ITER

The way to a new, clean, safe and unlimited energy

Victor Udintsev on behalf of Bernard Bigot, Director-General, ITER Organization

ITER

A multinational scientific collaboration without equivalent in history

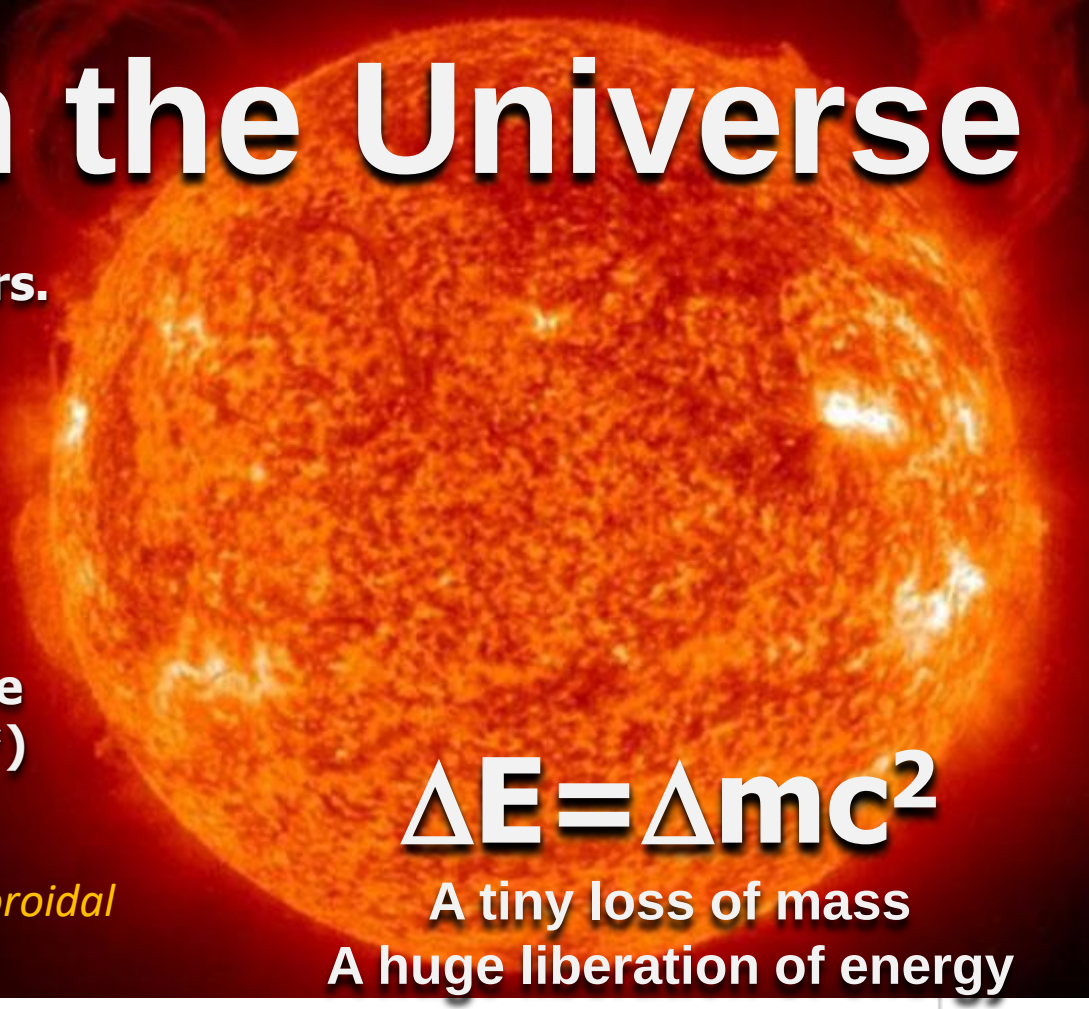
A large-scale experiment to demonstrate the feasibility of fusion energy

One of the biggest challenges for our civilization

Fusion in the Universe

- **Fusion powers the Sun and stars.**
- **In a fusion reaction, two light atomic nuclei combine, form a heavier nucleus and release energy.**
- **The Big Challenge: to reproduce in a fusion machine (Tokamak*) a similar reaction on Earth.**

** Tokamak: a Russian acronym for « Toroidal Chamber, Magnetic Coils ».*



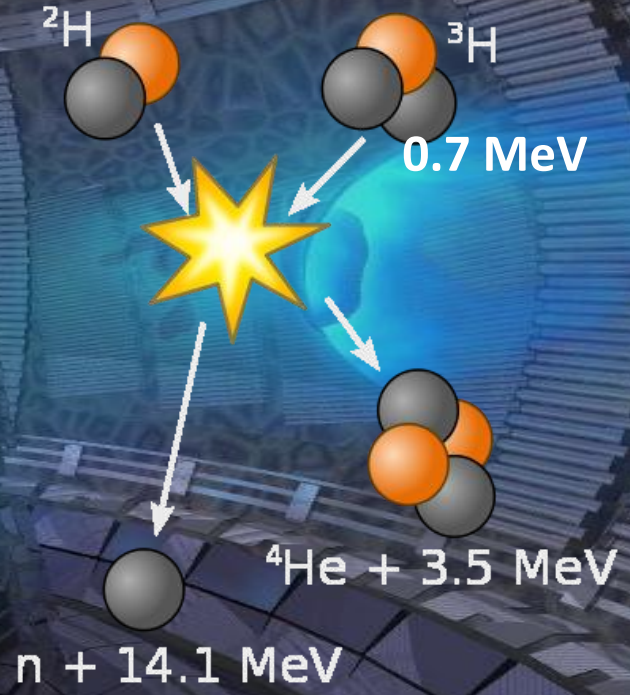
$$\Delta E = \Delta m c^2$$

A tiny loss of mass
A huge liberation of energy

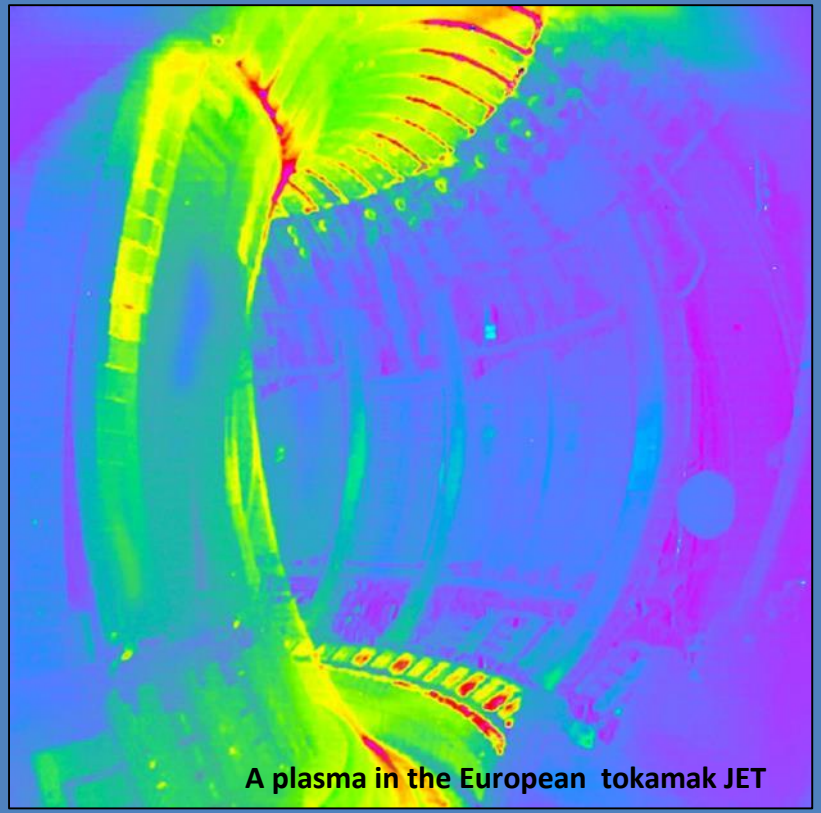
Fusion on Earth

1 gram of fusion fuels = 8 tons of oil

- A plasma of Deuterium + Tritium (hydrogen isotopes) is heated to more than 150 million °C.
- The hot plasma is shaped and confined by strong magnetic fields.
- Helium nuclei sustain burning plasma.
- Neutrons transfer their energy to the Blanket .
- In a fusion power plant, conventional steam generator, turbine and alternator will transform the heat into electricity.



Fusion's advantages

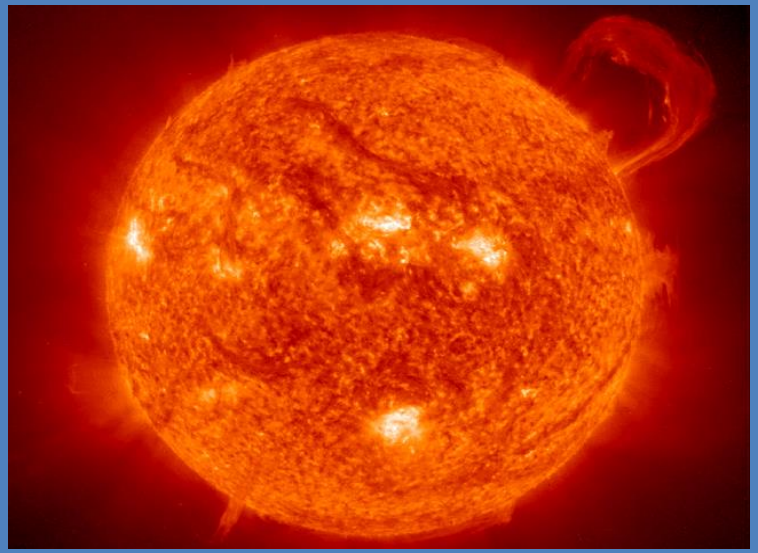


A plasma in the European tokamak JET

- A new energy source of massive, predictable and potentially continuous or variable power complementary of the renewable energies
- Safe, environmentally responsible
- Almost limitless supply of fuel for hundreds of millions of years, widely distributed around the globe
- No CO2 or other greenhouse gases
- No long-lasting high-activity radioactive waste

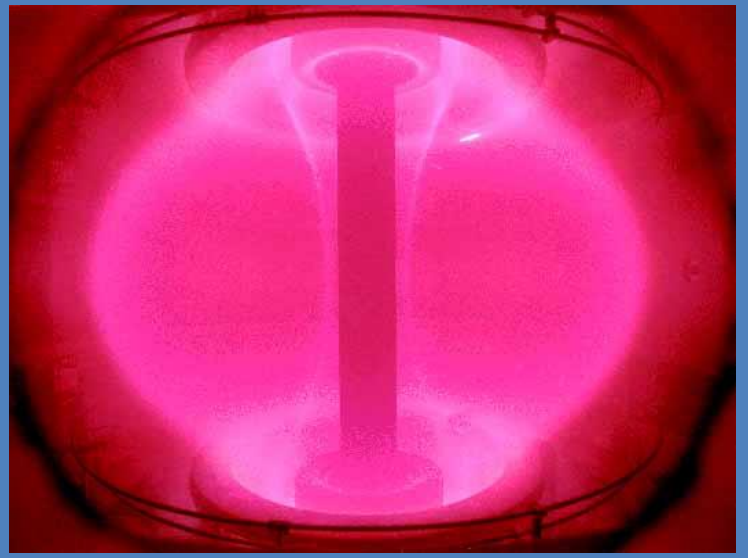
Power Creation: How do we do fusion on Earth?

