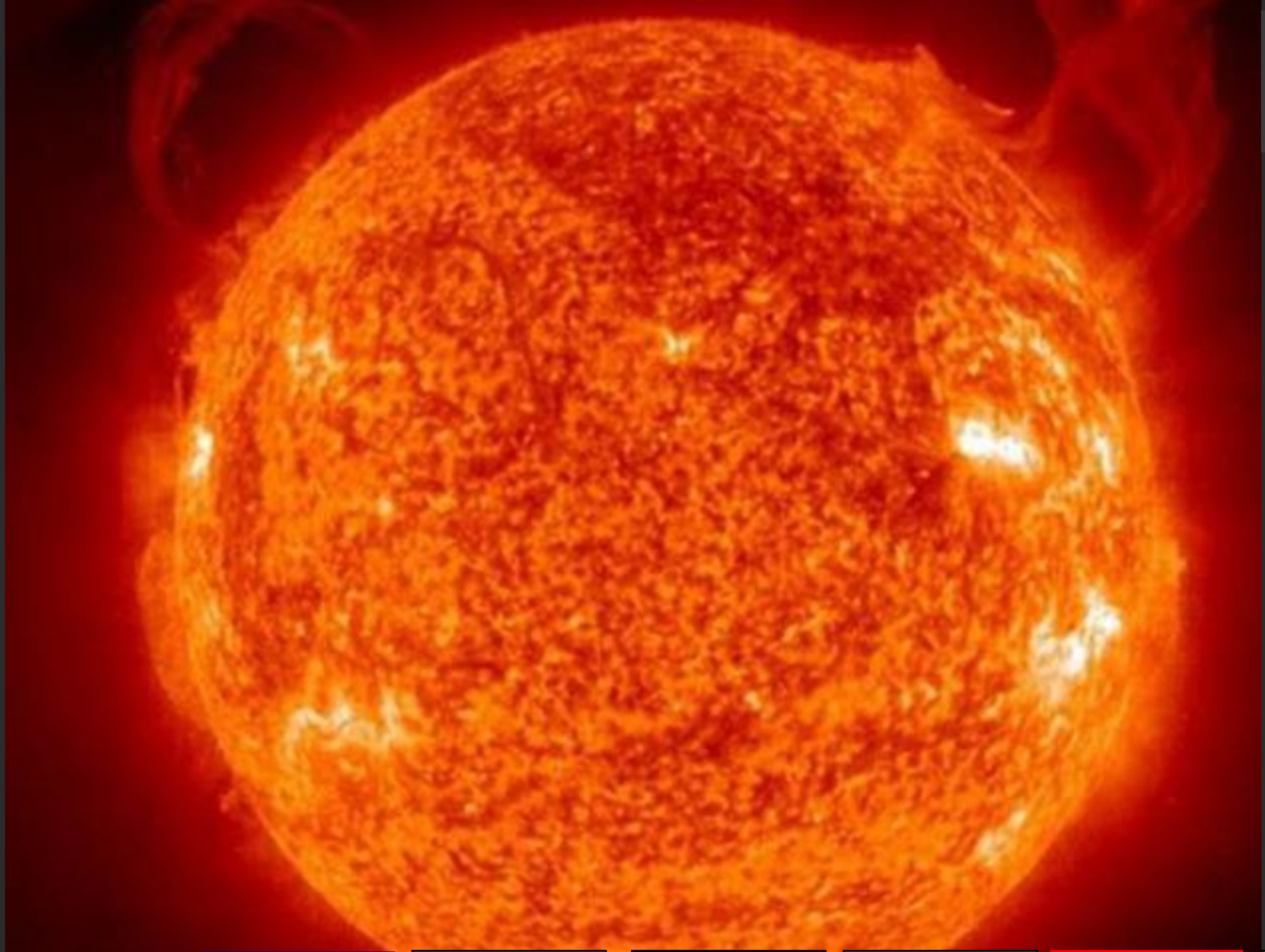
ITER: a star in the lab

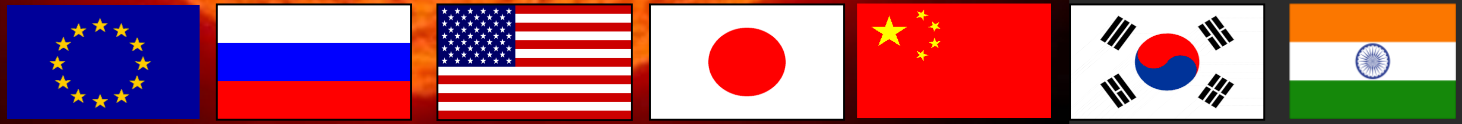
INFIERI, J. Jacquinot 31 August 2021

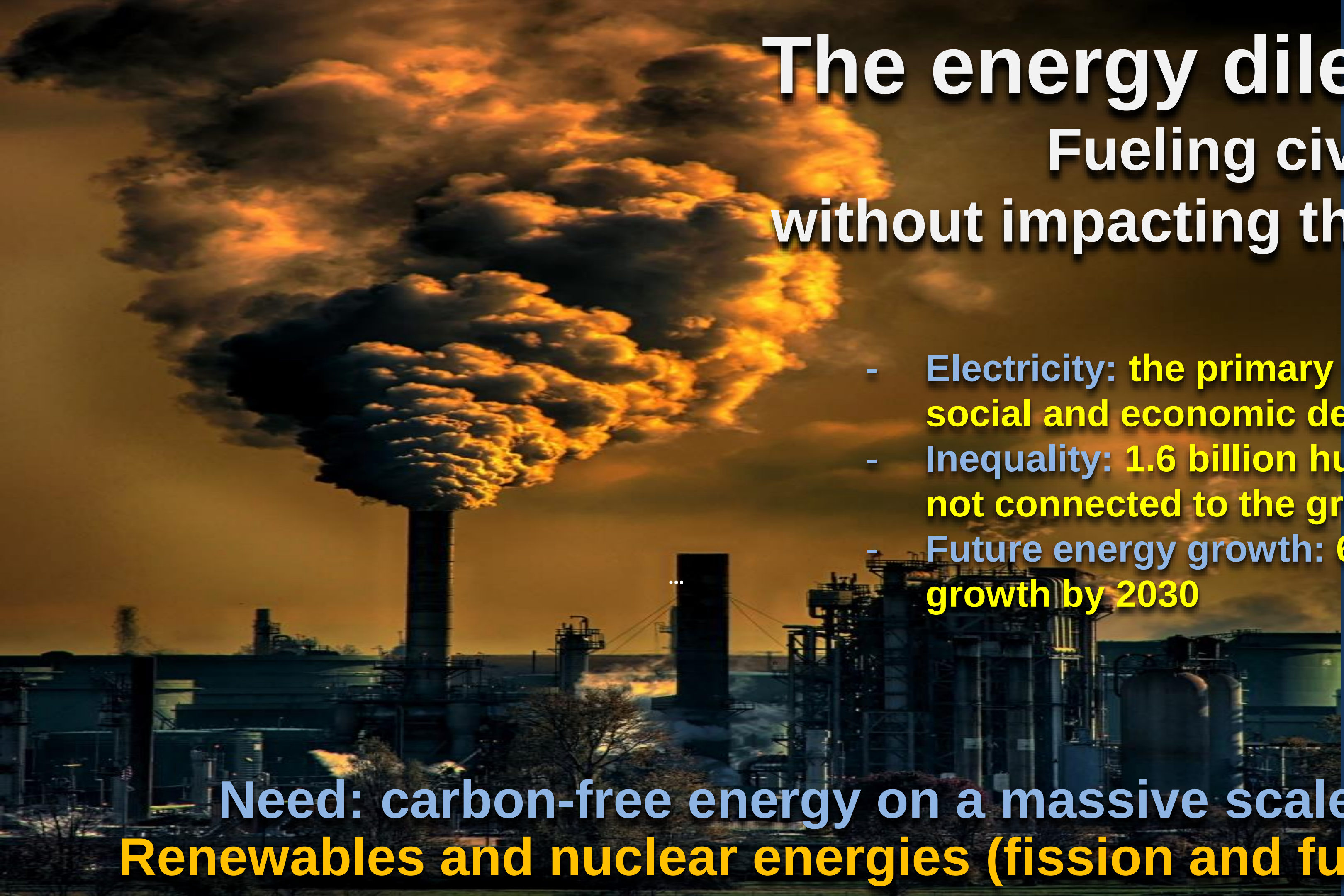


"The problem I hope scientists will have solved by the end of the century is nuclear fusion.

It would provide an inexhaustible supply of energy without pollution or global warming."

Stephen Hawking
(September 2010)





The energy dilemma:
Fueling civilization without impacting the planet

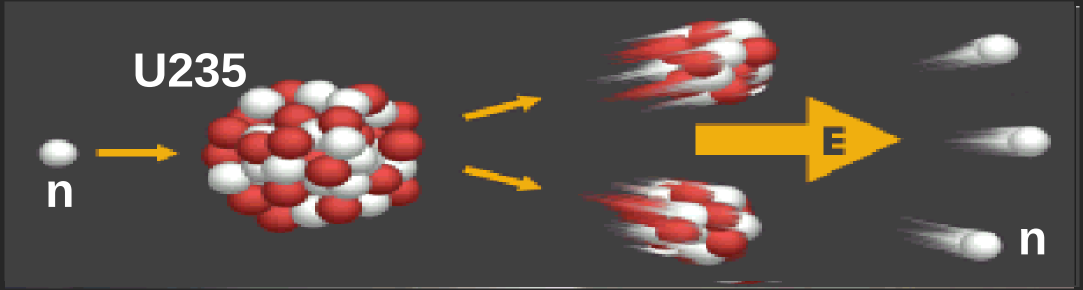
- **Electricity:** the primary vector of social and economic development
- **Inequality:** 1.6 billion humans still not connected to the grid
- **Future energy growth:** 60% more growth by 2030

Need: carbon-free energy on a massive scale!

Renewables and nuclear energies (fission and fusion)

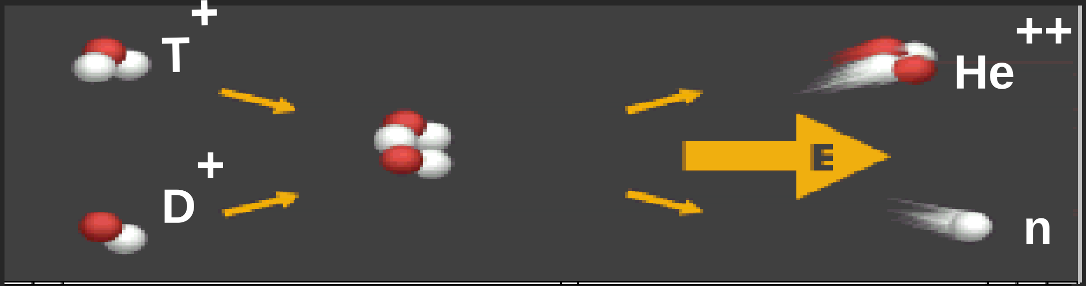
Fission / Fusion

Fission fuel:
Uranium
solid

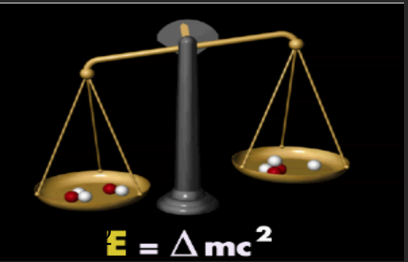


Neutrons
Chain reaction

Fusion fuel
hydrogen:
Gas, high T



Helium
Maintains the temperature



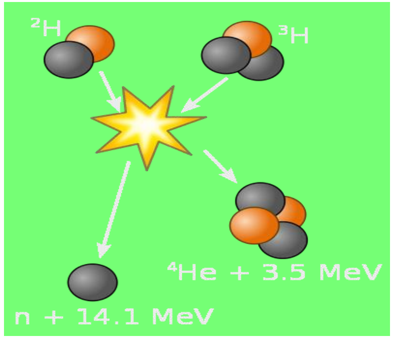
Fusion fuel: deuterium et tritium (1 g = 8 tons of oil)

Pros; No run-away, after-heat and long-lived high radio-toxicity wastes

Cons: very complex physics and technology to be demonstrated

Confining a 100 million degree plasma

- **Energy gain if: $nT\tau_E \sim 10^{21}$ m^{-3}.keV.s ~ 1 bar.s**
  - n (density) = 10^{20} particles/m^3 ➔ easy!
  - T (temperature) ≥ 10 keV ➔ achieved
  - τ_E (energy confinement time) ≥ 4s ➔ difficult requires a critical size



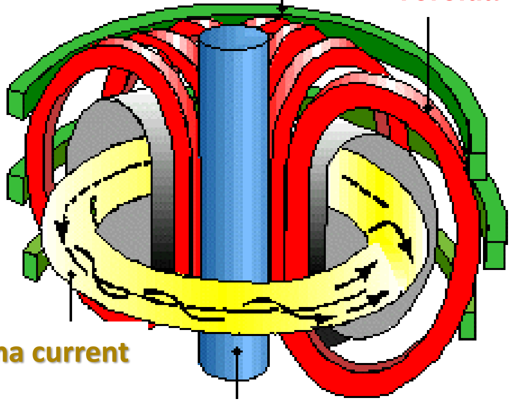
- **What machine size for a good efficiency? ➔ ITER**

- **Method:**

  - Hydrogen gas introduced in a vacuum chamber is heated. It becomes a plasma

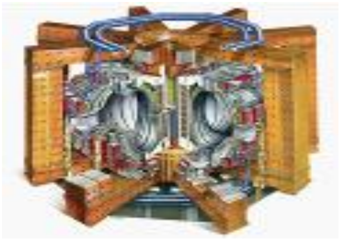
  - A strong magnetic field confines the plasma from the walls.

