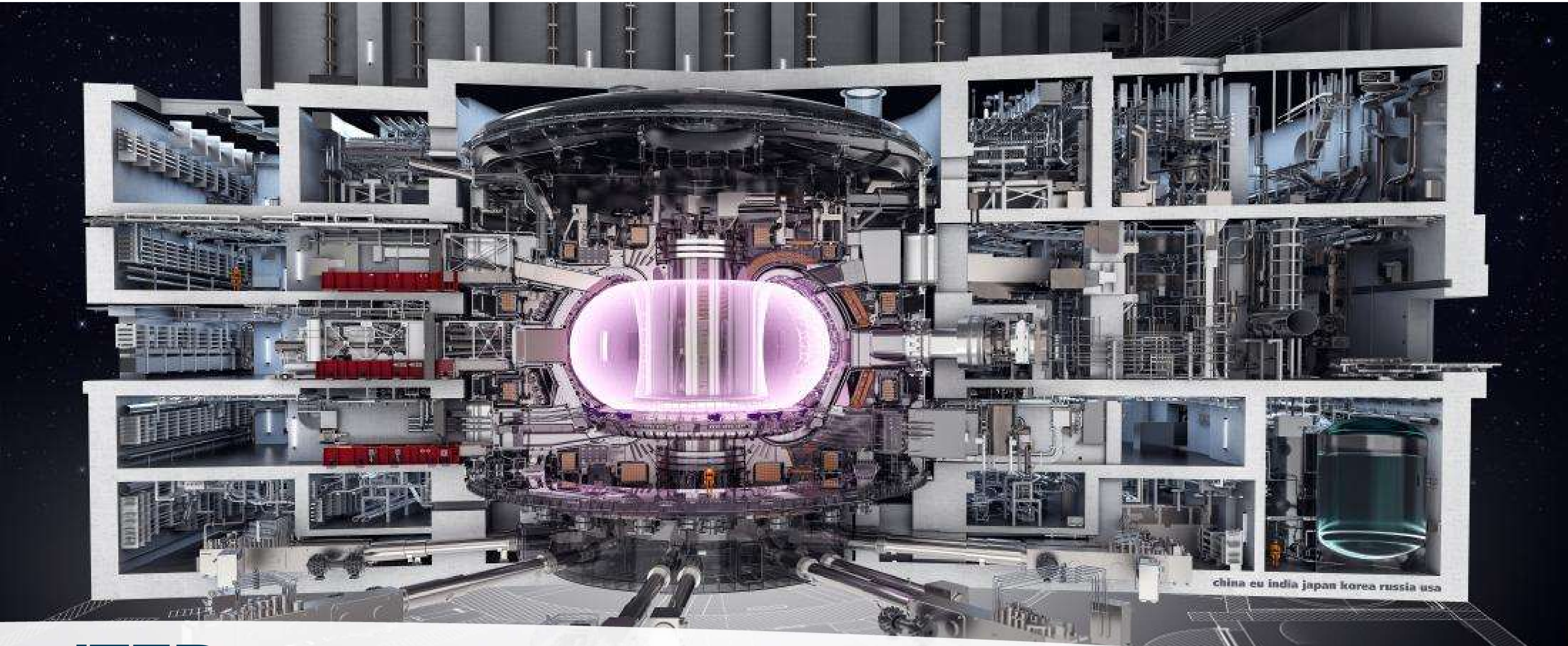

ITER

Conquering the Challenges of Fusion Energy

Sophie Carpentier & Laurent Ferrand

IET ACLN Webinar

14 November 2024

iter

china eu india japan korea russia usa

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

ITER

Conquering the Challenges of Fusion Energy – Part 1

Sophie Carpentier, Plasma Engineering Specialist

IET ACLN Webinar

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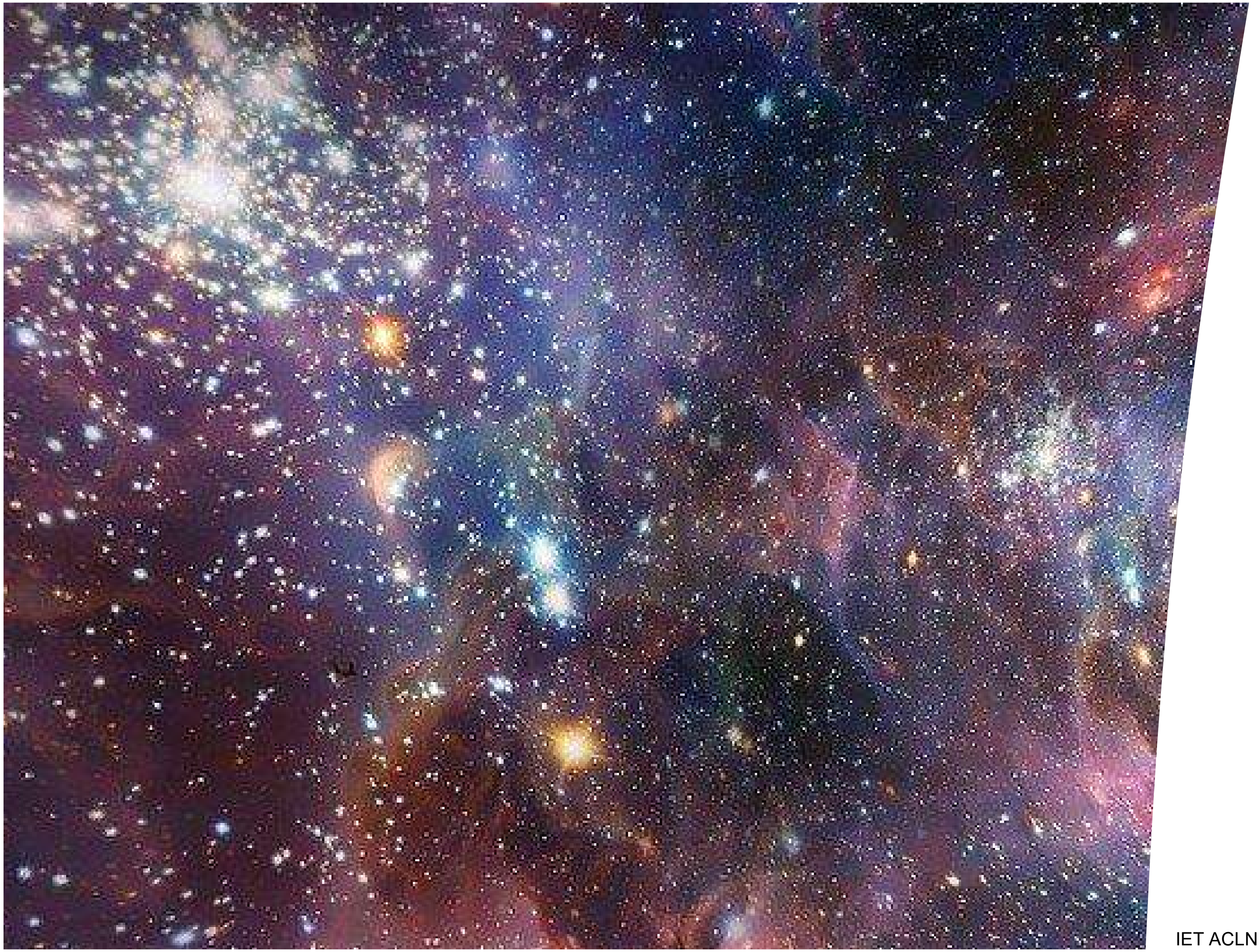
- **Introduction to Fusion**
- A bit of history & key figures
- How is organized the ITER international project
- ITER progress: construction site, tokamak assembly, difficulties
- Perspectives

… to Laurent’s Part 2: a concrete example

The challenges of designing and manufacturing components facing the plasma



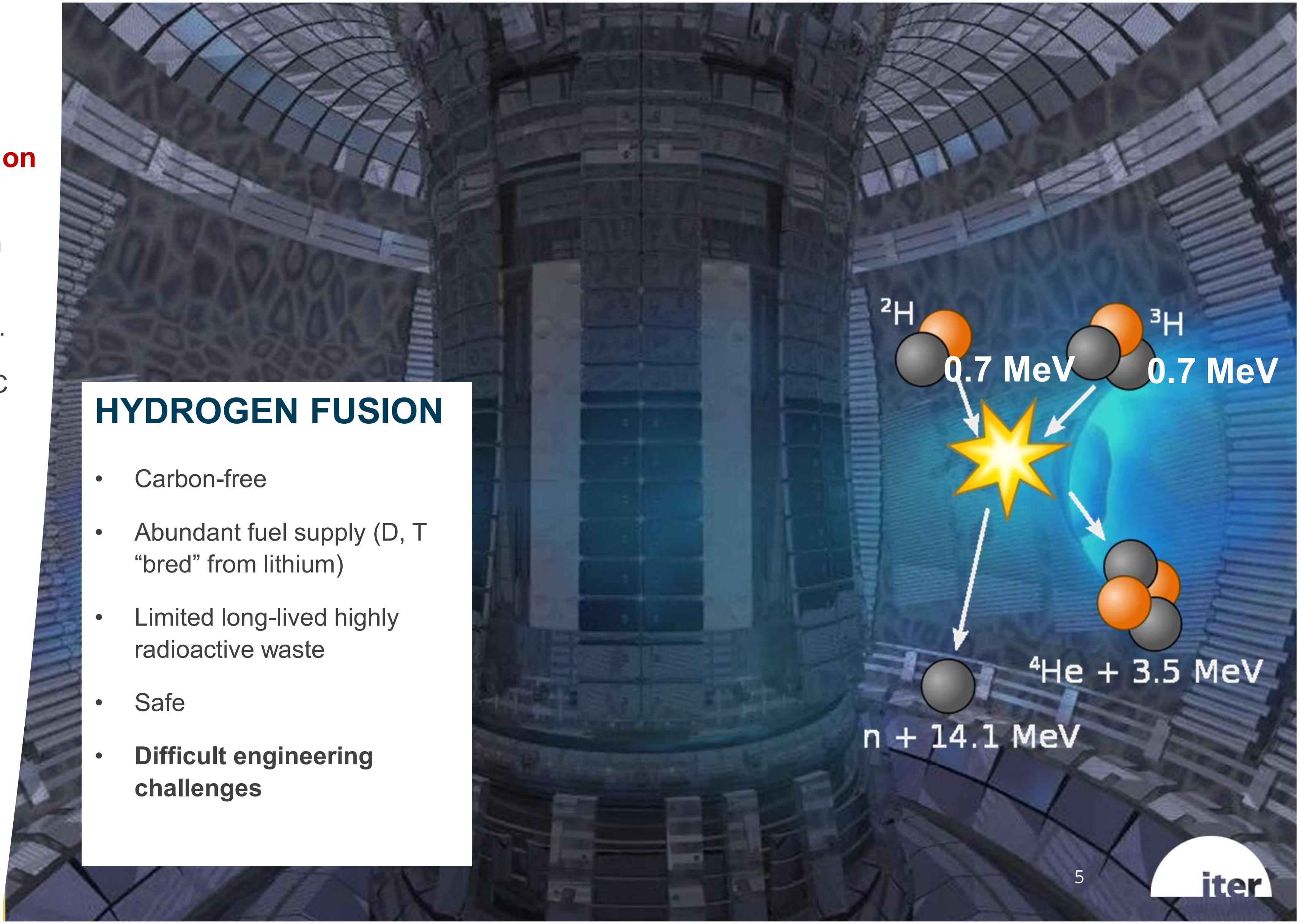
NUCLEAR FUSION IN THE UNIVERSE

- Solar power (the energy of the sun and the stars)
- Source of light, heat, and life on Earth
- Produced by gravitational forces, extreme temperatures and densities

FUSION ON EARTH

Magnetic confinement fusion

- Deuterium (D) + Tritium (T) produces Helium + a neutron
- Requires a precisely shaped and controlled magnetic field.
- Temperature: ~150 millions°C



HYDROGEN FUSION

- Carbon-free
- Abundant fuel supply (D, T “bred” from lithium)
- Limited long-lived highly radioactive waste
- Safe
- **Difficult engineering challenges**

HOW DOES IT WORK?

Inject DT gas.

Inject electric current to convert the gas to plasma.

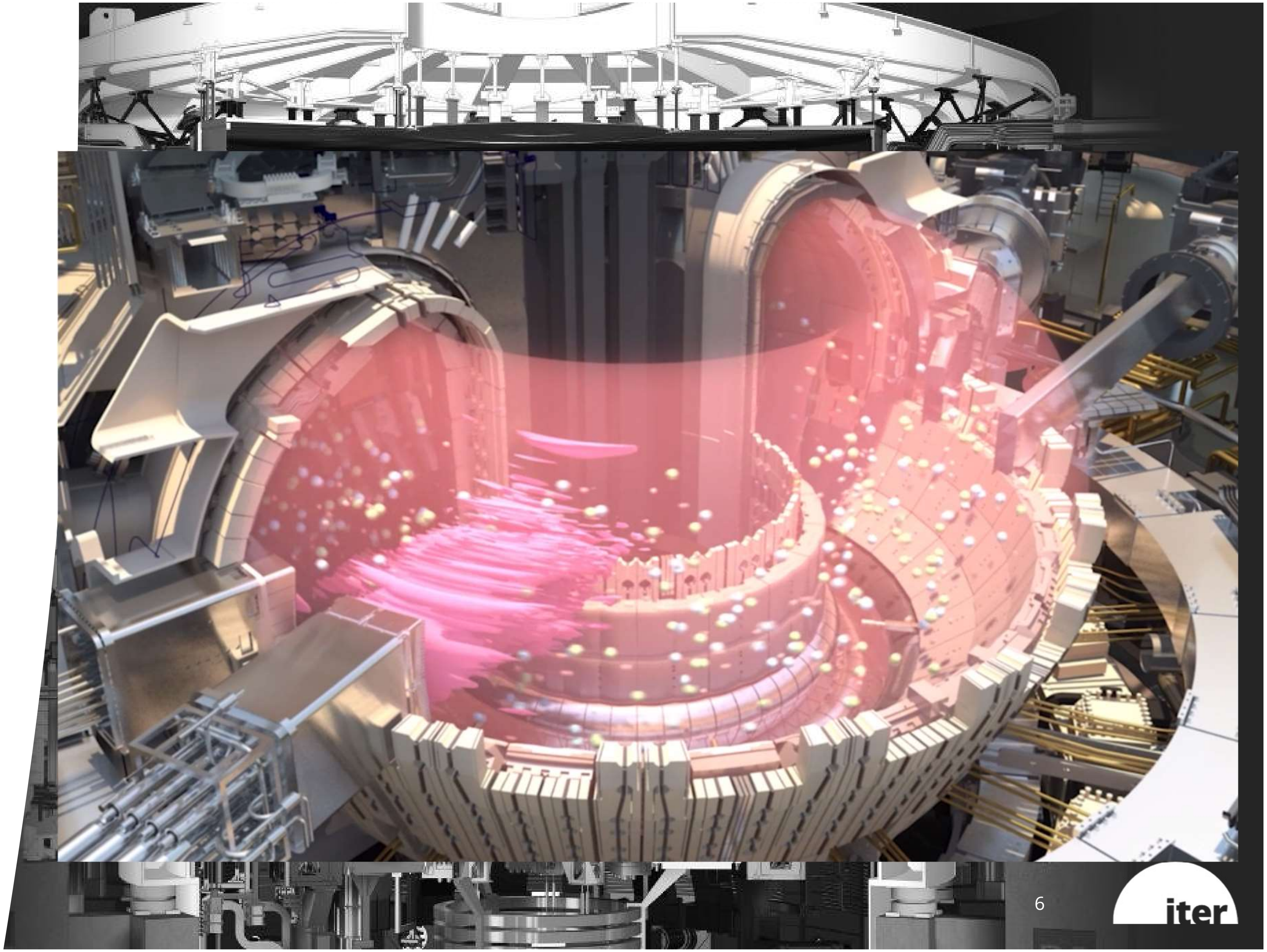
Inject electromagnetic waves to heat the plasma.

Inject high-energy neutral particles.

Combine these techniques to reach 150-million degrees.

