:**
- sample archive

# Modelling – 'Roadmap within a roadmap'

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**Resource 6**

## MODELLING – Multiple levels of activity required from understanding damage mechanisms to predicting materials failure

To predict onset of failure in components during operation.

### MULTI PHASE/MULTI GRAIN/WELDS (MICROSTRUCTURAL APPROACH)

Direction and approximate magnitudes/ rates of change for selected properties based on key failure modes, is required, on down-selected materials, in the **SHORT** term.
It will be vital to account for environmental conditions in the models (e.g. coolant).
The link between damage and changes to thermal conductivity and other bulk properties should form part of this work.
MOOSE framework (multi-physics C++ outputting directly to FEA) is available for Crystal Plasticity Finite Element Modelling to undertake such predictions but other platforms (and isogeometric algorithms) should also be considered. Can we use peridynamic modelling?
Refined and more accurate predictions with mechanistic understanding are required in the **MEDIUM** term for improved science on microstructural evolution.
Predictive models continuously validated with surveillance testing during operation, are envisaged **LONG TERM.**

To predict macroscopic stress and strain in materials during operation.

### STITCHING LENGTHSCALE AND TIMESCALE

A whole problem approach is advocated, to simulate materials responses in situ, applying tokamak operating conditions (especially dose-temperature of immediate environment).
Use of an elastic dipole tensor in Density Functional Theory – as well as Crystal Plasticity approaches -will enable moving from atoms to continuum modelling.
Evolution of materials at doses >0.1dpa is non linear and requires priority efforts in the **SHORT term.**
Quantitative models for deformation, including transmutation effects, should be possible in the **MEDIUM term.**

### SINGLE PHASE – SINGLE GRAIN (ATOMISTIC APPROACH)

Density functional theory and molecular dynamics have been used to deliver extensive understanding of DEFECTS in some *structural materials* moving to thermal equilibrium:
**Size and saturation** (power law pertains moving from point defects to dislocations)
**Structure** (is determined by local chemical bonds rather than elastic energy)
**Density** (brings high stress, triggering avalanches, leading to dislocation networks and defect clusters)
**Non linearity** (occurs as volume strain may be high where lattice strain is not; latter is lower due to pseudo planar effect of aggregated defects)
**Mobility** (determined by a critical threshold density of lattice obstacles)
**Volume** (increase is high for interstitial defects but not equal-and-opposite for dimensional changes brought about by void defects)
TRANSMUTATION triggered embrittlement lifetimes have been calculated for elements in mainstream DEMO materials.
More work is needed on a *wider range of materials (breeders, magnets, shields, insulators etc).*
Work on impact of nanoparticles (within grain / at grain boundary) is required.

