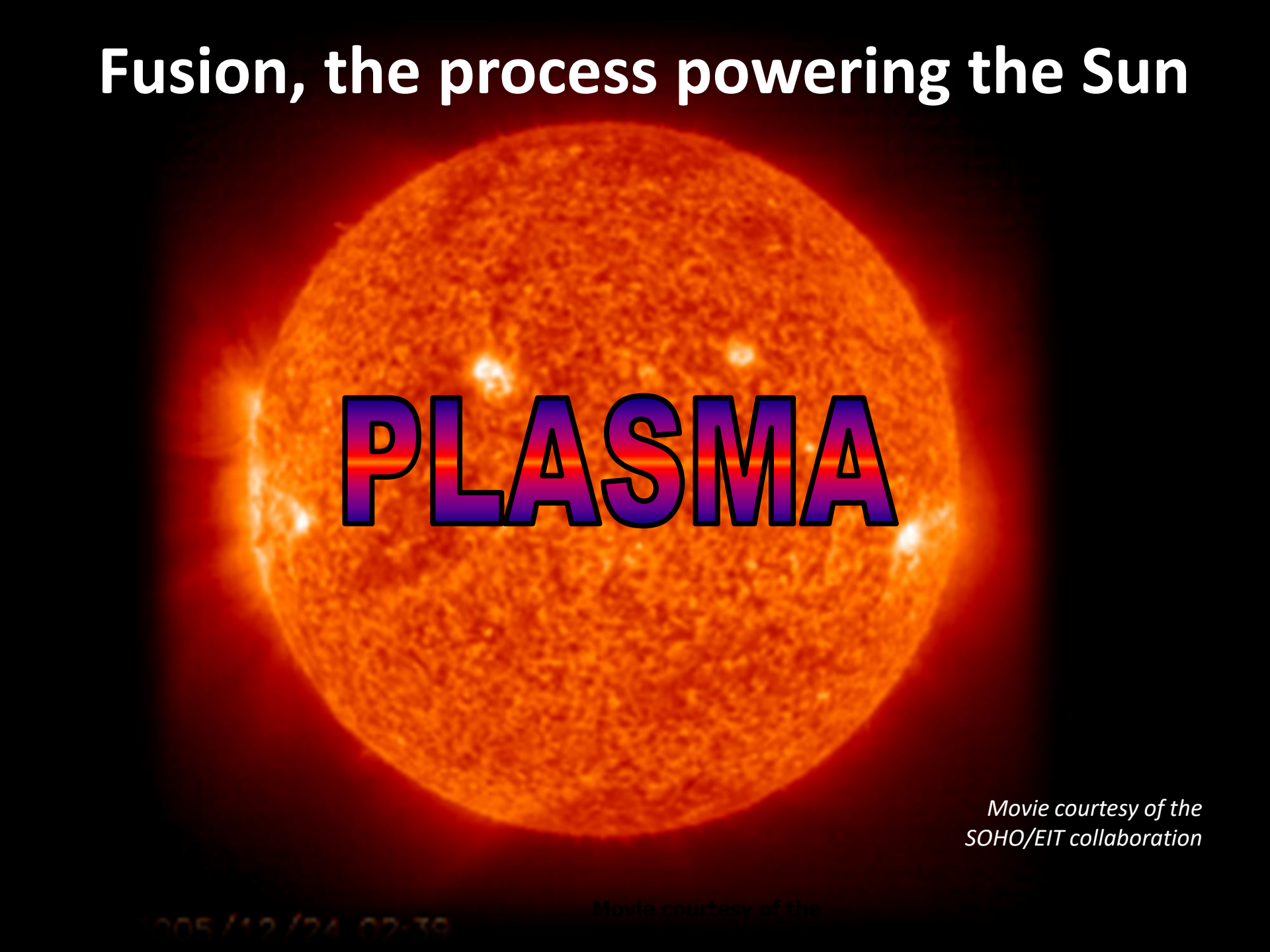
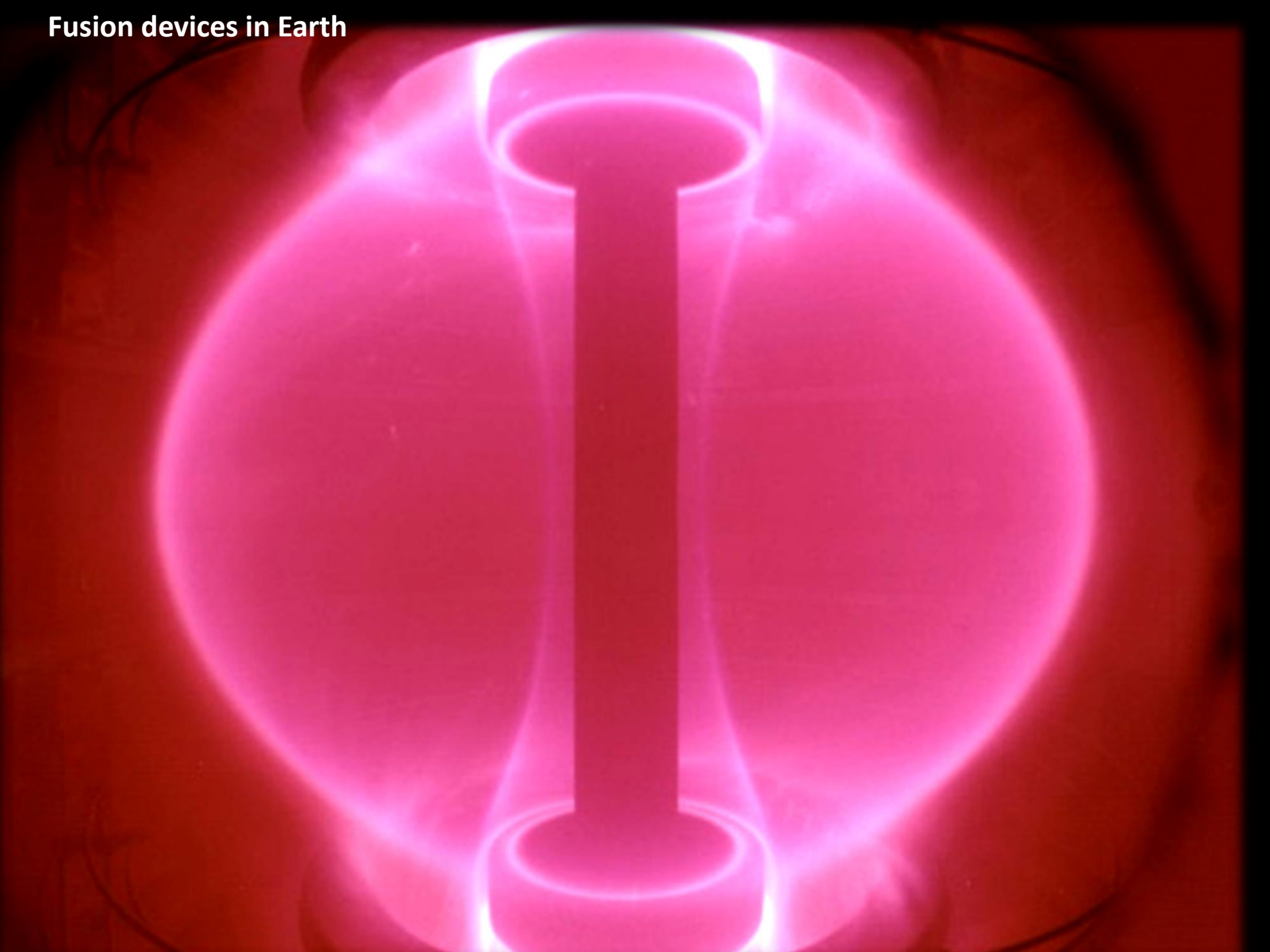
Fusion, the process powering the Sun

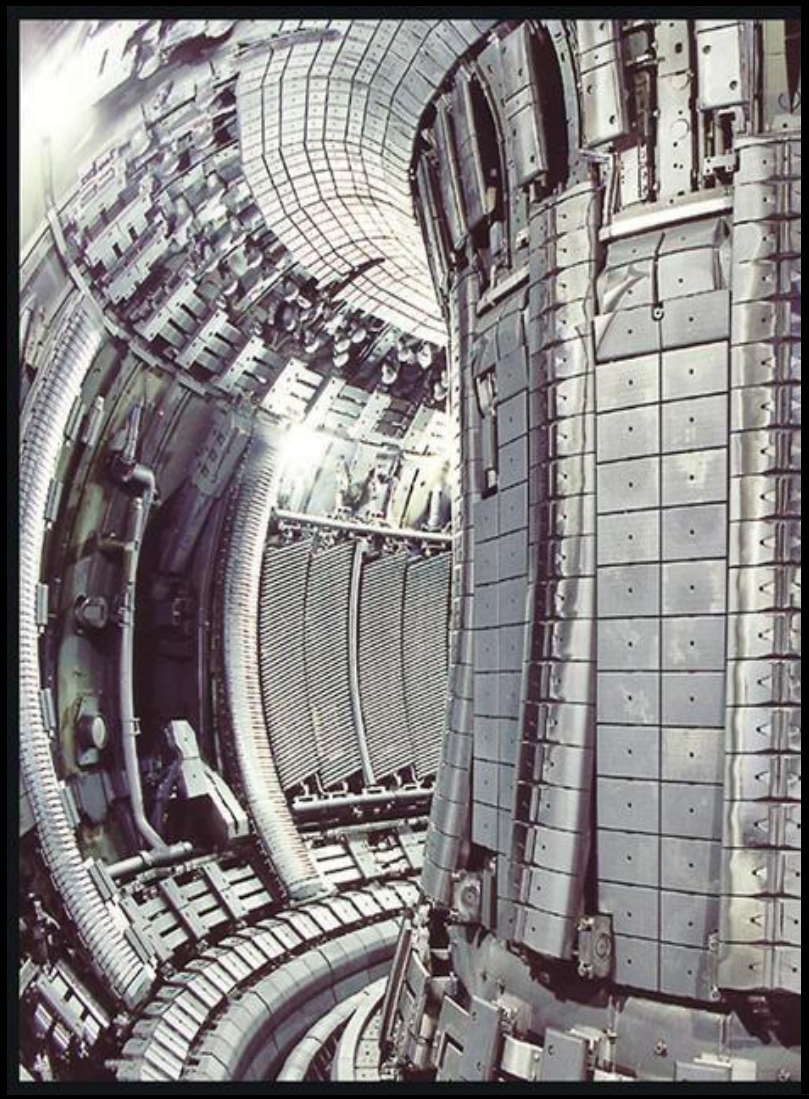


Movie courtesy of the SOHO/EIT collaboration

Fusion devices in Earth



Plasma inside JET
(Joint European Torus)



ITER - The Way to Fusion Energy

Paco Sánchez

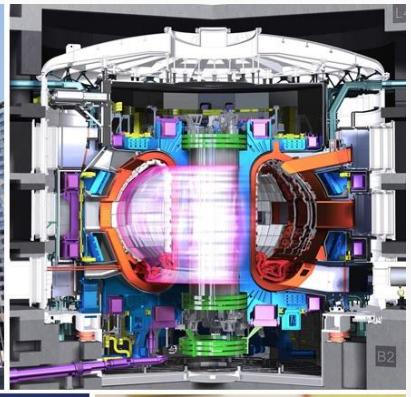
EU Gyrotrons Project Manager at *Fusion For Energy* (F4E)

CAS, 06 October 2023

FUSION FOR ENERGY (F4E)

The European Union organisation for the development of Fusion Energy

- F4E: public entity set up in 2007 for 35 years
- Headquarters: **Barcelona**
  Offices:
  - Cadarache, France
  - Garching, Germany
  - Naka and Rokkasho, Japan
- Mission: **bring fusion energy to Earth**
- Collaboration: **more than 500** Industries and Research Centers
- Team: engineers, physicists, commercial and procurement officers, project managers and administrators, working at the **frontiers of science and technology**
- **F4E contribution to ITER: 45%**



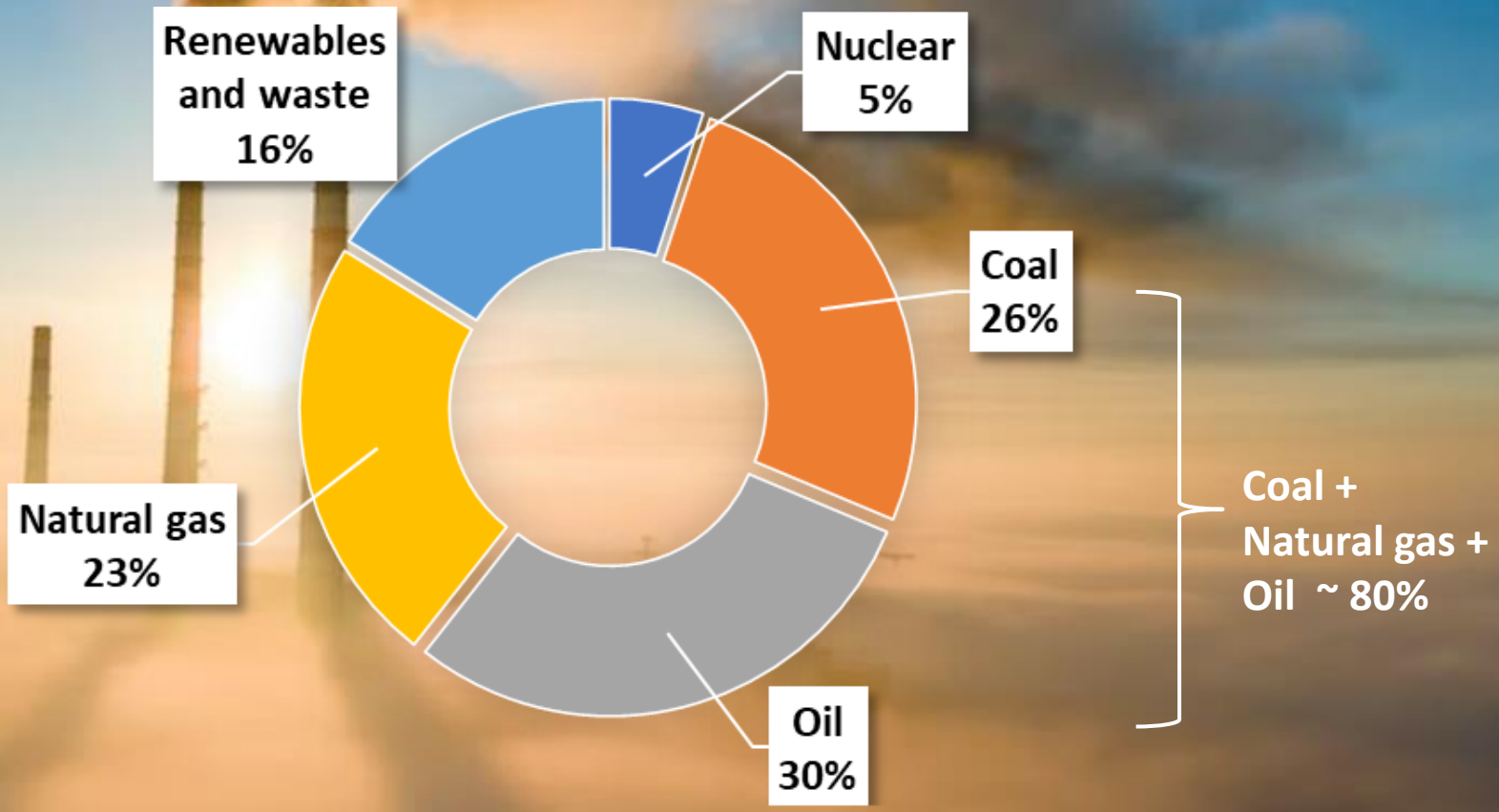
OUTLINE

- **Why** – The fusion promise
- **What** – Fusion principles
- **How** – Fusion technology
- **Where and When** – ITER

THE ENERGY CHALLENGE

FUSION FOR ENERGY

WORLD TOTAL ENERGY SUPPLY BY SOURCE (2021)

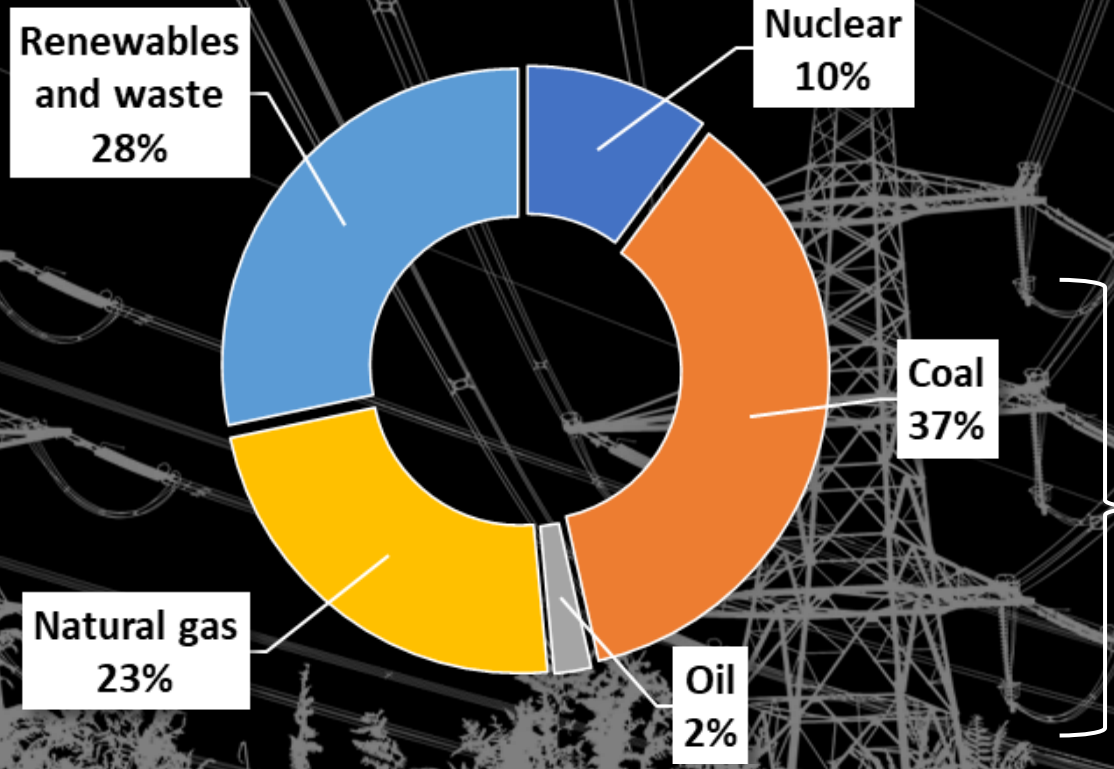


IEA (2022), World Energy Outlook 2022, IEA, Paris
https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0

THE ENERGY CHALLENGE

FUSION FOR ENERGY

WORLD ELECTRICITY GENERATION MIX BY FUEL (2021)

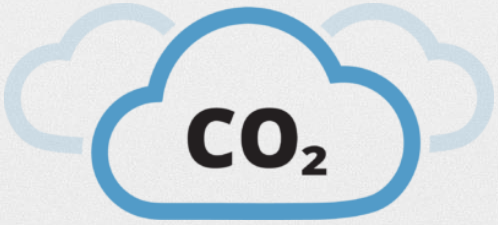


THE ENERGY CHALLENGE

A new energy source is required to …

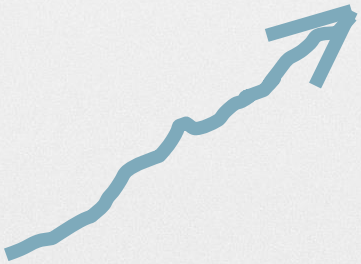
1

… replace the large dependence on fossil fuels



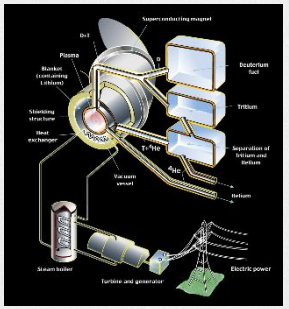
2

… help on the growing world energy needs



3

… offer industrial scale baseload electricity



THE FUSION PROMISE

Abundant fuels delivering clean and safe energy

Abundant

The basic fuels are plentiful and widely available

Security of supply

Clean

Fusion produces no greenhouse gas (CO_2) emissions

Safe

Fusion does not produce any long-lived radioactive waste

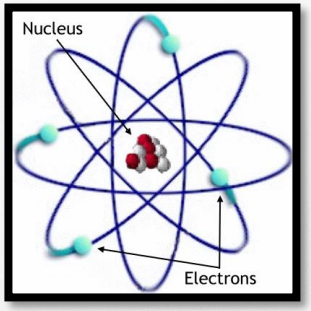
A fusion reactor can not run out of control

OUTLINE

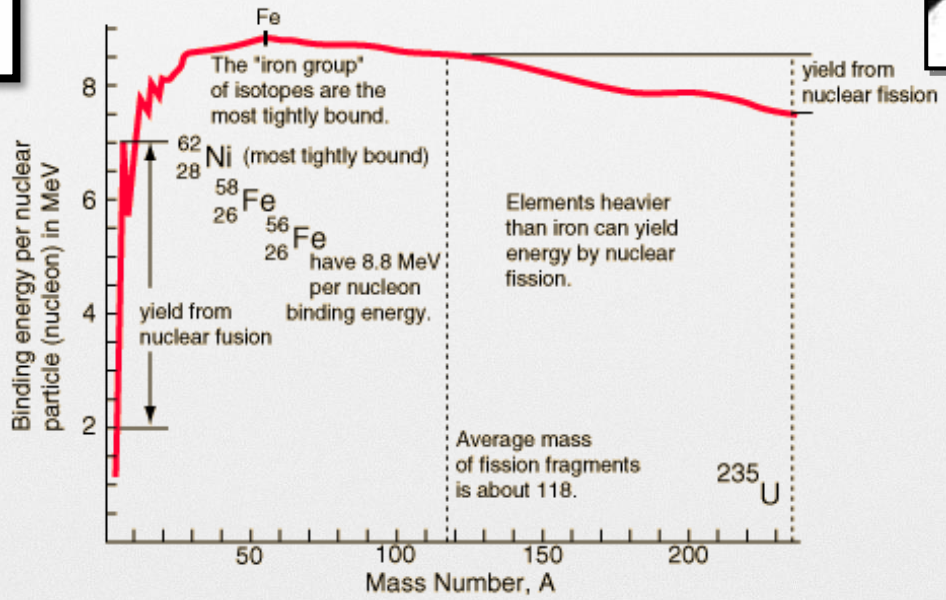
- **Why** – The fusion promise
- **What – Fusion principles**
- **How** – Fusion technology
- **Where and When** – ITER

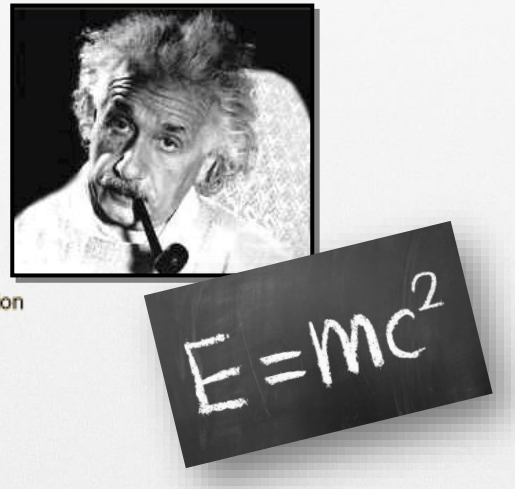
THE FUSION PRINCIPLES

Nuclear **Fusion** is the process by which two light nuclei (HYDROGEN isotopes) join together to form a heavier nucleus… and release **ENERGY**!



