FUSION FOR ENERGY

BRINGING THE POWER OF THE SUN TO EARTH

# Development of technologies for fusion, fission and beyond

## The path forward from EU perspective


**Stefan Wikman**

Head of Materials, Manufacturing & Metrology

# Scope

- Introduction to Fusion for Energy - F4E
- Fusion Reactor Environment vs Fission Reactor Environment
- Development, Manufacturing and Test Facilities
- The New Technology Development Programme

# F4E - The European Agency for ITER and Development of Fusion Energy

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- Headquarters: Barcelona, Spain
  Offices: Cadarache, France
  Garching, Germany
  Rokkasho, Japan
- Staff: ~460
- Budget

  Spent: €6.6 billion 2007-2020

  Present package: €7.3 billion 2021-2027

  *ITER, DONES, IFMIF, JT-60SA, R&D*

F4E is responsible to deliver Europe's contribution to ITER (about 50% of the budget)

# Fusion developed according to a European Roadmap

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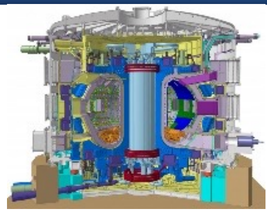
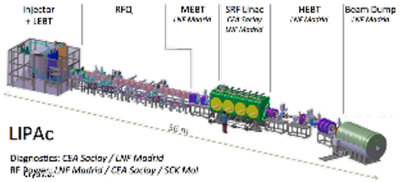
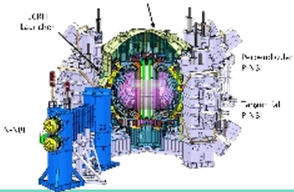


ITER

IFERC

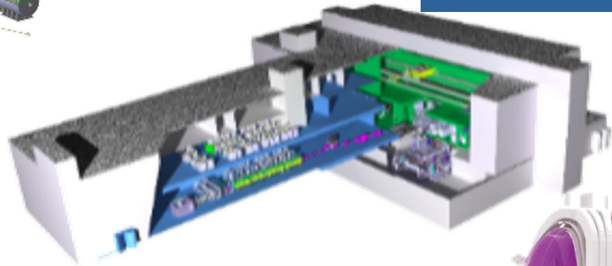



IFMIF-EVEDA

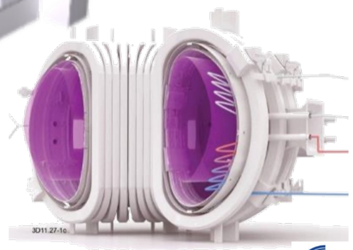


JT-60SA

F4E is responsible for the design & future construction of the **DEMO Orientated Neutron Source**



IFMIF - DONES



DEMONSTRATION FUSION REACTORS

EUROfusion

Short Term → Medium Term → Long Term

Technological Development Programme

# The ITER Project

International Thermonuclear Experimental Reactor

ITER Organization 7 Parties

Site: France
Saint-Paul-lès-Durance

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Delivery ≈ 20€ billion
(More like ≈ 30€ billion as much background work at national labs)

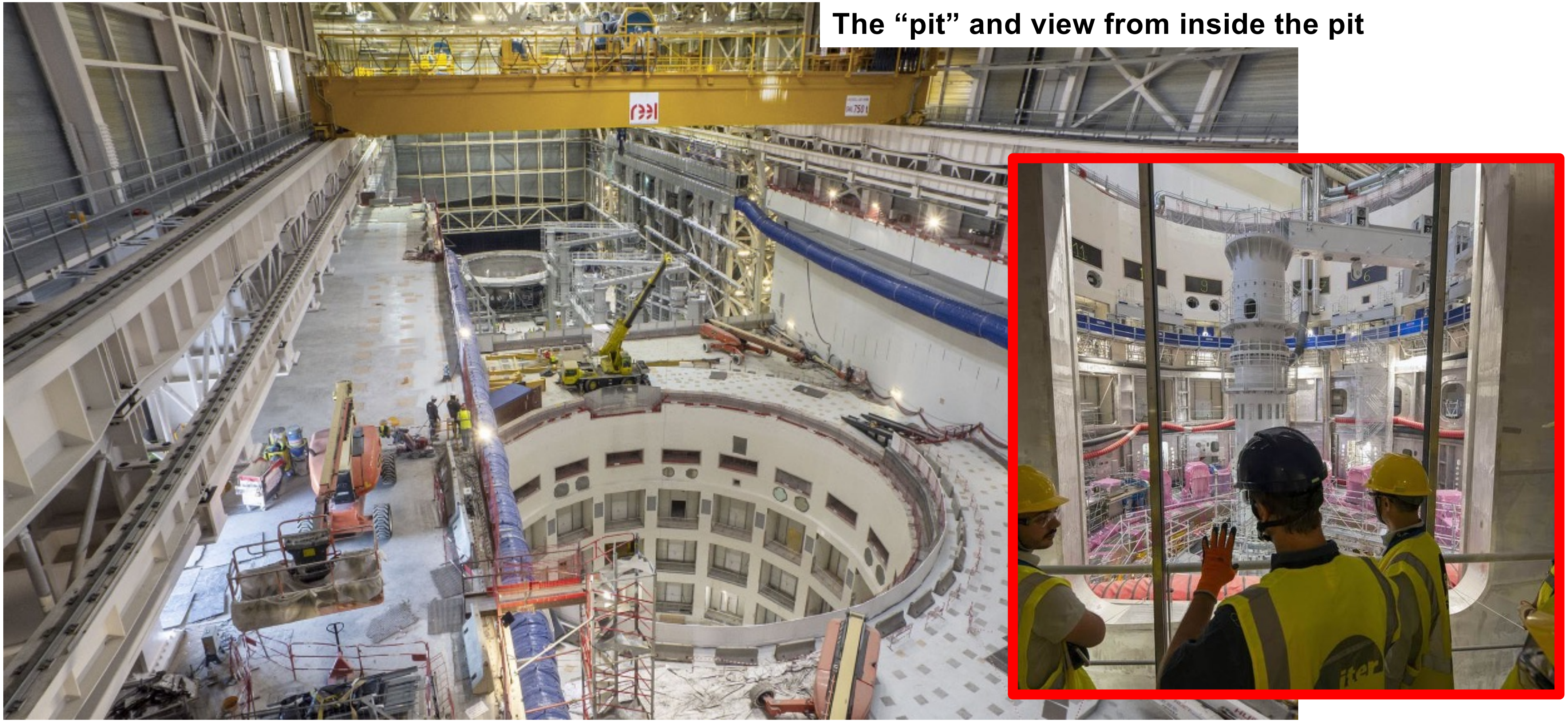
Aim: **Q ≥ 10**

ITER supports to pave the way to fusion power plants

Been the “fusion locomotive” for 2 decades…
- Generating spin-off’s
- Collaboration with other R&D facilities

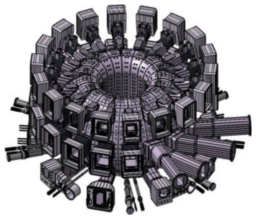
# ITER Tokamak Hall

The “pit” and view from inside the pit



# Size Perspective: The Vacuum Vessel

Vacuum Vessel

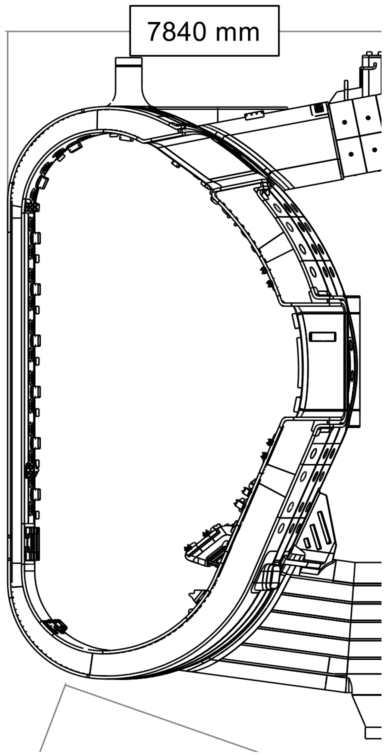


Weight: 5200 t (8500 t with all components)