Sun→Fusion



Picture courtesy of the SOHO/EIT collaboration

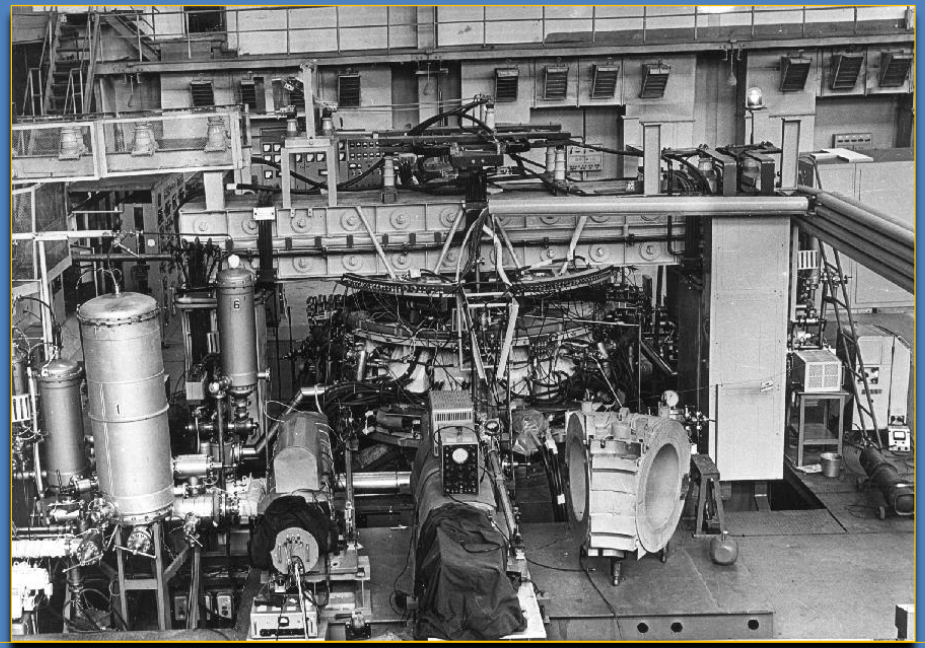
Our Approach to Fusion on Earth

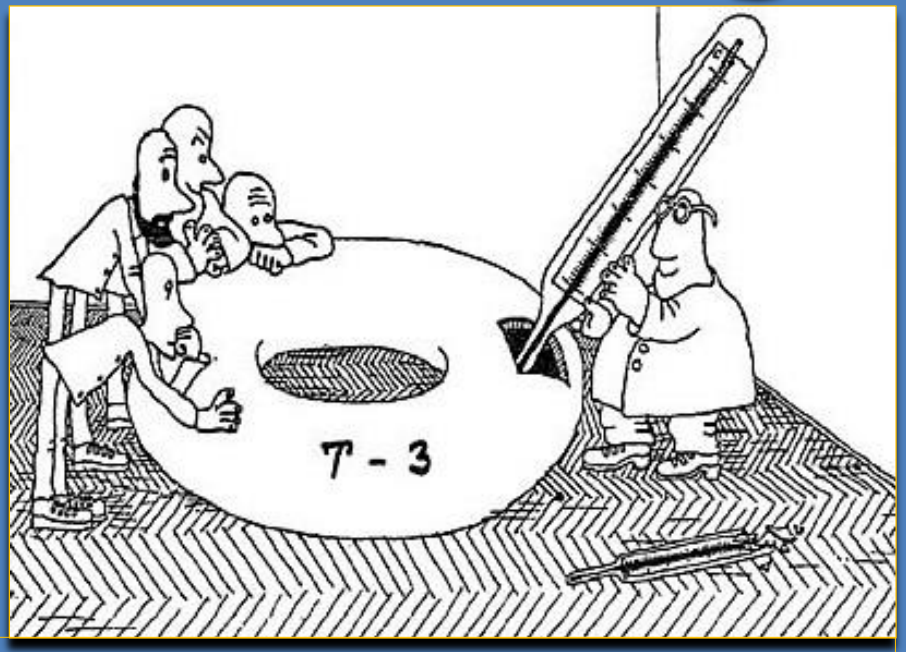


START Machine-CCFE UKAEA

- Magnetic Confinement Fusion-Tokamak

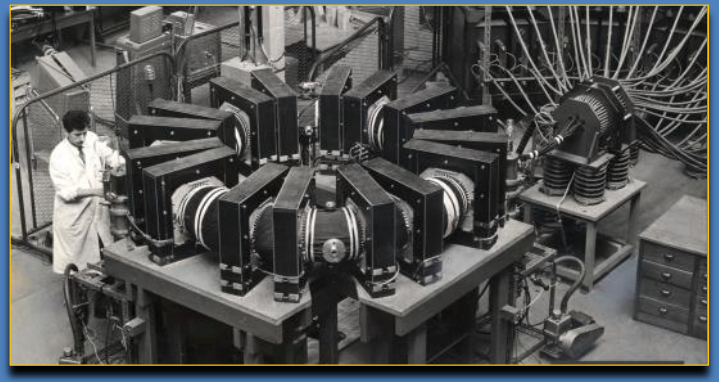
The tokamak breakthrough





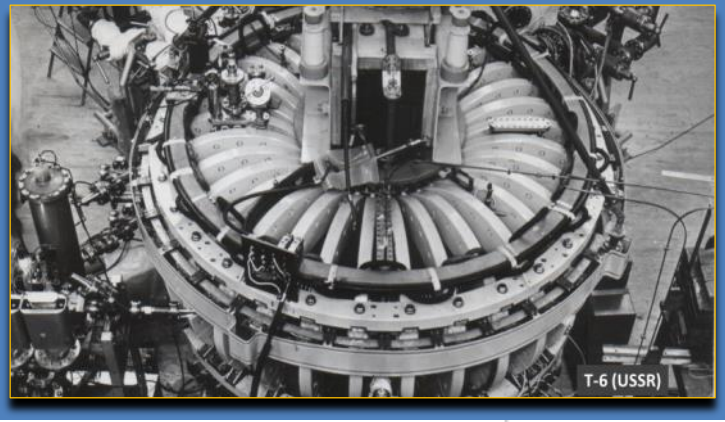
At the 1968 international fusion conference Russian scientists announced that their T-3 machine (a "**tokamak**") had produced plasmas with temperatures above 10 million °C, ten times higher than the best results achieved worldwide. A UK team was invited to verify with a newly developed technique of temperature measurements and remained almost a year at the Kurchatov Institute. The results were confirmed – a decisive breakthrough for the tokamak concept.

60 years of constant progress



TA-2000, France, 1957

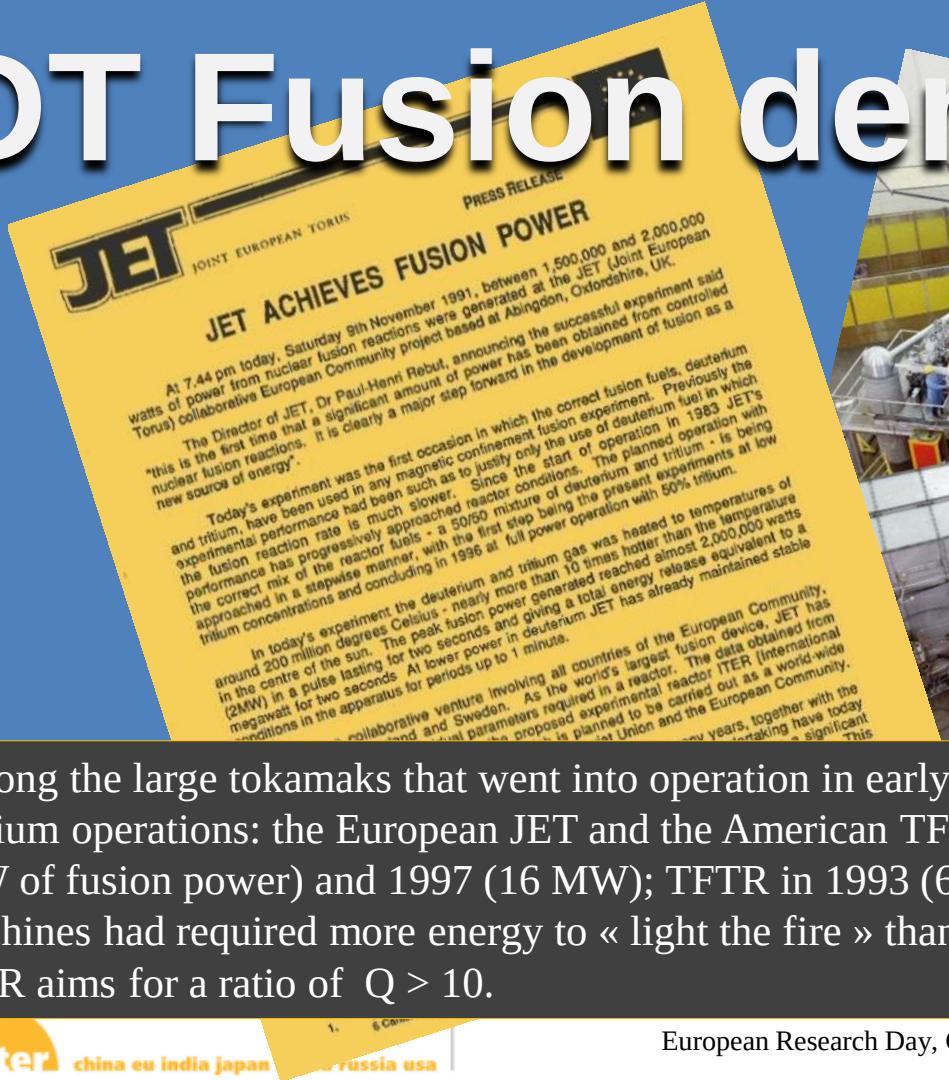
KSTAR, Korea, 2008



T-6, USSR, 1965

DIII-D, US (General Atomics-DOE) 1978 - Upgraded 1986

DT Fusion demonstrated!


JET JOINT EUROPEAN TORUS

PRESS RELEASE

JET ACHIEVES FUSION POWER

At 7.44 pm today, Saturday 9th November 1991, between 1,500,000 and 2,000,000 watts of power from nuclear fusion reactions were generated at the JET (Joint European Torus) collaborative European Community project based at Abingdon, Oxfordshire, UK.

The Director of JET, Dr Paul-Henri Rebut, announcing the successful experiment said "this is the first time that a significant amount of power has been obtained from controlled nuclear fusion reactions. It is clearly a major step forward in the development of fusion as a new source of energy".

Today's experiment was the first occasion in which the correct fusion fuels, deuterium and tritium, have been used in any magnetic confinement fusion experiment. Previously the experimental performance had been such as to justify only the use of deuterium fuel in which the fusion reaction rate is much slower. Since the start of operation in 1983 JET's performance has progressively approached reactor conditions. The planned operation with the correct mix of the reactor fuels - a 50/50 mixture of deuterium and tritium - is being approached in a stepwise manner, with the first step being the present experiments at low tritium concentrations and concluding in 1996 at full power operation with 50% tritium.

