

Innovations in Materials

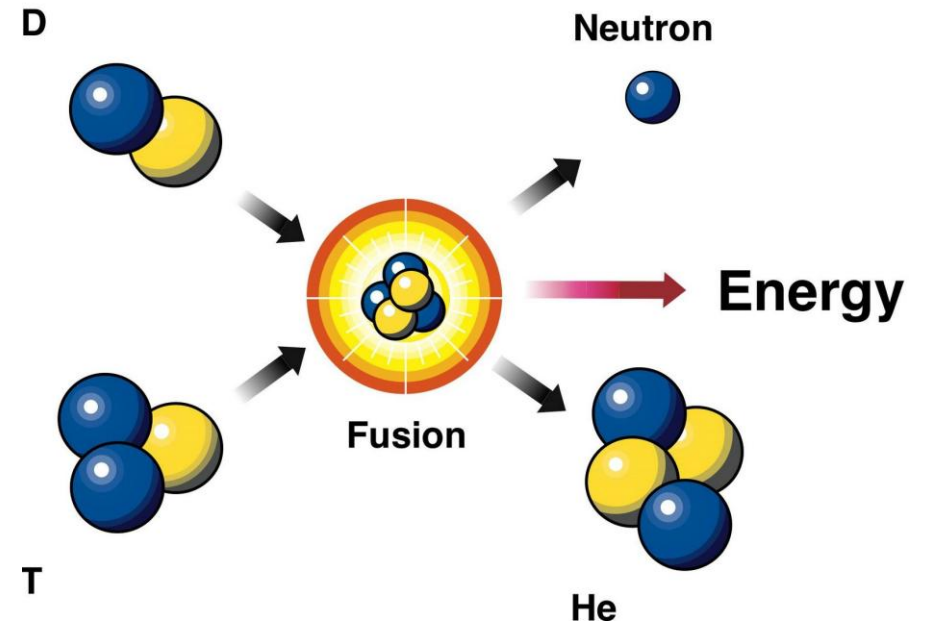
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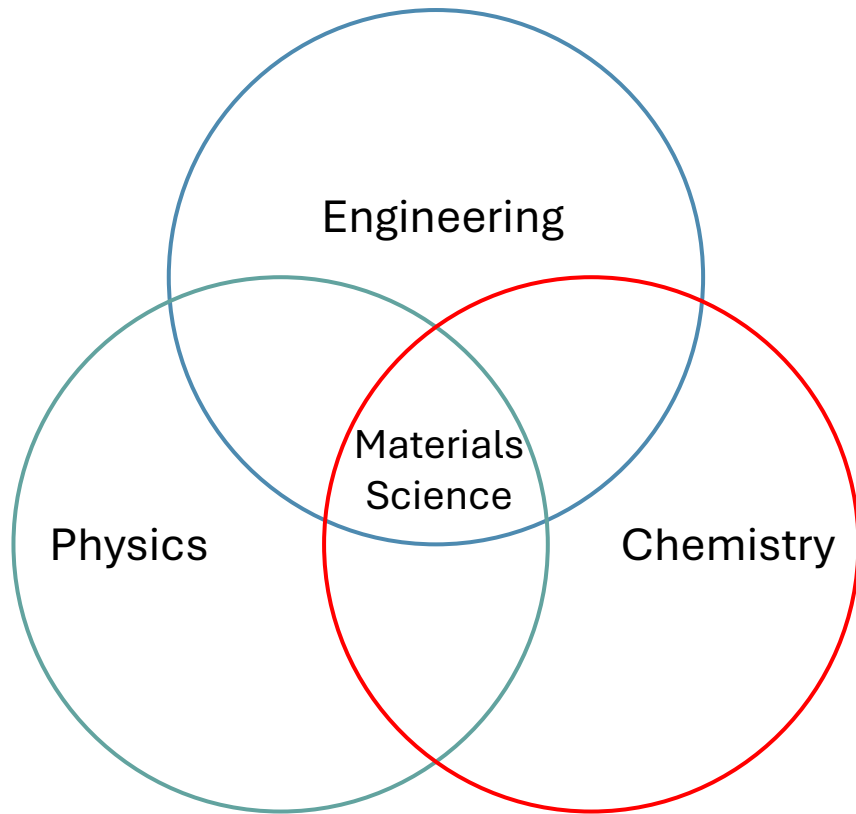


Background

- Materials Science MEng, University of Oxford (2015-2019)
- Materials Science DPhil, University of Oxford (Fusion CDT) (2019-2023)
 - Atom probe tomography analysis of Nb₃Sn superconducting wires for fusion reactor and particle accelerator applications
- Associate Fusion Engineer, IAEA, 2024-2026
- Senior Technologist, StandardX 2026-



What is Materials Science?



An interdisciplinary subject which explores the fundamental structure, properties and behaviour of materials. In understanding how materials behave we can engineer new and improved materials.

Modern Materials Science came from Metallurgy. In the 19th century it was shown that thermodynamic properties of a material are related to the physical properties of a material.

What is Materials Science?

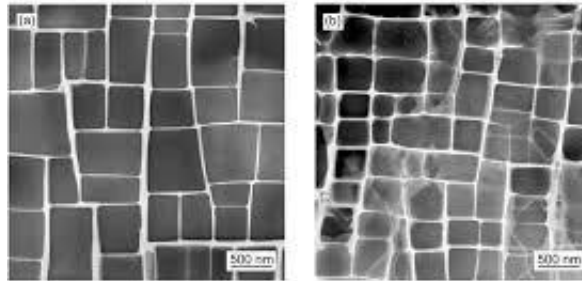
Processing



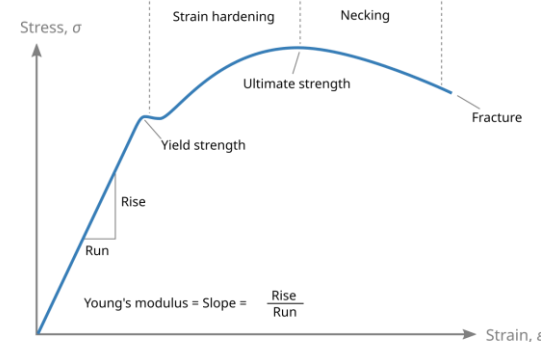
Casting, molding,
welding,
sputtering,
extruding ...

Structure

Scale= 10 millionth of a metre



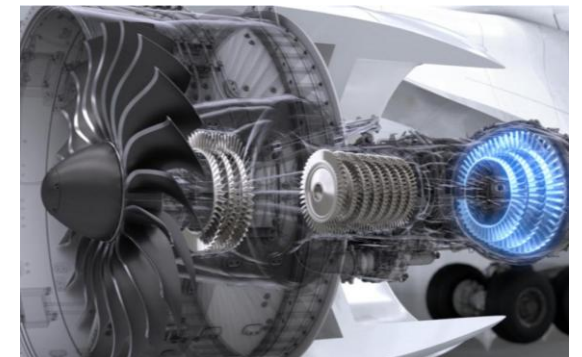
Properties



Hardness,
Density,
toughness,
melting point...

Performance

Optimising performance
to meet new challenging
conditions/requirements



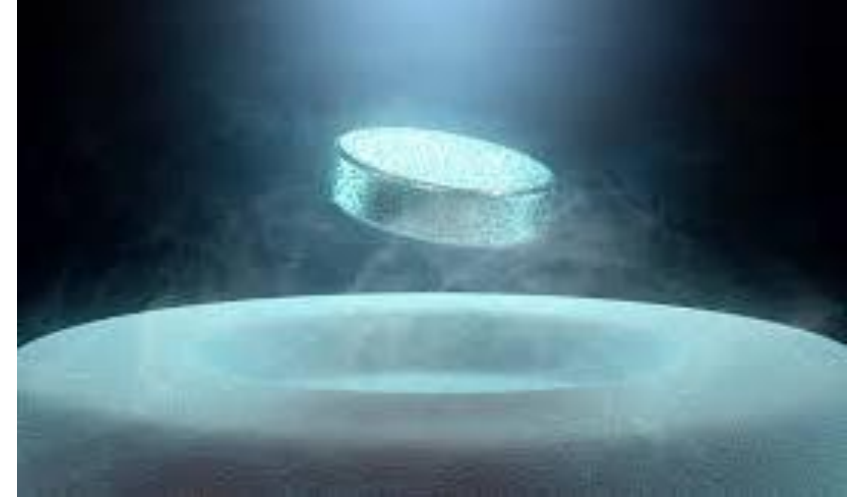
Examples of Materials Science in Action



Biomaterials



Semiconductors



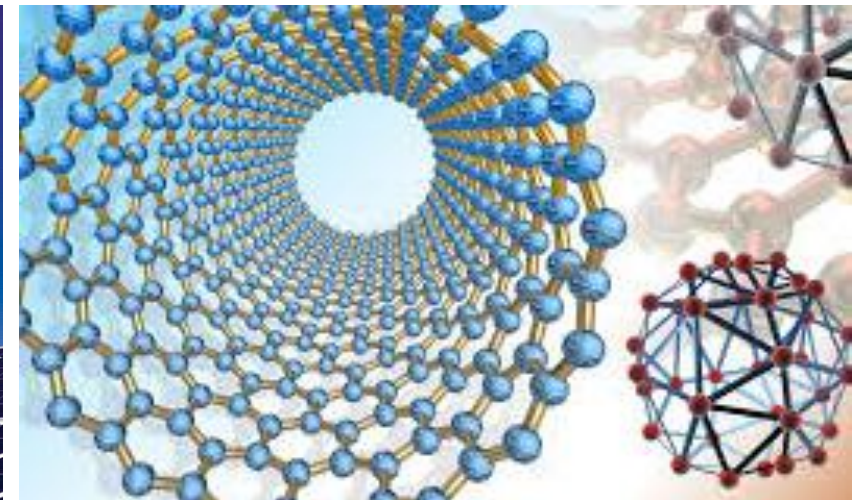
Superconductors



Superalloys



Energy Storage



Nanomaterials

Challenges for Materials Science in Fusion

'The engineering and materials challenges of creating what is essentially a 'Sun in a freezer' are formidable'

Prof. Susie Speller and Prof. Chris Grovenor,
University of Oxford



Challenges for New Materials in Fusion

Inside the fusion reactor

- Extreme temperatures on inner wall components
 - $T_{\text{plasma}} \sim 150$ million °C and maximum $T_{\text{surface}} \sim 2000$ °C
 - Plasma instabilities can cause sudden outbursts of plasma to the wall producing hotspots
- Vast amounts of radiation damage (high energy neutrons) – swelling, embrittlement, erosion, loss of structural integrity
 - 14.1 MeV neutrons (from DT reaction) minimum 7 times higher than fission neutrons
- High magnetic fields (for reactors which use superconducting magnets)

Challenges for New Materials in Fusion

Additional considerations

- Testing
 - Has this material ever been tested under such conditions before? Do we know how the material will change in structure? Is this acceptable? No material has ever been tested in realistic fusion conditions (long periods of operation), so how do we know these materials will work?
- Implications on the wider fusion system
 - Weight of the system, ITER will weigh 23,000 tonnes, 3 Eiffel Towers! Temperature gradient etc
- Waste disposal
 - Reduced activation materials for less radioactive waste and LLW
- Abundance of a material
 - Enough for a fleet of reactors?
- Cost at commercialization
 - Is there a path to reduce the cost of the novel material or to use a cheaper alternative?

