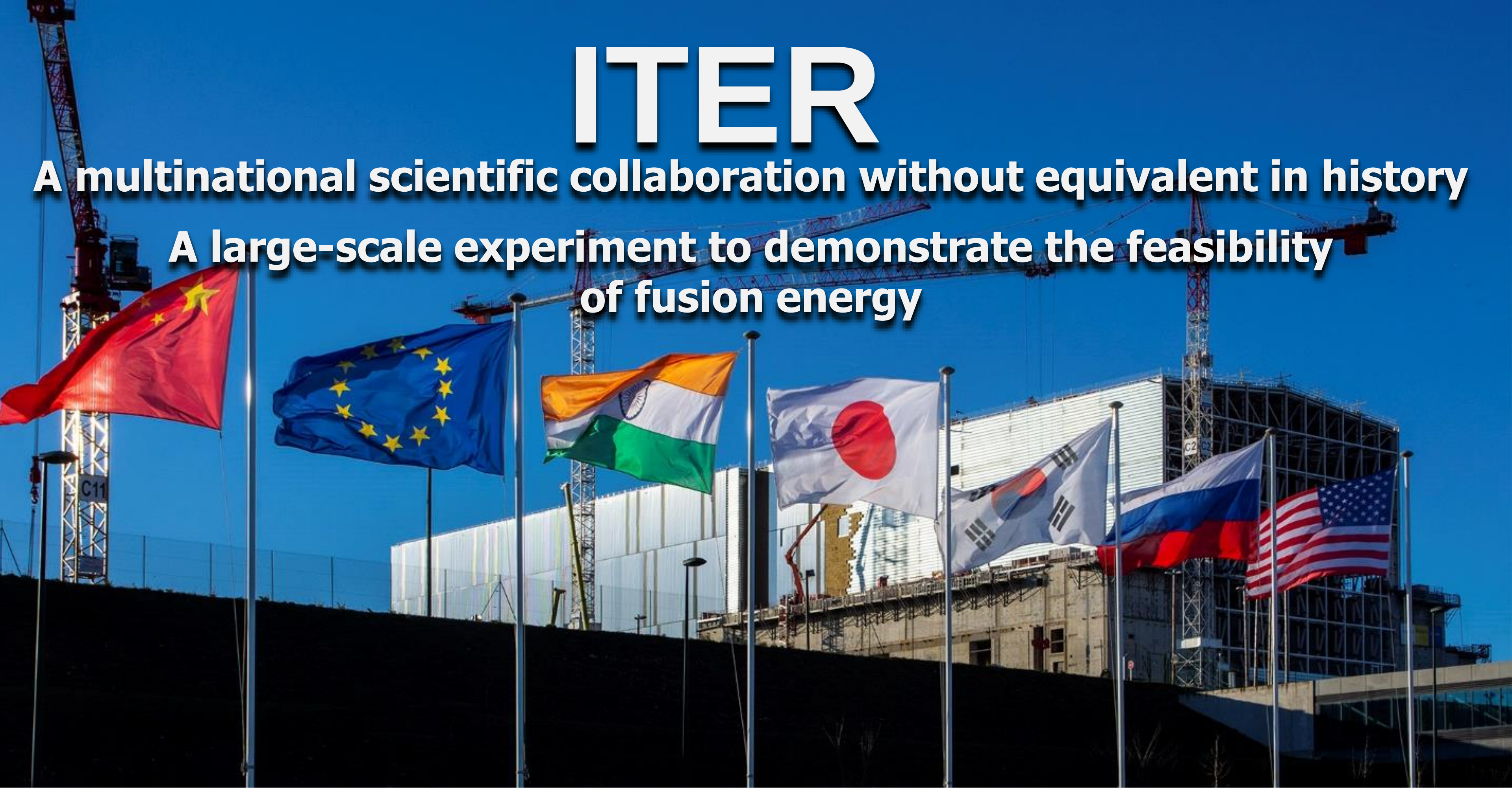
ITER
Energy for our future

Hélène Delmotte – 2021

ITER

A multinational scientific collaboration without equivalent in history

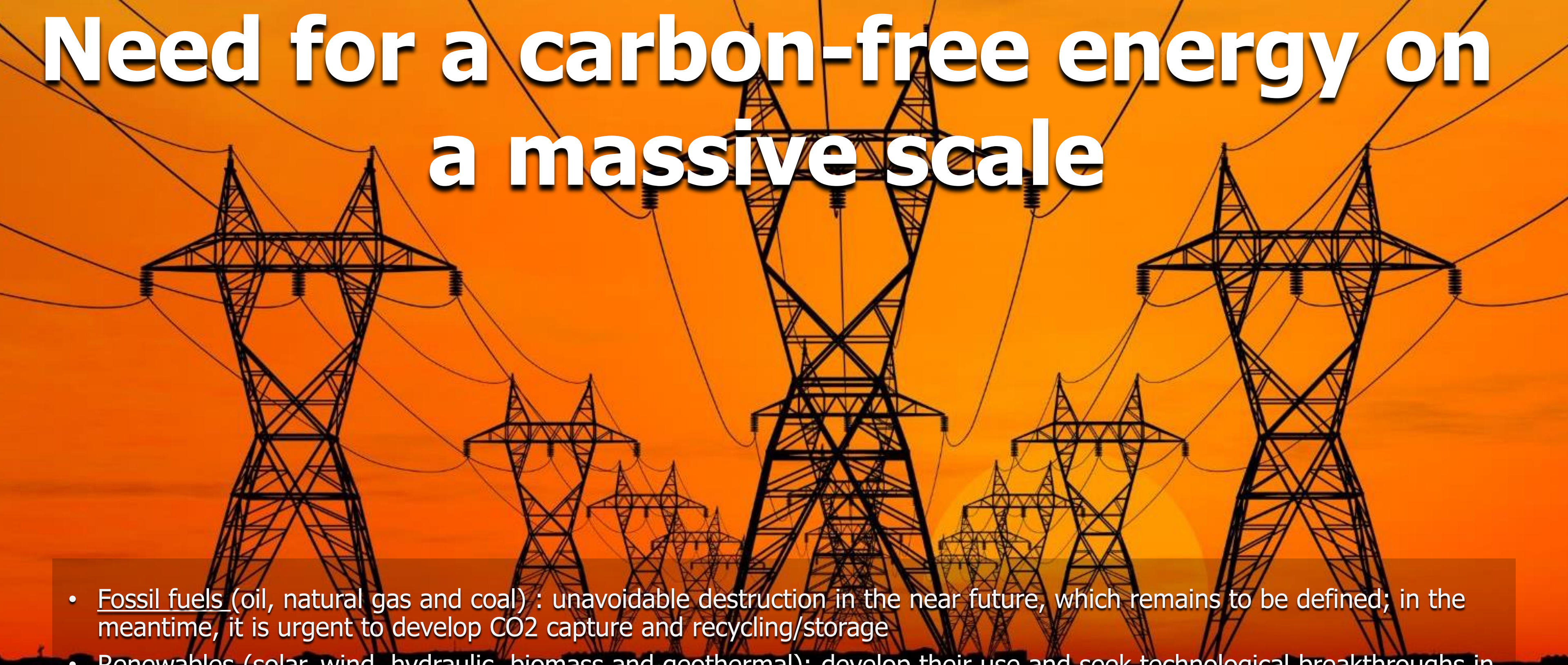
A large-scale experiment to demonstrate the feasibility of fusion energy



One of the biggest challenges for our civilization

- 1/3 of primary energy production is now mobilized to produce electricity worldwide.
- The International Energy Agency (IEA) anticipates an 80% increase in electricity demand by 2040 (33% of which from China, 15% from India).
- Access to electricity is the main vector of development of human societies.

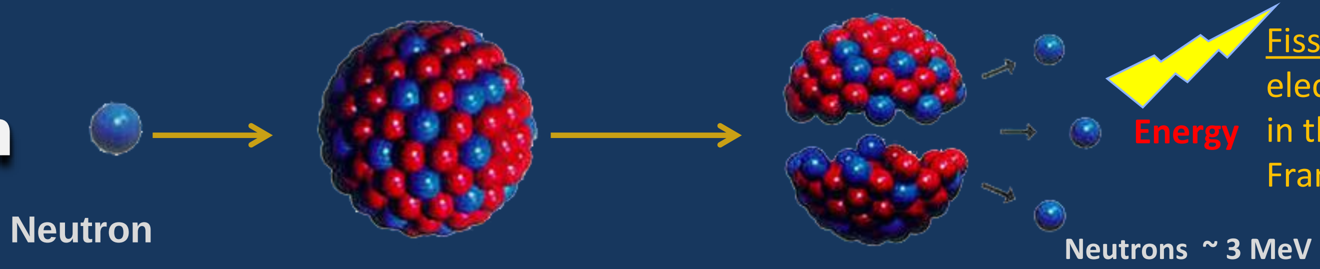
Need for a carbon-free energy on a massive scale



- Fossil fuels (oil, natural gas and coal) : unavoidable destruction in the near future, which remains to be defined; in the meantime, it is urgent to develop CO2 capture and recycling/storage
- Renewables (solar, wind, hydraulic, biomass and geothermal): develop their use and seek technological breakthroughs in production, distribution and storage
- Nuclear Fission: safety issues and constraints of long-lived waste management
- Nuclear Fusion: must demonstrate its scientific and technical feasibility

Separate... or reunite?

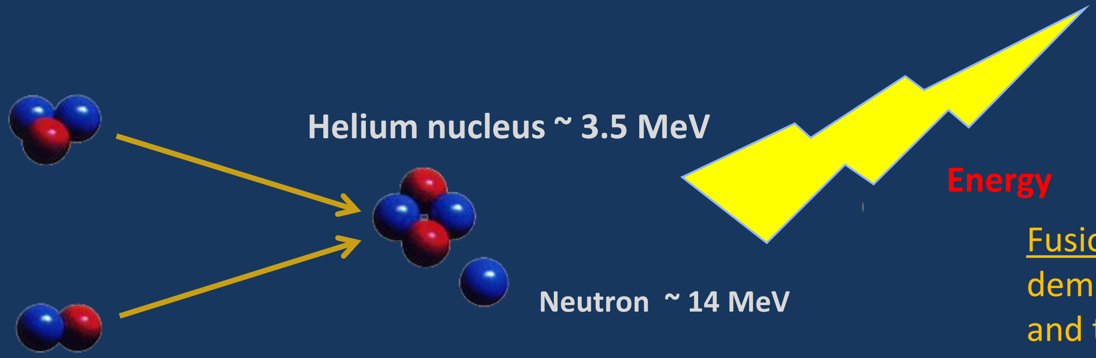
Fission



Fissile heavy nucleus (uranium)

Fission: ~ 10% of electricity production in the world (75% in France).