Nuclear: the energy is released after reaction between the **nuclei** of the atoms.

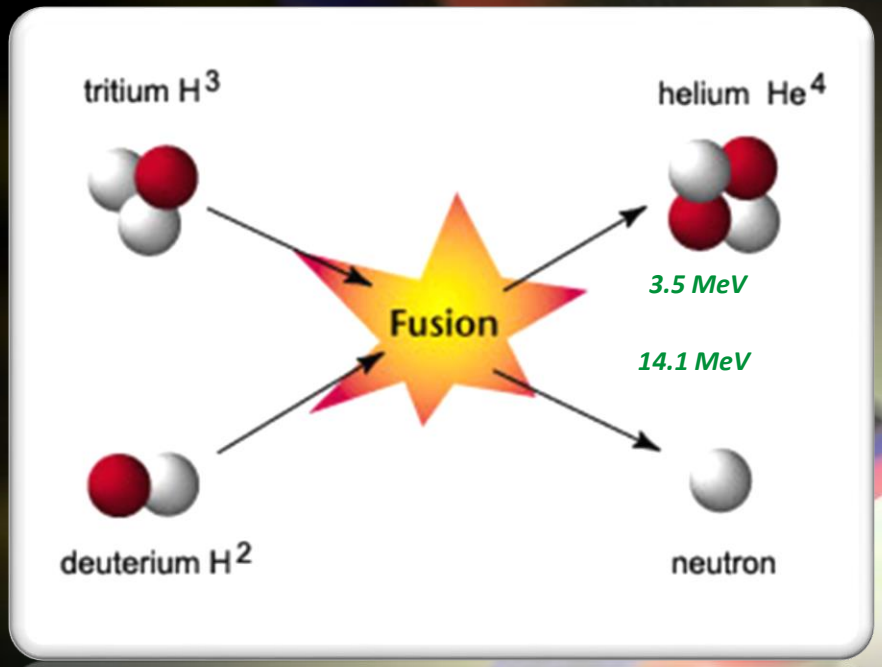




Experminentally desmonstrated in 1932 by Cockcroft and Walton

1920-1930: understanding the stars and the atom
R. d'Escourt Atkinson, F. Houtermans, E. Rutherford

THE FUSION PRINCIPLES



- **D** is obtained from water
- **T** will be generated in fusion plants, from Lithium reacting with fusion neutrons
- Fusion fuel (H isotopes) and product (He) are not radioactive

Most feasible fusion reaction on Earth is from Hydrogen isotopes: Deuterium (**D**) – Tritium (**T**)

THE FUSION PRINCIPLES

Huge energy released in nuclear reactions in comparison with the energy released by chemical reactions

+

=

ENERGY DENSITY CONTENTS

FUSION FOR ENERGY

Energy needs of 1 million population for a period of 1 week can be covered by:

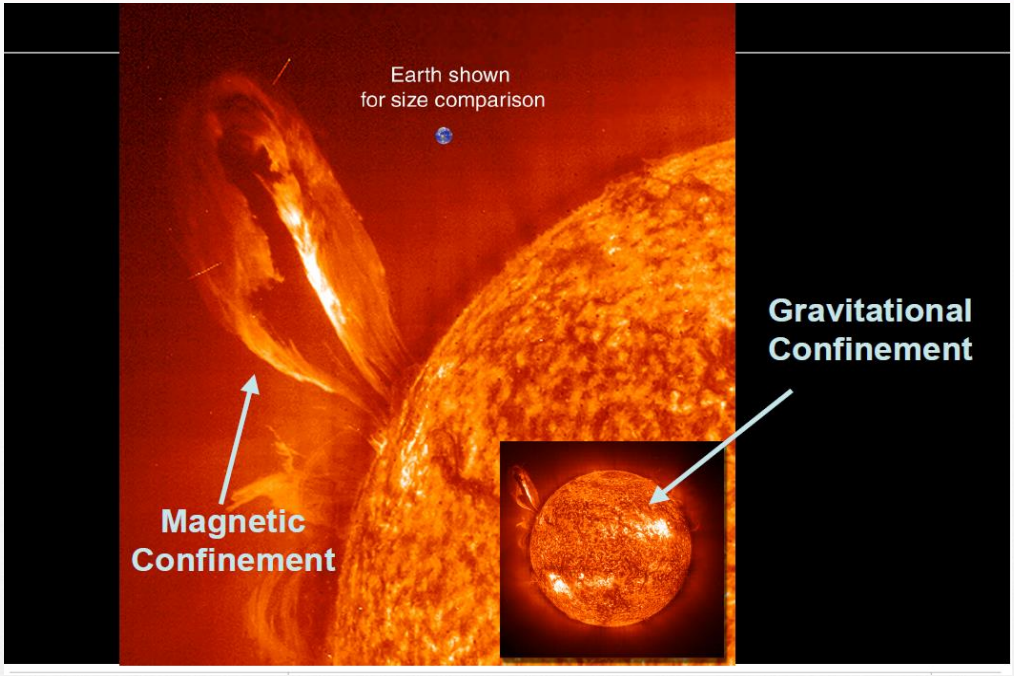
10 million kg of coal

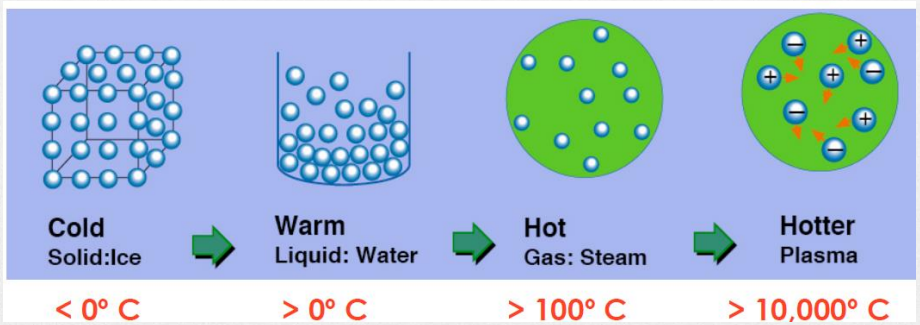
4.5 million litres of oil

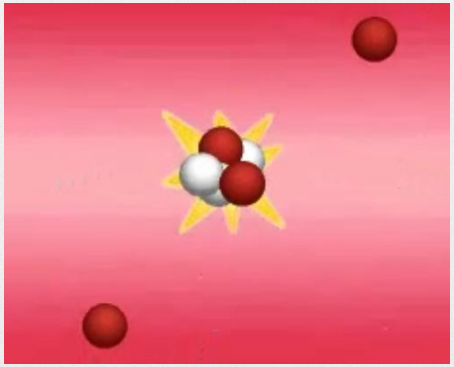
10 kg of uranium

1 kg of deuterium-tritium !

PLASMA, 4TH STATE OF MATTER



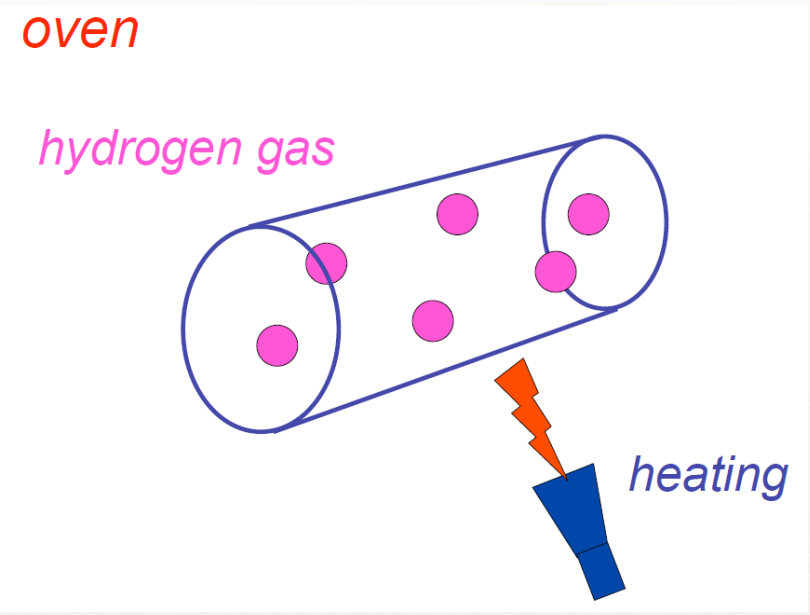


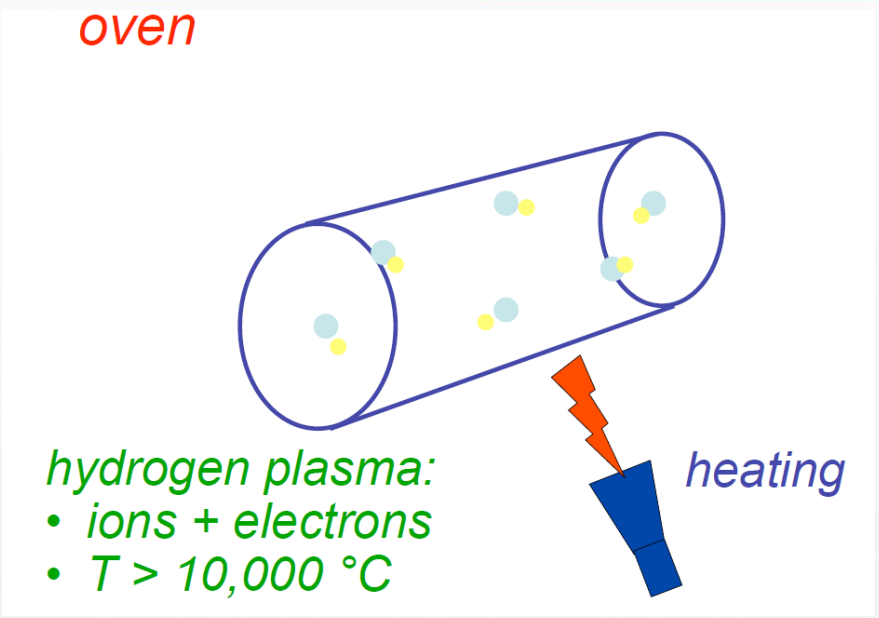


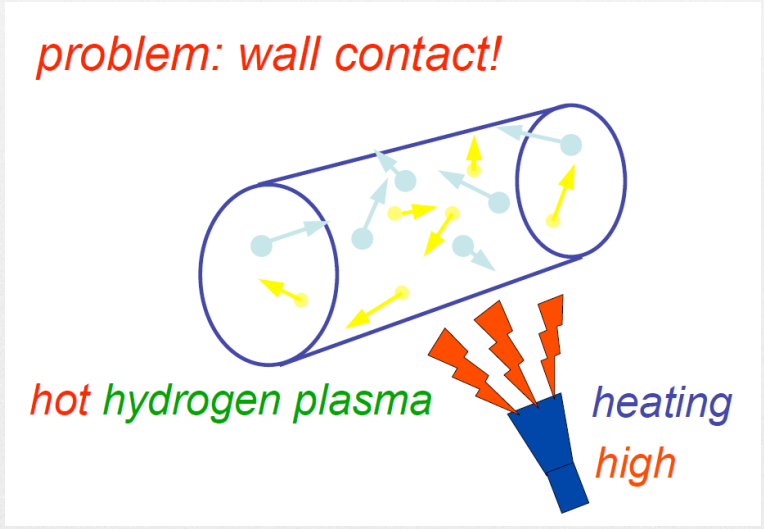
So, lets heat up the gas → plasma to 150.000.000 ºC, but… <u>where</u>?

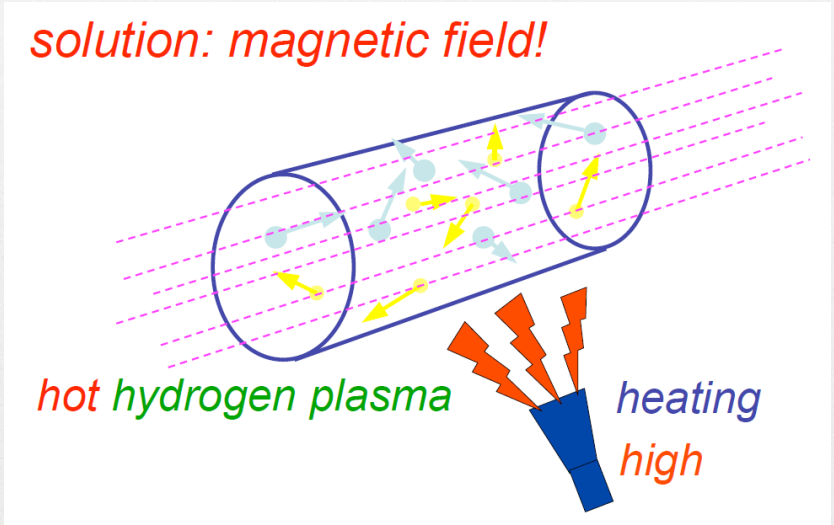
*Note: at high temperatures, electrons and nuclei are separated => **Plasma** … the 4th state of matter*

HOW TO CONFINE PLASMA ?

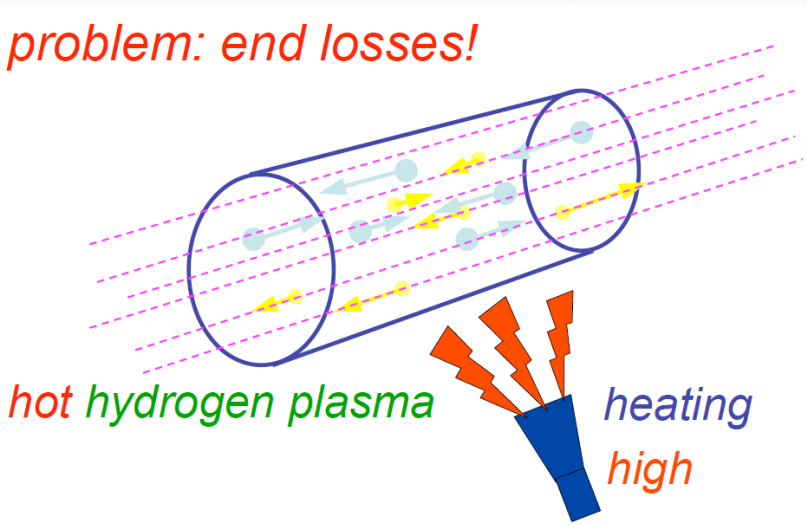


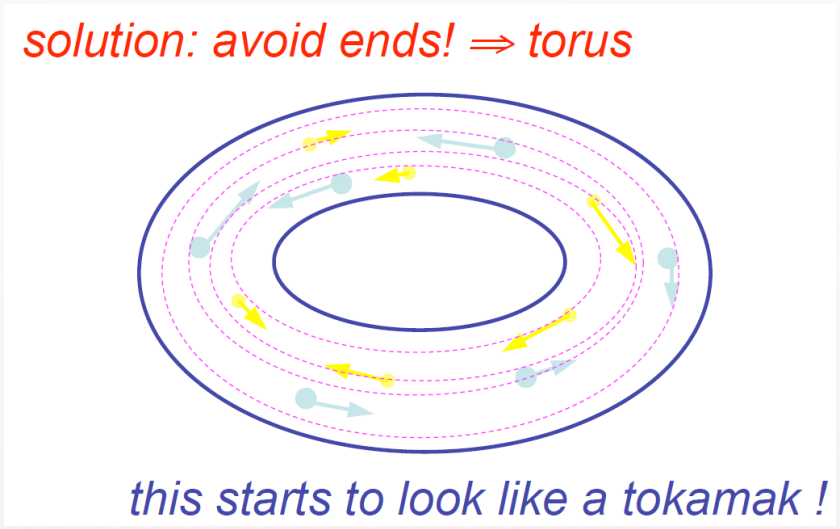




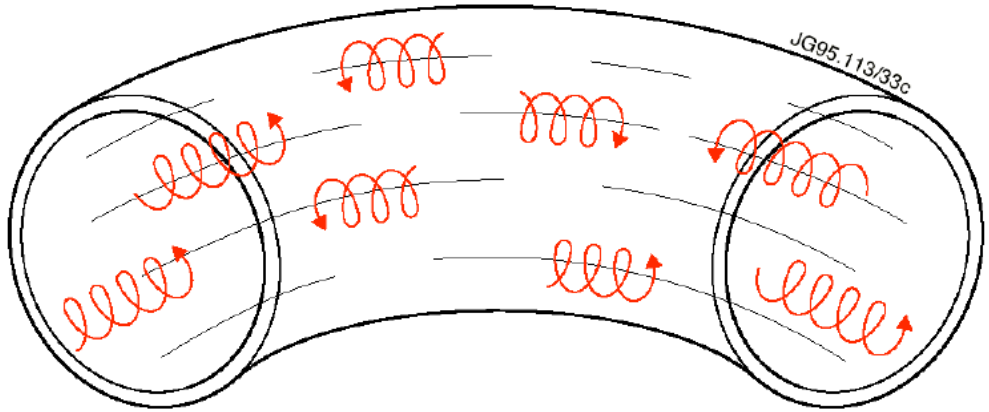


HOW TO CONFINE PLASMA ?





тороидальная
камера с
магнитными
катушками

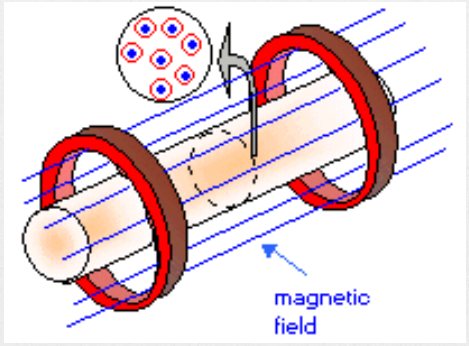


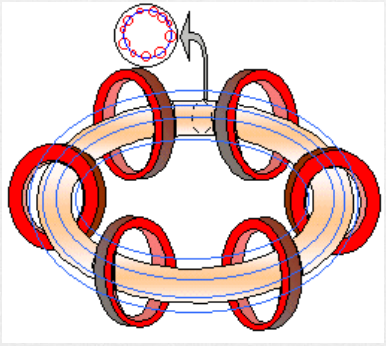
A special version of this torus is called a tokamak:

'toroidal chamber' and 'magnetic coil' (Russian)

HOW TO CONFINE PLASMA ?

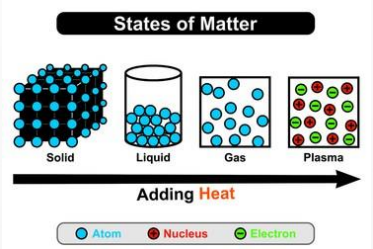
The solution:
the magnetic confinement!