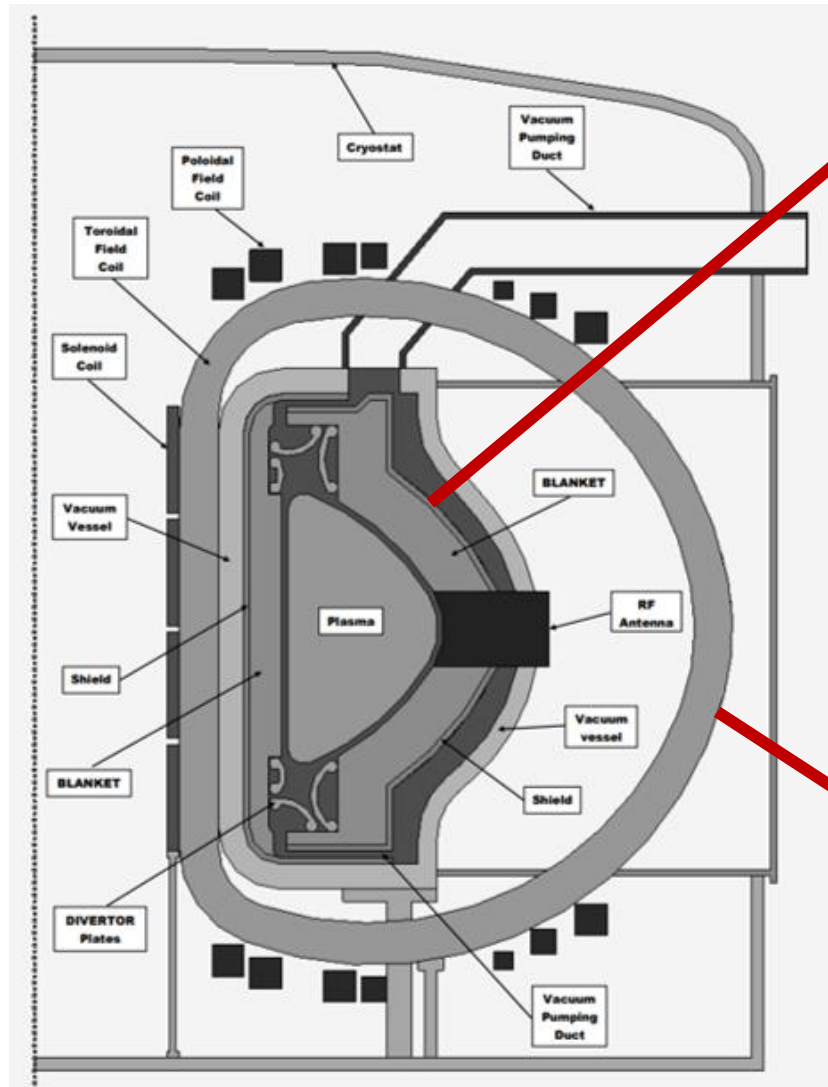
Conditions in Fusion Reactor

Example conditions from STEP tokamak

	Temperature (°C)	Peak steady state heat flux (MW/m ²)	Neutron flux at 14 MeV (n/cm ² /s)
Divertor			
Plasma facing	< 1300	STEP: 20 – 25, DEMO: 10	1.5 x 10 ¹⁴
Heat sink	< 600	STEP: 20 – 25, DEMO: 10	1.5 x 10 ¹⁴
First Wall			
Plasma facing	< 900	< 7	5 x 10 ¹⁴
Heat sink	< 900	< 7	3 x 10 ¹⁴
Shield	< 850	< 10	3 x 10 ¹⁴
Blanket			
Front (first wall heat sink)	< 900	< 7	3 x 10 ¹⁴
Back	< 700	< 2	5 x 10 ¹³
Pressurised water reactor (fuel cladding)	~ 300	~ 1	1 x 10 ¹³ (~ 2 MeV neutron)

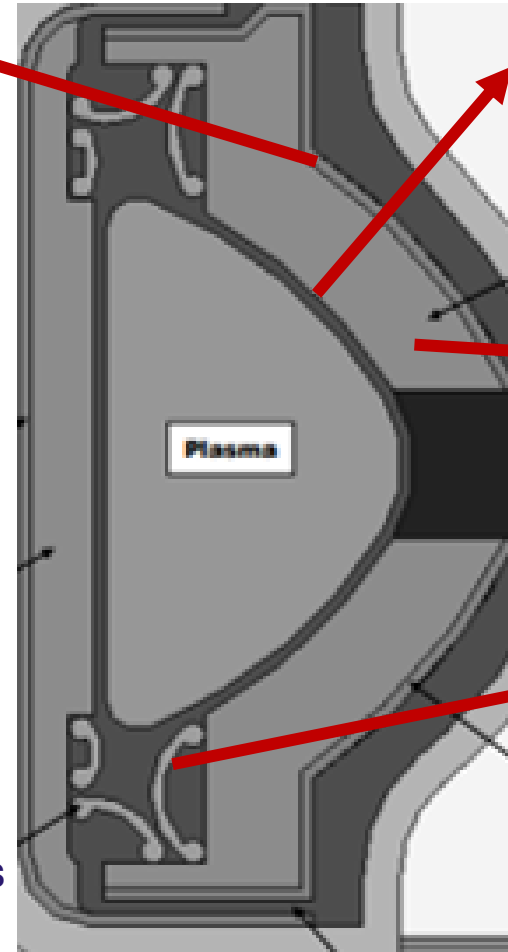
Challenges for Materials Science in Fusion

Fusion Device Breakdown



Shield: protects vital components from radiation emitted from the fusion process

Magnets: used to contain the plasma to reach fusion conditions



First Wall - nearest the plasma. ITER will use Tungsten with $T_m \sim 3400\text{ }^\circ\text{C}$

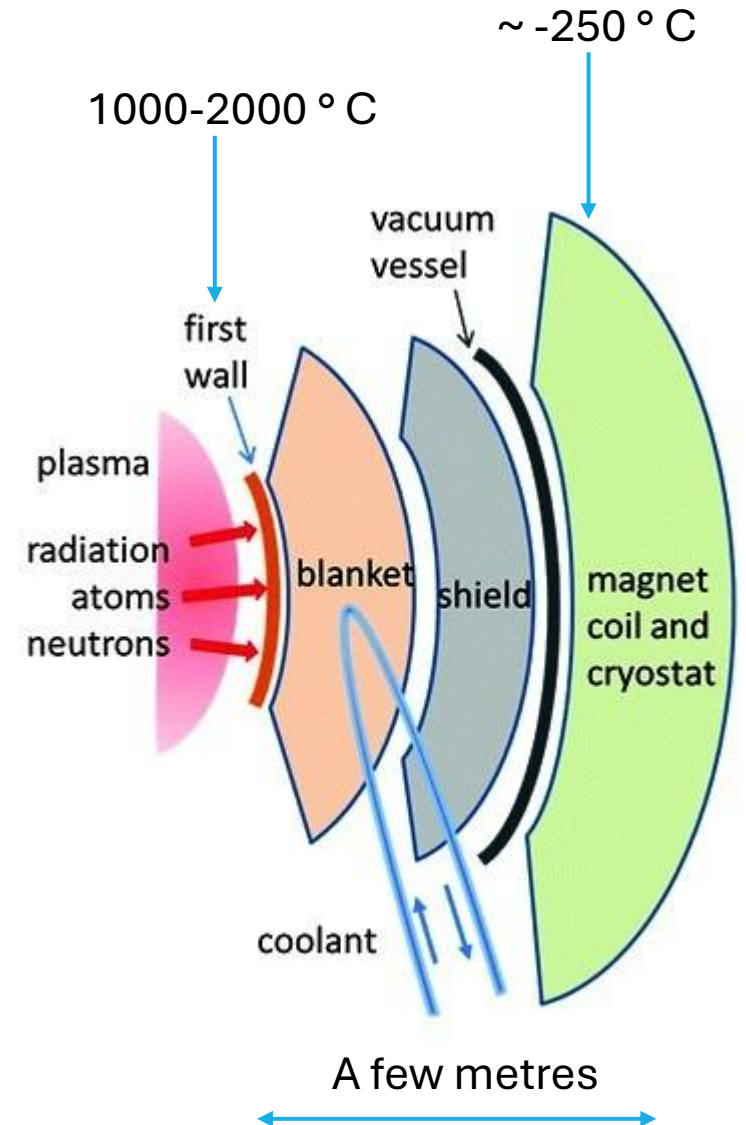
Blanket - breeds tritium required for the reaction (half life of 12 years), removes heat, and shields.

Divertor - removes excess heat and fusion "ash" (incl. impurities). ITER will use Tungsten.