Fusion



Light nuclei (D & T isotopes of hydrogen)

Fusion: ITER must demonstrate the scientific and technological feasibility.

Fusion in the Universe

- **1920-1930: Demonstration of hydrogen fusion reactions at the heart of the Sun and stars (Perrin, Eddington, Bethe, Rutherford...) .**
- **In a fusion reaction, two light atomic nuclei combine, form a heavier nucleus and release an important quantity of energy by loss of mass.**
- **1950: First research work for a peaceful use of fusion reaction**
- **The Big Challenge: to reproduce in a fusion machine (Tokamak*) a similar reaction on Earth.**

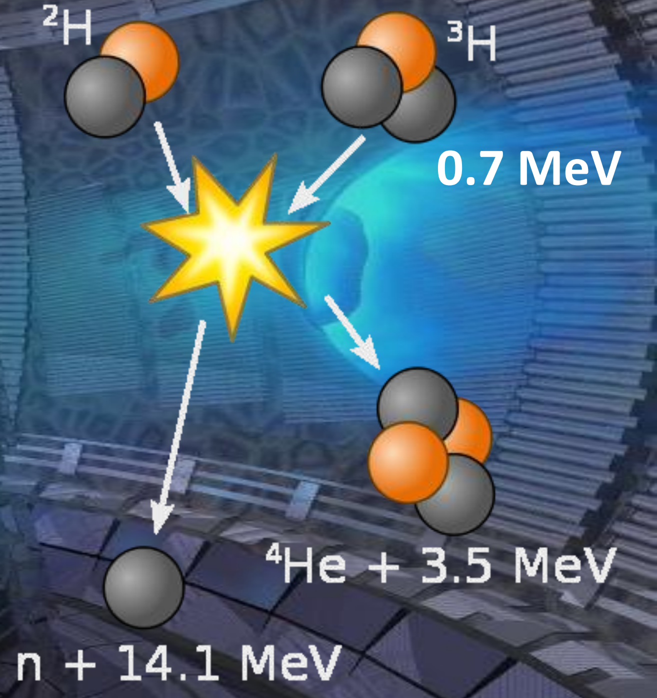
** Tokamak: a Russian acronym for « Toroidal Chamber, Magnetic Coils ».*

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

A tiny loss of mass
A huge liberation of energy

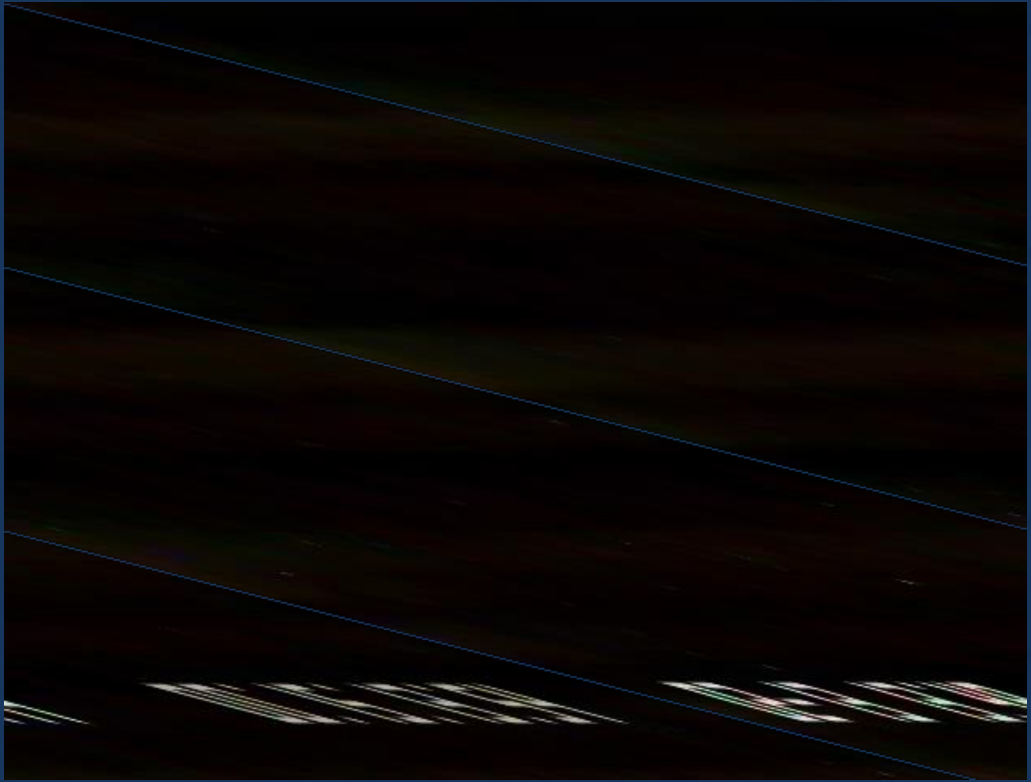
Fusion on Earth

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.**

Advantages of fusion



- A new source of massive energy predictable and potentially continuous and power complementary of the renewable energies
- Safe, environmentally responsible
- Almost limitless supply of fuel for millions of years, widely distributed around the globe
- No CO^2 or other greenhouse gases emission
- No production of long-lasting high-activity radioactive waste, unlike nuclear fission

← A plasma in the tokamak WEST (CEA-Cadarache)

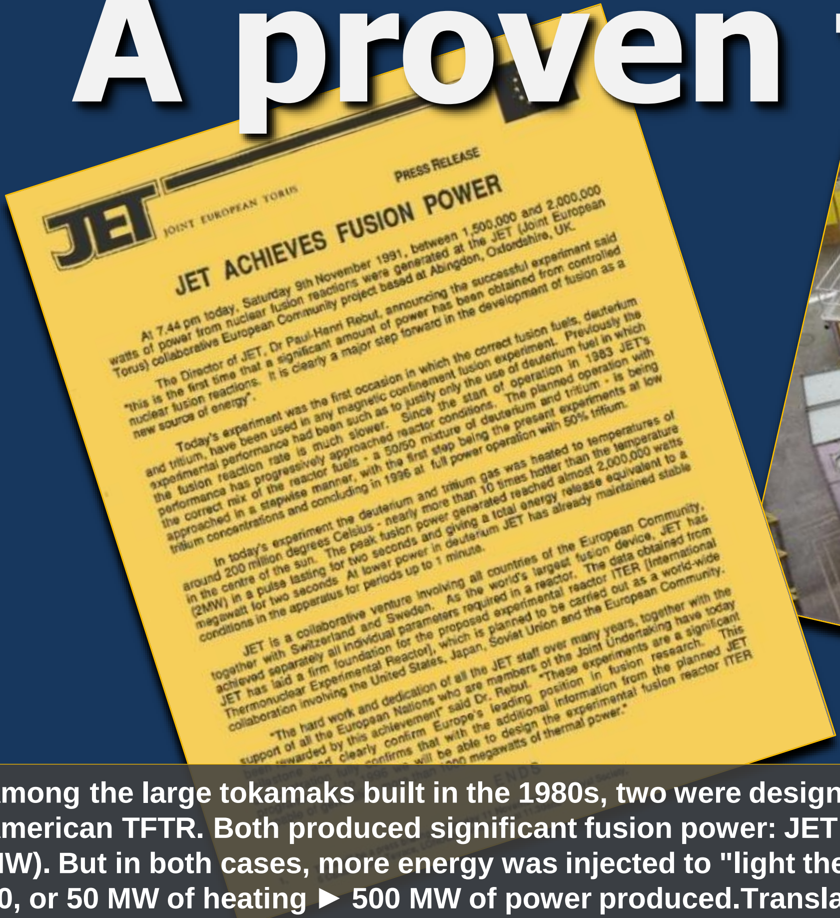
The fusion fuels

Lithium* contained in the battery of a single laptop computer and deuterium from half a bathtub of water can provide 200,000 kwh of electricity.

That's enough to cover the electricity needs of one person in Western Europe for 30 years.

**** Neutrons impacting Lithium generate Tritium***

A proven technology



PRESS RELEASE

JET JOINT EUROPEAN TORUS

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.

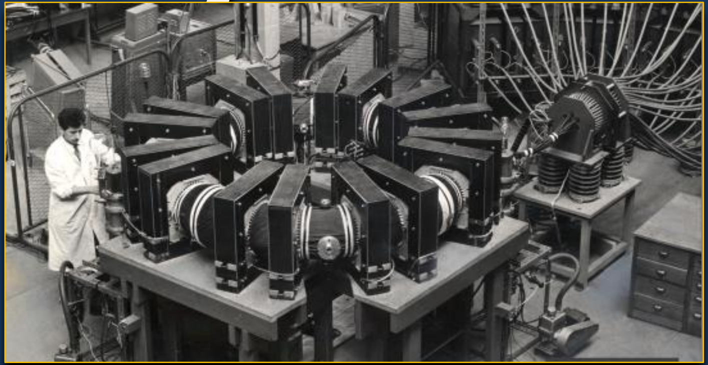
JET is a collaborative venture involving all countries of the European Community, together with Switzerland and Sweden. As the world's largest fusion device, JET has achieved separately all individual parameters required in a reactor. The data obtained from JET has laid a firm foundation for the proposed experimental reactor ITER (International Thermonuclear Experimental Reactor), which is planned to be carried out as a world-wide collaboration involving the United States, Japan, Soviet Union and the European Community.

"The hard work and dedication of all the JET staff over many years, together with the support of all the European Nations who are members of the Joint Undertaking have today been rewarded by this achievement" said Dr. Rebut. "These experiments are a significant ... and clearly confirm Europe's leading position in fusion research. This ... confirms that with the additional information from the planned JET ... will be able to design the experimental fusion reactor ITER ... 1000 megawatts of thermal power."