THE FUSION PRINCIPLES

At extreme temperatures, electrons are separated from nuclei and a gas becomes a plasma ➔ ionized state of matter similar to a gas



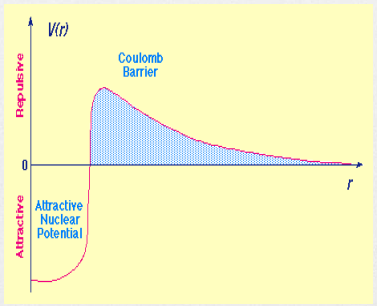
GOOD "Fusion Plasma"

1) **Many particles** to have enough collisions
   high Density (n_D)

2) **Particles & Energy** not leaking away too fast
   high Confinement Time (τ_E)

3) **High energy**
   high ion Temperature (T_i)

At the centre of the Sun, fusion takes place at very high particle densities due to the high gravity (~1.5 x 10^5 kg/m3) (~150 times the water density) and at temperatures of around 10 million K



Nucleus have to overcome the repulsive Coulomb forces so that they are close enough for fusion reaction to take place

Lawson's Criteria (Triple Product) ➔ $n_D \tau_E T_i > 3 \times 10^{21}$ (m^{-3} keV s)

OUTLINE

- **Why** – The fusion promise
- **What – Fusion principles**
- **How – Fusion technology**
- **Where and When** – ITER

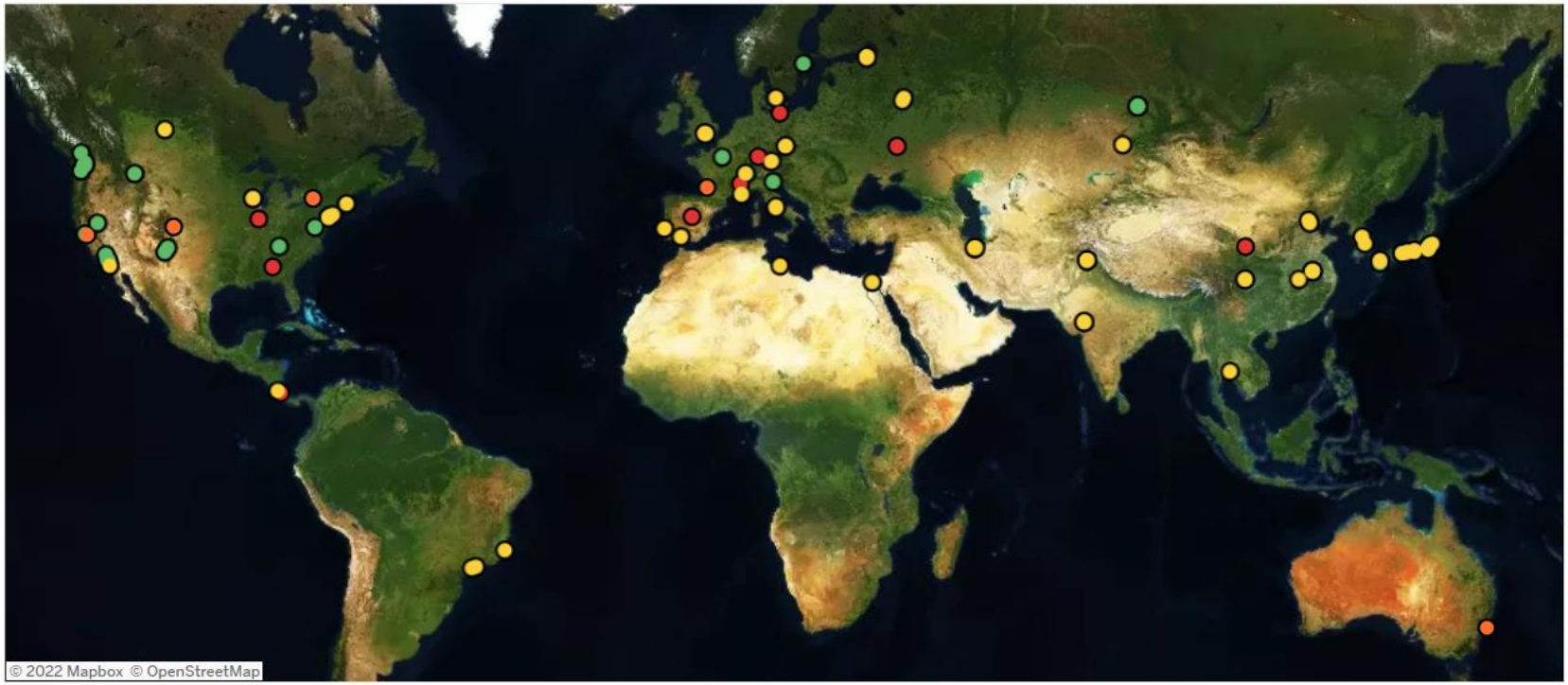
FUSION WORLDWIDE

FUSION FOR ENERGY

Total	Tokamaks	Stellarators/Heliotro..	Laser/Inertial	Altern. Concepts
134	74	13	9	38

Exp	Demo
125	9

- Tokamaks
- Stellarators/Heliotrons
- Laser/Inertial
- Altern. Concepts



Country	
United States	31
Japan	24
Russia	13
China	10
United Kingdo..	7
France	5
Germany	4
Pakistan	4
Brazil	3
India	3
Iran	3
Italy	3
Republic of K..	3
Canada	2
Costa Rica	2
Czech Republic	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
European Uni..	1
Kazakhstan	1
Libya	1
Portugal	1
Sweden	1
Thailand	1

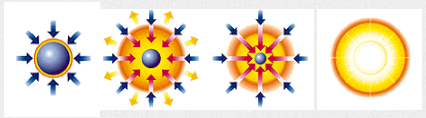
Operating	Under construction	Planned
96	10	28

Public	Private	Public-Private
107	26	1

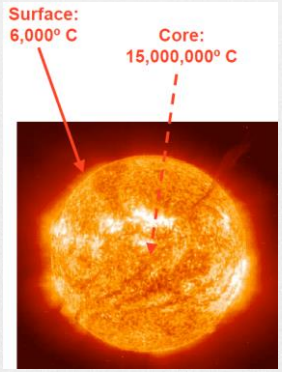
FUSION METHODS

From the Lawson's Criteria (Triple Product) ➔ $n_D \tau_E T_i > 3 \times 10^{21}$ (m^{-3} keV s)

Magnetic confinement	*Inertial*
$n \approx 10^{20}$ m^{-3}	$n \approx 10^{30}$ m^{-3}
$T \approx 10^{1}$keV $\approx 10^{8}$ K	$T \approx 10^{1}$ keV $\approx 10^{8}$ K
$\tau_E \approx 10^{0}$ s	$\tau_E \approx 10^{-9}$ s



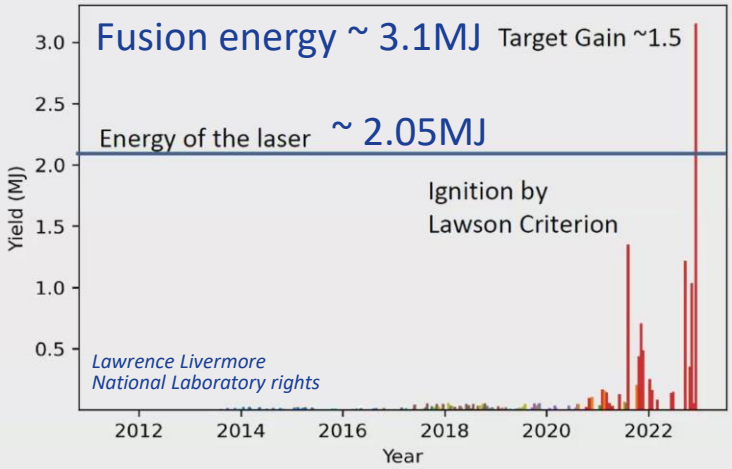
Temperatures 10 times higher than temperature of the Sun

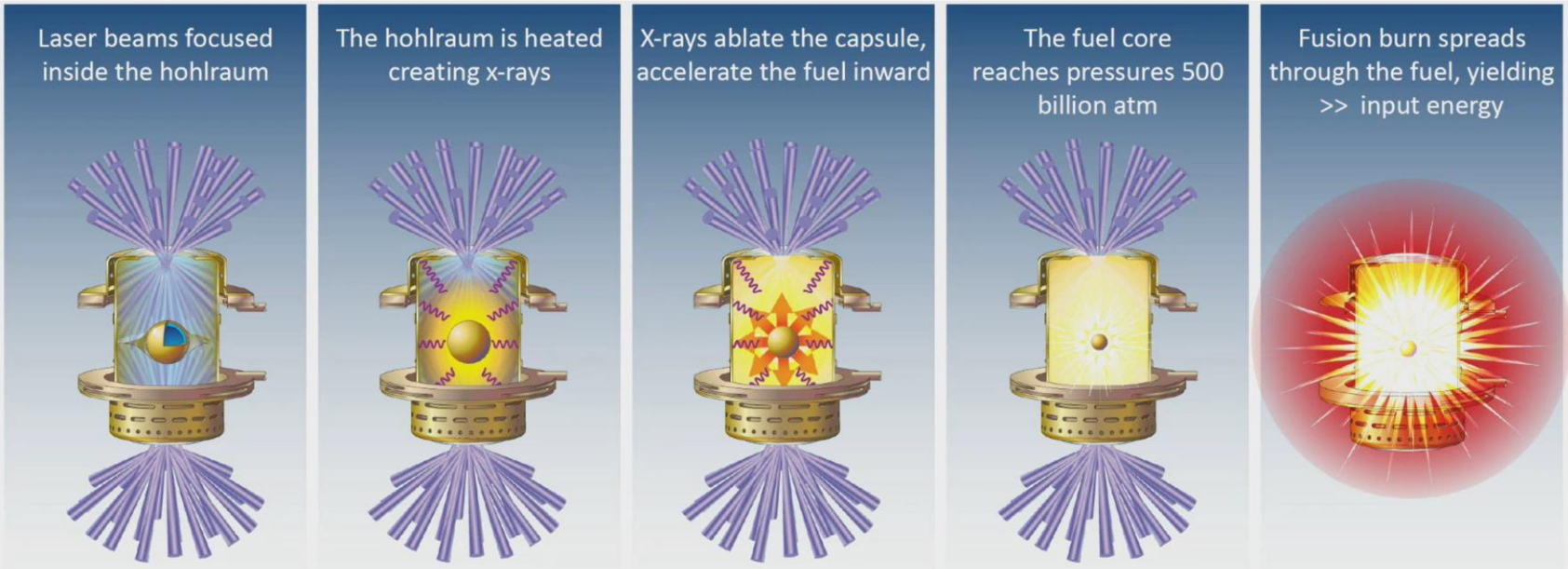


INERTIAL FUSION

Dec 05th 2022, first time fusion yields higher than laser energy on target

Achieved with laser indirect drive technique at the Livermore National Laboratory

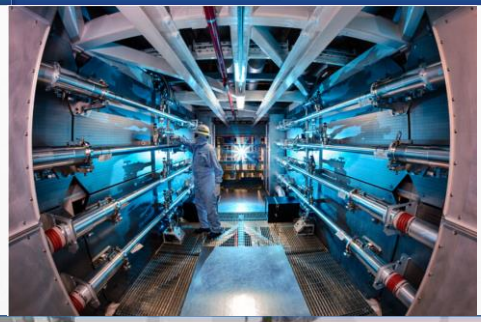




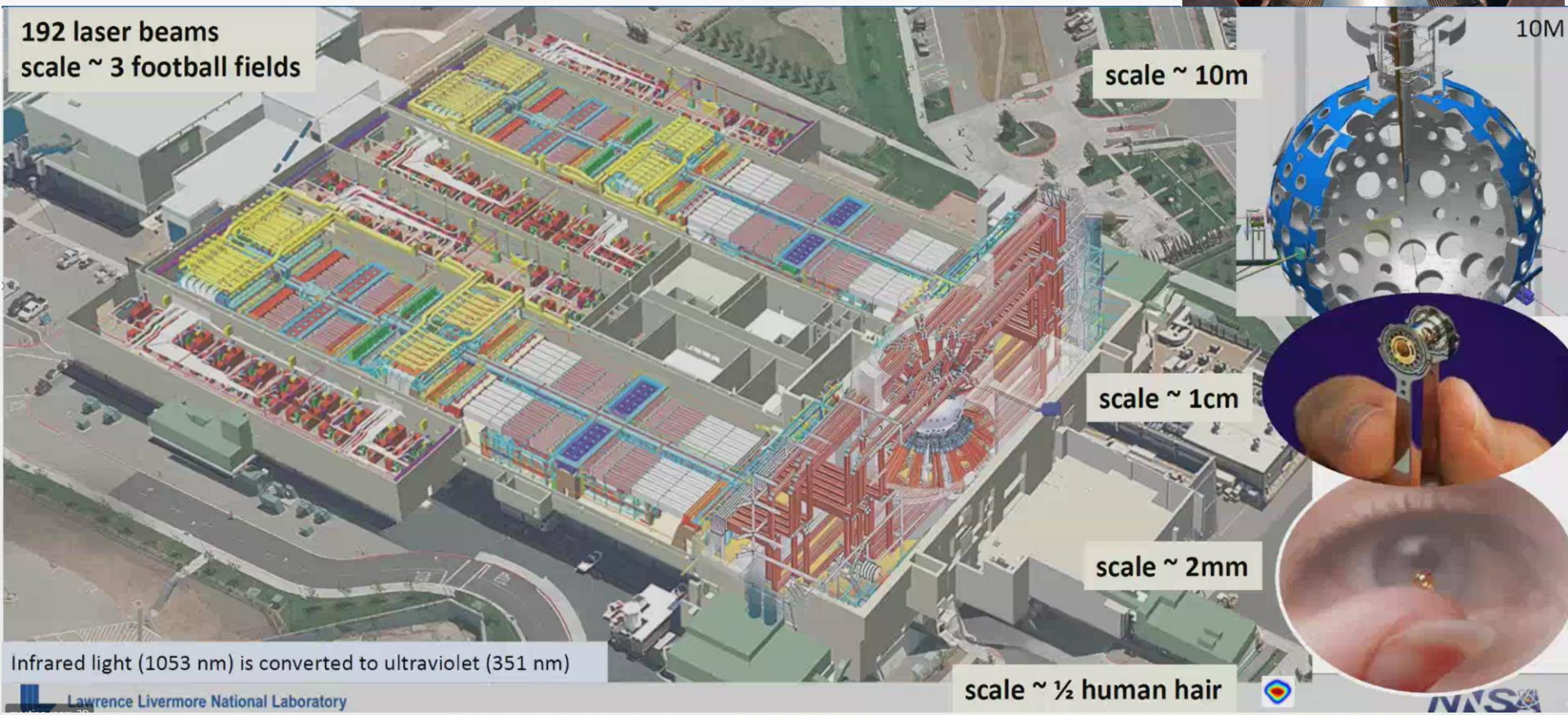
Lawrence Livermore National Laboratory rights

INERTIAL FUSION

FUSION FOR ENERGY



- Lasers energy consumption ~322MJ (< 100x energy on target)
- Pulse duration few tens of picoseconds (trillionth of a second)



MAGNETIC CONFINEMENT FUSION

FUSION FOR ENERGY

Poloidal field creation configurations

Tokamak

Plasma current

Induction: Transformer effect

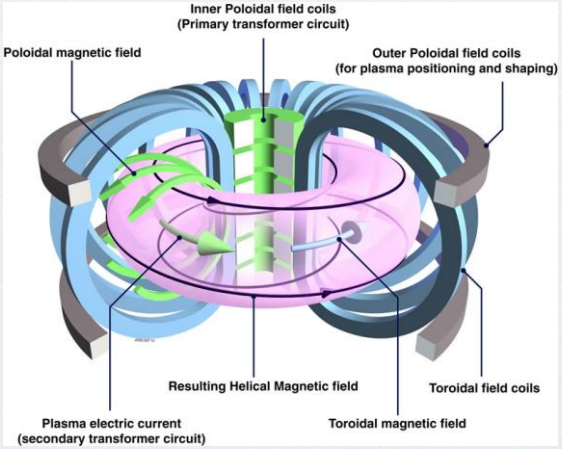
Limited duration time by magnetic flux

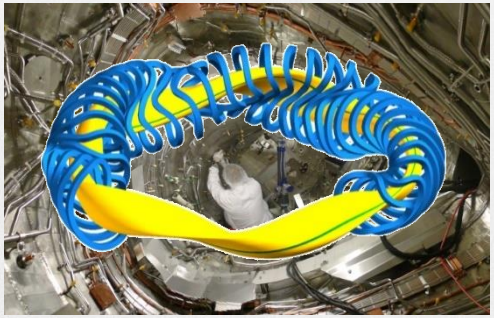
Poloidal field coils

Stellarator

Toroidal and poloidal magnets

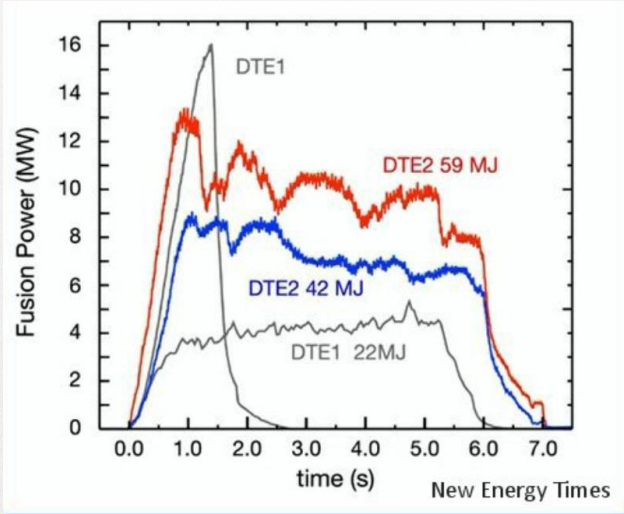
Complex design





Wendelstein 7-X, Greifswald, Germany

MAGNETIC CONFINEMENT FUSION



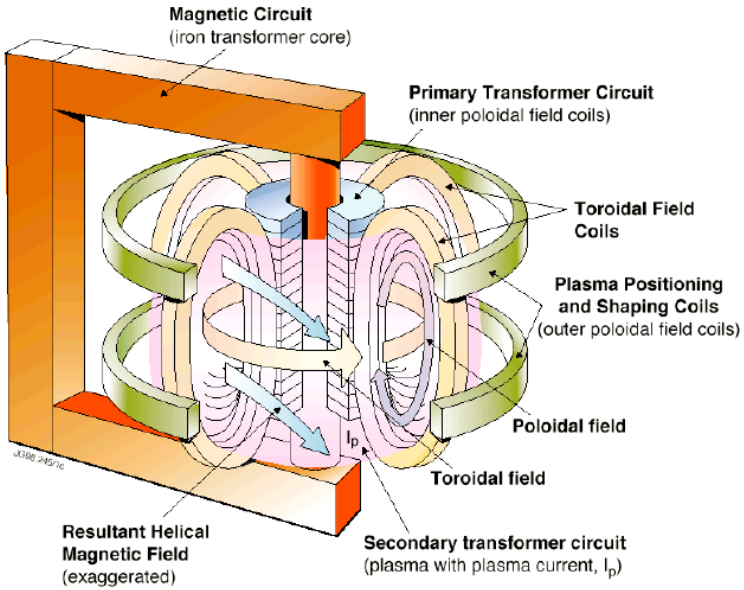
JET record fusion pulses announced Feb. 9, 2022. DTE1 are 1997 results. DTE2 are 2021 results.

EU Laboratories on magnetic confinement fusion

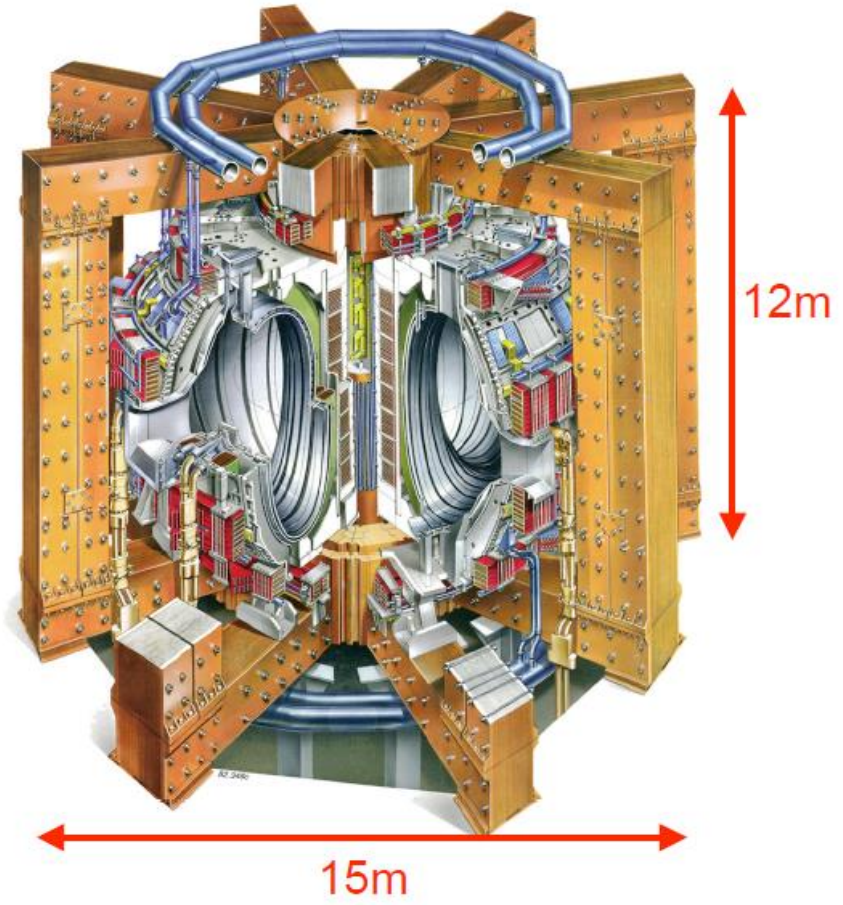
Fusion energy world record at JET, Culham, UK, in 1997 and 2021: 16MW in 1997, 59MJ in 2021