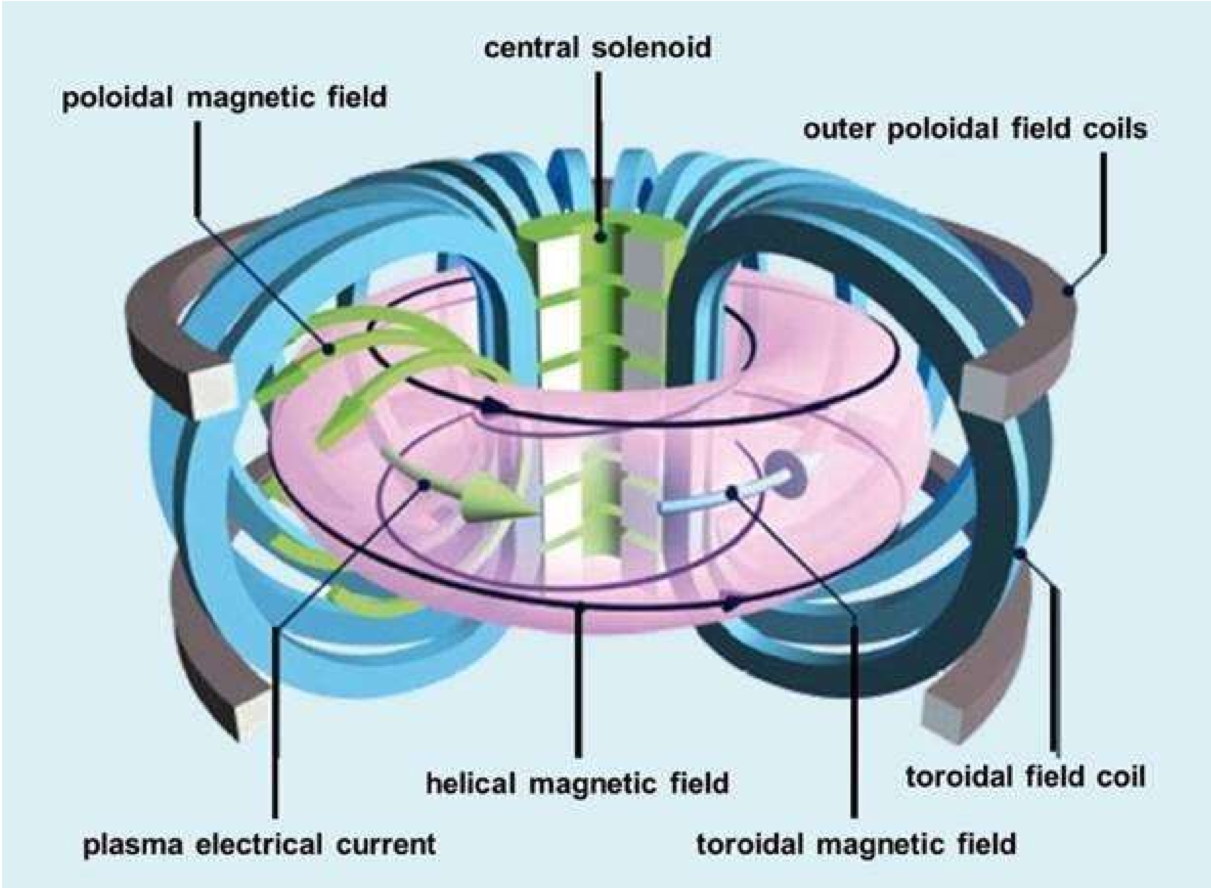
Desired outcome:
a ”burning” (largely self-heating) plasma,
amplification Q = 10.

THE CHALLENGE: TO CONTAIN AND SHAPE THE PLASMA.



THE PRINCIPLE OF A TOKAMAK

- Confine plasma in a donut shape (**torus**)
- Using magnetic fields
- Set of **toroidal** (vertical, D-shape) **magnetic coils** generates intense “toroidal” field, directed around the torus
- **Central solenoid** (magnet carrying electric current) creates a second **magnetic field** directed along the **“poloidal”** direction
- Two field components **result in a twisted magnetic field → confining** particles and allowing fusion reactions



from Russian: *“toroidal chamber with magnetic coils”*

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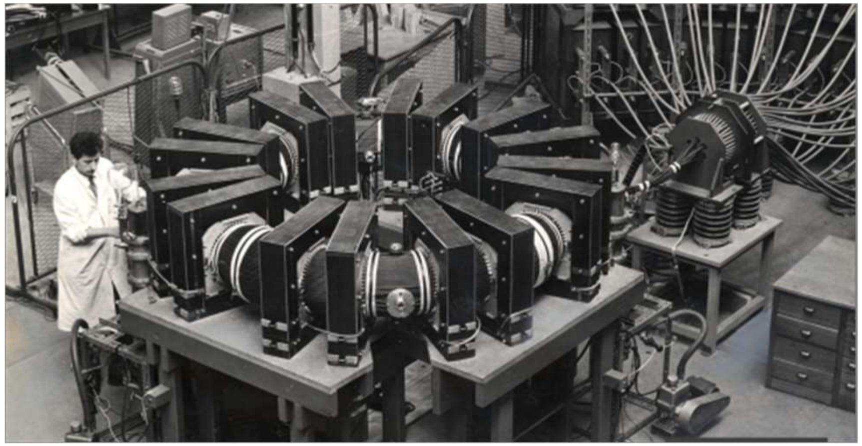
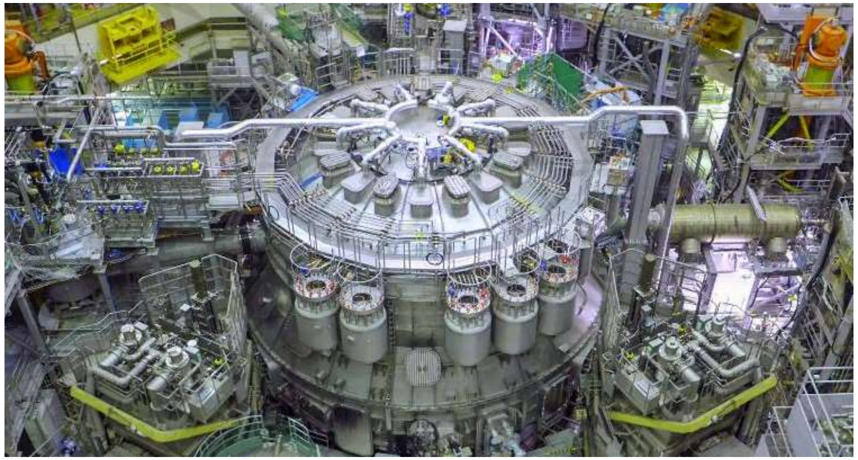
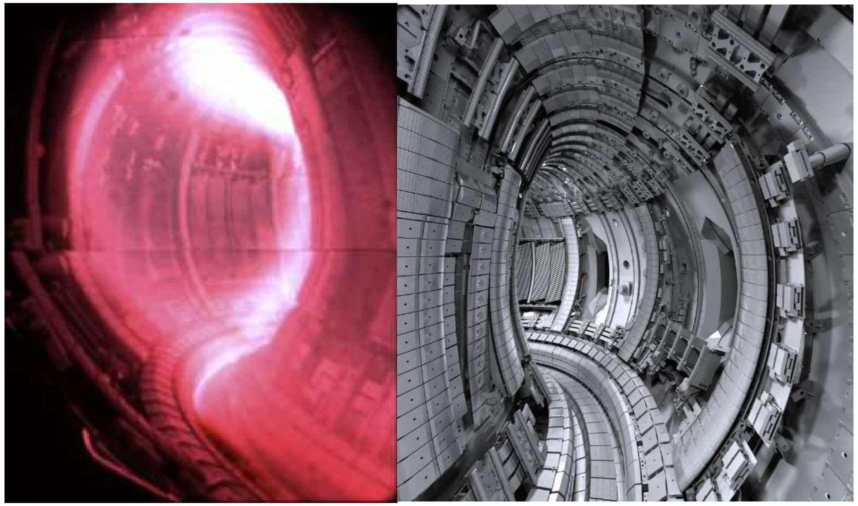
MORE THAN 60 YEARS OF PROGRESS



TA-2000, CEA
France, 1957

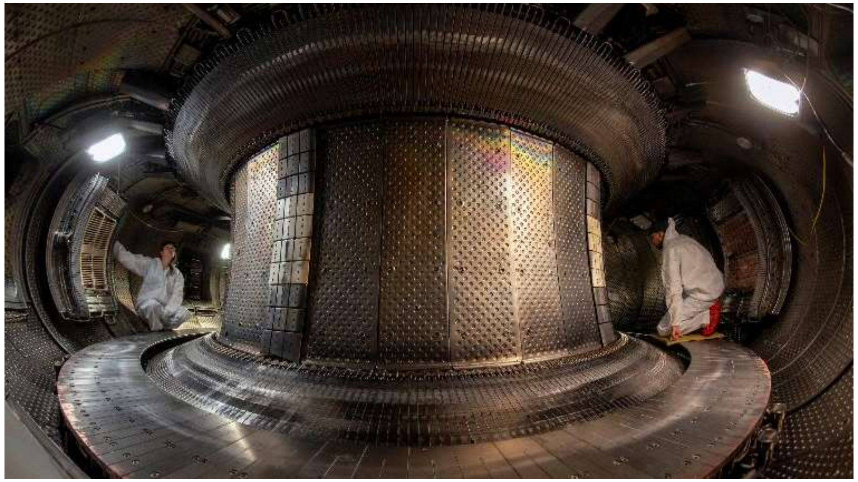
JT-60SA
Japon-UE, First
Plasma in Oct.2023,
V_{plasma} ~130m^3





JET (ITER-like wall),
UK, 1983-2023,
produced 69MJ of
energy (DT)

Tore Supra, CEA, Fr,
1988-today, longest
plasma ~6min30s
(became *WEST*, important
test bed for ITER)

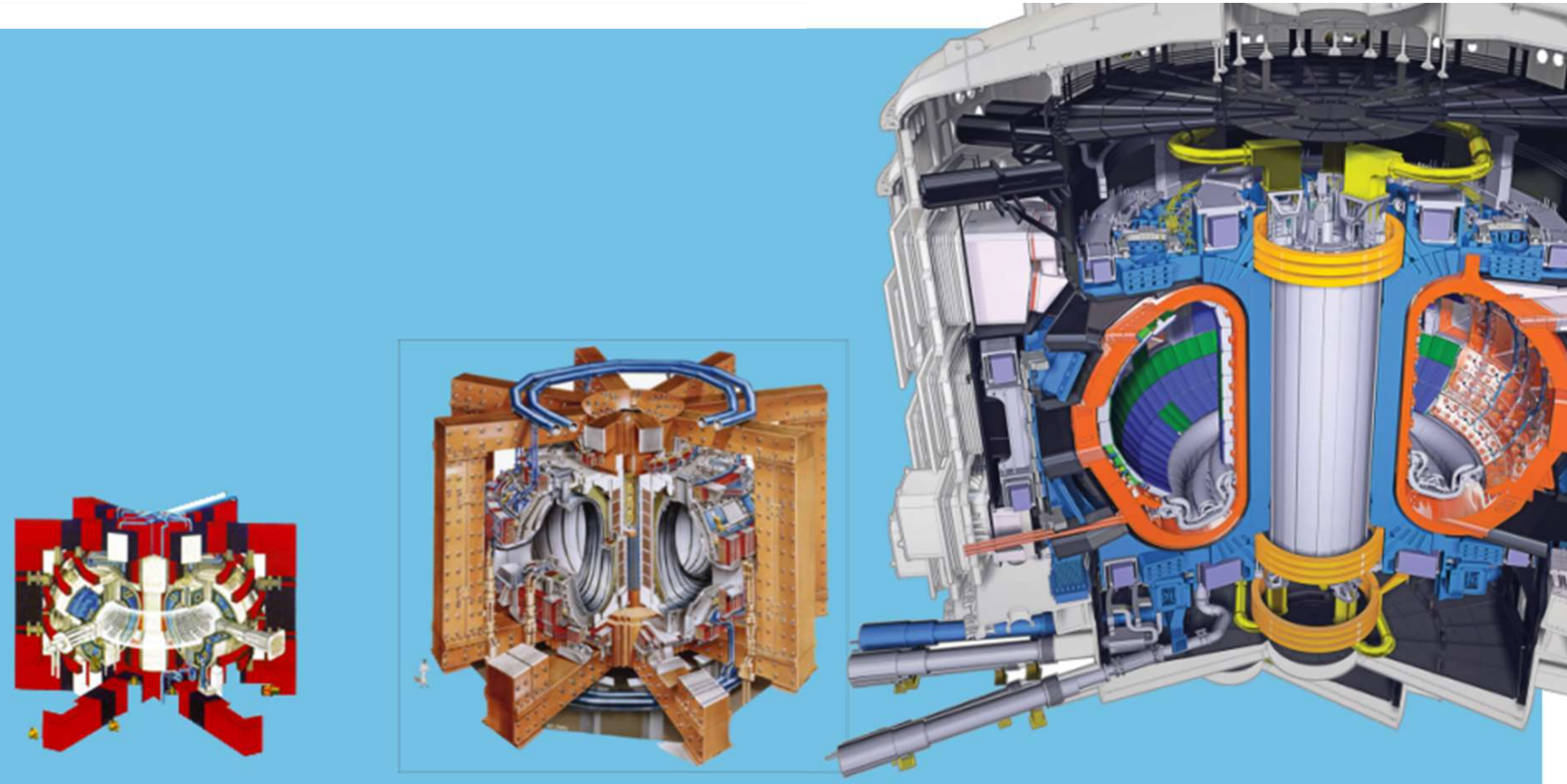


… far to be an exhaustive list → also other tokamaks and stellarators

SIZE MATTERS

Ratio of output thermal power over input heating power (Q) depends on:

- Magnetic field strength
- Plasma density
- Plasma volume



not to scale

Tore Supra (CEA-Euratom)		JET (Europe)		ITER (35 countries)	
V_{plasma}	25 m^3	V_{plasma}	80 m^3	V_{plasma}	830 m^3
P_{fusion}	~0	P_{fusion}	~16 MW	P_{fusion}	~500 MW
$P_{heating}$	~15 MW	$P_{heating}$	~23 MW	$P_{heating}$	~50 MW
T_{plasma}	~400 s	T_{plasma}	~30 s	T_{plasma}	>400 s
I_{plasma}	~1.7 MA	I_{plasma}	~5-7 MA	I_{plasma}	~15 MA

THE ITER TOKAMAK IN A NUSTSHELL

1 central solenoid, 1000t, 18m high

18 toroidal field coils, 17 m high, ~360 tons each

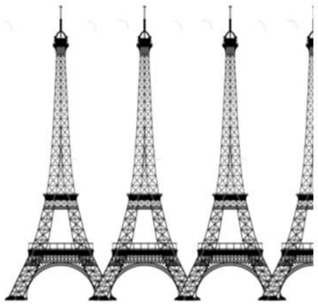
6 poloidal field coils, 8-24 meters diameter, ~ 250 to ~ 400 t