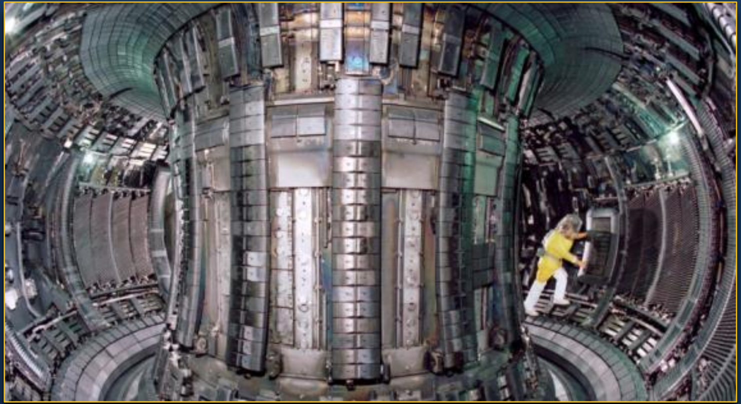
ENDS

Among the large tokamaks built in the 1980s, two were designed for deuterium + tritium operations: the European JET and the American TFTR. Both produced significant fusion power: JET in 1991 (2 MW) and 1997 (16 MW); TFTR in 1993 (6.2 MW) and 1994 (10 MW). But in both cases, more energy was injected to "light the fire" than the fire gave out (ratio of ~ 0.65). ITER is aiming for a ratio of 10, or 50 MW of heating ► 500 MW of power produced.Translated with www.DeepL.com/Translator (free version)

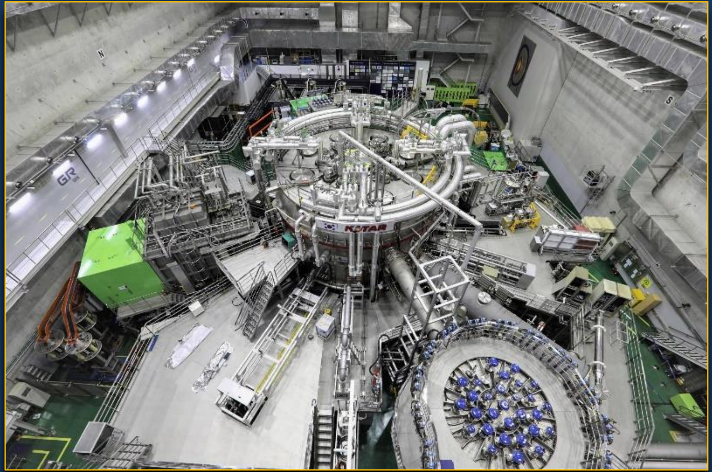
60 years of constant progress



◄ TA-2000, France, 1957



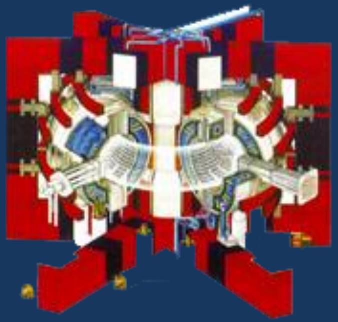
JET, Euratom, 1984 to present ►



◄ KSTAR, Korea 2008 to present

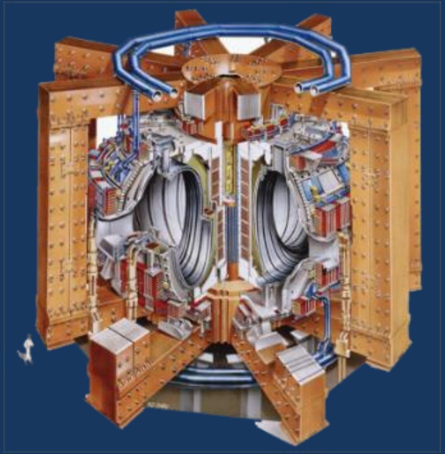
WEST (former Tore Supra, CEA-Euratom, 1988, now a testbed for ITER ►

Size matters



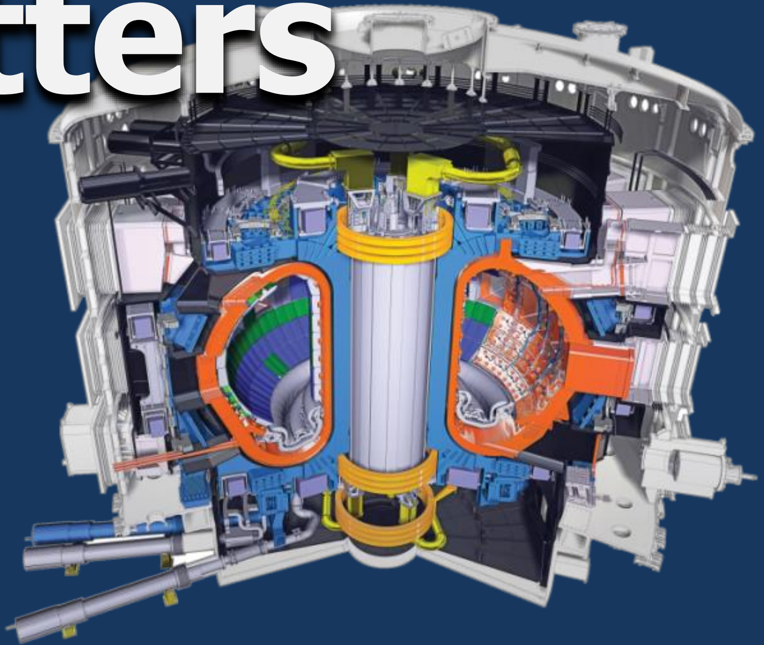
Tore Supra-WEST (France-CEA)

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



JET (Europe)

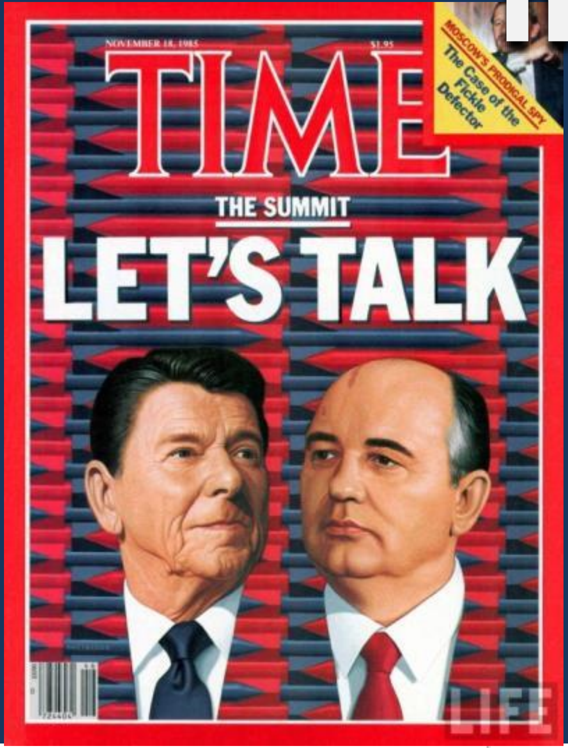
V_{plasma} 80 m^3
P_{fusion} ~16 MW
$P_{chauffage}$ ~23 MW
T_{plasma} ~30 s



ITER (35 countries)

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

« For the benefit of all mankind… »



1950s to 1970s :

- Exploration of plasma physics
- Building more and more powerful machines.
- Specialists understand that they will need a very large machine to demonstrate the feasibility of fusion

November 1985:

- Geneva Summit Reagan-Gorbatchev: decision to launch an international collaboration in fusion "for the benefit of all mankind".

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 is 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

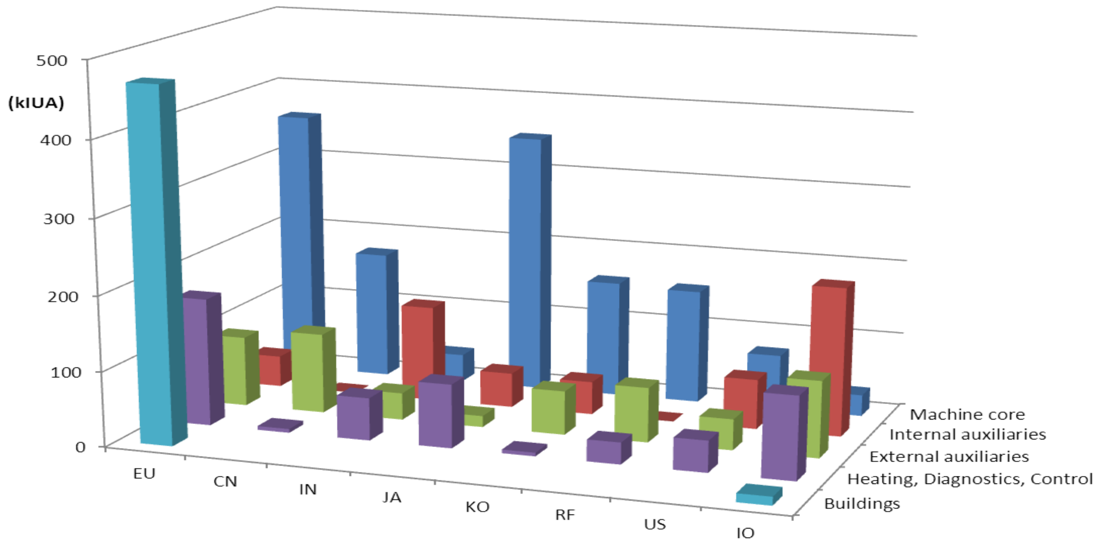
An integrated project:

Central Team & Seven Domestic Agencies

- The 7 ITER Members make cash and in-kind contributions (90%) to the ITER Project. Each one 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.