In today's experiment the deuterium and tritium gas was heated to temperatures of around 200 million degrees Celsius - nearly more than 10 times hotter than the temperature in the centre of the sun. The peak fusion power generated reached almost 2,000,000 watts (2MW) in a pulse lasting for two seconds and giving a total energy release equivalent to a megawatt for two seconds. At lower power in deuterium JET has already maintained stable conditions in the apparatus for periods up to 1 minute.

collaborative venture involving all countries of the European Community, and Sweden. As the world's largest fusion device, JET has ual parameters required in a reactor. The data obtained from the proposed experimental reactor ITER (International is planned to be carried out as a world-wide et Union and the European Community. ny years, together with the taking have today significant This

Among the large tokamaks that went into operation in early 1980s, two were designed to perform Deuterium-Tritium operations: the European JET and the American TFTR. Both achieved DT fusion : JET in 1991 (2 MW of fusion power) and 1997 (16 MW); TFTR in 1993 (6.2 MW) and 1994 (10 MW). However, both machines had required more energy to « light the fire » than the fire had given in return (ratio of Q ~ .65). ITER aims for a ratio of Q > 10.

ITER: from paper project to steel-and-concrete reality

November 1985
At the Geneva Summit P^{dt} Reagan and Secretary G^{al} Gorbatchev give a decisive political push to an international collaboration on fusion *"for the benefit of all mankind"…*

January 2007
Preparation works by France (clearing, levelling, etc.) begins on the 42-hectare ITER Platform.

August 2010
Construction works begin in earnest.

Today
Construction on the ITER site and components manufacturing by the ITER Members are progressing in accordance with the 2016 baseline.

Global challenge, global response

- 28 June 2005: The ITER Members unanimously agreed to build ITER on the site proposed by Europe
- 21 November 2006: The ITER Agreement was signed at the Élysée Palace, in Paris.

The seven ITER Members represent more than 50% of the world's population and about 85% of the global GDP

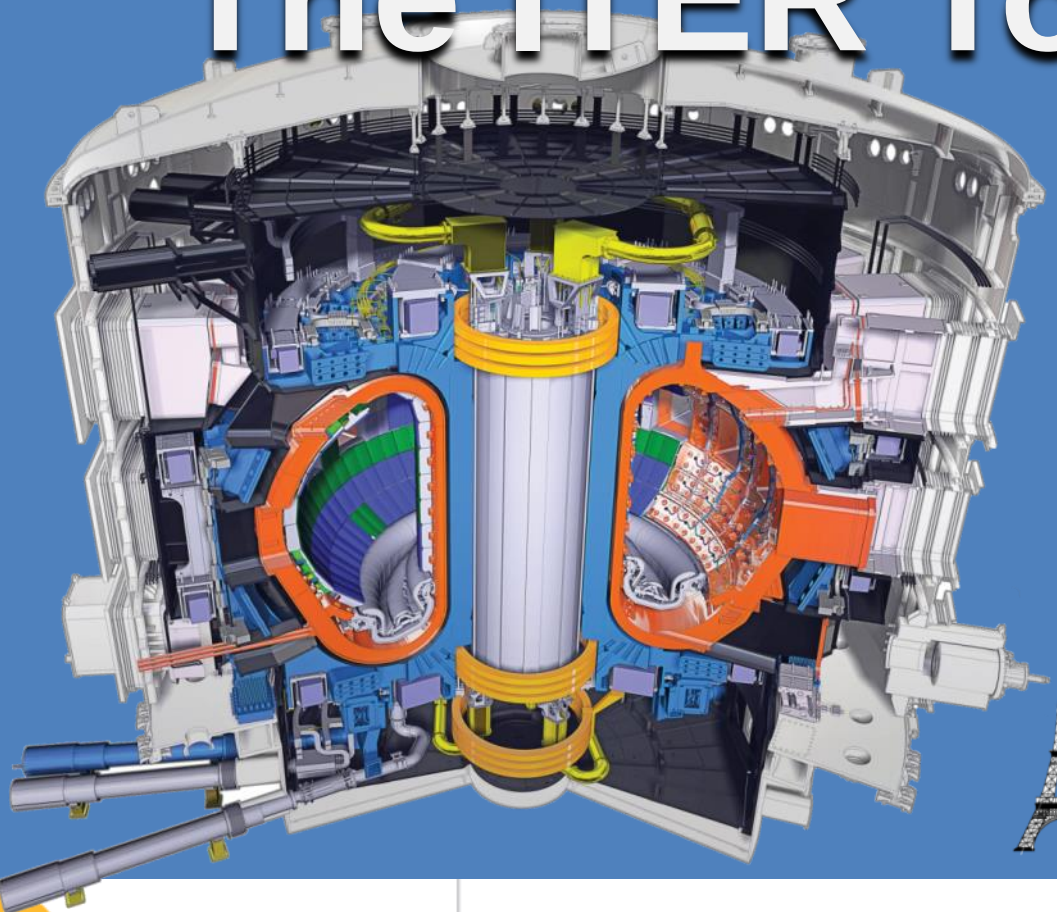
China EU India Japan Korea Russia USA

ITER: an integrated project:

Central Team & Seven Domestic Agencies

- The 7 ITER Members make cash and in-kind contributions (90%) to the ITER Project. They have established Domestic Agencies to handle the contracts to industry.
- The ITER Organization Central Team manages the ITER Project in close collaboration with the 7 Domestic Agencies.
- The ITER Members share all intellectual Property generated by the Project.

The ITER Tokamak



Vacuum Vessel: ~ 8 000 t.
TF Coils: ~ 18 x 360 t.
Central solenoid: ~ 1 000 t.
Etc.
Total ~ 23 000 t.

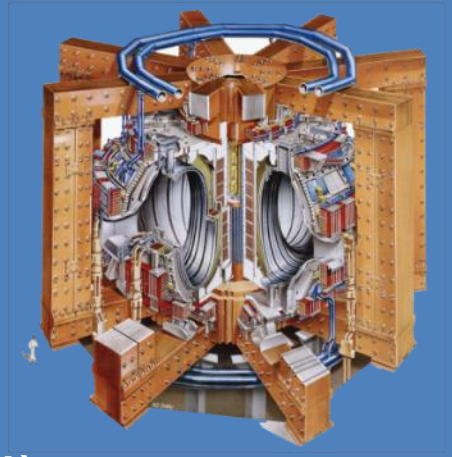
R=6.2 m, a=2.0 m,
I_p=15 MA, B_T=5.3 T,
23,000 tonnes

3,5 times the weight of the Eiffel Tower!

Size matters

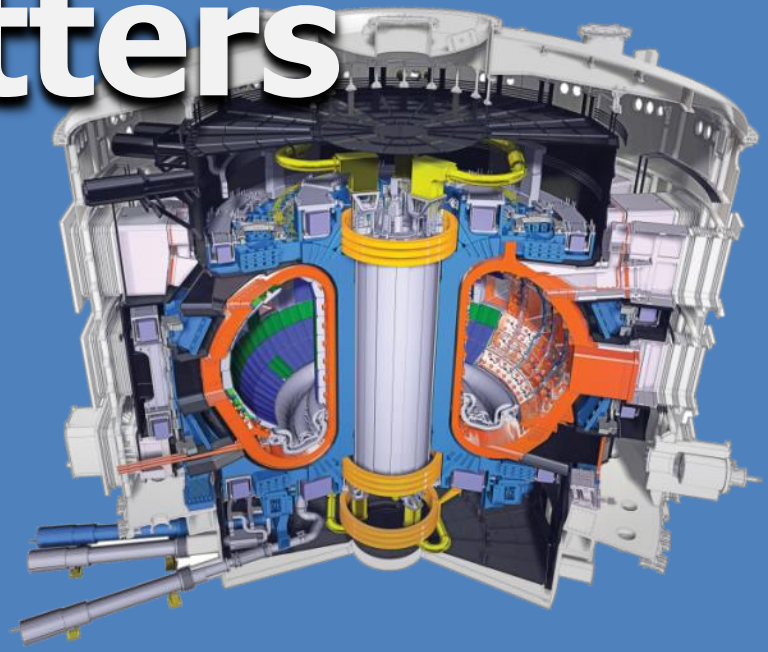
Tore Supra-WEST (France-CEA)

V_{plasma} 25 m^3
P_{fusion} ~0
$P_{chauffage}$ ~15 MW
T_{plasma} ~400 s



JET (Europe)

V_{plasma} 80 m^3
P_{fusion} ~16 MW
$P_{chauffage}$ ~23 MW
T_{plasma} ~30 s



ITER (35 countries)

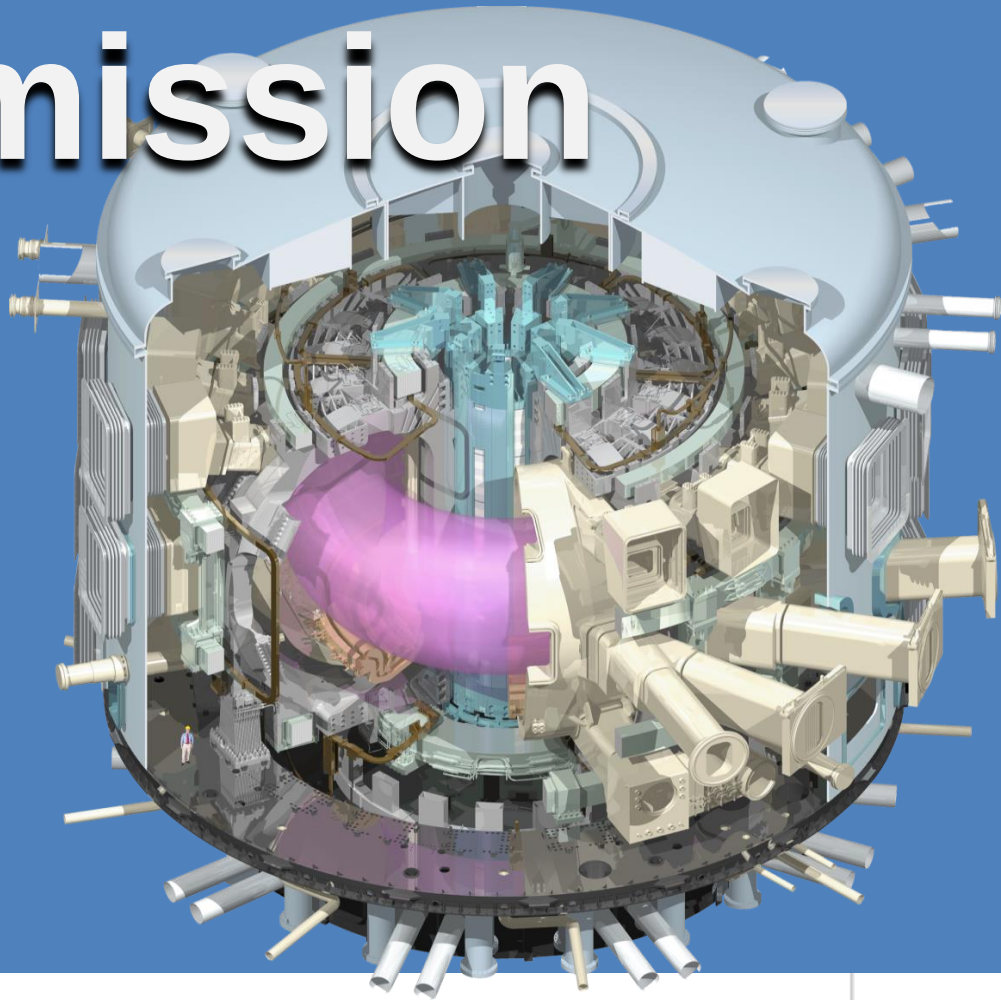
V_{plasma} 830 m^3
P_{fusion} ~500 MW
$P_{chauffage}$ ~ 50 MW
T_{plasma} > 400 s

ITER mission

To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes

ITER is the only magnetic fusion device under construction aimed to produce a burning plasma

Input (heating) 50 MW → Output 500 MW, to achieve extended burn of a DT plasma with dominant alpha-particle heating (Q ≥ 10)



How does it work?