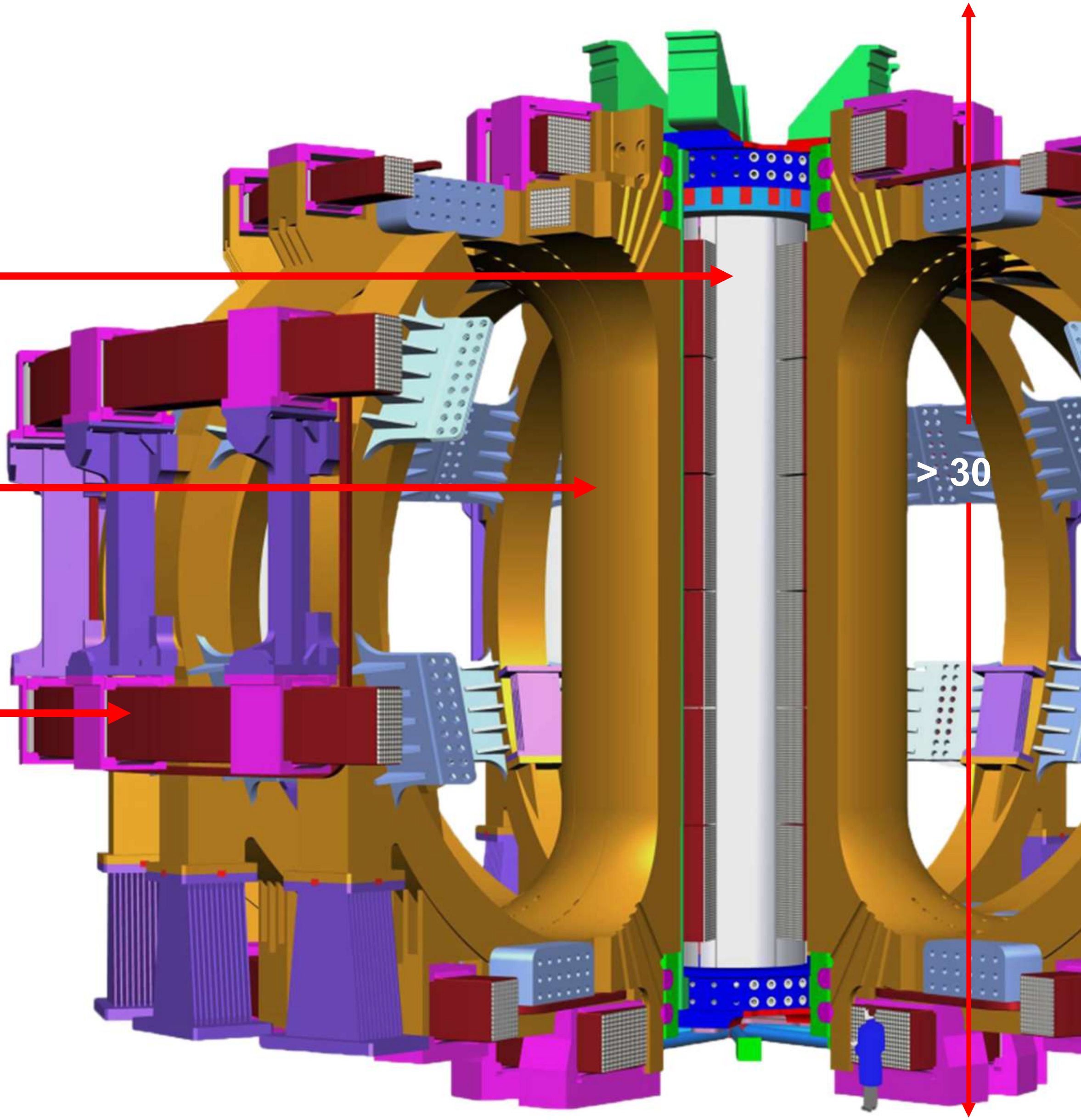
Vacuum vessel: ~ 8 000 t

…

Total ~ 23 000 t

3,5 times the Tour Eiffel mass!





THE ITER NARRATIVE: *FROM IDEA TO REALITY*

November 1985

R. Reagan and M. Gorbachev at the Geneva Summit
→ international collaboration for the benefit humanity

November 2006

The ITER agreement is signed at Paris, by the French president and ITER members. Cadarache is chosen to be the ITER site.

August 2010

From 2007 to 2010, France levelled and cleared the ITER worksite. The construction started in 2010.

Today

The construction of ITER buildings and many systems is almost finalized, Remains the tokamak assembly itself.

https://www.iter.org/project/road-iter

- Introduction to Fusion
- A bit of history & key figures
- **How is organized the ITER international project**
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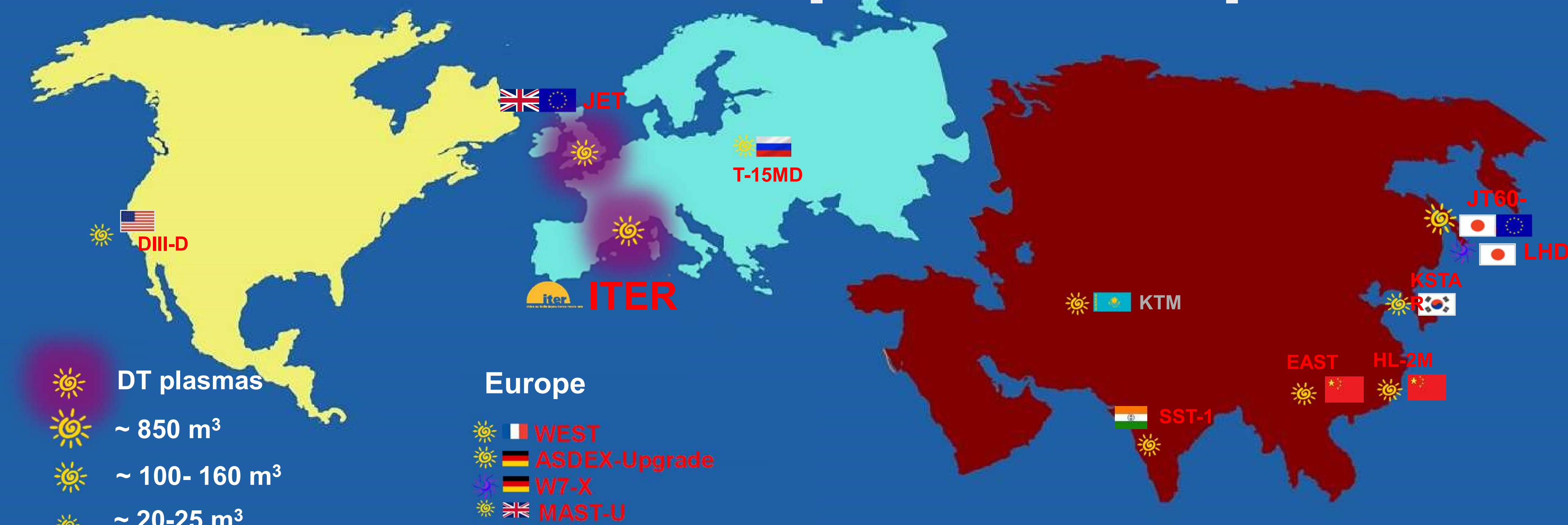
Worldwide challenge, international response

Seven ITER members
> 50% of the world population
85% of the world GDP

China EU India Japan Korea Russia USA

A worldwide partnership

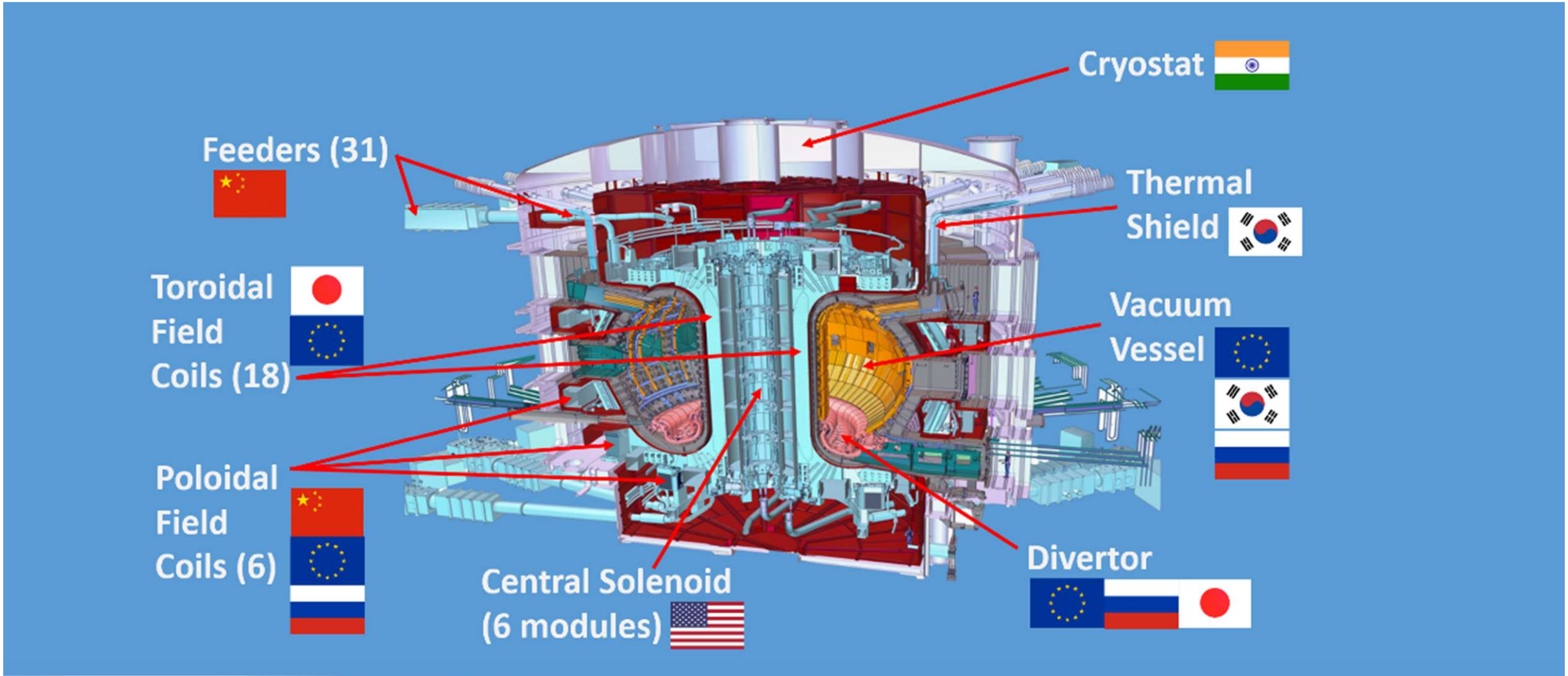


- ITER benefits from all the results of research undertaken by the international community since the beginning of the 1950’s.
- For scientific aspects, the *International Tokamak Physics Activity* (ITPA) allows coordinating research programs in fusion devices and collecting valuable conclusions for the future experimental program.

An Integrated Project

ITER Organization = Central Team + 7 Domestic Agencies

- **The 7 ITER members contribute <u>in-kind</u> to the ITER program**
- **To this end, they all created a Domestic Agency**
- **Europe, as host, contributes ~45%**
- **Non-EU members contribute ~9% each**
- **ITER members share the full Intellectual Property**



WHO MANUFACTURES WHAT?

The ITER Tokamak is comprised of more than 1 million components.

This picture shows a simplified breakdown of ITER Member contributions.

The *Council* approves the ITER RoadMap

Representatives of the 7 members of the ITER project, 33rd Council, Nov. 2023

- **The ITER Council meets twice a year (in June and November) at the ITER Headquarters (ITER site, Cadarache, Saint Paul-lez-Durance)**
- **The 7 ITER members assess all inputs to validate the roadmap (ITER schedule and resources):**
  - ***Science and Technology Advisory Committee* (STAC)**
  - ***Management Advisory Committee* (MAC)**
  - ***Financial Audit Board* (FAB)**

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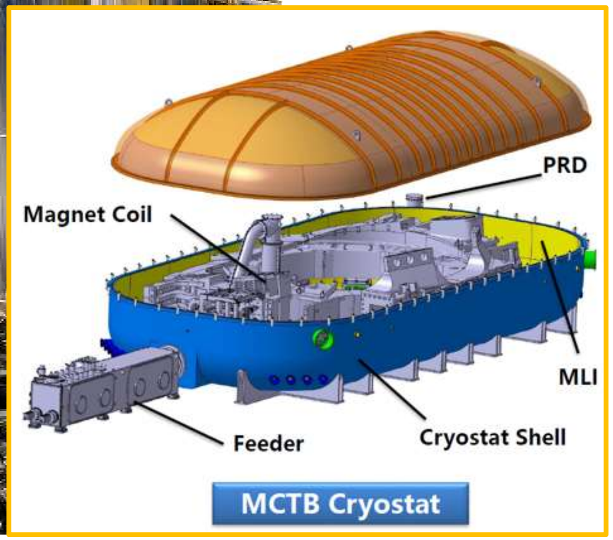
CRYOGENICS PLANT COMMISSIONING

Helium gas compressor and gas distribution network has completed functional testing in July 2024.

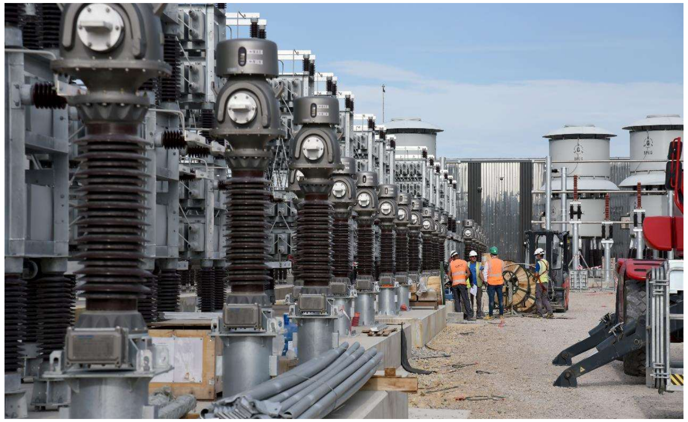
This completes the performance test of the first compressor train.

The commissioning plan targets making the first liquid helium this year, with the near-term goal to support operation of a Magnet Cold Test Bench (MCTB) under construction.



SUPPORT SYSTEMS COMMISSIONED

Heat rejection and cooling water system



Reactive Power Compensation Commissioning

Chilled water system (condensers and evaporators)

Electron Cyclotron Heating energization of the 22kV main switchgear

PF/TF/CC MAGNET MANUFACTURING AND DELIVERY

All Poloidal Field coils have been completed and delivered (PF2 pictured at right)

All 19 Toroidal Field coils (18 + 1 spare) have been completed and delivered.

12 of 18 correction coils have been completed and delivered.

Last TF coil delivery, December 2023

CENTRAL SOLENOID DELIVERY AND SUB-ASSEMBLY

Four CS modules have been delivered.

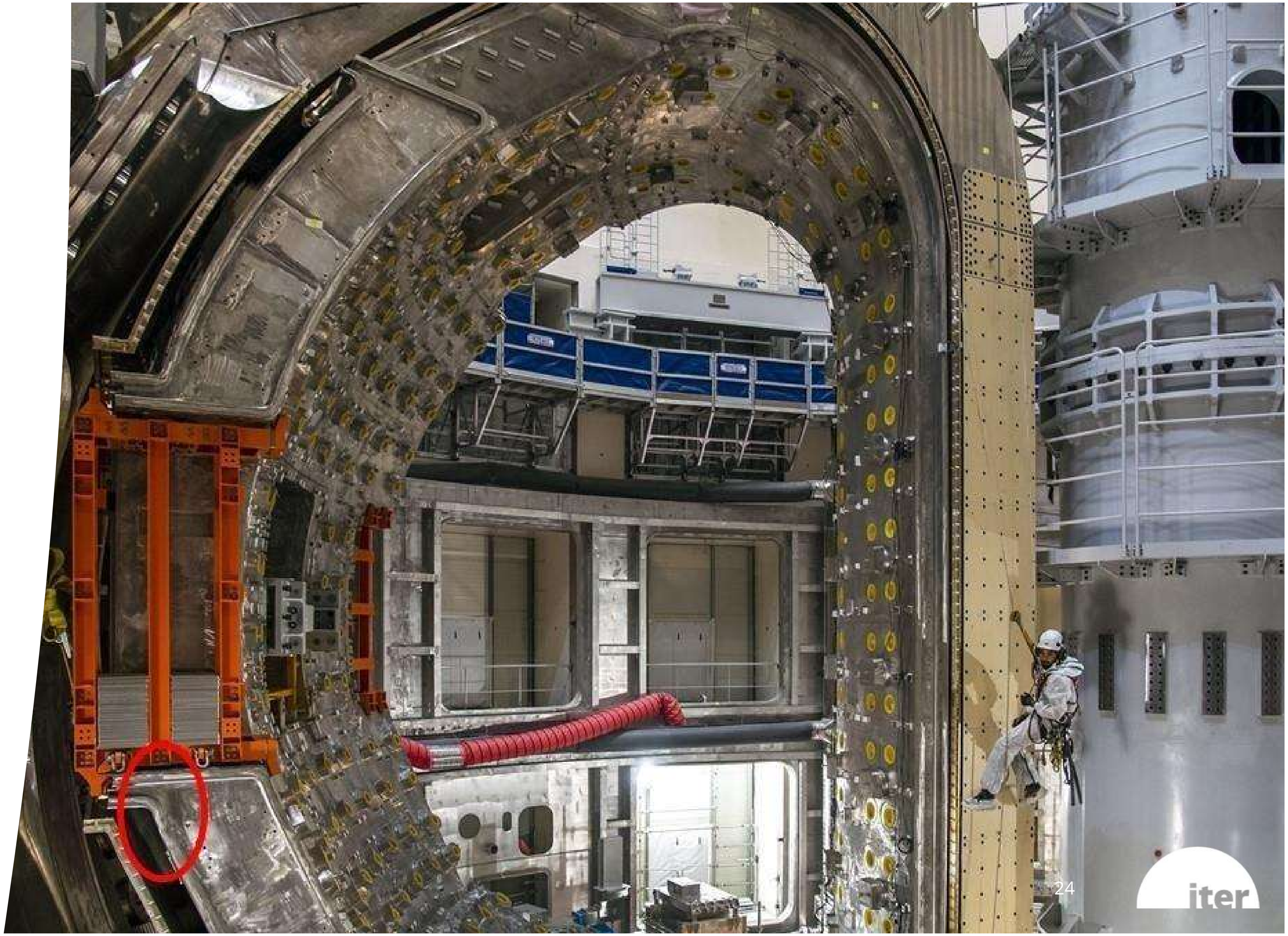
Two modules are stacked and aligned, and a third is in progress.