Challenges for Materials Science in Fusion

Key Areas of Materials R&D

- Shield – materials with high atomic numbers are effective neutron reflectors and can absorb and slow down neutrons
- First Wall – high melting point materials resistant to neutron bombardment
- Divertor – high T_m metals and ceramics (e.g. tungsten)
- Blanket – multi-component system with:
 - A breeder material (e.g. Pb-Li, FLiBe, Lithium ceramics)
 - A structural material (e.g. RAFM steel, Vanadium alloys etc)
 - A coolant
- Magnets – higher field for smaller devices, significant progress with superconducting magnets in recent years





Enabling Technologies

Developments in Materials Science

- High Temperature Superconducting Magnets (magnetic confinement)
- Lasers (inertial confinement)
- Plasma-facing Materials
- Tritium Breeding Blanket Materials
- Test Facilities

High Temperature Superconductors

Superconductors

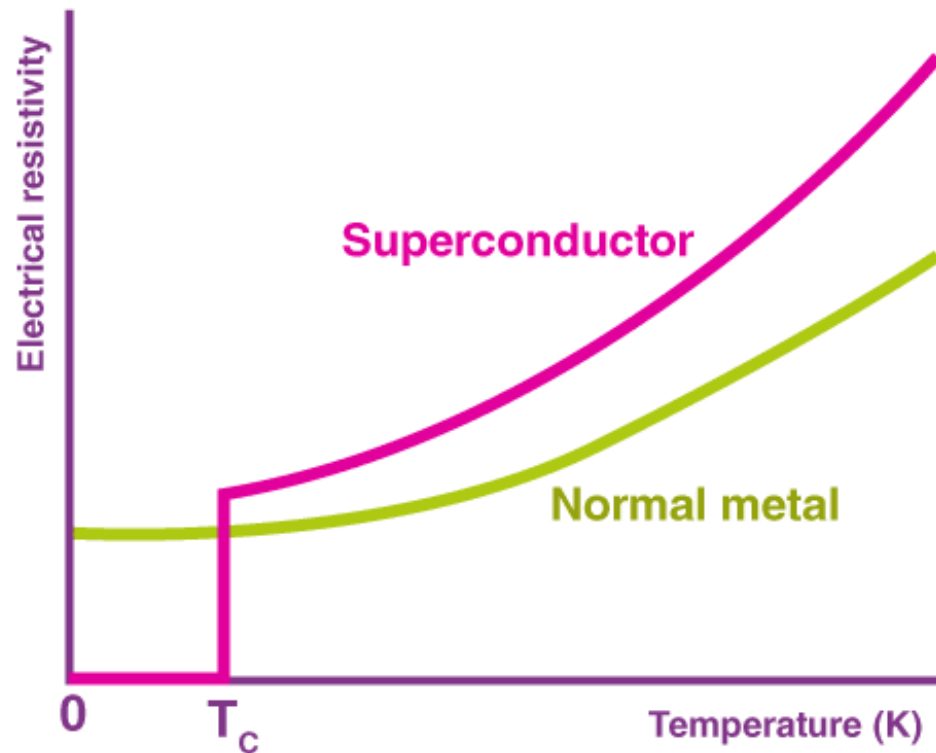
- One method of confining the plasma is by using a magnet field
- For a tokamak:

$$\text{Fusion Power} \propto B^4 R^3$$

- Therefore, in simplistic terms, increasing the magnetic field means a smaller machine can be built for a same fusion power.
- Traditional magnets, cannot reach the high magnetic field requirements due to high ohmic resistance – in JET the Cu magnets reached a maximum field of 3.45 T, but JET was not intended for fusion power.
- For the next generation of fusion machine, the magnetic field needed to increase, so fusion developers began looking at other options...

High Temperature Superconductors

Definition of a superconductor



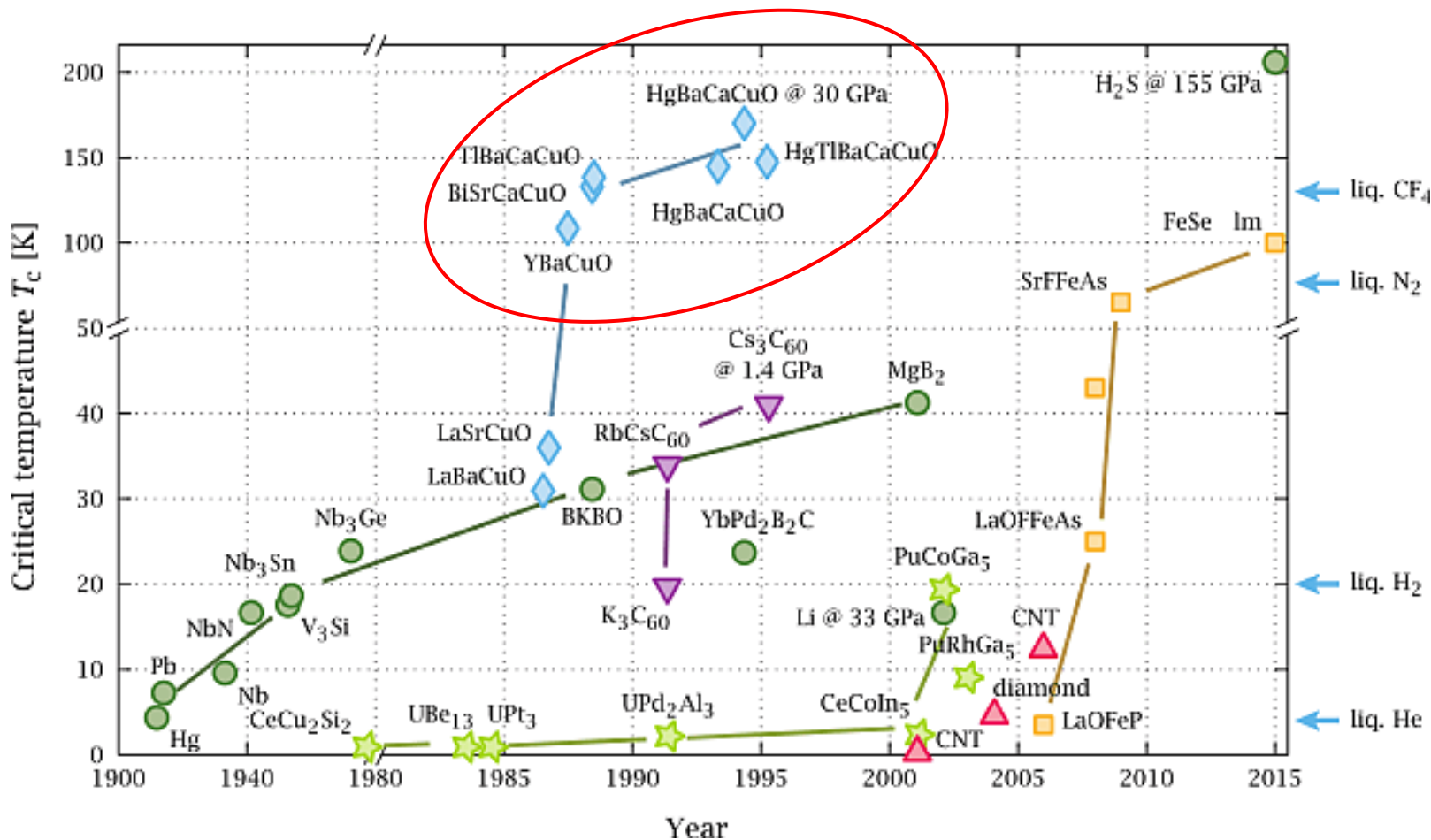
Below the critical temperature of a superconductor, the superconductor has zero resistance*.

These temperatures are all cryogenic (the golden goose would be a room temperature one).

*Very very low DC resistance

High Temperature Superconductors

Superconductors – HTS above T_c 77K



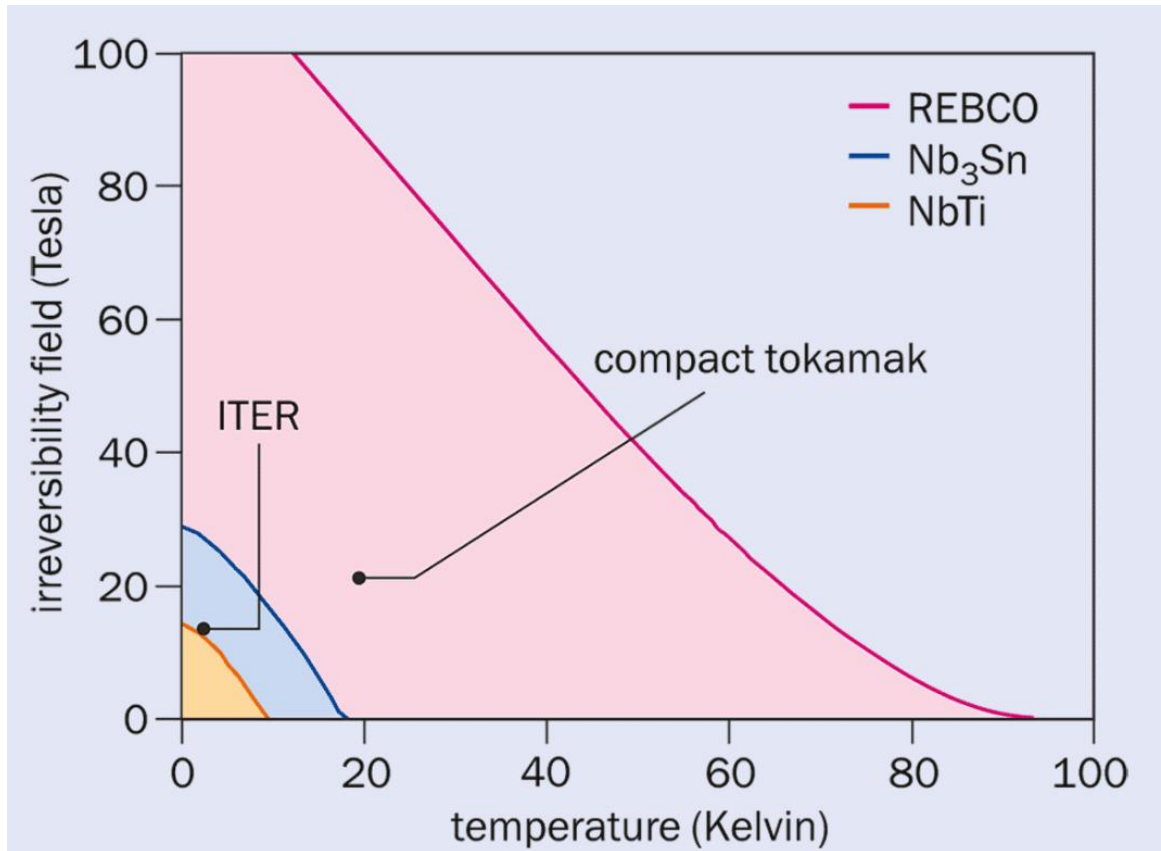
Rare earth barium copper oxides (REBCO) materials have a higher critical temperature than common Low Temperature Superconductors. Benefits:

- Can operate above liquid nitrogen temperatures (reduction in capital and operating costs of cryoplant).
- Higher maximum field than conventional low temperature superconductors.