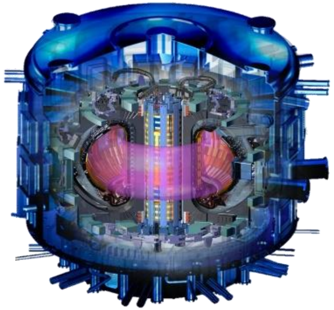
  - Fusion born helium atoms maintain the plasma temperature

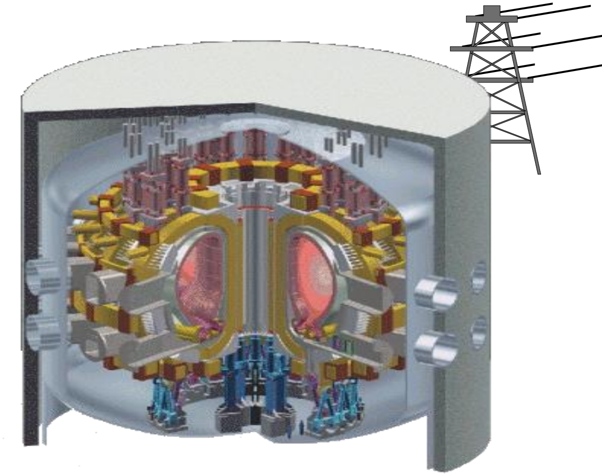


ITER : an essential step towards a fusion reactor

ITER: the first device exceeding the critical size for self heating as in a star



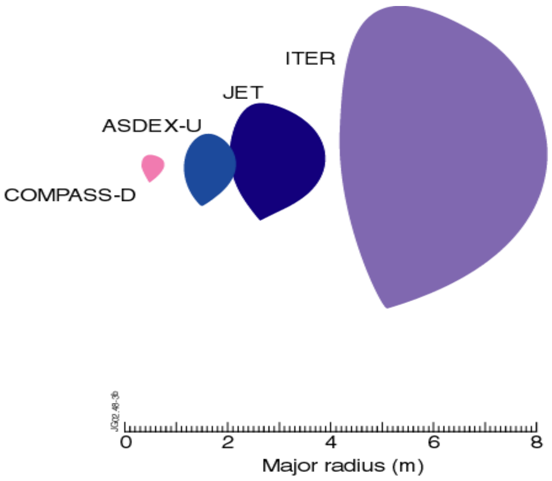




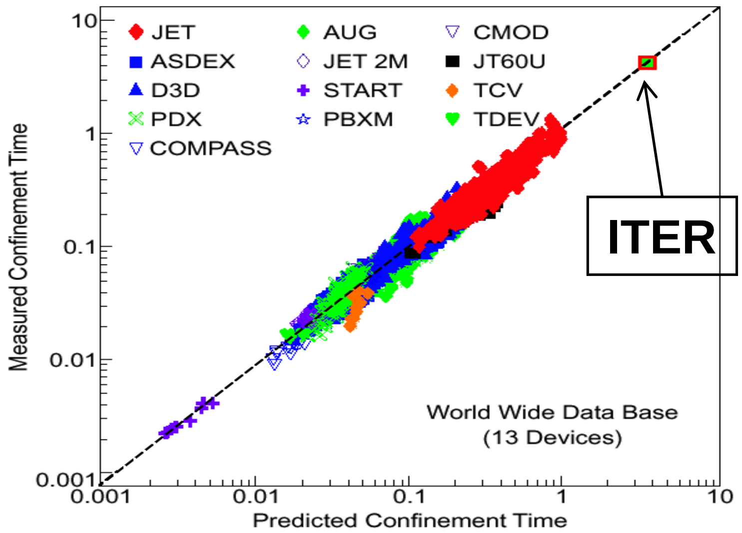
National	***JET** (EU)*	***ITER***	***DEMO***
25 m^3	*80 m^3*	*800 m^3*	*~ 1000 - 3500 m^3*
~ 0	*~ 16 MW_{th}*	*~ 500 MW_{th}*	*~ 2000 - 4000 MW_{th}*
Q ~ 0	Q ~ 1	Q ~ 10	Q ~ 30
6 minutes	10 sec	10’ to CW	CW
0%	10 %	70 %	80 à 90 %

↑ ------------------------------ ↑ ------------------------------ *Self heating* ↑ ---------------------- ↑

Dimensioning ITER: the wind tunnel method



Tokamaks cross sections compared to ITER



Confinement law:
3 main parameters: ρ^*, ν^*, β_N

Gyro-scale **turbulence** dominates transport

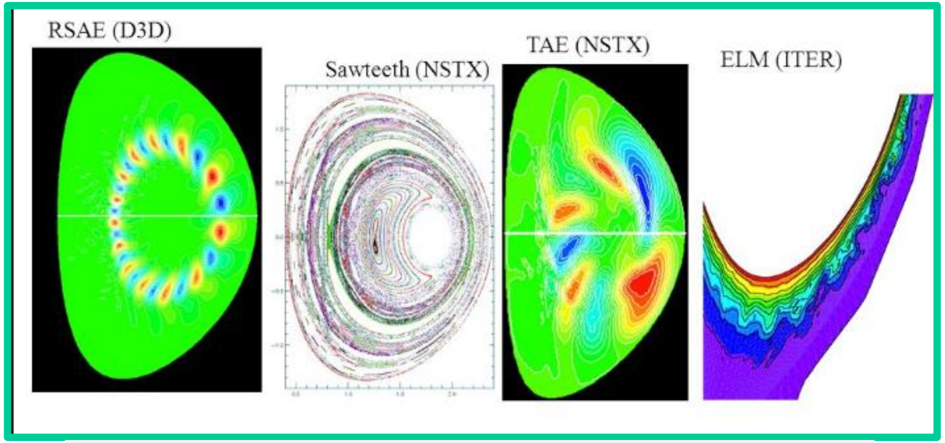
$\rho^* = mv/(qaB)$ Gyro Bohm ➔ $\omega_c \tau_E \equiv [\rho_*]^{-3}$

- **Scaling law**
  - **$H=\tau/\tau_{scaling}$ H~1**
  - **$\tau_{scaling}$ α I R^2 $P^{-2/3}$**

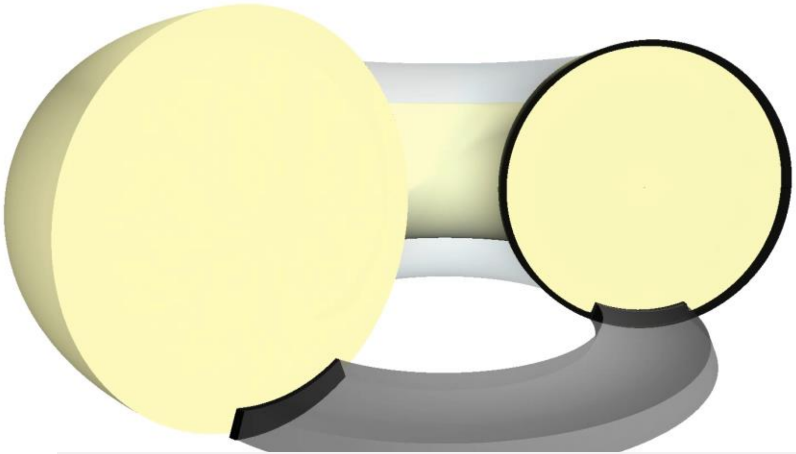
Fluid and Gyro-kinetic simulations: now connecting to the edge

Small scale turbulence: 5D gyro-kinetic codes use massively paralleled computers (e.g. Gysella was tested with 450000 cores in IBM Juqueen Germany).

Large scale instabilities: Non linear fluid codes (e.g. JOREK)



Simulation with non linear fluid codes

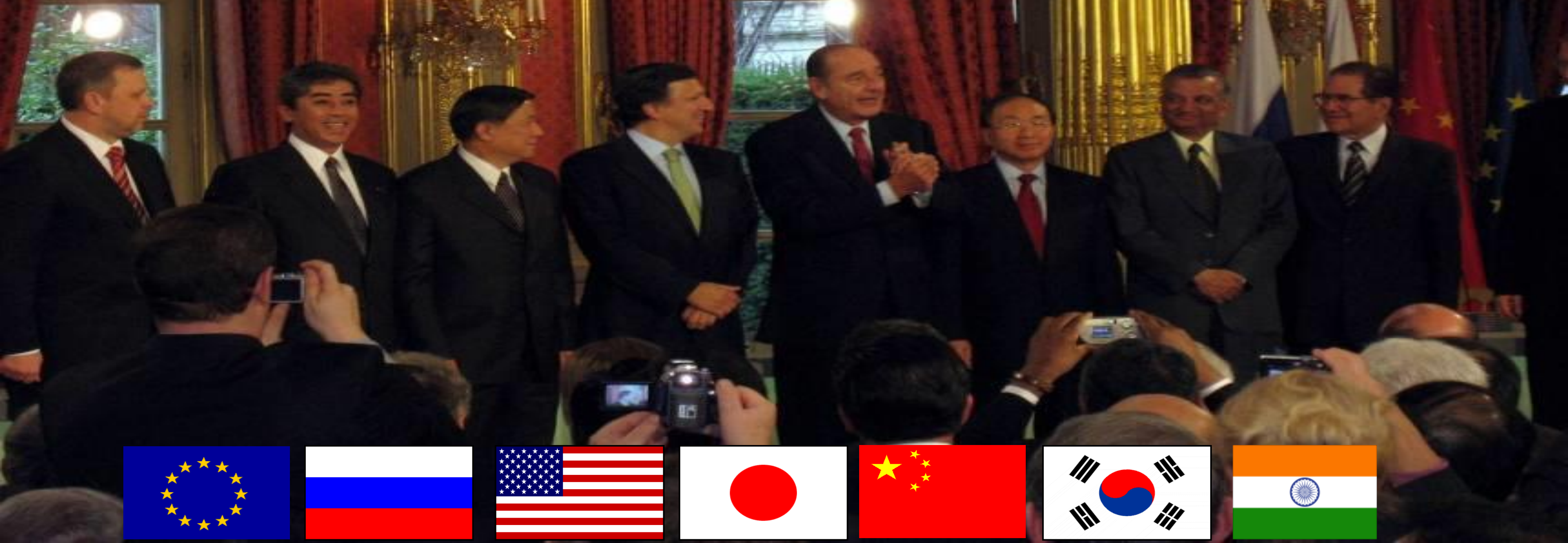


Gyro-kinetic ion turbulence simulation

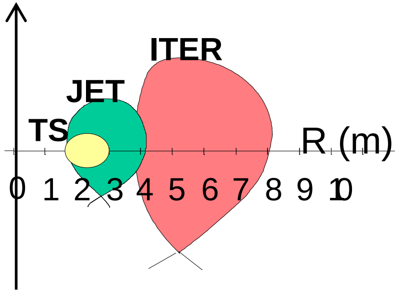
Next steps: exa-scale super calculators for first principle predictability of burning plasmas

ITER International Organisation:

