Technological Challenges for Fusion Energy Production

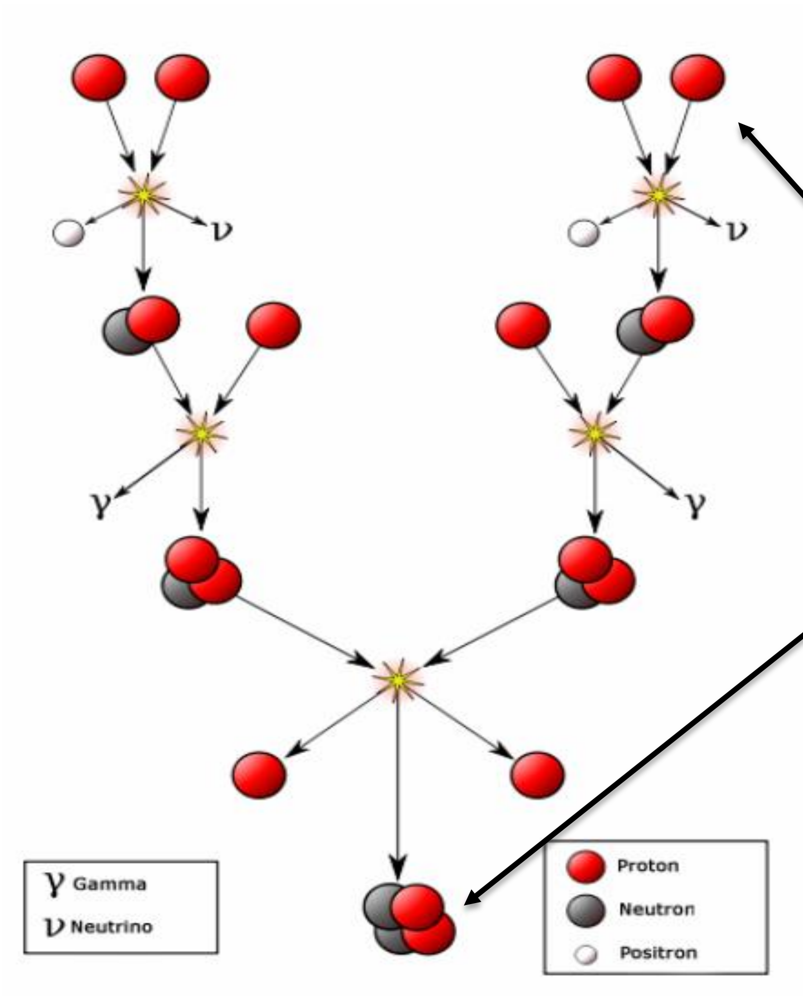
Konstantina Mergia

Fusion technology Group
Institute of Nuclear and Radiological Science and Technology, Energy and Safety
NCSR Demokritos

NCSR 54th Summer School, 4th July 2019

FUSION on the Sun

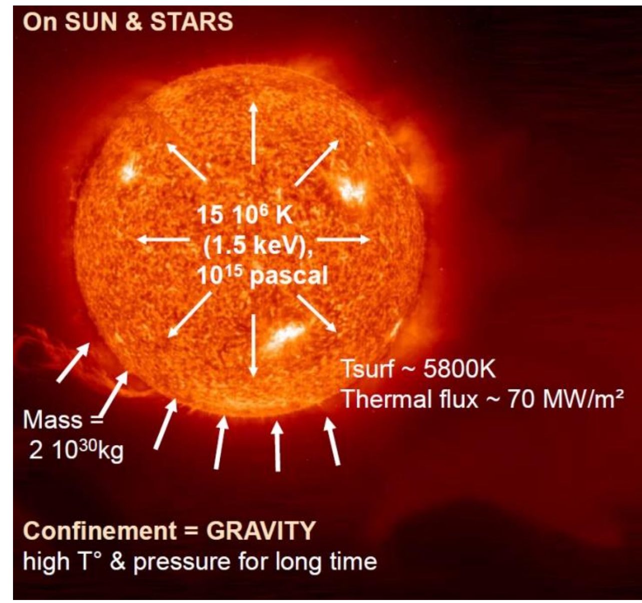
Every second, our Sun turns 600 million tonnes of hydrogen into helium, releasing an enormous amount of energy.



Hydrogen

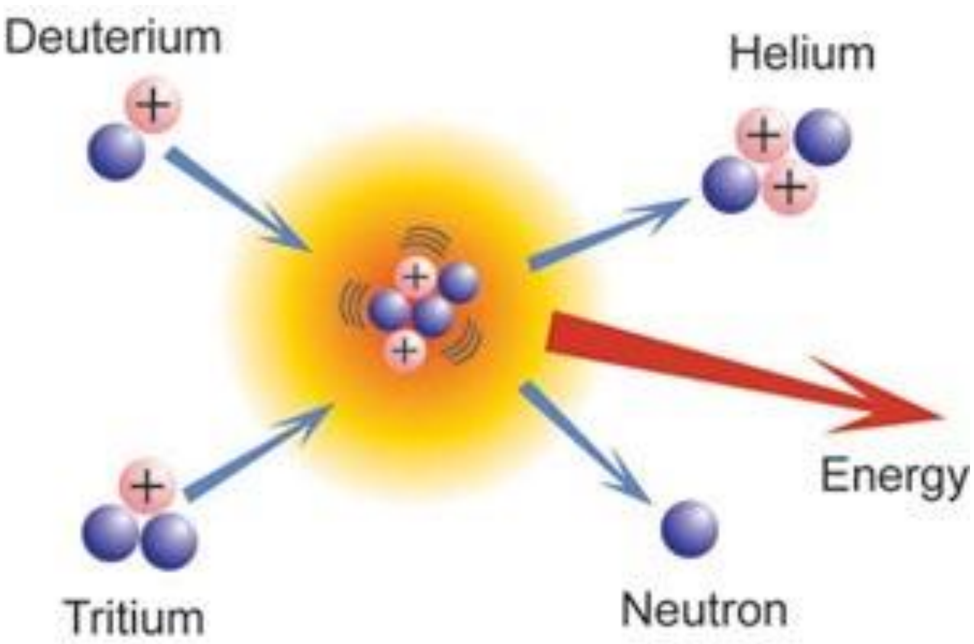
helium

Burning for
4.6 billion years



Hydrogen
will be exhausted in
5.6 billion years

FUSION on Earth



$m_{D+T} - m_{He+n}$

$$E = \Delta m \cdot c^2$$

Kinetic Energy

3.5 MeV 14.1 MeV

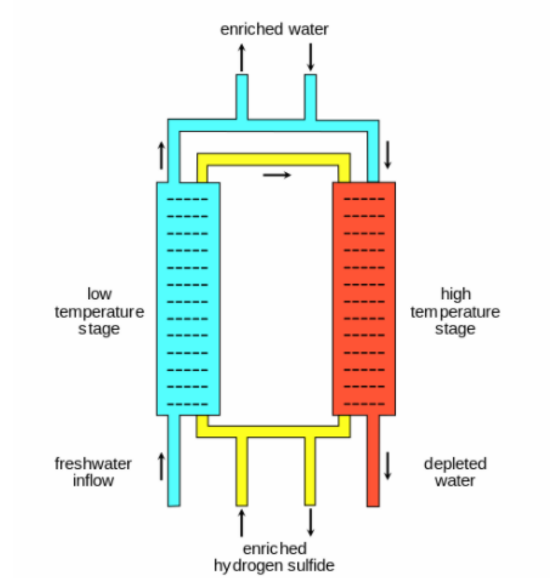
$$^2_1D + ^3_1T \rightarrow ^4_2He + n, \quad K.E. = +17.6 MeV$$

Where do we find the fuel?

1 litre of water contains
0.033 g of Deuterium

Can we extract it?

Girdler sulfide (GS) process



Isotopic exchange process
$H_2O + HDS \rightleftharpoons HDO + H_2S$

Cost 1 kg 680 USD

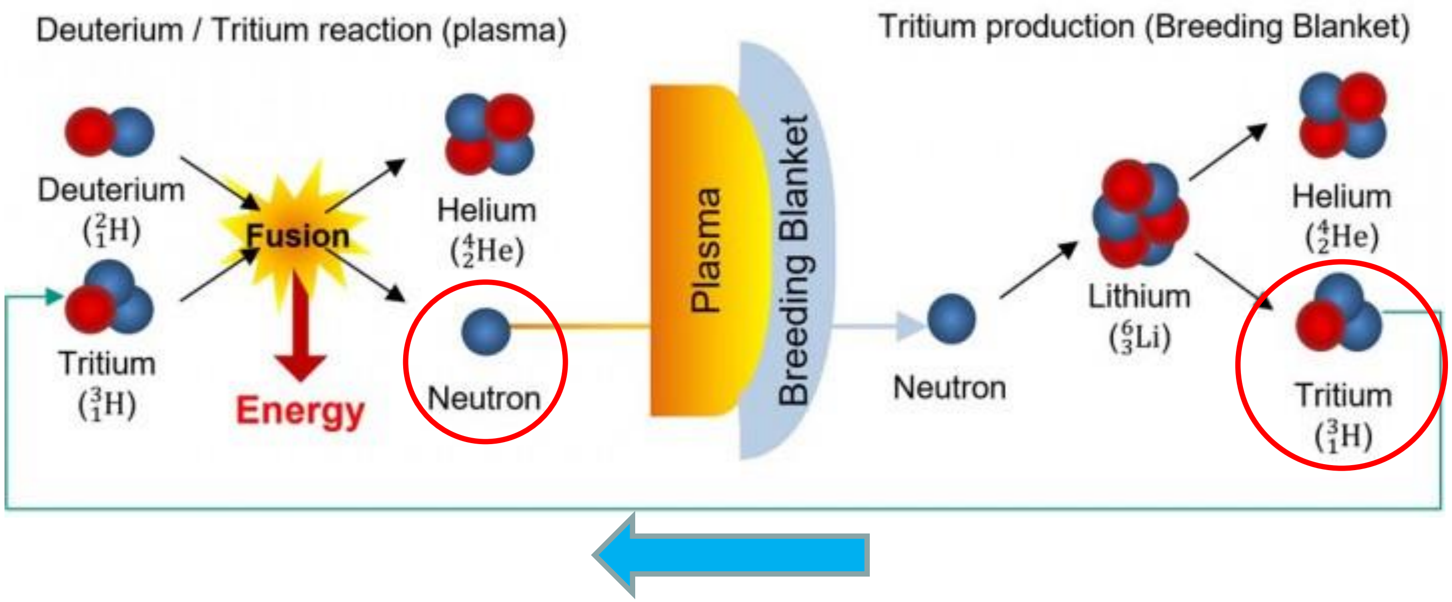
What about Tritium?

Breeding Tritium

Tritium is scarce but it can be produced from Lithium

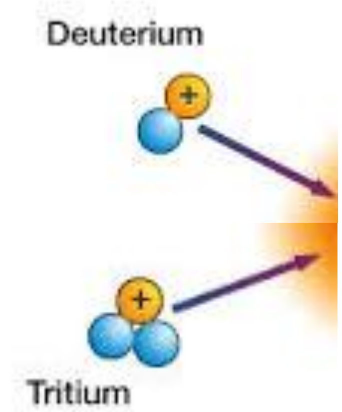
$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H + 4.8\,MeV$$

Use the neutrons from the fusion reaction (breeding)

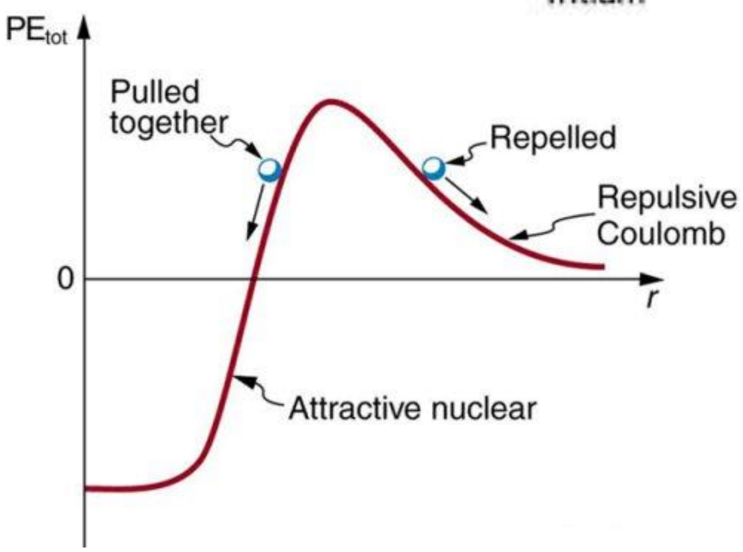


A 1 GW electric fusion power plant would consume around 100 kg of deuterium and 3 tonnes of natural lithium in a year whilst generating 7 billion kilowatt-hour.