2018 | 2020 | 2022 | 2024 | 2026 >>>

Resource 7

# MODELLING FOR PERFORMANCE ASSURANCE ON IRRADIATED MATERIALS – UKAEA effort to 2021

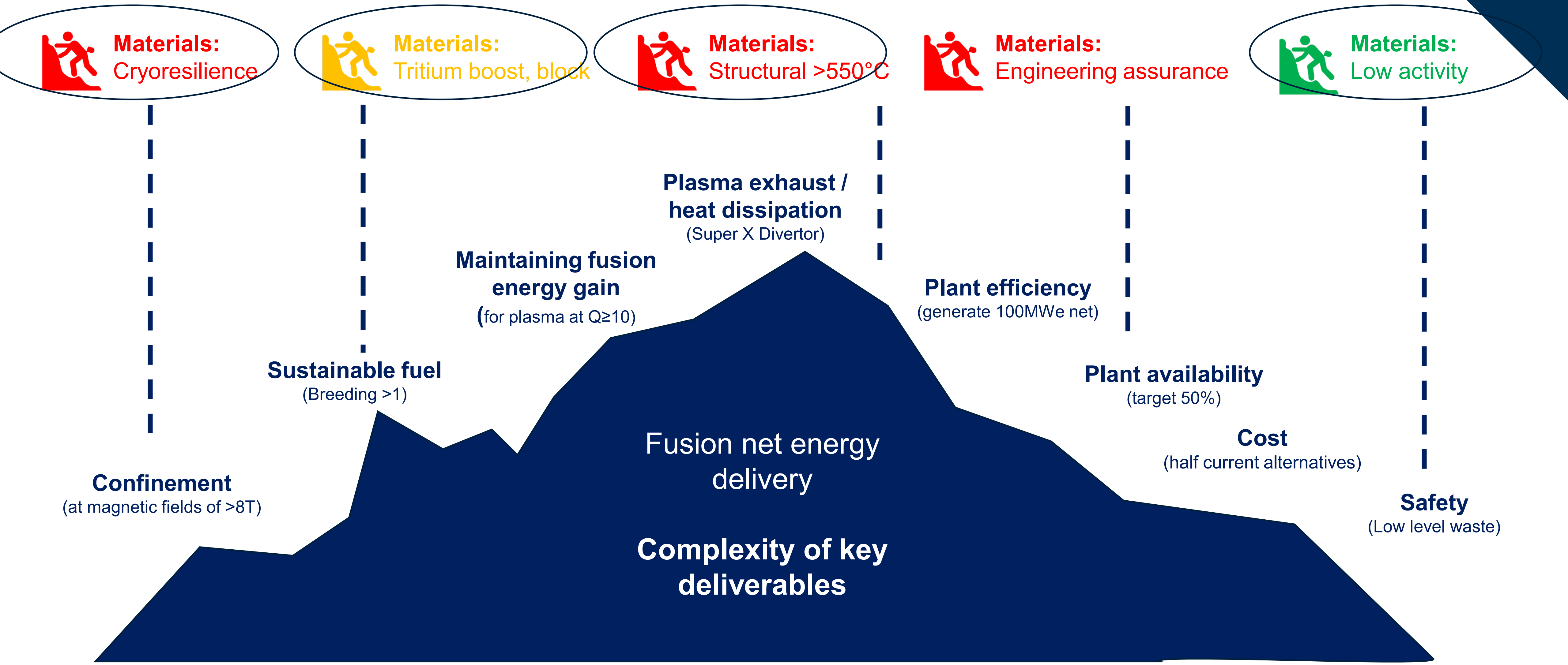
UK Atomic Energy Authority

| Baseline materials for STEP and DEMO, and some nearest alternatives | Engineering scale | | | | |
|---|---|---|---|---|---|
| | Base materials: displacement damage | Base materials: transmutation damage (including gas) | Base materials: Tritium retention | Engineering materials: radiation hardness | Engineering materials: Failure mechanisms |
| **Structural materials**<br>• EUROFER<br>• Castable RAFM complex nanostructured alloy<br>• ODS | Fe, FeCr | Fe, FeCr | Only relevant with sub-optimal barrier coatings | Only for FeCr | |
| **Armour materials**<br>• Tungsten<br>• Other metals & alloys (Be, SMART) | | | Only relevant with sub-optimal barrier coatings | W, less for alloys | |
| **High heat flow materials**<br>• CuCrZr | Cu | | | | |
| **Breeder materials (substrate / breeder / amplifier)**<br>• SiCf-SiC composite<br>• Li ceramics<br>• $BeTi_{12}$<br>• Liquids (LiPb) | | Basic neutronics | N\A – extraction based on destructive methods as required | | |
| **Magnet materials**<br>• resistive aluminium<br>• $Nb_3Sn$ / NbTi doped<br>• REBCO | | Neutronics | N/A | | |
| **Window materials**<br>• Beryllium, Molybdenum, Silica | | Neutronics | | | |