A unique formula

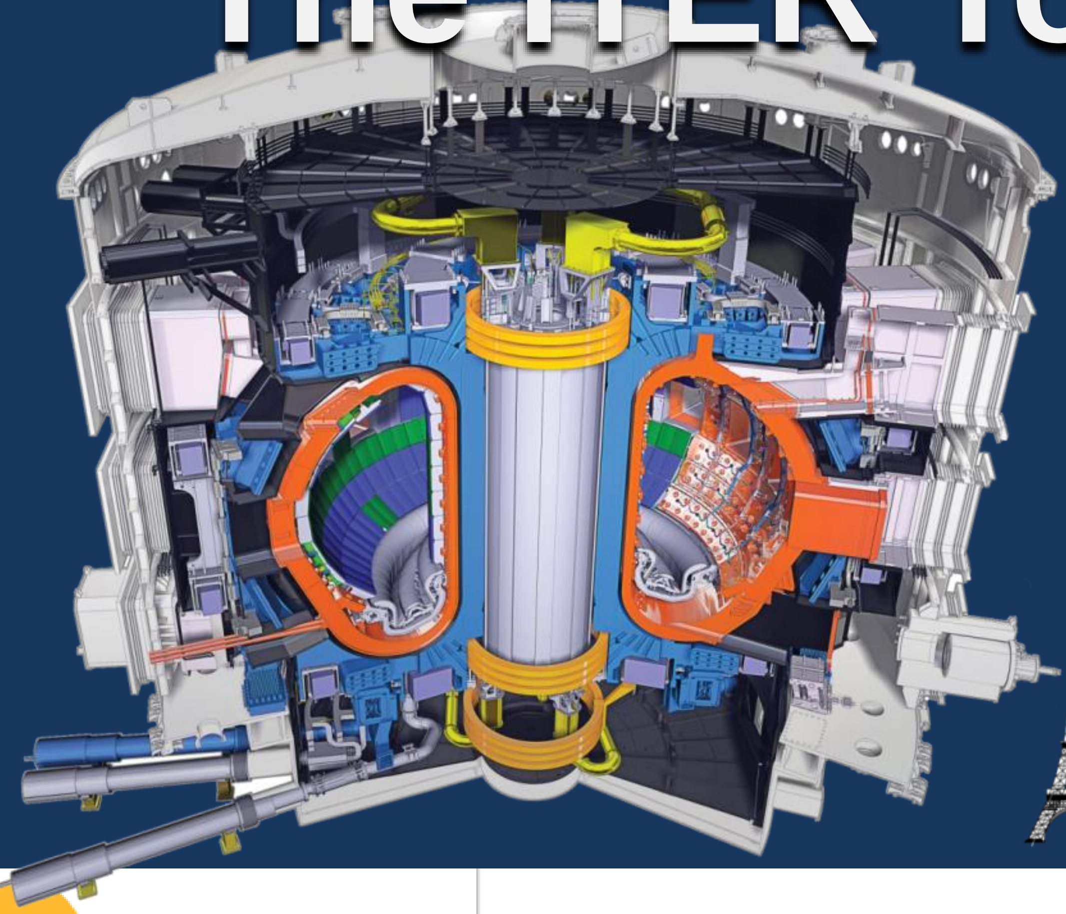
The seven ITER Members manufacture the machine and auxiliary parts. Europe is also building almost all the buildings



China, India, Japan, Korea, Russia and the United States each have responsibility for ~ 9% of procurement packages.

Europe's share, as Host Member, is ~ 45% (construction and manufacturing).

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!

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 heated to 150 million °C?

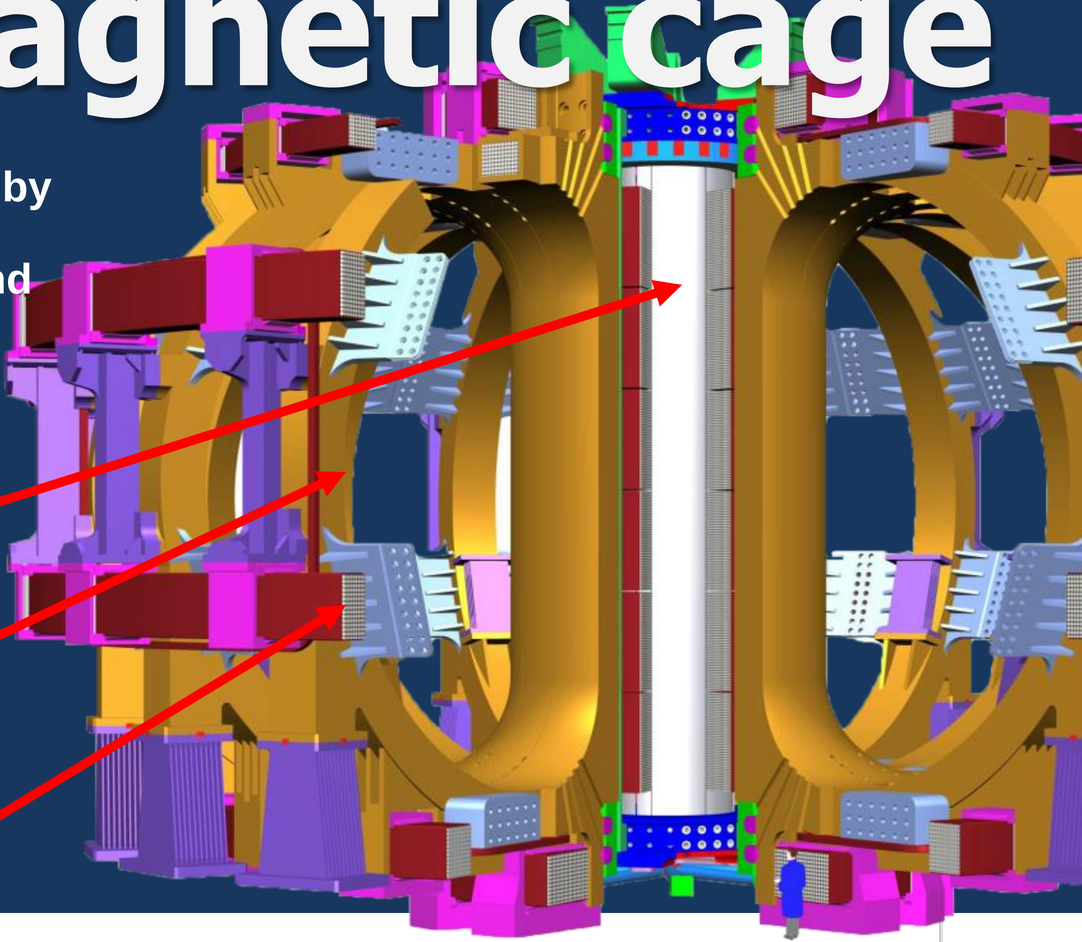
A large magnetic cage

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

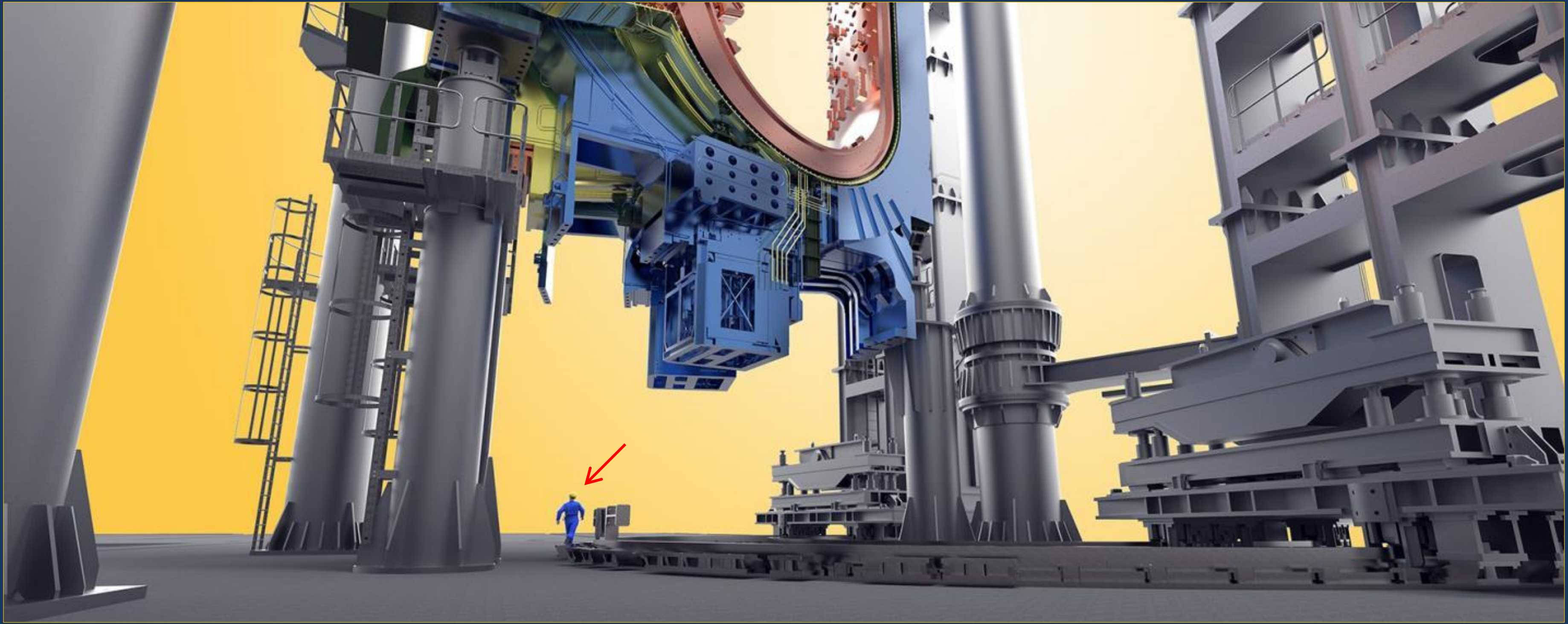
- 1 central solenoid, 18 m high, 1,000 tons, powerful enough to lift an aircraft-carrier out of the water

- 18 Toroidal Field Coils, 17-metre high, 360 tons each.

- 6 Poloidal Field Coils, 8 to 24 m. in diameter, 200 to 400 tons.



Naval construction-size components...