MAGNETIC CONFINEMENT FUSION

FUSION FOR ENERGY



Joint European Torus: JET

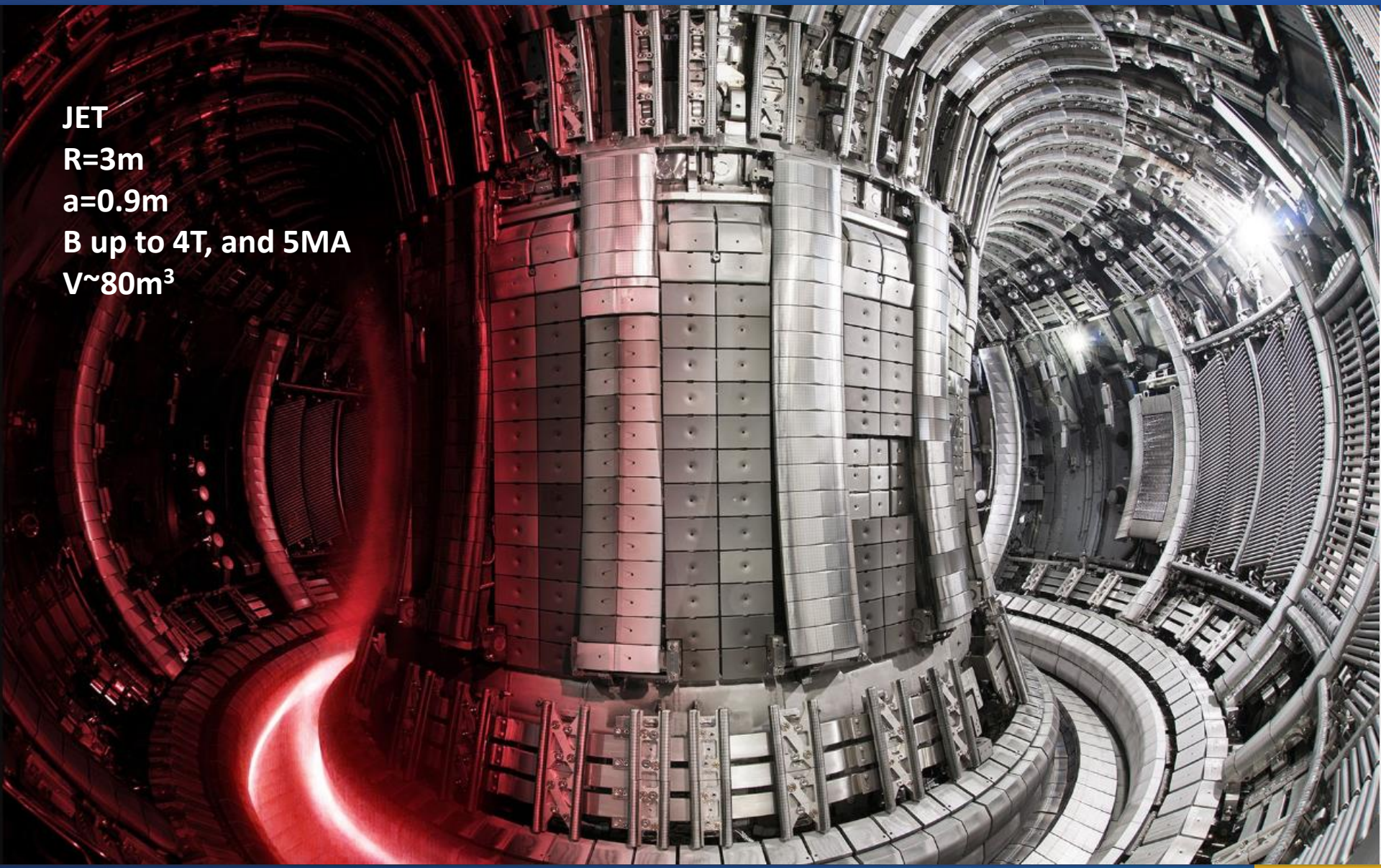


The Tokamak:

- toroidal magnetic field is produced by external magnetic field coils
- plasma current produces poloidal magnetic field
- result is a set of nested helical surfaces
  ⇒ plasma confinement

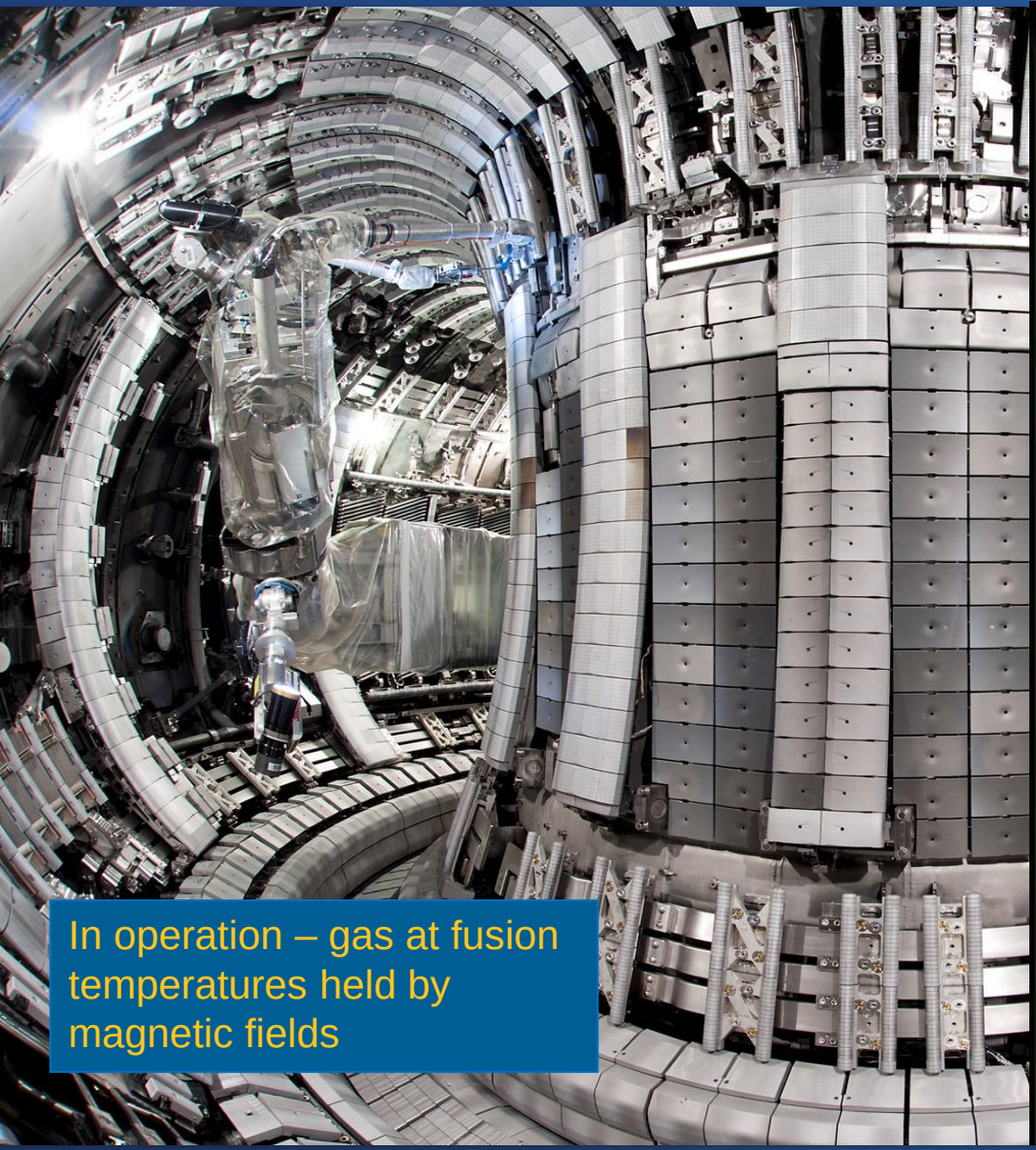
MAGNETIC CONFINEMENT FUSION

FUSION FOR ENERGY



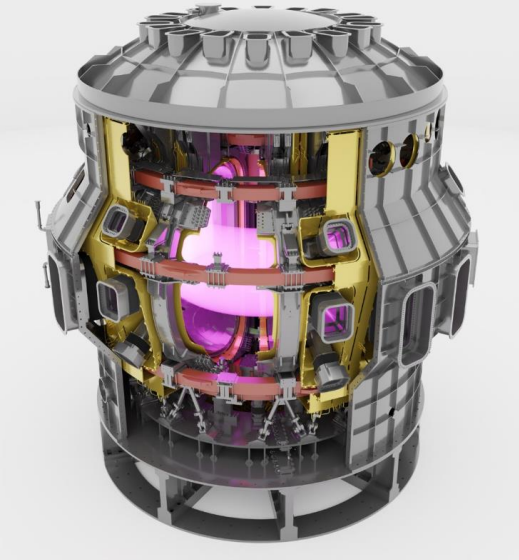
MAGNETIC CONFINEMENT FUSION

FUSION FOR ENERGY



In operation – gas at fusion temperatures held by magnetic fields

MAGNETIC CONFINEMENT FUSION

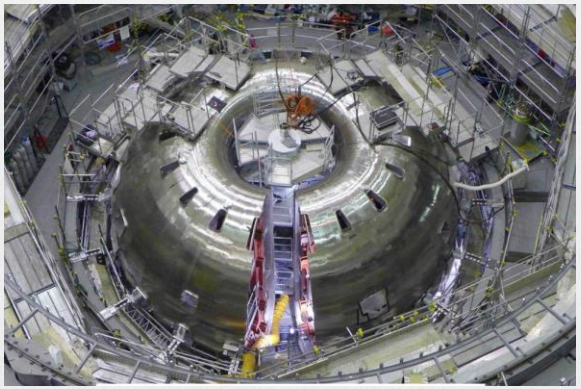


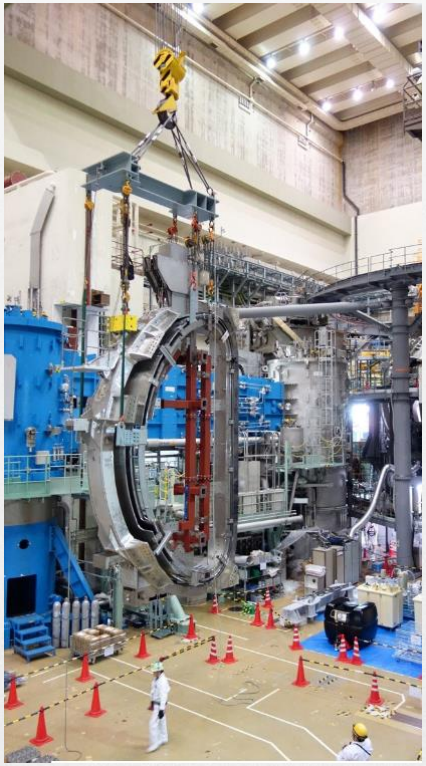
R=2.96m
a=1.18m
2.25T (NbTi), 5.5MA

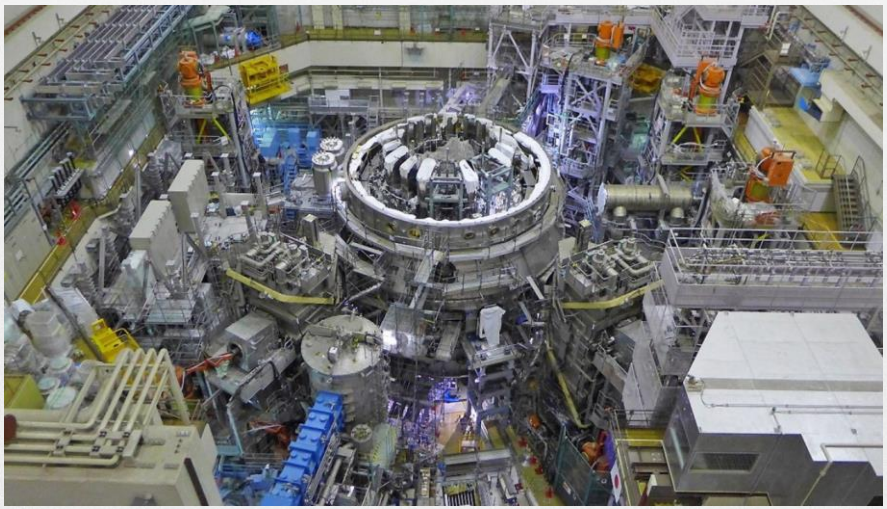
The new JT60-SA: result of the *Broader Approach* agreement between EU & Japan, implemented by **F4E**

First plasma in 2023! It will be the largest existing magnetic confinement fusion device (before ITER).

- Main objective: addressing physics issues for ITER and DEMO
- plasma temperatures of over 100-200 million °C

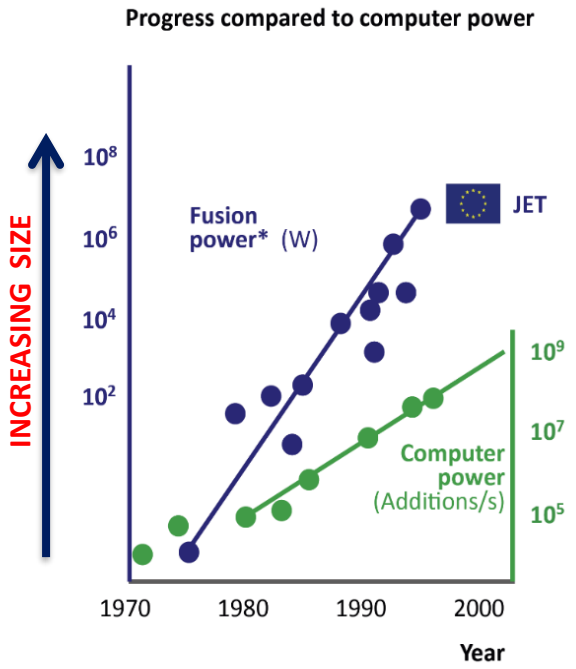






Mar 2015 → May 2018 → Today

TOWARDS COMMERCIAL POWER PLANTS



Source: USDOE, EFDA

* Equivalent power with DT fuel

** ITER Project, construction started 2009

Entering into operation in 2024

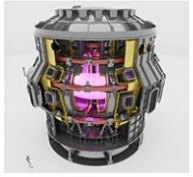
~80% construction

TODAY

Next steps

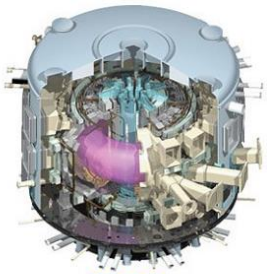
JET

80 m^3



JT-60SA

135 m^3

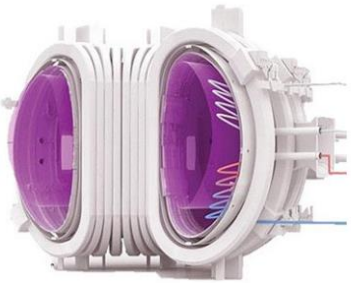


ITER

800 m^3

(one-third the size of an Olympic swimming pool)

~ 500 MW_{th}



DEMO

~ 1000 – 3500 m^3

(half to one and a half times the size of an Olympic swimming pool)

~ 2000-4000 MW_{th}

+ other parallel magnetic confinement fusion projects (e.g. W7-X, Broader Approach)

OUTLINE

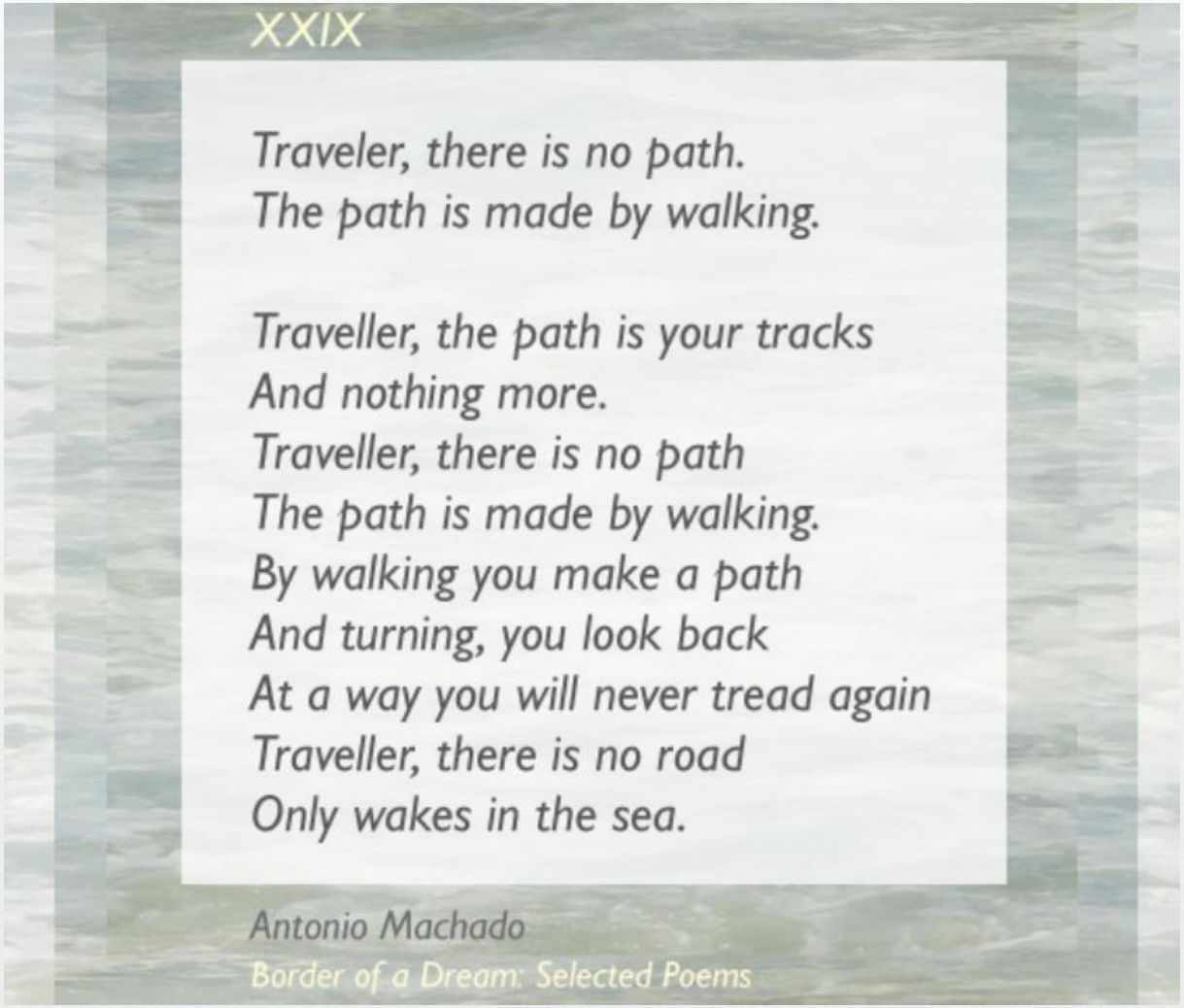
- **Why** – The fusion promise
- **What – Fusion principles**
- **How – Fusion technology**
- **Where and When – ITER**

ITER - THE WAY TO FUSION ENERGY

Iter : **"The Way" or "The Path" (in Latin)**

ITER : **International Thermonuclear Experimental Reactor**

Iter : "The Way" or "The Path" (in Latin), and the Path is Made by Walking



XXIX

Traveler, there is no path.
The path is made by walking.

Traveller, the path is your tracks
And nothing more.
Traveller, there is no path
The path is made by walking.
By walking you make a path
And turning, you look back
At a way you will never tread again
Traveller, there is no road
Only wakes in the sea.

Antonio Machado
Border of a Dream: Selected Poems

ITER - THE WAY TO FUSION ENERGY

FUSION FOR ENERGY

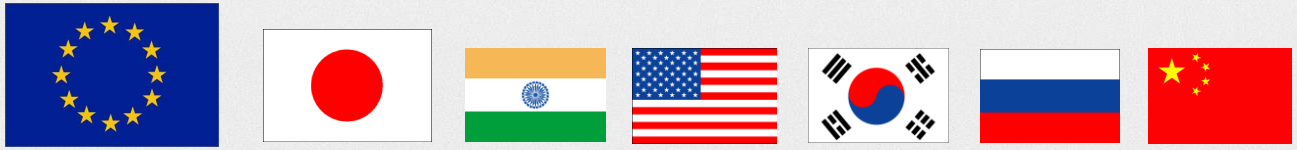
The beginning: The ITER

- On **1985**, for peaceful purposes, the URSS proposed to U.S.A. the idea of a collaborative **international project** to **develop fusion energy**.
- From 1988 to 1992 the conceptual design is developed.
- On 2001, the final design for the ITER was approved by the Members (EU, Japan, Russia and U.S.A.)
- In 2003, China and Korea joined, followed by India in 2005

Nationalities of the people involved in ITER

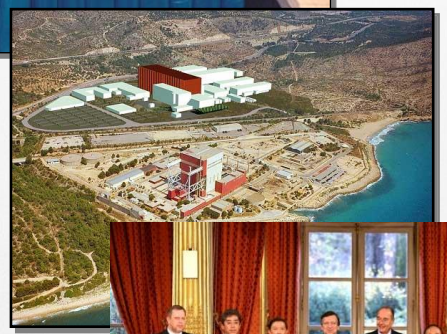
What is ITER Organization (IO)?

- Since **2007**, IO is a large **scientific collaboration** to prove the viability of fusion as an energy source
- The **ITER Members are 35 countries**: China, the EU, India, Japan, Korea, Russia and U.S.A. **Each member has a Domestic Agency**.
- Its **purpose** is to provide for and promote **cooperation** among its Members for the **Benefit of the ITER Project**



iter
china EU india japan korea russia USA

ITER - THE WAY TO FUSION ENERGY



1985 Gorbachev, Reagan & Mitterrand suggest building next-step device at Geneva Superpower Summit (CCCP, US, EU, JA)
1988 Initiation of the Conceptual Design Studies
1992 Signature of the ITER EDA Agreement (4 parties)
1999 US withdraws – but re-enters 2003
2001 Design completed
2003 China, Korea joins
2005 Site selection, India joins
2006 Signature of ITER Agreement (7 parties)
2007 IO entered into force
2020 Tokamak assembly starts …

ITER - THE WAY TO FUSION ENERGY

Seven (7) parties (members),
Representing 50% of the World population,
Manufacturing 90% of the ITER components in the countries,
to guarantee a fair and wide sharing of knowledge and technology...