Starting requirements



Deuterium and Tritium must be close to fuse

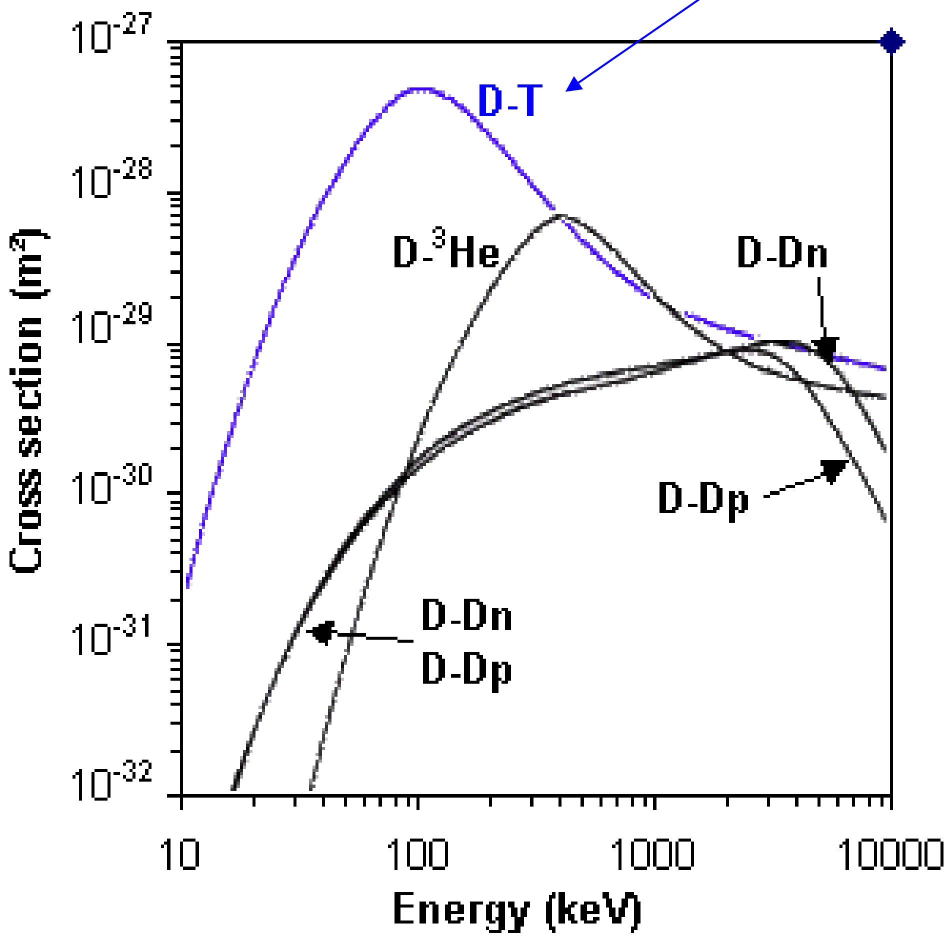


- Particle kinetic energy must be high enough to overcome the mutual electrostatic repulsion

→ Need for high temperatures !

How high temperatures...?

$${}_1^2D + {}_1^3T \rightarrow {}_2^4He + n + 17.6MeV(K.E.)$$



Kinetic Energy=10-20 keV =kT

1 eV ≈ 11604 K

→ T ~ 200 million K

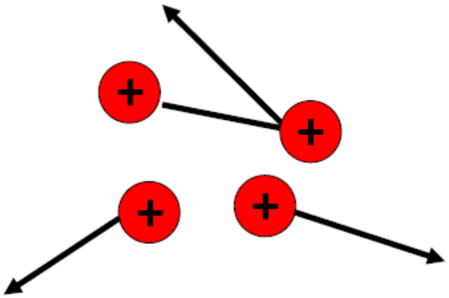
High temperature is not sufficient…

- The particles must also be **close enough** to react

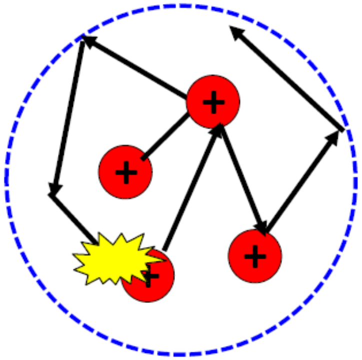
  → High density

- They must also **stay close to each other long enough** to allow the reaction to take place

  → Long confinement time



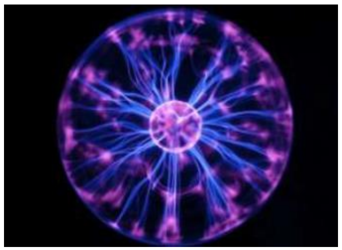
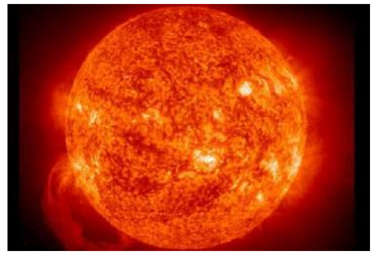
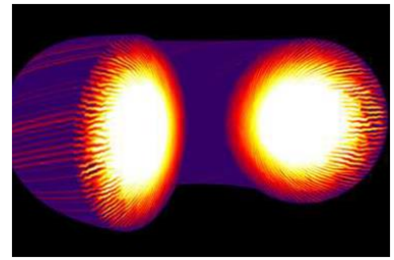
No confinement
Particles are scattered and lost
No fusion occurs



Ideal confinement
Particles are scattered but fusion eventually occurs

Lawson criterion

For high efficiency we need a large value of the triple product
plasma density × **temperature** × **confinement time**

- The Lawson criterion and its extension, the triple product, are a good figure of merit for the conditions required to reach ignition (self-sustaining reaction).

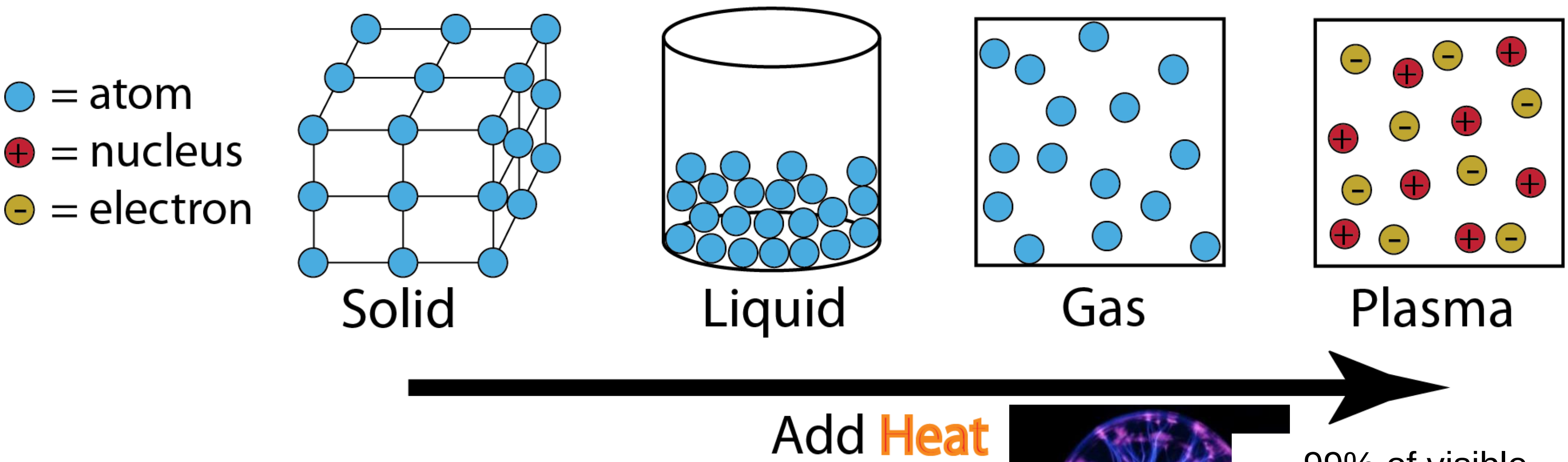
$$n_i \times T \times \tau_E \sim 5 \times 10^{21}\ \mathrm{keV \cdot s \cdot m^{-3}}$$

Typical values: $n_i \sim 1.5 \times 10^{20}\ \mathrm{m^{-3}}$, $T \sim 10\ \mathrm{keV}$, $\tau_E \sim 3\ \mathrm{s}$

At such temperatures confinement by material walls is not possible.

How do we achieve this?

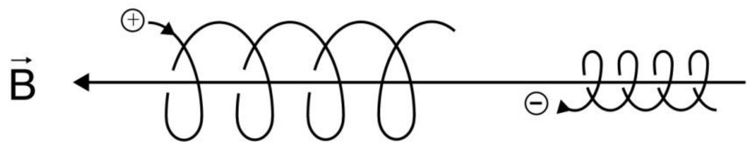
At T ~ 200 million degrees, matter is in the **plasma state**

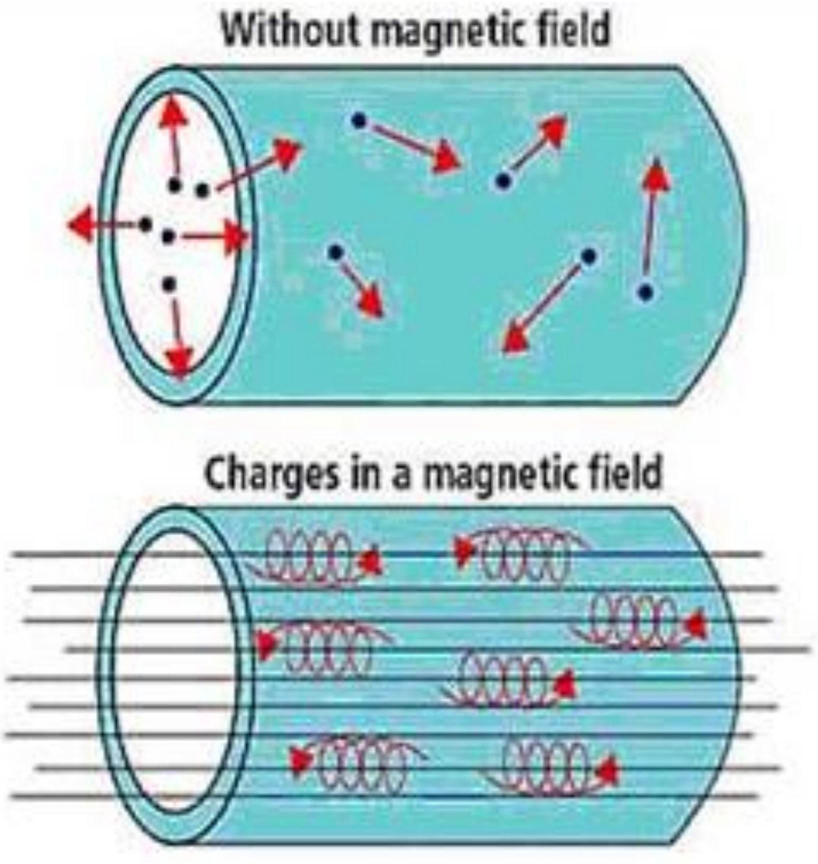


99% of visible matter in the Universe is **plasma**

Plasmas consist of charged particles—positive nuclei and negative electrons—that can be shaped and confined by magnetic fields.