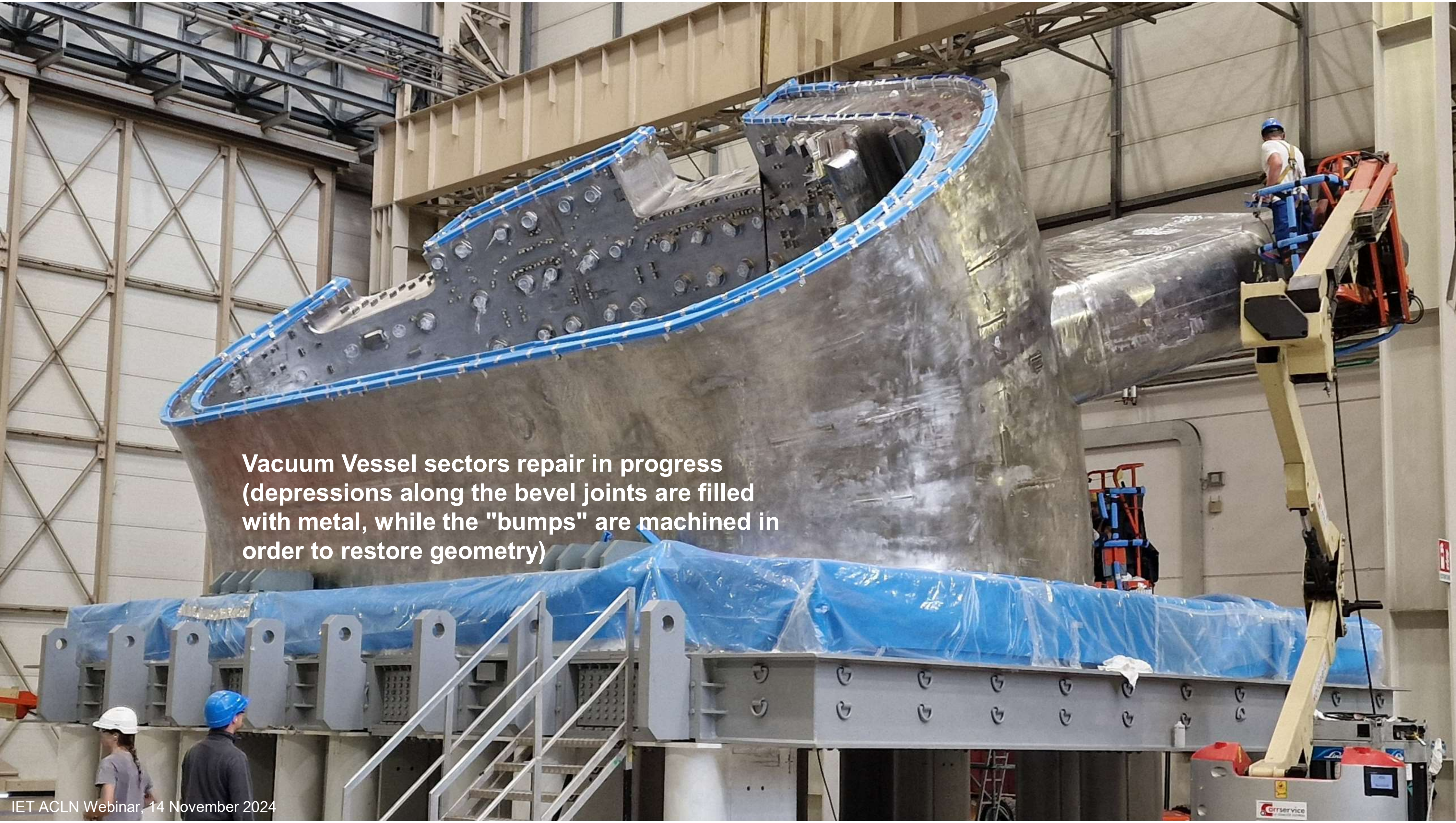
All six modules plus a spare are scheduled to be delivered by mid-2025.

Stacking third module, August 2024

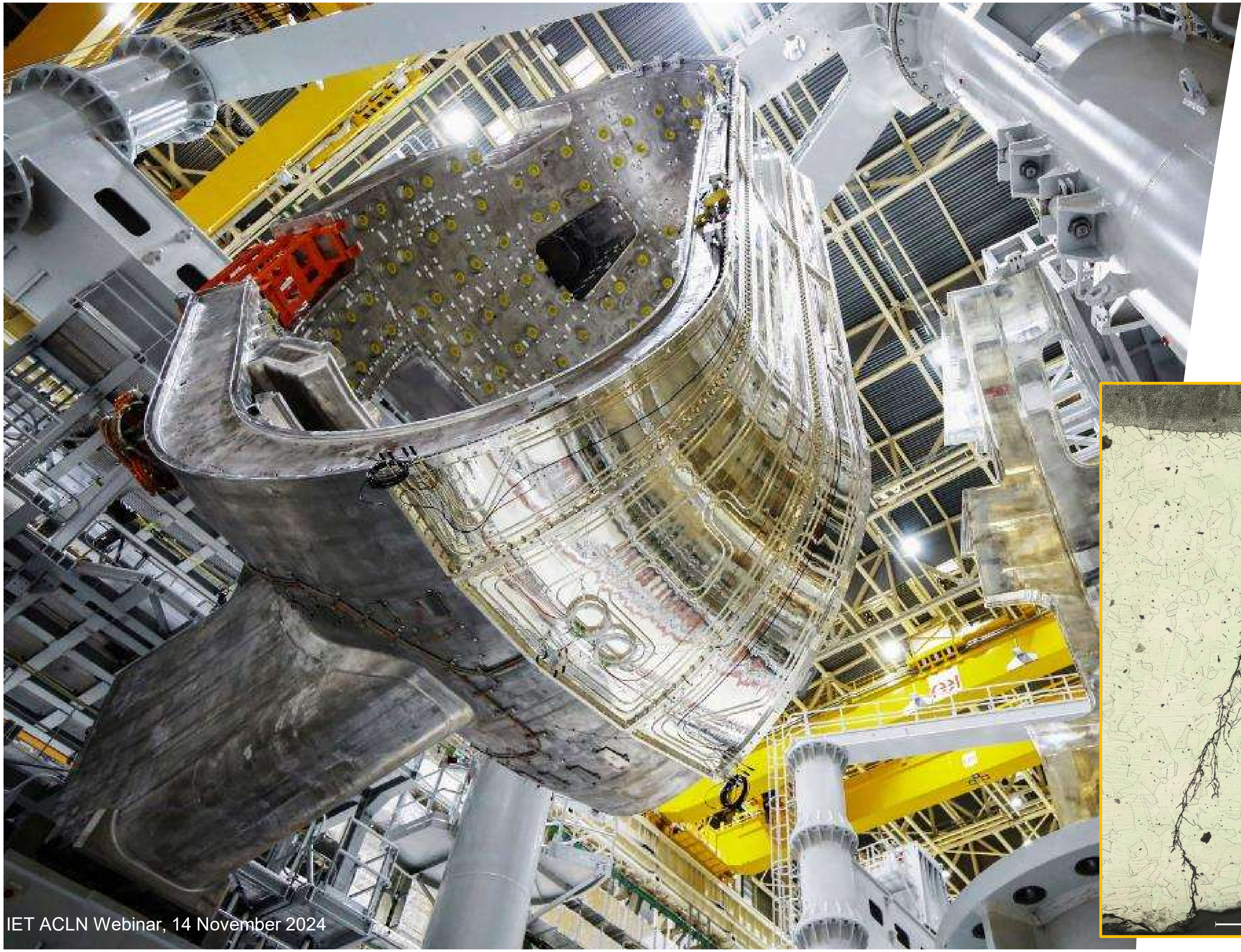
CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

Vacuum Vessel sectors have geometric non-conformities in the field bevel joints.



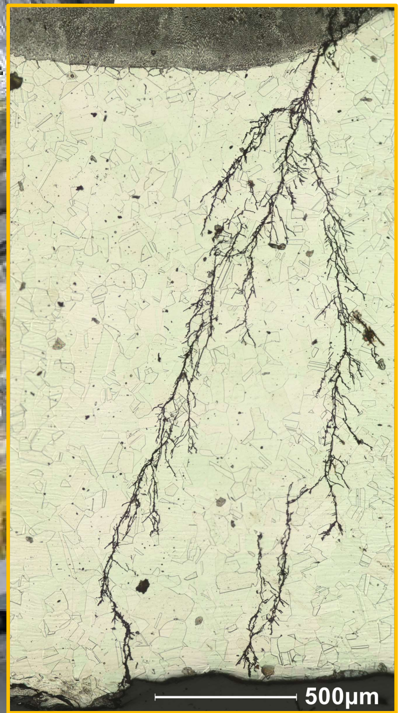


Vacuum Vessel sectors repair in progress (depressions along the bevel joints are filled with metal, while the "bumps" are machined in order to restore geometry)



CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

Leakage identified in thermal shield cooling piping due to chloride stress corrosion.



VVTS REPAIR PROCESS

- Replacement of corroded pipes with new 316L pipes
- 2mm panel machining to eliminate potential panel corrosion risk
- Surface polishing replacing Ag coating for good emissivity: surface roughness less than 0.1µm – lower emissivity at 80K

VVTS MANUFACTURING

A risk mitigation measure: a contract to manufacture 3 (or more) new VVTS sectors progressing as planned.

The ITER worksite

- ~ 3 000 people, 90 nationalities
- ~ 500 EU companies (~80% french)
- Management of important co-activity on the worksite
- **ITER *« Safety First »***

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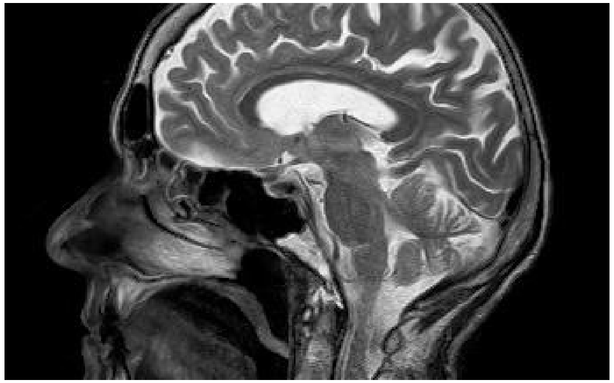
INNOVATION AND SPIN-OFFS FROM ITER

ADVANCING MEDICINE, MANUFACTURING, AND MORE

Superconductor magnet advances →
Enhanced mapping of the human brain



Complex aluminum structures →
Enhanced electric train bodies

Explosive forming →
High-strength components such as aircraft

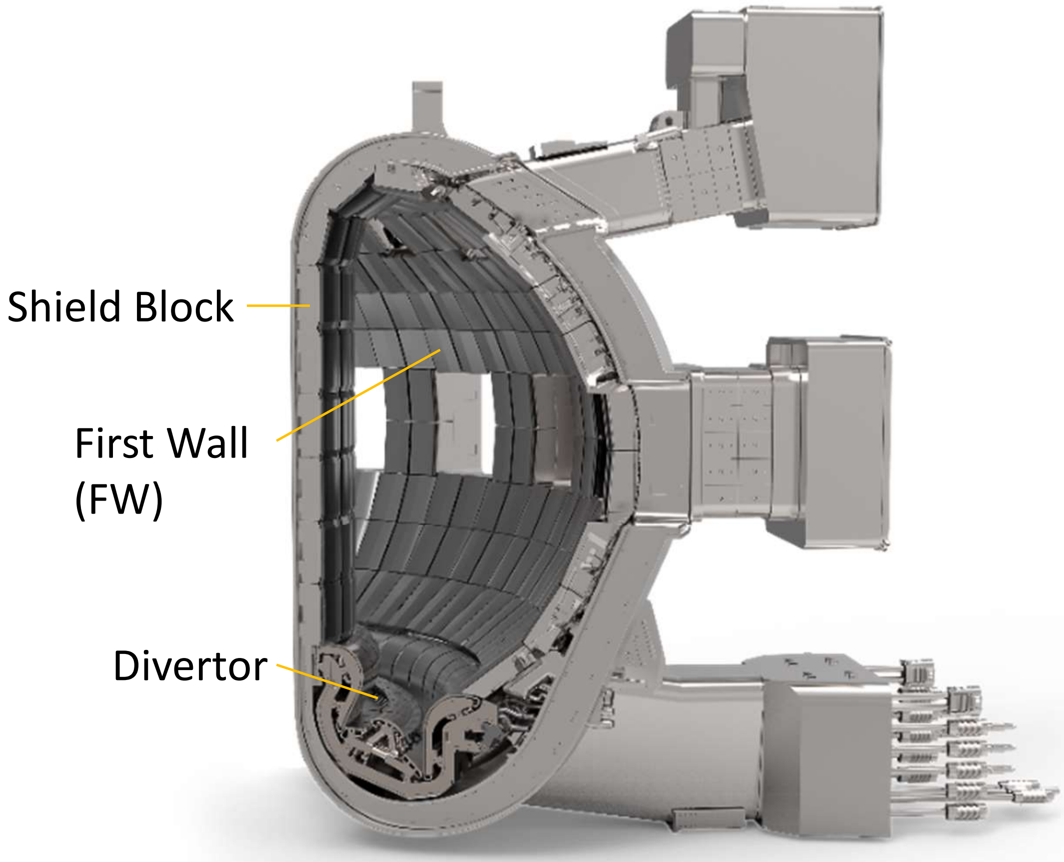
High-precision diagnostics →
Enhancements for geothermal energy, laser welding, cancer treatment, etc.

Laurent’s Part 2: a concrete example

The challenges of designing and manufacturing components facing the plasma

The tungsten Divertor and First Wall will experience high loading conditions

- Operating conditions:
  - Injection high-energy neutrals = 33 MW
  - Electron cyclotron heating system ~ 60 MW
  - Ion cyclotron heating system ~10-20MW
  - Burn flat-top duration ~300s
  - 15 MA | 5.3T
- Normal 'steady-state' operation:
  - 1-3 GJ to FW if high tungsten radiation
  - 5-20 MW/m^2 to Divertor plasma-facing components
- Thermal transients too !