Not attempted  Underway  Completed

# Materials as enabler across the Fusion Roadmap





# Specific requirements – materials in application specific contexts

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## DIRECTION OF TRAVEL

### METALS AND ALLOYS (STRUCTURAL / HEAT SINK / ARMOUR)

| | | | |
|---|---|---|---|
| Castable variants - Complex Nanostructured Alloys (CNAs) | Optimise high temperature mechanical properties (especially creep) through novel thermomechanical treatments on RAFM variants at fabrication scale (new quench, temper sequences). | Explore alternative size, density, locatio[n] (carbides, nitrides, aluminides) to optimi[se] allow casting in first instance. | |
| Powder metallurgy variants - Oxide Dispersion Strengthened (ODS) Alloys | Tune yttrium oxide content to reach acceptable balance between formability and irradiation resilience /high-temperature performance. | Improve consistency in powder metallurgy methods (superior powder sizes/ morphologies) to optimise stoichiometry to reduce O, N and C contaminants and decrease activation in service. | Optimise homogeneity a[…] at scale. May be assiste[d] alloying such as the Surf[…] of gas Atomised powder[…] Reactive Synthesis (STA[…] |
| Grade 91/92, RAFM and austenitic (316SS) steels | Priority is to find a high temperature (>550°C) ferritic martensitic variant - pushing past current ductile to brittle transition temperature challenges. | Austenitic improvements in irradiation […] accommodate transmutation He (inclu[…] | |
| Boron-strengthened steels (e.g. MARBN) | Can we replace Co in these? | Control rods contain Ni which needs lower activation alternative. | |
| CuCrZr | Priority is to find a high temperature (>300°C) variant for heat sinks. | Self passivating surfaces needed for plasma facing variants in the event of oxygen exposure – focus on recrystallisation. | Address coolant corrosion issues. |

Chronology based on priority or building complexity →

**Examples**

## DIRECTION OF TRAVEL

### CERAMICS AND COATINGS (BLANKET WALLS, CIRCUIT COATINGS, FLOW SEPARATORS)

| | | | | | |
|---|---|---|---|---|---|
| CERAMIC MONOLITHS | Compare impact of manufacturing routes (e.g. SITE, NITE, CVI, PiP, polymeric precursor 3D printing) and architectures on relative irradiation resilience of resulting microstructure. | Develop Transient Phase Liquid Bonding compatible with fusion-relevant materials. Evaluate joinability with metals. | Consider thermo electric ceramic elements for heat-electrical conversion direct to plant. | | |
| CERAMIC COMPOSITES: SiCf-SiC, TiC, ZrC, HfC variants, Tungsten carbide, Mullite-mullite | Compare known benefit of neutron transparency of SiC with sparse data on irradiation breakdown of C in this composite at 14 MeV in context of breeder front wall or continuous (non welded) breeder structure. | Understand relative impact of SiC fibre nano-crystallinity vs strength of fibre-matrix interface on irradiation resilience. | Find alternative, lower activation and non-pyrolysing interphase materials, relative to graphite. | Explore alternative weave architectures and impregnation styles to modify electrical and radiation reflection at phase interfaces. | Understand role of macroscale porosity vs microscale atomic lattice layers for helium permeation and release under transmutation. |
| COATINGS: $AlO_x$, $Er_2O_3$, nitrides (CrN, BN) | Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C. | Corrosion trials utilising static and flowing conditions, with oxygen content monitoring. | Tritium permeation trials up to temperatures of 650°C. | Evaluation of additive manufacture (AM) to apply coatings to complex geometries. | Stacking trials to optimise thickness vs delamination. |

### CERAMICS (BREEDERS AND AMPLIFIERS)

| | | | | |
|---|---|---|---|---|
| CERAMIC SYSTEMS: Li orthosilicate, Li metatitanate, Li zirconate, Alternatives with lead | Improve crush resistance in pebble breeder ceramics and explore alternative physiologies to pebbles. | Define required $^{6}Li$ enrichment. | Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C. | |
| | Mitigate segregation of non-multiplying zones in $BeTi_{12}$ as amplifier. | Mitigate U impurity in Be amplifier compounds. | Identify and investigate alternative Li multiplier composites as well as broader suite of multipliers: $LaPb_3$, $Zr_5Pb_4$, $YPb_2$. | Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C. |