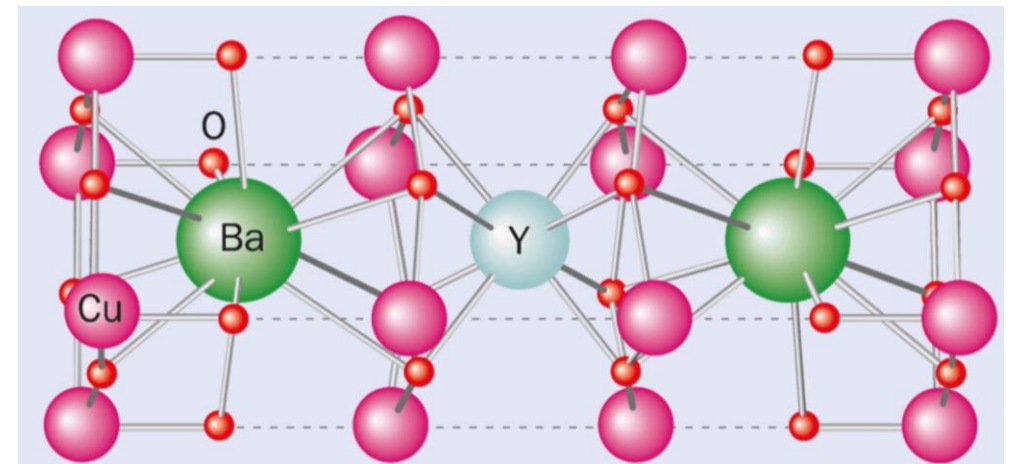
There is no agreed theory (like BCS) for HTS materials, this is still unknown!

High Temperature Superconductors

Superconductors - REBCO



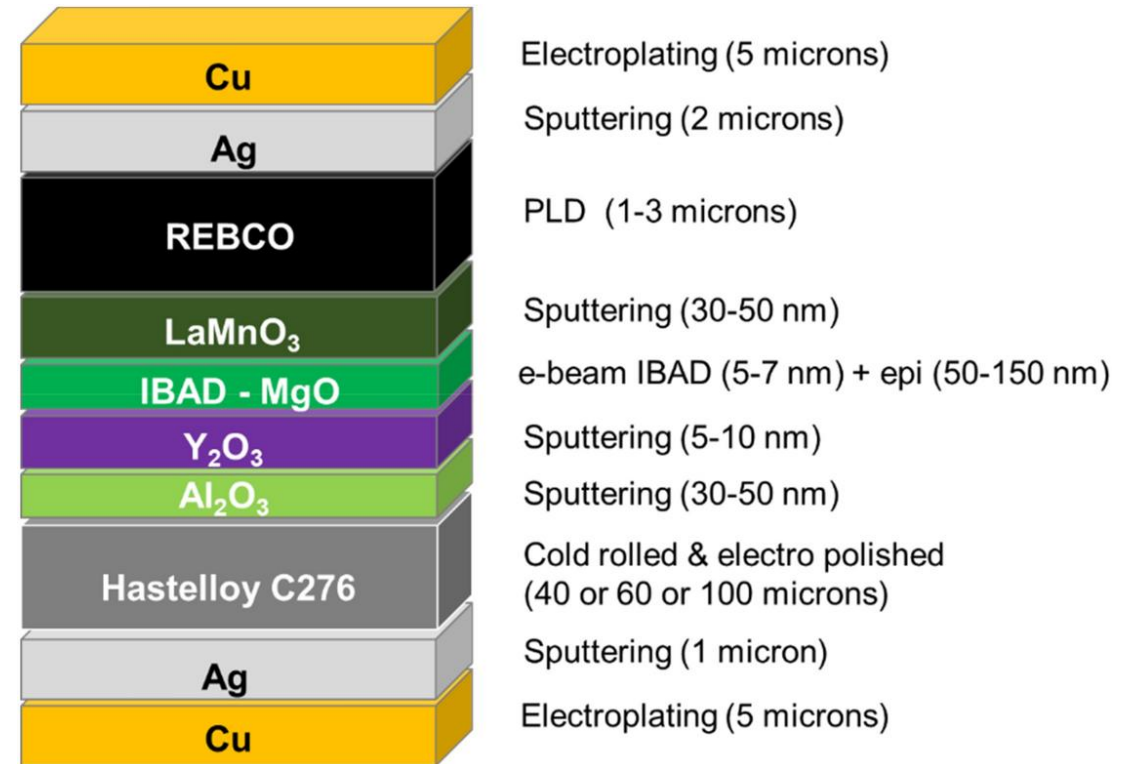
For higher fields REBCO materials are required, the most developed is YBCO, but there are challenges....



High Temperature Superconductors

Superconductors - YBCO

- Brittle – need to be made into tapes rather than drawn into thinner wires like Nb-Ti or Nb₃Sn
- Sensitive to nearly all impurities – oxygen affecting the performance
- Ideally single crystal to minimize reduction of current but will need to be multiple grains
- Performance reduces with neutron irradiation – shielding is very important!

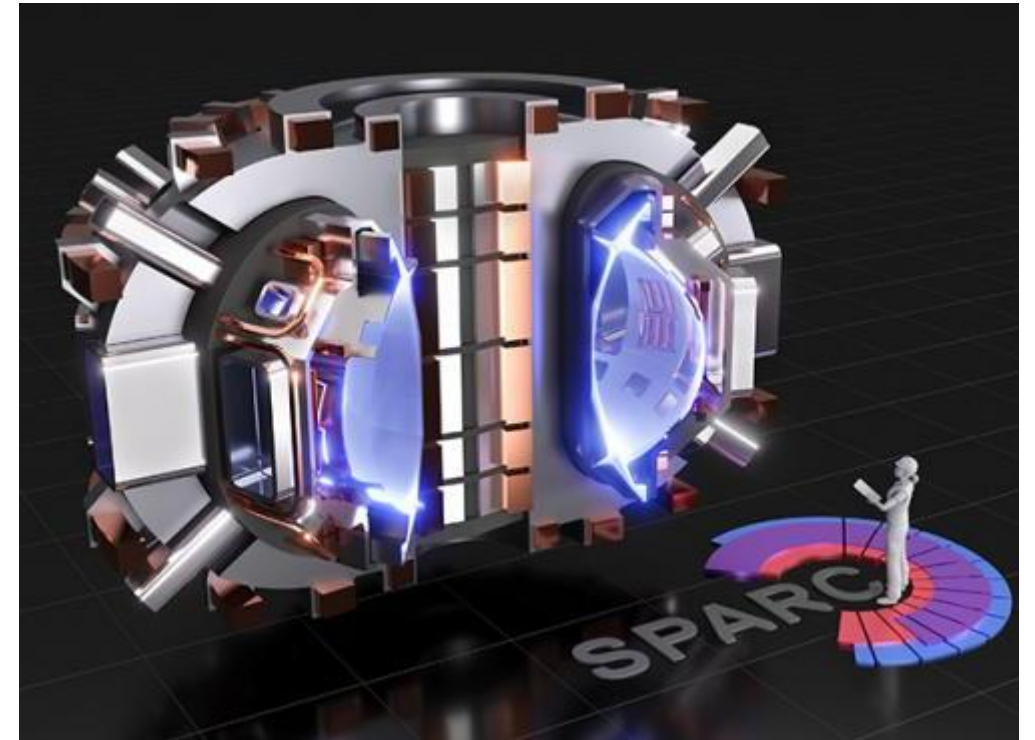


Sci Rep **11**, 2084 (2021)

High Temperature Superconductors

Timeline of YBCO

- YBCO proved difficult produce in long lengths and remained small scale until 2010's when lengths of km scale wires were produced. Issues remained: cost, performance etc.
- The inflection point came when Commonwealth Fusion Systems (world's biggest fusion company) selected YBCO for their SPARC tokamak.
- CFS placed an order with SuperOx (now Faraday) for nearly 300km of YBCO tape. SuperOx produced this in 9 months in 2020, and from 2019-2023 scaled production of tapes by 20 times!
- September 2021 CFS demonstrated their TFMC magnet (made of 16 pancakes of wound YBCO tapes) and it hit the 20 T target. A huge moment for YBCO, HTS and fusion!