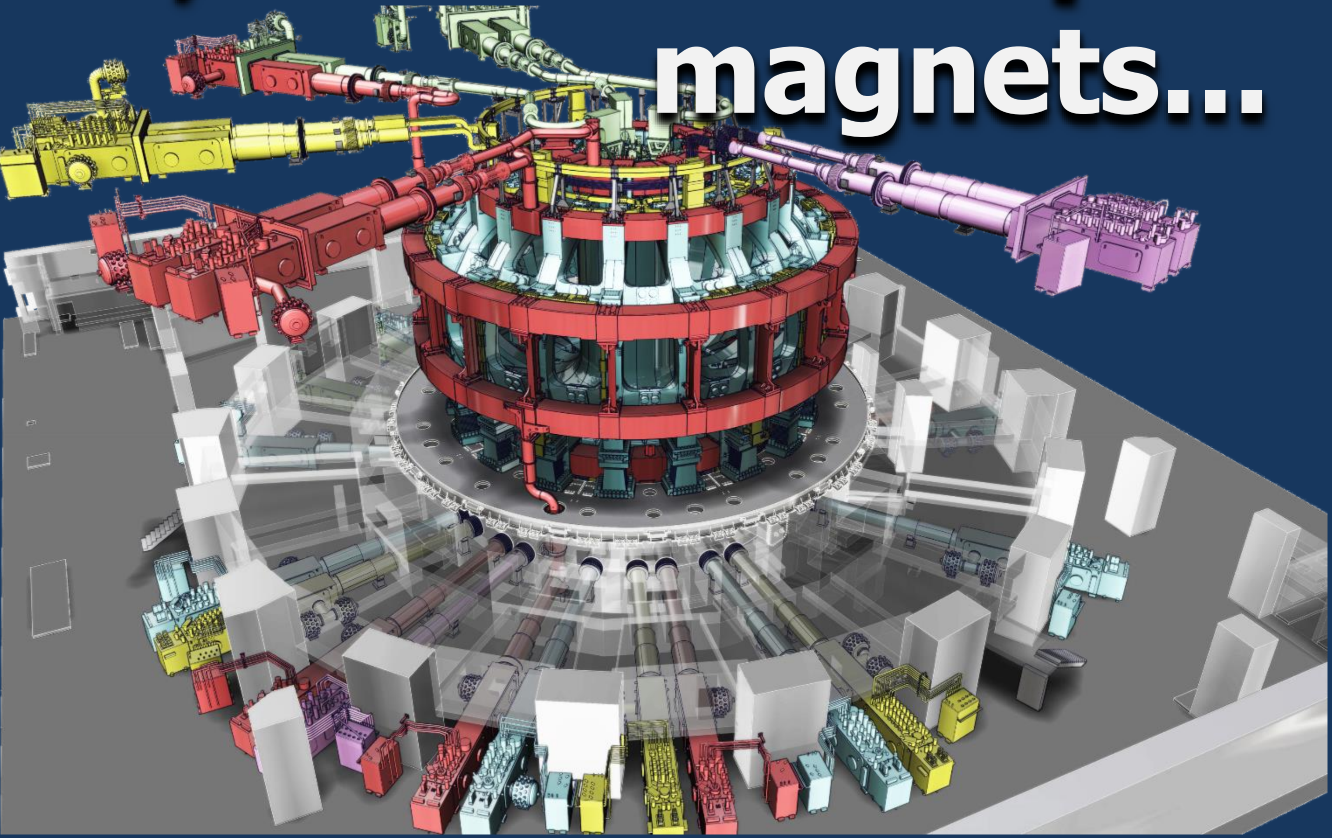


Inside the Assembly Hall, giant tools (procured by Korea) will handle loads up to 1,500 tons

...watch-like precision

In the workshops of Mitsubishi Heavy Industry, Japan, vertical insertion of the winding of a toroidal field (TF) magnet into its housing.
The assembly weighs more than 300 tons and the assembly tolerances are 0.2 millimeters.

10,000 tons of superconducting magnets...



Superconducting magnets can carry more current and generate stronger magnetic fields while using much less electricity.

Niobium-tin or niobium-titanium magnets are cooled to 4K (-269°C) by a helium flow.

Magnetic energy = 51 Gigajoules

18th & 19th ITER Council in 2016 endorse updated Schedule

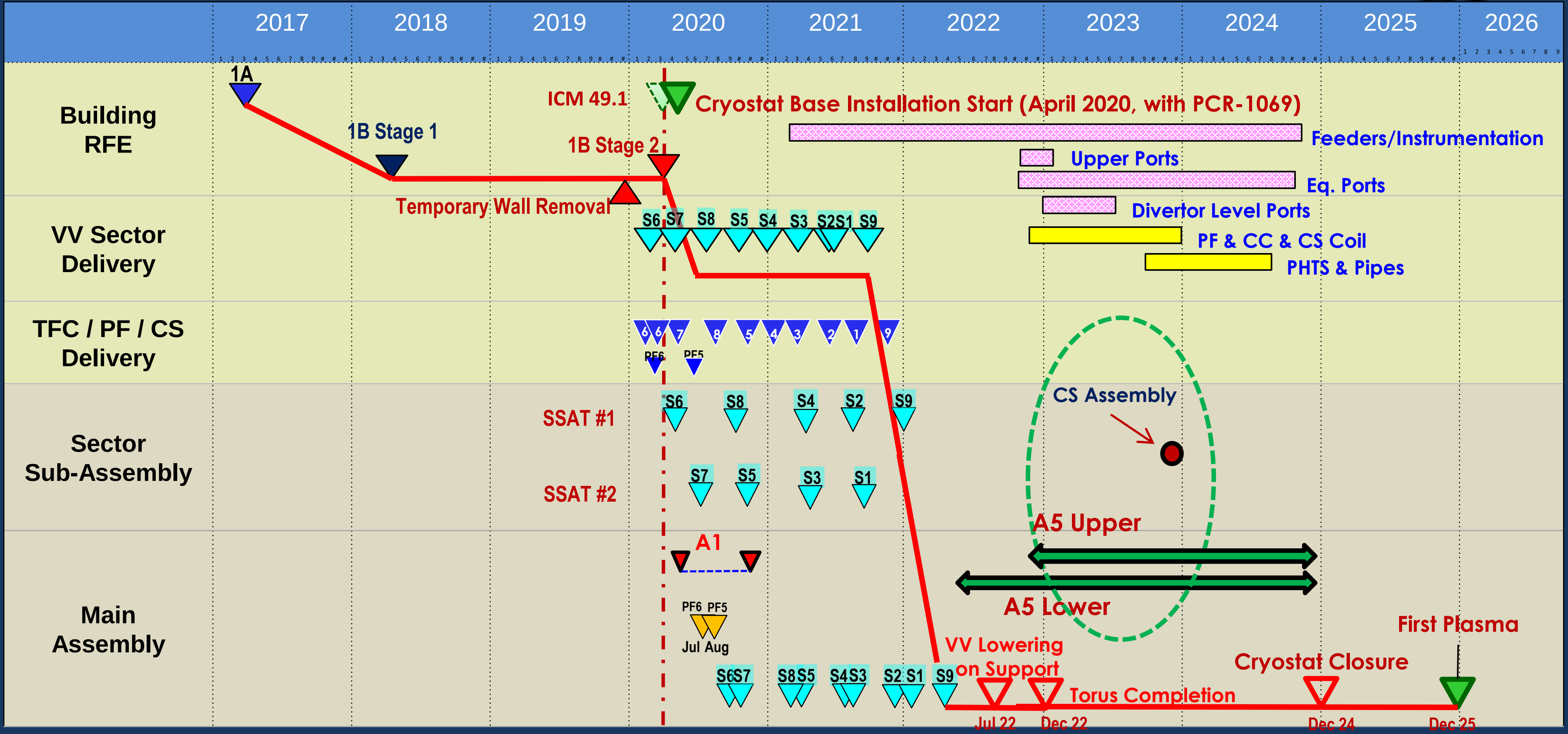
ITER Council convenes twice a year in June and November at ITER Headquarters

First Plasma in December 2025; first physics experiment in 2028; full fusion power (DT plasma) in 2035

The updated schedule is challenging. It represents the best technically achievable path forward to First Plasma.

Members now have all the elements needed to go through their domestic processes of obtaining approval for the Resource-Loaded Integrated Schedule

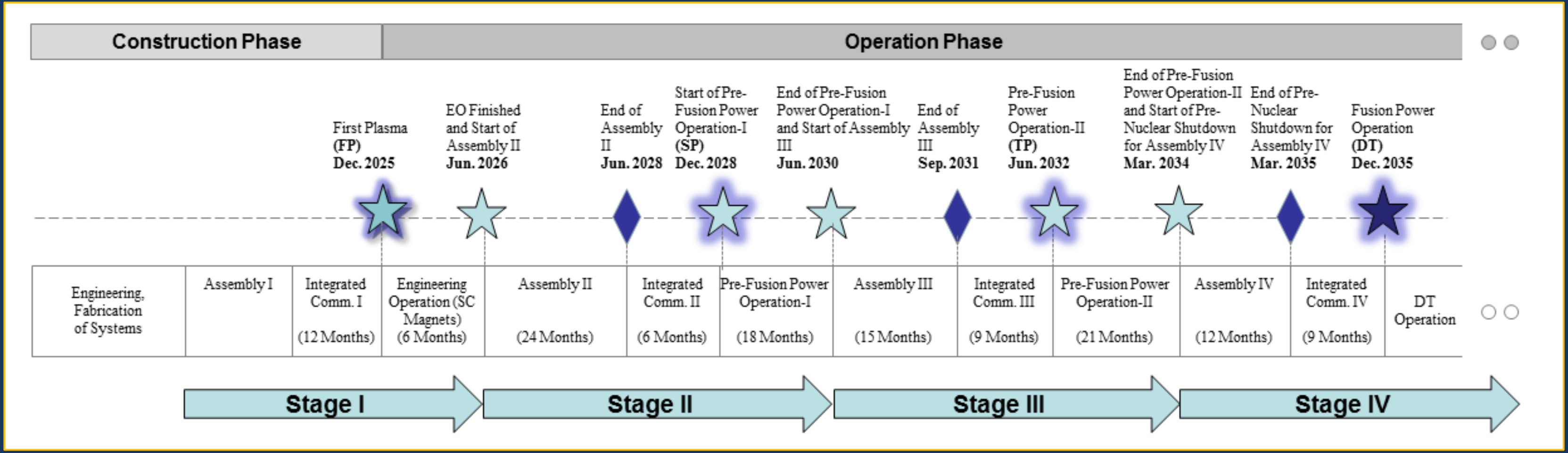
Details of Revised Construction Strategy