Chronology based on priority or building complexity →

# SUMMARY

## Key waypoints in fusion landscape

| | 2020 | 2024 | 2028 | 2032 | 2036 | 2040 |
|---|---|---|---|---|---|---|
| Key waypoints in fusion landscape | • STEP concept design starts | • ITER first plasma<br>• STEP concept design review | • DEMO Conceptual Design Consolidation | • STEP build starts | • ITER high power operation | • STEP first plasma<br>• DEMO build starts |

| Fusion Roadmap driver | Materials Roadmap | Near Term | Stretch Targets / Disruptors |
|---|---|---|---|
| New regulatory framework for fusion without high level waste | **Enable low activation waste predominance in fusion** | ▪ Weldable, cost-effective Reduced Activation Ferritic Martensitic (RAFM) structural materials<br>▪ High purity raws for armour, structure, divertor baseline materials<br>▪ Full tritium inventory model across plant material interfaces (first wall, cooling circuit, detritiation plant) | ▪ 'Dust'-free armour materials for safe recycling |
| Breeding ratio >1; fuel self sustainability | **Boost breeding ratio, block tritium losses** | ▪ New breeder materials beyond orthosilicates and titanates, developed via UK compact neutron source facility<br>▪ Mitigate segregation of non-multiplying zones in $BeTi_{12}$ amplifier<br>▪ Tritium permeation barriers for balance of plant | ▪ Additive manufactured Li ceramic as continuous blanket<br>▪ Feasible alternative multipliers ($LaPb_3$, $Zr_5Pb_4$, $YPb_2$)<br>▪ Optimised tritium extraction microstructures |
| High fusion energy through effective confinement at high magnetic fields (>8T) | **Define the possible in irradiation resilient magnets, insulation at cryogenic temperatures** | ▪ Irradiation tests on REBCO to E>0.1MeV / ~0.001 dpa (current limit) at operating T, spectrum, B<br>▪ Improved insulation e.g. novel amorphous ceramics or imides<br>▪ Understanding of annealing path in irradiated cryogenically-cooled resistive aluminium | ▪ Cryogenic irradiation tests on REBCO beyond ~0.001 dpa (aiming for overtest to 0.1dpa) |
| Plant efficiency (100 MWe) | **Develop higher temperature structural materials (>550°C)** | ▪ Fabrication-scale microstructural tuning of castable complex nanostructured alloys (carbide / nitride / more inert precipitates) to reach >600°C<br>▪ Optimised SiC-SiC composites (nanostructured SiC fibre for enhanced irradiation resilience; pyrolysis free interphases; transmutation gas routine architecture) | ▪ Weldable and lower cost ODS / HiP'd powermetallurgy variants to reach 700°C<br>▪ Additive manufactured divertor materials with integrated cooling structures<br>▪ Thermo electric first wall /divertor material for direct plant output contribution |
| Plant availability (50%) and cost (£10bn) | **Deliver engineering assurance for materials under powerplant conditions** | ▪ Synergistic dual ion beam irradiation campaigns (proton + load; proton + corrosion; proton + cryo) on baseline materials for low dpa mechanical property degradation<br>▪ First Finite Element based failure prediction models *across* microstructures<br>▪ Simulated in situ (dose-temperature conditions) material response via 'whole problem approach' utilising physics-derived atomistic response laws | ▪ Synergistic irradiation campaigns (neutron + load; neutron + corrosion; neutron + cryo) on baseline and novel materials with emphasis on high dpa impact quantification on mechanical properties (especially creep-fatigue)<br>▪ Stitched length- and time-scale failure prediction models<br>▪ Modelled transmutation gas impact on mechanical degradation |

# Next steps…

UK Atomic Energy Authority

- ✓ This Roadmap aims to place before the UK materials community a **STARTING POINT** – there should be iterations of the narrative as familiarity grows
- ✓ It has been **LOCALLY SHAPED** but there are many opportunities to **COLLABORATE INTERNATIONALLY**
- ✓ Early hooks are offered for the UK materials **SUPPLY CHAIN** and **REGULATORS** so vital to delivering commercial fusion
- ✓ The aim is to gather stakeholders around common themes and **GENERATE MOMENTUM** - there is an implied invitation to get involved – from experiment to investment and planning…. Via a **National Steering Group** (~ Editorial Group)

ITER (2025) → STEP BUILD (2032) → STEP (2040) → DEMO (2050)