ITER main chamber

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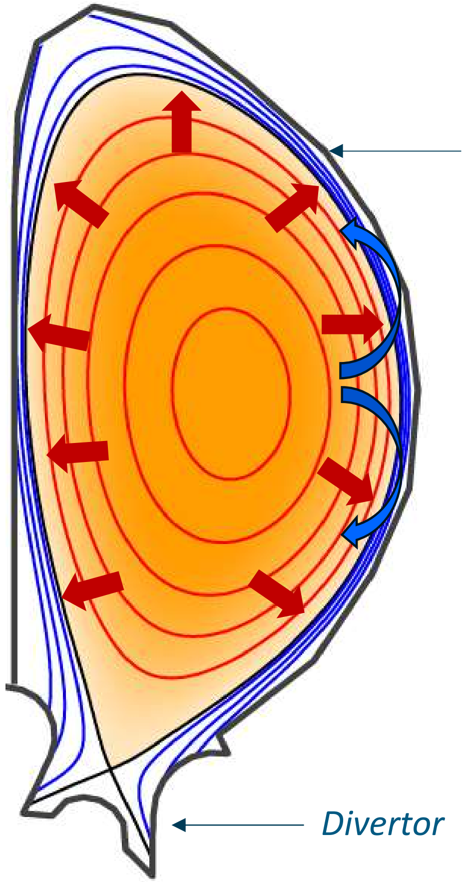

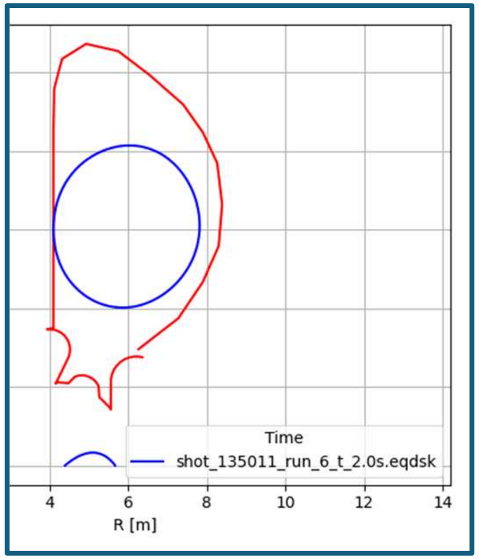

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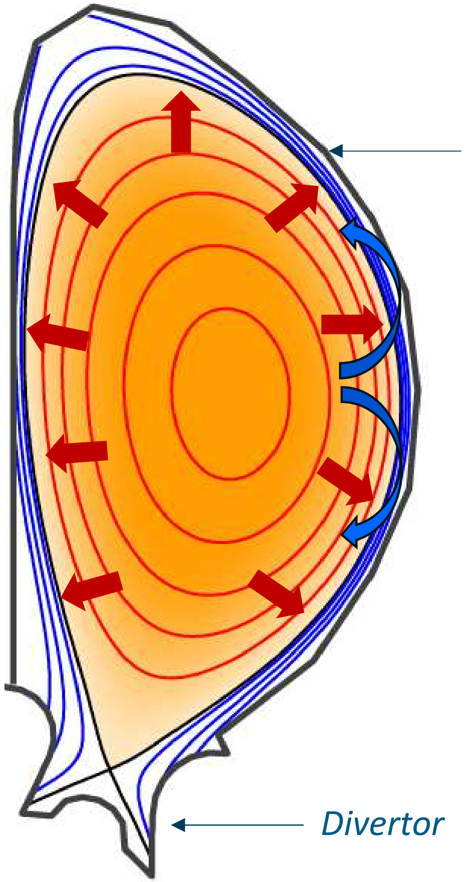
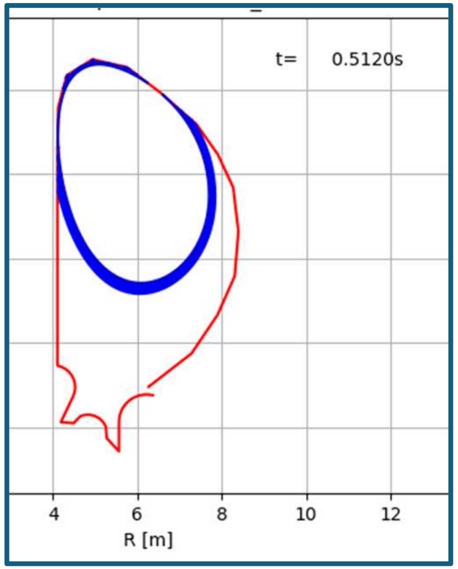




Thank you!

ITER Open Doors Day

ITER

Conquering the Challenges of Fusion Energy – Part 2

Laurent Ferrand, Divertor Coordinating Engineer

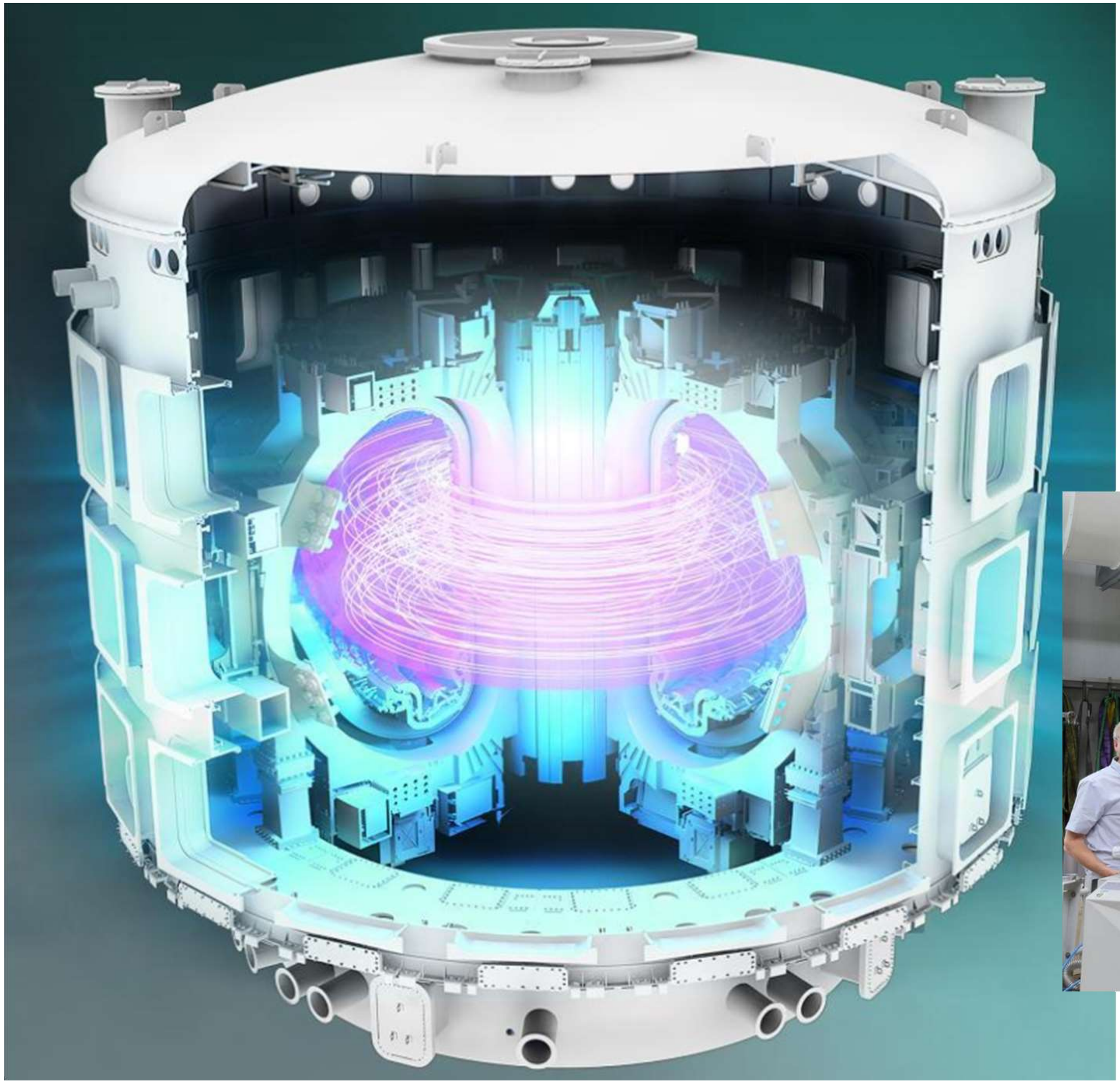
IET ACLN Webinar

14 November 2024

china eu india japan korea russia usa

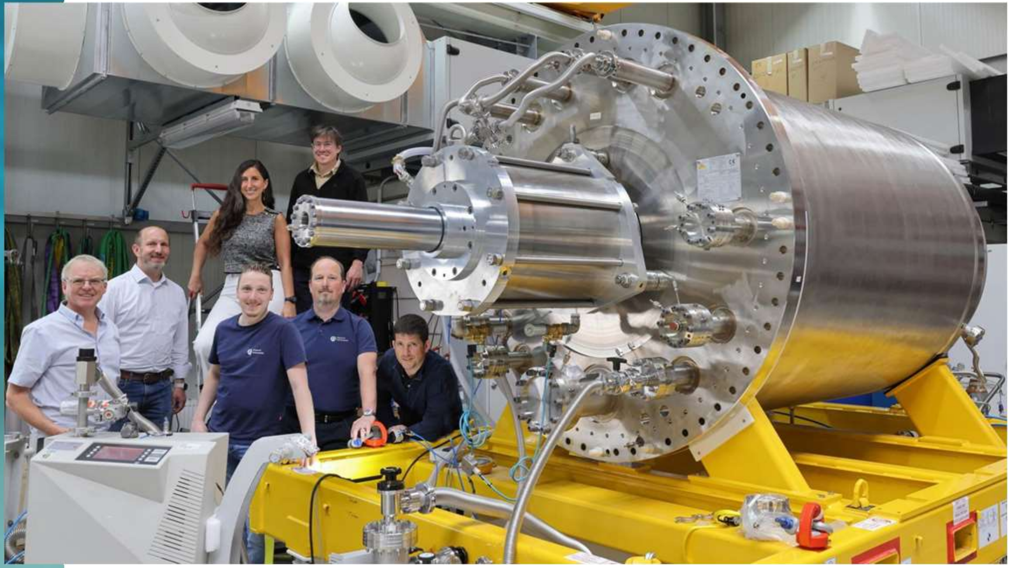
ABSTRACT

- Plasma Facing Components: sitting in a hostile and demanding environment
- How to perform with Vacuum / Electro-Magnetic / Nuclear constrains
- Power Handling



PLASMA FACING COMPONENTS – PERFORMING IN ULTRA-HIGH VACUUM

- One of the largest and the most complex high vacuum systems ever built
- 6 torus cryopumps
- Density of primary vacuum ≈ 1 to 10 million times lower than that of atmosphere
- First series Torus Cryopump FAT in May 2024
- 2 concerns: cleanliness and leak tightness



PLASMA FACING COMPONENTS – PERFORMING IN ULTRA-HIGH VACUUM

- The ITER Vacuum Group has published a handbook that outlines the necessary rules in design, manufacturing, assembly, and handling to achieve and maintain the various ITER vacuums (aka Vacuum Quality Classes).
- Cleanliness: particular attention at all stages is key
- Clean Rooms, Clean Work Plan, Cleaning Procedures, prior approval of fluids and material for the relevant vacuum quality class, baking as part of final cleaning. Selection/Qualification of techniques.
- Leak tightness: Hot Helium Leak Test in operating conditions

INTERNATIONAL STANDARD — ISO 15614-1

First edition 2004-06-15

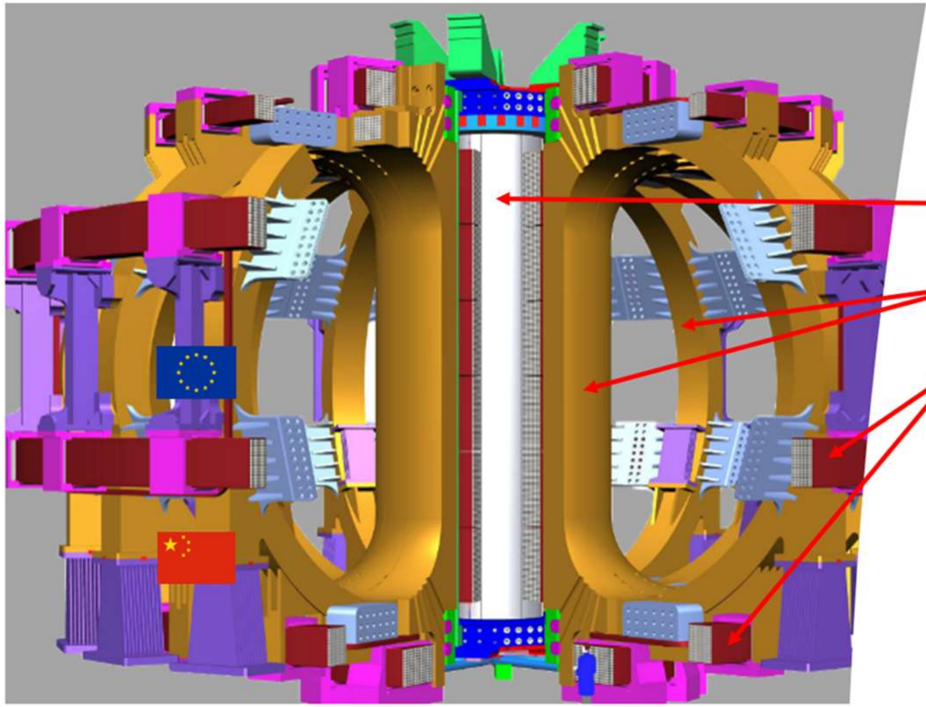
Specification and qualification of welding procedures for metallic materials — Welding procedure test —

Part 1:
Arc and gas welding of steels and arc welding of nickel and nickel alloys

PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH ELECTRO-MAGNETIC LOADS

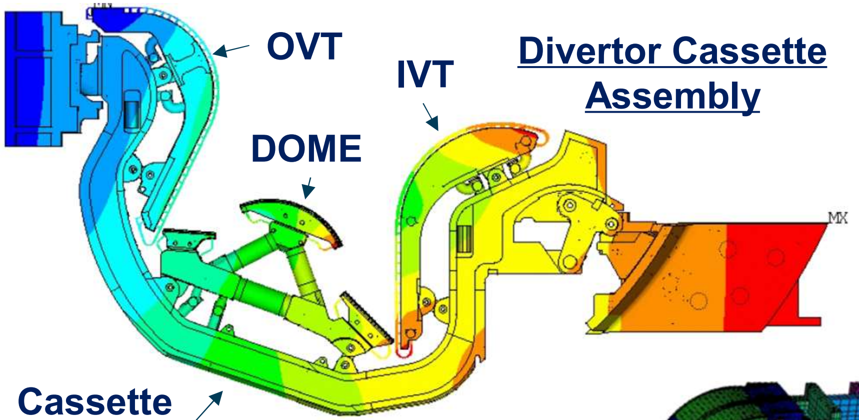
- Despite the relatively high hydraulic pressure in the components which is the basis for the selection of standards for manufacturing and testing (EN13445 – Unfired Pressure Vessel), the primary loads applied on the Internal Components are Electro-Magnetic Loads, by a factor of ≈10.
- This is due to the large amount of energy stored in the magnets, which is converted to loads on the internal components in case of transient events (plasma “disrupting”).
- The high and cyclic EM loads represent one of the toughest challenges for the Internal Components.