We can control the charged particles in a plasma using intense magnetic fields.



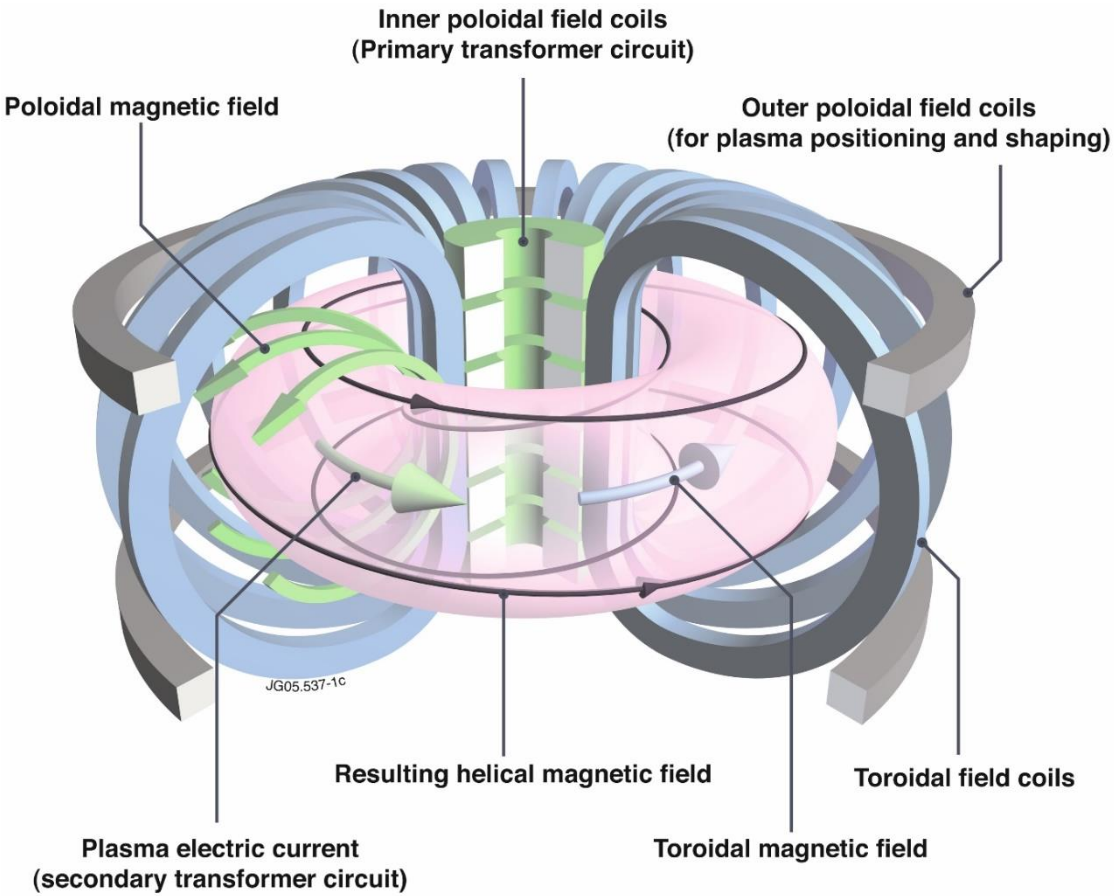


But still have losses from the sides!

Tokamak: The machine which confines the plasma

Tokamak: **To**roidalnaja **ka**mera **ma**gnitnaja **k**atushka

toroidal **cha**mber with **ma**gnetic **c**oils



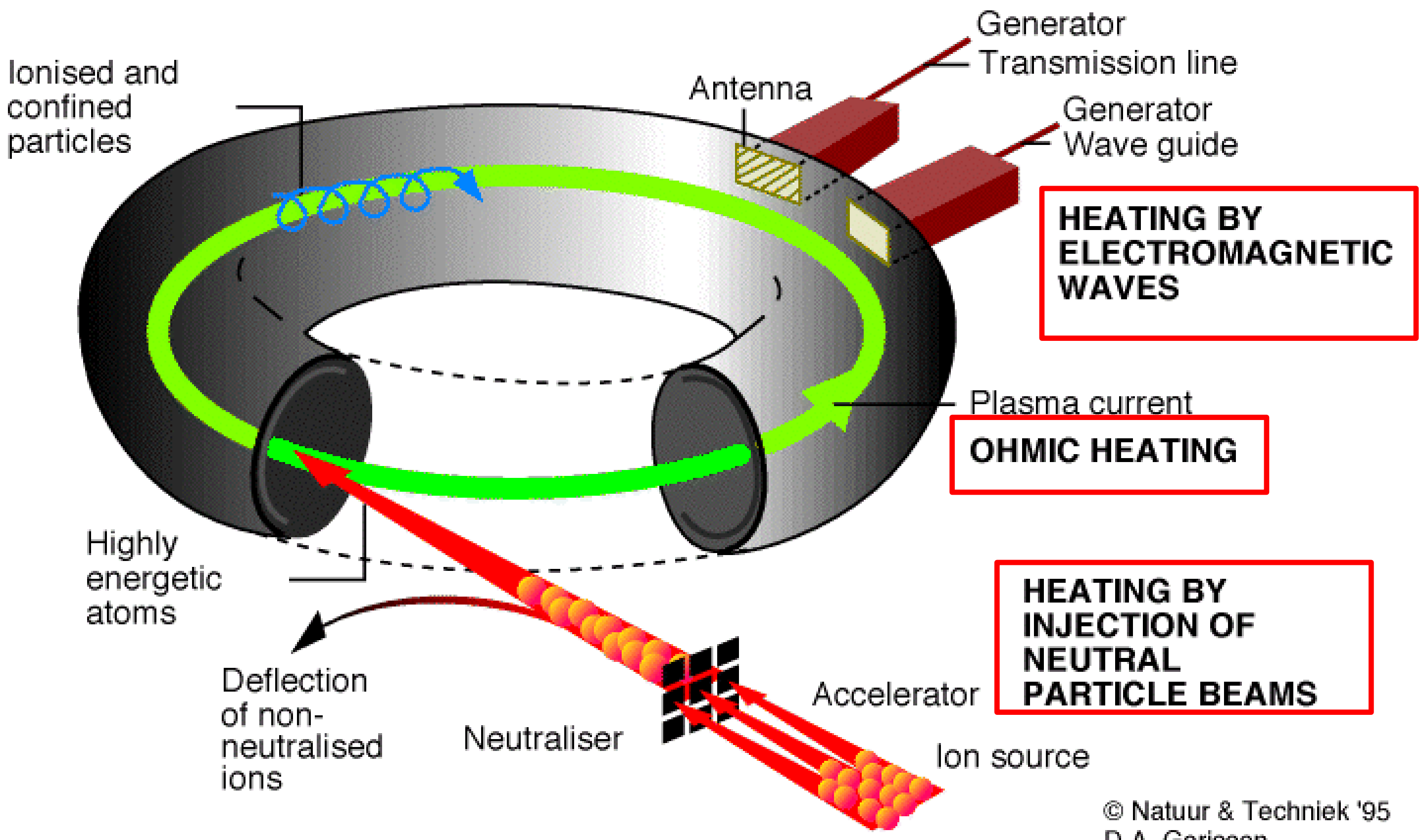
Tokamaks were invented in the 1950s by the Soviet physicists **Igor Tamm** and **Andrei Sakharov**, inspired by an original idea of **Oleg Lavrentiev**

They use external coils to generate a helical magnetic field

Magnetic field coils:

- Guide the plasma particles
- Generate a current in the plasma
- Shape the plasma

Plasma heating



+ alpha particle heating in D-T fusion systems

Each heating system is capable of delivering over a 1 MW of power to the fuel

Plasma diagnostics

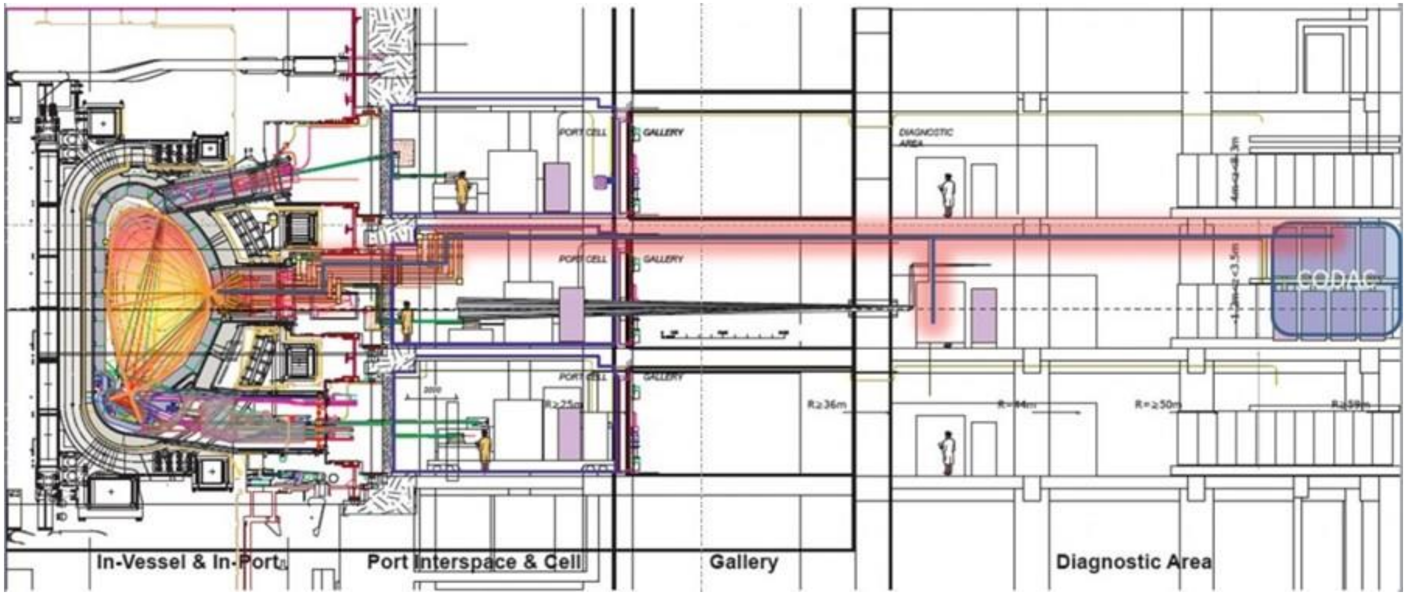
It is not possible to insert a thermocouple into plasma to measure its temperature

All systems must be based on

- Natural emission of the plasma
- Interaction with laser light or particle beams

- to measure plasma temperature, density, emission
- to control, evaluate and optimize plasma performance

In addition magnetic, neutron, etc., diagnostics

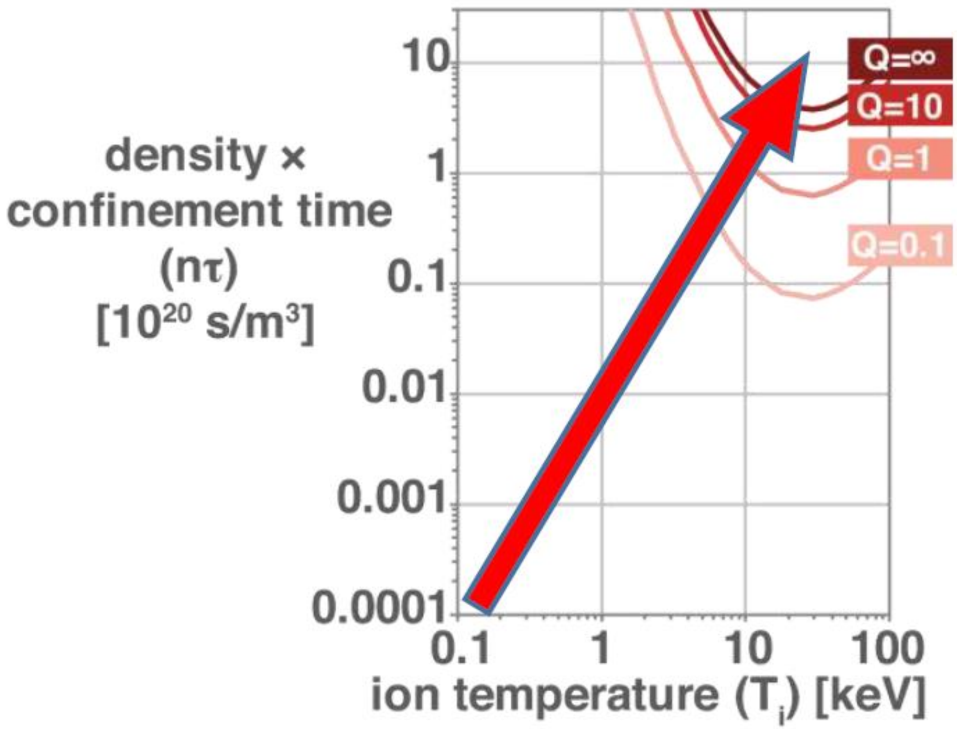


About 50 individual measurement systems will help to control, evaluate and optimize plasma performance in ITER and to further understanding of plasma physics.