# Next steps - I

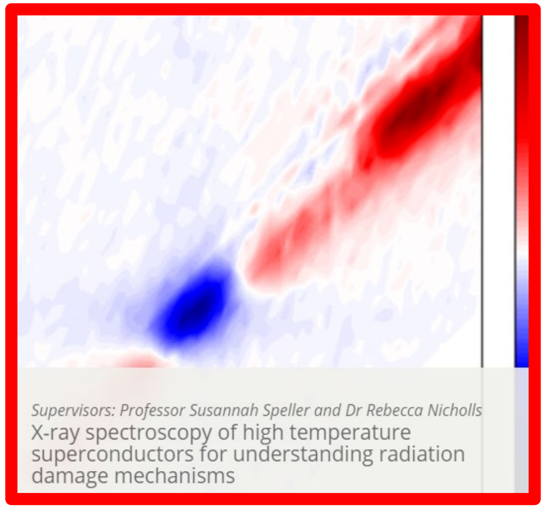
**Materials:**
Engineering assurance

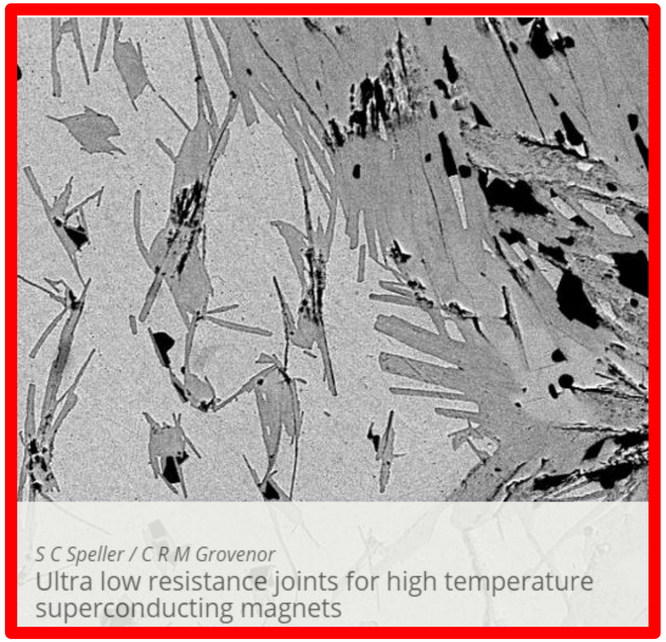
**Materials:**
Structural
>550°C

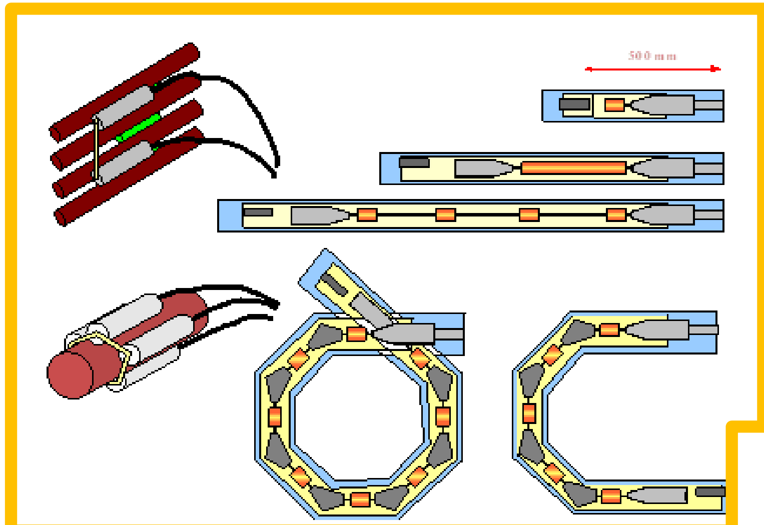
**Materials:**
Cryoresilience

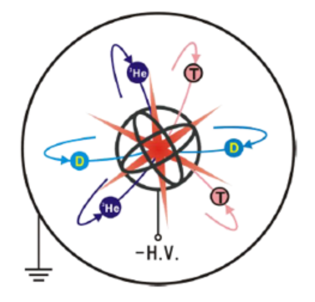
**Materials:**
Tritium boost,
block

**Materials:**
Low activity

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# Next steps - II