FUSION FOR ENERGY

ITER : International Thermonuclear Experimental Reactor

To demonstrate the scientific and technological viability of controlled fusion for power production…

- … by generating 500 MW of fusion power
- Fusion power at least 10 times the power to heat the plasma (amplification factor Q=10)
- in long-pulse operation (up to 3600s)
- aiming at steady-state operation
- Develop fusion reactor relevant technologies
- *Note: Research facility (no electricity from fusion produced or delivered to the grid yet)*

ITER - THE WAY TO FUSION ENERGY

FUSION FOR ENERGY

Major plasma radius	6.2 m
Minor plasma radius	2.0 m
Magnetic field	5.3 T
Plasma Volume	**840 m^3**
Plasma Current	**15 MA**

Typical Density	10^{20} m^{-3}
Typical Temperature	**20 keV**
Neutron flux	0.5 MW/m^2
Fusion Power	**500 MW**
Energy factor Q	**10**

ITER - THE WAY TO FUSION ENERGY

FUSION FOR ENERGY

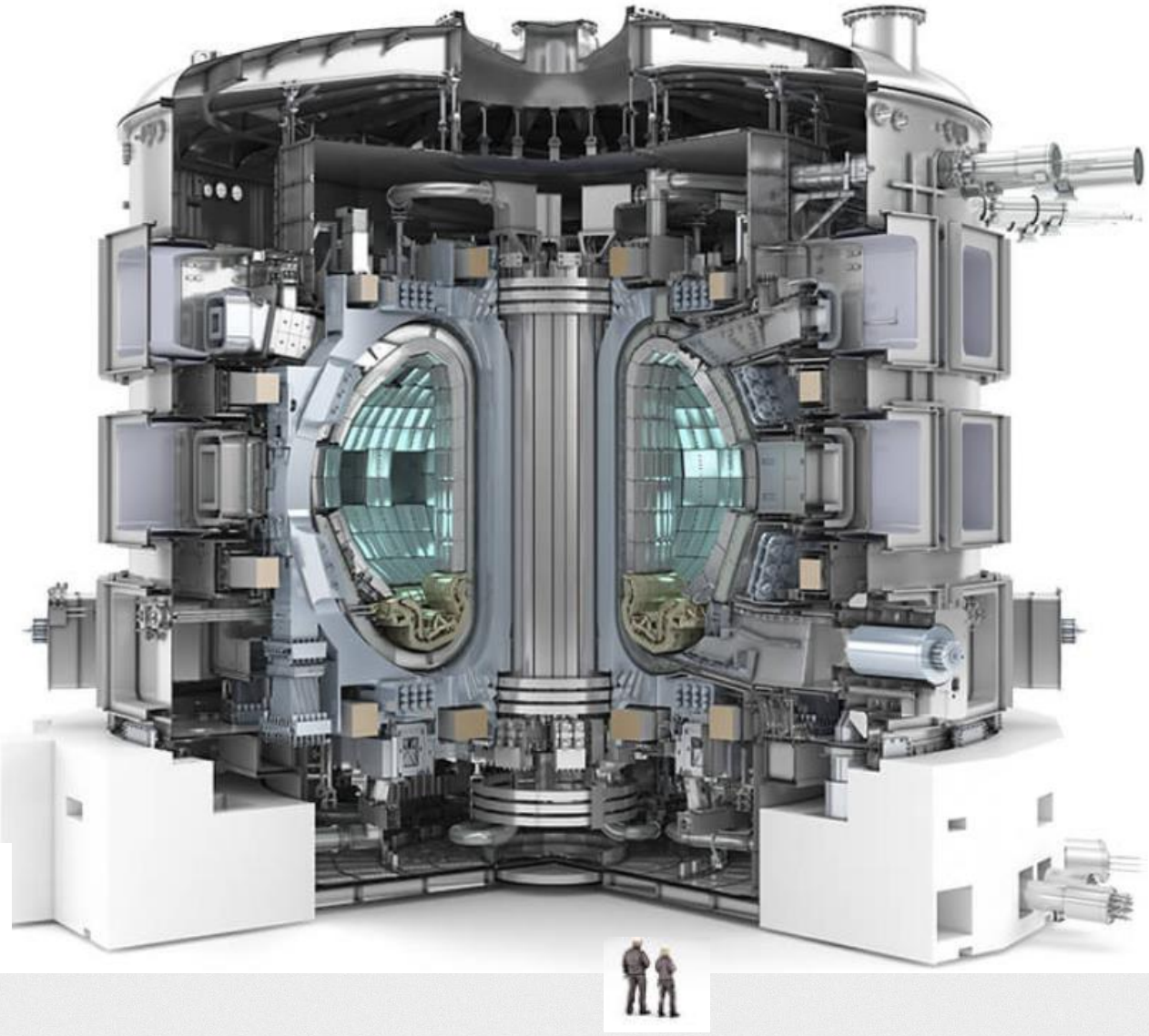
Some key figures about ITER

24 m high
30 m wide

23 000
Tonnes

1 000 000
Number of Components

830 m^3
Plasma volume



ITER - THE WAY TO FUSION ENERGY

FUSION FOR ENERGY

ITER - THE WAY TO FUSION ENERGY

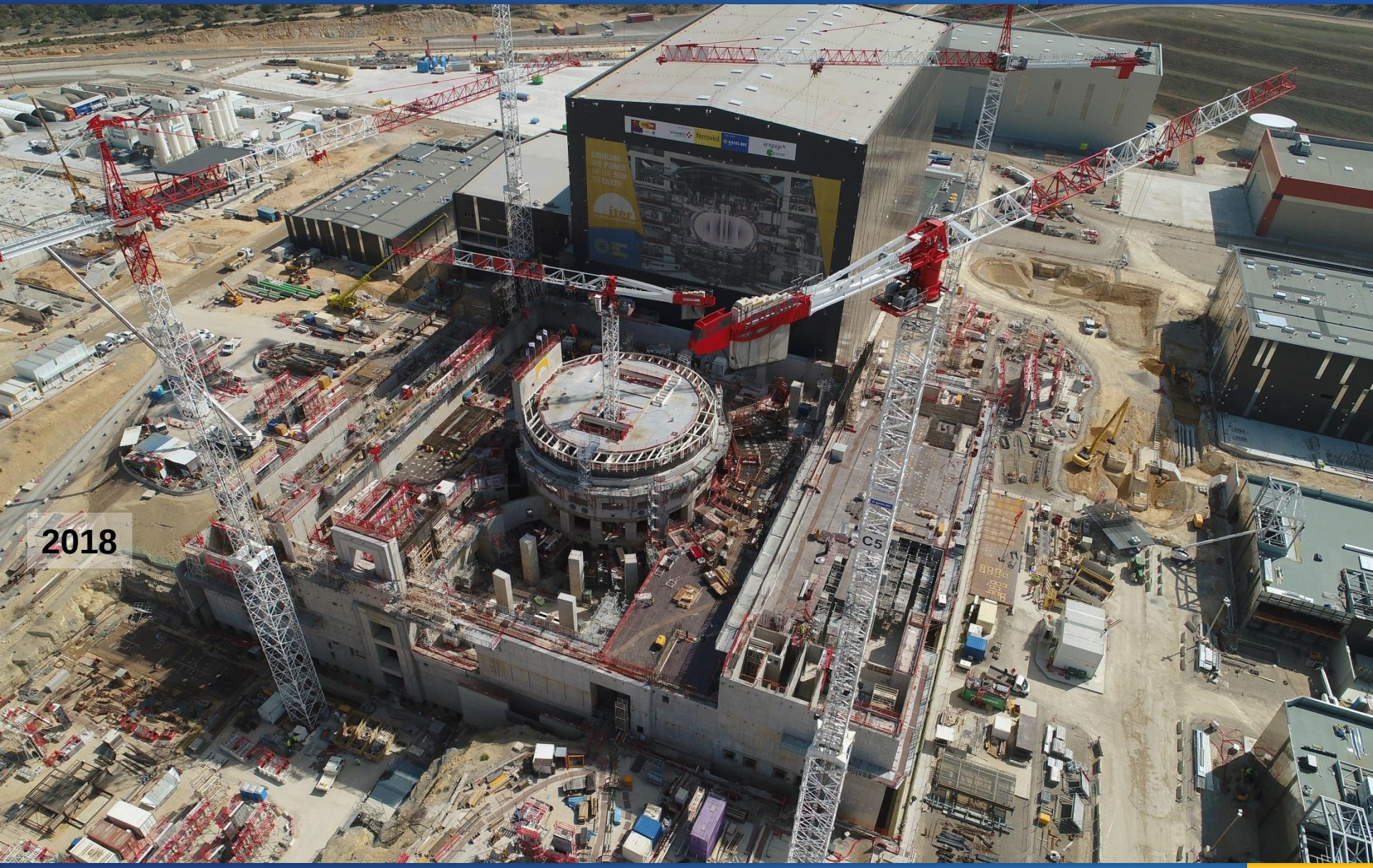
FUSION FOR ENERGY

ITER - THE WAY TO FUSION ENERGY

FUSION FOR ENERGY

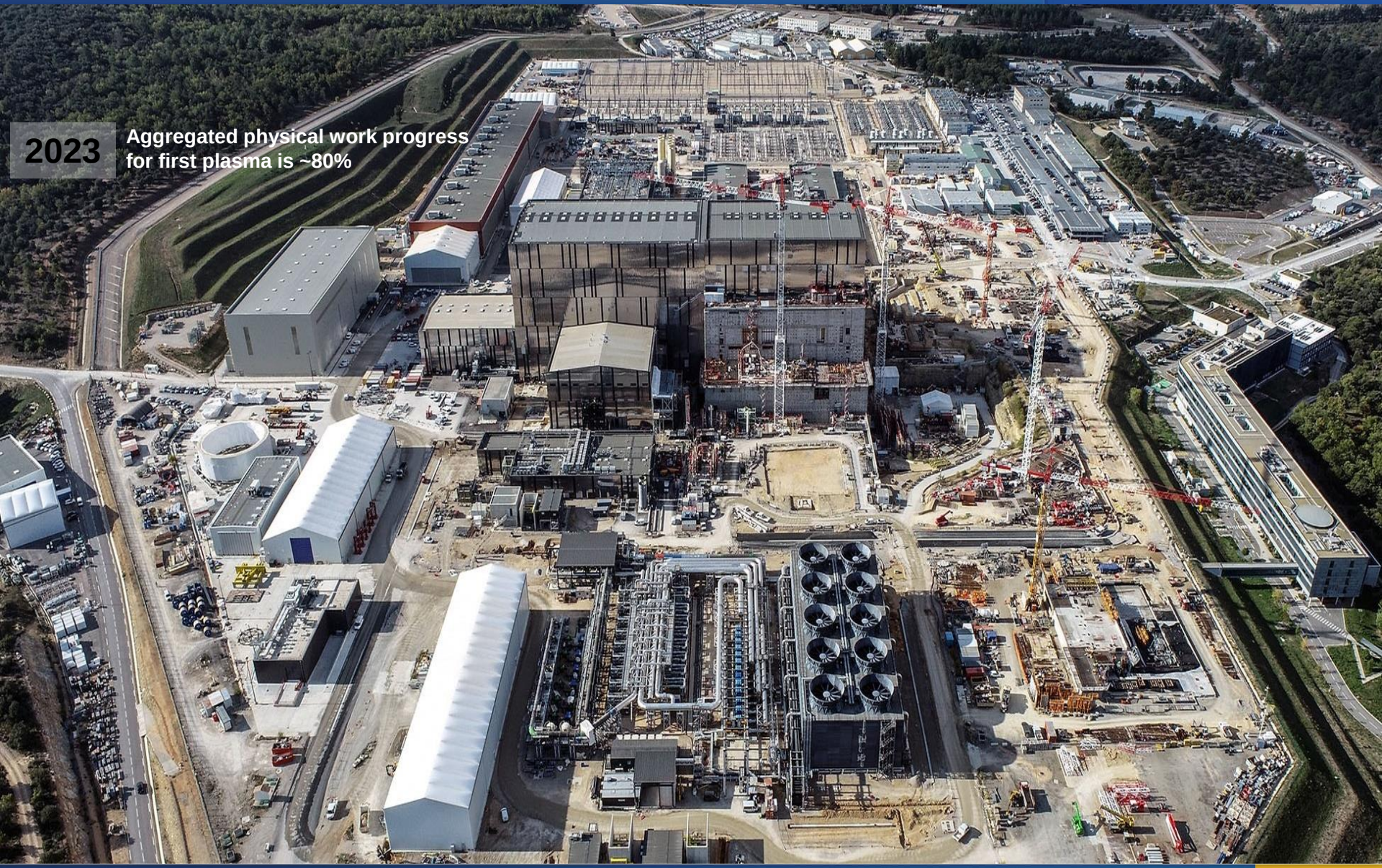
ITER - MAIN SYSTEMS

FUSION FOR ENERGY

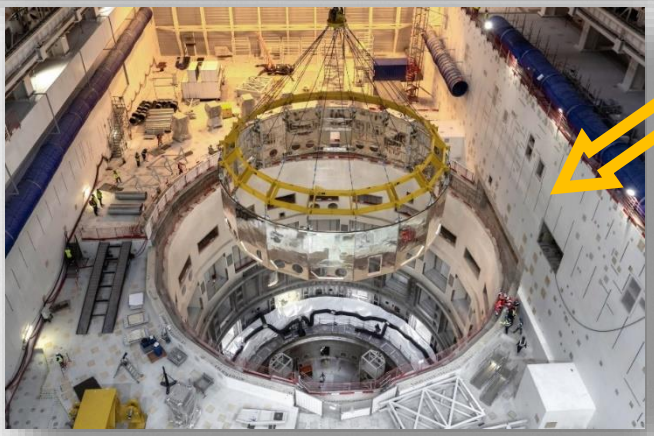


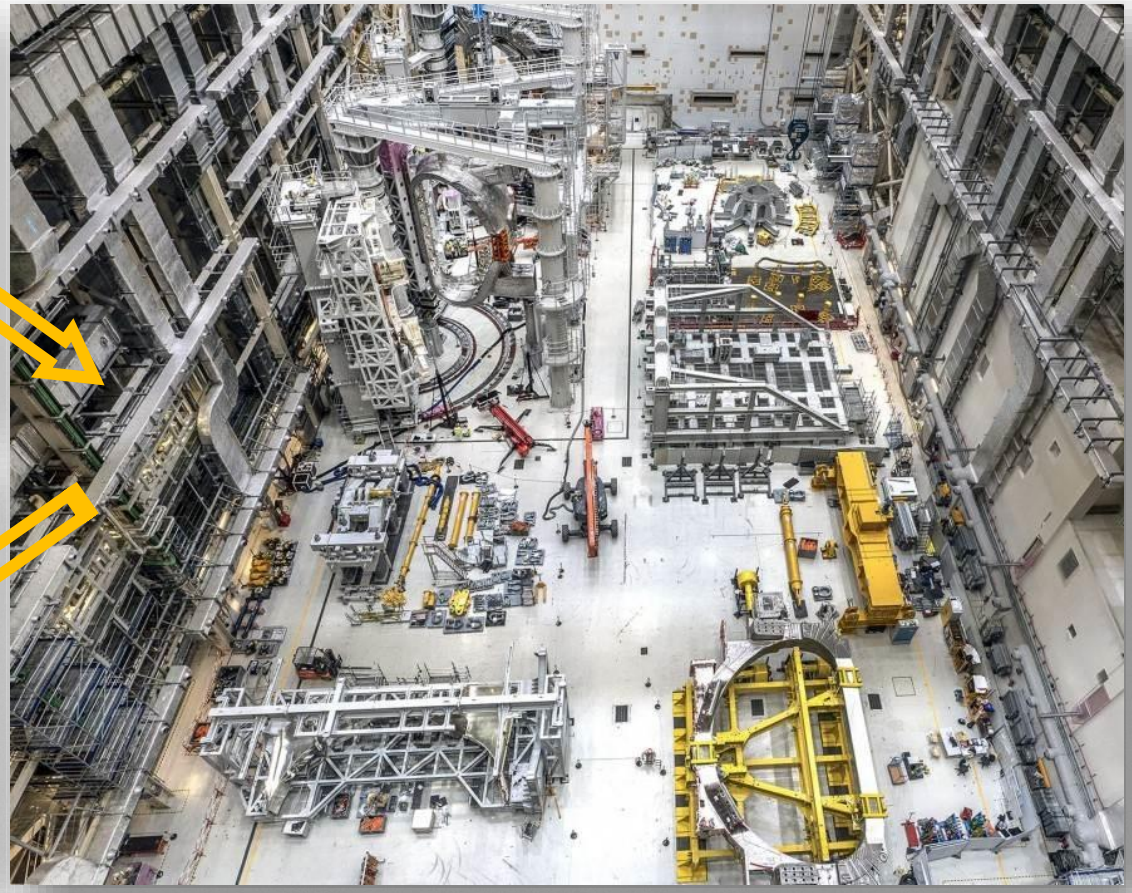
ITER - THE WAY TO FUSION ENERGY

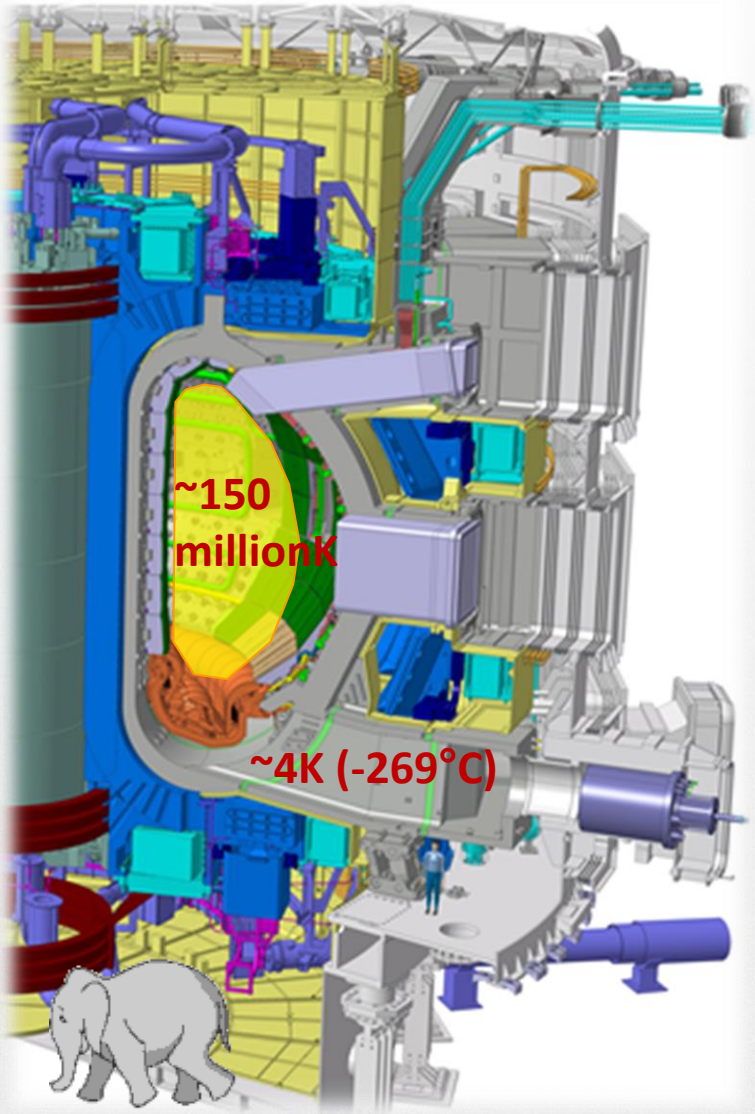
FUSION FOR ENERGY



ITER - THE WAY TO FUSION ENERGY







In-vessel components (**BLANKETS**, **DIVERTOR**)

VACUUM VESSEL (9 sectors)

TOROIDAL FIELD COILS (Nb3Sn, 18 coils, 4 °K)

POLOIDAL FIELD COILS (NbTi, 6 coils, 4 °K)

CENTRAL SOLENOID (Nb3Sn, 6 modules, 4 °K)

THERMAL SHIELDS (80 °K)

CRYOSTAT (24m high, 28m diameter)

CRYOPUMPS

PLASMA HEATING (Radiofrequency EC & IC, Neutral Beam Injectors)