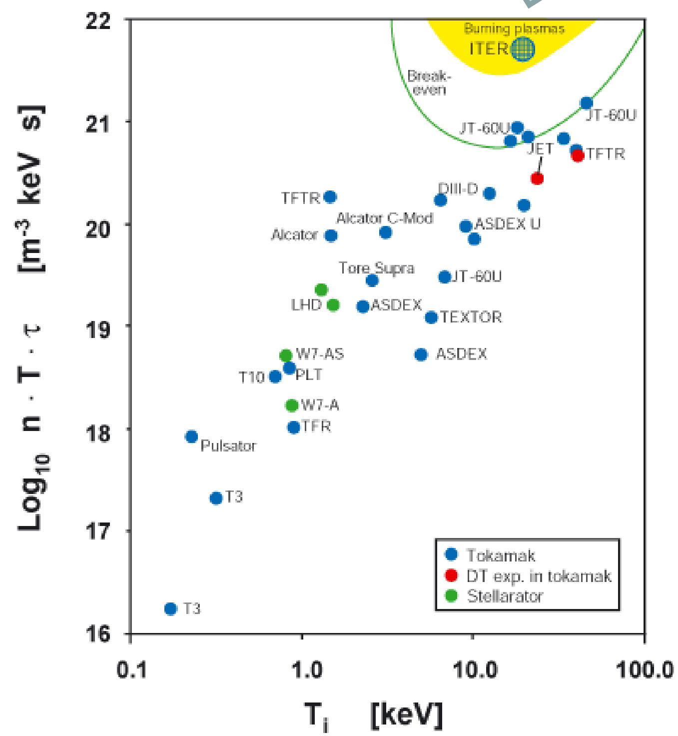
Source: ITER

How close are we...?

$$Q = \frac{Fusion\ energy\ output}{Energy\ input}$$

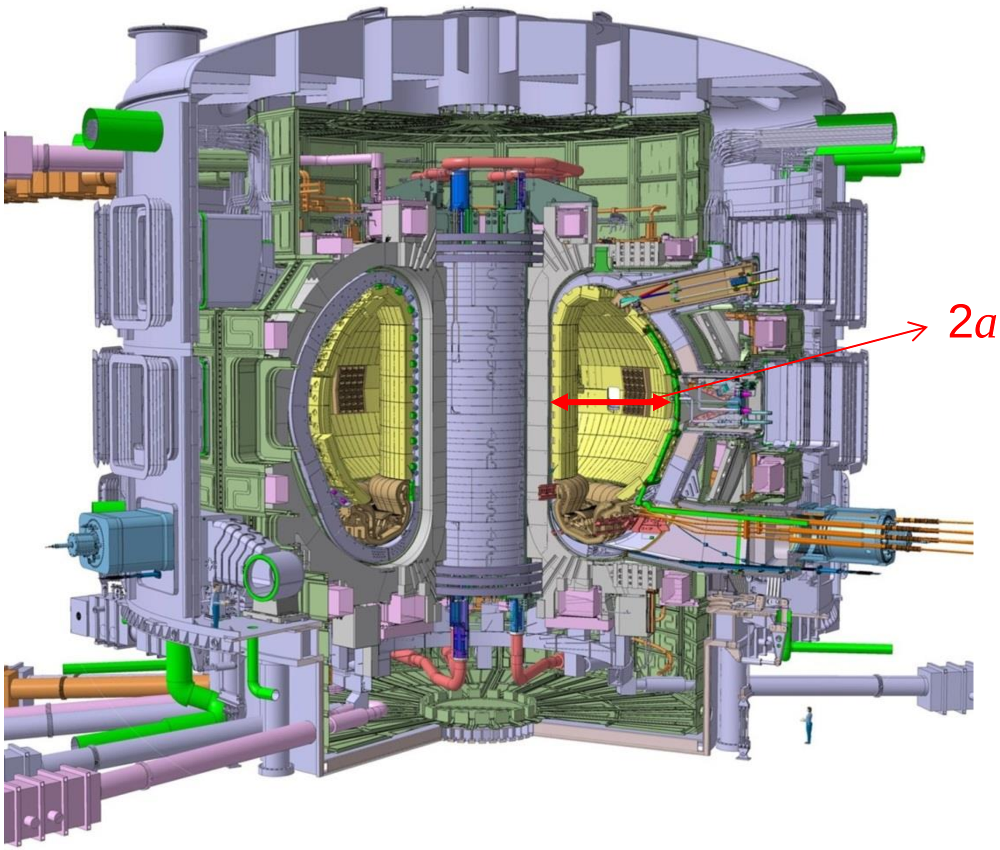


ITER
Q=10



Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years…

Size requirements



- Confinement time scales approximatelly with size

$$\tau_E \propto \tfrac{1}{2}\, a^2$$

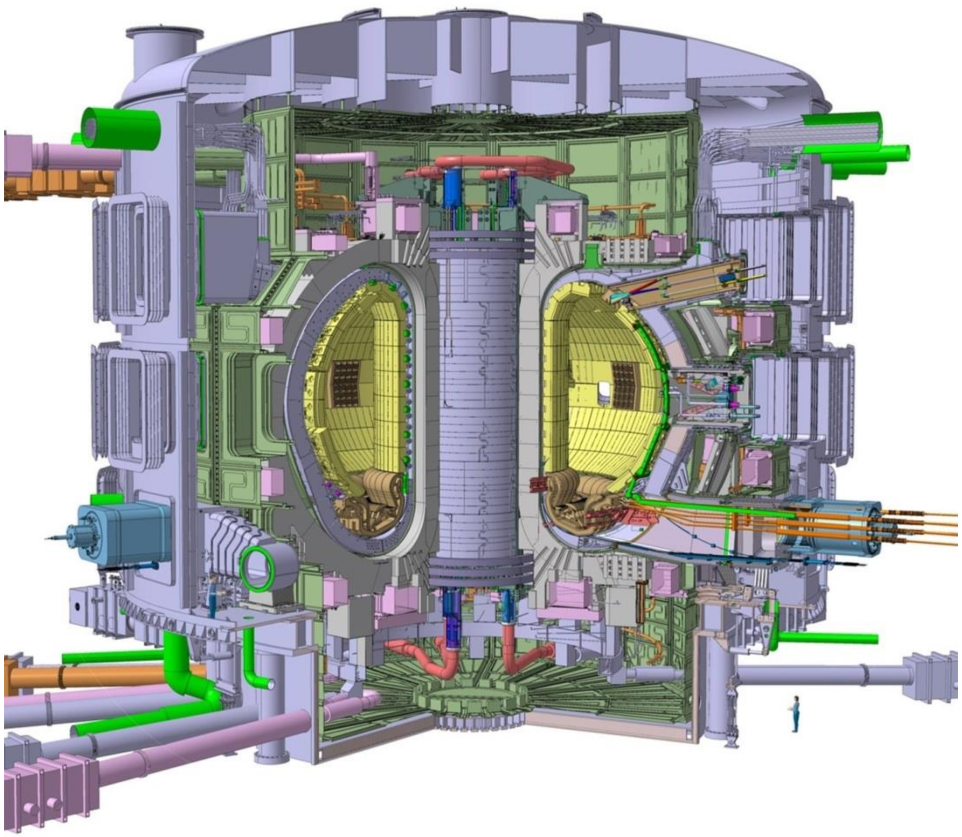
- Where a is the minor radius

JET : a = 1.25 m, $\tau_E \sim 1\text{s}$

ITER : a = 2 m, $\tau_E \sim 4\text{s}$

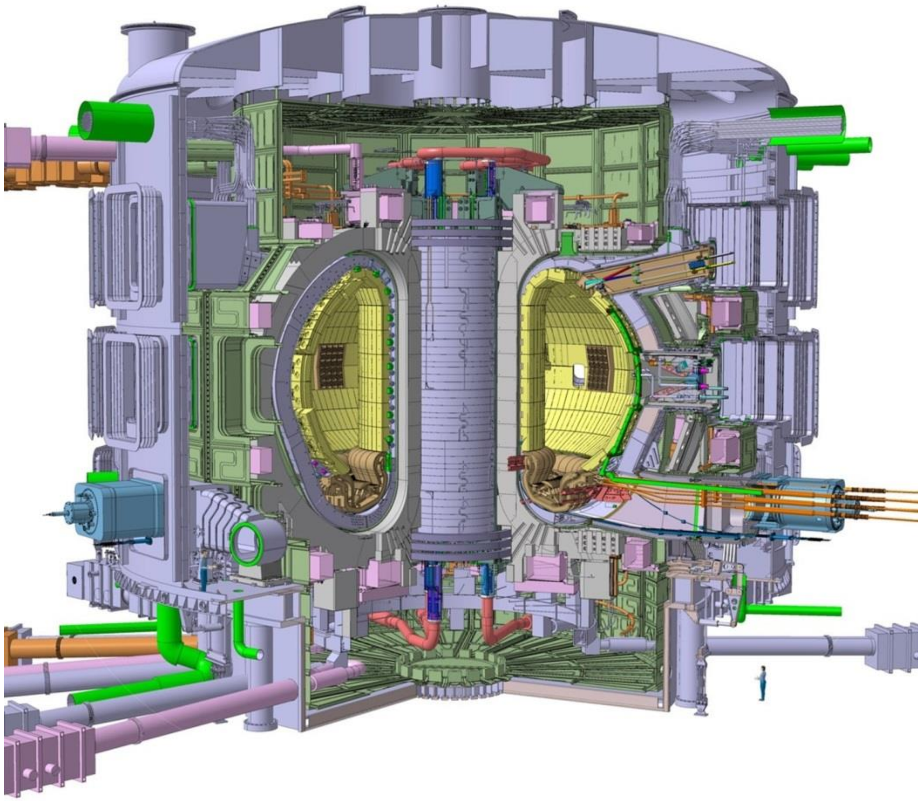
Complex System

- Many systems!