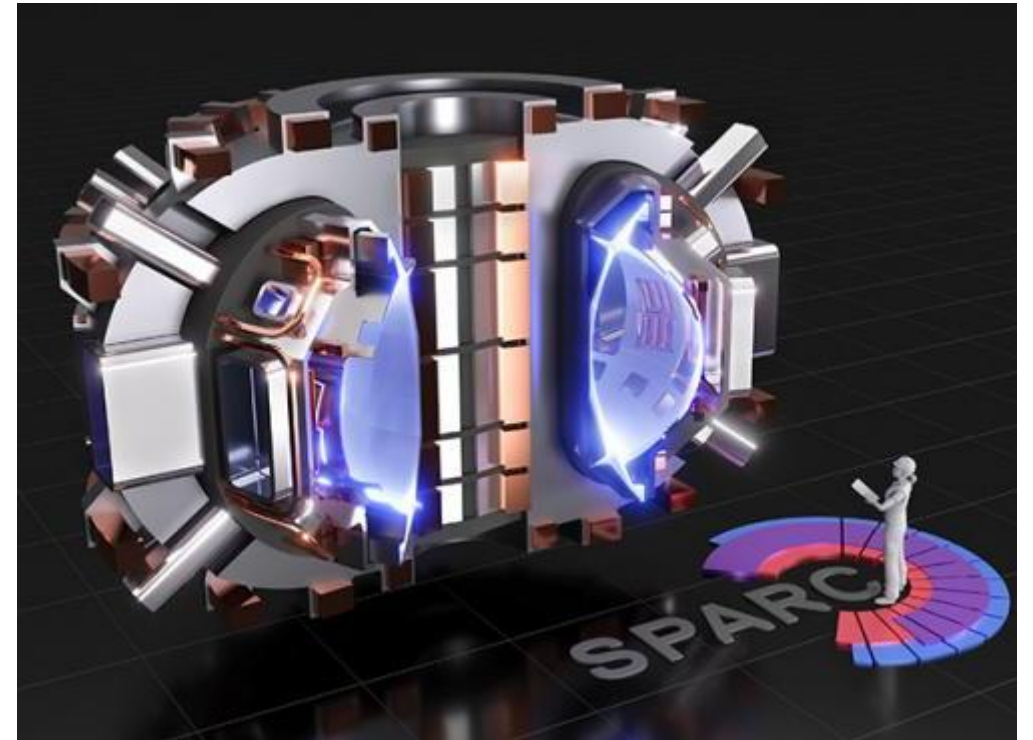


SPARC tokamak, Commonwealth Fusion Systems

High Temperature Superconductors

Superconductors - YBCO

- This pioneered the way for other companies to select YBCO magnets for different magnetic designs (e.g. tokamaks and stellarators)
- There are still significant challenges: tapes are expensive to manufacture and the magnets are the most expensive component of SPARC, so magnet protection systems are vital!
- YBCO has come a long way with the new demand from fusion, however, a single tokamak will require 20,000km of YBCO each, so challenges remain...



SPARC tokamak, Commonwealth Fusion Systems

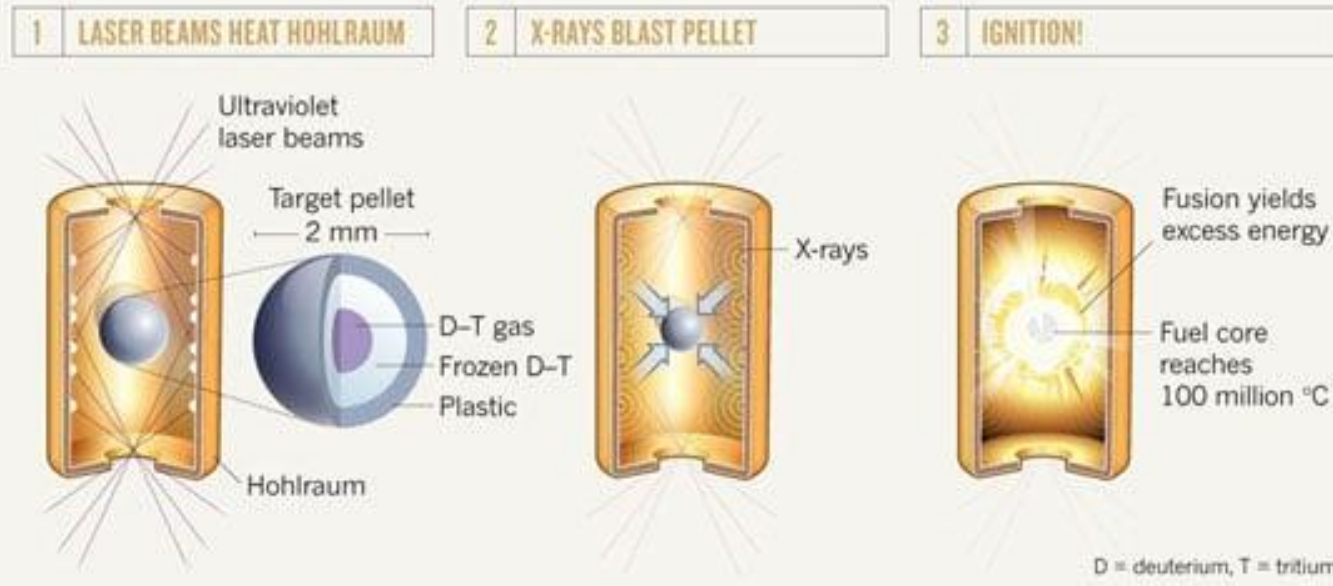
Lasers

Purpose

For inertial confinement approaches a laser can be used to confine the plasma.

THE NIF'S FUSION STRATEGY

As the NIF's laser beams hit the gold hohlraum capsule (1), they generate X-rays that blast the outer layer of the pellet (2), compressing the hydrogen isotopes until they fuse (3).



There are direct and indirect methods to use lasers, with most choosing indirect, as it has been the most studied and has achieved the best energy output

In indirect ICF a container called a hohlraum (gold cylinder) contains the fuel pellet.

Lasers on the pellet cause x-rays to compress the internal fuel pellet and cause a fusion reaction.

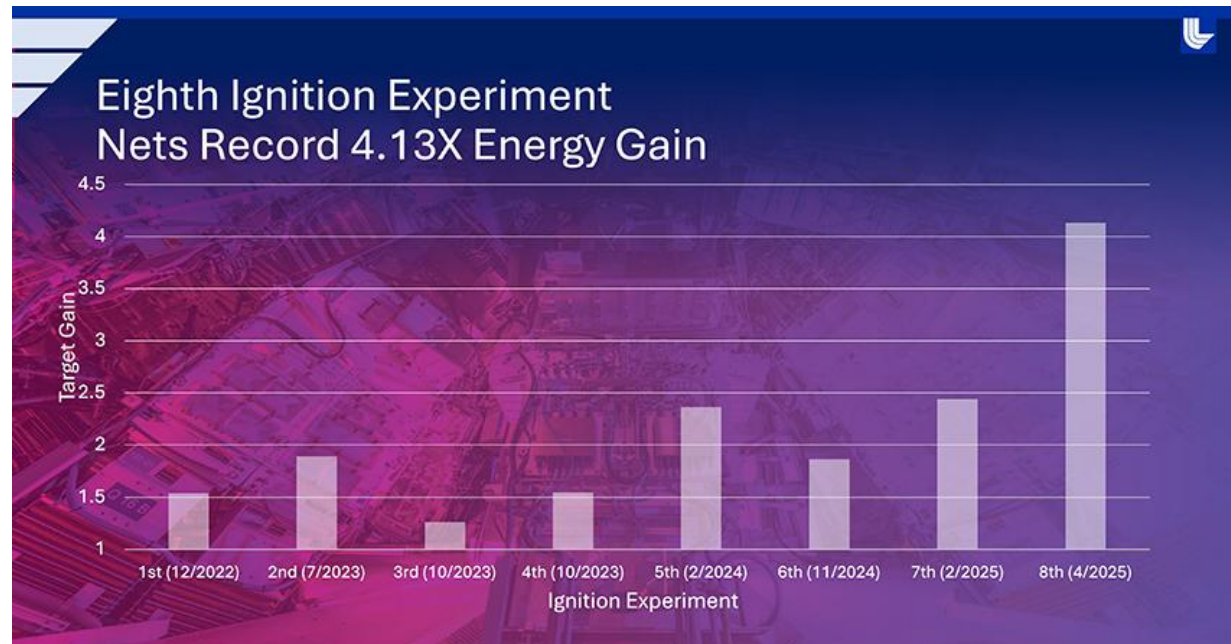
Lasers

INSERT NIF image

National Ignition Facility (NIF)

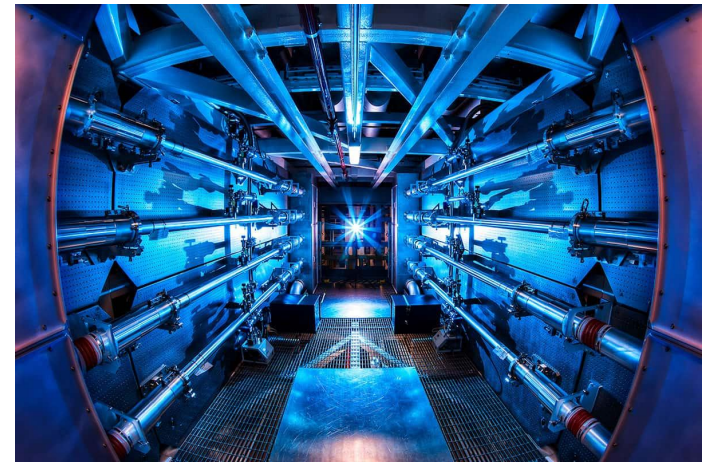
NIF is a government facility in the United States which achieved ignition using 192 powerful lasers

- Ignition: the point at which more energy is generated than is consumed. For NIF ignition was first achieved in 2022, with 3.15 MJ out compared to 2.05 MJ to the fusion target – a phenomenal achievement. **However**, this doesn't account for the energy required to power the 192 lasers, roughly the 150 times the energy it delivers!
- For inertial fusion to become commercial, the power of lasers needs to increase and the cost of the laser systems needs to decrease.
- Not to mention the repetition rate of the shots, 8 in 4 years is nothing compared to the likely 10 needed per second...



Lasers

Progress from NIF



- Extensive work went into the hohlraum design, with micron level machining and modelling required to make sure the x-rays correctly compressed the fuel pellet. This was both an achievement of modelling and precision manufacturing.
- NIF demonstrated that an ICF approach using lasers could be possible, albeit in a very expensive science facility with only 8 shots over 4 years with more power out than on the target. NIF also has $\sim 1\%$ wall-plug efficiency with only 2 MJ of the lasers 300 MJ energy reaching the target, cost approximately \$3.5 billion and is the size of three American football pitches.
- Several private fusion companies have begun developing their own lasers for an ICF approach, using more novel materials for an optimised design.

Lasers



Diode-pumped Solid State Lasers (DPSSL)

This is the most widely developed laser type across several private fusion companies, including LongView Fusion and Inertia Enterprises.

- Approach uses solid-state lasers, the diodes emit the same wavelength as the Nd glass absorbs, eliminating spectral waste of flash lamps. This produces a wall plug efficiency of 15-20%.
- The science for this type of laser is established, the most challenging part is the supply of semiconductor diodes, but this is a scale-up and cost question – not fundamental physics. Costs for semiconductor diodes are already falling, this continuation will make this technology more economically feasible.