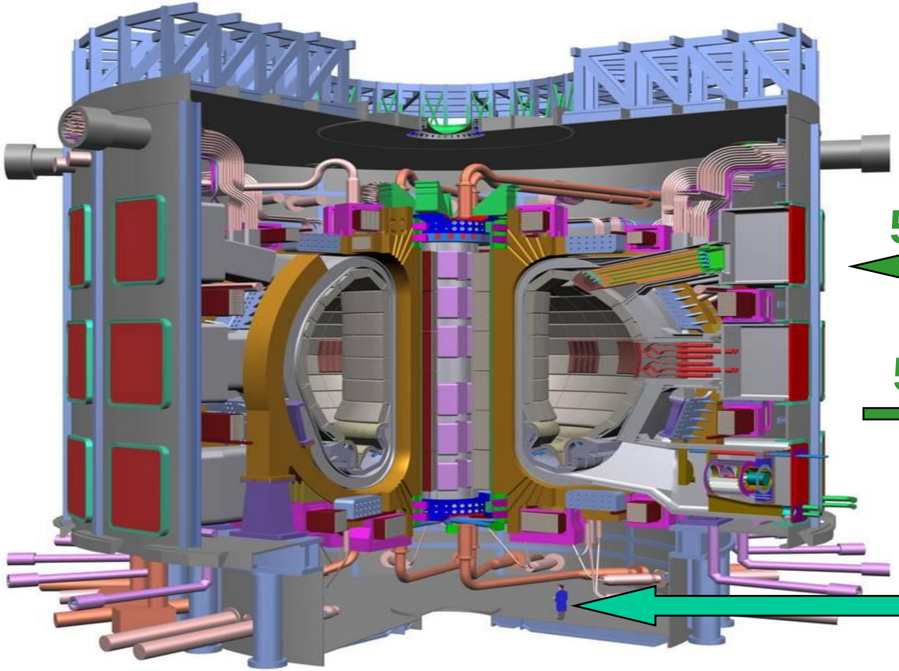
Created in 2007, treaty based as UN or UNESCO
7 partners, 35 countries, 90% in-kind procurement
2000 personnel now on Cadarache site
Undertaking similar to CERN