- Superconducting Coils
- Vacuum vessel with pumping systems
- Heating systems
- Cooling systems
- Gas introduction and handling systems
- Diagnostics
- Tritium breeding

Complex System



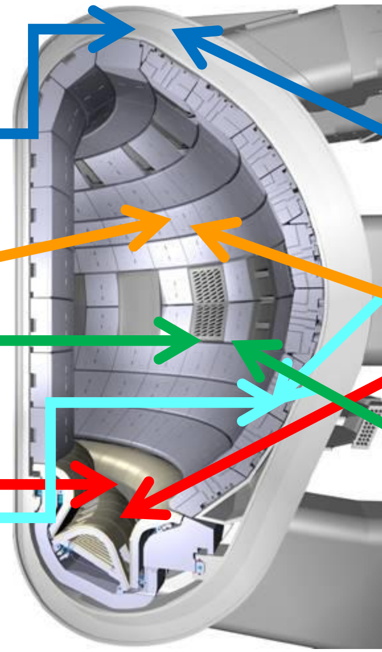
- All this in an environment with very high fluence of 14 MeV neutrons!
- Need a blanket to absorb neutron energy in order to:
  - Transfer their energy to heat
  - Protect sensitive components
  - Breed Tritium from Lithium
- The high neutron flux also requires:
  - Remote handling techniques
  - Development of advanced materials
  - Very good operational reliability

Technologically very demanding!

Fusion reactor: plasma and materials

Materials at different reactor locations

- Vacuum Vessel & Shield
- Plasma facing components
- Divertor
- Blanket & First wall
- Diagnostics
- Plasma heating, fueling systems,
- Magnets
- Vacuum pumping system…



Materials utility

Structural materials

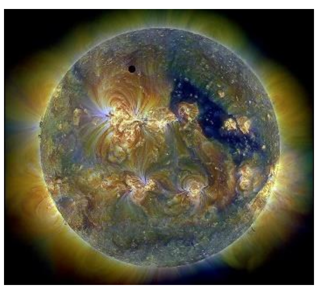
Plasma facing materials

Functional materials

Environment of Fusion reactor materials

Fusion materials and components have to withstand and operate at extreme environment

- **High temperatures**
- **High heat loads**



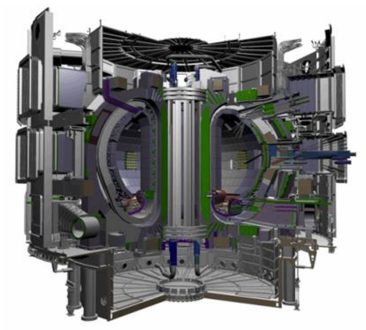
- **High fluxes of energetic particles & neutrons**

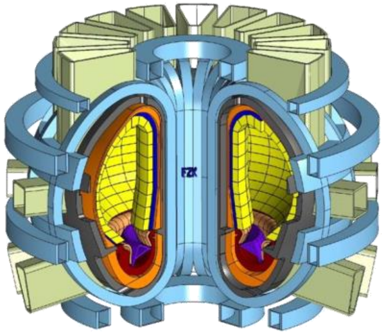
- **Strict safety requirements**
- **Low environmental impact**

Fusion Material Research at "Demokritos"

Going on for 20 yrs (from 1999)

For ITER & DEMO applications


ITER

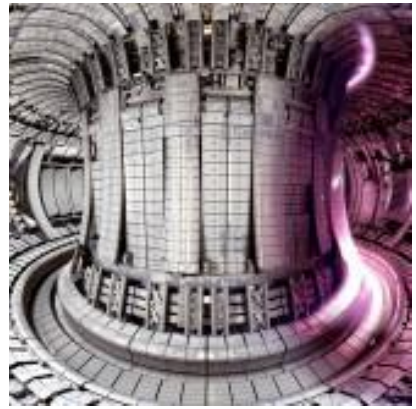


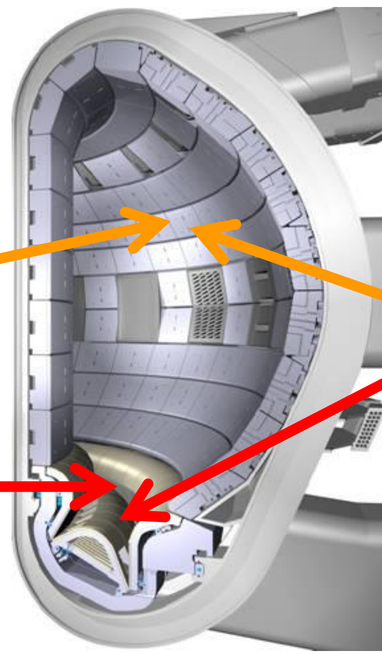
DEMO

- Plasma facing materials & components
- Structural materials
- Functional materials
- Neutron irradiation effects & mechanical performance
- Experimental validation of irradiation effects modelling
- Radiological assessment of materials

Funded by the European Union (www.euro-fusion.org) **and General Secretariat for Research and Technology**

Plasma Facing Components & Materials



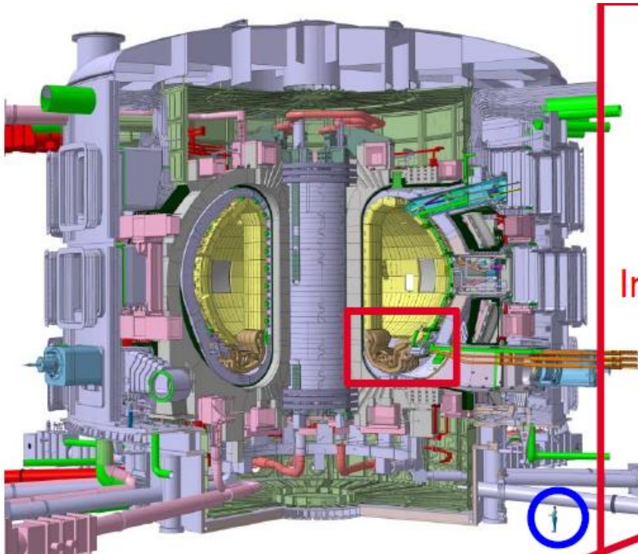


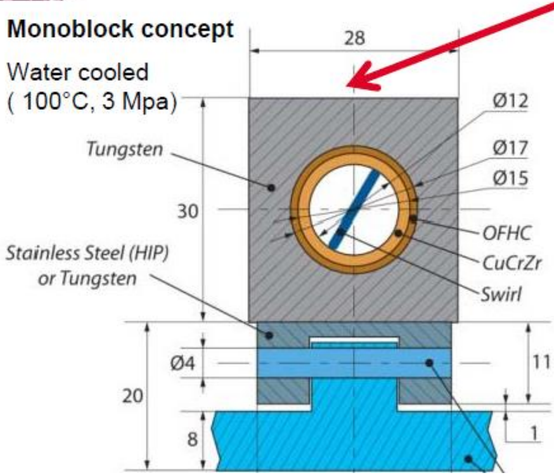
- Plasma facing components
- Divertor

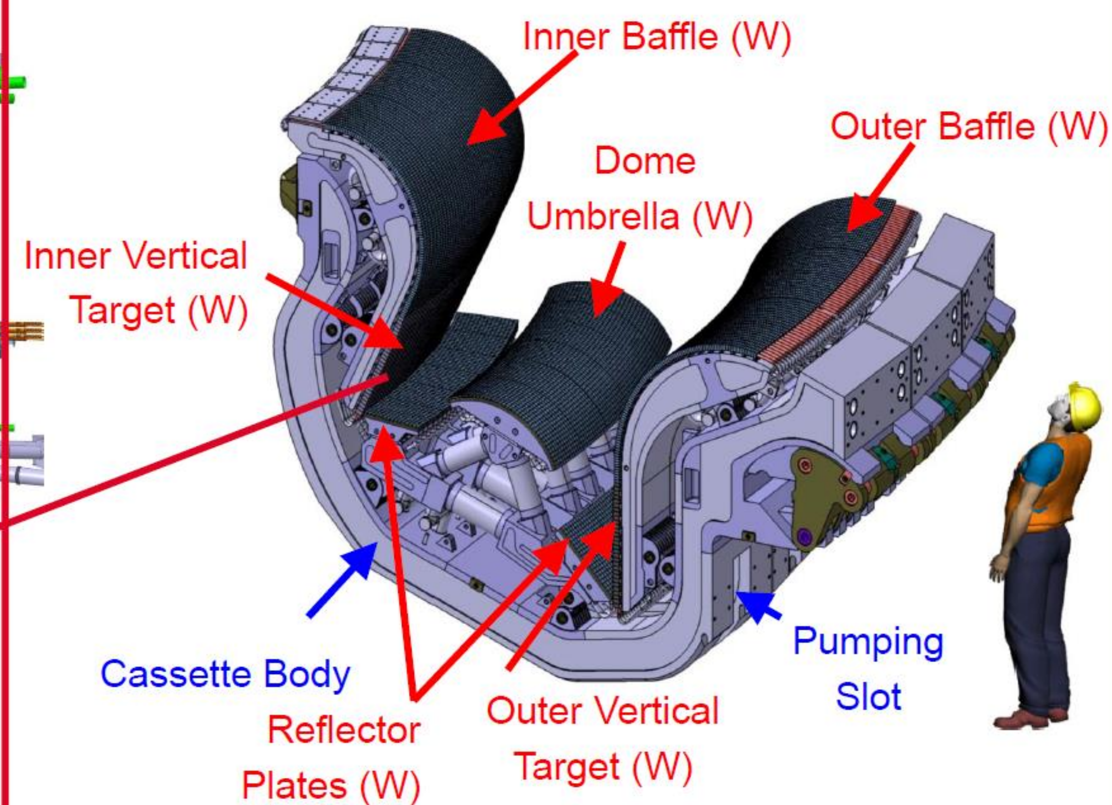
Plasma facing materials

ITER divertor

The divertor is one of the most crucial components in a fusion device.
It removes the heat load and acts as the exhaust of the device (removal of helium ash).





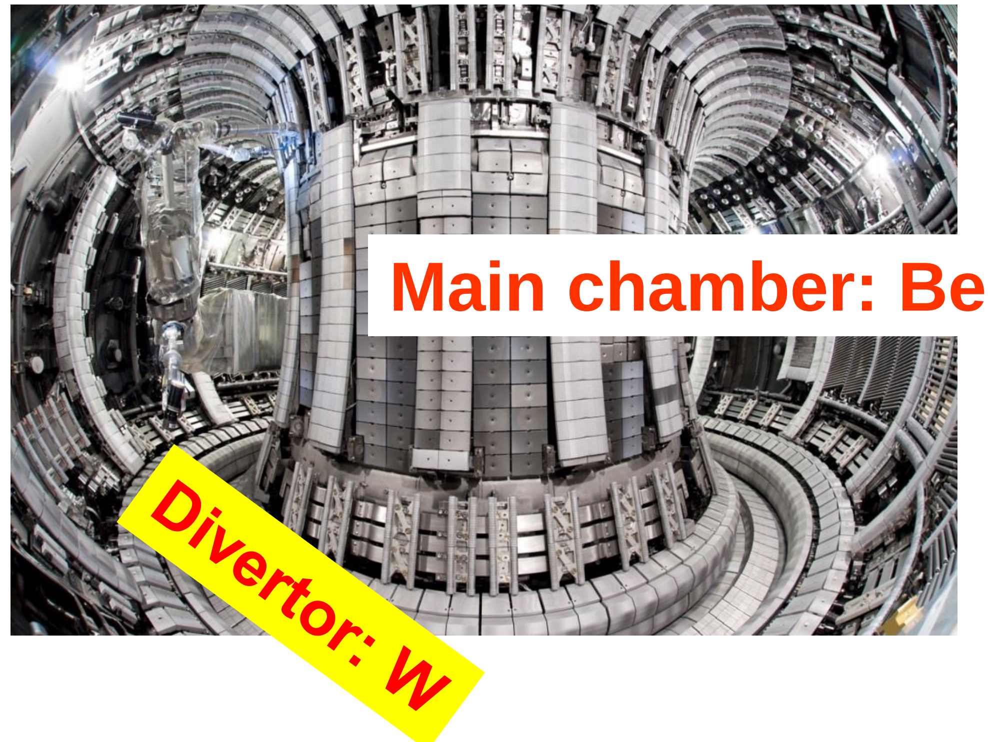


Divertor cost>100 M€ (54 cassettes), manufacturing: 6-8 years, installation & commissioning: 1 year