Lasers



KrF (Krypton Fluoride) Laser

- Lower TRL with component validation, but this has the potential to reach 7-10% wall plug efficiency.
- The main advantages are the simpler construction, no frequency-conversion step needed, lowest instability risk, gas medium is refreshed so no fatigue in optics
- However, still in a relatively low TRL, and scale is below that which will be needed for fusion.
- Xcimer are pursuing this type of laser.

Lasers



Ultrashort Pulse/Femtosecond Laser

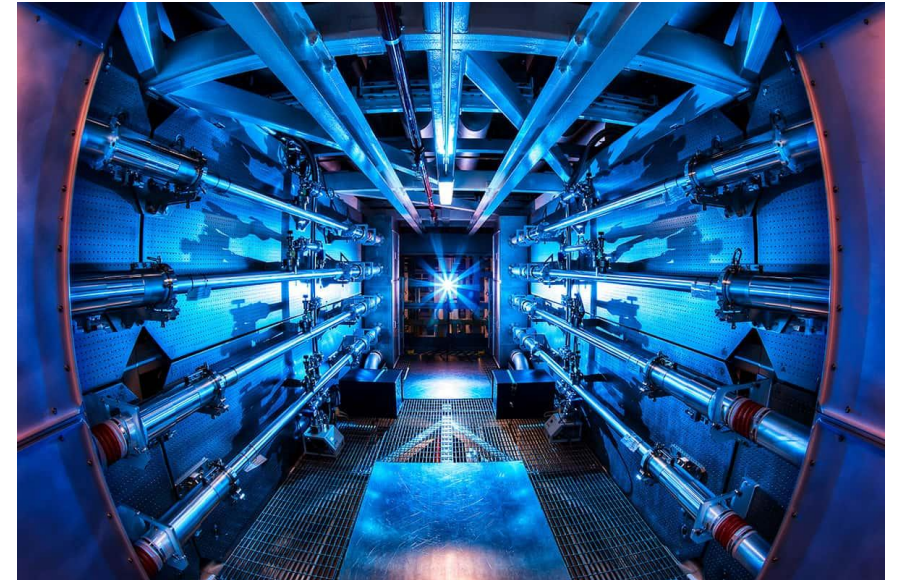
- This is proof of concept physics and is being developed by Marvel Fusion. A diode-pumped femtosecond laser, with the first facility under construction in Colorado.
- Efficiency is yet unknown, but aims to be competitive with other laser technologies
- Uses a different fuel (p-B11) instead of D-T with the idea that no tritium breeding will be required and lower radiation damage on the facility. However, p-B11 needs around 10x hotter temperature than D-T.

Lasers

Progress

Ignition from NIF has shown that indirect laser-driven fusion is possible, next steps are:

- Design and build high-powered lasers at a fraction of the cost of NIF
- Increase the wall plug efficiency from 1%
- Increase the repetition rate to closer to 10 reps per second!

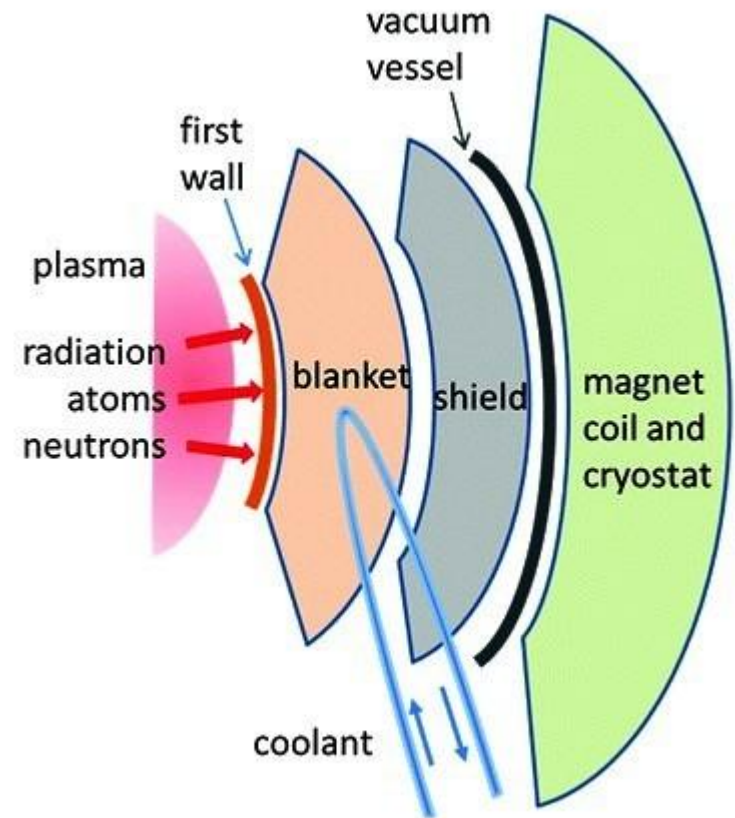


Plasma Facing Materials

Purpose

Are the materials which directly 'see' the plasma. They have to with stand:

- Intense heat fluxes: ITER needs to withstand 10-20 MW/m² in steady-state operation, with the surface of the sun ~60 MW/m²
- Survive neutron bombardment – for DT fusion, this is 14 MeV neutrons, that cause displacement damage, transmutation and embrittlement over time.
- Other effects include...



Multiple components are PFM, these include first wall, divertor and tritium breeding blanket.

Radiation Damage of Materials: Overview

Even at 30-50% of the melting temperature of a material there is significant radiation damage which needs to be accounted for during the lifetime of the component
(STEP Divertor 1300°C so $T_m \sim 2600-4300$ °C higher than most materials!)

Plasma Facing Materials

Beryllium – First Wall

Pros

Low atomic number won't impact plasma cooling (has few electrons to dilute the plasma),

Getters oxygen, which improves plasma efficiency

Cons

**Low melting temperature (1287 °C),
Undergoes neutron induced swelling**

Biological hazard

Uranium is an impurity which can undergo fission or decay to Plutonium!

In 2023 ITER decided to switch from Beryllium for the first wall to Tungsten

Plasma Facing Materials

Tungsten – Divertor and First Wall

Pros
High T_m (3,410 °C)
High thermal conductivity and sputtering threshold (low erosion rates)
Low swelling and tritium retention

Cons
High atomic number (cools plasma)
Poor machinability
High ductile-to-brittle transition temperature (above 700 °C) which increases!
Undergoes transmutation into a W-18Re-3Os alloy after irradiation at 50 dpa
Poor thermal compatibility with Cu alloys used for heat sinks at
Upper limit of operation 1200 °C

Plasma Facing Materials

Tungsten – Developments

- Very high melting point means tungsten cannot be conventionally cast and it is brittle at room temperature – so ITER's tungsten monoblocks are made from powder. Additive manufacturing solutions include:
 - Laser bed powder diffusion (LBPD) offer resolution of 50-100 μm and therefore can be used to create complex cooling channels in the tungsten.
 - Electron beam melting (EBM) uses an electron beam rather than a laser, minimising residual stress and done under vacuum eliminating embrittlement from oxygen
 - Directed Energy Deposition (DED) laser/electron beam melts feedstock powder onto a substrate, importantly this can be used for in-situ repair of damaged components.
- Oxide dispersion strengthened tungsten – oxides to pin grain boundaries, inhibiting grain growth, suppressing recrystallisation and traps for helium cluster before they become bubbles.
- Tungsten-based composite alloys – dispersion strengthened and controlled porosity

Plasma Facing Materials

Tritium Breeder Blankets

Purpose: tritium has a half-life of 12.3 years and cannot be found in useful quantities on earth. Tritium needs to be produced in-situ for commercial fusion.

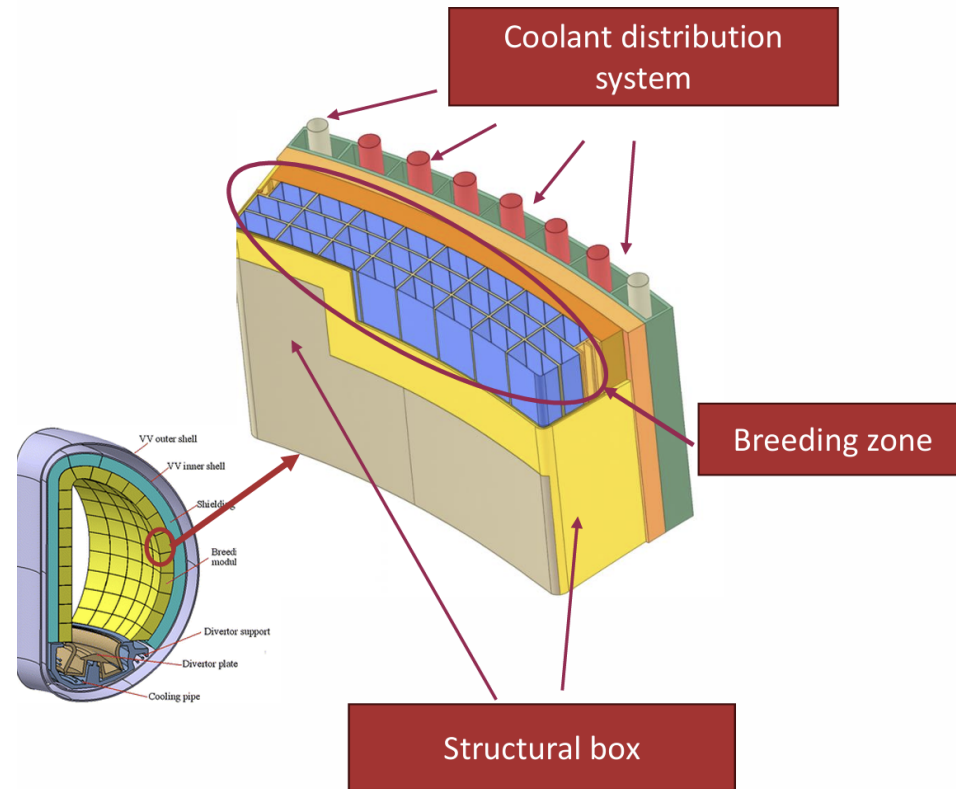
- No tritium breeder blanket system has ever been demonstrated in fusion conditions, tritium breeding blankets are a huge challenge for fusion (an area of genuinely scientific discovery).
- **${}^6\text{Li} + \text{n (thermal)} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.8 \text{ MeV}$ (preferred as higher yield and requires lower energy neutron)**
 - **${}^7\text{Li} + \text{n (fast)} \rightarrow {}^4\text{He} + {}^3\text{H} + \text{n} - 2.466 \text{ MeV}$**
- ${}^6\text{Li}$ is only found in about 7.6% of Li naturally, so either enrichment to ${}^6\text{Li}$ is required, or a neutron multiplier to achieve enough tritium breeding.