ITER target: 500 MW_{th}



A device ~ twice the size of JET



50 MW_{th}

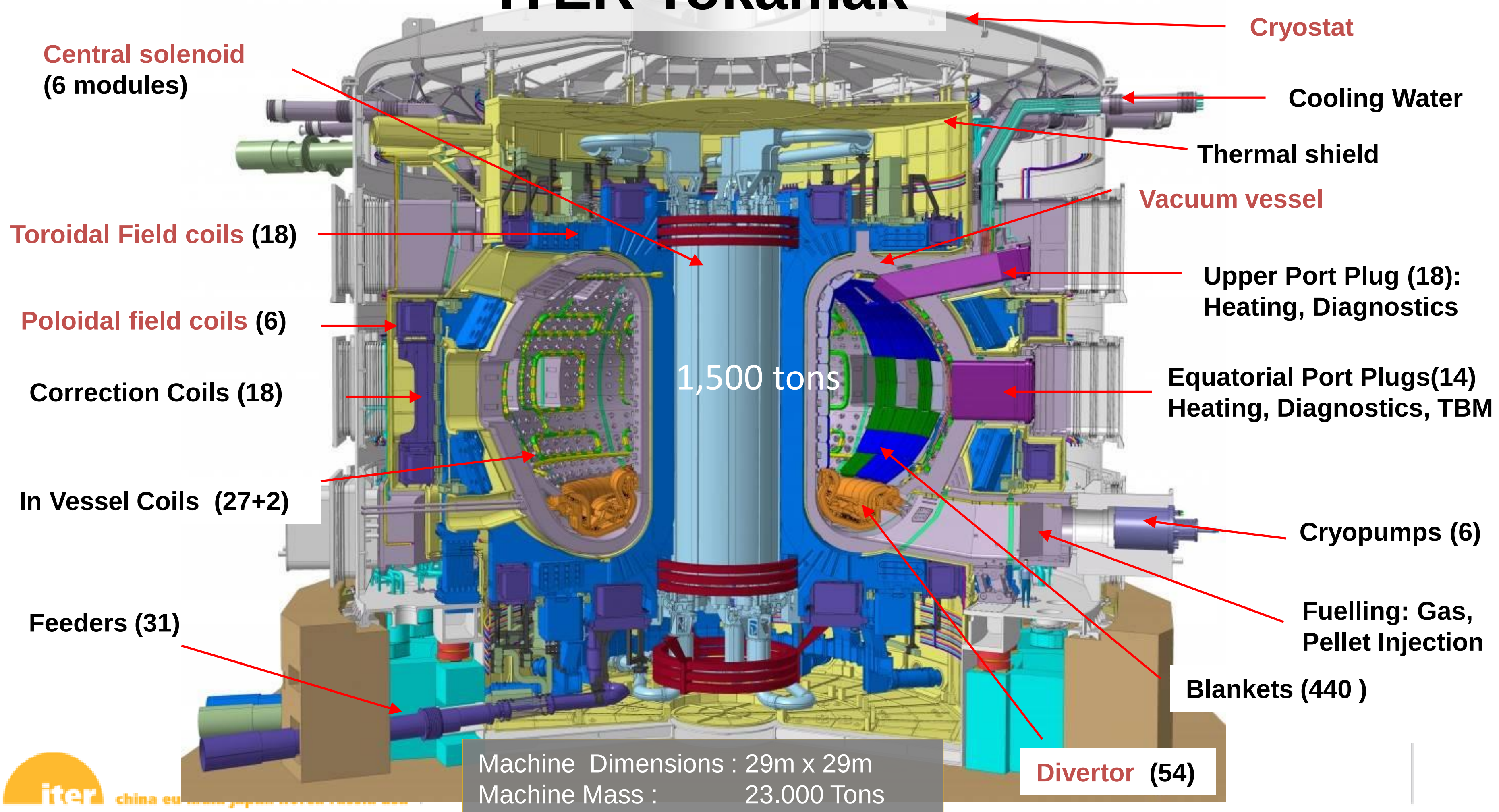
500 MW_{th}

Self heating by fusion born helium

Fusion technologies

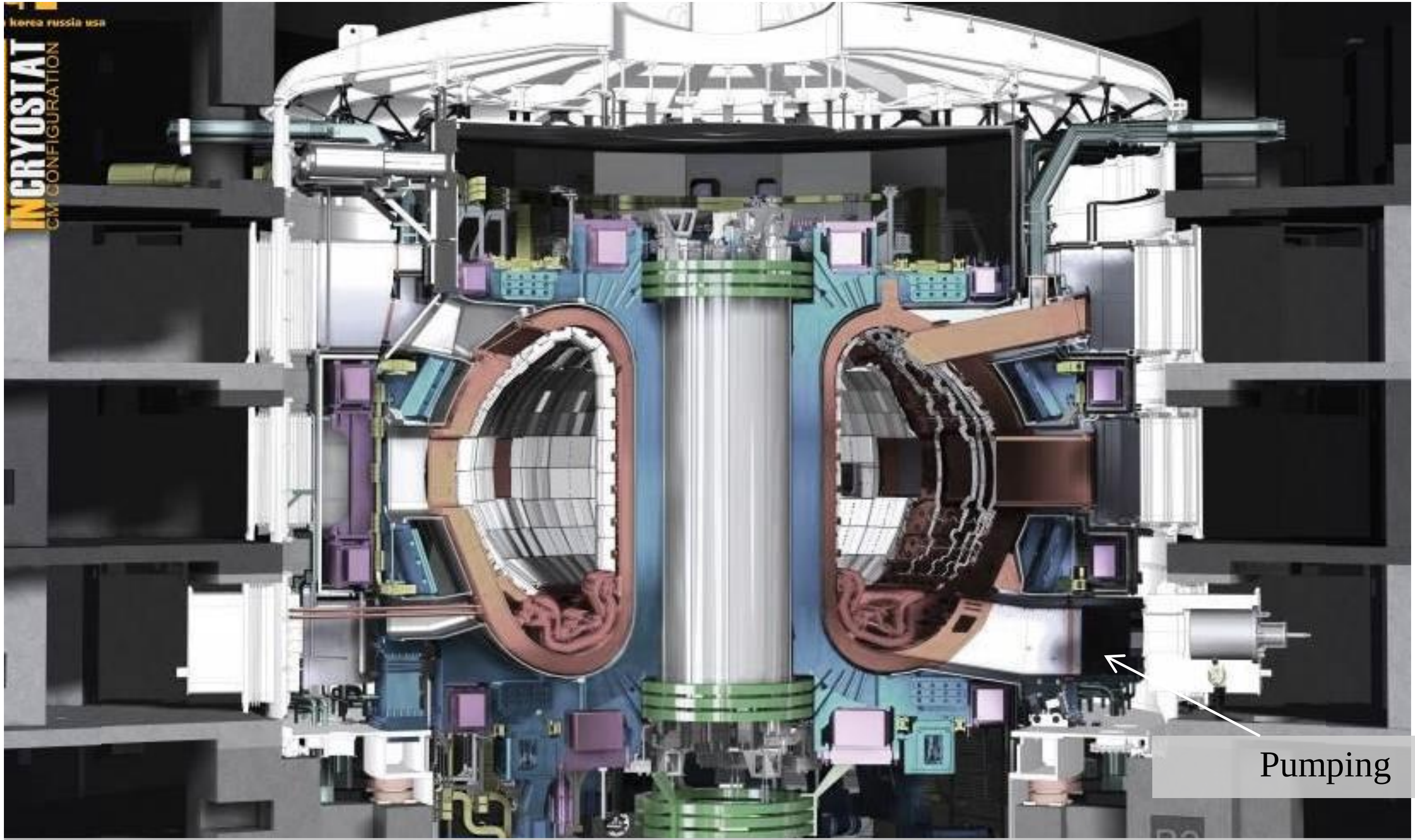
Homo sapiens

ITER Tokamak



iter china eu india japan korea russia usa

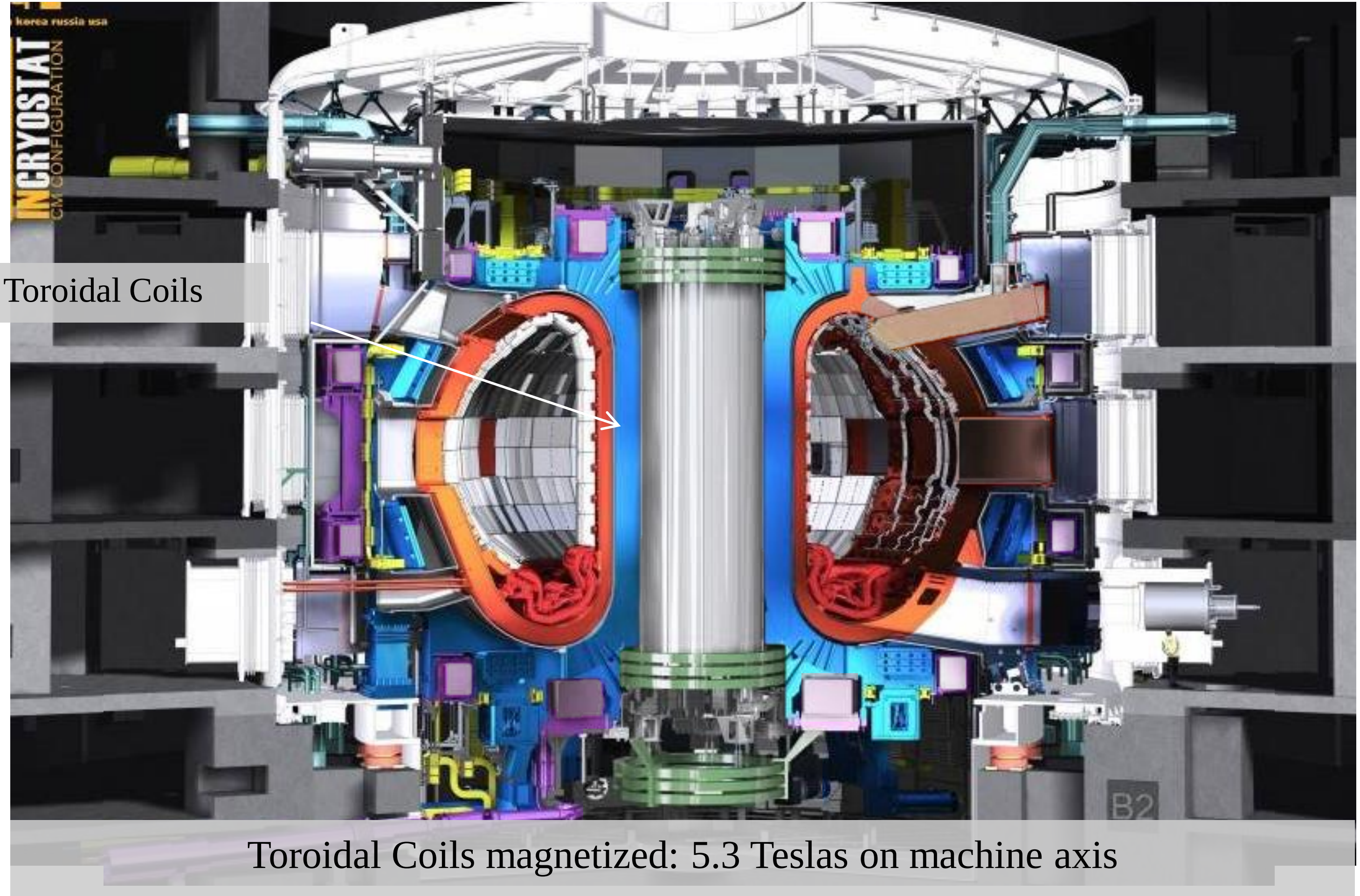
Preparation for Tokamak operation



Pumping of all gas from the vacuum chamber : high vacuum of 10^{-8} millibar

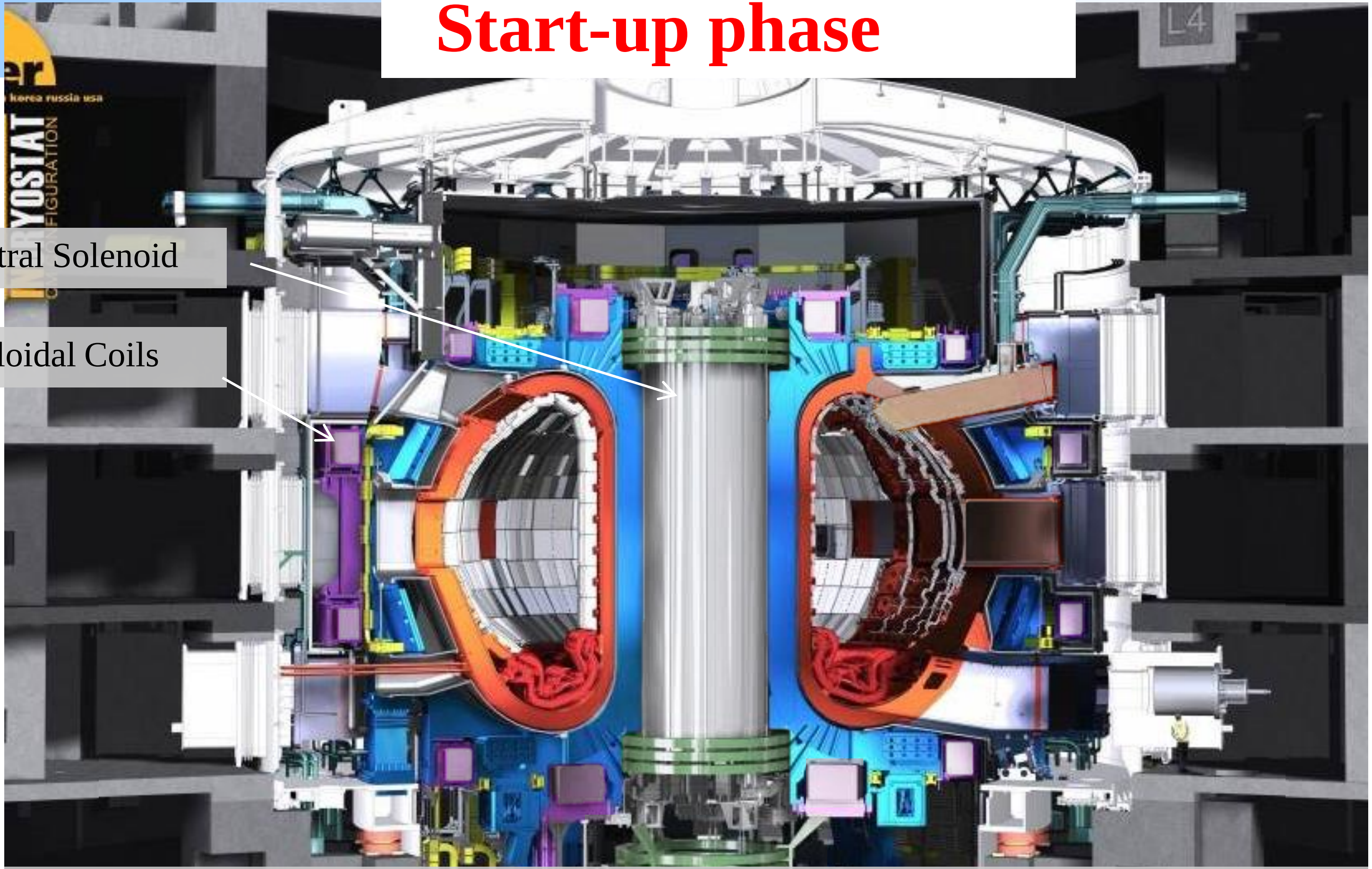
Baking , Glow Discharge

Preparation for Tokamak operation



Toroidal Coils magnetized: 5.3 Teslas on machine axis

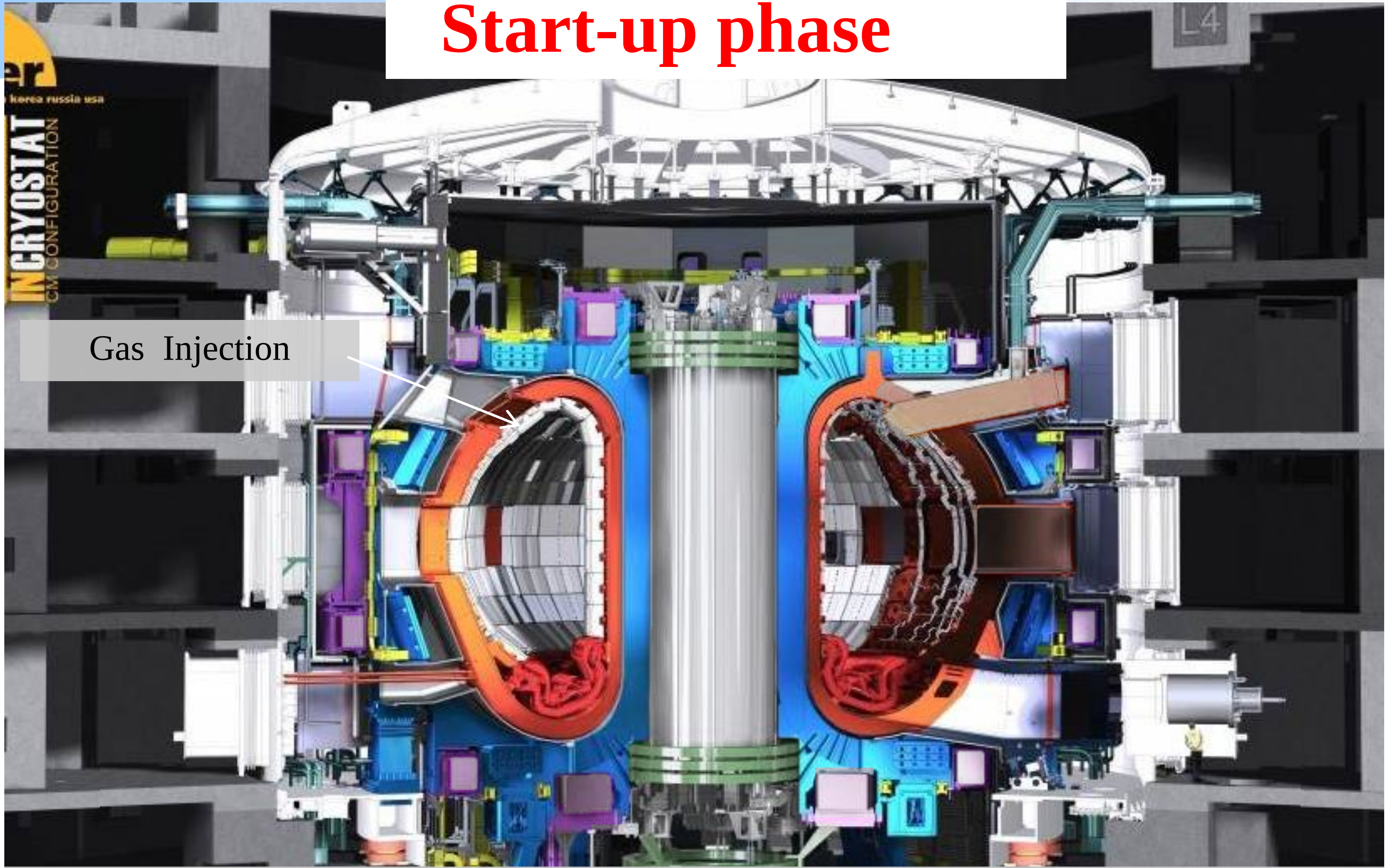
Start-up phase



Pre-magnetization of CS and PF

Voltage applied until the CS reaches full flux

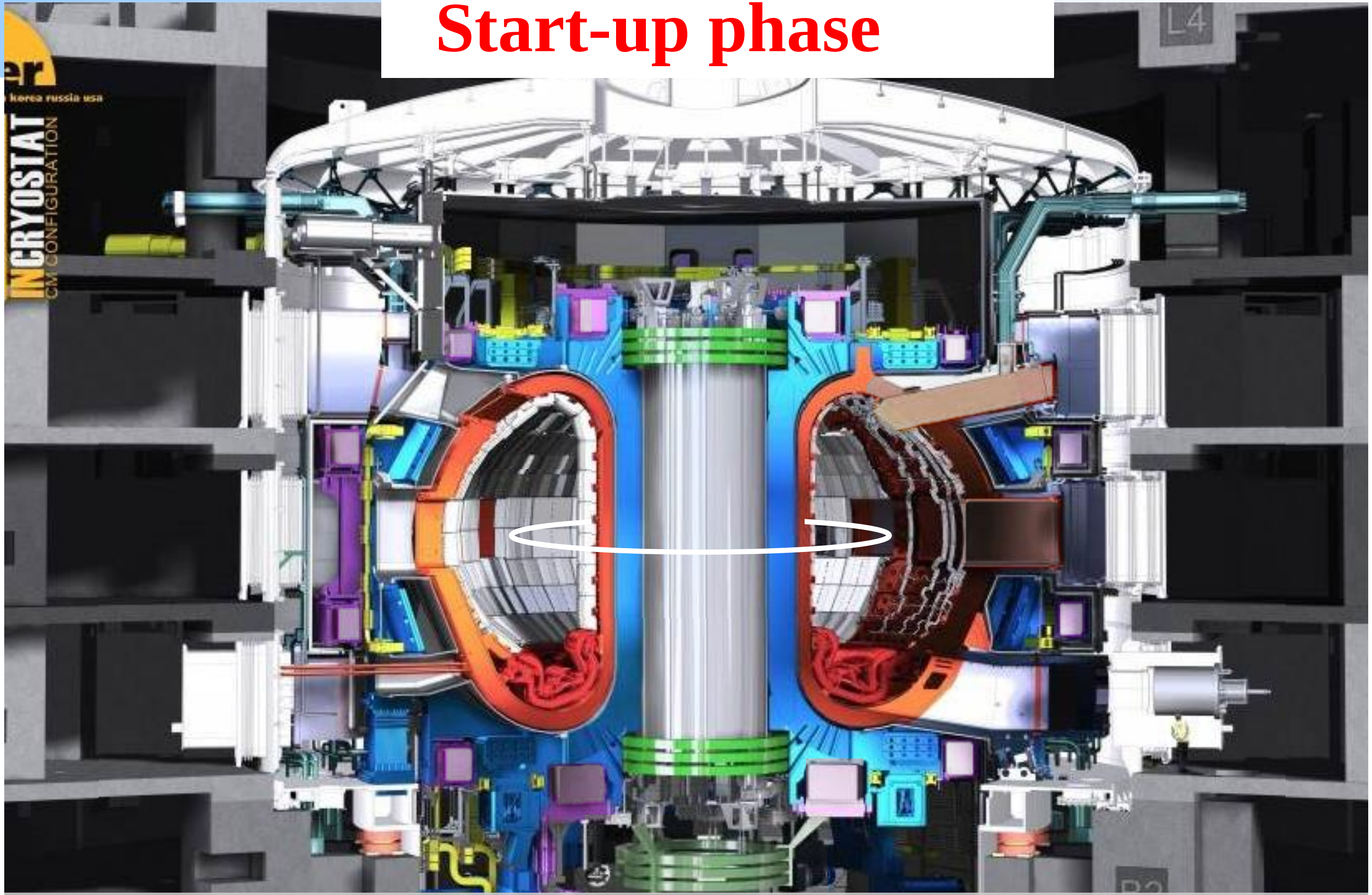
Start-up phase



Gas Injection (D or D/T)