**Materials:** Engineering assurance

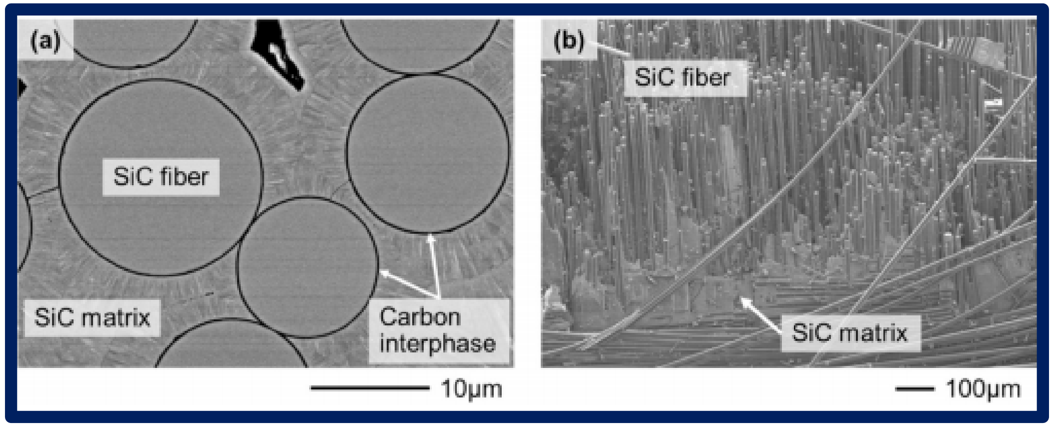
**Materials:** Structural >550°C

**Materials:** Magnets > 8T

**Materials:** Li based breeders

**Materials:** Low activity

## SiC SiC working group

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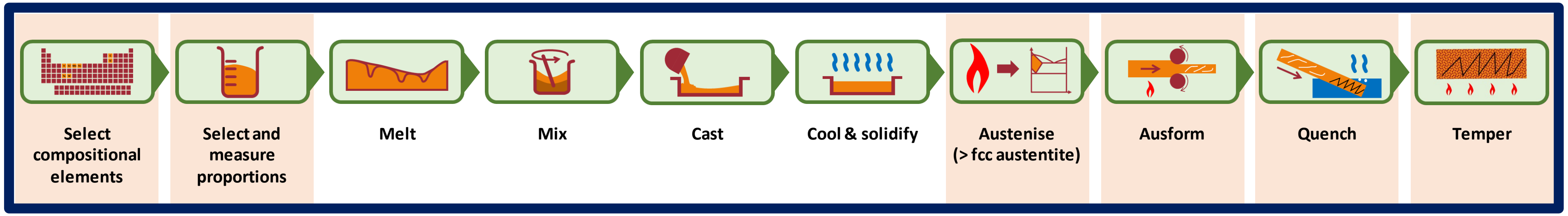
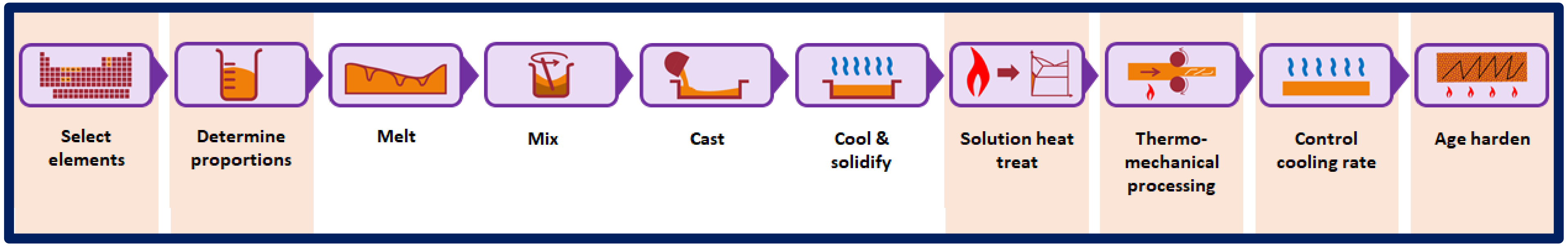
## NEURONE bid