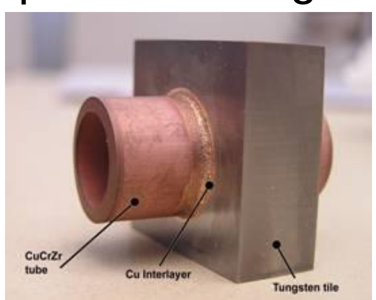
Investigation of Plasma Facing Materials at Demokritos

Investigation of the ITER-like wall JET main chamber and divertor Tiles with respect to

- Material migration
- Material deposition
- Erosion
- Formation of new compounds



Investigation of residual stresses in Plasma Facing Components using Neutron diffraction

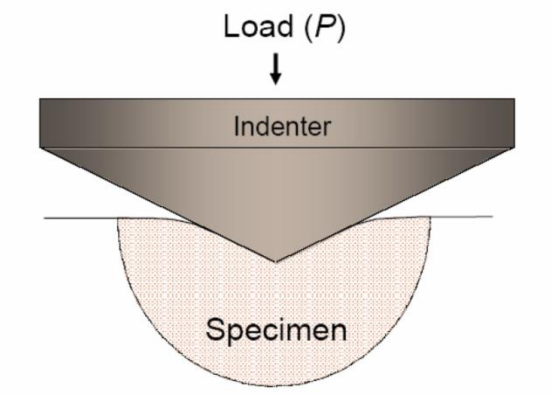


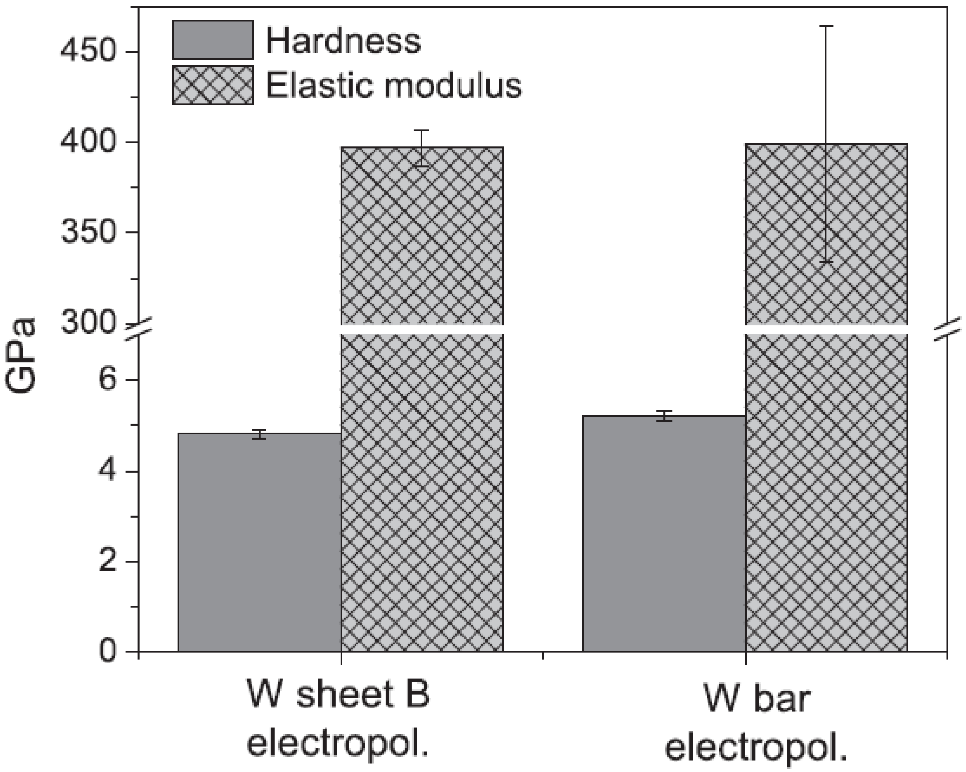
Mechanical and structural properties of neutron irradiated W based materials for ITER, DEMO and beyond.

Investigation of Plasma Facing Materials at Demokritos

Mechanical Properties of W based materials

Nano-indentation is used to measure the mechanical properties of various candidate W materials as a function of depth





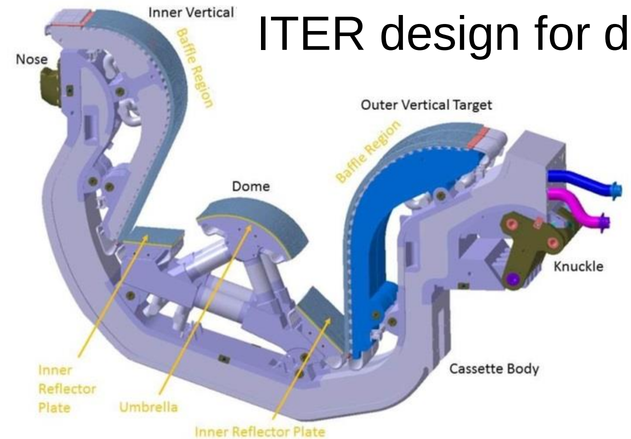
S. Krimpalis, et al. Phys. Scripta (2017)

Investigation of Plasma Facing Materials at Demokritos

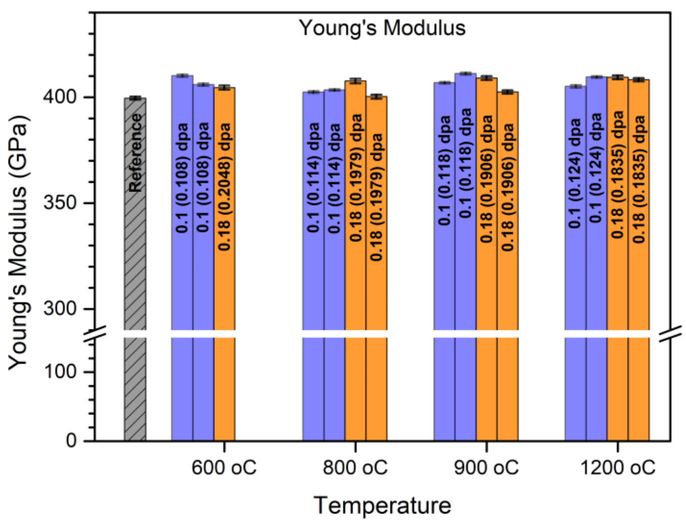
Effects of neutron irradiation on mechanical properties

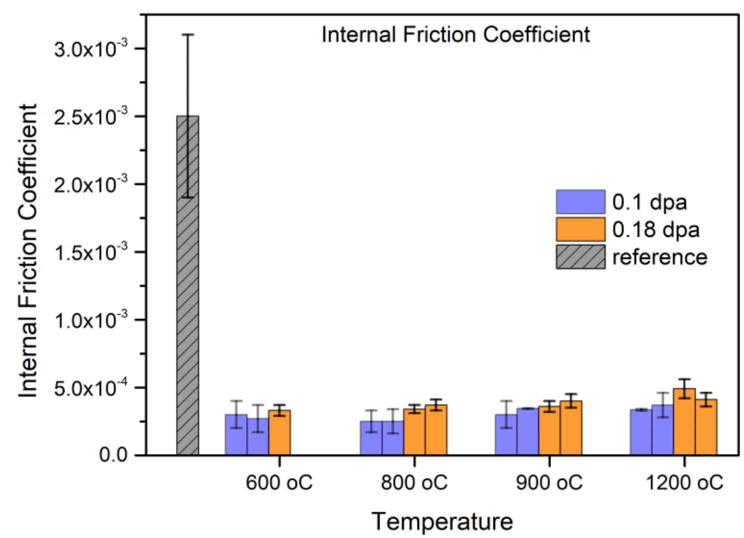
- W is candidate material for divertor

ITER design for divertor



Neutron irradiated W single crystal irradiated at 0.1 & 0.18 dpa





S. Dellis *et al.*, PFMC 2019

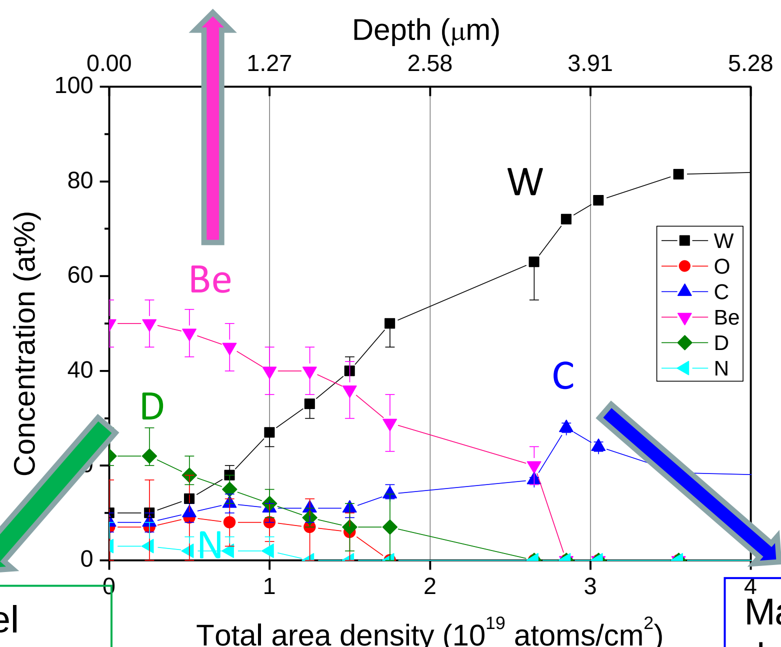
Investigation of Plasma Facing Materials at Demokritos

ITER-like wall of the JET tokamak

Investigation of
- material deposition/migration
- fuel retention
- erosion
- formation of new compounds

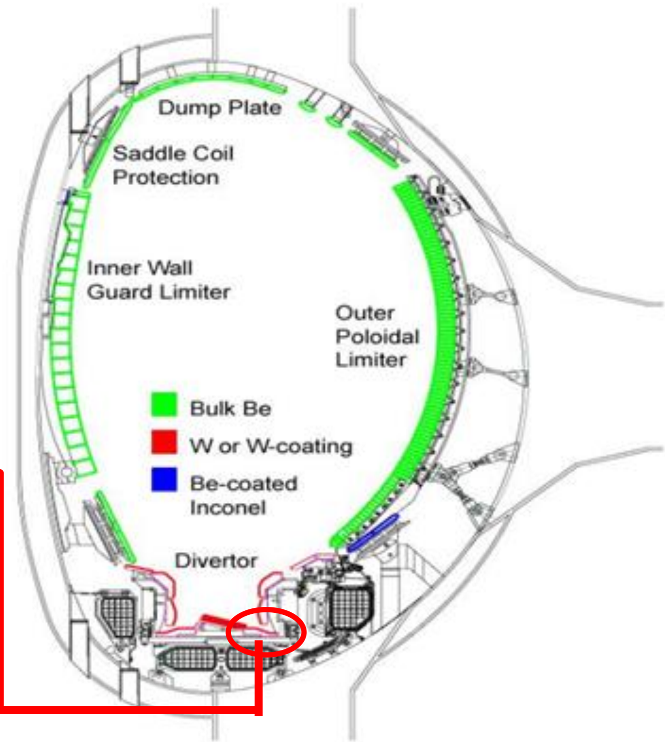
of the metallic ITER-wall Tiles from the divertor and main chamber at JET tokamak