Run a strong electrical current in the DT gas: You have created a plasma.

Continue heating by way of electromagnetic waves.

Inject high-energy neutral particles.

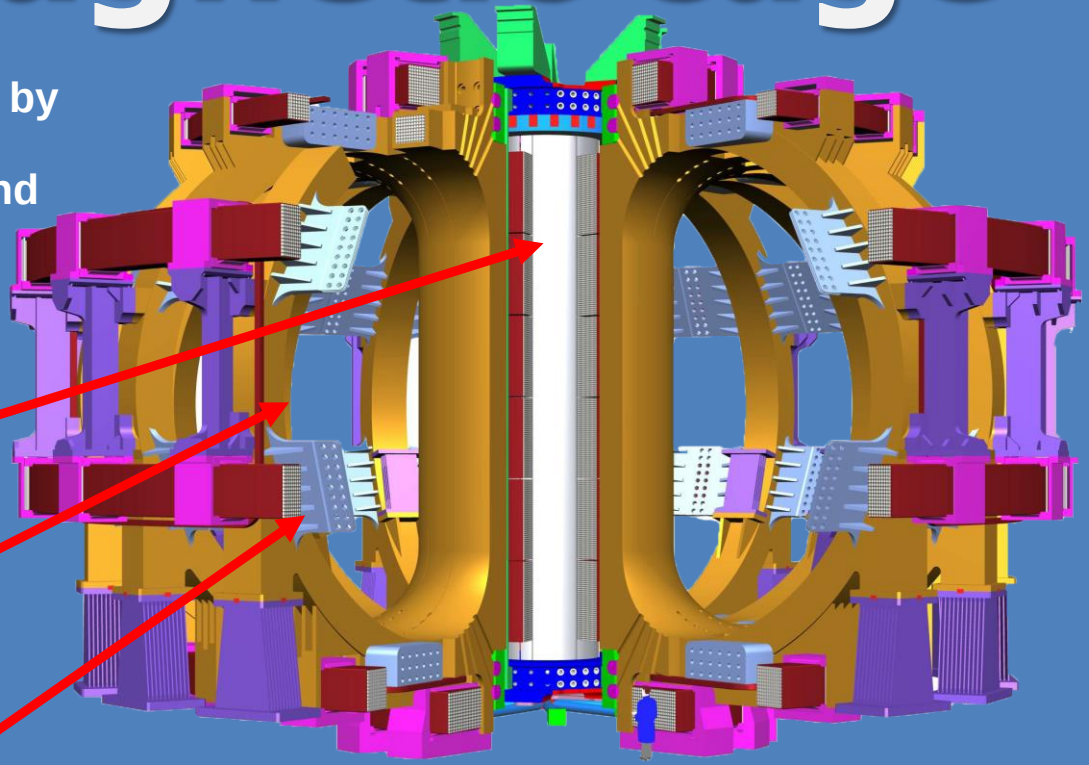
By combining these different heating techniques, you reach the requested temperature for fusion reactions to occur.

But what can contain something that is 10 times hotter than the core of the Sun?

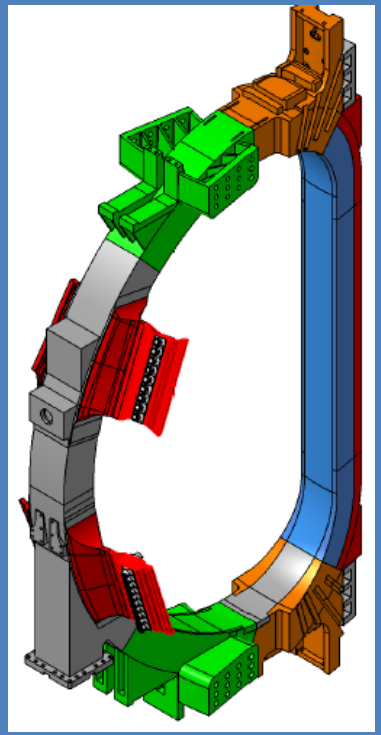
A large magnetic cage

An intense magnetic field, generated by powerful superconducting magnets shape and confine the hot plasma, and keep it away from the vacuum vessel wall.

- **1 central solenoid, 13 m high, 1,000 tons, powerful enough to lift an aircraft-carrier out of the water**
- **18 Toroidal Field Coils, 17-metre high, 360 tons each.**
- **6 Poloidal Field Coils, 8 to 24 m. in diametre, 200 to 400 tons.**



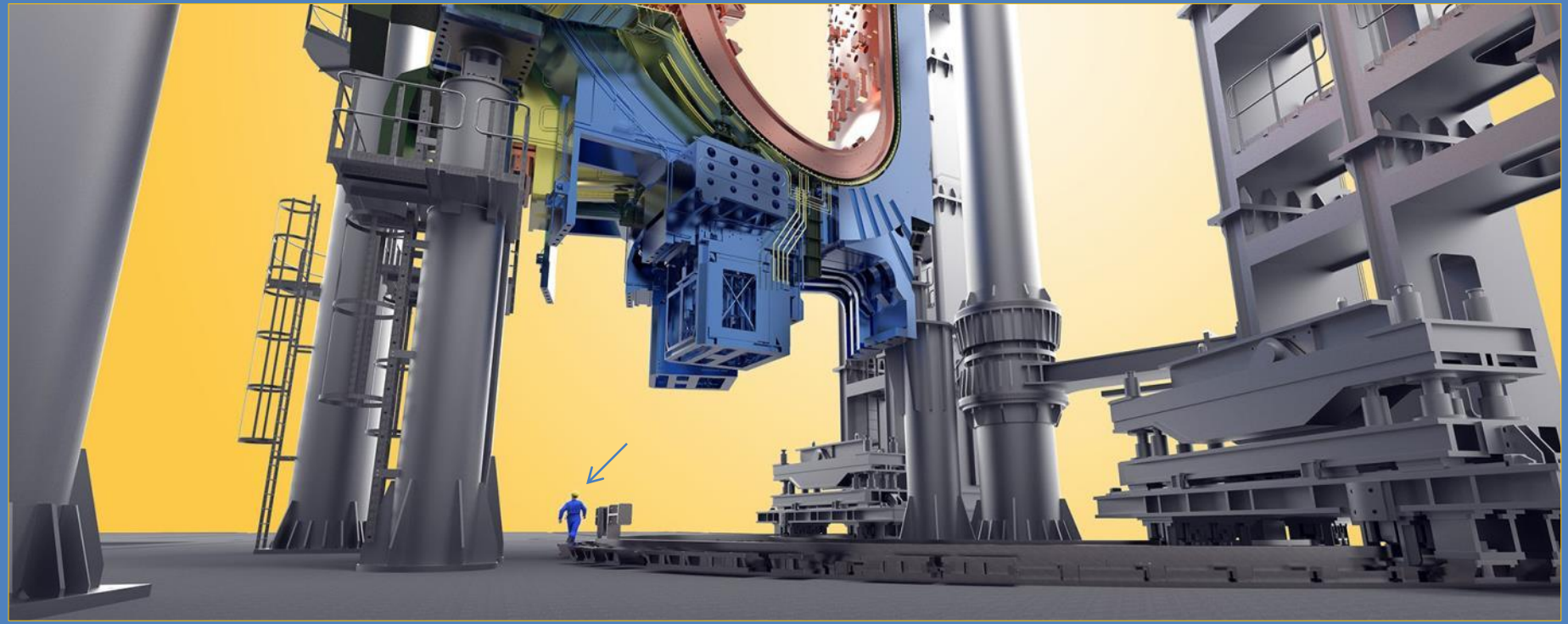
TF Coil – To contextualise



Mass of (1) TF Coil:
16 m Tall x 9 m Wide, ~360 t

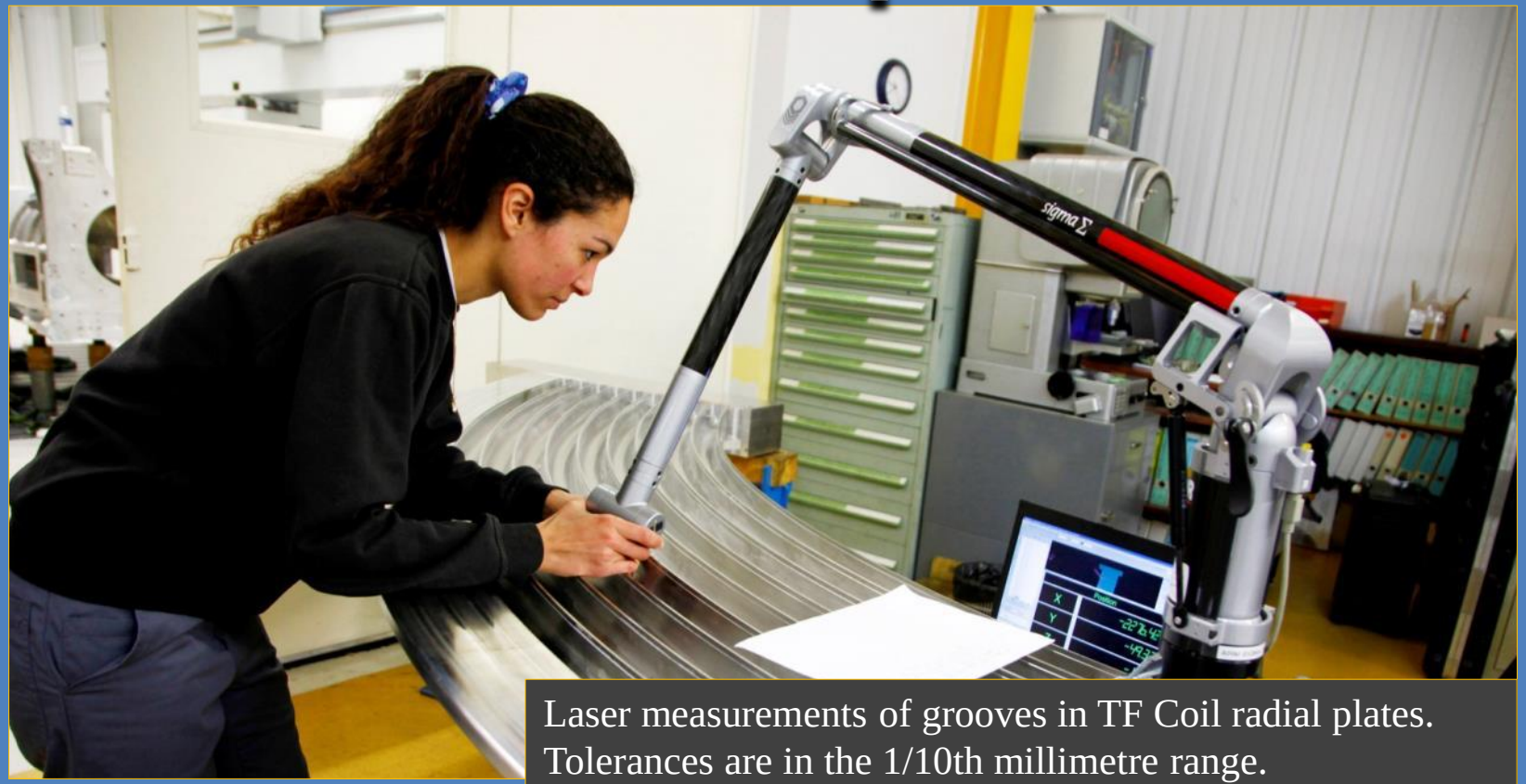
Boeing 747-300
(Maximum Takeoff Weight) ~377 t