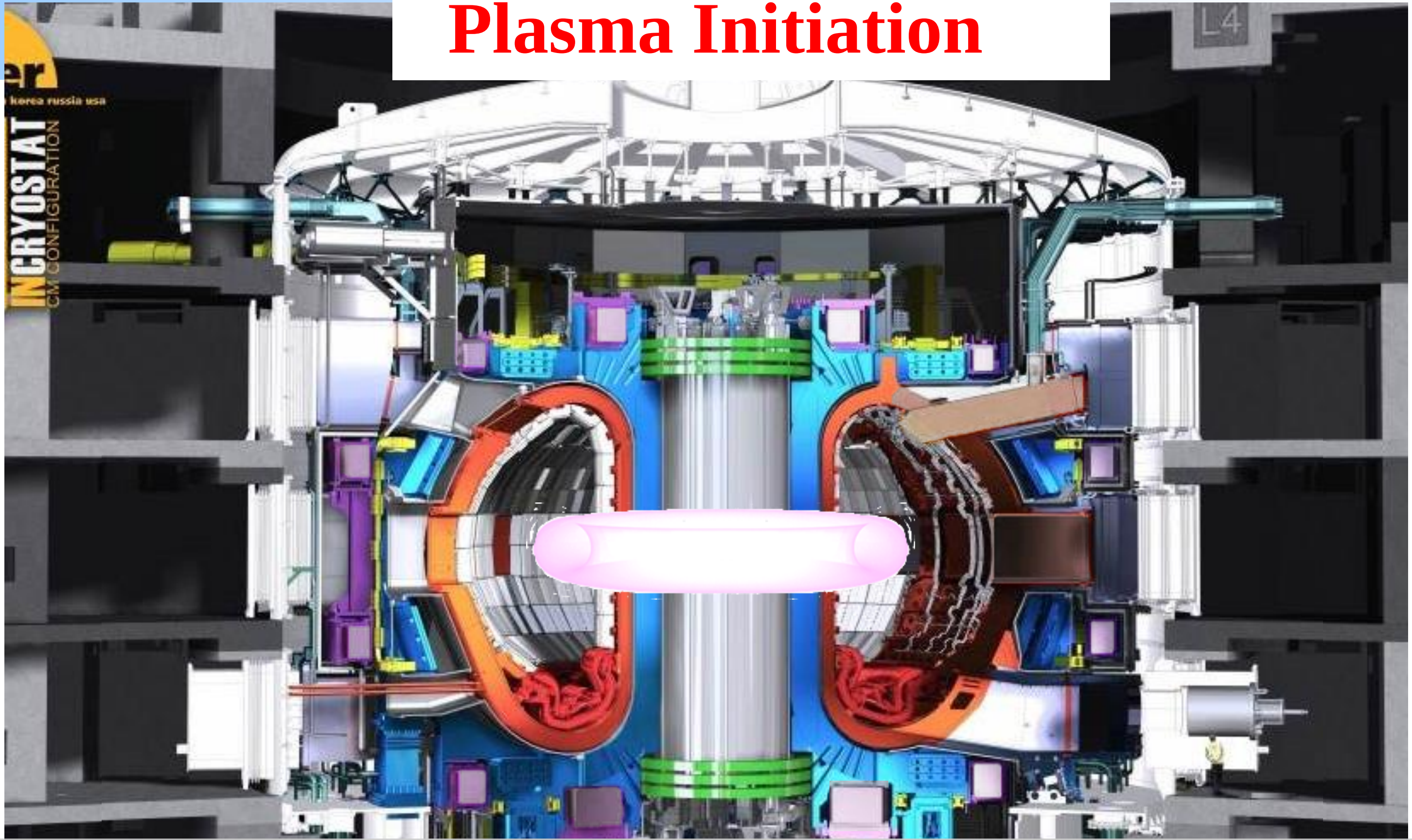
Pressure rises to a few 10^{-5} millibar. (0.5 mPa)

Start-up phase



Discharge the CS flux through resistors to raise loop voltage to induce breakdown

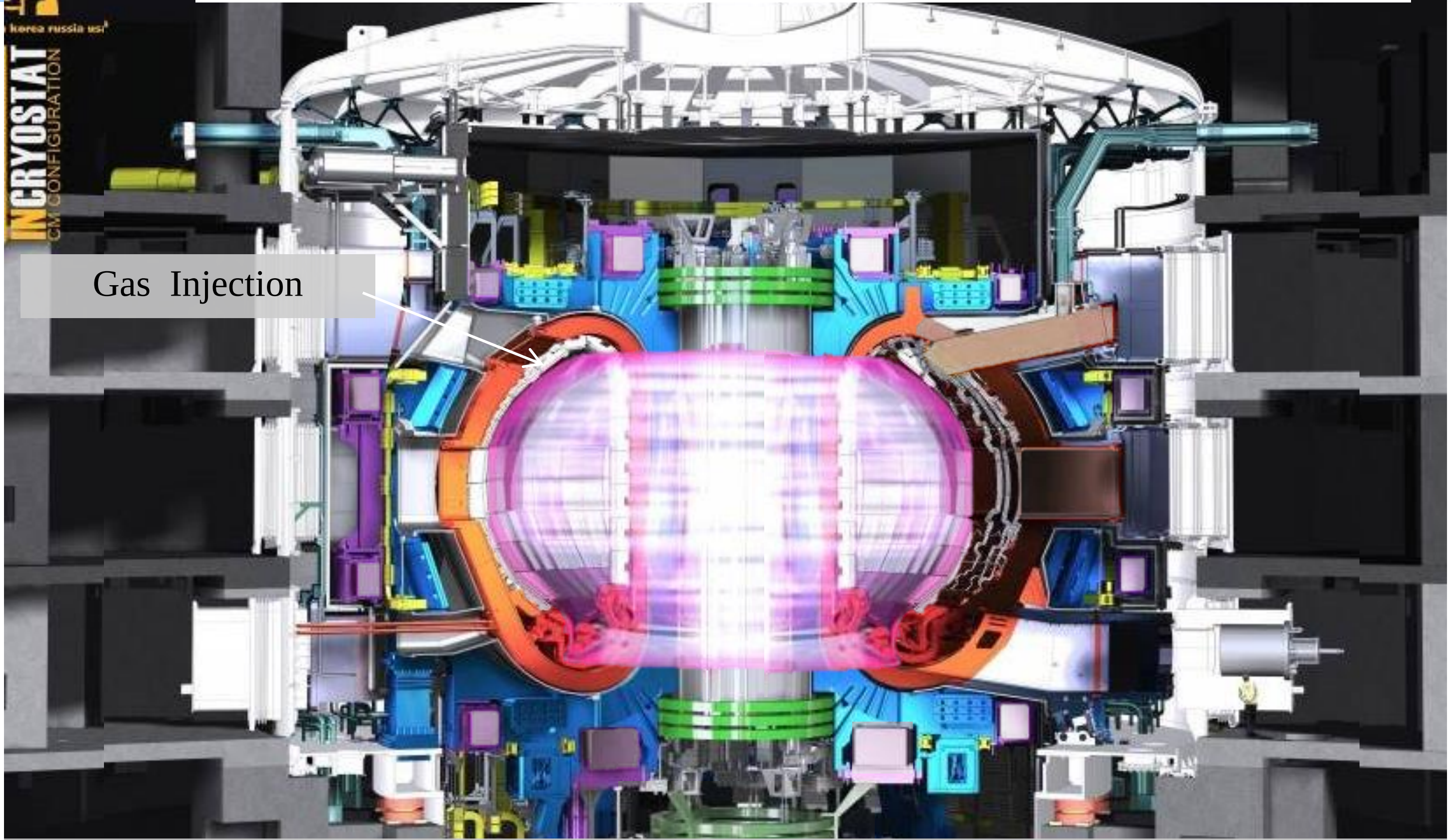
Plasma Initiation



Voltage breaks down the gas, ionizes it, and creates the plasma

Plasma current raised by transformer action: the change of the CS coil current (primary current) induces the plasma current (secondary current)