A staged approach to DT plasma

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

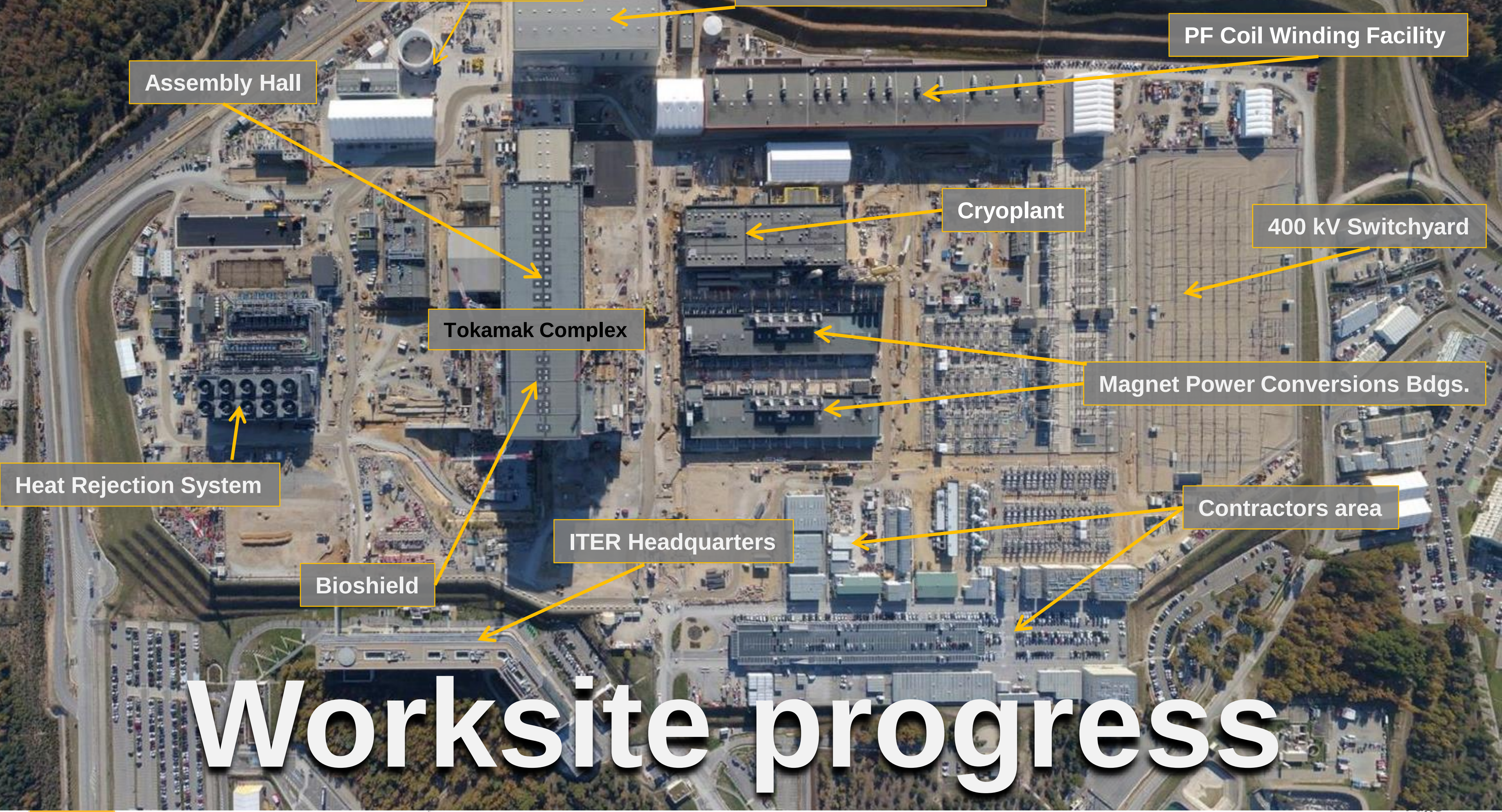
- ✓ Schedule and resource estimates through First Plasma (2025) consistent with Members' budget constraints
- ✓ Proposed use of 4-stage approach through Deuterium-Tritium (2035) consistent with Members' financial and technical constraints



On the way to First Plasma
73% of the work is done

According to the stringent metrics that measure project performance, 73 percent of the "*total construction work scope through First Plasma*" was completed.
Since 2016 years, the current monthly progression rate is in the order of 0.7 %.

Worksite progress



Worksite progress

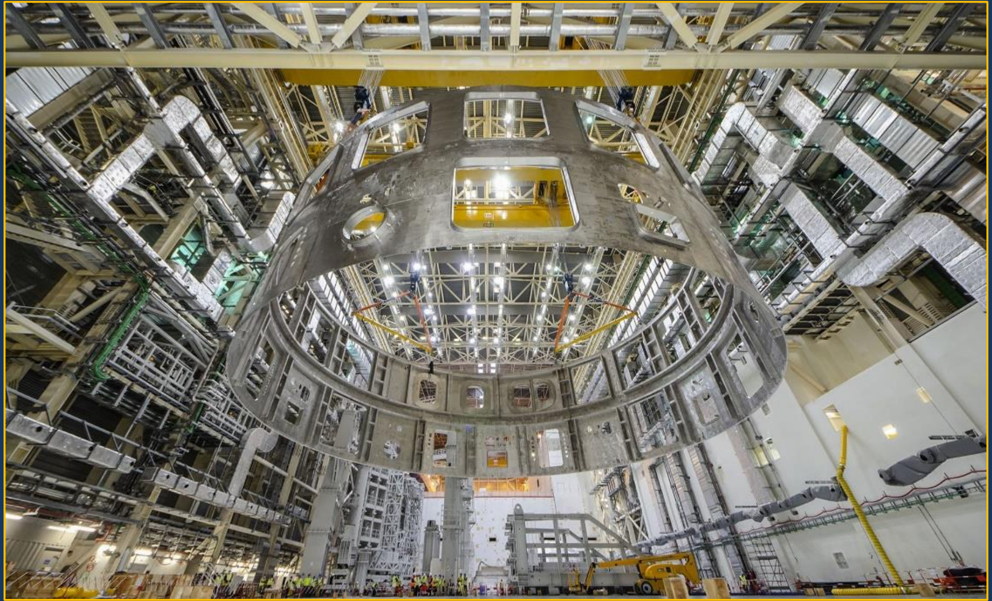
April 2014 – Nov. 2020

75% civil works completed by Europe

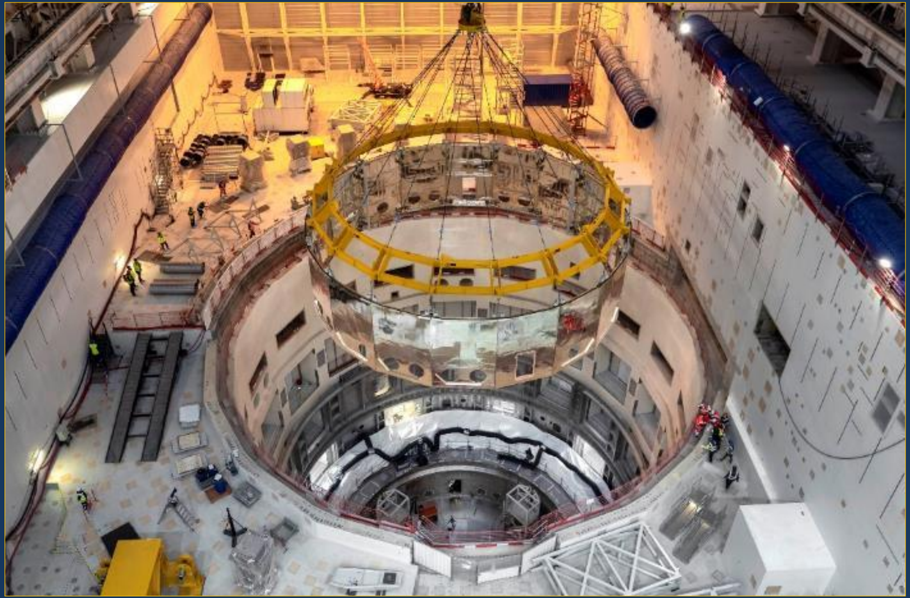
Spectacular Operations

On May 26-27 2020, the base of the Cryostat (1,250 t; procured by India) was successfully inserted into the Tokamak Assembly Pit.

Spectacular Operations



Cryostat Lower Cylinder lift,
31 August 2020



Inserting the Cryostat thermical shield
14 January 2021

...by the ITER route

Unloaded at the port of Fos-sur-Mer, the components cross the Etang de Berre on a special barge and travel the 104 km long "ITER Route". The journey to the ITER site takes three to four nights. The ITER Itinerary was developed by France (State and CD 13). 110 M€ of work carried out in 2009-2012.

Massive arrivals

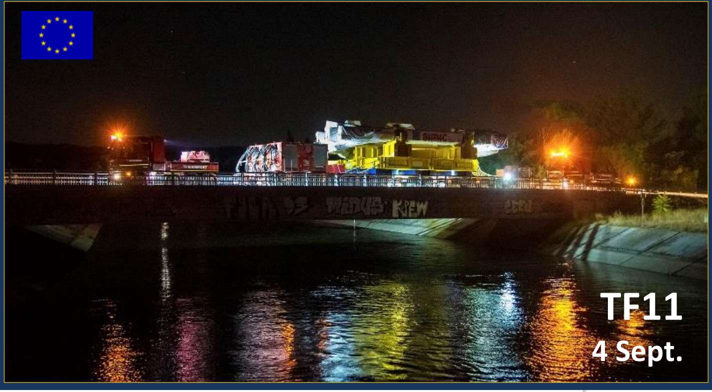
TF9
17 April

TF12
25 April

PF6
23 June

TF13
3 July

Vacuum Vessel Sector # 6
Unloaded 22 July



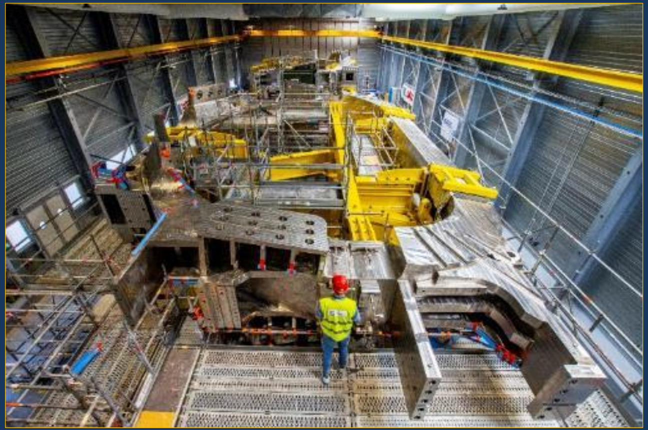
TF11
4 Sept.