Naval construction-size components…



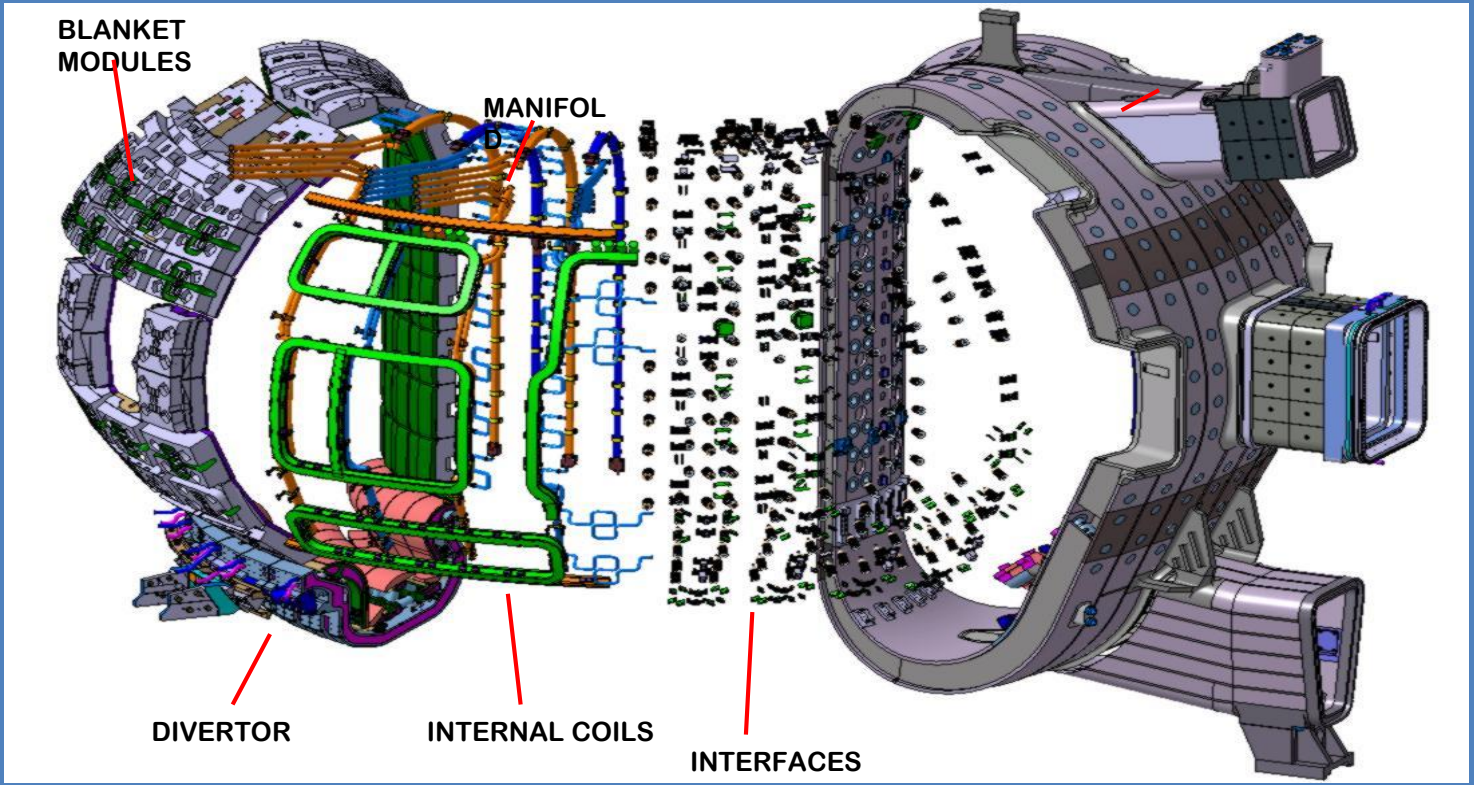
Inside the Assembly Hall, giant tools will handle loads up to 1,500 tons

…watch-like precision



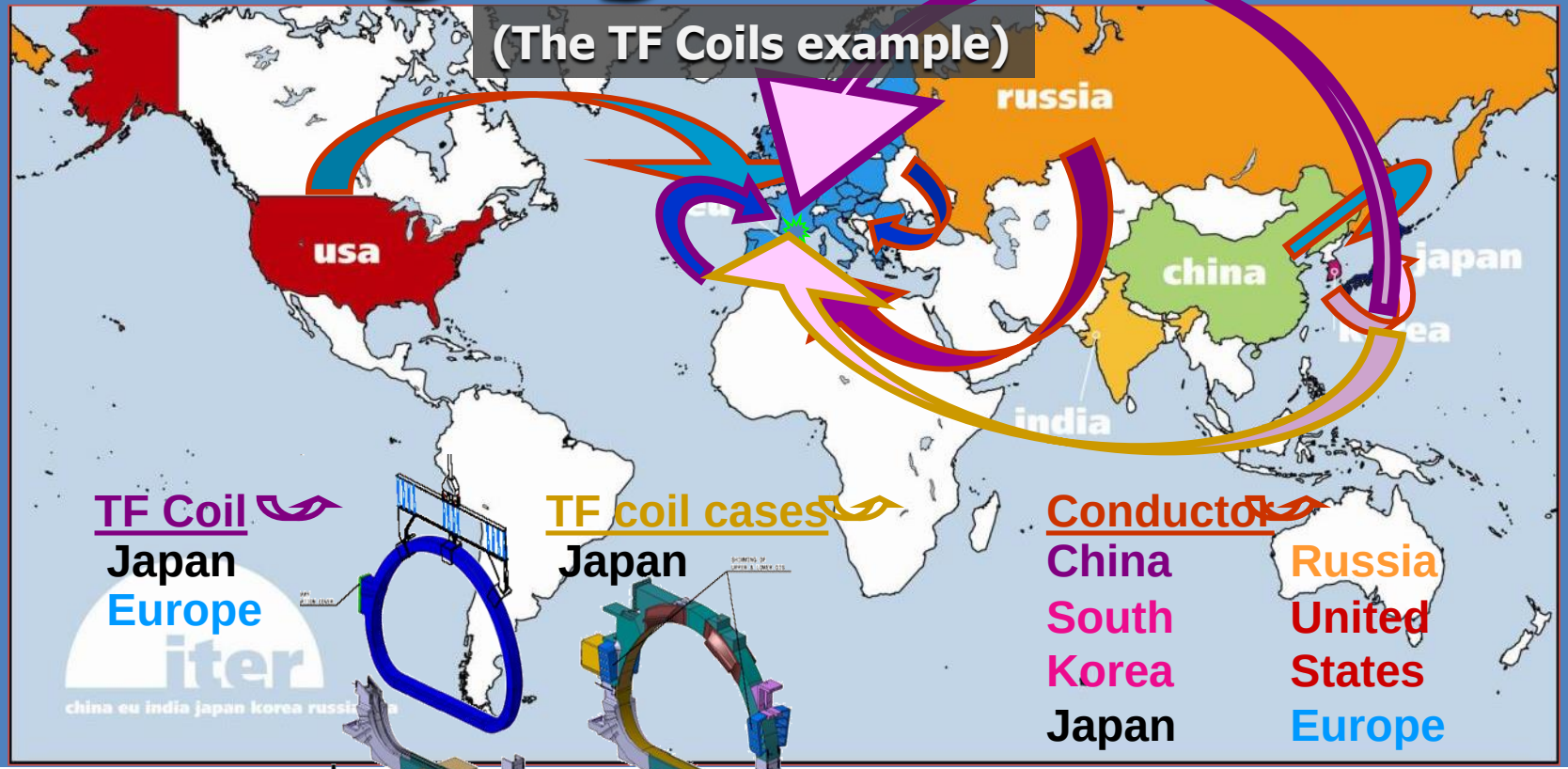
Laser measurements of grooves in TF Coil radial plates.
Tolerances are in the 1/10th millimetre range.

The integration challenge

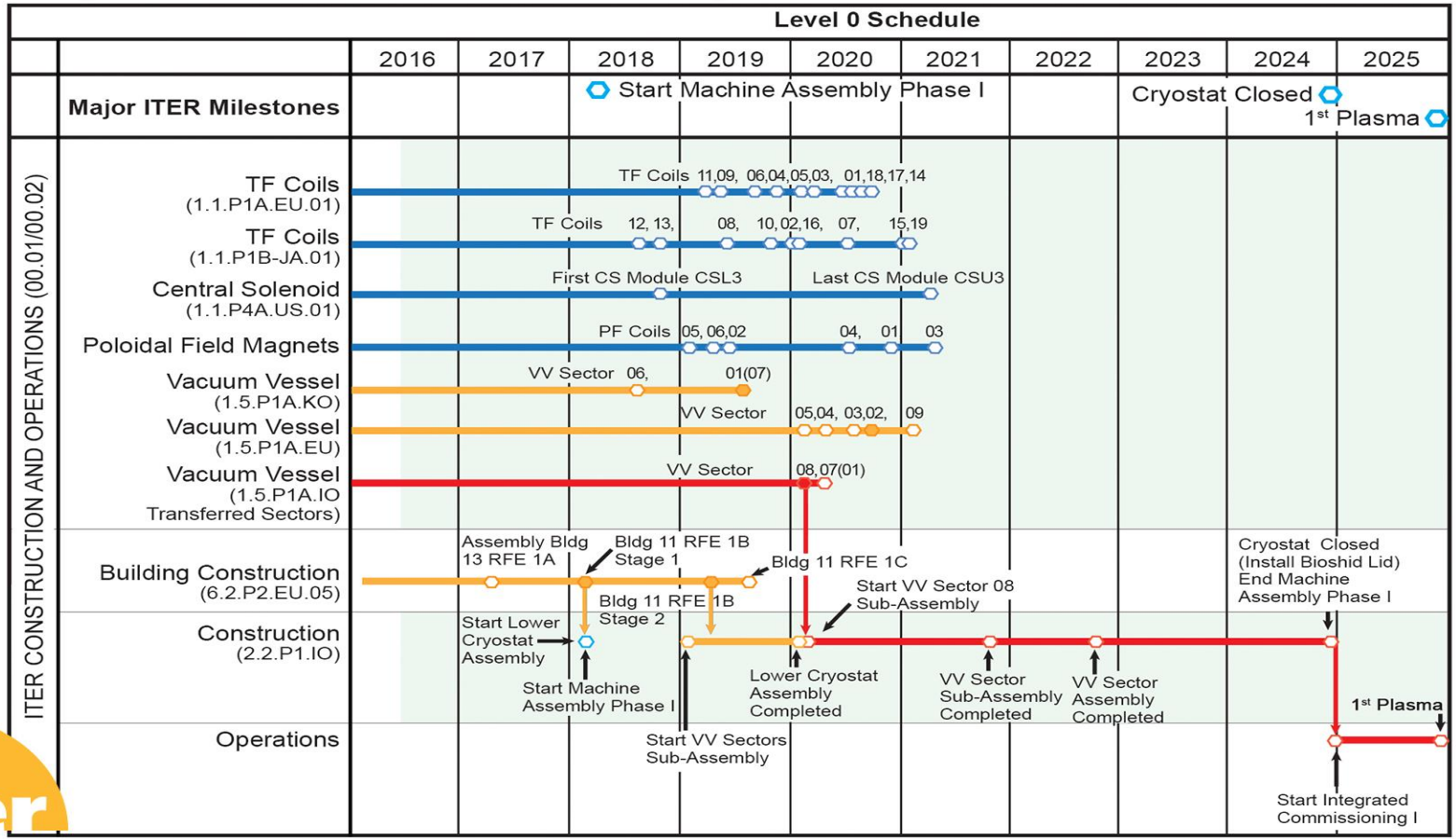


Managing collaboration

(The TF Coils example)