Earth’s Magnetic Field:
0.00005 Tesla



Magnetic Cage ~10 Tesla
or 200,000 x Higher

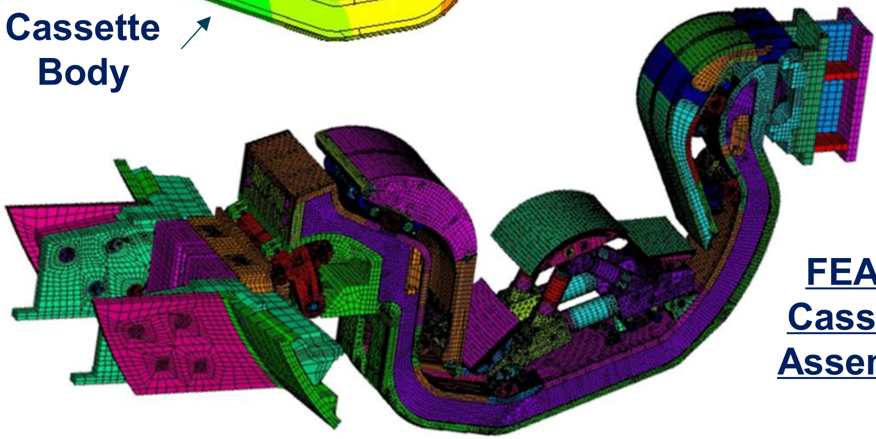
PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH ELECTRO-MAGNETIC LOADS



Divertor Cassette Assembly

- Structural Integrity verification as per Internal Components specific criteria

- High efficiency coefficient for all structural material:
- Material mill grain size, micrographic and volumetric (among others) inspection with stringent criteria: we reject inclusions that could weaken the bulk material (or become leak path precursor)
- Welding and NDE Qualification as per top tier standards
- 100% Welding volumetric NDE with tight acceptance criteria


FEA of Cassette Assembly

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 17636-1

January 2013

ICS 25.160.40 — Supersedes EN 1435:1997

English Version

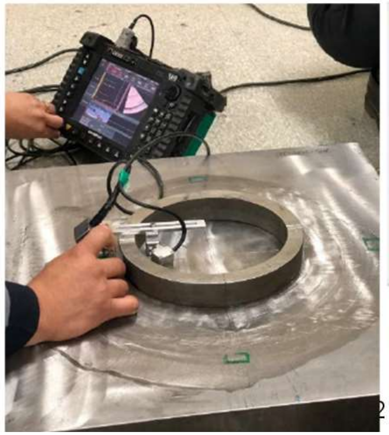
Non-destructive testing of welds - Radiographic testing - Part 1: X- and gamma-ray techniques with film (ISO 17636-1:2013)

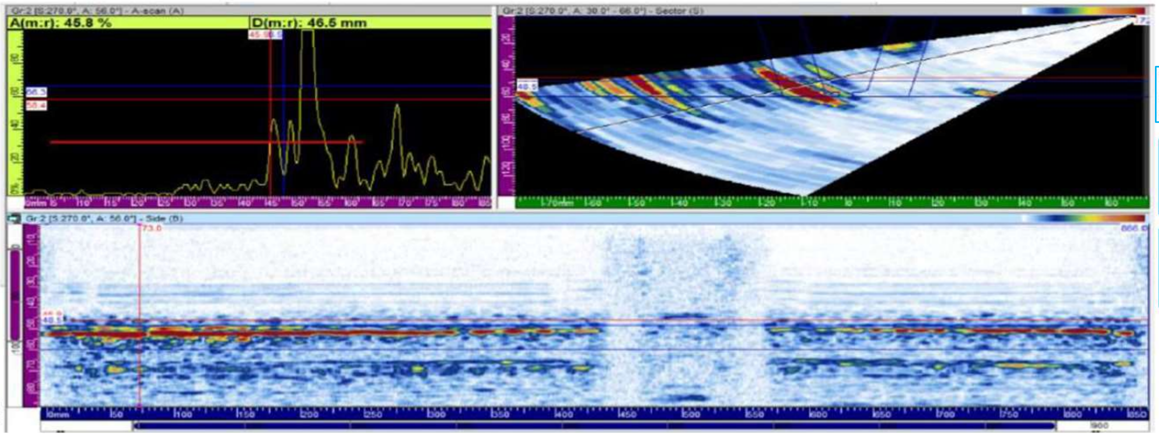
INTERNATIONAL STANDARD

ISO 22825

Second edition 2012-05-15

Non-destructive testing of welds — Ultrasonic testing — Testing of welds in austenitic steels and nickel-based alloys



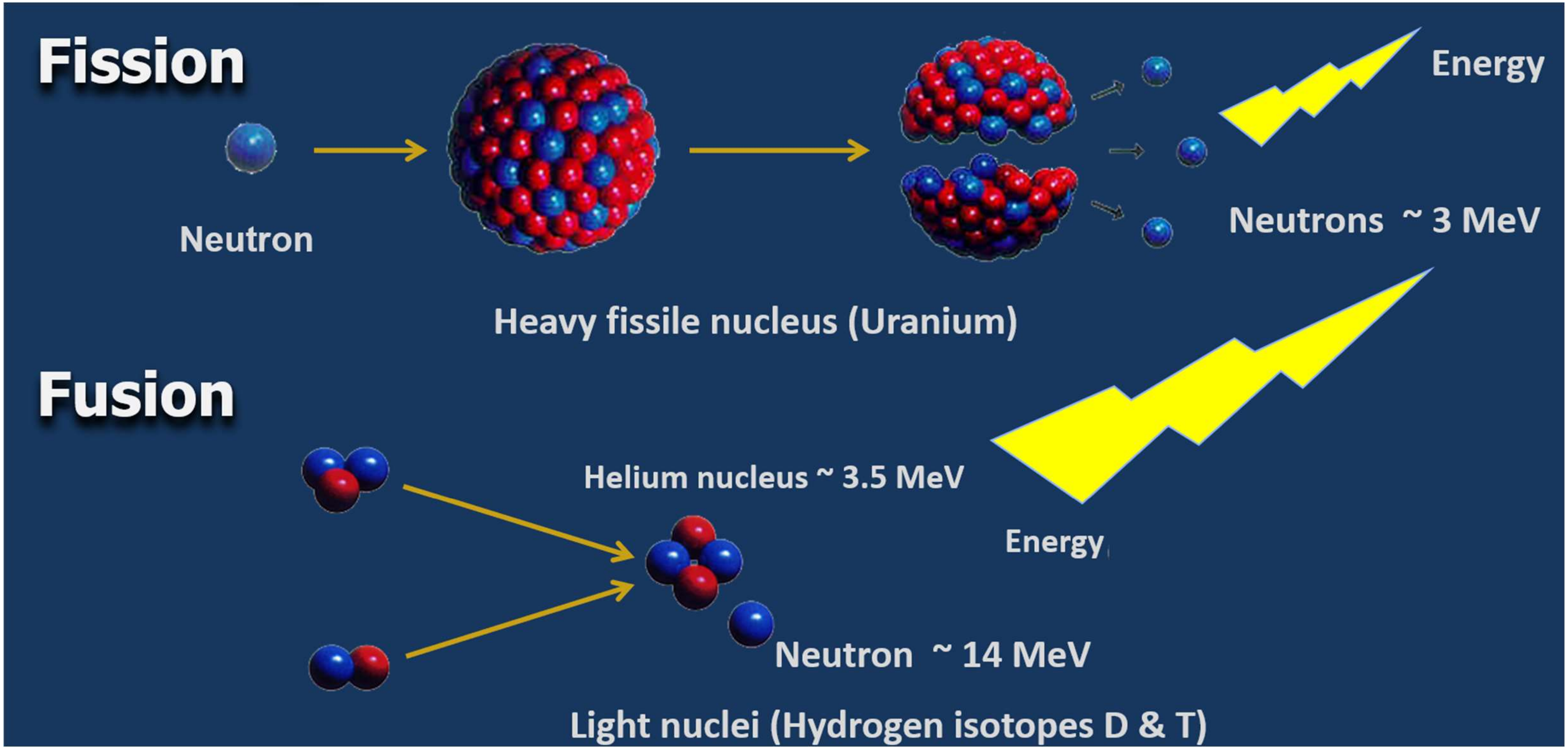


Vacuum quality class 1 components [ITER Vacuum Handbook ITER_D_2EZ9UM v2.5] which are machined from austenitic steel and which are of final thickness less than 5 mm, shall be made from cross-forged material which is Electro-Slag Remelted (ESR) or Vacuum Arc Remelted (VAR).

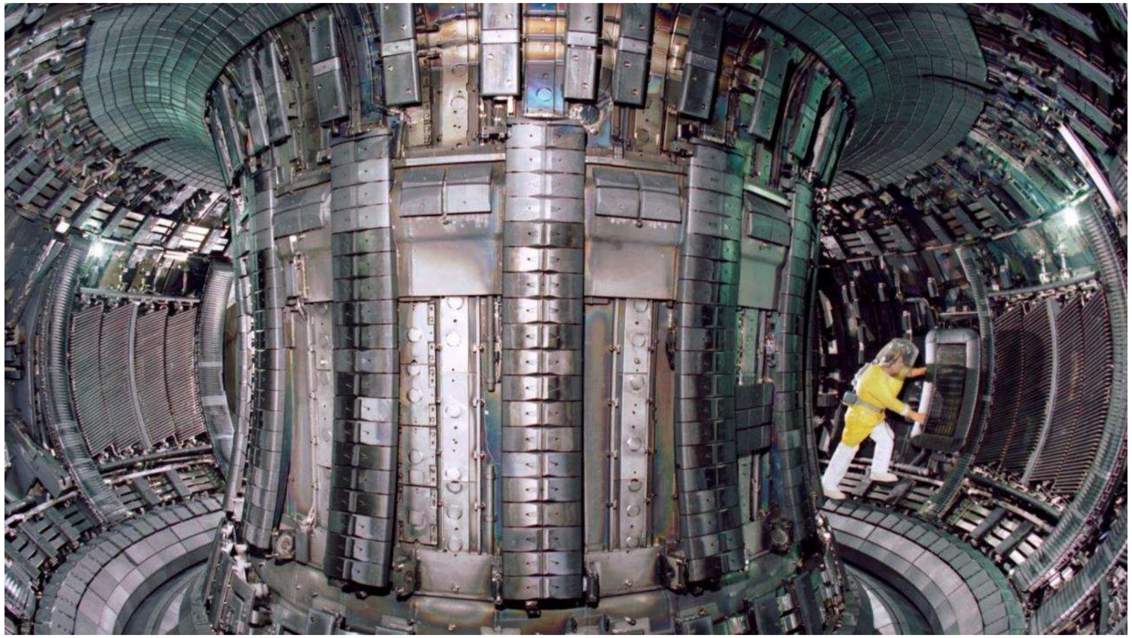
For final thickness on the Divertor Inner Vertical Target of less than 5mm with a vacuum boundary, the acceptance criteria shall be for isolated and grouped discontinuities of "one third of the final thickness" equivalent diameter of flat bottom hole for normal probe. Such cases shall be specifically mentioned in the UT procedure.

The relative magnetic permeability of the finished forgings shall be measured at room temperature after solution annealing. The value measured shall be lower than or equal to 1.03 (for fields of over 80000A/m (1000Oe)) as per as per Test method 3 or 5 of ASTM A342 (method is not restricted to ASTM A342).

PLASMA FACING COMPONENTS – PERFORMING UNDER FAST NEUTRONS IRRADIATION



PLASMA FACING COMPONENTS – PERFORMING UNDER FAST NEUTRONS IRRADIATION



Element	Content, wt. %	
	min	max
Fe	base	
C		0.06*
Mn	4.0	6.0
Si		1.00
Cr	20.5	23.5
Ni	11.5	13.5
P		0.040
S		0.030
Mo	1.50	3.00
N	0.20	0.40**
V	0.10	0.30
Nb	0.10	0.30
Ta		0.01
Co		0.05

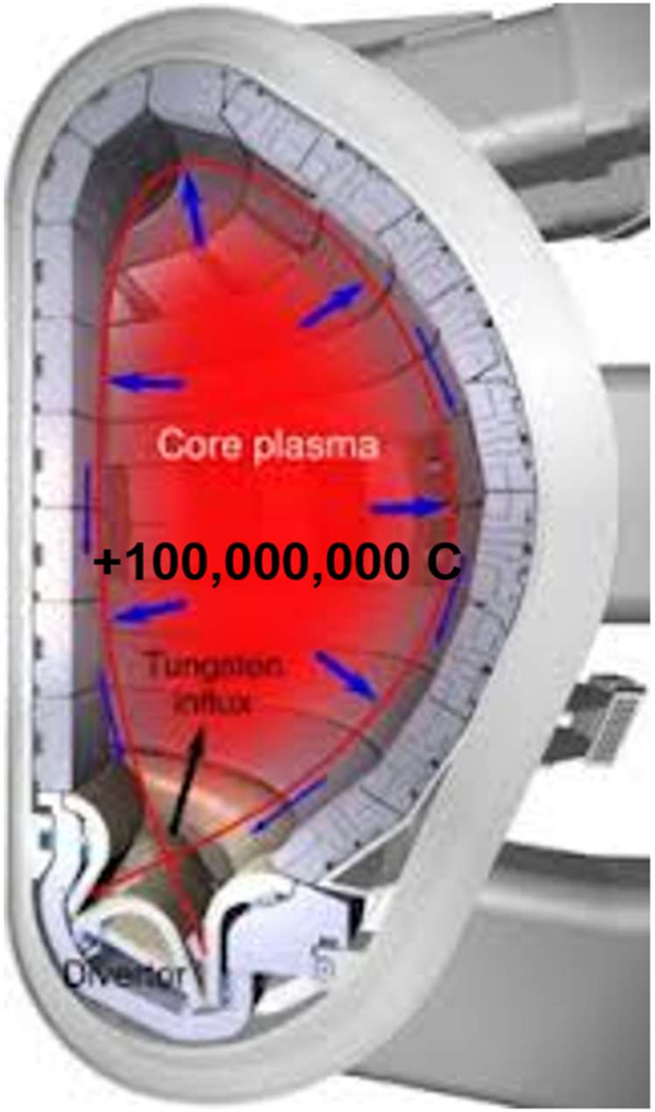
Table 1: Chemical composition

- One of the main requirements of ITER as a Nuclear Installation (INB): the ALARA principle.
- Even though the Internal Components are not protection important components, requirements apply.
- Concern: Activation of bulk material and activated corrosion products
  - ✓ Selection of material (i.e. avoid those with radioactive isotopes)
  - ✓ Radio-protection requirements in the material specifications
- Concern: Detrimental effect of nuclear irradiation on material properties
  - ✓ Material selected shall be compliant with ITER research plan
  - ✓ New grades developed in research facilities for next fusion steps

PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

In normal conditions (steady-state), plasma-facing components receive radiation power as well as convected heat fluxes from the plasma: in the range of 5 $MW.m^{-2}$ on the Blanket First Walls, and 10 $MW.m^{-2}$ on the Divertor at the plasma strike points (even up to 20 $MW.m^{-2}$ during short transients).