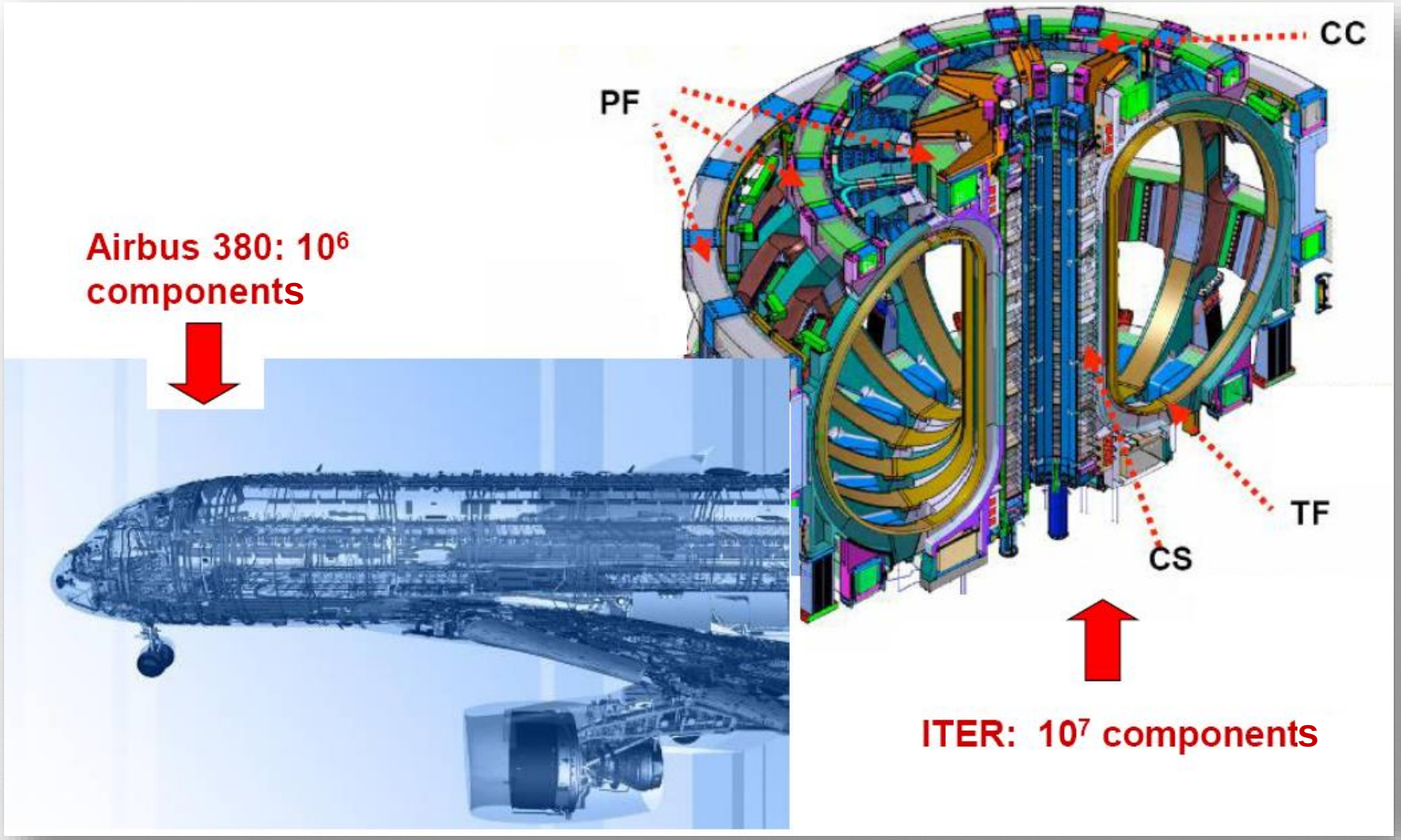
PLASMA FUELLING (pellets, puffing)

DIAGNOSTICS (plasma measurements)

REMOTE HANDLING

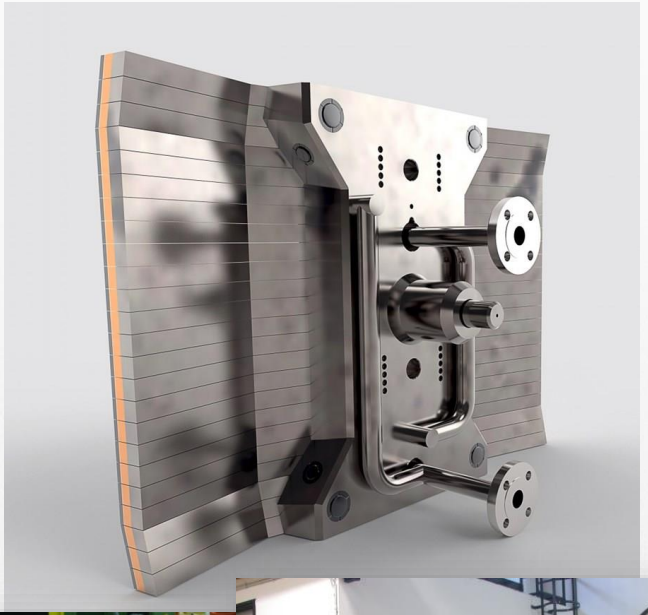
+ PLANT SYSTEMS

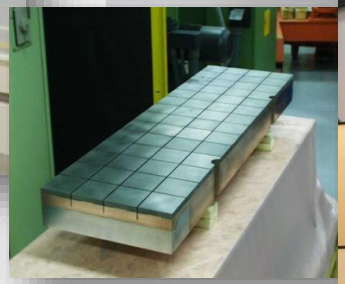
ITER - MAIN SYSTEMS

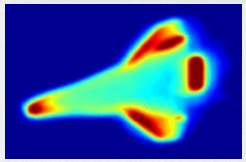


CIEMAT courtesy

FIRST WALL AND DIVERTOR







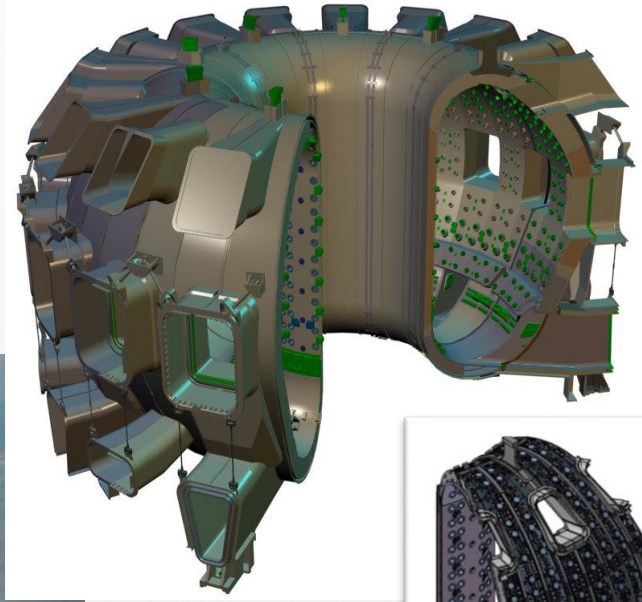
Exposed to heat loads of ~20MW/m2 => higher than space shuttle re-entering the Earth's atmosphere, comparable to those at the surface of the Sun

VACUUM VESSEL

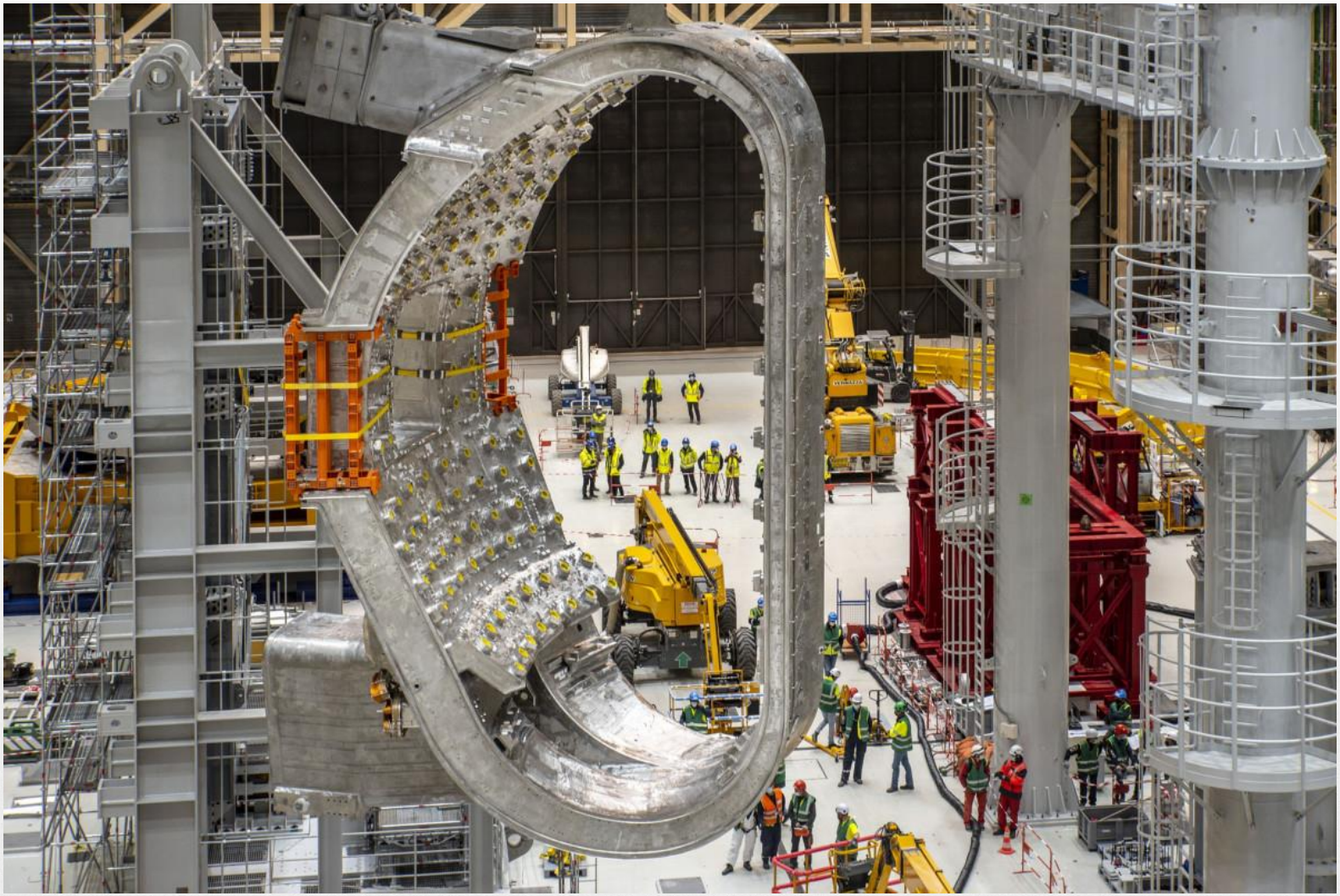
Vacuum 10^{-5} Pa

Double shell 60 mm thick of SS 316 L(N)-IG

19.4m outer diameter, 11.3m height, 5200 tons



VACUUM VESSEL



ITER - MAIN SYSTEMS

FUSION FOR ENERGY

MAGNETS

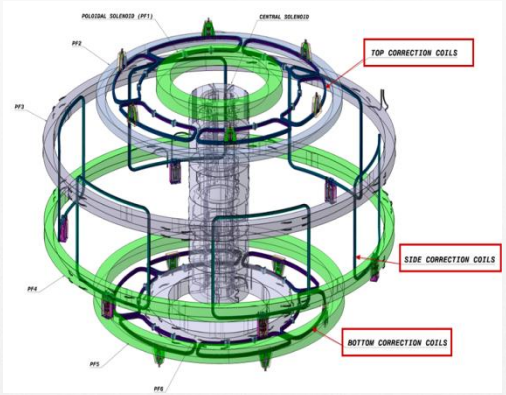
48 superconducting coils (~9800 tons) + correction coils + feeders!

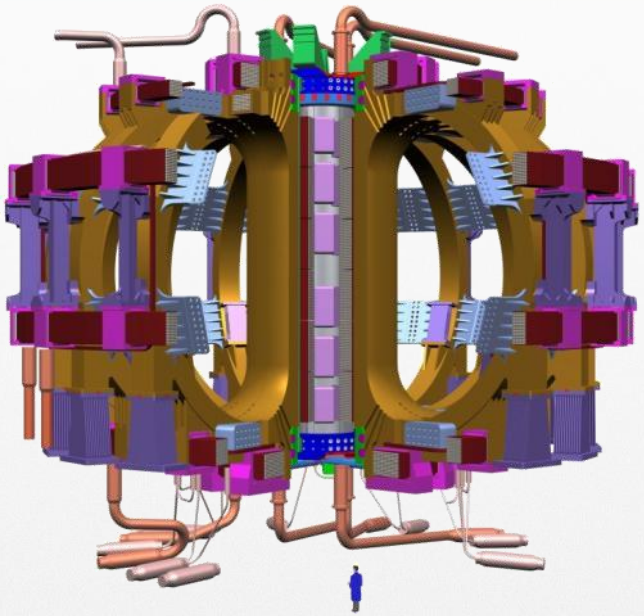
~150,000 km of strand

11.8 T peak TF field

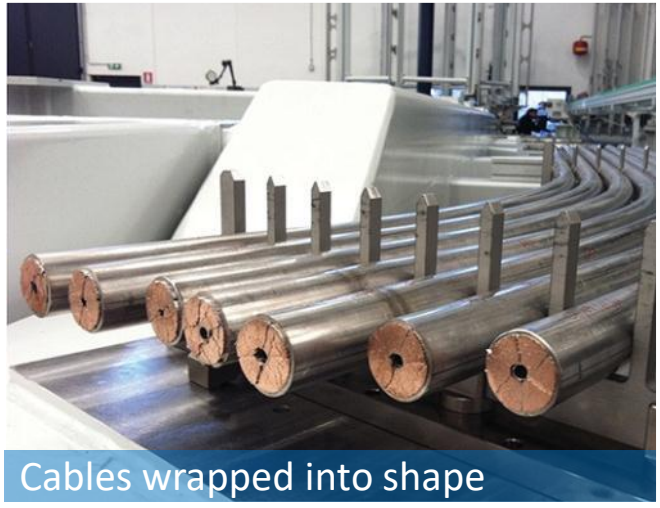
68 kA peak current

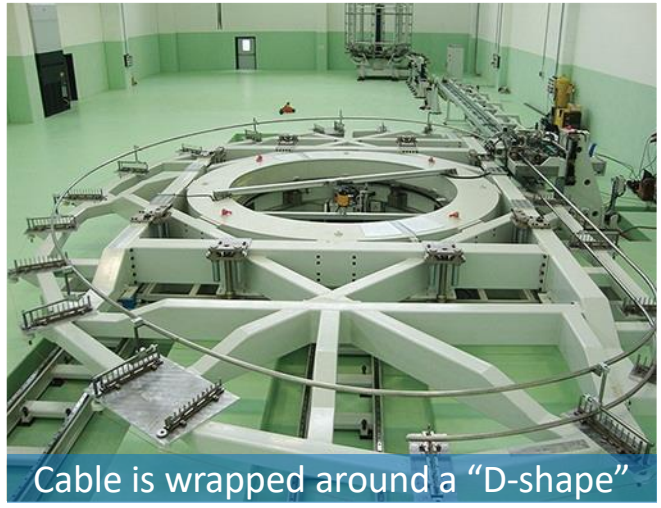
51 GJ of stored energy






Spool of cable


Cables wrapped into shape


Cable is wrapped around a “D-shape”

MAGNETS

ITER - MAIN SYSTEMS

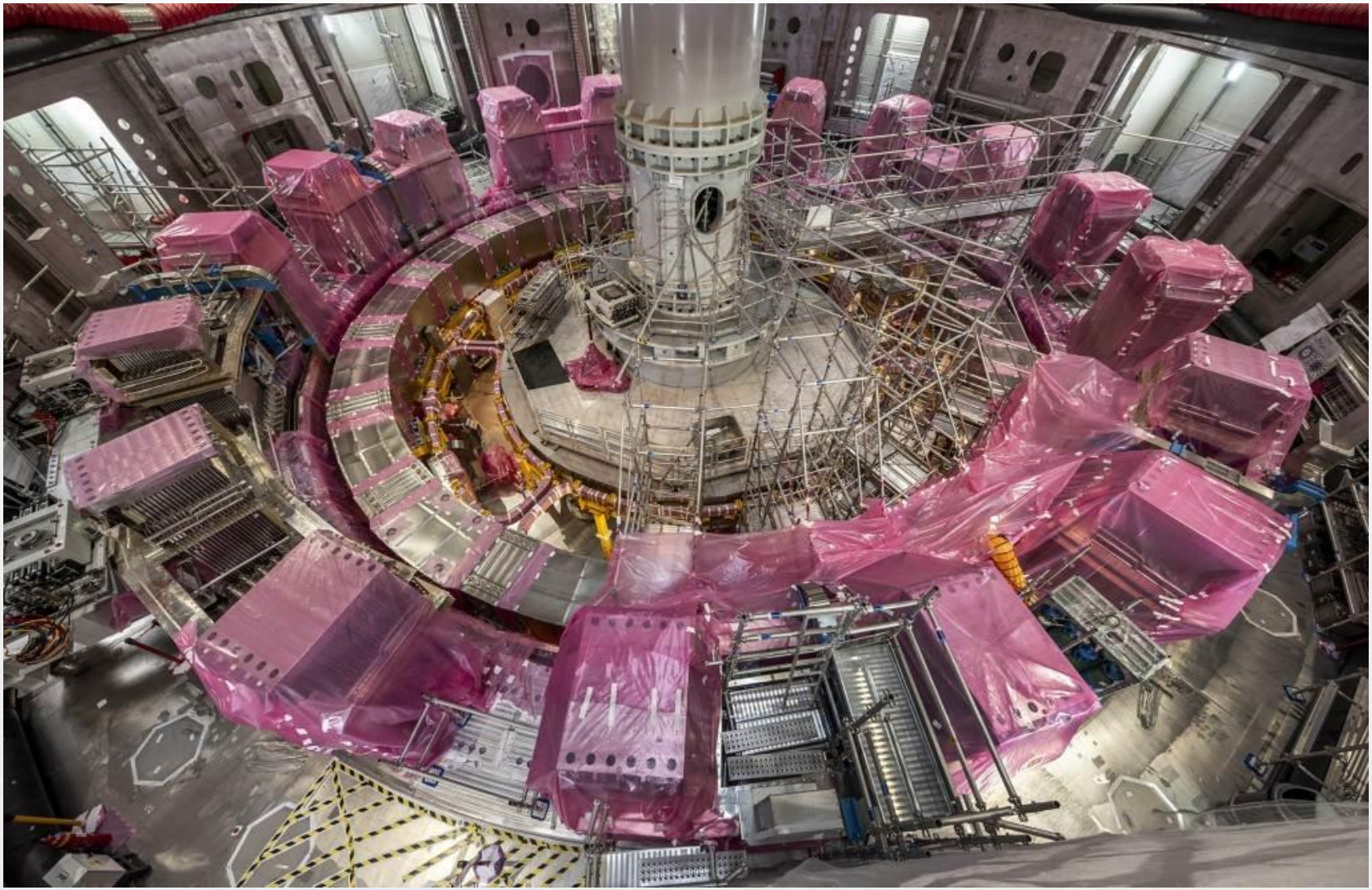
FUSION FOR ENERGY

MAGNETS

18 D-shaped Toroidal Field Coils

Each 19x7m, 320 tons 

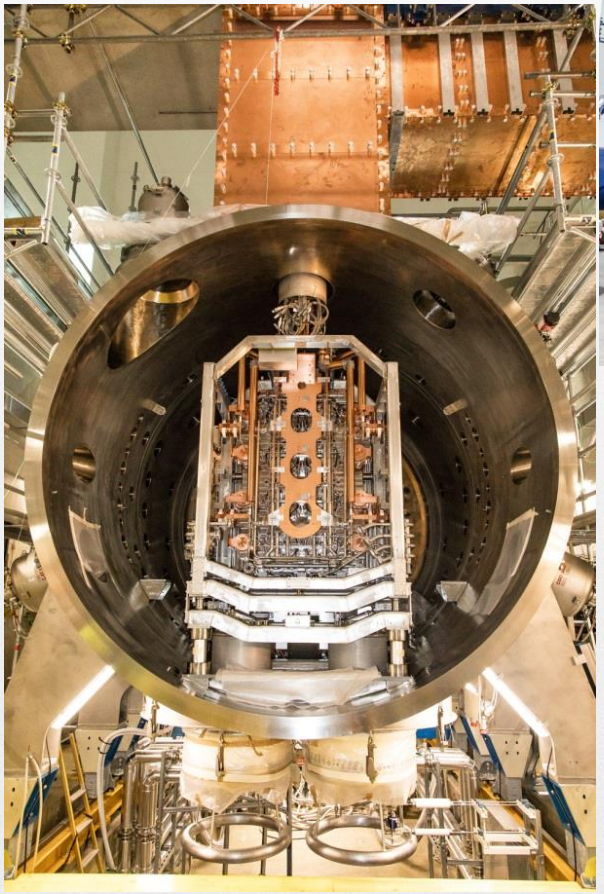
MAGNETS



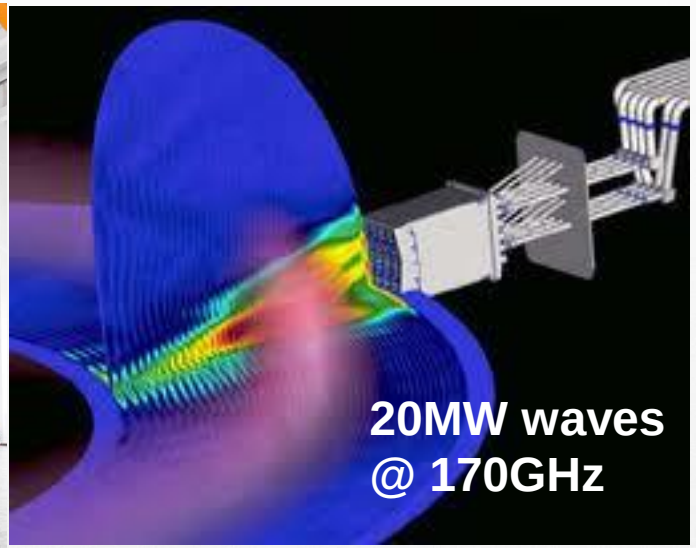
ITER - MAIN SYSTEMS

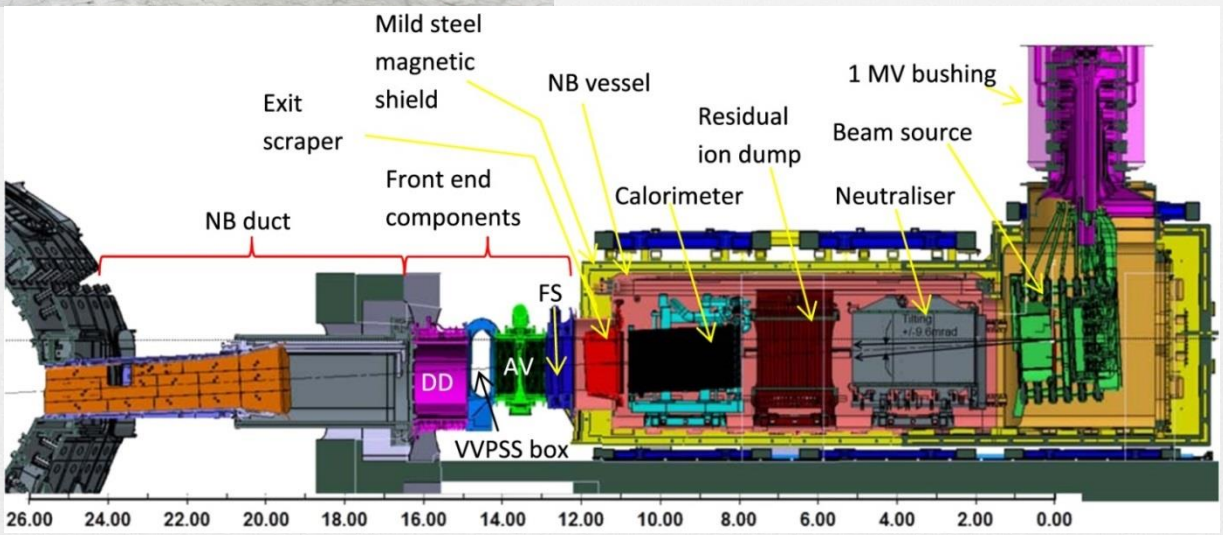
FUSION FOR ENERGY

HEATING SYSTEMS (NEUTRAL BEAM, RF)