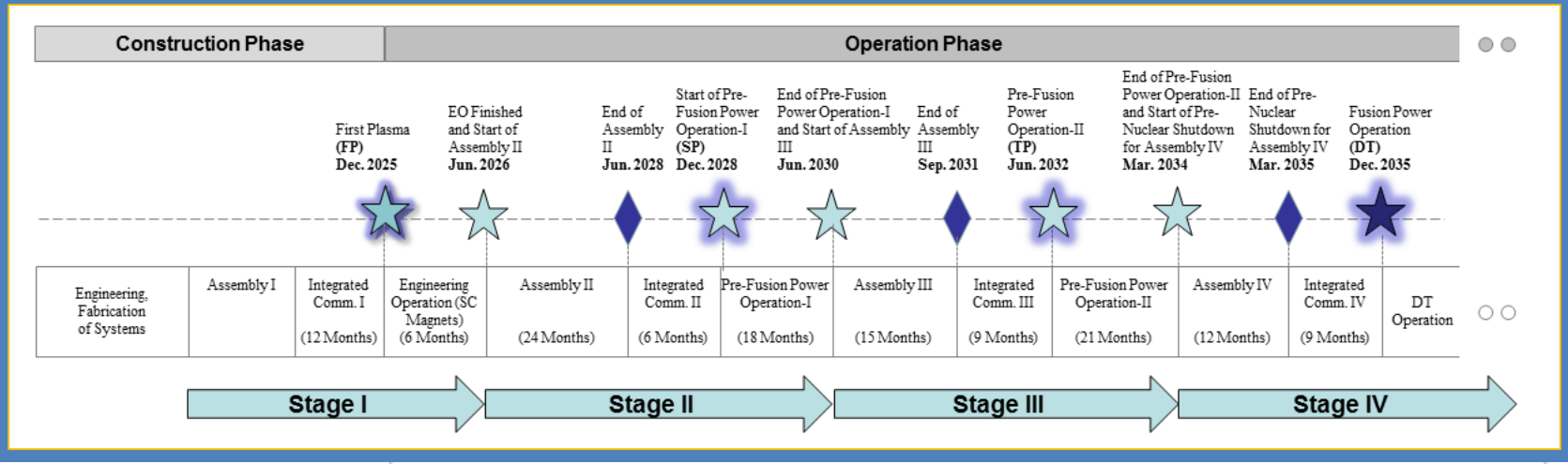
Major assembly milestones



A staged approach to DT plasma

Extensive interactions among IO and DAs to finalize revised baseline schedule proposal

- ✓ Schedule and resource estimates through First Plasma (2025) consistent with Members' budget constraints
- ✓ Proposed use of 4-stage approach through Deuterium-Tritium (2035) consistent with Members' financial and technical constraints

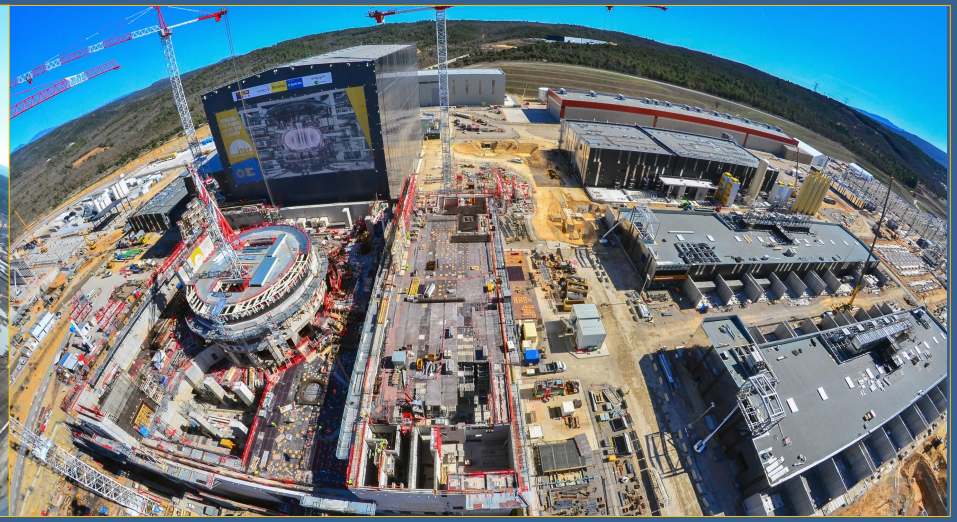


Halfway to First Plasma

According to the stringent metrics that measure project performance, 50 percent of the "total construction work scope through First Plasma" is now complete. More than 750 publications, from a total of 41 countries, hailed the accomplishment.

Worksite progress

February 2015 – April 2018

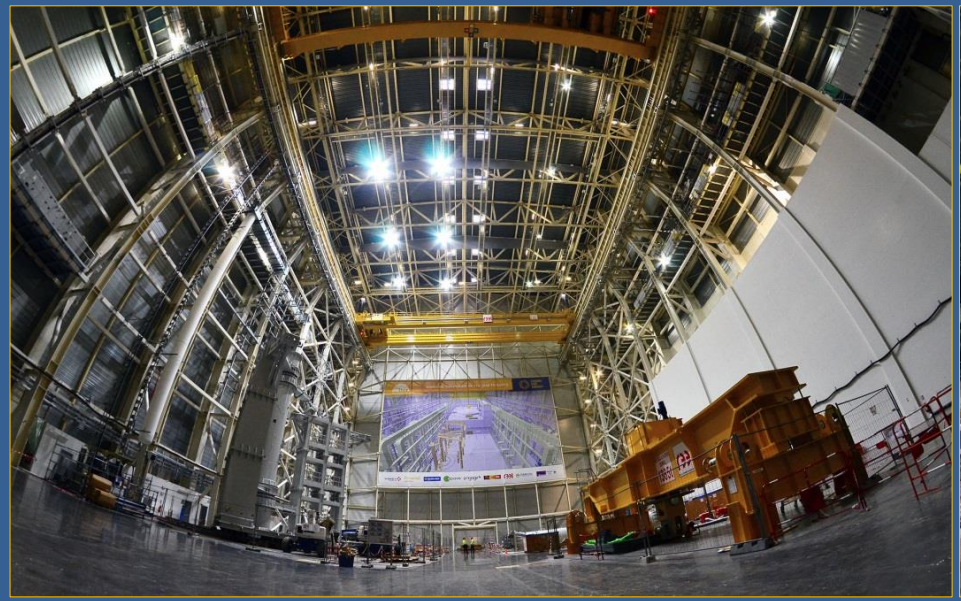


Worksite progress

Tokamak Complex

The bioshield is now finalized. Openings in the wall are for the cryostat bellows that will connect the machine to the port cells designed to give access to systems such as remote handling, heating and diagnostics. Under a protective “lid” work progresses on the tokamak’s “crown”.

Assembly Hall



Before being integrated in the machine, the components will be prepared and pre-assembled in this 6,000 m2, 60-metre high building. The Assembly Hall is equipped with a double overhead travelling crane with a total lifting capacity of 1,500 tons. Load tests, both static and dynamic (1,875 – 1,650 tonnes), were finalized in December 2017. To the right, the installation of the sub-assembly tool (SSAT-1) is progressing

Cryoplant

The ITER Cryoplant will be the largest single platform cryofacility in the world. It will distribute liquid helium to various machine components (superconducting magnets, thermal shield, cryopumps, etc.). The last of 18 skids supporting the helium compressors was installed atop their massive four-metre-high concrete pads in November 2017.

Radiofrequency heating

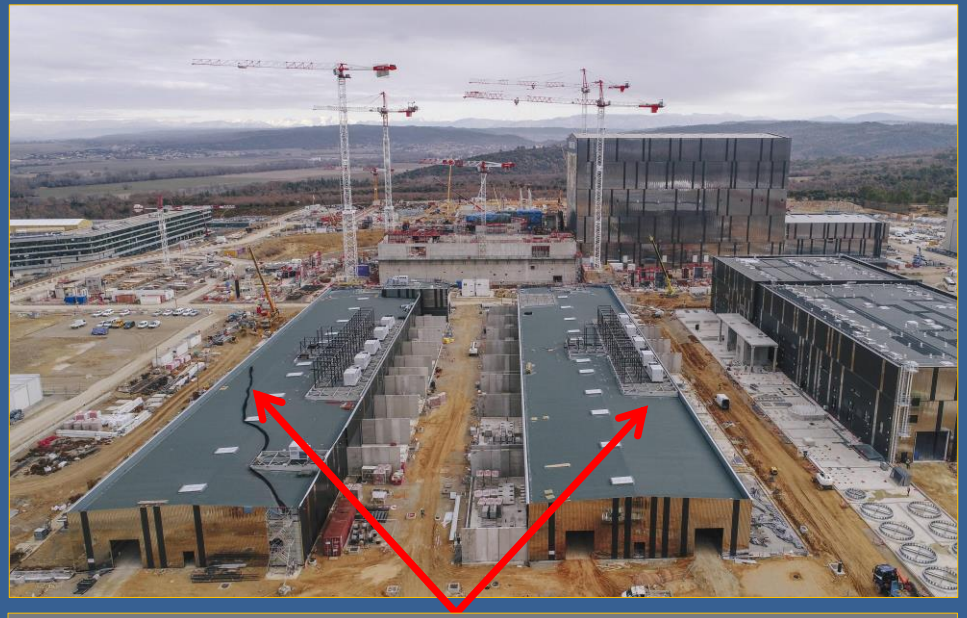
Adjacent to the Assembly Hall, the building that will house the plasma heating systems (microwave and radio frequency) is ready to be equipped.

This girder is part of the gantry crane that will be used to install radio frequency and microwave heating components. It was installed in December 2017.