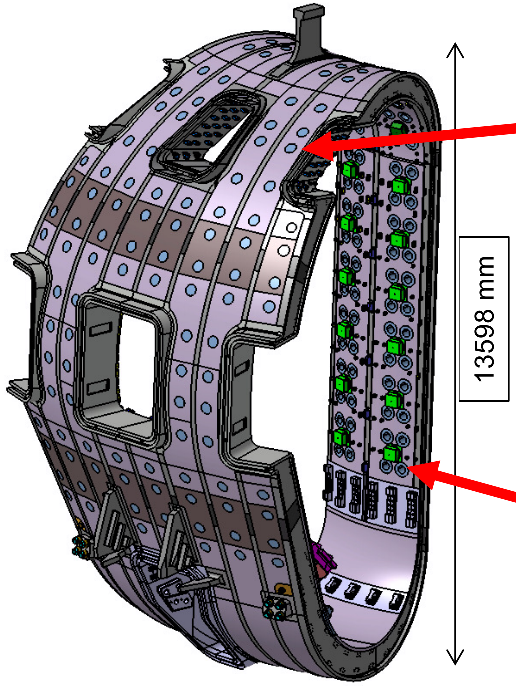
Interior volume: 1400 m³ (840 m³ v)

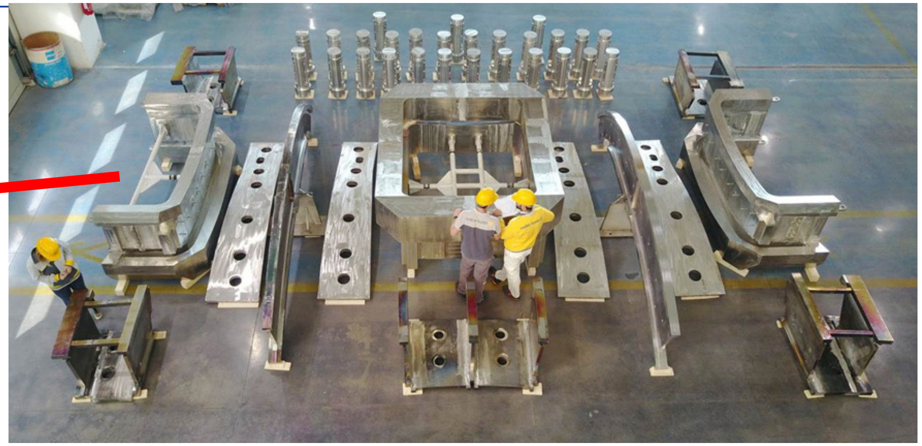
Made up from 9 Sectors, internal shields + access ports

Eiffel tower 10,100 t




**Typical sector**



## FAQ’s: Why participate in the field of Fusion?

- Fusion is a quickly expanding field, spin-offs and much more than ITER.
- Achieve unique qualification of a material/process/component and be ready for the next step.

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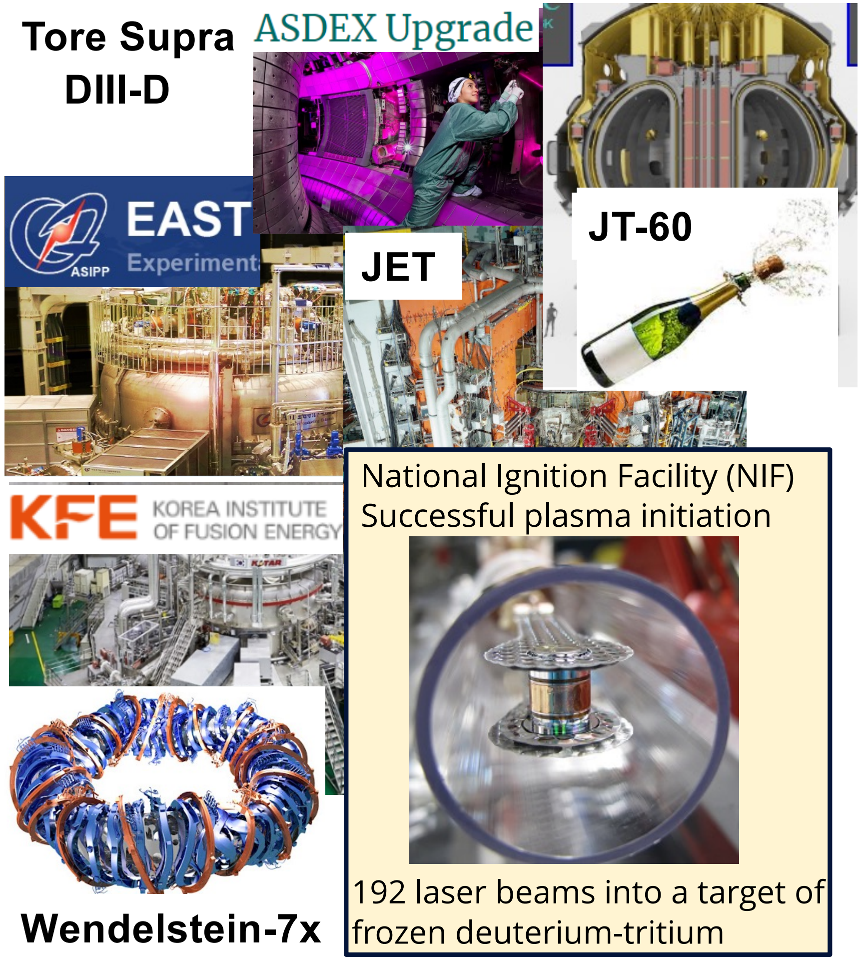
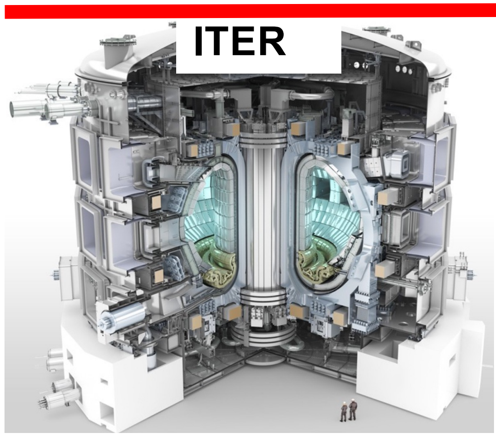