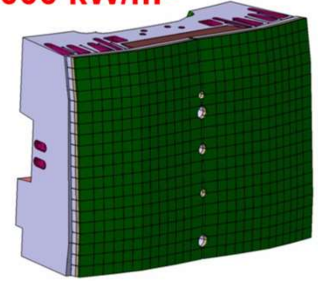
- 269 C



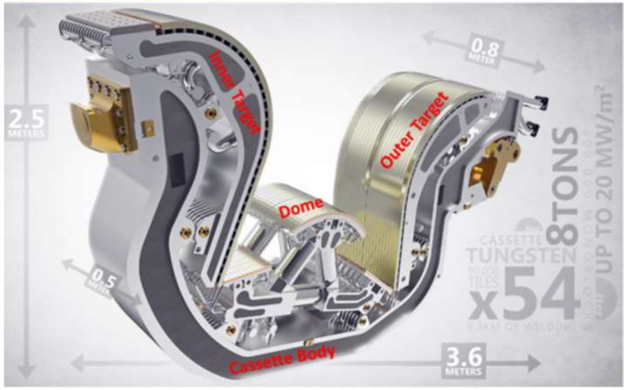
Temperature difference
> 100,000,000 C

Summer sunny day
1 kW/m²

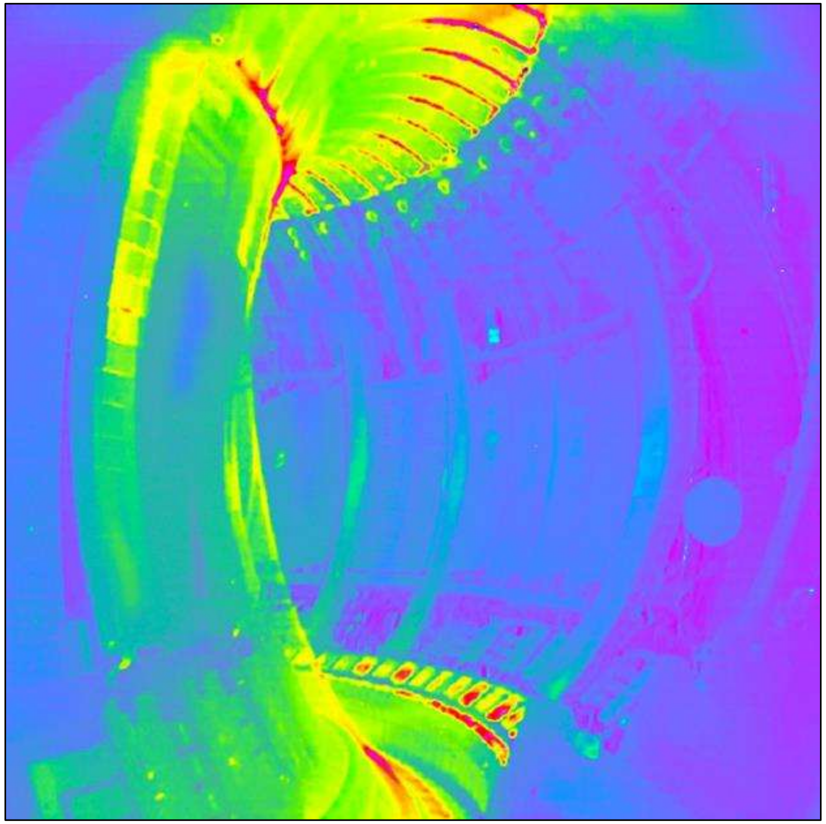
ITER Blanket
5,000 kW/m²

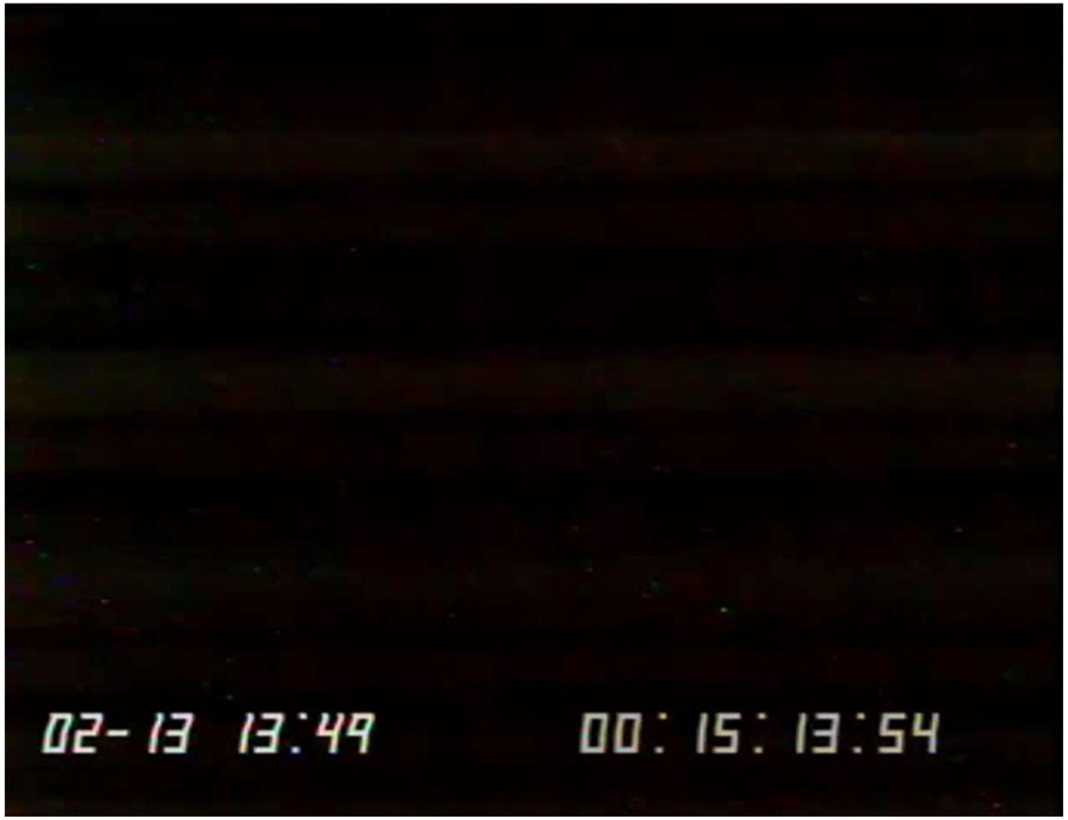


ITER Divertor
20,000 kW/m²



PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX





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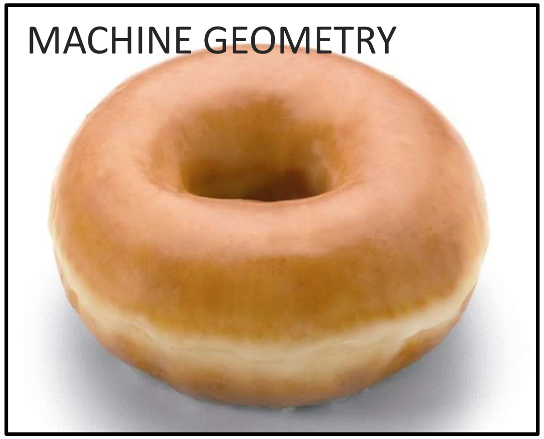
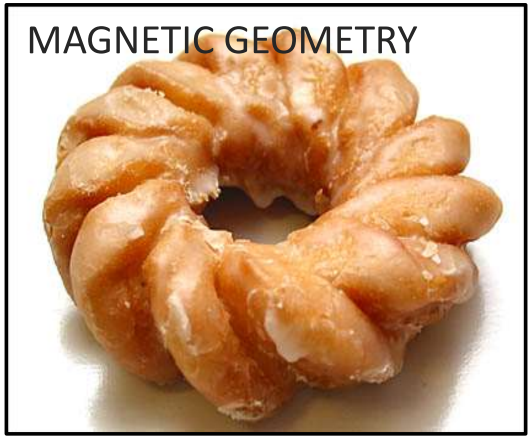
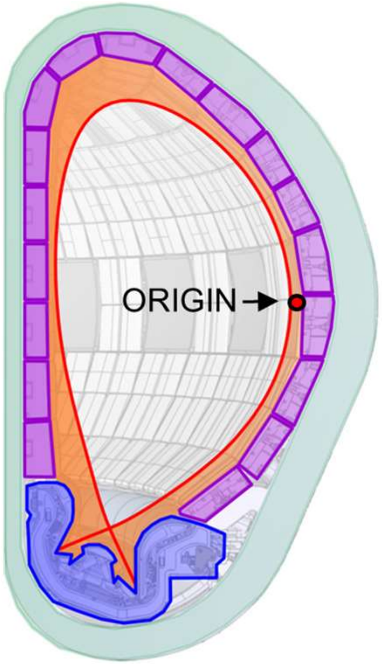
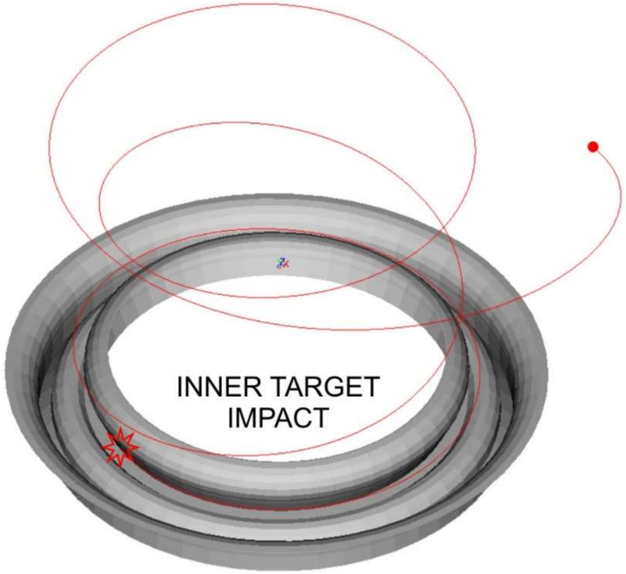


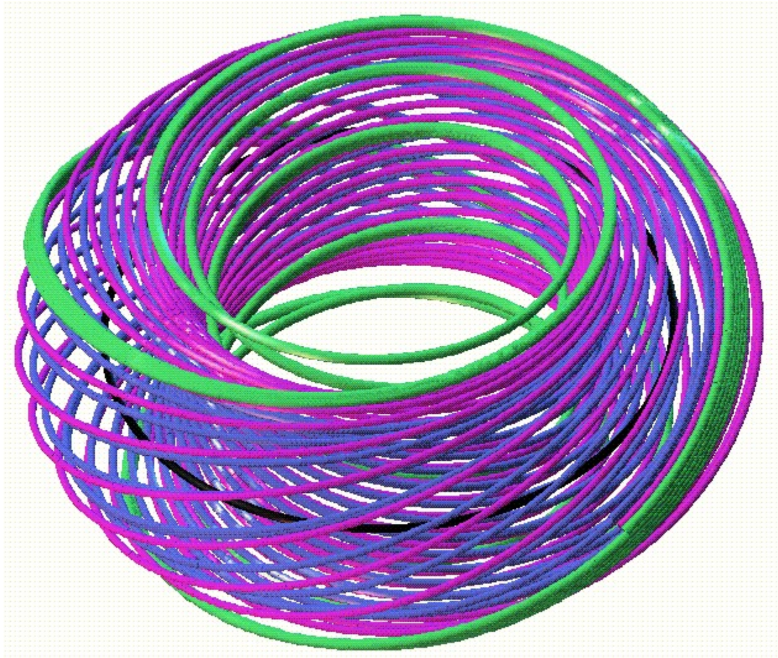


Like the EM loads, the heat fluxes are high and cyclic, and represent arguably the toughest challenge for the Plasma Facing Components.

The high heat fluxes are deposited on the surfaces following the field lines, at a glancing angle: geometry is key, leading edges gaps and steps must be avoided.

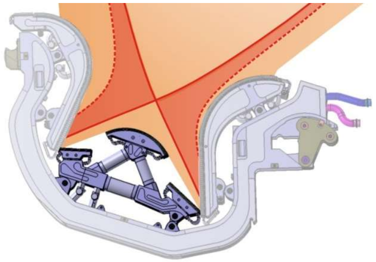




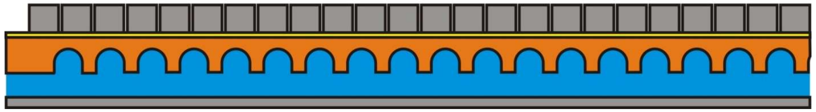


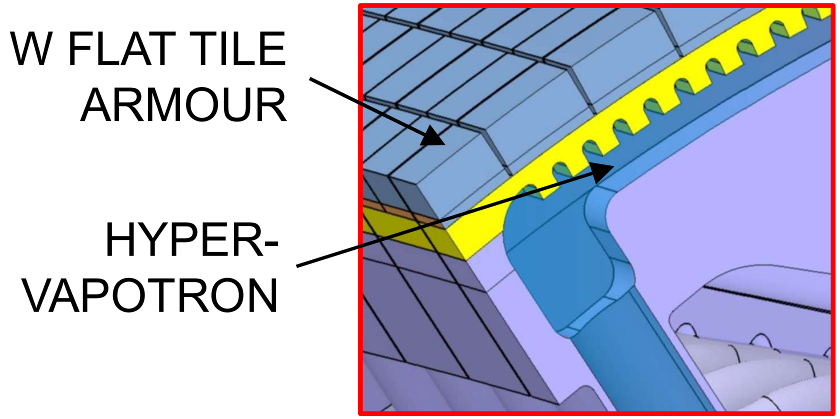
PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

Hypervapotron Concept



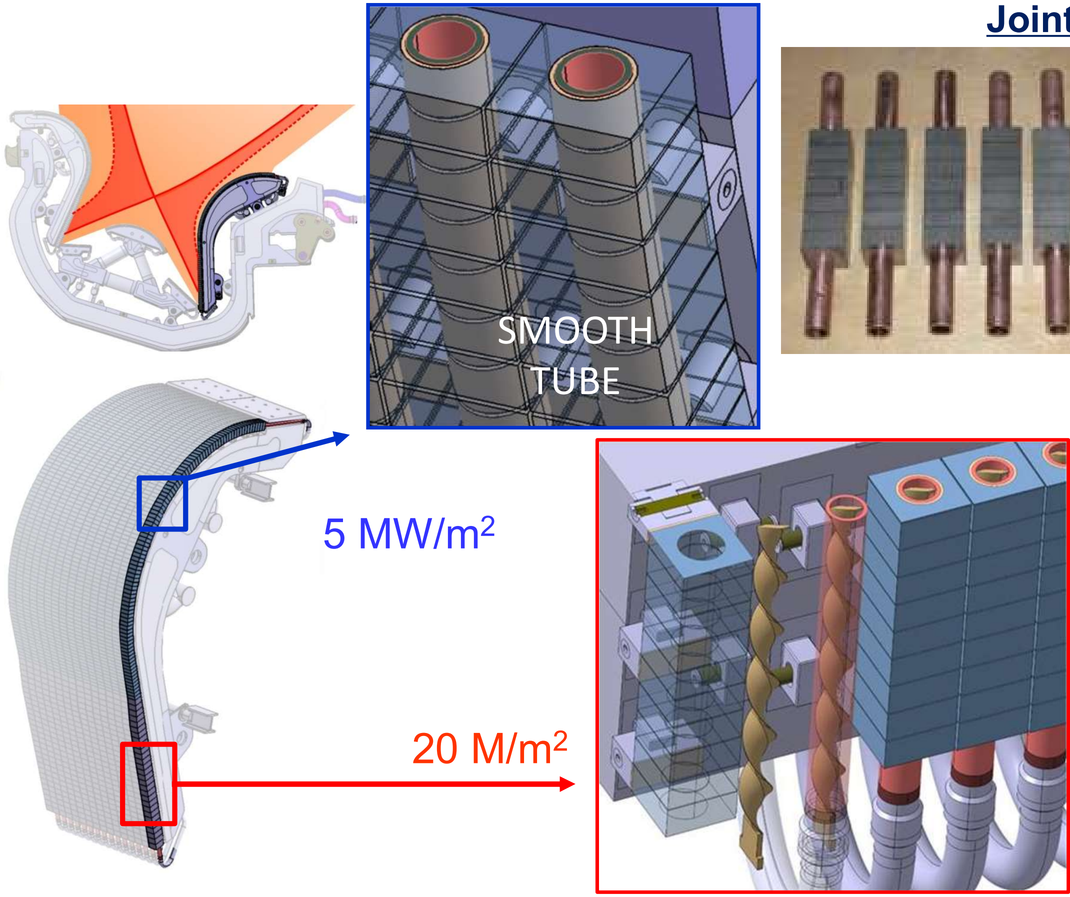
- The Dome in the Divertor and the Blanket First Wall rely on the hypervapotron concept.
- This concept uses tungsten tiles as armour material brazed on a CuCrZr/316L(N)-IG structure. The hypervapotron geometry provides heat removal capabilities compatible with the expected heat fluxes.