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The University Of Sheffield.
MANCHESTER 1824 The University of Manchester
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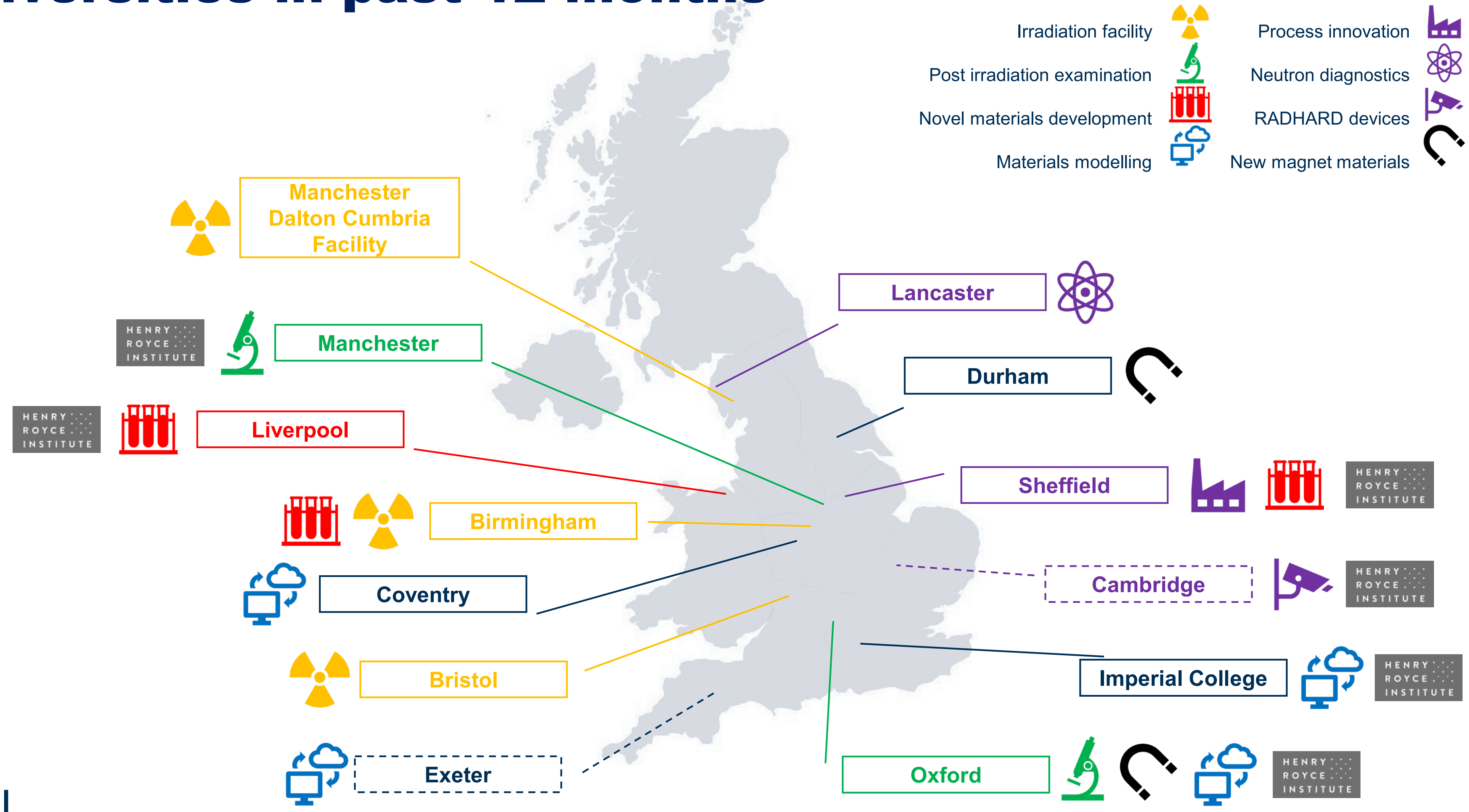
# UKAEA Materials: Roadmap interface with UK universities in past 12 months

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