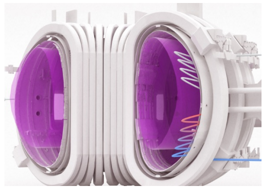

National Ignition Facility (NIF)
Successful plasma initiation

192 laser beams into a target of frozen deuterium-tritium

Running Fusion Projects



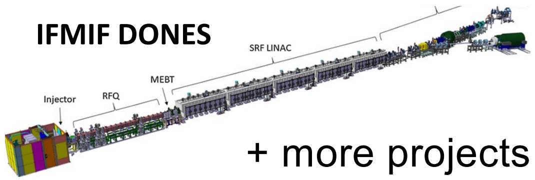

Gen IV Fission



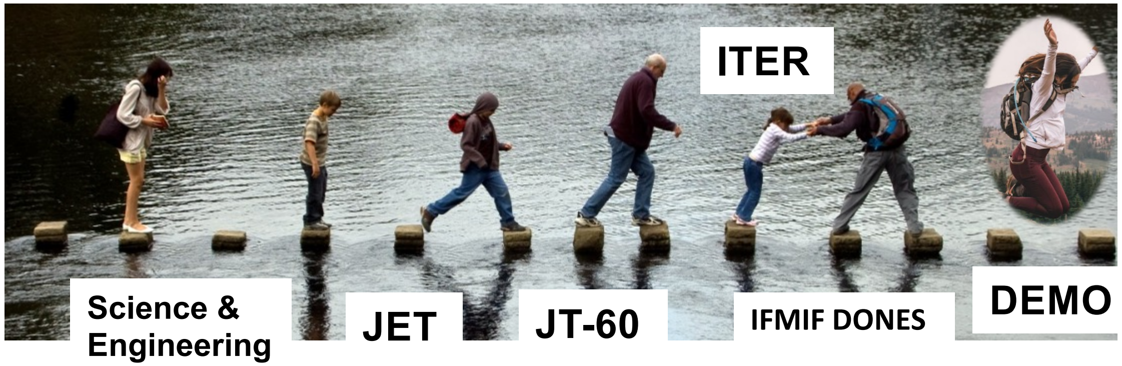
DEMO

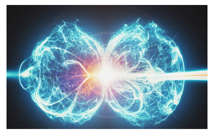

Power Plant – still no defined concept

IFMIF DONES




+ more projects on the way Novatron, Proxima Fusion …

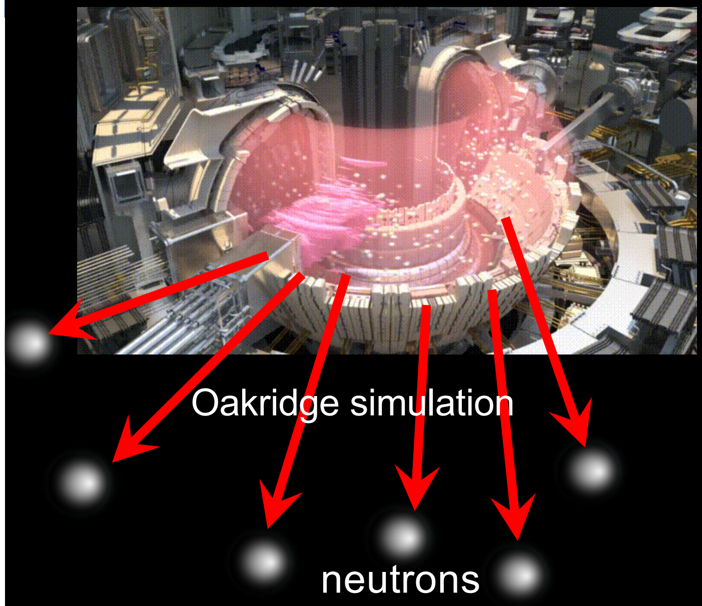


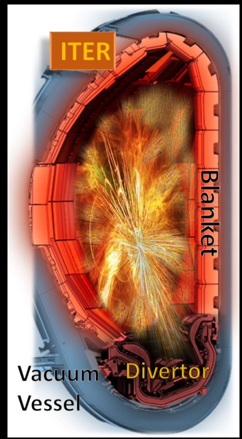



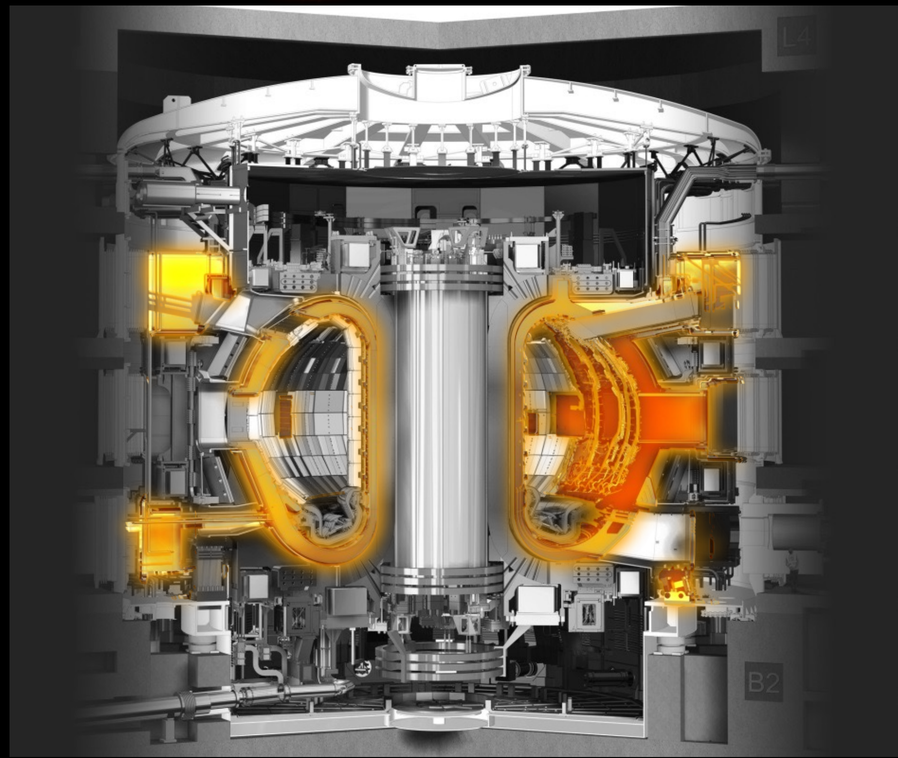
Fusion Energy

**Fusion Community: Produce "little sun's" on Earth**

**Challenging already for ITER and other test reactors, but real challenge comes with fusion power plants**



**High energy neutrons collide with the walls generating damage, transmutation's, kinetic heating and gamma.**

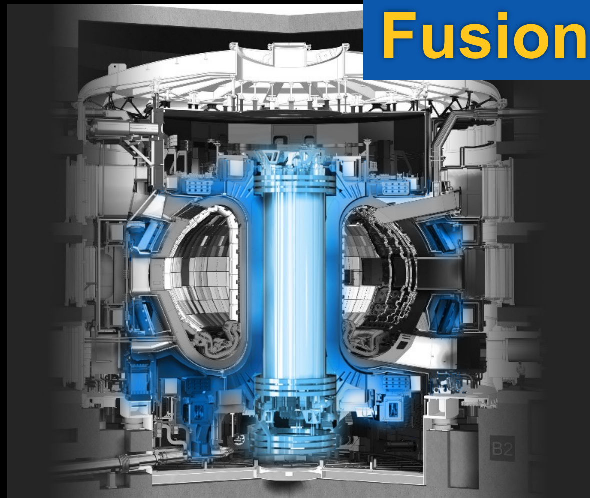
# Development and Manufacturing Challenges



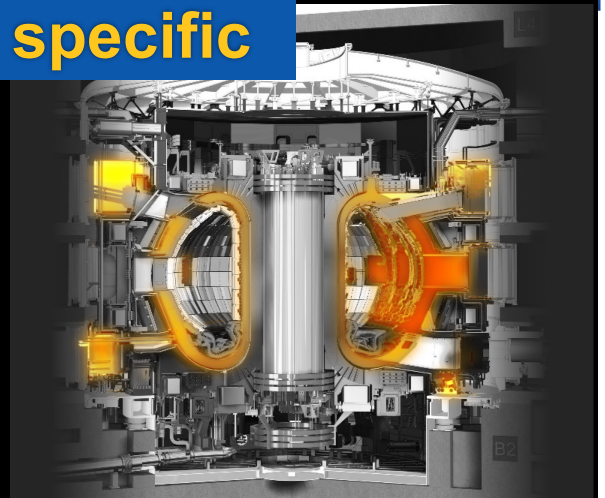
Fusion specific

The most extreme temperatures side by side requires assessment and qualification

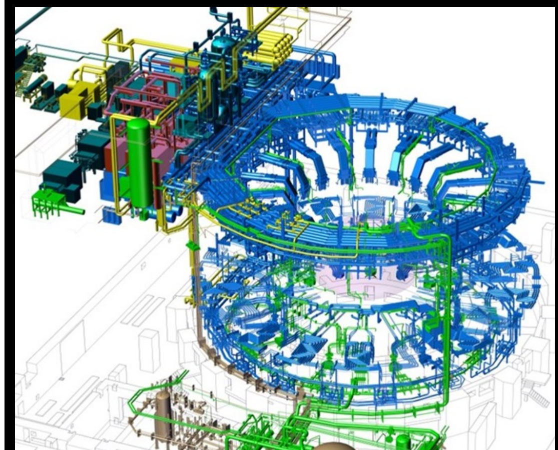
- High magnetic loads and permeability important (magnets need shielding also)
- High mechanical loads generated
- Fatigue and creep (high temperature)
- Irradiation resistant material
- Introduction of new manufacturing processes and joining processes



Magnets at -269 °C



Plasma up to 150.000.000 °C



**Complex cooling systems common for power plants**

- What coolant media for heat transfer (molten salt, liquid metal, He, water etc)? … and at what temperature and what materials?