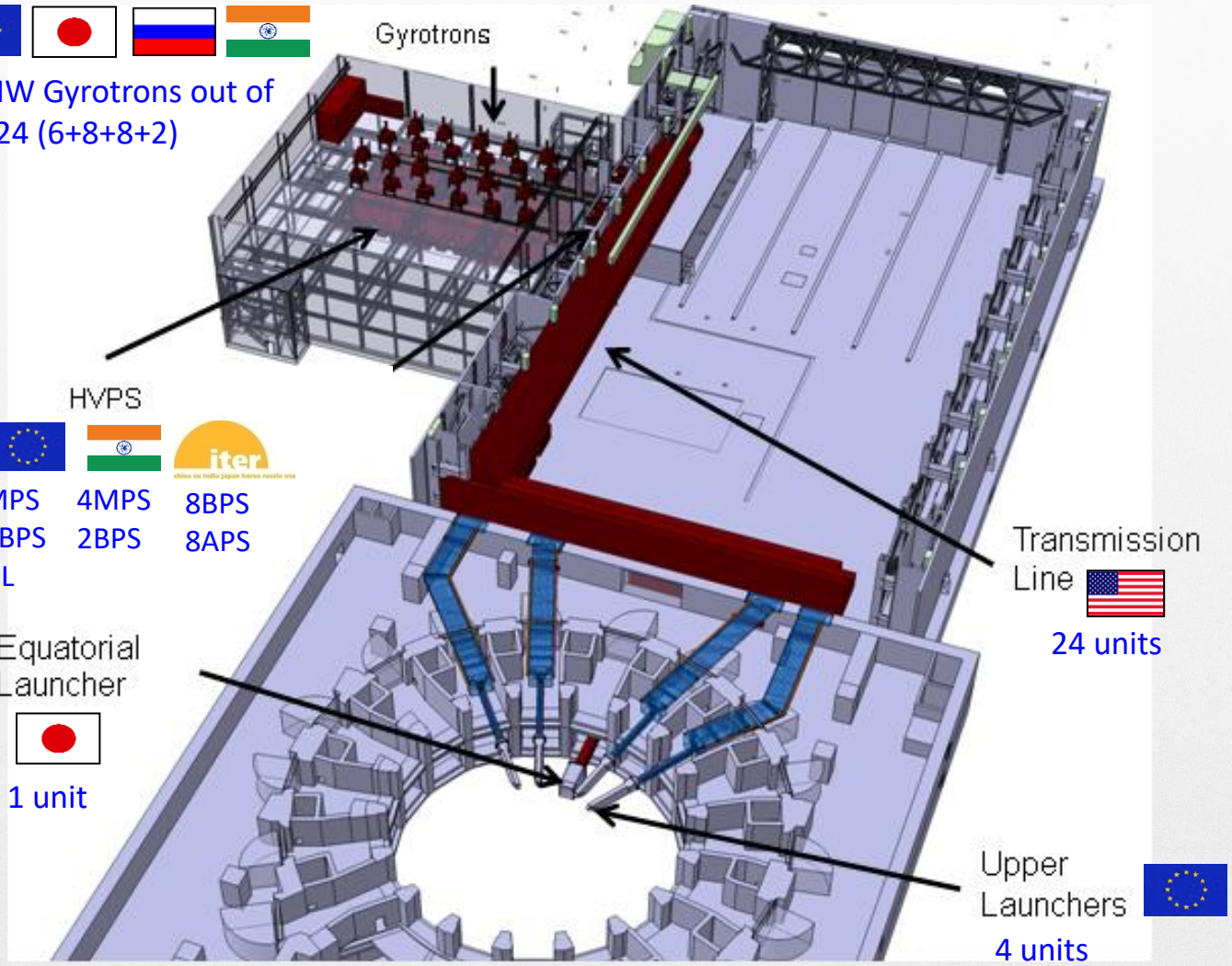


33MW @ 1MV system



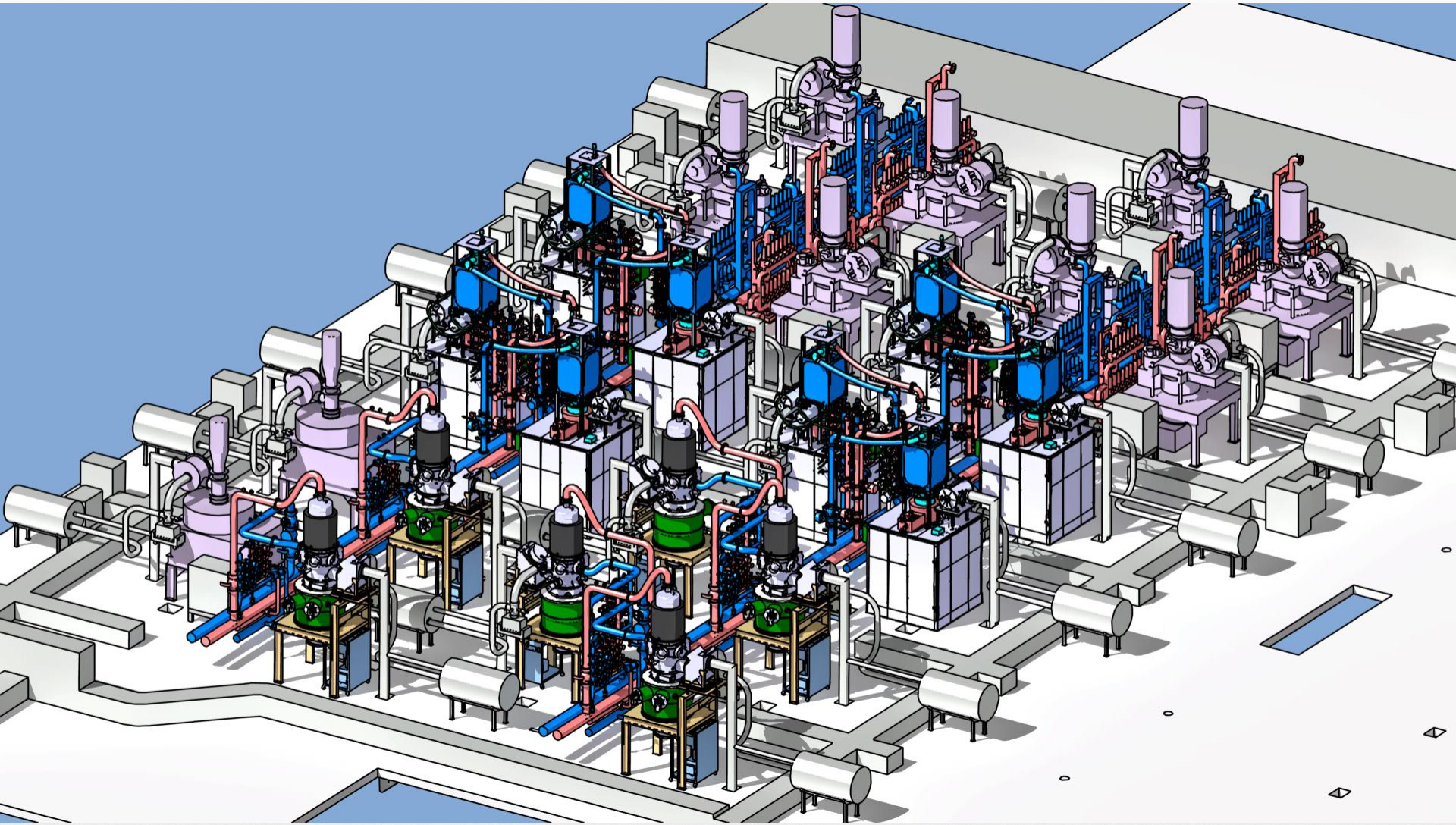


Electron Cyclotron (EC) and RF Sources (Gyrotrons)

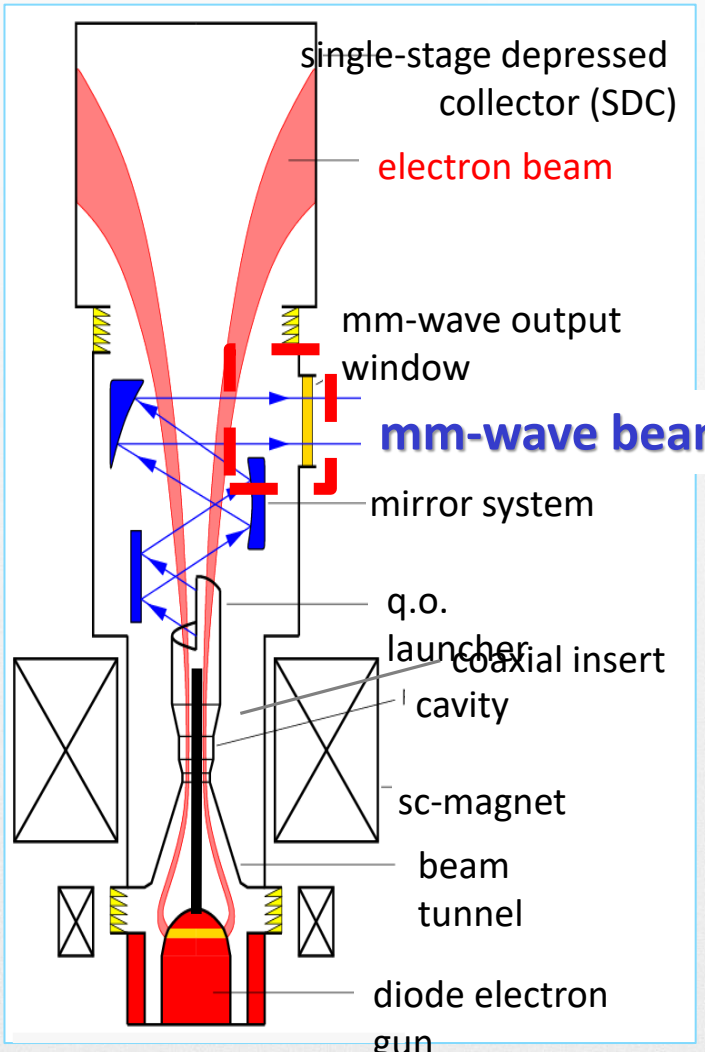


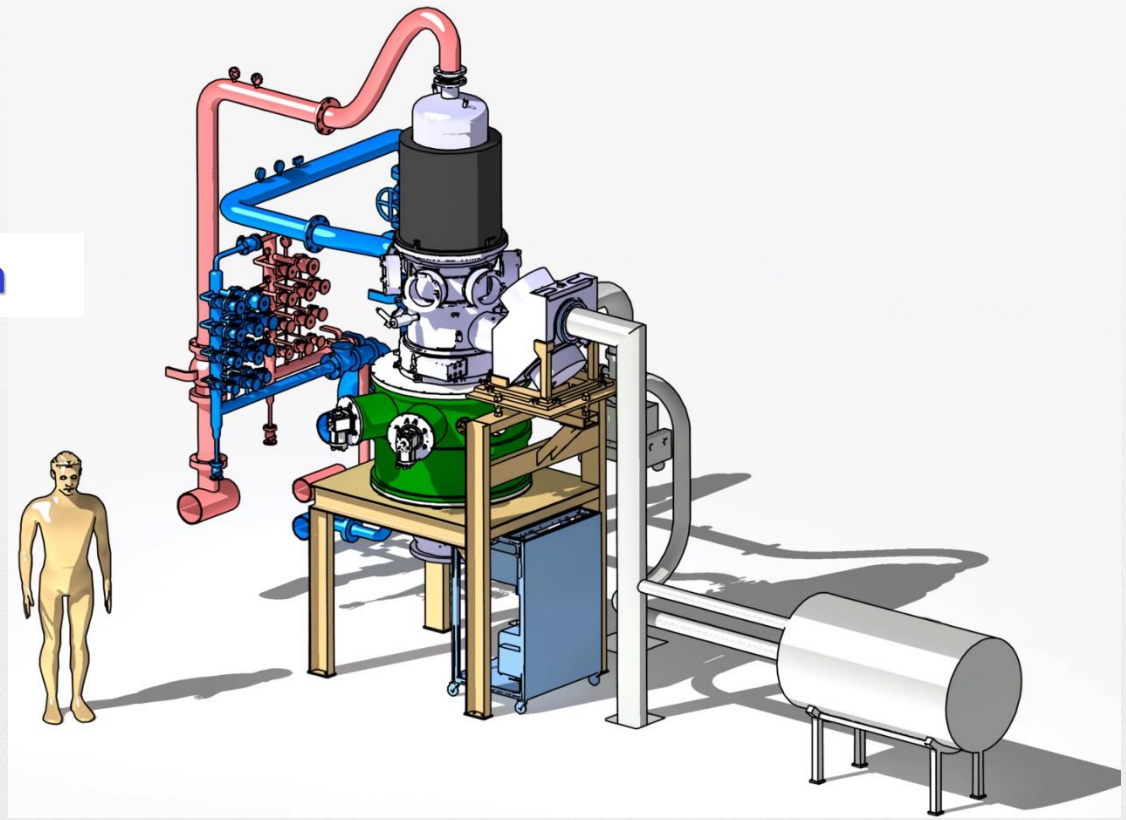
FUSION FOR ENERGY

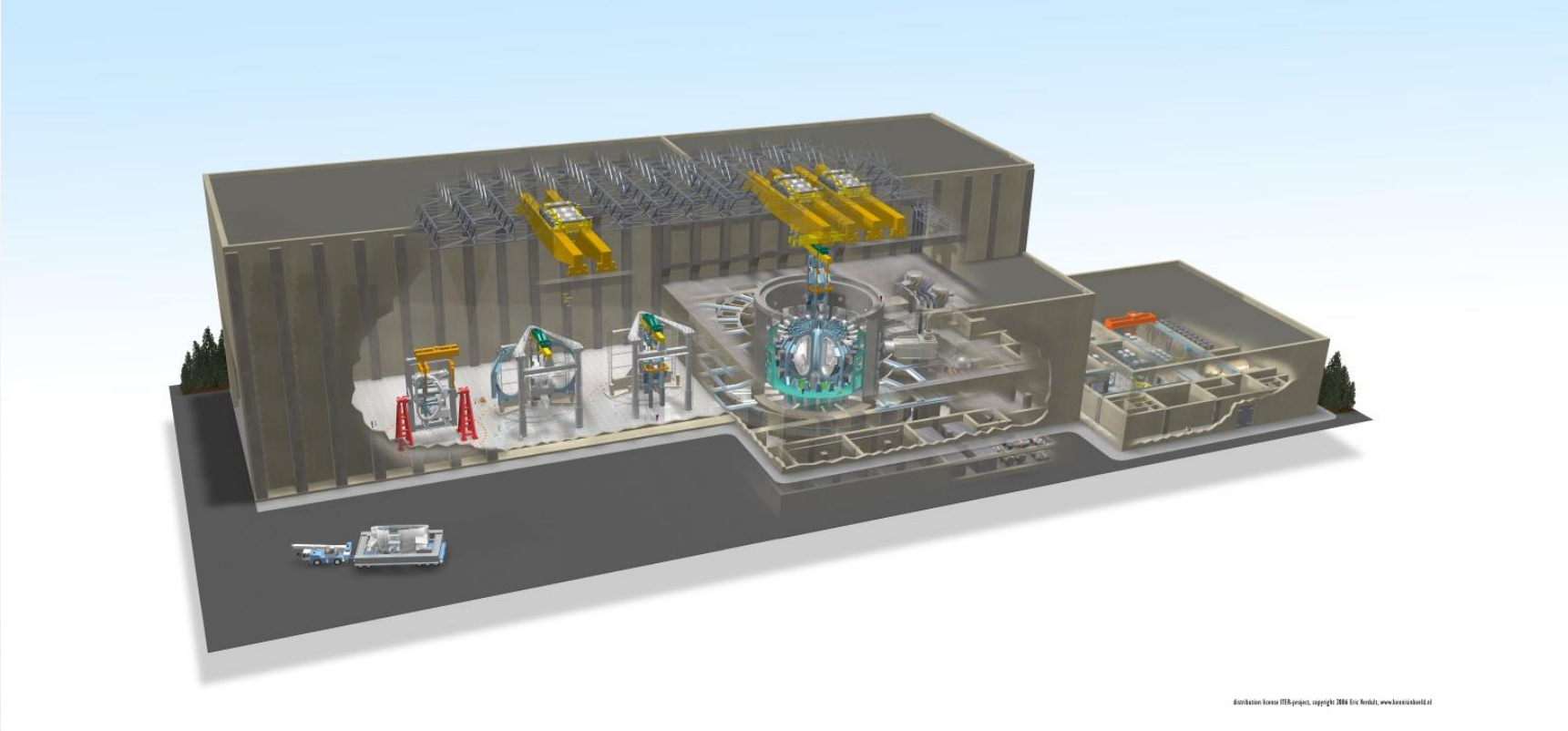
Electron Cyclotron (EC) and RF Sources (Gyrotrons)



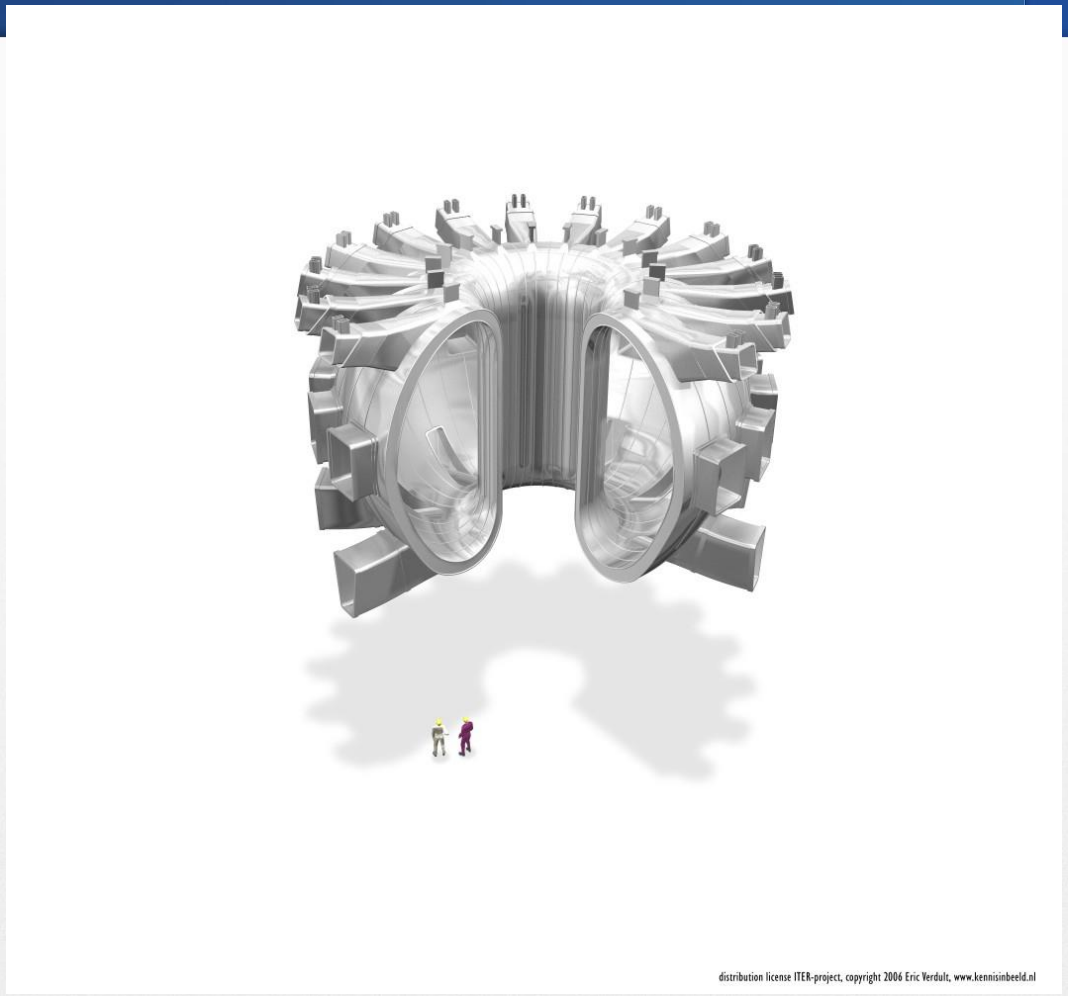
Electron Cyclotron (EC) and RF Sources (Gyrotrons)