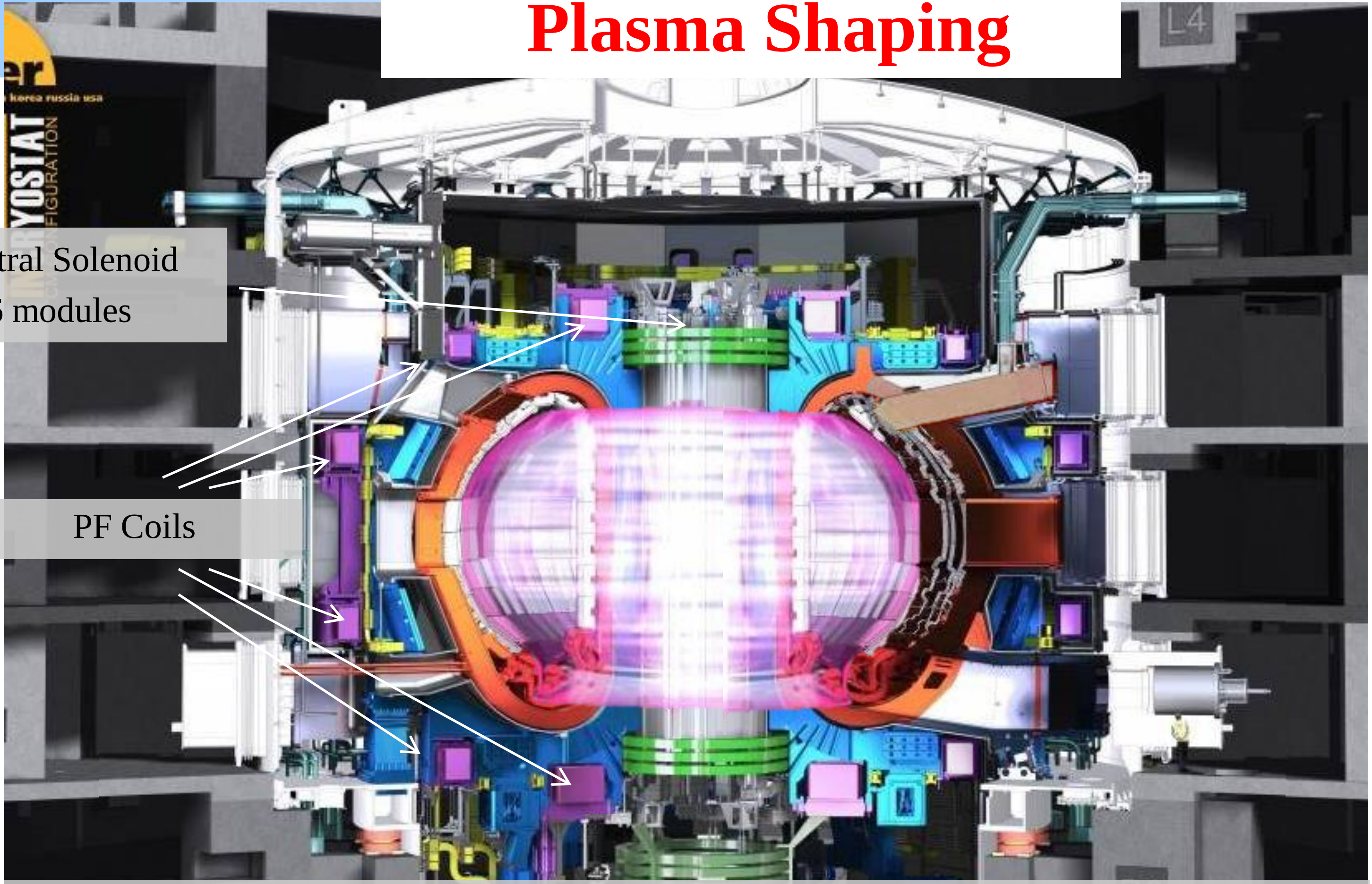
Current and Density Ramp Up



Current in the plasma increased until 15 MA

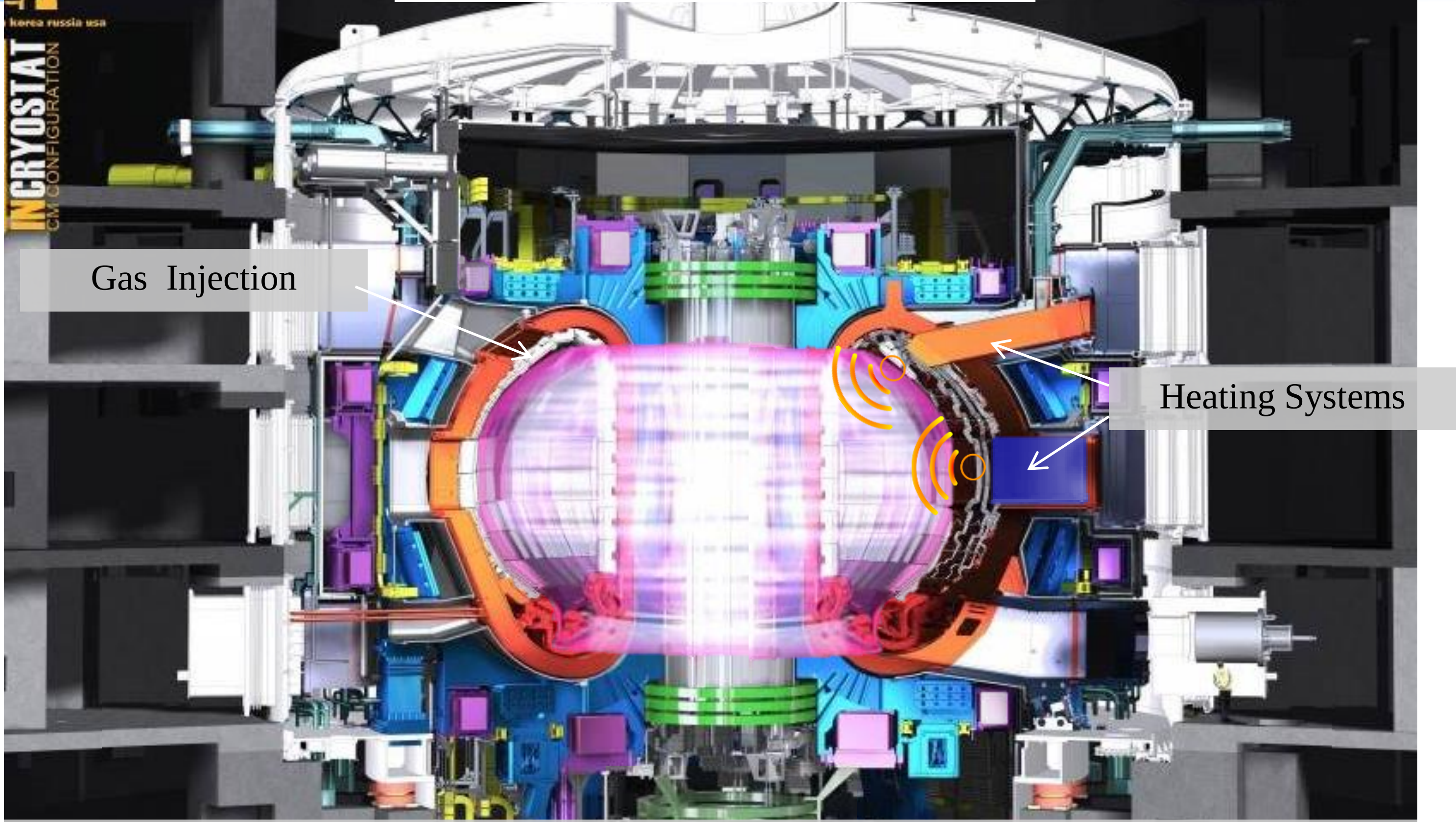
The plasma density is brought to the required value by gas and pellet injection

Plasma Shaping



Feedback-controlled adjustment of the plasma position, plasma cross-section, and plasma current through PF and CS coils

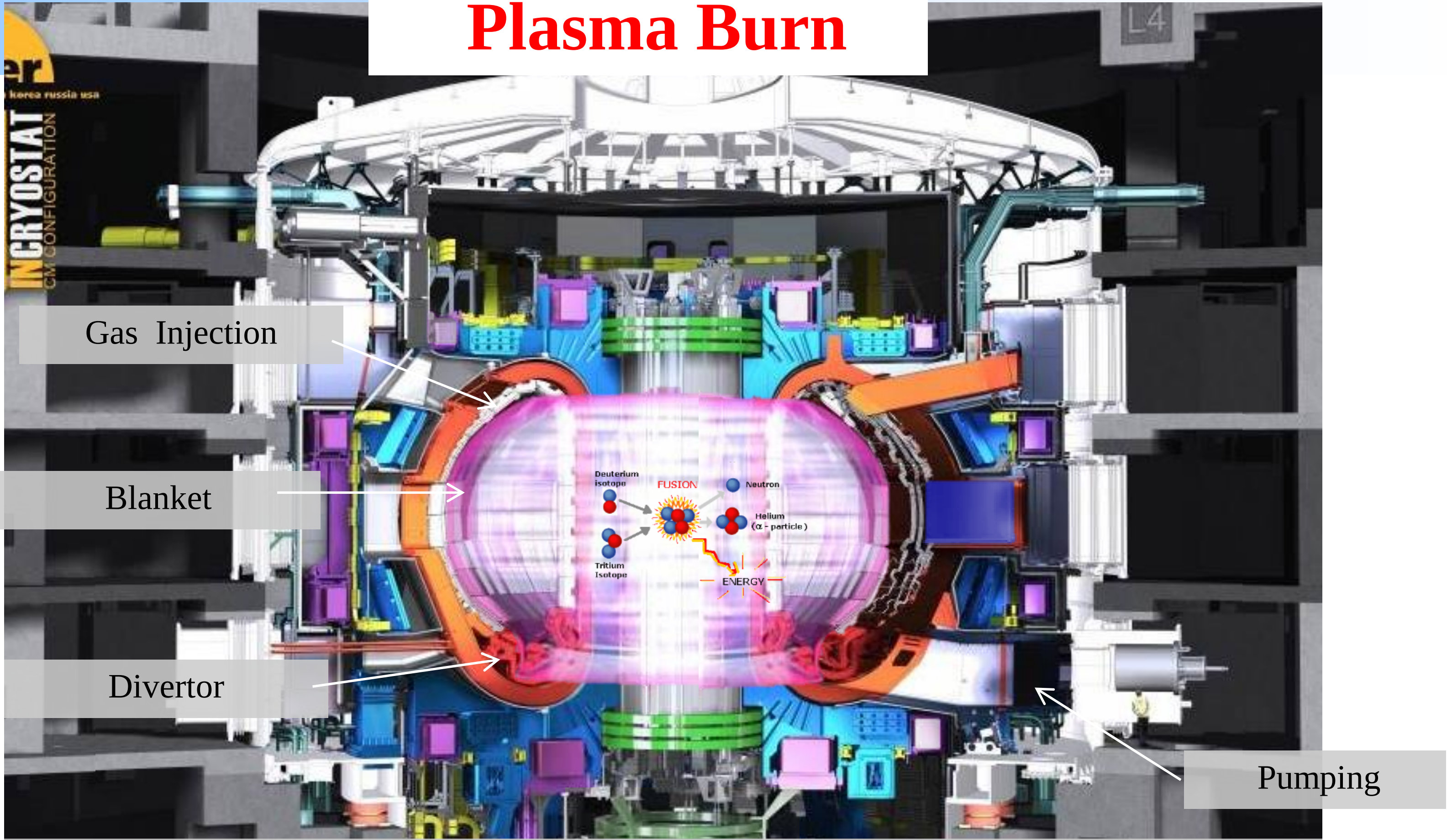
Plasma Heating



Plasma current first heats the plasma by resistance

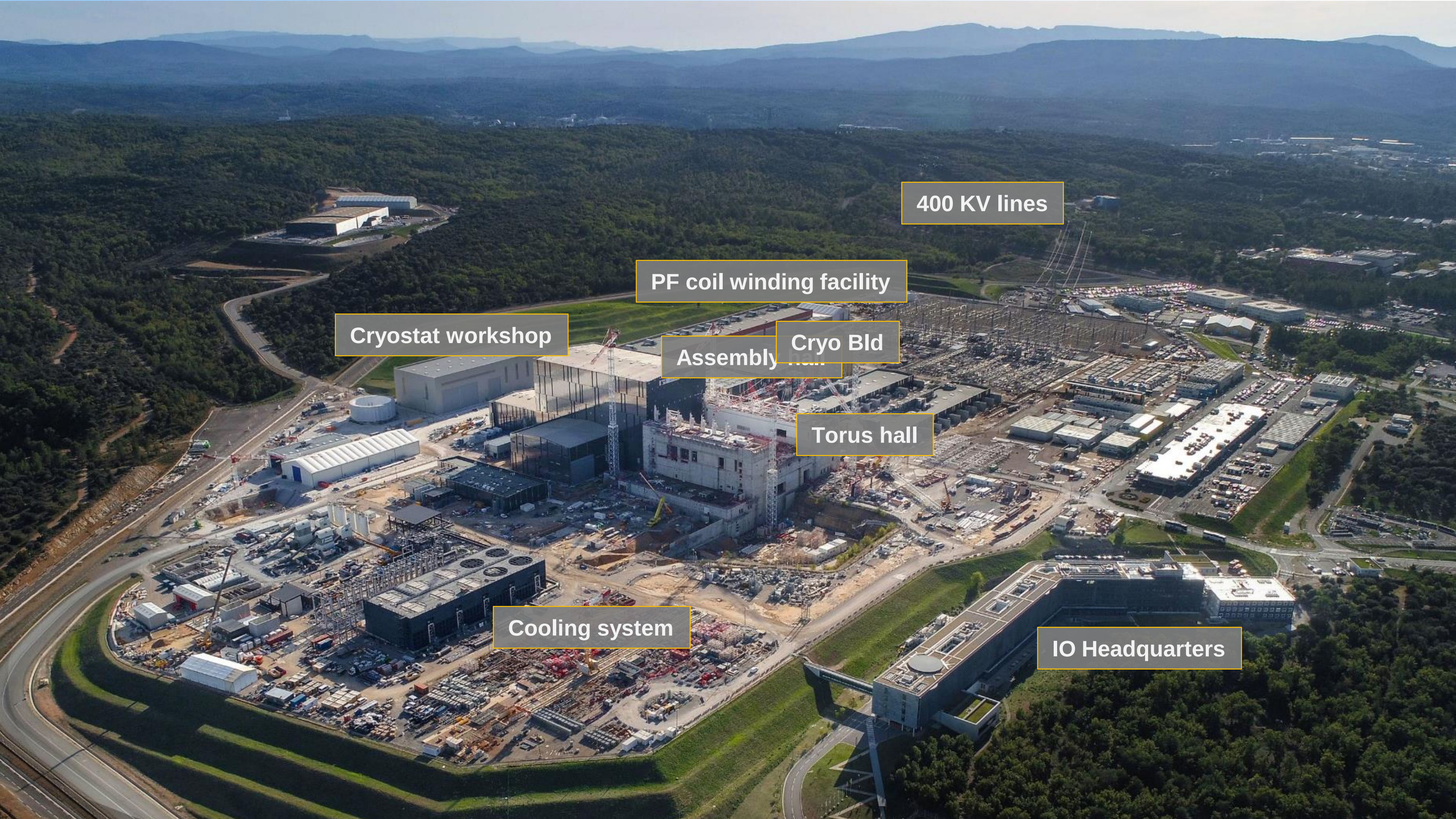
Then external heating is added up to 50MW