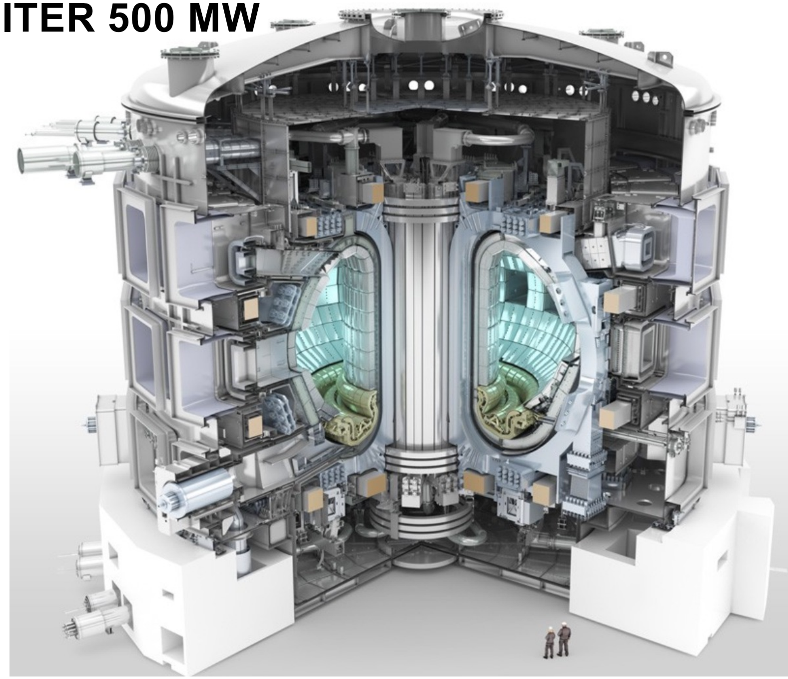
- Corrosion resistant material needed while enduring the thermal shocks and swelling/damage due to irradiation

# Fusion vs Fission

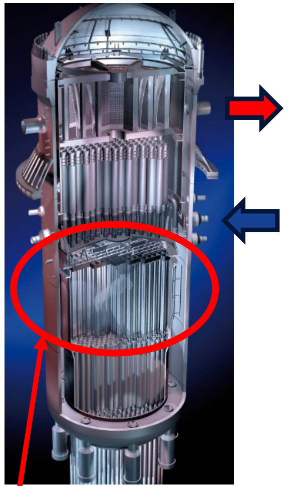
## The cores are very different, but heat transfer and power generation similar

**Fusion (ITER) vs Fission (BWR – Boiling Water Reactor)**

**ITER 500 MW**

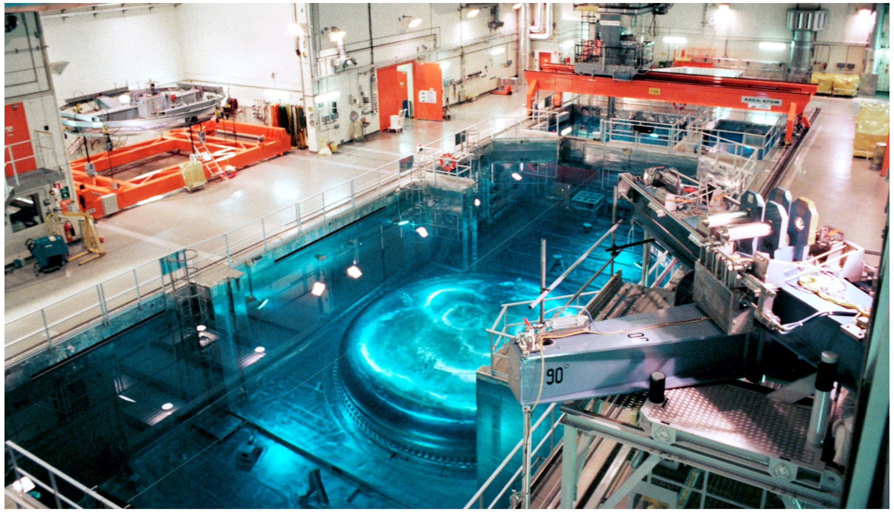


**Ultra High Vacuum System**
**Fuel: few single grams**




**BWR Core**
**(fuel assembly**
**150 - 250 tonnes)**

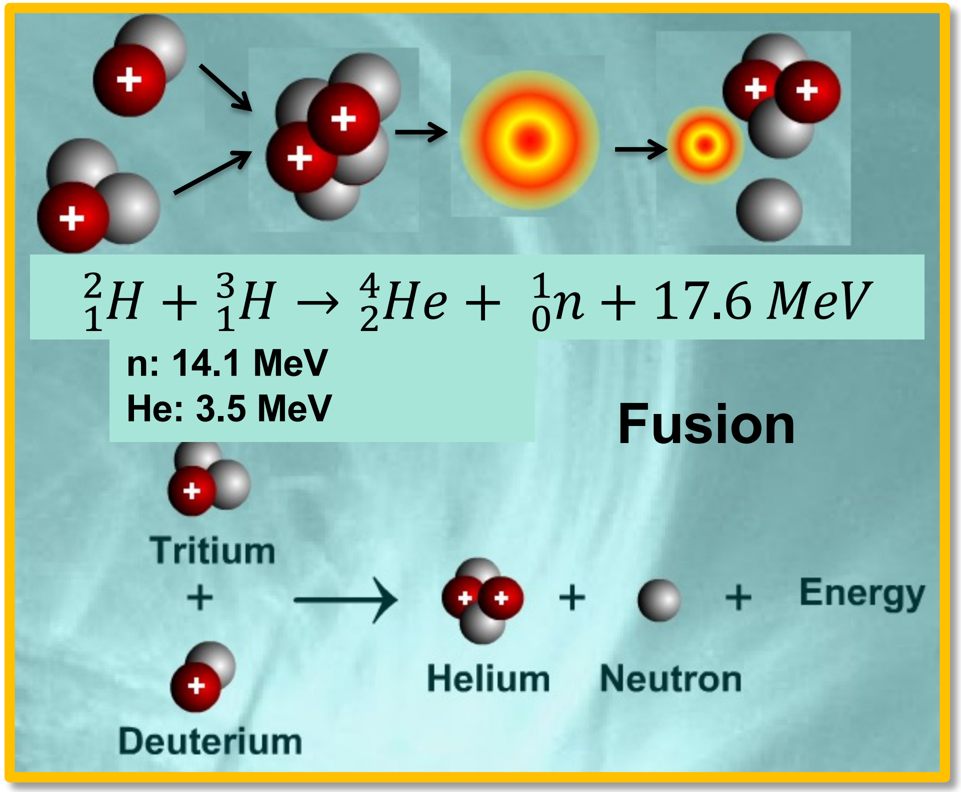
**Oskarshamn O3, Sweden, 1450 MW**



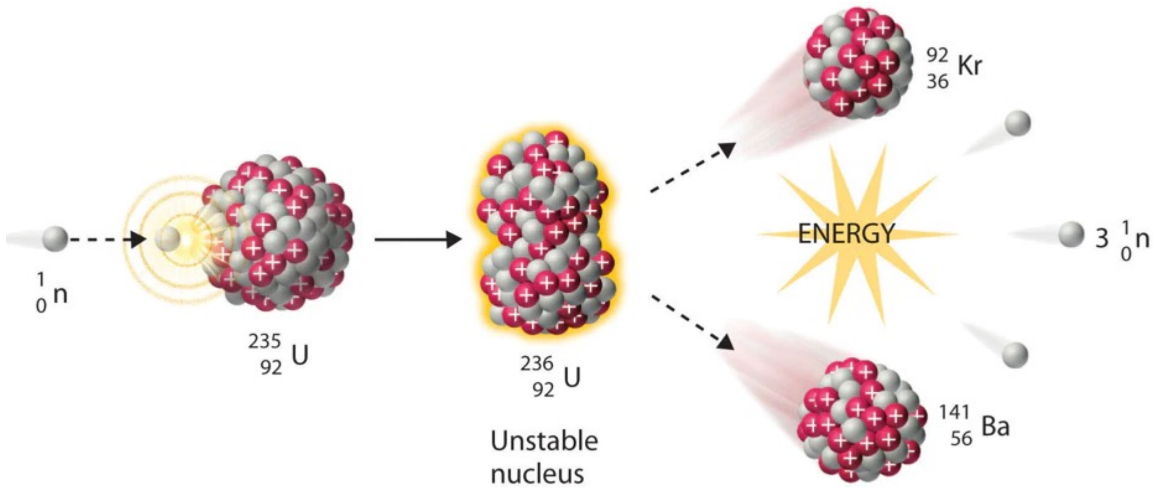
**BWR immersed in water**

- **In a fusion reactor core the particles moves “freely”**
- **In a fission reactor core the particles are moderated (slowed down) by water**