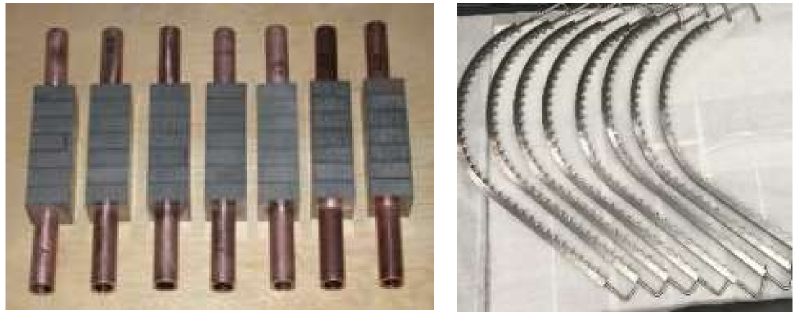


PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

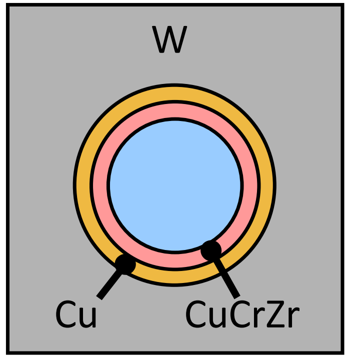
Monoblock Concept



Joint Integrity Testing



Monoblock Materials

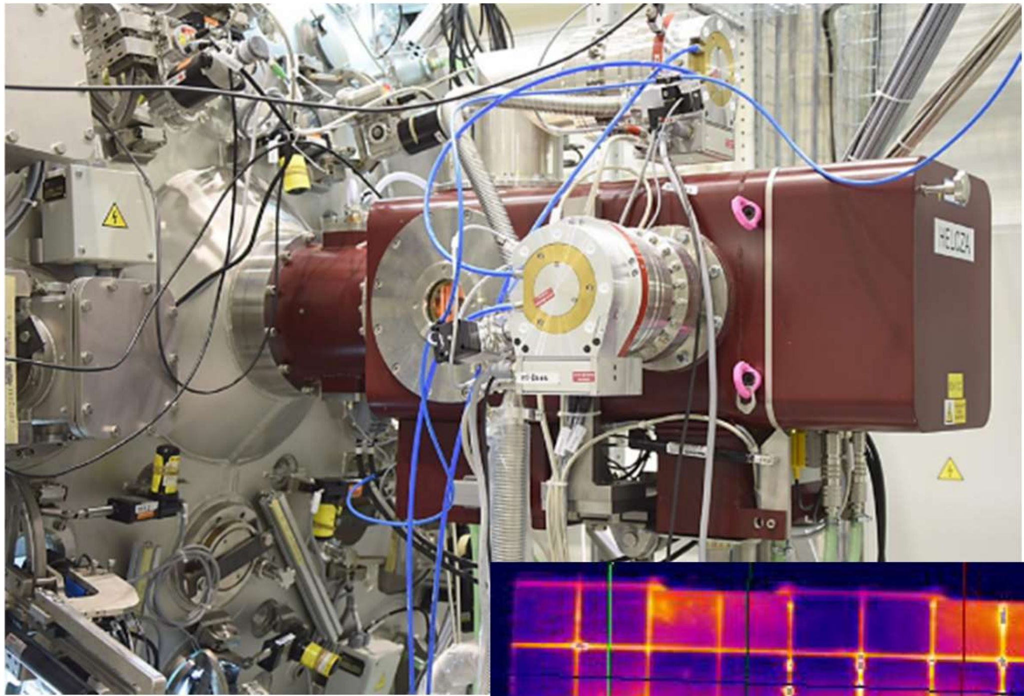


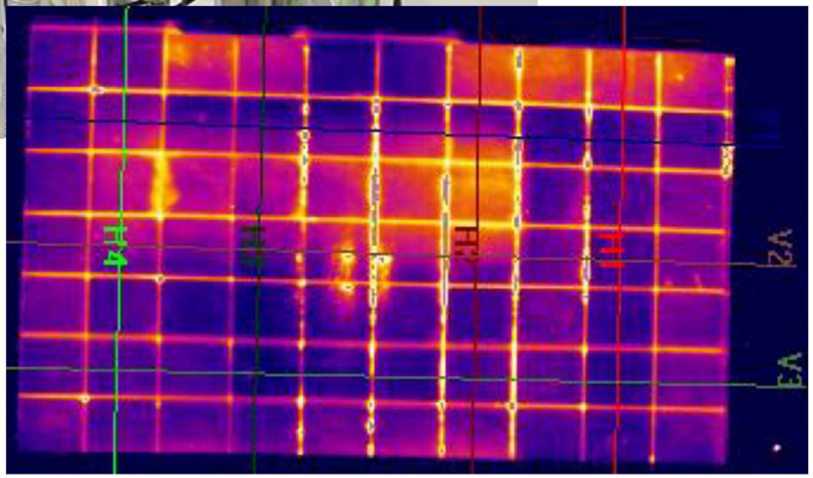
The Inner and Outer Targets in the Divertor rely on the monoblock concept.

This concept uses tungsten blocks as armor material brazed or HIPed on a CuCrZr tube. A swirl tape in the region close to the strike point improves heat removal by preventing laminar flow.

PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

High Heat Flux Testing

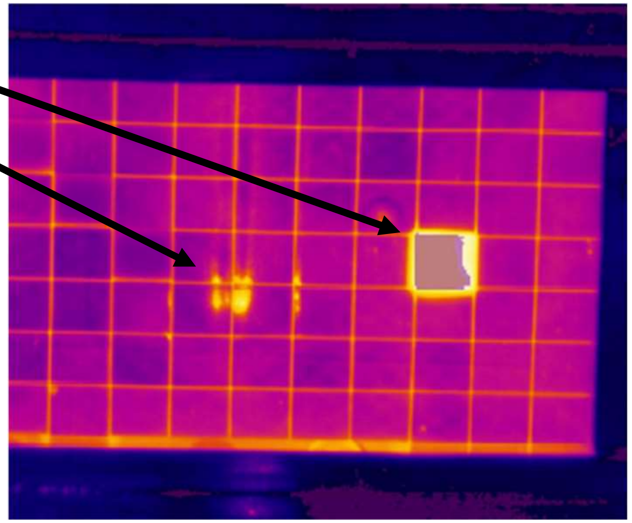




- First as part of process qualification and then to check continuous quality along production, high heat flux tests are required.
- Plasma facing units are extracted from the production line and submitted to intense heating by electron beam gun.
- This cyclic test is looking for flaw growth at the level of the joint between the monoblock and the tube.

Loss of tile!

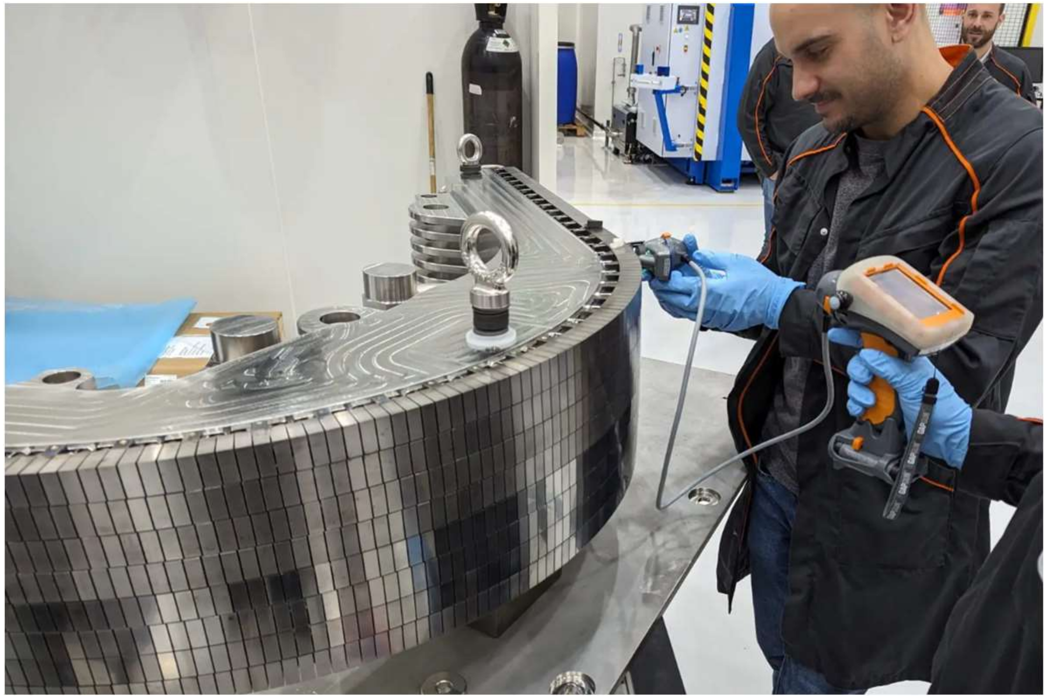
Defect!



PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

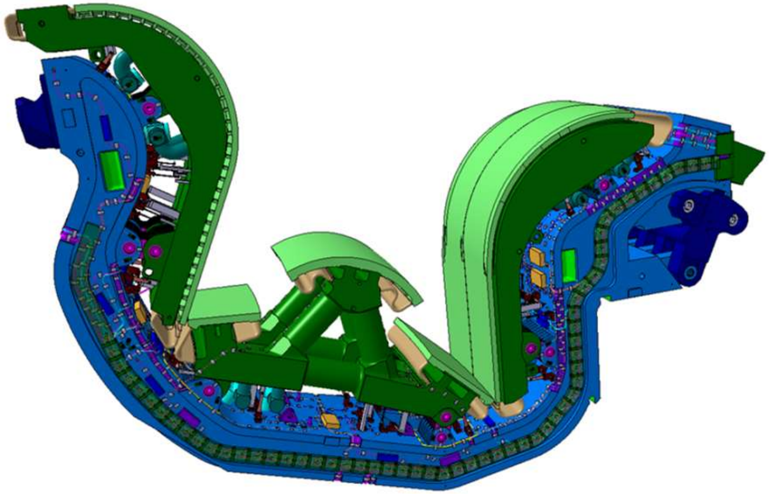
Dimensional Inspection

- Dimensional inspection is among the key requirements in the production and acceptance of internal components.
- Stringent tolerances specified in the drawings must be inspected in accordance with top tier standard requirements and ITER’s Dimensional Metrology Handbook.

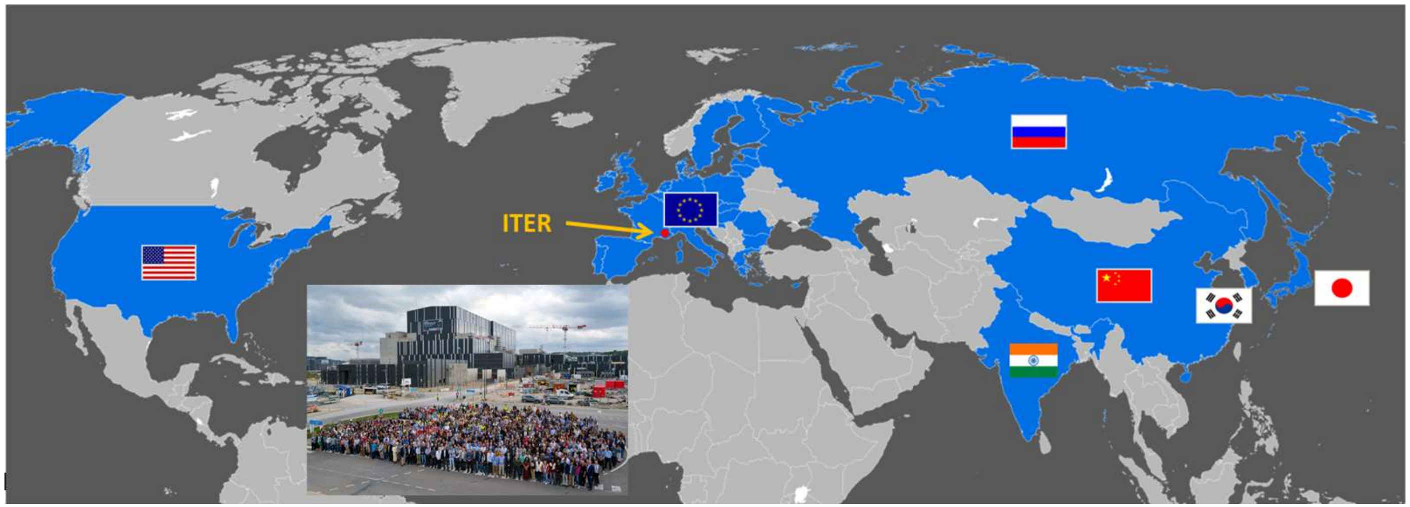


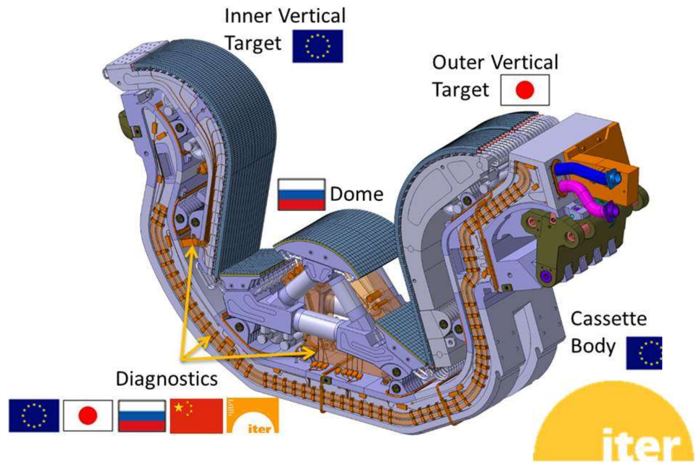
PLASMA FACING COMPONENTS – PERFORMING UNDER HIGH HEAT FLUX

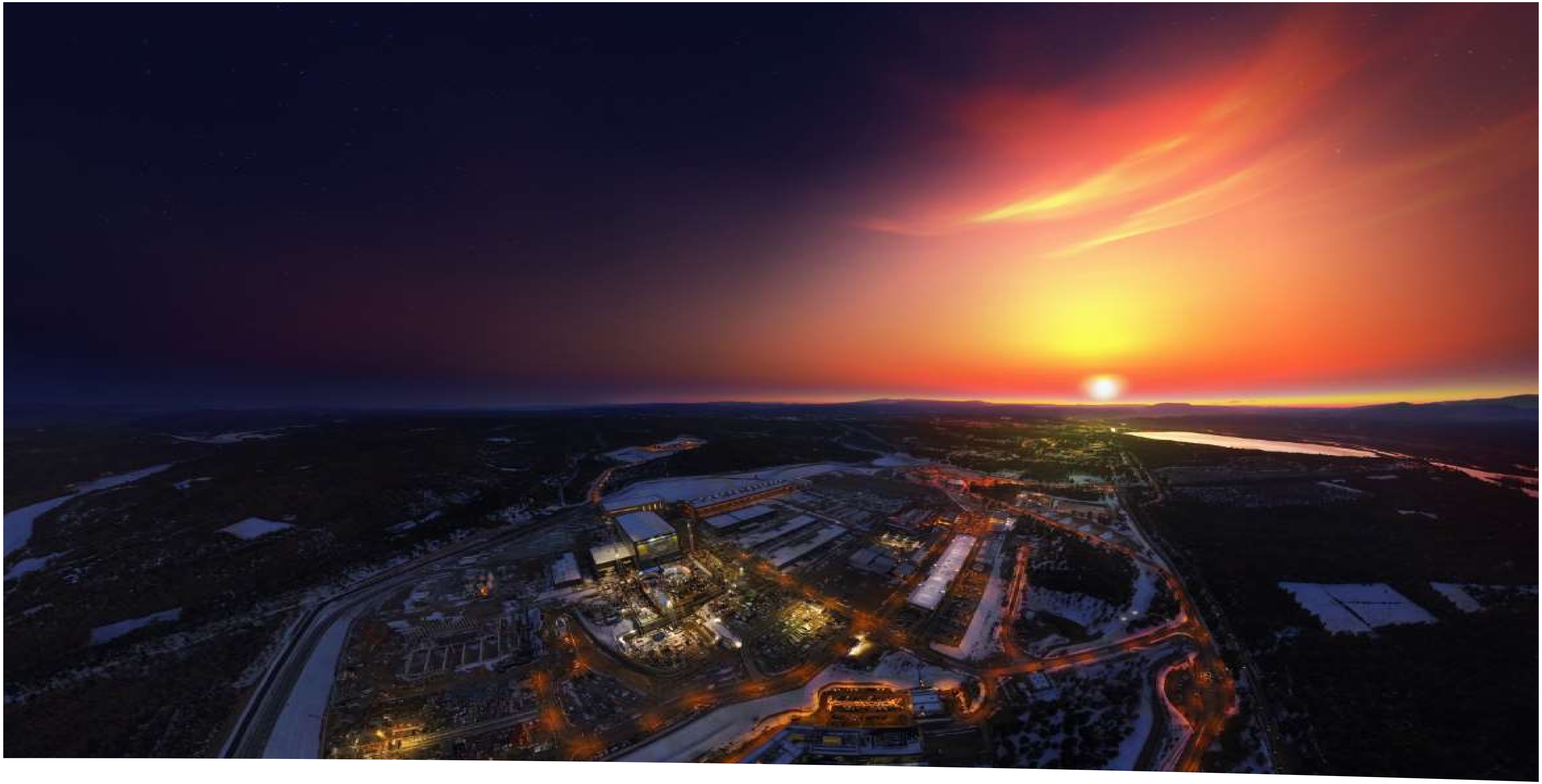
Other Challenges



- ITER is one of the most multi-cultural big science projects. The seven ITER Members represent more than 50% of the world's population and about 85% of the global GDP.
- ITER is not only one of the major scientific and technological challenges of the 21st century but also creates a new collaborative culture contributing to the world peace.
- Various normative environments and standard frameworks.
- Integration: Blanket and Divertor house 10's of different types of diagnostics from all parties and IO.
- Moving from mock-ups and prototypes to series production.







Thank you!

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china eu india japan korea russia usa