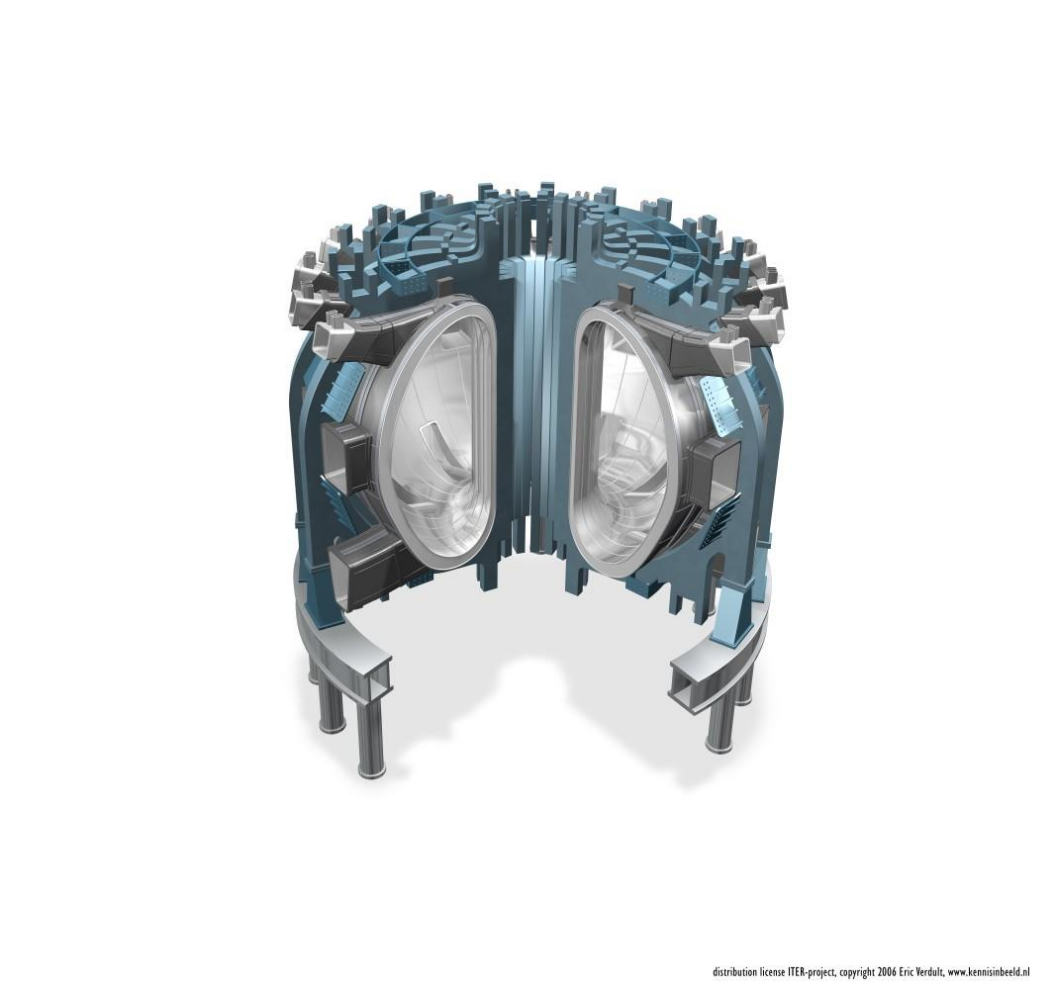




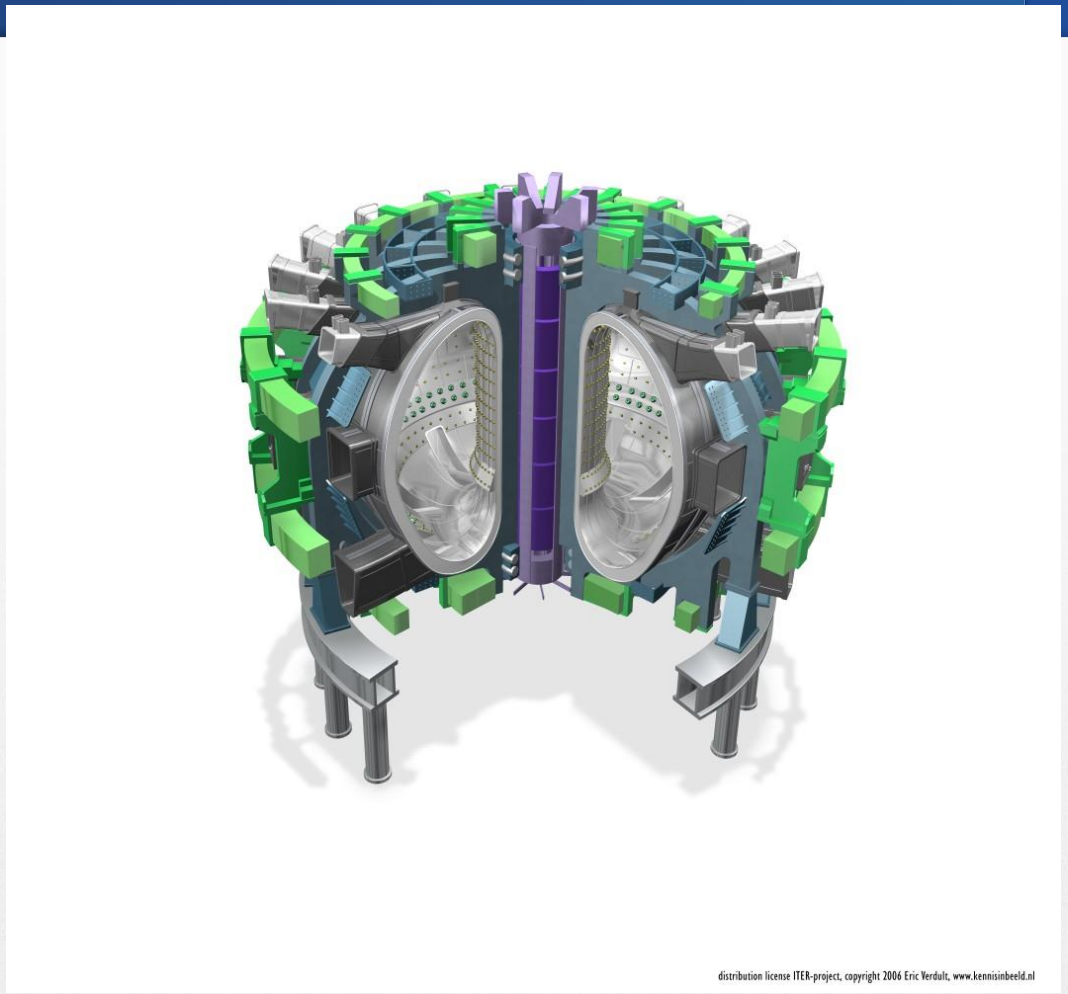
Tokamak Building



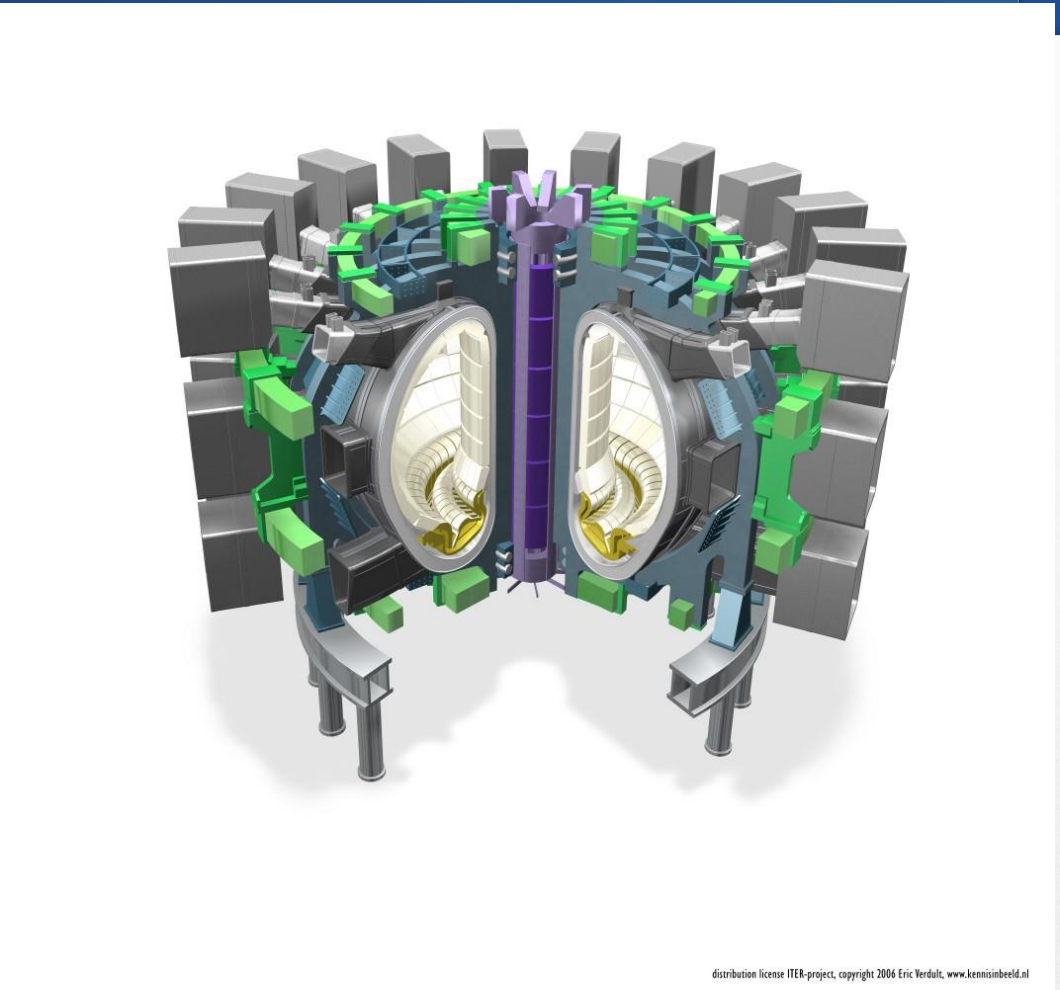
Tokamak – Vacuum Vessel



Tokamak – TF Magnets and Structure

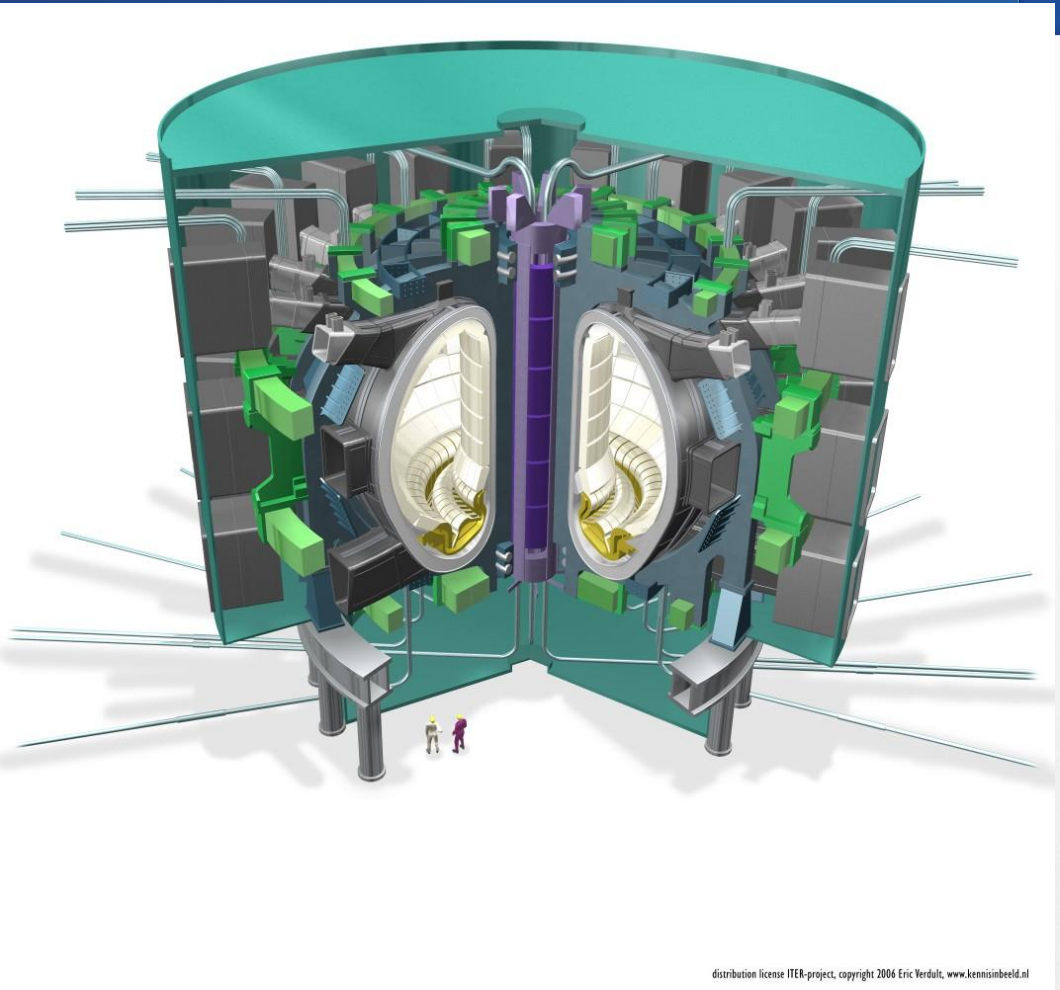


Tokamak – PF Magnets

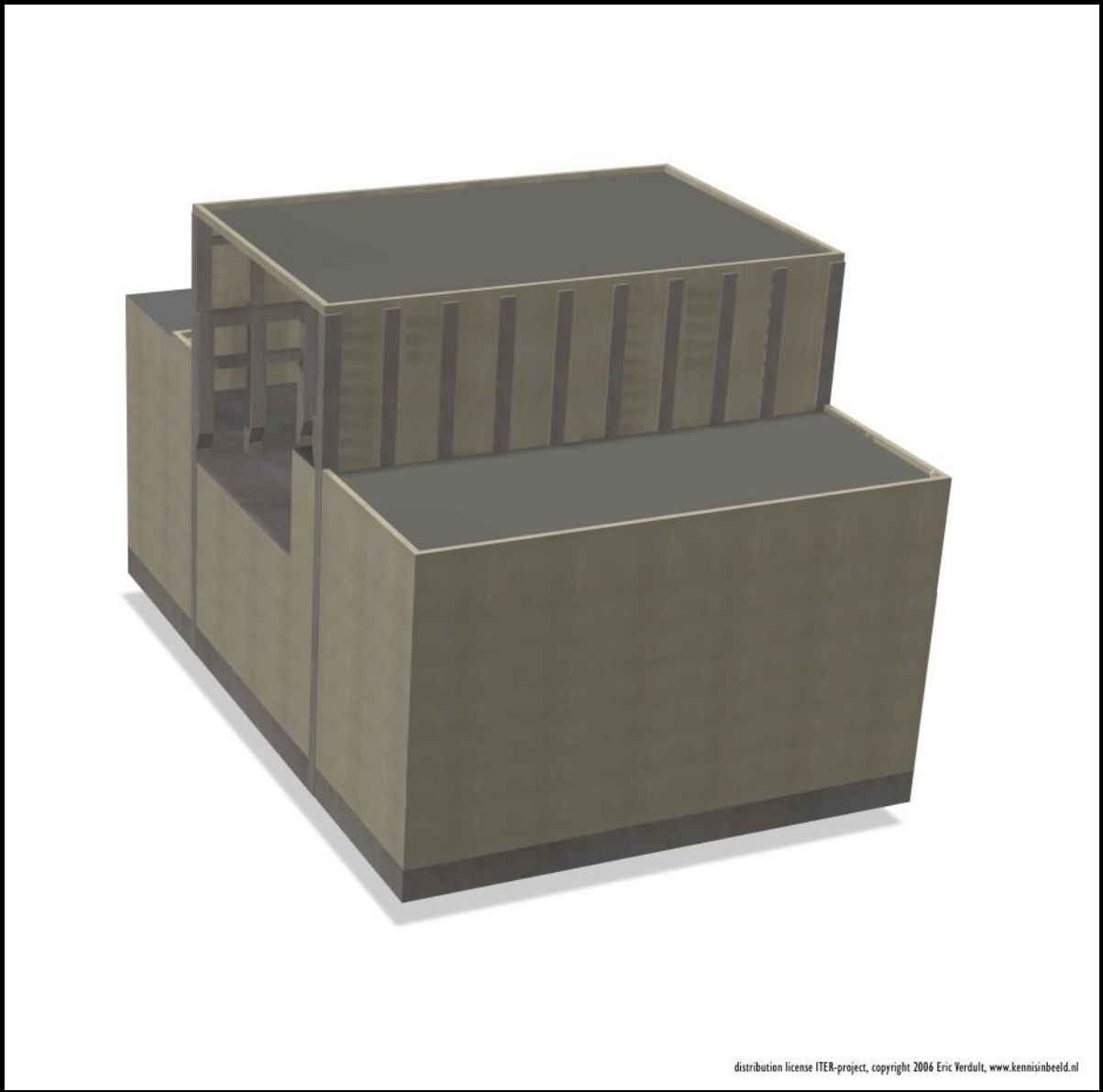


Tokamak – Ports and Blanket Modules

ITER - MAIN SYSTEMS



Tokamak – Cryostat

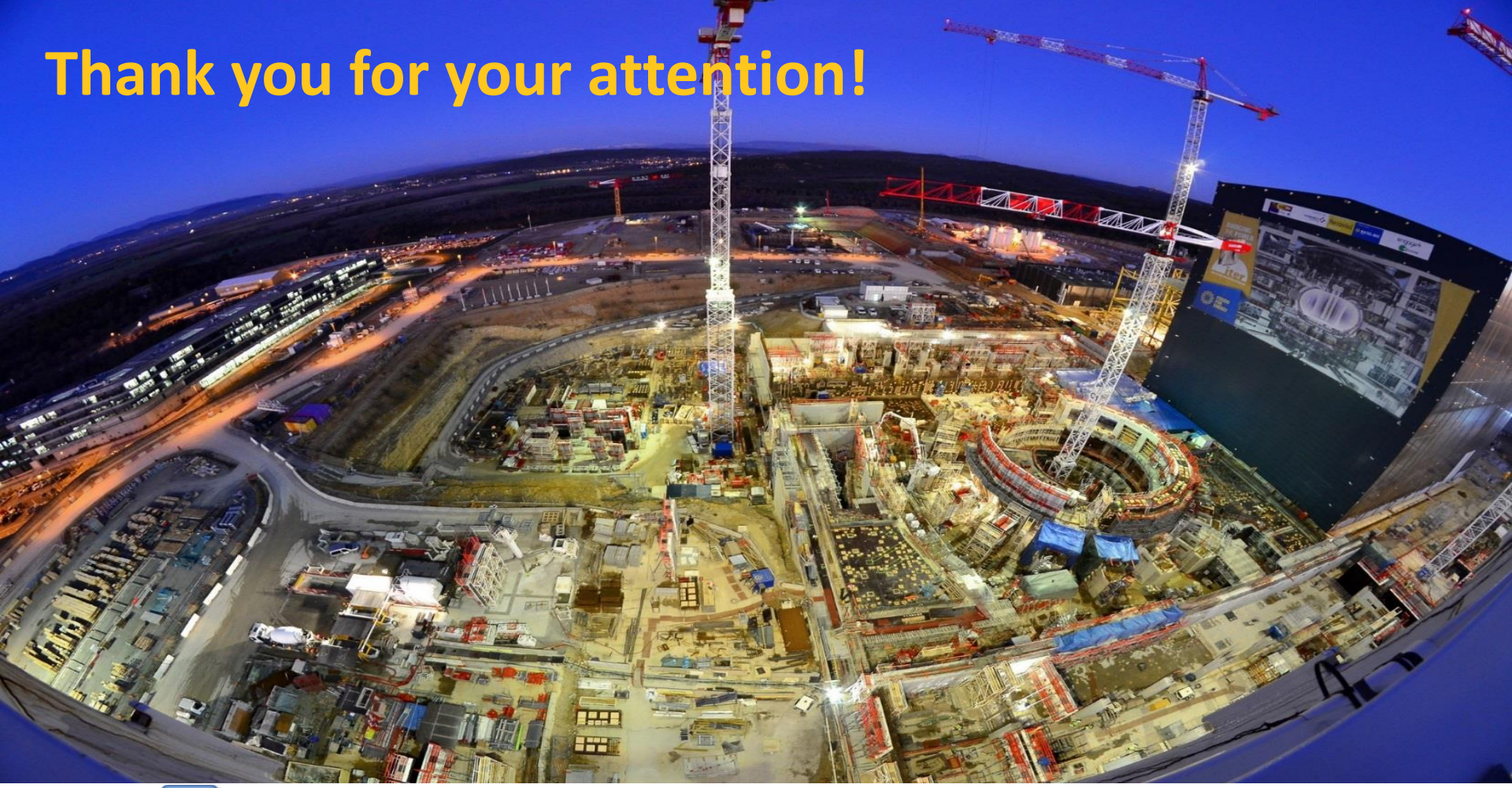


Tokamak – Whole construction

Caminante, son tus huellas el camino y nada más.
Caminante, no hay camino: se hace camino al andar.
Al andar, se hace camino, y al volver la vista atrás
se ve la senda que nunca se ha de volver a pisar.
Caminante, no hay camino, sino estelas en la mar.

Iter - The Way - Caminante

Thank you for your attention!



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