# Fusion vs Fission




## Fission




**neutron energy in spectrum ≈ 0.7 – 2 MeV**
(moderated down to thermal neutrons for easier absorption to maintain chain reaction)

Thermal **n**: 2200 m/s
**n** at fission moment: “5000 – 20000” m/s
Fast fusion **n**: 52000 m/s

# The European Test Blanket Modules (TBM)

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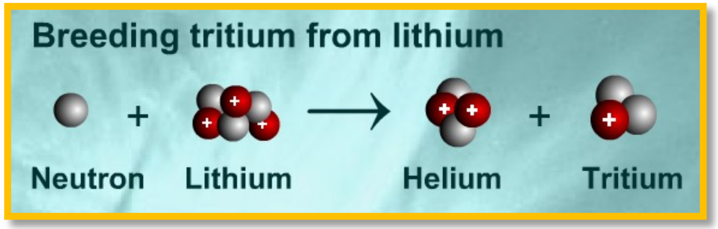
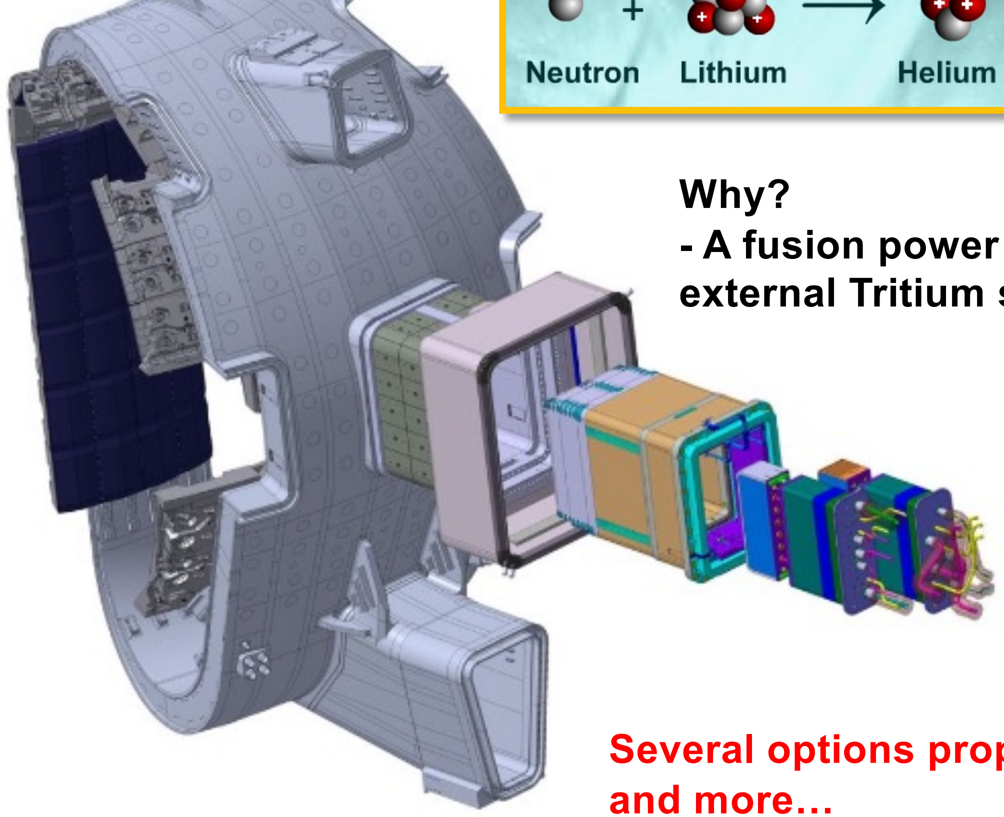
**A fusion plant also needs to generate more fuel (tritium)**




Tritium is a radioactive species having a half-life of 12.32 years



**Why?**
**- A fusion power plant wouldn't be efficient if relying on external Tritium supply!**

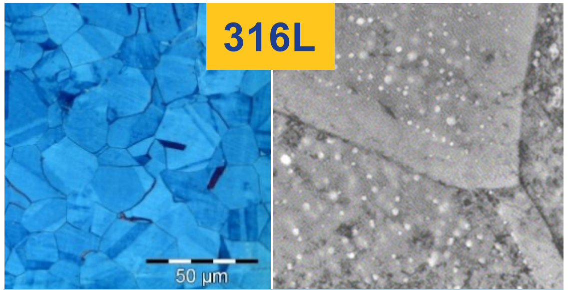
**Requires extensive testing to develop**

**2 Concepts investigated via F4E:**

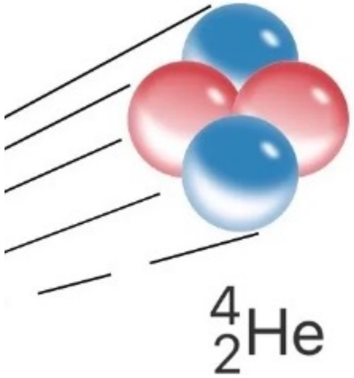
- Water Cooled Lithium Lead Test Blanket System
- Helium Cooled Ceramic Pebble Test Blanket System

**Several options proposed as coolant media: Liquid salt, Liquid Metals, Helium and more…**

# Case Study: What about 316L after irradiation and dimensional stability? New materials are needed!!



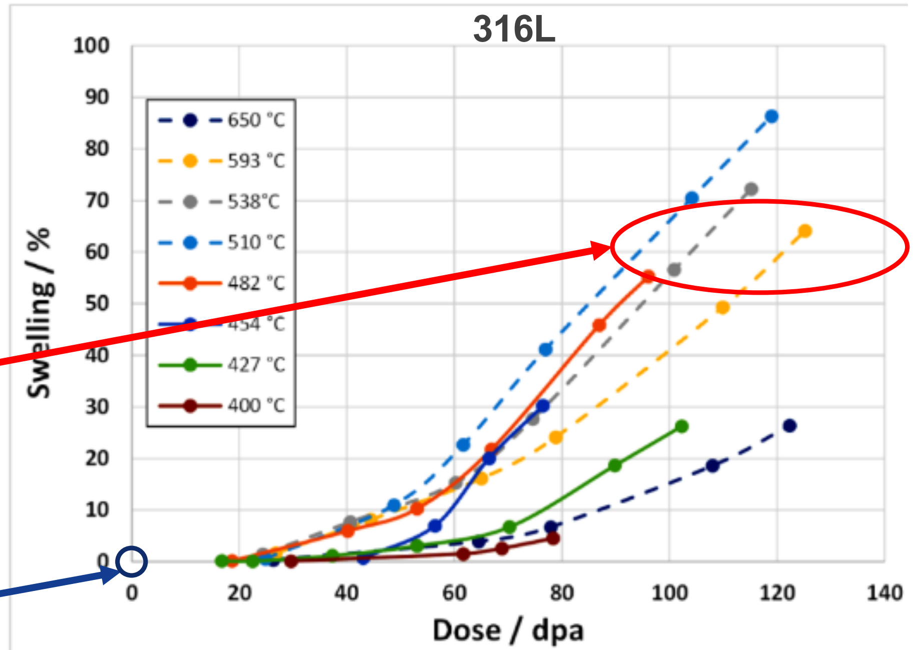

Left: Standard plate material
Right: Neutron irradiated structure with voids and blurred microstructure




*Irradiation causes helium production (alpha particles) inside the microstructure eventually forming "He-bubbles"*

**Fusion Power Plants**

**ITER is ok**




**Effect of Neutron Irradiation on the Mechanical Properties, Swelling and Creep of Austenitic Stainless Steels**

by Malcolm Griffiths [1,2,3]

[1] Department Mechanical & Materials Engineering, Queens University, Kingston, ON K7L 3N6, Canada
[2] Department of Mechanical & Aerospace Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada
[3] ANT International, 448 50 Tollered, Sweden

## Effects

- ❖Neutron irradiation tends to **damage the well-defined structure of crystalline materials** changing the material properties such as strength, hardness, ductility.
- ❖The increasing number of dislocations results in **increased strength and hardness**, but less energy is needed for failure as **toughness and ductility decrease**.
- ❖Fast neutron bombardment of steels also results in **swelling** (volume increase) and **radiation-induced creep**.