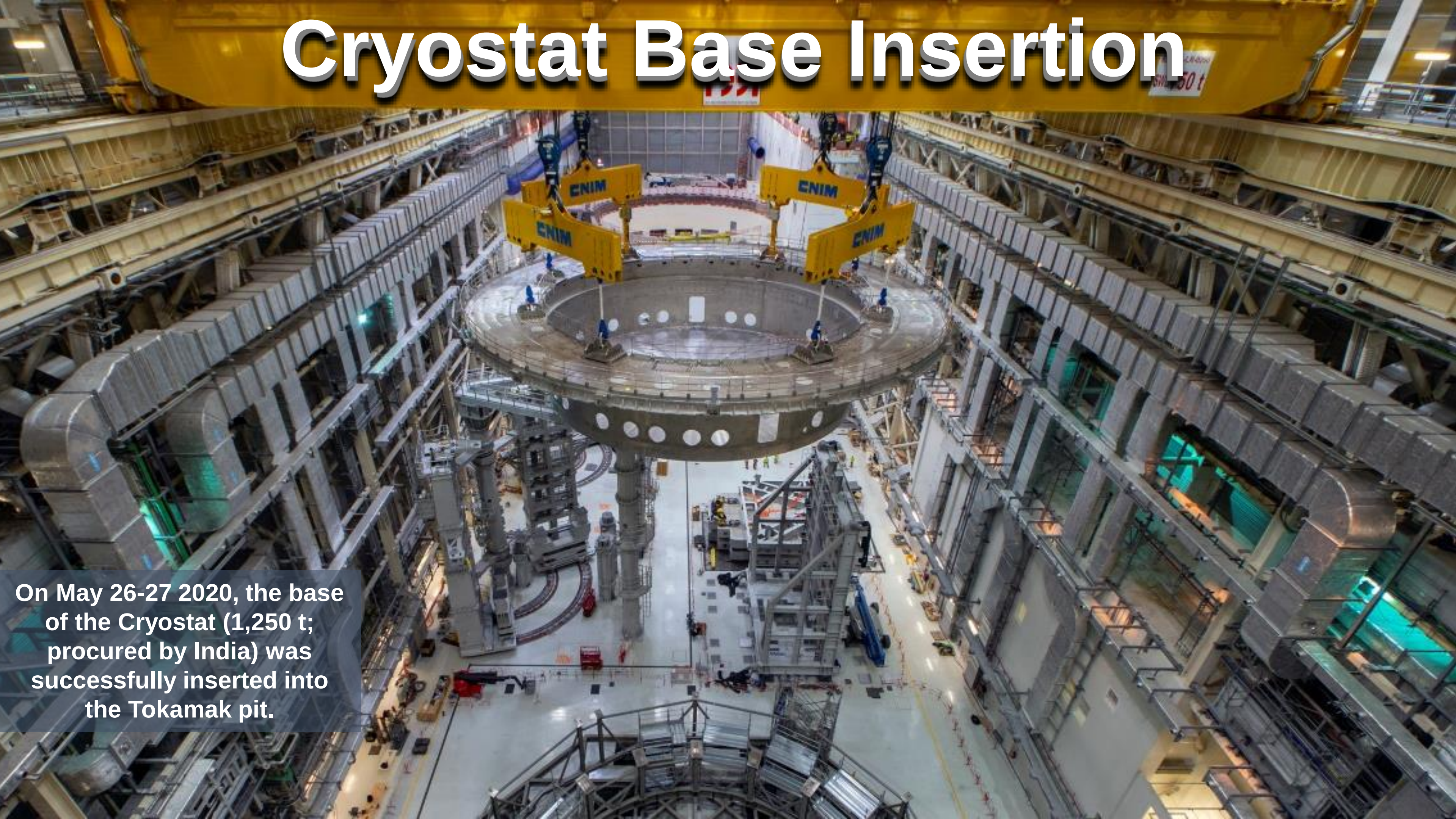
Plasma Burn



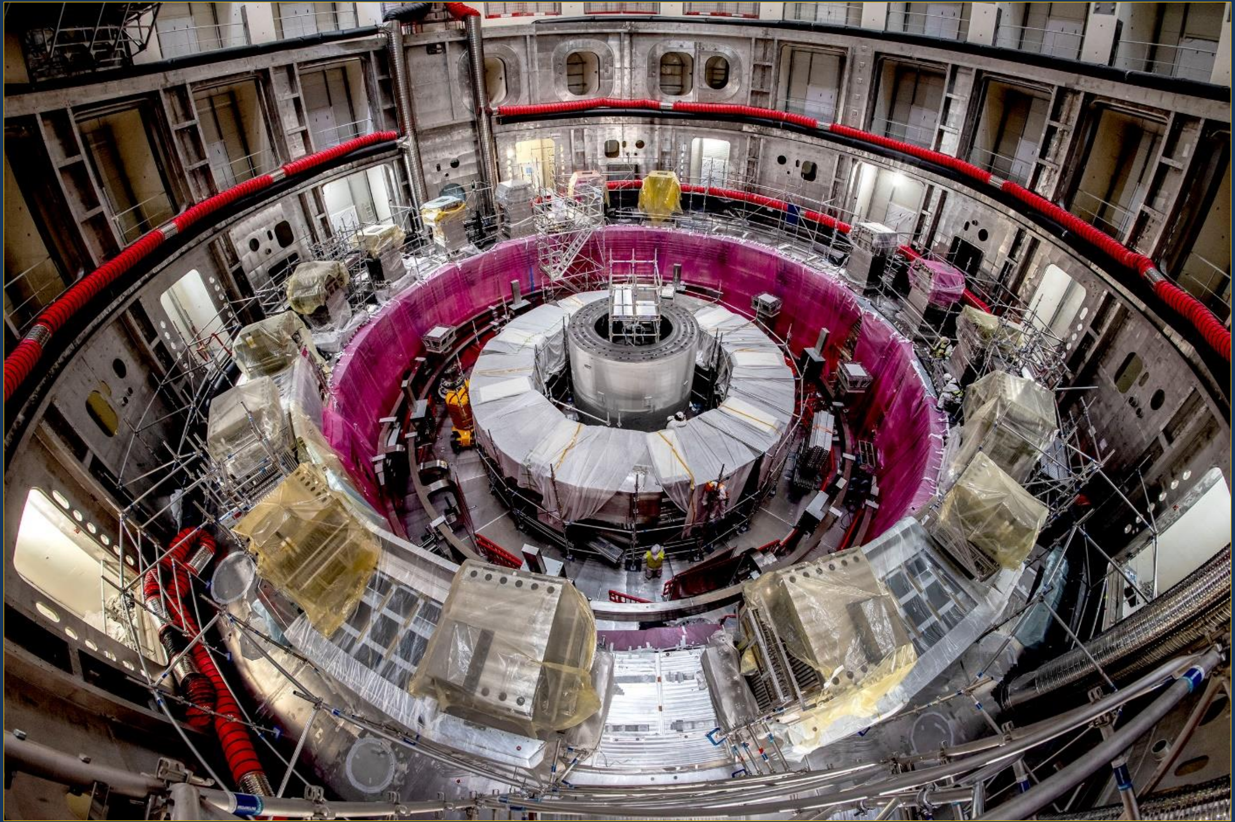
Conditions for thermonuclear reactions reached

Plasma constantly refueled and unburnt fuel recovered from exhaust


400 KV lines
PF coil winding facility
Cryostat workshop
Assembly
Cryo Bld
Torus hall
Cooling system
IO Headquarters


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

The Tokamak is taking shape!



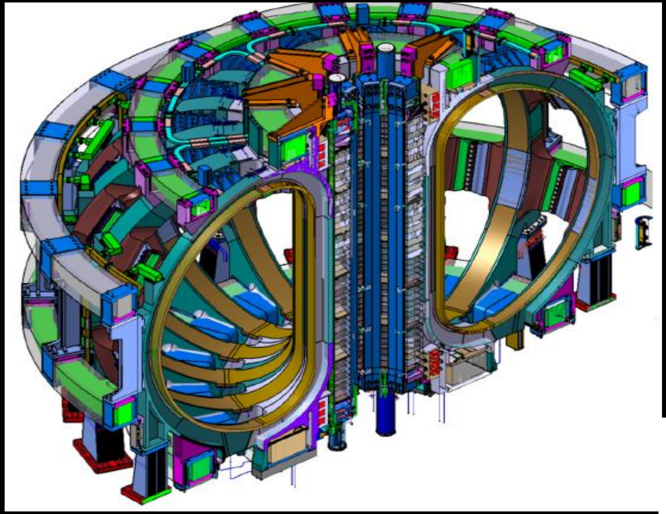
The 30 m x 30 m cryostat is being assembled and welded on site. The lower cylinder and the base sections are now in place.

NOW installed: the bottom half of the cryostat and its thermal shield, a large PF coil, gravity supports etc.

First Sector Subassembly …

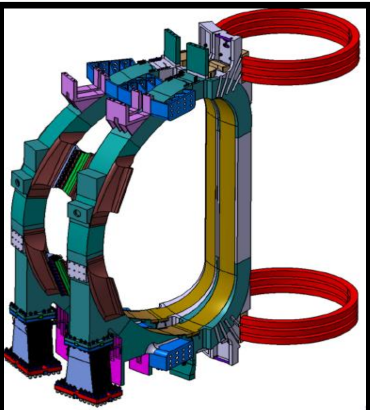
First vacuum vessel in place for subassembly April 2021

ITER Magnet System

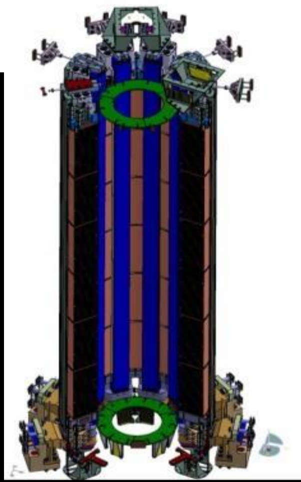


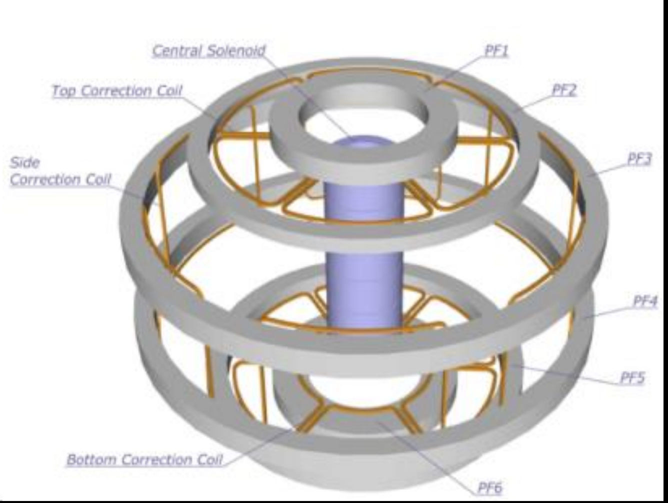
- **At the heart of the ITER tokamak is the largest superconducting magnet system ever designed**
  - 18 Nb_3Sn Toroidal Field (TF) Coils,
  - a 6-module Nb_3Sn Central Solenoid (CS),
  - 6 NbTi Poloidal Field (PF) Coils,
  - 9 NbTi pairs of Correction Coils (CCs).