Plasma Facing Materials

Tritium Breeder Blankets

To achieve self-sufficient tritium breeding the tritium breeding ratio MUST be more than one – in a real system (with losses) this is a minimum of ~ 1.05 - 1.1 depending on the materials chosen.

Breeder Blanket components



- **Structural materials**
Provide mechanical strength, while forming the pressure boundary and channels for coolants and breeding materials.
- **Breeders**
Generate tritium by nuclear reactions between fusion neutrons and Li-containing materials
- **Neutron multipliers**
Increase the effective neutron yield in the blanket (via $(n,2n)$ or similar reactions) to boost tritium breeding
- **Coolants**
Remove the heat from the blanket and transfer it to power conversion systems while keeping temperatures within allowable limits.

Plasma Facing Materials

Solid Tritium Breeders

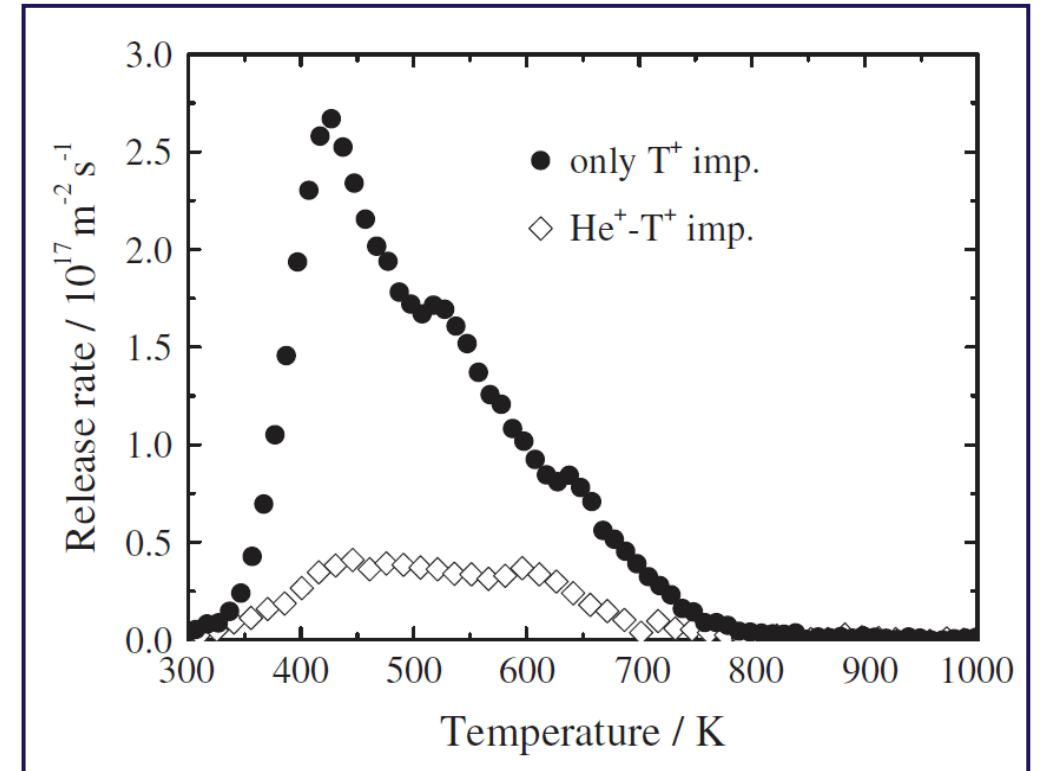
Lithium containing ceramics (e.g., Li_2TiO_3 , Li_4SiO_4)

- Source of Li which transmutes to T (plus He).

The below differ, depending on the ceramic:

- ✓ Neutron multiplier for TBR > 1 (e.g. Be_{12}Ti).
- ✓ High thermal conductivity for efficient heat recovery.
- ✓ Good thermal, chemical and mechanical stability.
- ✓ Compatible with structural materials.

- X Lower Li density compared to liquid Li.
- X Effect of radiation damage and He formation on T release not fully known.



From: M. Kobayashi et al. J. Nucl. Mater. 455 (2014) 735-738.

Plasma Facing Materials

Liquids

- Rather than a solid which gets damaged and will need replacing, why can't a fusion reactor use a recirculating liquid which is constantly 'self-repairing'?
- Benefits: Liquid metals or molten salts will not be melted by interactions with the plasma and will not accumulate radiation damage. Liquid metals or molten salts have multiple functions, including first wall, breeder and coolant.
- Candidates:
 - Liquid Li
 - FLiBe
 - PbLi

Plasma Facing Materials






Tritium Breeder Blankets: Liquids

Materials options	Advantages	Drawbacks
Pure Li	<ul style="list-style-type: none"> • Can act as breeder, multiplier and coolant, suitable for “self-cooled” blankets. • Liquid metal, immune to irradiation damage. • Maximum possible Li atom density, can be used without a separate multiplier. • On-line Li-6 replenishment possible • Unexpensive and available at industrial scale. 	<ul style="list-style-type: none"> • May still require Li-6 enrichment. • Extremely reactive with air and water and flammable. • Strongly corrosive to most structural alloys: only V-alloys and SiC_f/SiC as options. • T control requires permeation barriers • T-extraction processes not mature (same as PbLi?)
PbLi	<ul style="list-style-type: none"> • Can act as breeder, multiplier and coolant, suitable for self-cooled or dual-cooled blankets. • Liquid metal, immune to irradiation damage. • On-line Li-6 replenishment possible. • Inexpensive basic elements 	<ul style="list-style-type: none"> • Needs higher Li-6 enrichment than ceramics+Be. • Exothermic reaction with water, double walls required. • Corrosion limits, unless coatings and are used. • T control requires permeation barriers • Neutron activation from Pb (Po-210) and impurities;
FLiBe	<ul style="list-style-type: none"> • Can act as breeder, multiplier and coolant, suitable for “self-cooled” blankets. • Molten salt, immune to irradiation damage. • Low Tritium solubility limits T permeation and blanket inventories. • On-line Li-6 replenishment possible 	<ul style="list-style-type: none"> • Neutron absorption in F limits TBR: requires high Li-6 enrichment or additional multipliers. • Highly corrosive: Ni alloys (no RA) or advanced coatings. • Reactive with water/steam → toxic and tritiated HF. • Complex T chemistry complicates T extraction. • Supply of Be is scarce.

Tritium Breeder Blanket

Developments

- ITER TBM programme which will test four different blanket types, starting in 2039. This timeline is too distant for commercial projects

Port N°	First TBM	Second TBM
16 (F)	<p>TBM-1: <i>Water-Cooled Lithium-Lead (EU)</i></p> <p>→ <i>Liquid eutectic Pb-Li: Li as breeder, Pb as neutron multiplier</i></p> <p>→ <i>Water at 15.5 MPa, 295-328°C</i></p> 	<p>TBM-2: <i>Helium-Cooled Ceramic Pebble (joint KO & EU)</i></p> <p>→ <i>Li-ceramic as breeder, Be as n-multiplier</i></p> <p>→ <i>Helium at 8.0 MPa, 300-500°C</i></p>  
18 (S)	<p>TBM-3: <i>Water-Cooled Ceramic Breeder (JA)</i></p> <p>→ <i>Li-ceramic as breeder, Be as n-multiplier</i></p> <p>→ <i>Water at 15.5 MPa, 280-325°C</i></p> 	<p>TBM-4: <i>Helium-Cooled Ceramic Breeder (CN)</i></p> <p>→ <i>Li-ceramic as breeder, Be as n-multiplier</i></p> <p>→ <i>Helium at 8.0 MPa, 300-500°C</i></p> 

The question of testing

Materials Test Facilities

- No commercial fusion reactor exists, therefore no materials have been tested under commercial fusion conditions – this is a chicken and egg situation:
 - Do we build test facilities to test EM loads, neutron damage, high heat fluxes or a combination of these in advance of any commercial reactor?
 - What do we need to make sure is tested and validated before use?
 - Who is building facilities and how will the knowledge be shared?

Materials Test Facilities

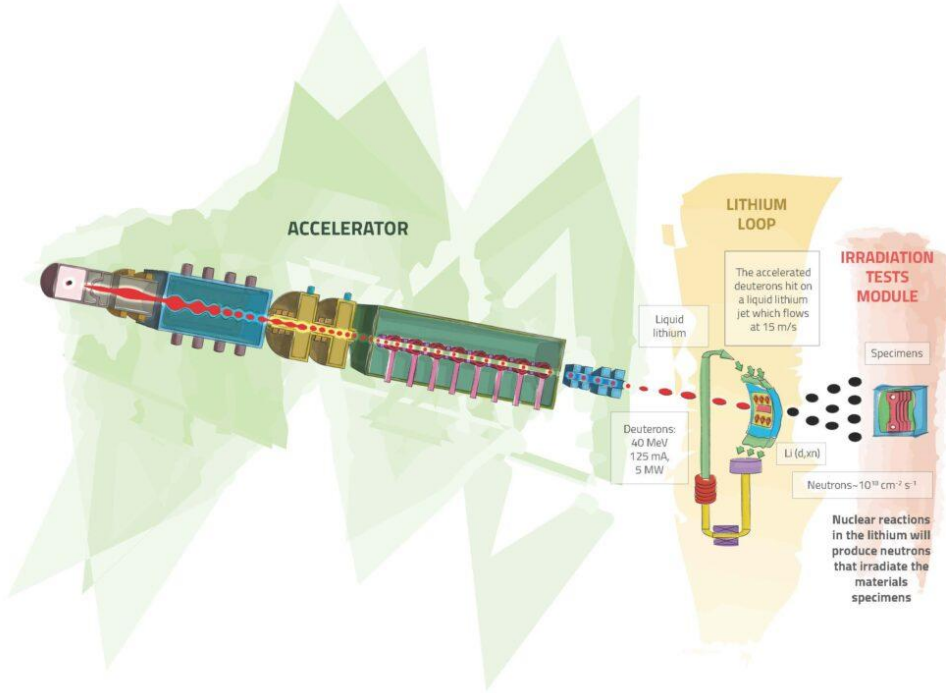
New Facilities

- International and National programmes are designing and building new test facilities to validate materials for fusion reactors:
 - Tritium Breeding Blankets: ITER (2039) and BEST (2027), in addition other tritium fuel cycle loops are planned including UKAEA (H3AT 2028), Kyoto Fusionneering.
 - EUROfusion: IFMIF-DONES and VNS
 - UKAEA: LIBRTI, CHIMERA
 - FOAK Private Fusion Reactors: SPARC online before 2030

Test Facilities: EUROfusion

IFMIF-DONES from 2034

- Aim: qualifying materials under fusion-like irradiation.