Material migration and deposition



Fuel retention

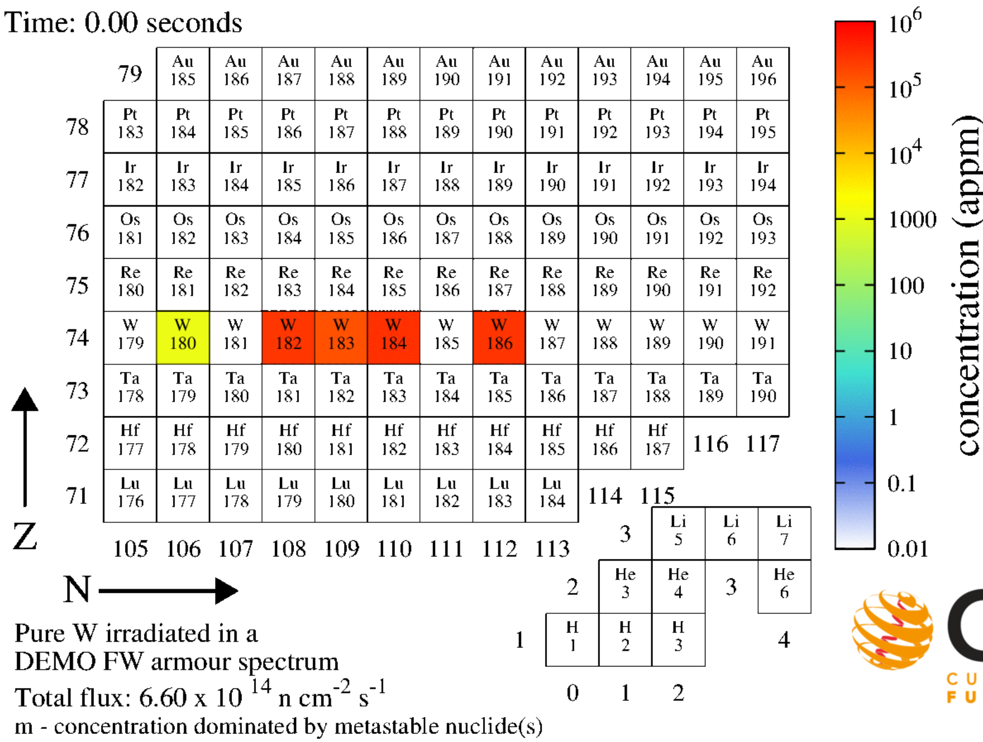
Material deposition

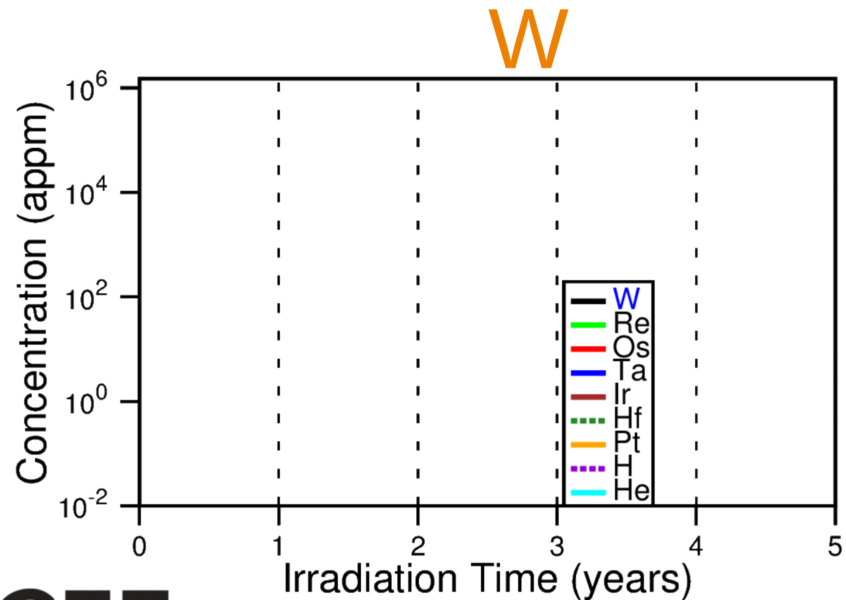


W/CFC, JET tokamak

Lagoyannis et al. Nuclear Fusion (2017)

W Transmutations due to exposure to neutrons



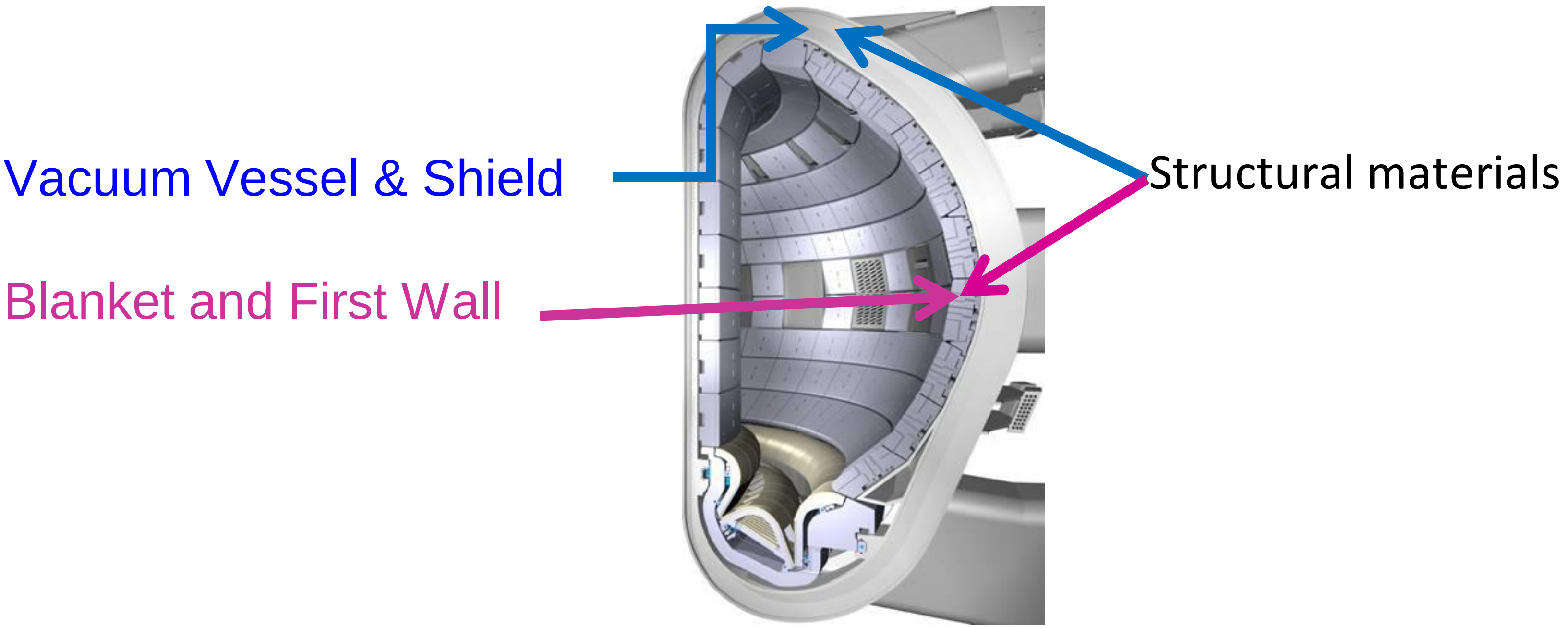


CCFE CULHAM CENTRE FOR FUSION ENERGY

M. R. Gilbert et al., *Nucl. Sci. Eng* (2013)
M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

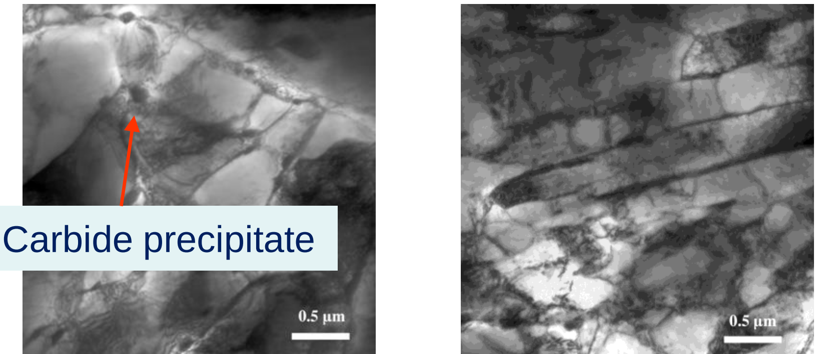
Initially pure natural tungsten, exposed to neutrons with the spectrum of a DEMO fusion reactor, transforms into other elements, including rhenium, osmium, helium and hydrogen. Accumulation of helium above a critical concentration gives rise to grain boundary embrittlement. Accumulation of rhenium gives rise to the formation of Re-rich precipitates, which also embrittle tungsten further, and reduce its thermal conductivity.

Structural Materials

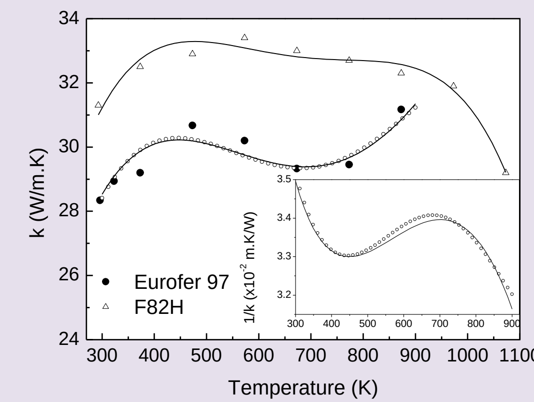


EUROFER : Microstructure and physical properties

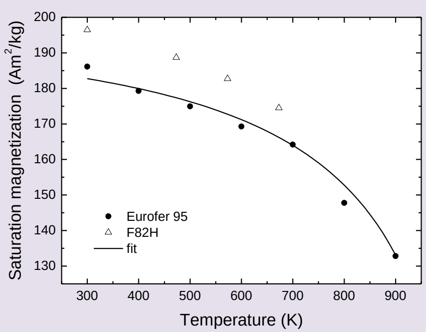
Characterization of EUROFER 97 steel physical properties and comparison with theoretical models



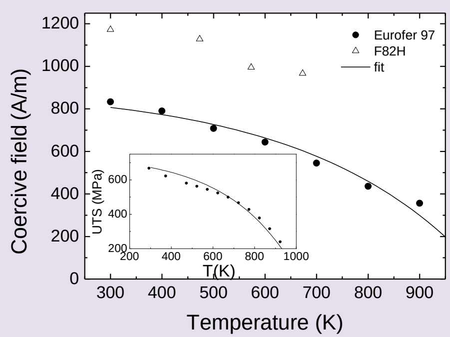
TEM images of the Eurofer-97 steel



Thermal conductivity versus temperature Measurements and theoretical model



Saturation magnetization versus temperature of EUROFER-97



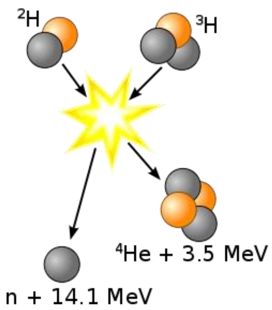
Coercive field & ultimate tensile strength versus temperature of EUROFER-97

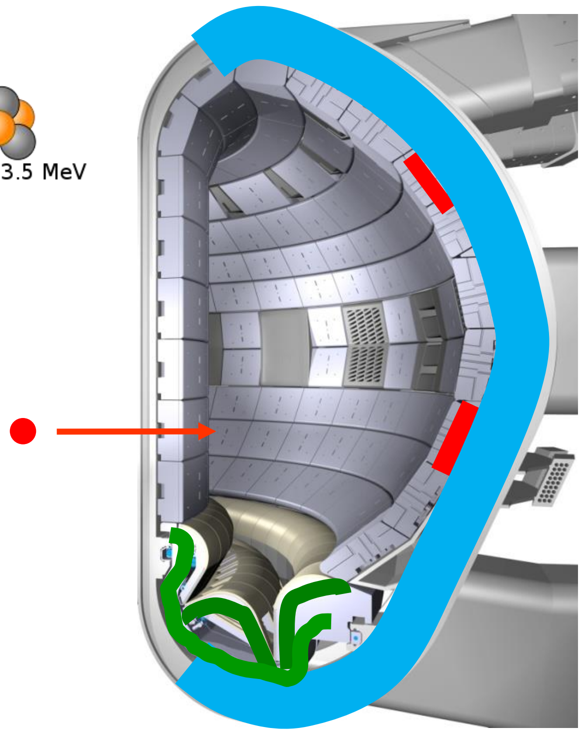
Correlation of magnetic and mechanical properties for EUROFER 97 steel