Massive arrivals

TF 05

18 December 2020

Equip before assembling



The recently delivered toroidal field coils n° 9 and 12 are being equipped, prior to the pre-assembly operations.

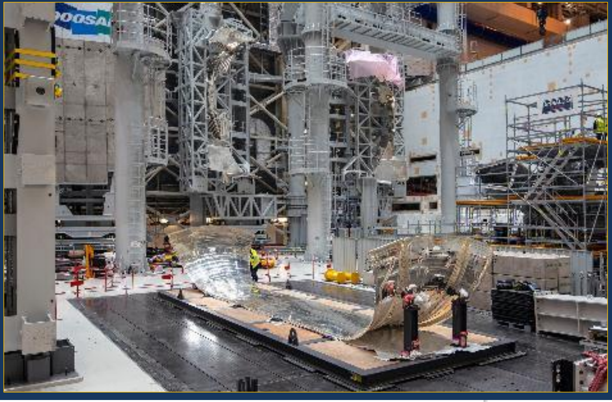
Delivered to site on June 26, the No. 6 poloidal field coil, supplied by Europe and manufactured in China, was finalized on site. It has passed the very low temperature tests and will be inserted in the machine assembly well in April 2021.

The vacuum chamber sector # 6, supplied by Korea and delivered in early August 2020, will be joined to the toroidal field coils # 12 and 13 and there corresponding heat shield section to form the first "pre-assembly".

Towards the first "pre-assembly"

With the delivery, in early August, of a first vacuum chamber sector (VVS No. 6) manufactured in Korea, ITER will be able to proceed with the first of the nine "pre-assemblies" that constitute the Tokamak core.

A "pre-assembly" is composed of a vacuum chamber sector, two toroidal field coils and a heat shield section.



Pre-assembly gantry (SSAT)

Installing the systems

5,5 km of cryogenic lines

AC/DC conversion
(8 km of busbars)

Heat
evacuation
(1,200 MW)

Reactive power
compensation
(1 hectare of high-tech
equipment)

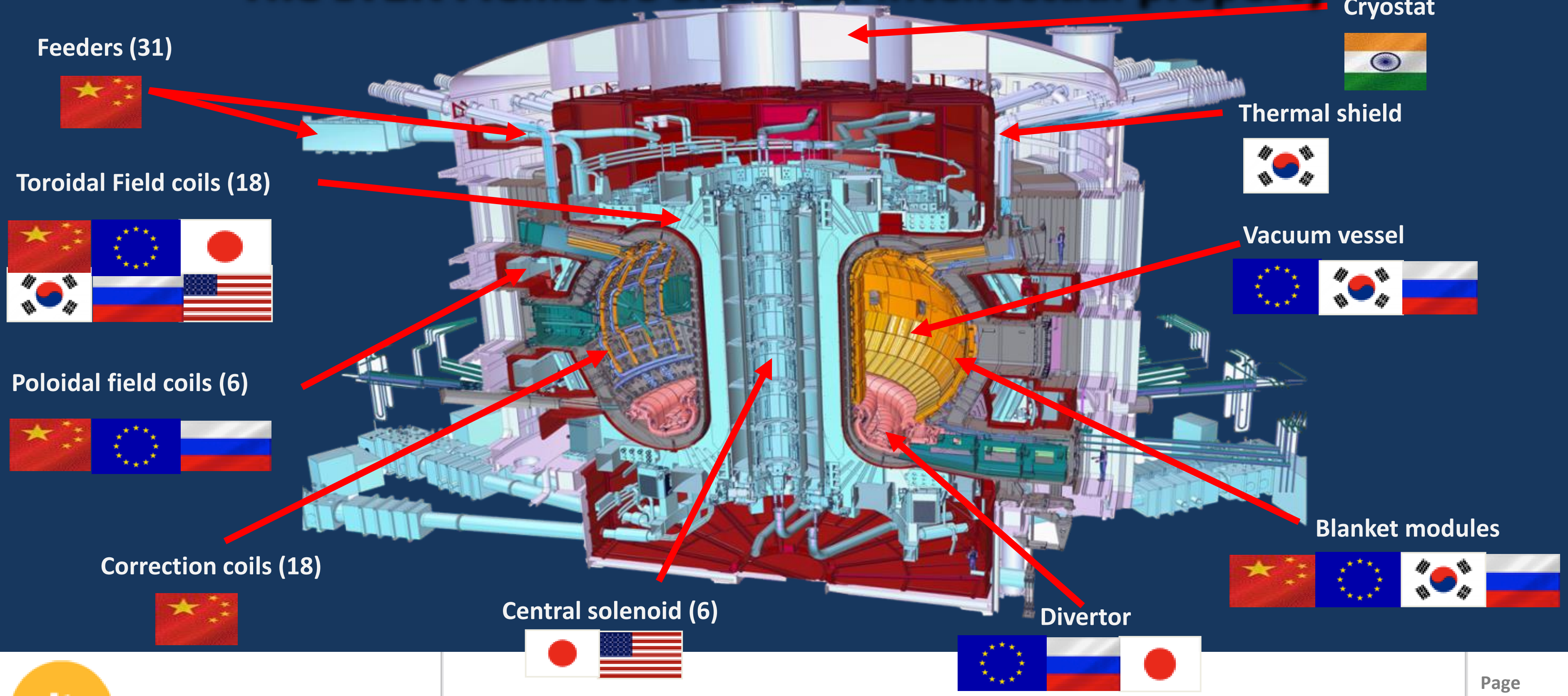
28 July: official launch of the assembly phase

Emmanuel Macron:

« ITER is an act of confidence in the future [...] Thanks to science, tomorrow can be better than yesterday. »

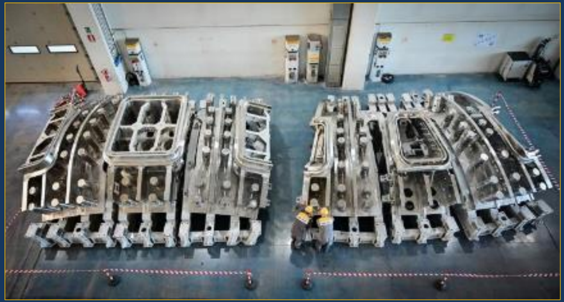
Who manufactures what?

The ITER Members share all intellectual property



Manufacturing in progress

Toroidal field coils: the 70 "double pancakes" for the ten vertical coils (out of a total of 19), for which Europe is responsible, have been produced. The first coil was delivered to the site in April 2020, the second in September and the third in December.



Vacuum chamber: Europe is manufacturing 5 of the 9 sectors of the Tokamak vacuum chamber. All of them are being manufactured with completion rates ranging from 66% to 89%.

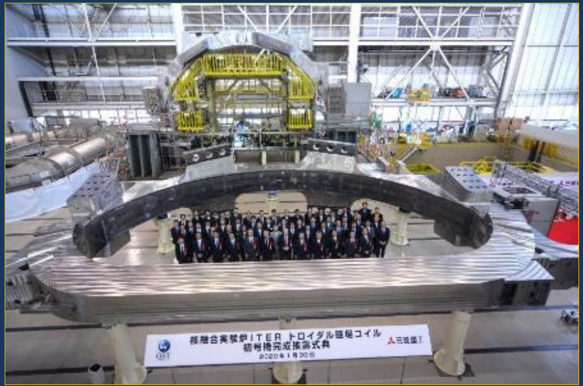
Between 2008 and 2017, ITER has created 40,000 jobs/year in Europe.
More than double this number is expected in the coming years.

Poloidal field coils: Because of their size (17 - 24 m diameter), 4 of the 6 ring coils are manufactured on site by Europe; PF n°5 and PF n°2 are finalized. The manufacturing of PF n°4 is in progress.

Manufacturing in progress

More than 1,600 tons of equipment for the magnet feeding system ("feeders") are supplied by China.

Japan supplies 9 of the 19 toroidal field coils (including one spare) of the tokamak. The first of them (TF12) was delivered on April 17, 2020, the second (TF13) on July 3.



Manufactured in India to be assembled and welded on site, the last elements of the Cryostat (top lid) are shipped according to the assembling schedule.

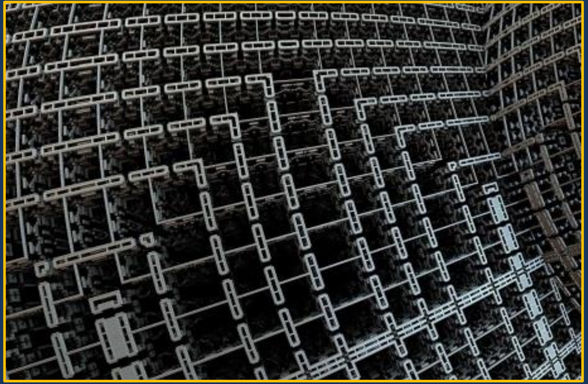
Manufacturing in progress

Korea is responsible for the construction of 4 of the 9 sectors of the vacuum chamber. The first one has been delivered, the other three have been completed at a rate of 86-99%.

The six central solenoid modules (plus one spare) are entering the final stages of manufacturing at General Atomics' workshops near San Diego, California.

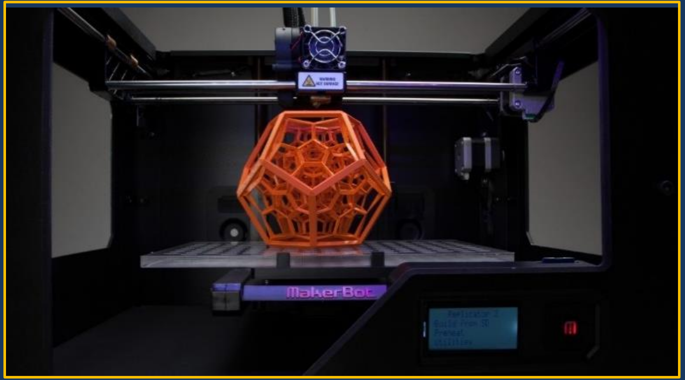
The manufacturing of the poloidal coil n°1 (9 meters in diameter, 193 tons) is entering its final phase. This coil is the smallest of the six ring coils of the machine. It will be installed shortly before the closure of the cryostat.