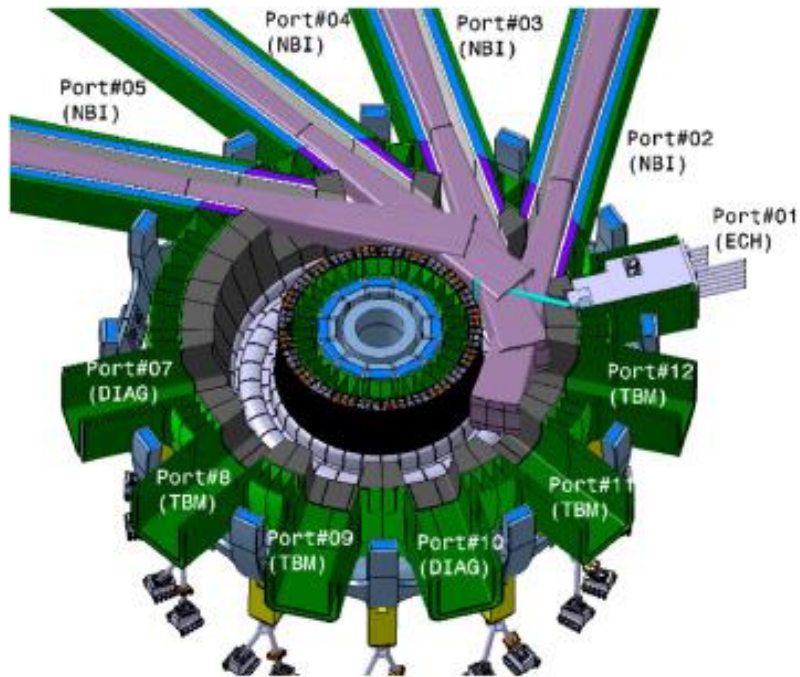


1. 'Generate materials irradiation test data for design, licensing, construction and safe operation of the fusion demonstration power reactor (DEMO)
2. Generate database for benchmarking of radiation responses of materials hand in hand with computational material science.
3. To provide a neutron source producing high energy neutrons at sufficient intensity and irradiation volume. In order to reach this objective, a new Facility (the DONES Facility) will be designed, build and operated.'

Test Facilities: EUROfusion

Volumetric Neutron Source (VNS), EUROfusion (planned)

Aim: Small tokamak designed to test breeding blanket materials and their resistance to irradiation. The tokamak will produce 14 MeV neutrons and operate alongside ITER.



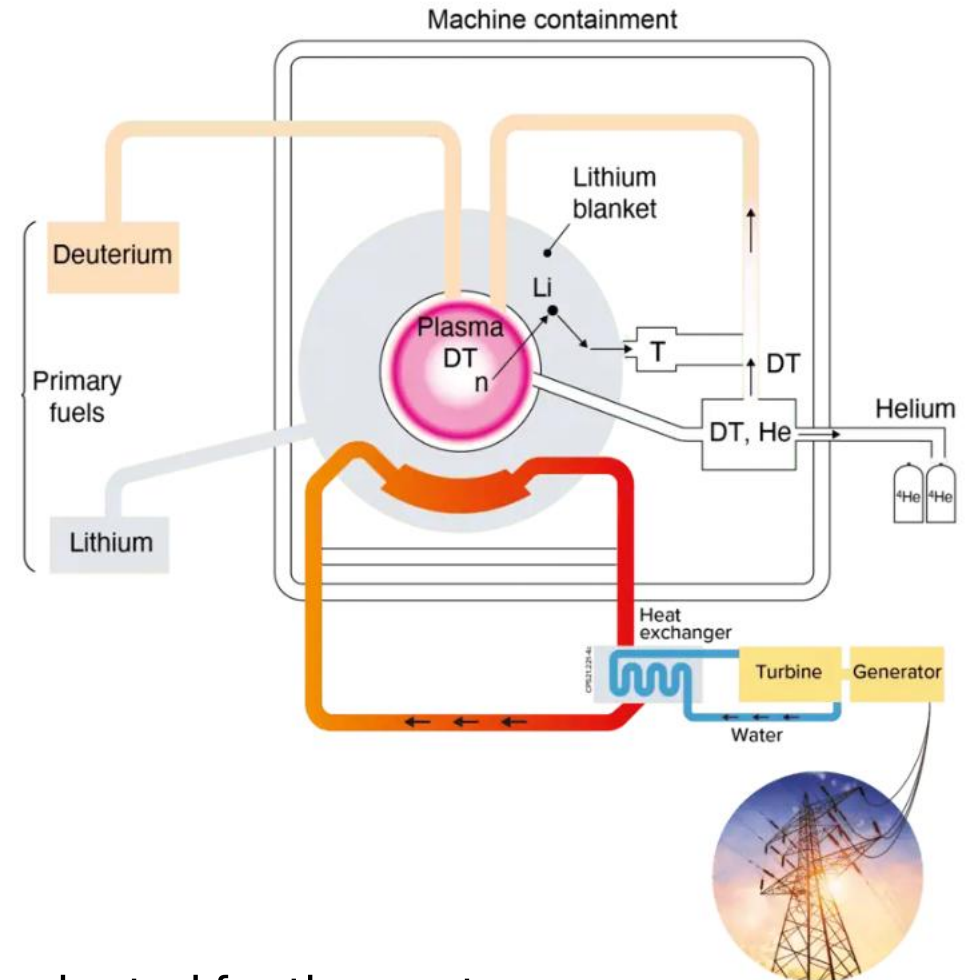
- Designed to maximise the neutron irradiation on the wall to mimic the conditions in an operating tokamak.
- Complements IFMIF-DONES as this is aimed to test entire components.

Test Facilities: UKAEA

The Lithium Breeding Tritium Innovation (LIBRTI) Programme

‘LIBRTI aims to demonstrate that for a given neutron flux into a specified lithium substrate, we can predict and reproducibly achieve, quantified tritium breeding and output.’

Tom Barrett, UKAEA



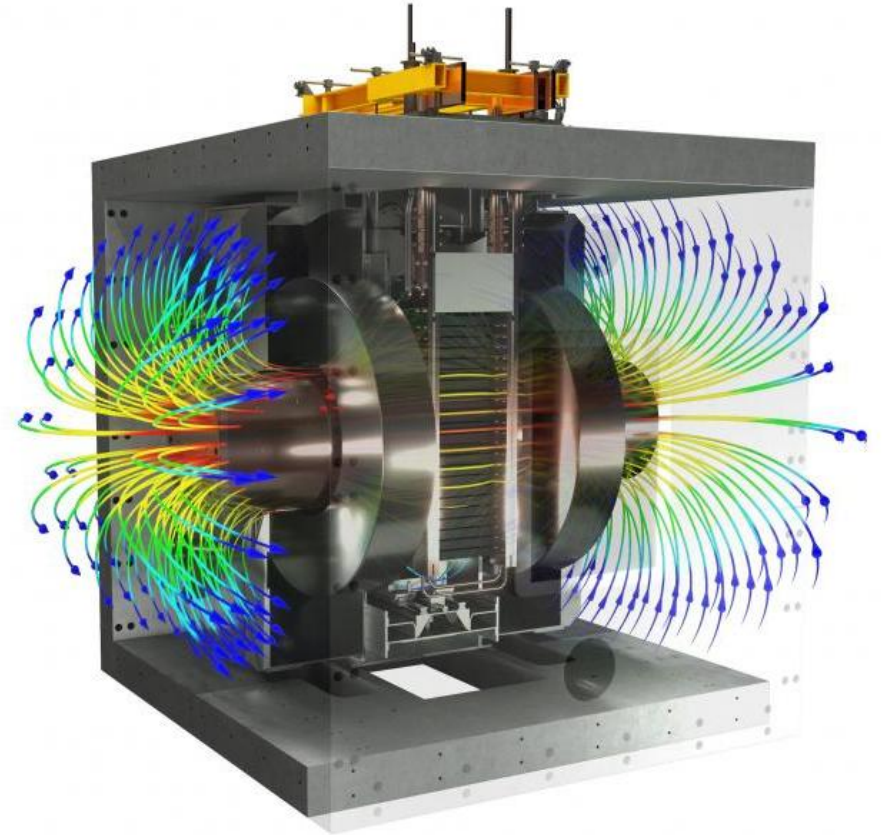
SHINE Technologies (US private fusion company) has been selected for the neutron source

Test Facilities: UKAEA

CHIMERA

'CHIMERA will simultaneously subject components to:

- High temperatures
- High heat flux
- Static and pulsed magnetic loads
- Thermal cycling, fatigue, creep and other failure modes
- Under vacuum, air or inert gas'



AI and ML for Materials Science

Materials Databases

- Clean Air Taskforce developing their Materials Database. This takes known materials data and places properties in a database, aimed at standardising across the sector.
- [DuctGPT: A Generative Transformer for Forward Screening of Ductile Refractory Multi-Principal Element Alloys – ScienceDirect](#). A database to help design ductile materials for extreme environments.
- In theory, scrapping known materials data helps to optimise and down select materials for a given purpose quicker. However, without any data under given fusion conditions, this may only become useful when test facilities come online.

Summary

There are many advancements in Materials Science which are helping to advance towards commercial fusion energy. A lot more work is needed and more enthusiastic Materials Scientists are required to help solve these problems!

Any questions?

