ITER
Vers l’énergie du futur

Dr Alain BECOULET, Directeur de l’Ingénierie – ITER Organization

Répondre aux besoins de la société sans nuire à la planète

- Les combustibles fossiles assurent encore 65% de la production d'électricité dans le monde.
- L'Agence internationale de l'énergie (IEA) prévoit une augmentation de la demande mondiale d'électricité de l'ordre de 80% d'ici 2040, dont 33% procédera de la demande chinoise, 15% de la demande indienne.
- L'électricité est le principal vecteur de développement des sociétés humaines.

Quelles options pour une production massive et décarbonée?

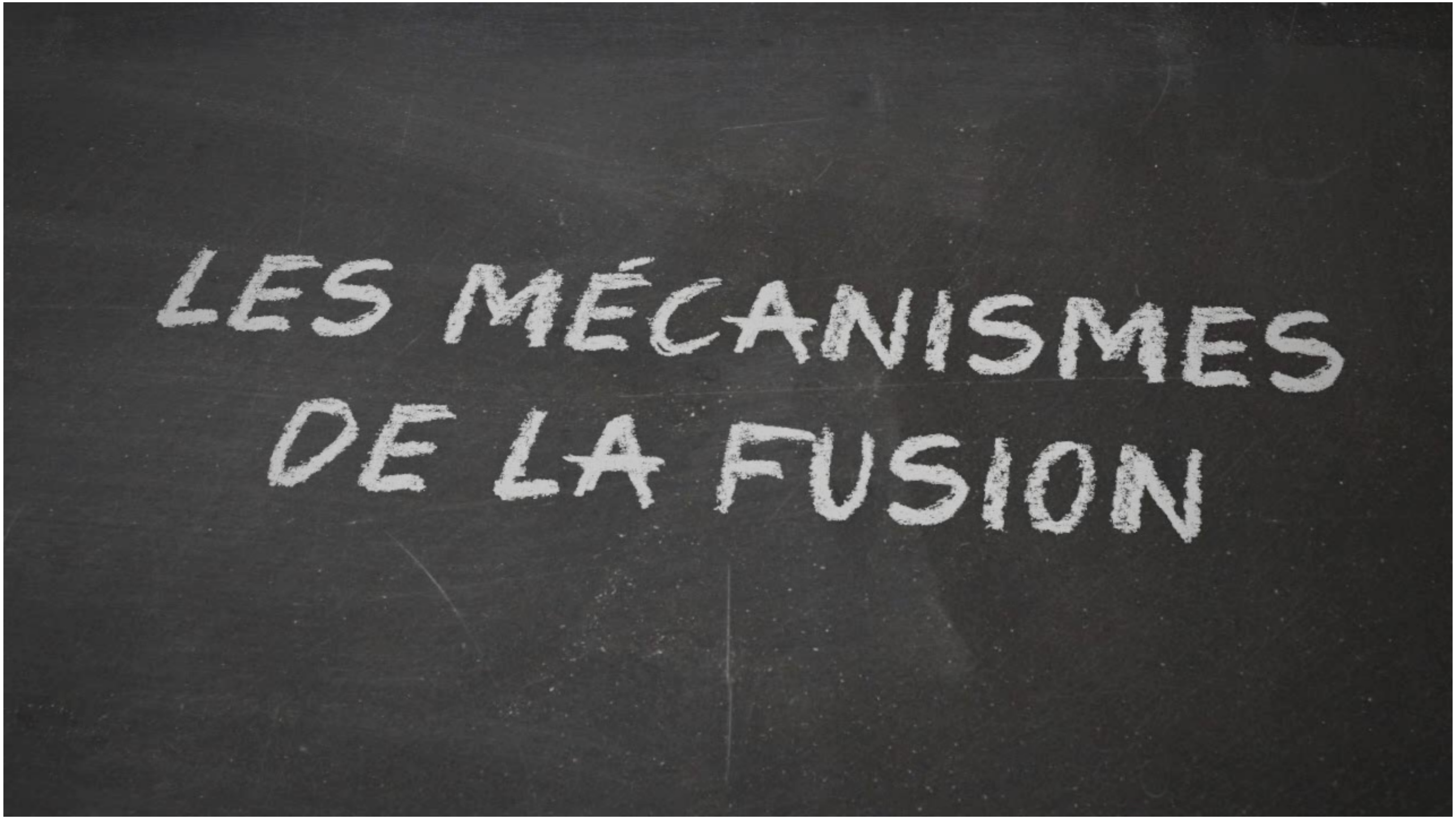
- Renouvelables: production intermittente, faible densité, ne peuvent répondre aux besoins de l'industrie et des mégapoles.
- Fission nucléaire: enjeux de sûreté et contraintes de la gestion des déchets à vie longue
- Fusion de l'hydrogène: doit apporter la démonstration de sa faisabilité scientifique et technique