Pair of TF Coils



CS Coil



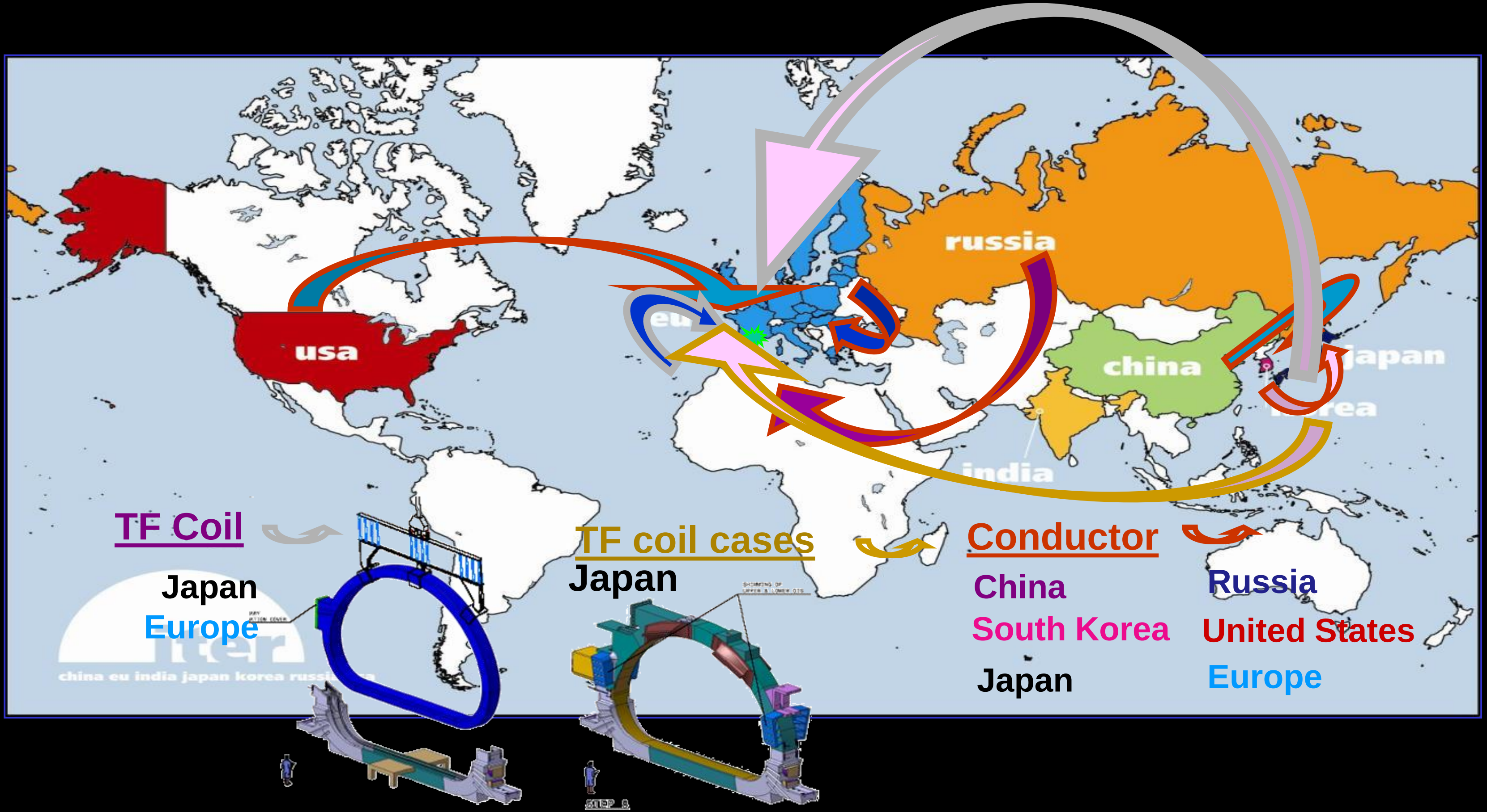


PF 1

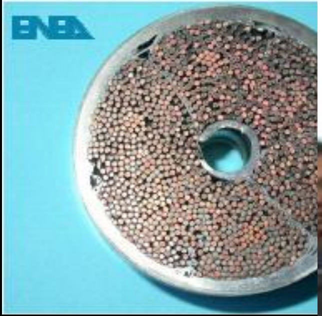
PF 2-6

CCs

Manage collaboration (TF Coils)

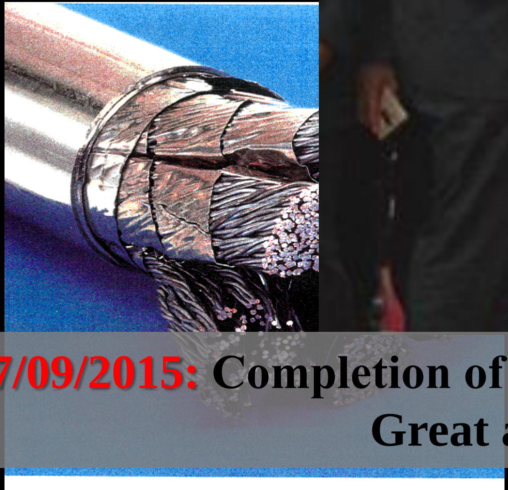


TF Conductor Procurement



40 mm diamete

ITER TF Con

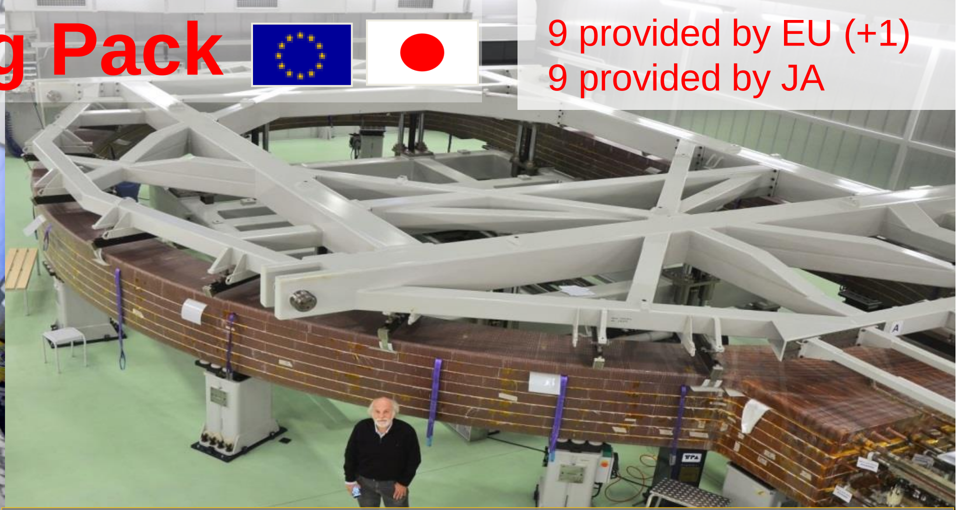


17/09/2015: Completion of a 8 year procurement of the superconductor cable. 610 million €. Great achievement of common harmonized process.

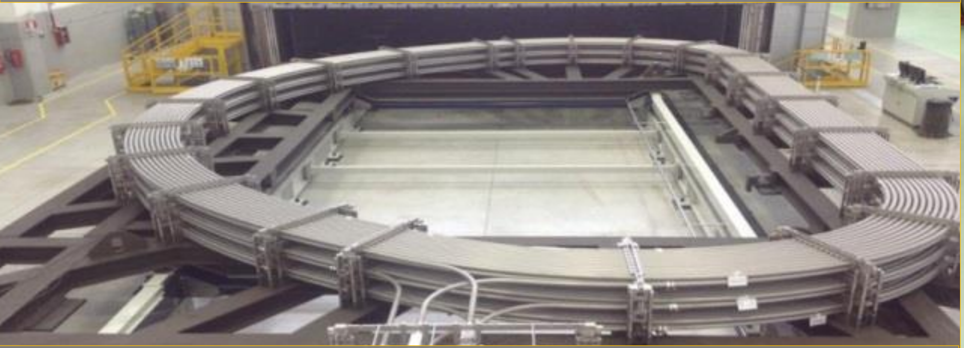
TF Winding Pack

9 provided by EU (+1)
9 provided by JA

The radial plates that hold the conductor of the toroidal field coil: D-shaped stainless steel structures with grooves machined on both sides along a spiral trajectory.



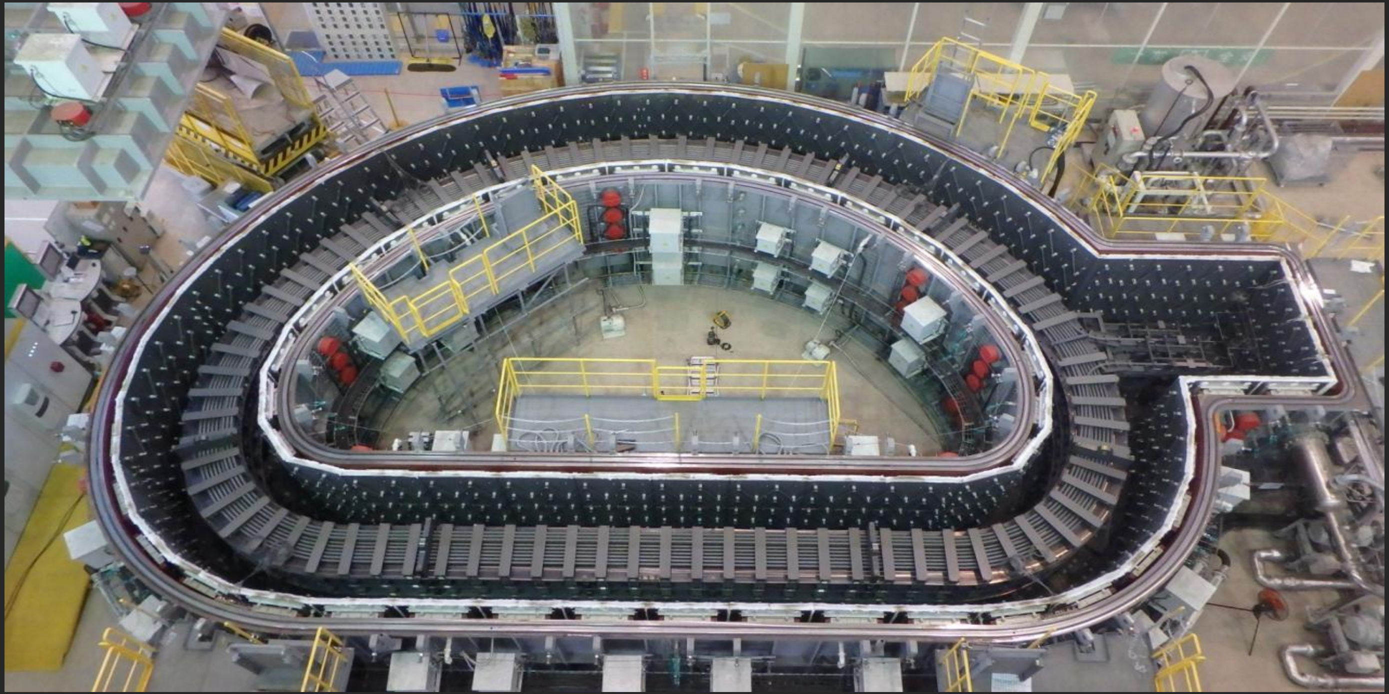
TF Coil Winding Line



Toroidal field coil high-temperature treatment to form niobium-tin superconductor compound.

The first toroidal field coil winding pack – the 110-ton inner core of ITER's TF Coils was completed in April 2017

Manufacturing progress



The D-shaped pancake windings are heat treated at 650 °C for 100 hours to react tin and niobium to form the superconducting compound .

Toroidal Field Coil

One of the completed TF coils delivered by Japan

PF Coil winding facility

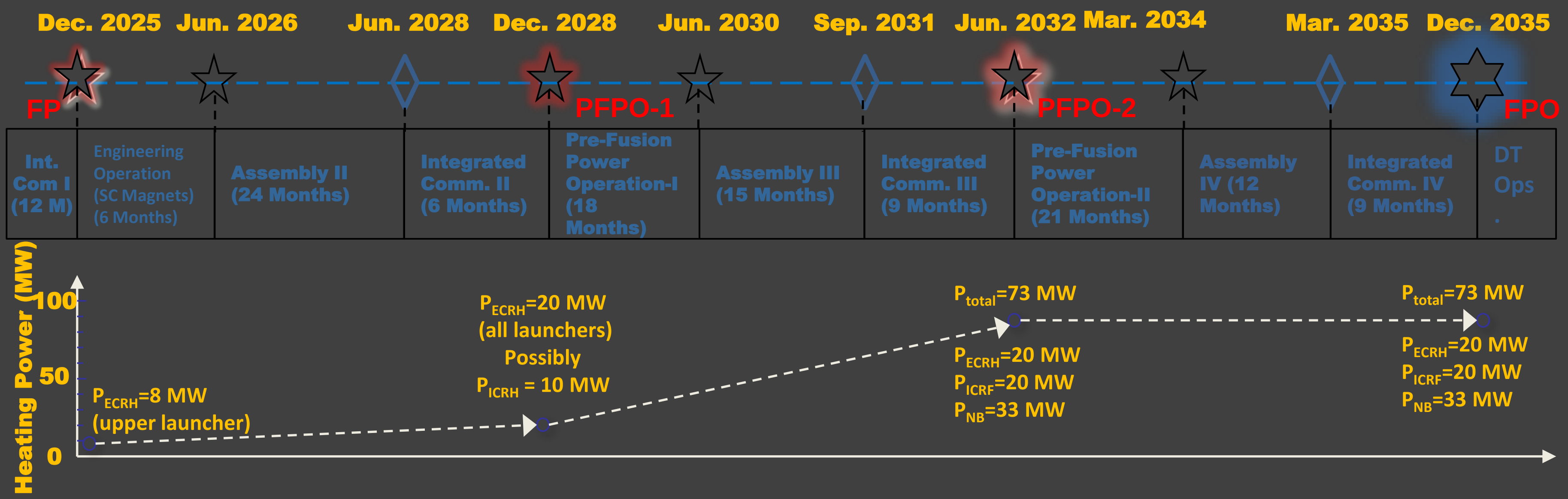
On site fabrication of the 4 largest Poloidal Field Coils (17 to 24 m in diameter).

Fabrication, central solenoid (USA)

From 13T to -13T in 100s! Cable of 45 KA (45x45mm), 576 fil NbSn + 288 fil Cu at 4.5 K

Staged approach to DT plasma

- 4 operational phases with staged introduction of heating power and measurement capability.
- First plasma in 2025 / 2026; full power in 2035. Total operation time may exceed 20 years



ITER is progressing well ☺

Let us continue to work together to make fusion energy a reality

For an extended tour of the ITER worksite, please visit:
https://www.iter.org/news/videos/571