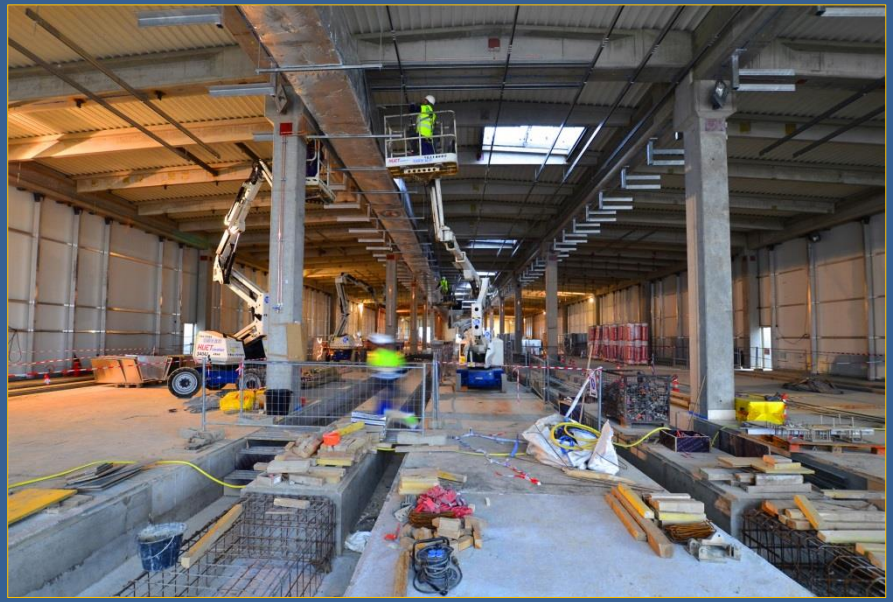
Electrical network

The connexion of the 400 kV switchyard to the French grid was successfully demonstrated on 30 March.

Electrical conversion



Two large Magnet Power Conversion buildings will host the transformers and converters (AC ► DC) feeding power to the ITER magnets.

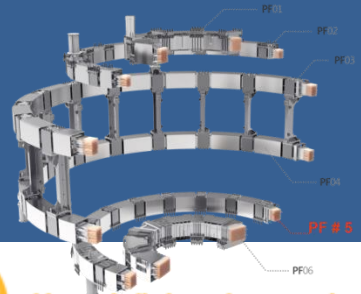


The twin buildings are now ready for equipment. Electrical components from China, Korea and Russia will be progressively installed inside of the building as well as in the exterior bays.

Cryostat workshop

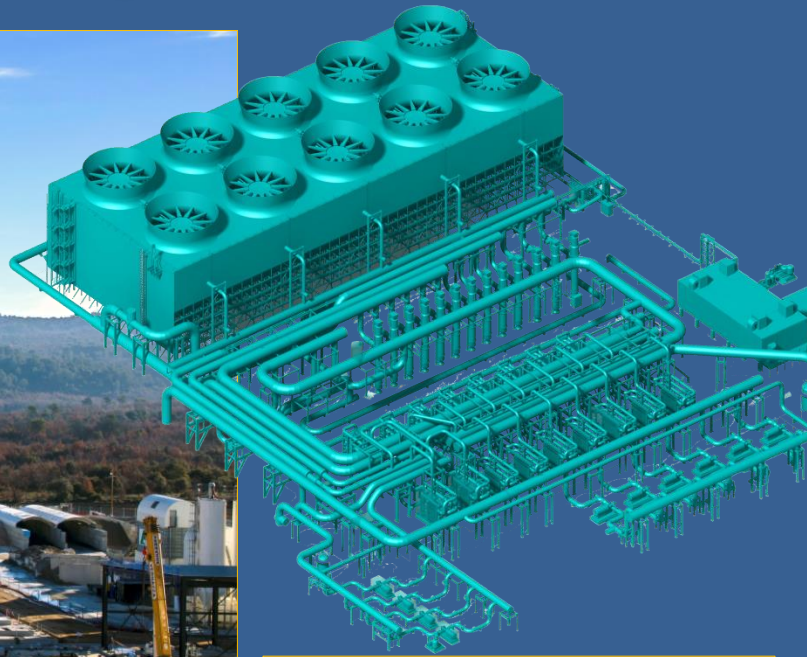
Manufactured in India, the 30 m x 30 m cryostat (the insulating vacuum vessel that encloses the machine) is being assembled and welded on site.

PF Coil winding facility



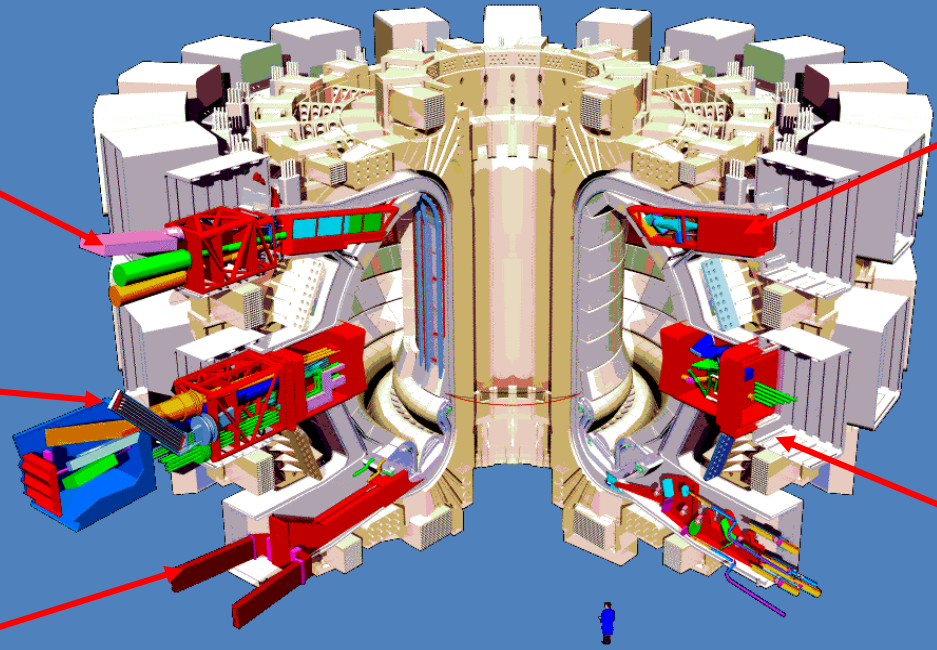
Too large to be transported by road, four of ITER's six ring-shaped magnets (the poloidal field coils, 17 to 24 m, in diametre) will be assembled on site by Europe in this 12,000 m² facility. Resin impregnation operations have begun for PF Coil # 5 (17 m. diametre, ~ 350 tonnes).

Cooling water systems



ITER power will be partly evacuated by cooling towers (procured by India).

Analyzing the plasma - ITER Diagnostics



UPPER PORT
(12 used)

EQUATORIAL PORT
(6 used)

DIVERTOR PORT
(6 used)

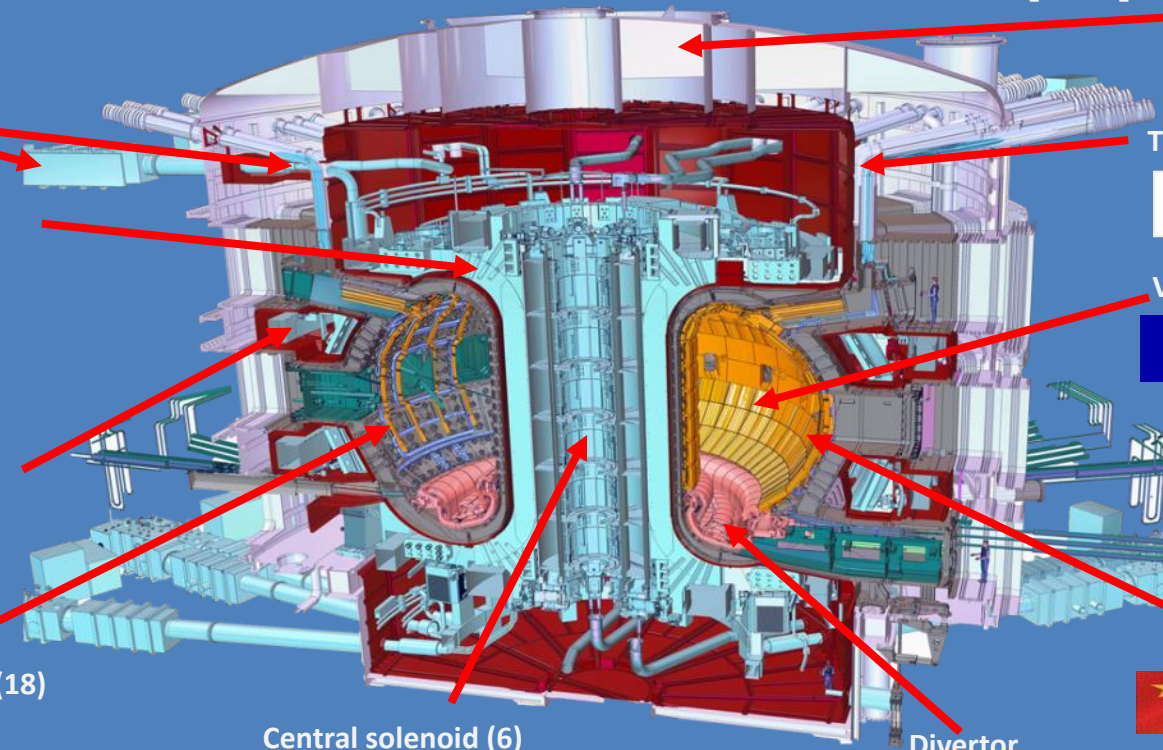
VESSEL WALL
(Distributed Systems)

DIVERTOR CASSETTES
(16 used)

- About 50 large scale diagnostic systems are foreseen:
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species

Who manufactures what?

The ITER Members share all intellectual property



Feeders (31)

Toroidal Field coils (18)

Poloidal field coils (6)

Correction coils (18)

Central solenoid (6)

Divertor

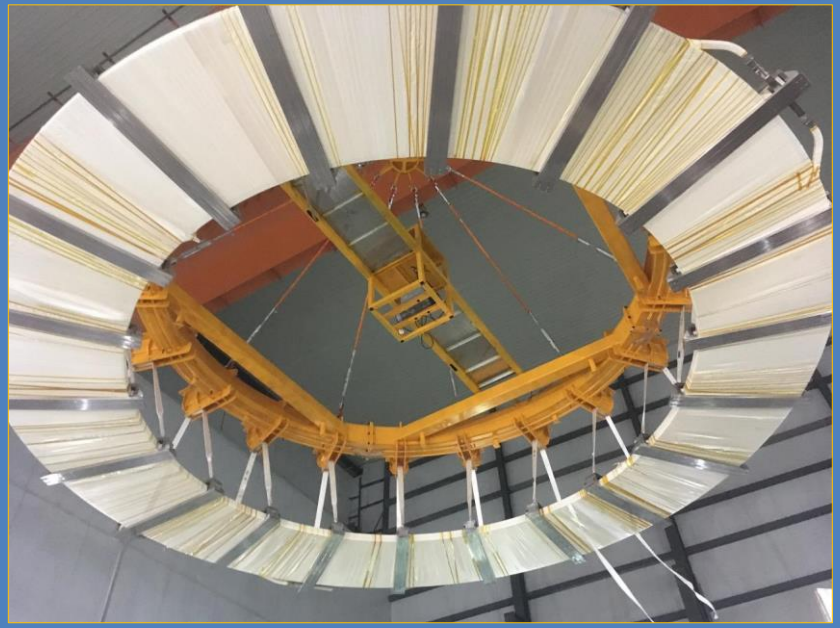
Blanket modules

Vacuum vessel

Thermal shield

Cryostat

Manufacturing progress



Work is underway in China (under contract with Europe) to manufacture 9 double pancakes for poloidal field coil # 6.