Innovation & spin offs



High technology filters

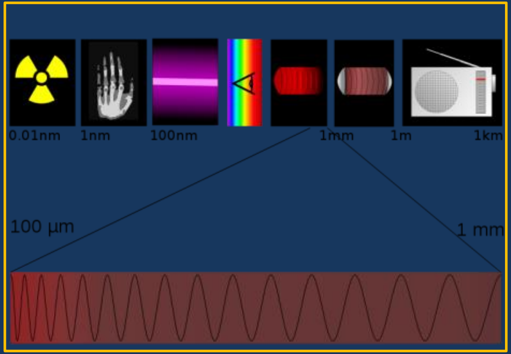
Medical magnetism



3D printing for complex shapes

Power electronics

Explosive forming

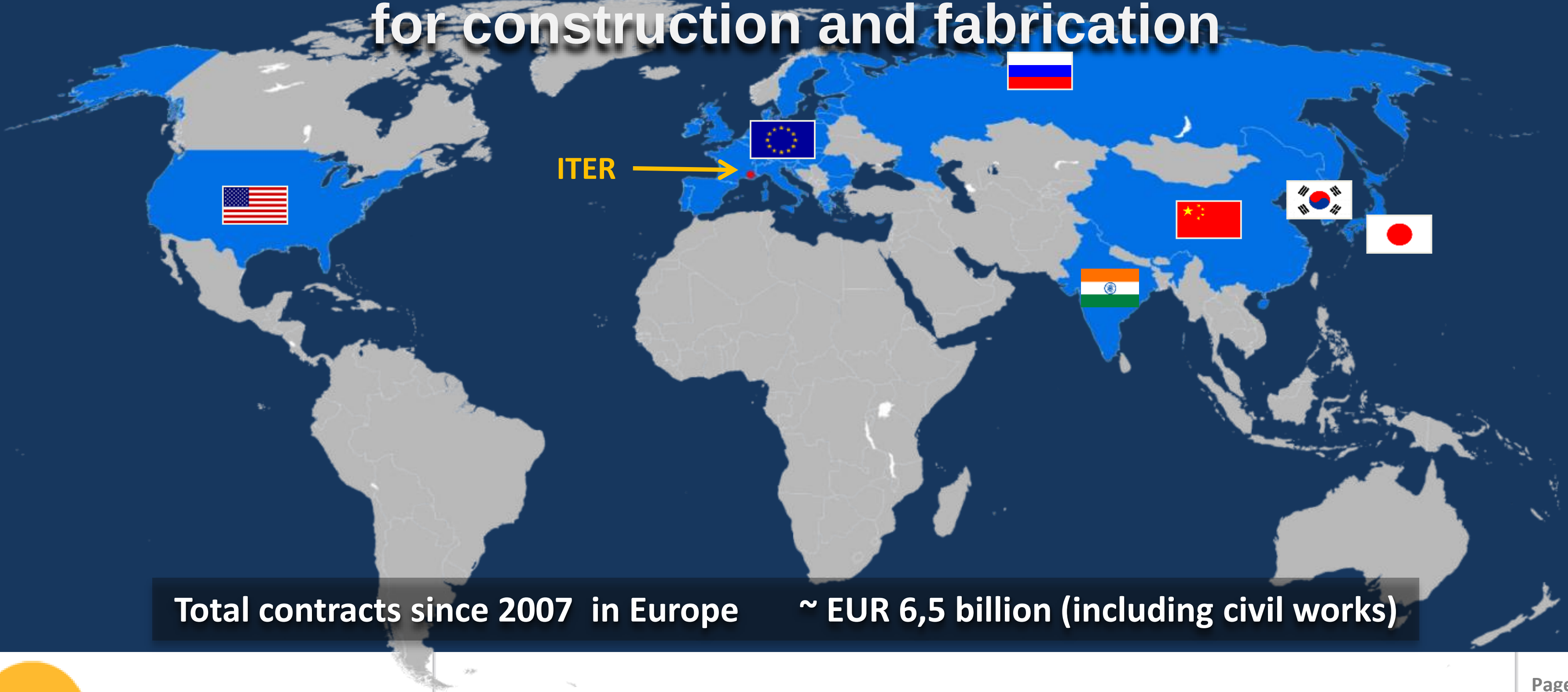


Ultrahigh speed transmission

Etc.

Economic benefits

More than 9.5 billion euros in contracts for construction and fabrication



Total contracts since 2007 in Europe ~ EUR 6,5 billion (including civil works)

The ITER worksite

- *2,300 workers, technicians and engineers today, up to 3,000 in the coming years;*
- *ITER construction represents 18 million working hours (2010-2020).*
- *Nearly 500 European companies (80% of which are French) are present as subcontractors on the ITER site.*

ITER safety

- The fusion reaction is inherently safe.
- There is never more than one gram of fuel reacting in the vacuum chamber.
- The slightest disturbance brings the plasma to an end.
- It is physically impossible for the reaction to spiral out of control and for the core to melt.
- In the event of a loss of electrical power, the heat will naturally escape.
- Important safety margins for external risks (earthquakes, floods...)

ITER is a "Basic Nuclear Installation" under French regulations and as such is subject to inspections by the French Nuclear Safety Authority (ASN).

Radioactivity and waste

ITER will not generate high-level, long-lived waste

During normal operation, the radiological impact of ITER on the most exposed populations will be a thousand times less than that of natural radioactivity

The most unlikely scenarios, such as a fire in the Tritium facility, would have a lesser impact on neighbouring populations than natural radioactivity

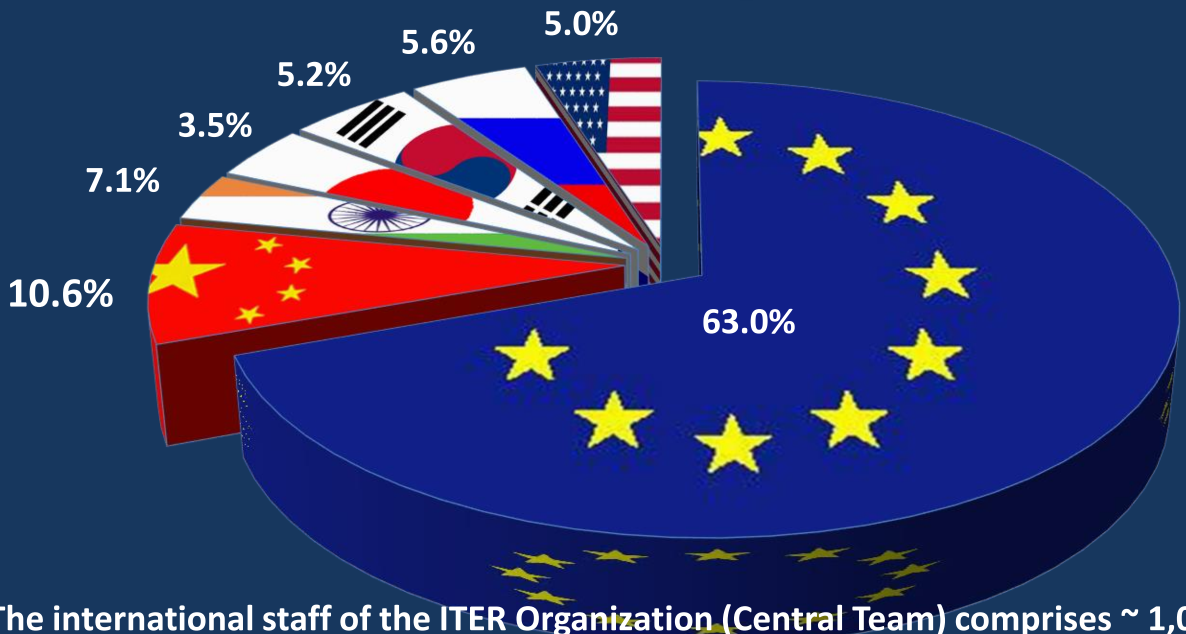
ITER is subject to French safety and security regulations

How much does it cost?

Construction phase: ITER Organization	€8.2 billion (2018 value)
Supplies in kind by Members	€12.5 billion (estimated)
Operation phase	€300 million /year
Shutting down phase	€281 million (value 2001)
Dismantling phase	€ 530 million (value 2001)

Who works for IO?

Distribution by Member & IPA

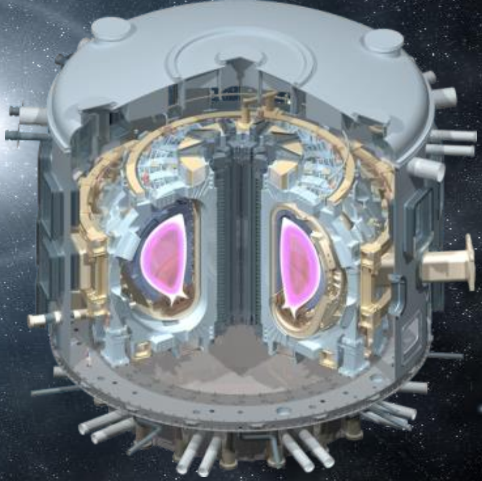


August 2019

The international staff of the ITER Organization (Central Team) comprises ~ 1,000 persons (35 countries).
Close to 500 contractors and experts are directly working for ITER in Saint-Paul-lez-Durance, France.
More than 3,000 specialists are involved in ITER throughout the world.

ITER and beyond

The ITER Members are developping conceptual designs for the « next-step » machine (DEMO).



ITER

800 m^3

$\sim$ 500 MW_{th}

DEMO, next-step machine

$\sim$ 500 Mw_e, 1 200 MW_{th}

Towards indusrialisation

~ 2040: At the end of five years of full-power operations and system optimization, ITER should have demonstrated the feasibility of hydrogen fusion and convinced policymakers and industry of its potential.

~ 2045: Industry could consider starting construction of the first fusion power plants.

~ 2055-2060:Industrialization phase

From ~ 2060:Toward a 50-60% fusion/fission, 40-50% renewable energy mix.

Onward toward First Plasma!

Thank you for your attention

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