K. Mergia and N. Boukos, J. Nucl. Mater. (2008)

Neutron effects on structural materials

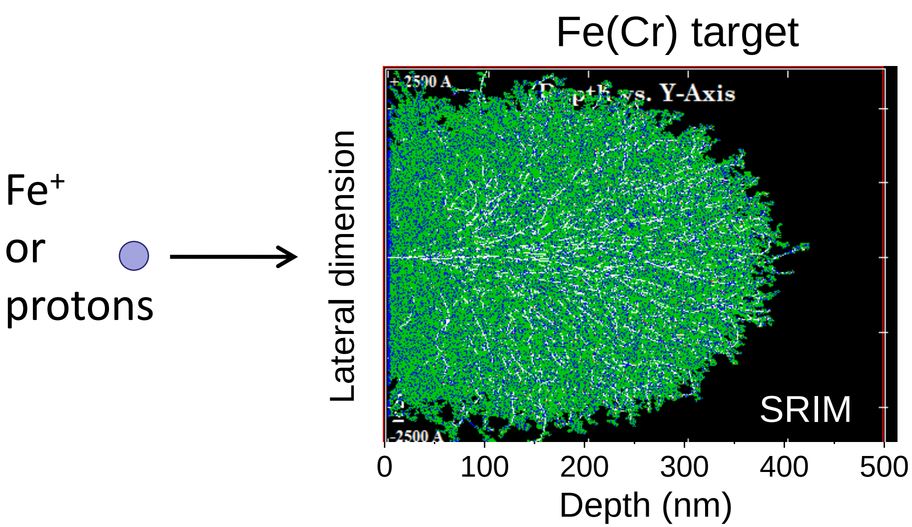
Use of ion beams to imitate the neutron induced damage on structural materials





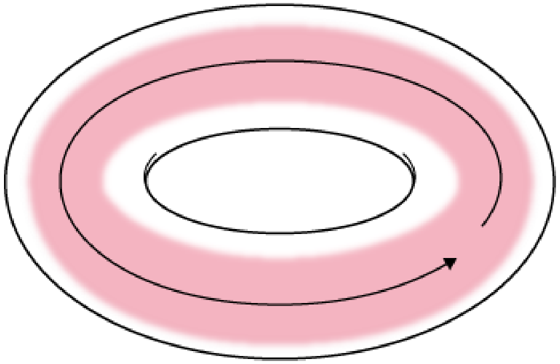
<u>Structural materials</u>

- **Vacuum vessel**
- Blanket
- Divertor body

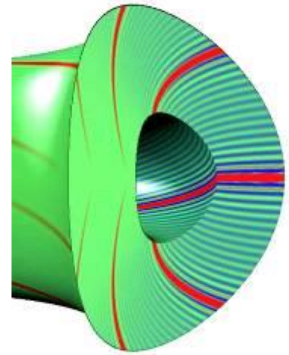


- Understanding of radiation damage effects and experimental validation of modeling
- Microstructural and magnetic effects
  - ✓ Swelling
  - ✓ Grain growth
  - ✓ Magnetic properties changes

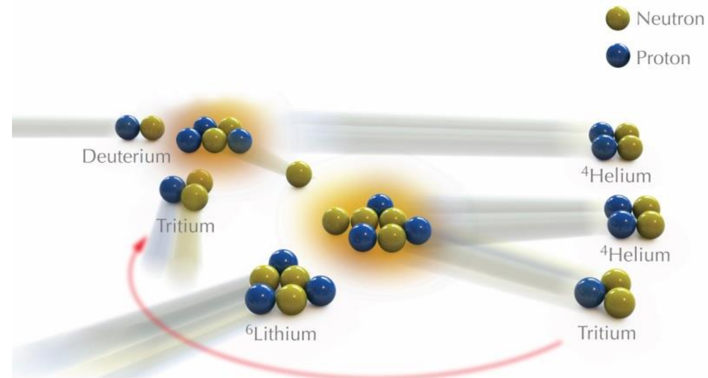
Key technological challenges: plasma and materials



Develop stable operational regimes at high confinement

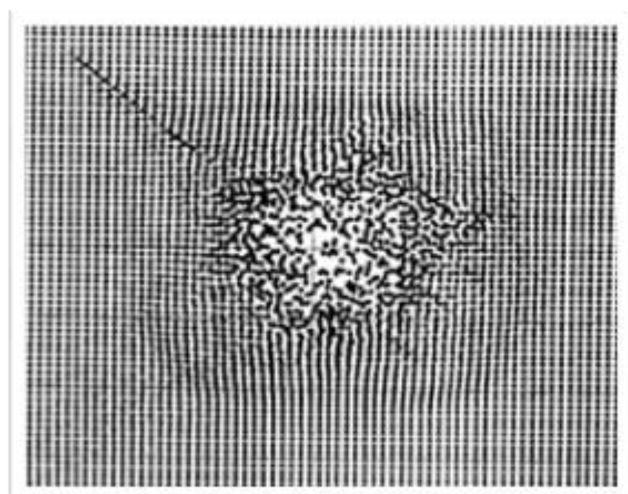


Reduce energy losses, control heat loads, plasma impurities and instabilities



Develop Tritium breeding technologies

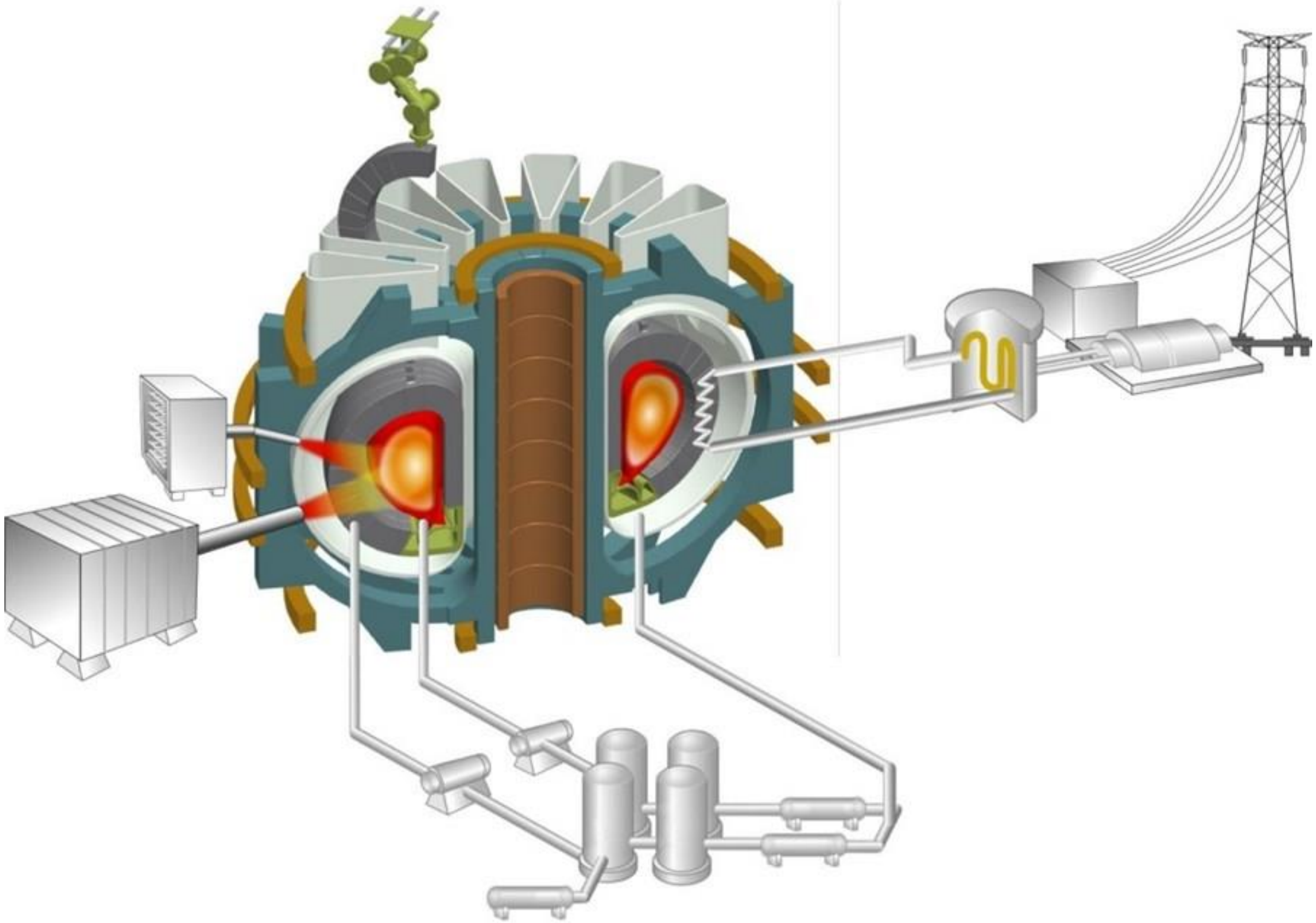
Deal with complexity



Develop neutron resistant materials

Develop heat resistant materials

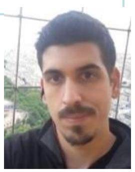
The realization of fusion energy on earth requires combined forces worldwide to cope with the technological and scientific challenges



Acknowledgements

Research Reactor
technical &
scientific staff

TANDEM accel.
technical &
scientific staff



V. Chatzikos
PhD student

Spyros Aleiferis

Dora Vasilopoulou

Marilia Savva

G. Apostolopoulos,
Senior Researcher

M. Axiotis,
Post Doc. researcher

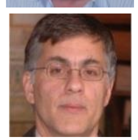
N. Boukos,
Research Director

E. Devlin,
Research Director

M. Gjokas,
Researcher

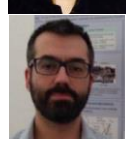
S. Harissopulos,
Institute Director

V. Ioannou-Sougleridis,
Research Director



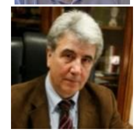
Z. Kotsina,
Post Doc. researcher

S. Krimpalis,
Former Post Doc. Res.



A. Lagoyannis,
Senior Researcher

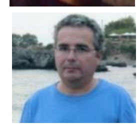
S. Messoloras,
Emeritus Research Director



D. Niarchos,
Institute Director

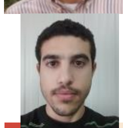
K. Papamichail,
former PhD student

M. Pissas,
Research Director

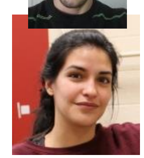


Th. Speliotis,
Researcher

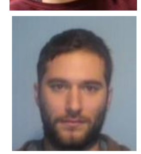
I. Stamatelatos,
Research Director



A. Theofilou
PhD Student



E. Tsompopoulou,
Former PhD Student

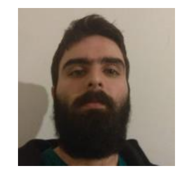


P. Tsavalas,
PhD Student

G. Vekinis,
Research Director

Sp. Dellis
Post Doc. researcher

Ef. Manios
Post Doc. researcher



D. Papadakis
PhD student

Val. Paneta
Former Post Doc. Res.

Irini Michelakaki
Former Post Doc. Res.

Περισσότερα για τη Σύντηξη…

Δρ Δώρα Βασιλοπούλου,
«*Παραγωγή ενέργειας μέσω θερμοπυρηνικής σύντηξης: Ένας ήλιος…πάνω στη γη*”
15:30-16:00, Αίθουσα Θ. Παραδέλης, Κτήριο 6, 1ος όροφος

Dr Spyros Aleiferis,
«*Θερμοπυρηνικοί Αντιδραστήρες Σύντηξης: Εργαλεία Διάγνωσης»*
16:30-17:00, Αίθουσα Θ. Παραδέλης, Κτήριο 6, 1ος όροφος

Thank you for your attention