China has successfully completed the first component of the feeder package: the cryostat feedthrough for poloidal field coil #4,

Magnet Systems, Power Systems, Blanket, Fuel Cycle, Diagnostics

Manufacturing progress

European contractors have finalized 2 of 10 toroidal field coil winding packs.

The pre-production cryopump was delivred in August 2017 More than 15 companies in Europe were involved in its manufacturing,

Buildings, Magnet Systems, Heating & Current Drive Systems, Vacuum Vessel, Divertor, Blanket, Power Systems, Fuel Cycle, Tritium Plant, Cryoplant, Diagnostics, Radioactive Materials

Manufacturing progress

Thousands of in-wall shielding pieces have been manufactured, passed factory acceptance, and are being prepared for shipment.

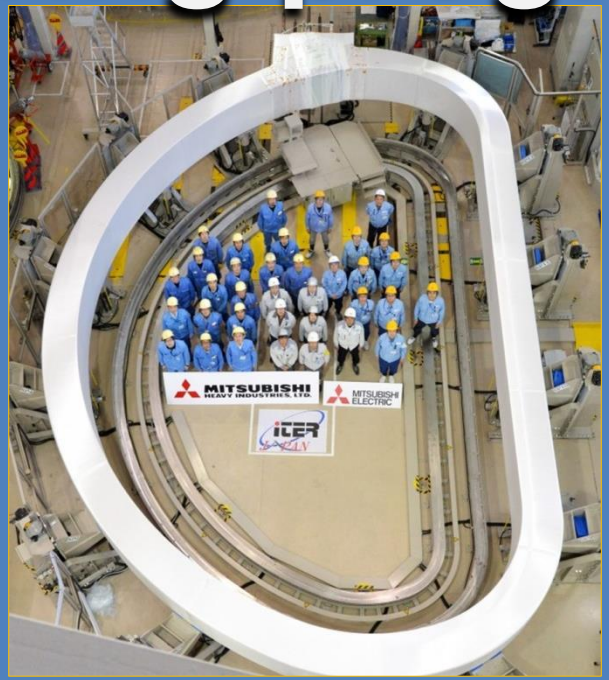
As Fabrication is launched in India for the Upper Cylinder, welding operations for Tier 2 of the Lower Cylinder began on 19 Feb. 2018.

Cryostat, Cryogenic Systems, Heating and Current Drive Systems, Cooling Water System, Vacuum Vessel, Diagnostics

Manufacturing progress

Japan

In September 2017, the Japanese Domestic Agency and suppliers celebrated the completion of conductor fabrication; in all, 43 km (745 tonnes) of conductor were produced.



In a major production milestone the first TF winding pack has been completed at Mitsubishi Futami plant.
Similar operations are ongoing at Keihin Product Operations of Toshiba Corp.

Magnet Systems, Heating & Current Drive Systems, Remote Handling, Divertor, Tritium Plant, Diagnostics

Manufacturing progress

The technically challenging fabrication of the ITER vacuum vessel is progressing in Korea, where Hyundai Heavy Industries has completed the first poloidal segment for sector #6

Korean manufacturer Taekyung Heavy Industries in Changwon has manufactured and assembled the second sector sub-assembly tool (SSAT #2) and installed all actuators.

Vacuum Vessel, Blanket, Power Systems, Magnet Systems, Thermal Shield, Assembly Tooling, Tritium Plant, Diagnostics

Manufacturing progress

Fabrication and qualification tests of PF1 winding pack stack sample were successfully completed.

Electrical equipment prototypes were tested and qualified at the Efremov Institute in Saint Petersburg.

Power Systems, Magnet Systems, Blanket, Divertor, Vacuum Vessel, Diagnostics, Heating & Current Drive Systems

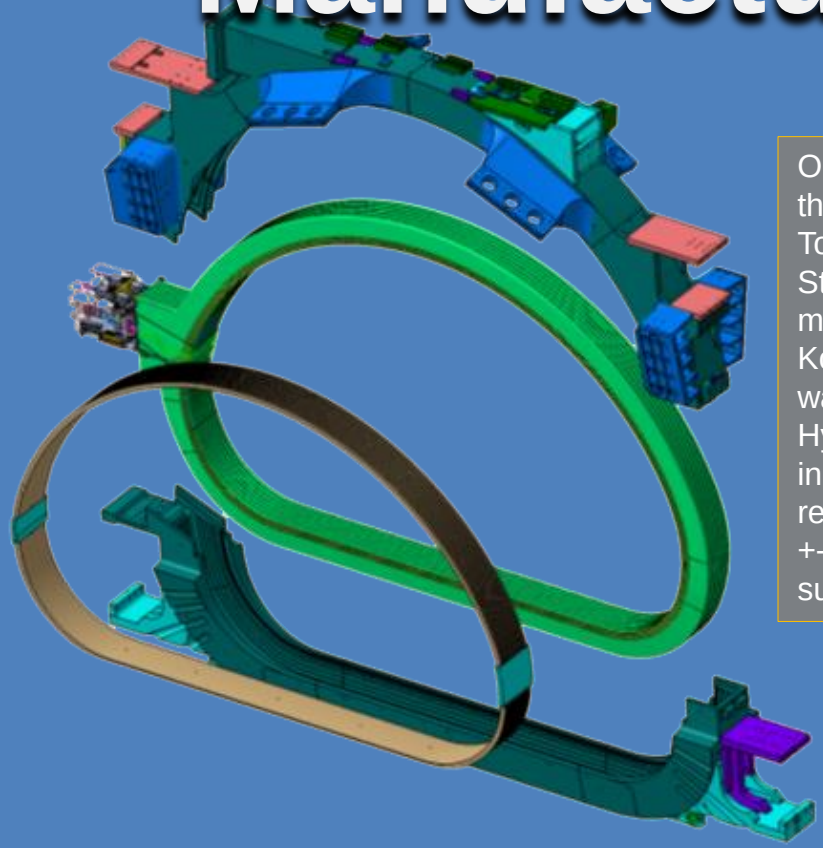
Manufacturing progress

General Atomics is fabricating the 1,000-ton Central Solenoid). Final spool of niobium-tin conductor from Japan was delivered on 3 May.

Module tooling stations are in place and being commissioned, including the heat treatment furnace shown here.

Cooling Water System, Magnet Systems, Diagnostics, Heating & Current Drive Systems, Fuel Cycle, Tritium Plant, Power Systems

Manufacturing progress



On 18 December 2017 the fitting test for the first Toroidal Field Coil Structure (20 m high), manufactured partly in Korea, partly in Japan, was completed at Hyundai Heavy Industry in Ulsan. Tolerance requirements of 0.5mm +- 0.25mm were successfully met!

Door-to-door delivery

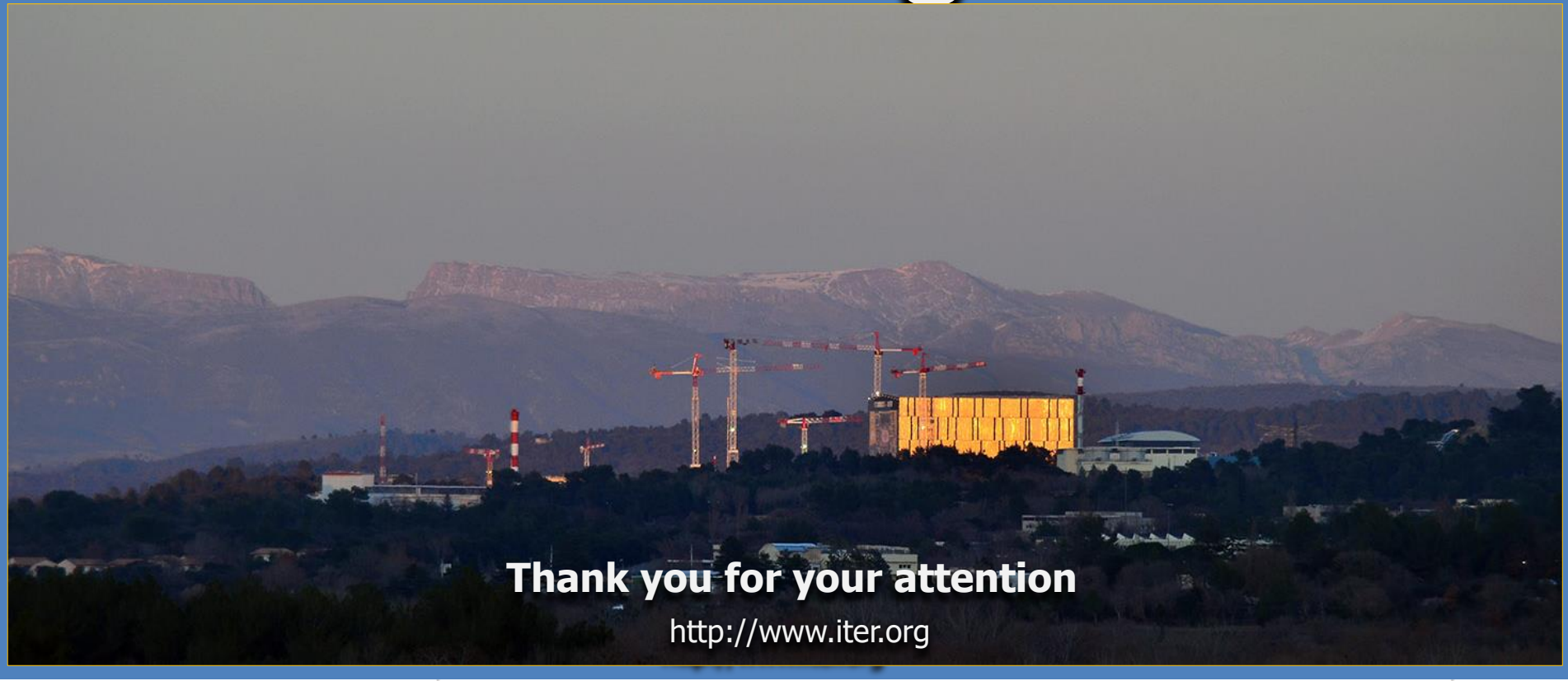
62 Highly Exceptional loads (HEL) delivered by 23 convoys.
210 HEL expected before 2025 - 18 expected after 2025

Unloaded at Marseille industrial harbour, components are ferried through the inland sea Etang de Berre on a specially designed barge and delivered to ITER by way of the 104-km long “ITER Itinerary” (a part of France’s contribution to the ITER project). The journey to the ITER site takes 3 to 4 nights.

Challenges ahead for ITER until construction completion

- ITER Organization, Domestic Agencies and suppliers working as "**One-ITER Team**" with a strong project culture
- Strict respect by suppliers for **quality and safety** requirements
- Strict respect by all stakeholders for the **schedule requirements**, in particular for the **required delivery dates** for materials and equipment on the ITER site
- Reliable and fully **integrated assembly/construction sequences** on ITER site
- Contracting with high performing and experienced companies for the **assembly activities** in the Tokamak Complex
- Setting in place a well-suited organization in charge of **commissioning**
- Setting in place a well-suited organization to conceive and execute the **progressive take-over of the machine**, ultimately for its operation and maintenance
- **Timely, reliable availability of the planned and committed resources from the seven ITER Members**

ITER is moving forward!



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