## Rhenium and Osmium is generated from Tungsten

After reaching only 1.25 dpa at 800ºC the pure W transmuted to consist of **2% Re** and **0.2% Os** (nature.com)

**Variation between experimental data!**

Transmutation rate strongly depending on irradiation conditions as flux, speed of neutrons and temperature.

<u>Each facility will yield a different transmutation rate.</u>

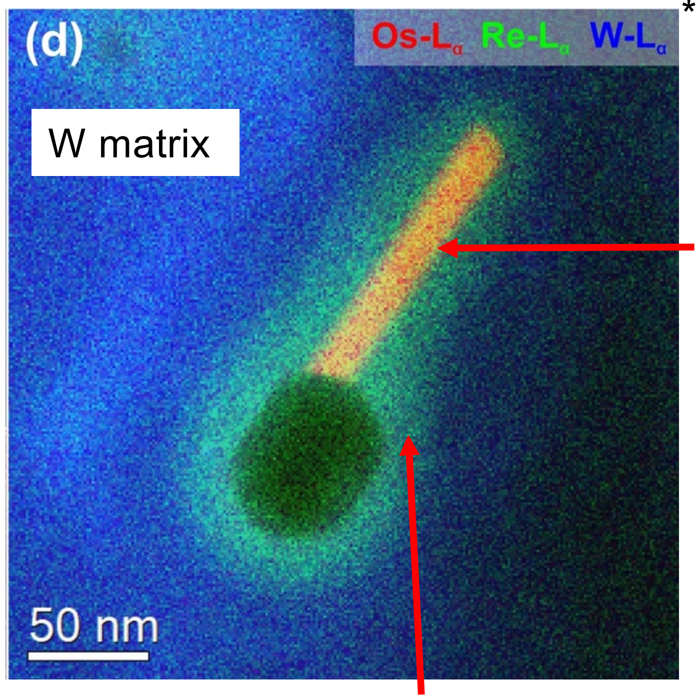
**Pure Tungsten is the main route today , but new variants and alloys needs development.**

**ITER W needs:**

**75 – 100 tons of W as 1 – 1.5 million tiles**

Assessment of design ongoing

Qualification will follow




* nature.com

**Os rich precipitate**

**Re rich "cloud"**

# Neutron damage mechanisms

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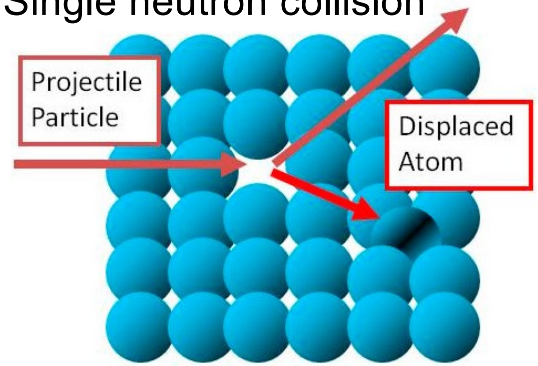
Single neutron collision



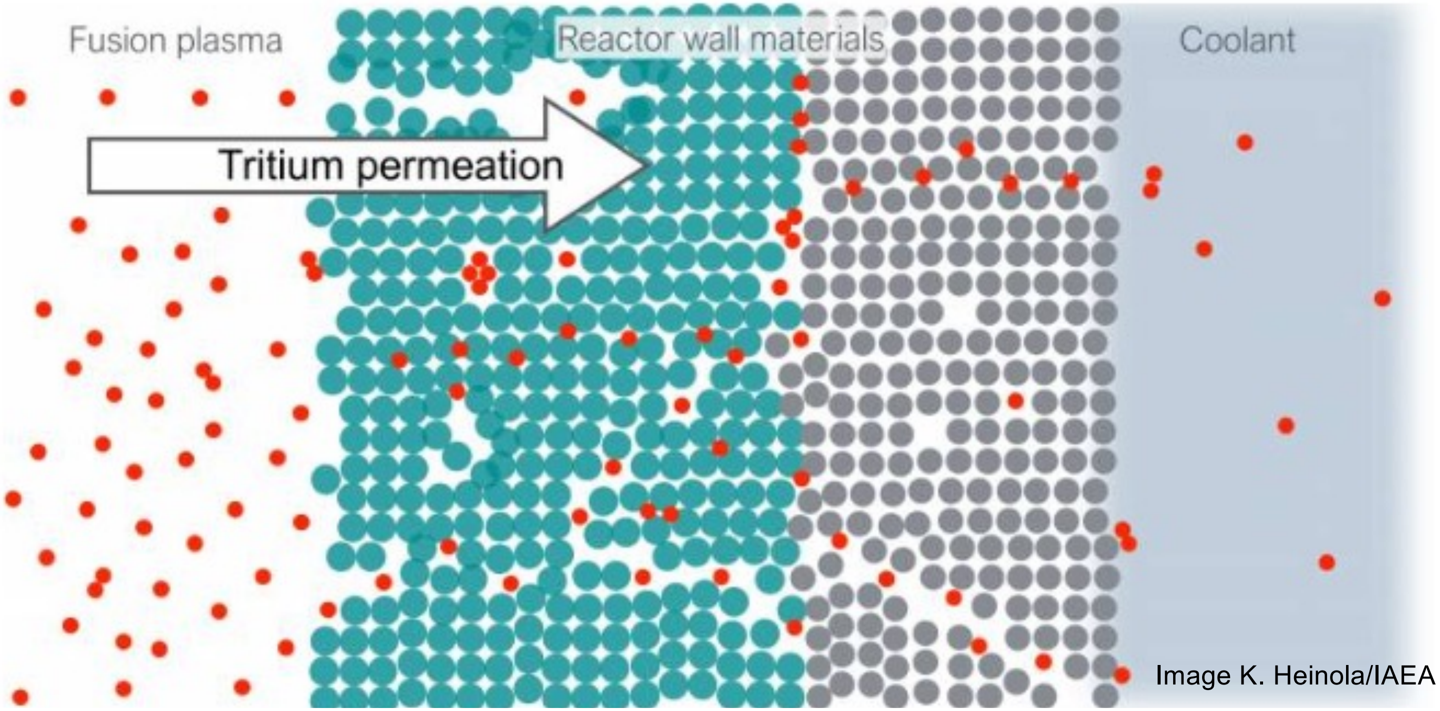
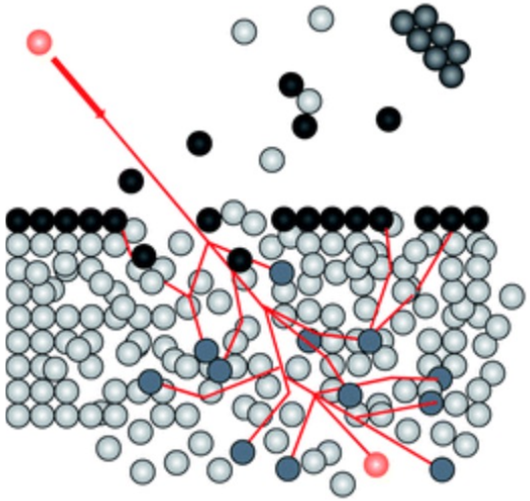




Image K. Heinola/IAEA

Tritium for fusion  is rare and valuable -> priority to avoid losses into walls.

Chain reactions of cascade collisions



Neutrons are important -> kinetic energy heating & tritium breeding
But… fast neutrons generates damage.

# Neutron Sources are important to assess influence of neutrons on materials

**Available sources with opportunities and limitations for fusion**

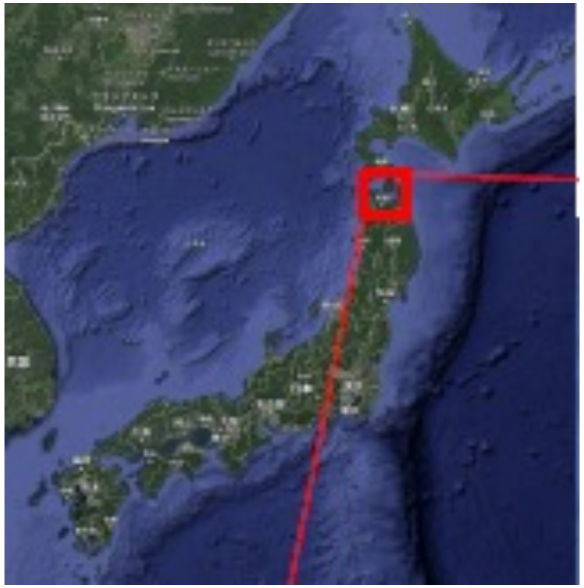
- Fission Test Reactors: limited to 0.7 – 2 MeV (max 3 MeV) 1 order or magnitude to low and complex setup
- Spallation Sources: not exact fusion fluence generating “damage” but much better than test reactors. Very important asset to map influence of neutrons on materials and property changes (**ESS can contribute to materials development**)
- Modelling: cannot extrapolate data for fusion conditions (results unpredictable and not acceptable for licensing) – needs experimental validation (Spallation Sources, Test Reactors, DONES)

All materials needs assessment due to expected higher production rate of He and dislocation damages Irradiation Swelling, Transmutations and Direct Damage.

Candidate structural materials for fusion are for example Reduced Activation Ferritic Martensitic (RAFM) steels
- EUROFER97 (Europe)
- F82H (Japan)

Many materials to test and list getting longer? Synergies with Gen IV !!

IFMIF-DONES research infrastructures for testing, validation and qualification of the materials to be used in fusion power plants.



IFMIF, Rokkasho, Japan

DONES, Granada, Spain

## What is DONES?
## Purpose: Final reactor design requires actual operational conditions for licensing

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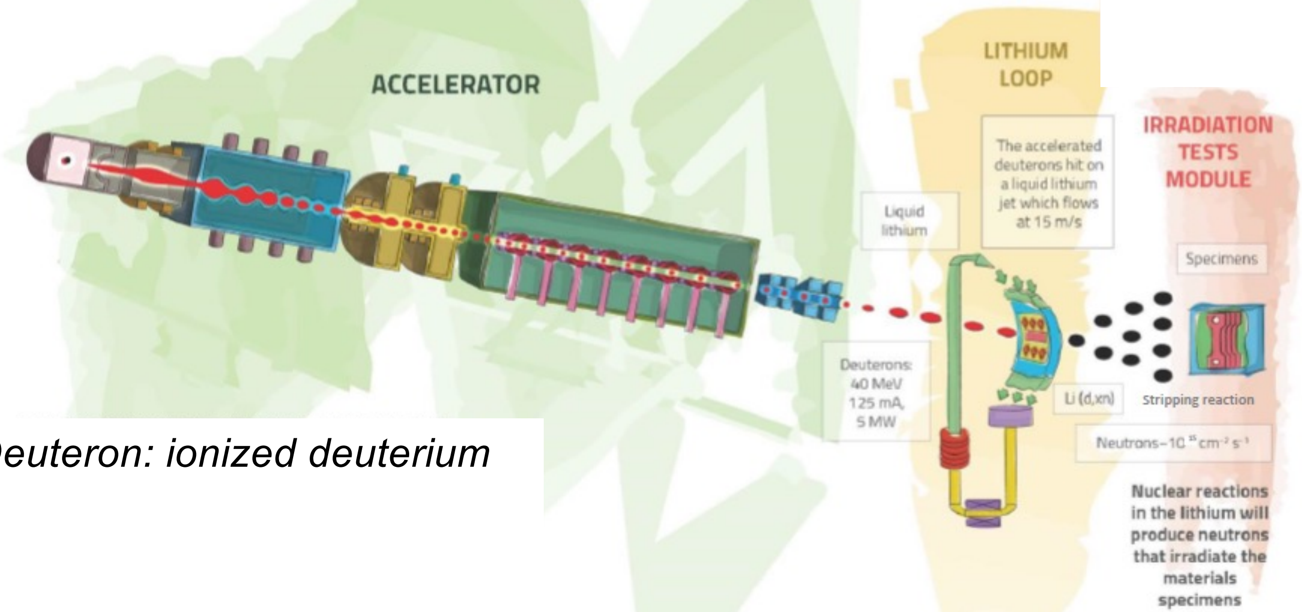
IFMIF

# Fusion Neutron Source

DONES

- **Best fulfilled with a D-Li stripping source**
  - Deuteron particle accelerator at 40MeV and 2x125 mA
  - A lithium loop flowing at 15m/s and 250°C
  - Test modules housing the material specimens
  - Basis for the **International Fusion Material Irradiation Facility**




*Deuteron: ionized deuterium*

**IFMIF-DONES Facility conditions**

<u>High Flux Test Module:</u>

20 dpa/fpy in 130 $cm^3$

10 dpa/fpy in 400 $cm^3$

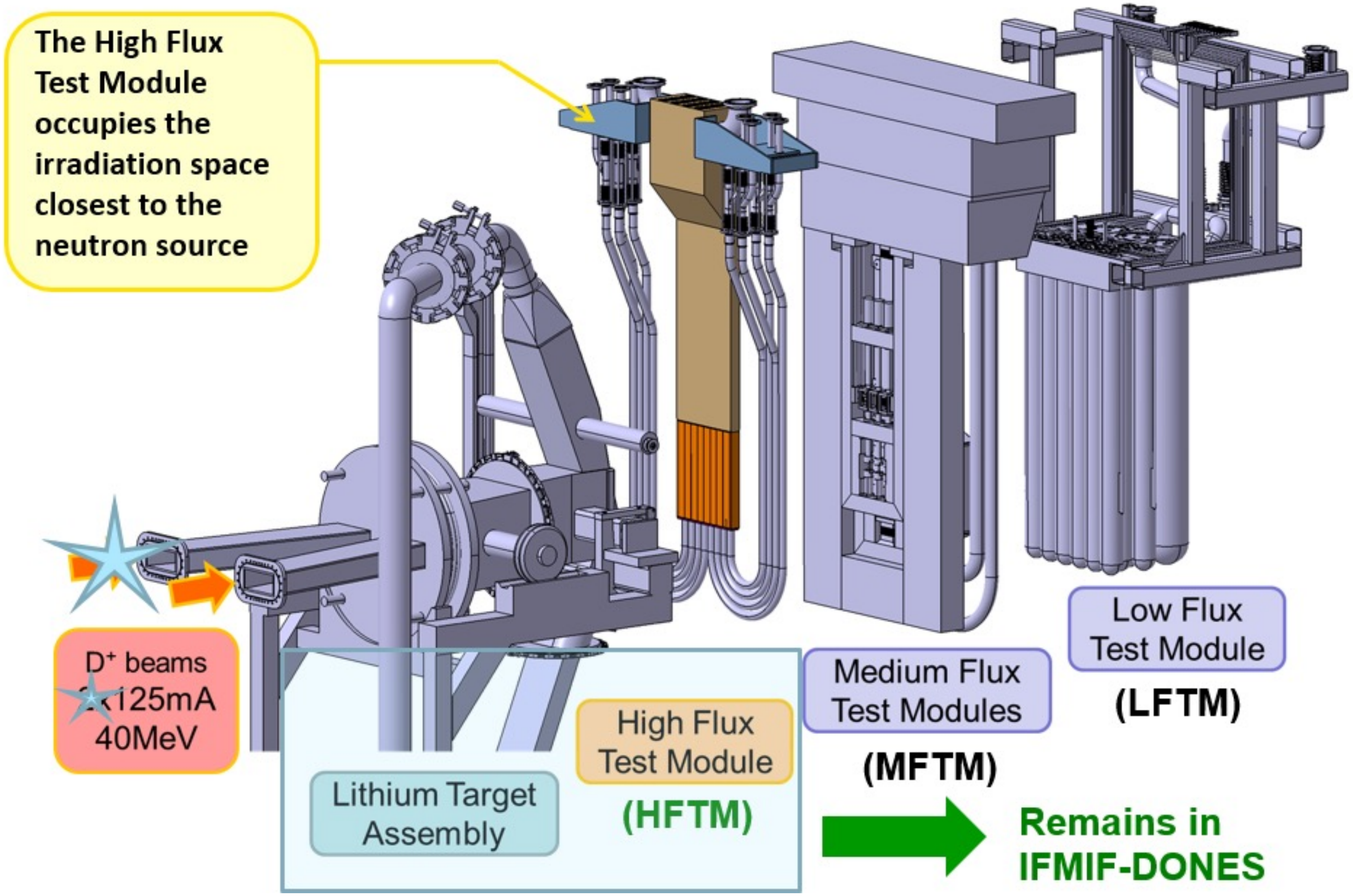
Controlled Temperature:

250 < T < 550 ºC

A neutron flux of ~ $10^{15}$ $n/cm^2/s$ is generated with a neutron spectrum up to 55 MeV energy

Yann CARIN and Angel IBARRA

# Test Module scheme foreseen for IFIMIF (and DONES)



# Qualification and readiness reviews

In-depth assessment and qualification of your product (even if starting small)

## Solving material issues to verify performance

- **Definition of Design Criteria –** *What properties shall be met to withstand operational conditions?*
- **Definition of Acceptance Criteria –** *What is an acceptable defect/performance?*
- **Qualification According to Codes & Standards –** *Variants of tests.*
- **Irradiation Campaigns at ITER Relevant doses –** *Variants of tests.*
- **Assessment of Corrosion in Heat Transfer Systems –** *Corrosion is the main parameter determining the lifetime of any power plant!*

**Thereafter a Reality-Check**

- Can targets on material properties be achieved by series production
- Manufacturability and inspection
- Based on testing which does not appreciably degrade the components?
- Acceptance programme can never fully guarantee actual performance
- The ease with which components can be replaced

Over the years a high variation of test specimens have been irradiated (last decade).

# Manufacturing of Advanced Reactors

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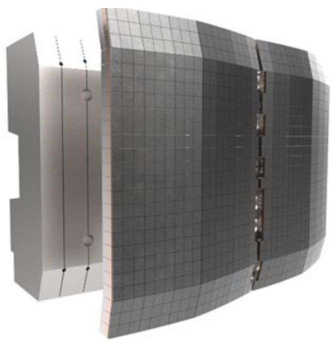
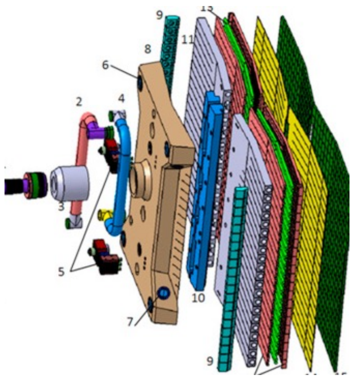
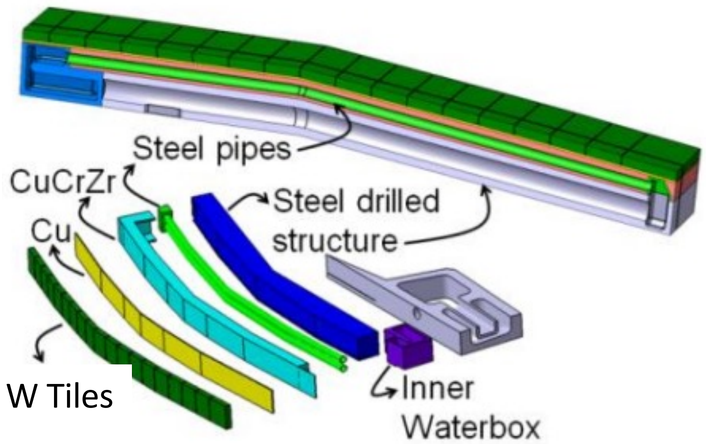
**Up to 10.000 hours conventional manufacturing of typical meter size components for ITER – then assembly etc…**
**Lots of lessons learnt and possibilities to do much better!**





ITER FIRST WALL




**Some Key Areas:**

- Additive Manufacturing – Ramping up and increasingly important (France now base design of SMR on AM)
- Joining Techniques (Electron Beam Welding, Hot Isostatic Pressing, Powder-HIP)
- Large Scale Manufacturing (efficient implementation of prototypical approach)
- Non-Destructive Examination
- Supply Chain (opportunities)
- Nuclear Codes & Standards

# Technology Development Programme

## “Industry in Driving Seat”

## Background

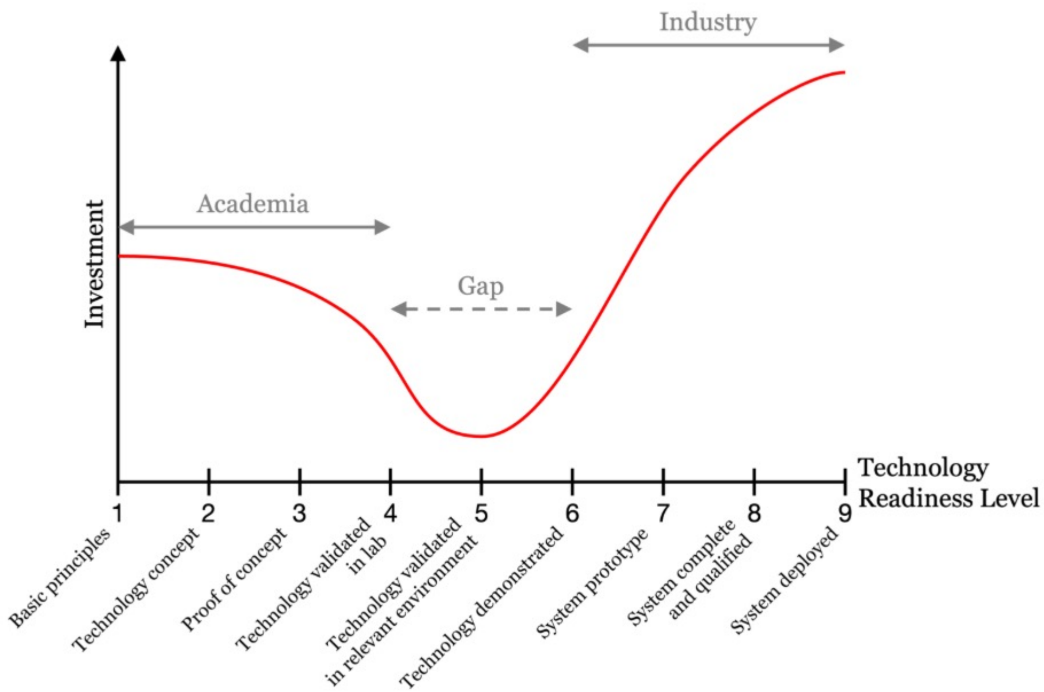
- F4E has successfully involved more than 2700 companies and at least 75 R&D organisations, as part of Europe’s contribution to ITER up to now.
- Over 400 new technologies, tools and processes, while generating at least 20 start-ups, and joint ventures.
- ITER Deliveries are being completed → critical to addres: promoting closer collaboration with private entities through

## Purpose

➢ Support labs and small + medium size companies who got potential key competences.

➢ **Beyond ITER:** ITER been a “stepping stone” to fusion energy –build on lessons learnt towards power plants. *Implementation of new technologies that couldn’t be used for ITER, interesting for other facilities or other areas.*

➢ Funding to “Bridge” Technology Readiness Level (TRL) – potential technologies, no commercial product/market.



# How to select what to be included in the TDP?

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Consolidated

Definition of assessment parameters and priorities

Critical Technologies Mapping
(F4E expertise)


Call for proposals

Selection also to consider Spin-Off to different fields

Call for Tenders

- Electrical Engineering
- Manufacturing
- AI
- Materials
- Processes

etc etc

About 10 concepts for tender per year

Each concept awarded to up to 3 suppliers (< 30 contracts)

Up to 3 variants to solve each topic

**Questions for you to address to the TDP**
What is holding development back?
What is the threshold to pass?
Why is the market not ready/interested?
…

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