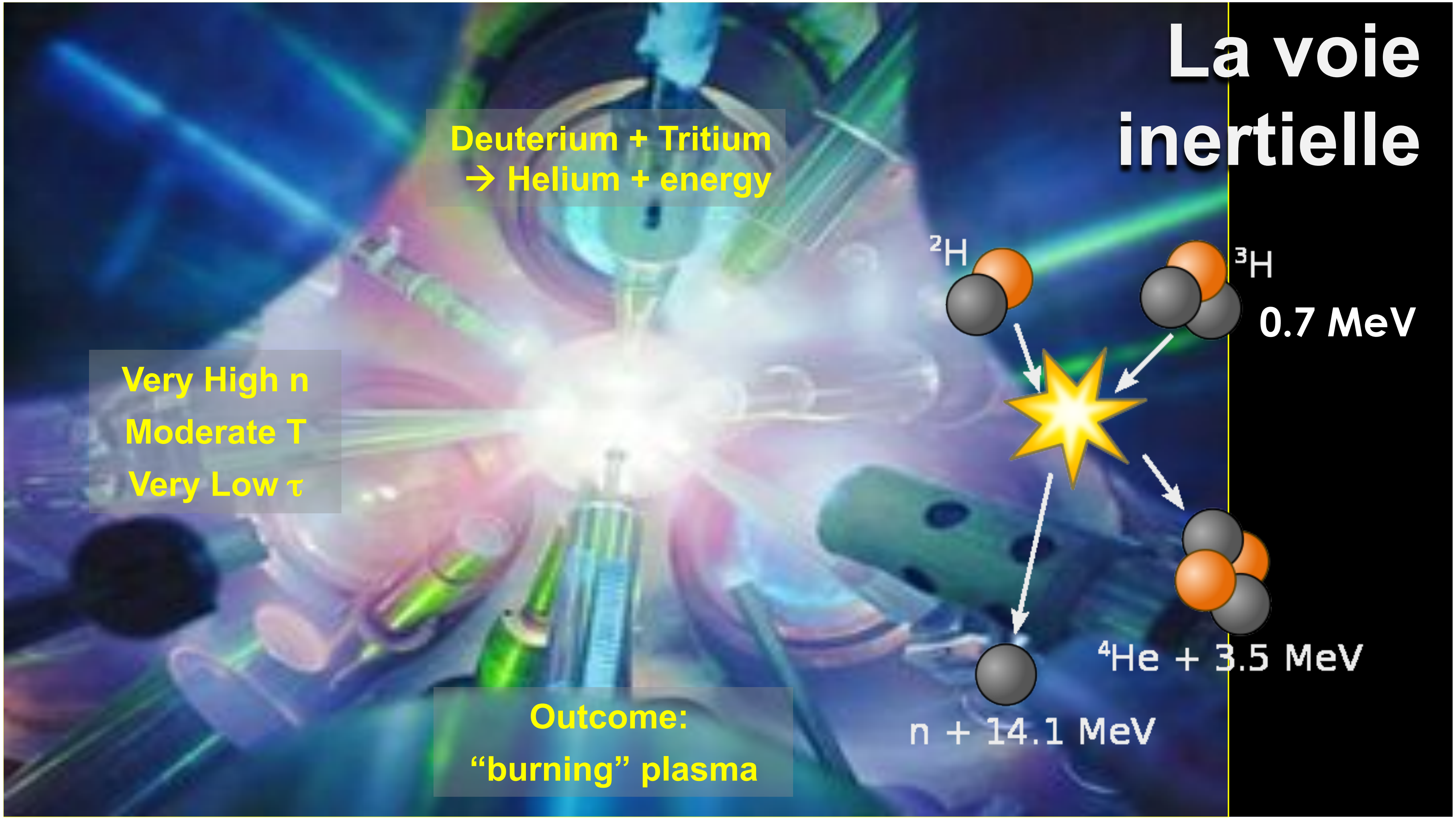
Fusion de l’hydrogène: l’énergie du Soleil et des étoiles

- **1920-1930: Mise en évidence des réactions de fusion de l’hydrogène à l’œuvre au cœur du Soleil et des étoiles (Perrin, Eddington, Bethe, Rutherford…)**
- **Dans une réaction de fusion, deux noyaux atomiques légers se combinent, forment un noyau plus lourd et libèrent une grande quantité d’énergie par perte de masse.**
- **1950: premiers travaux de recherche pour une utilisation pacifique des réactions de fusion.**

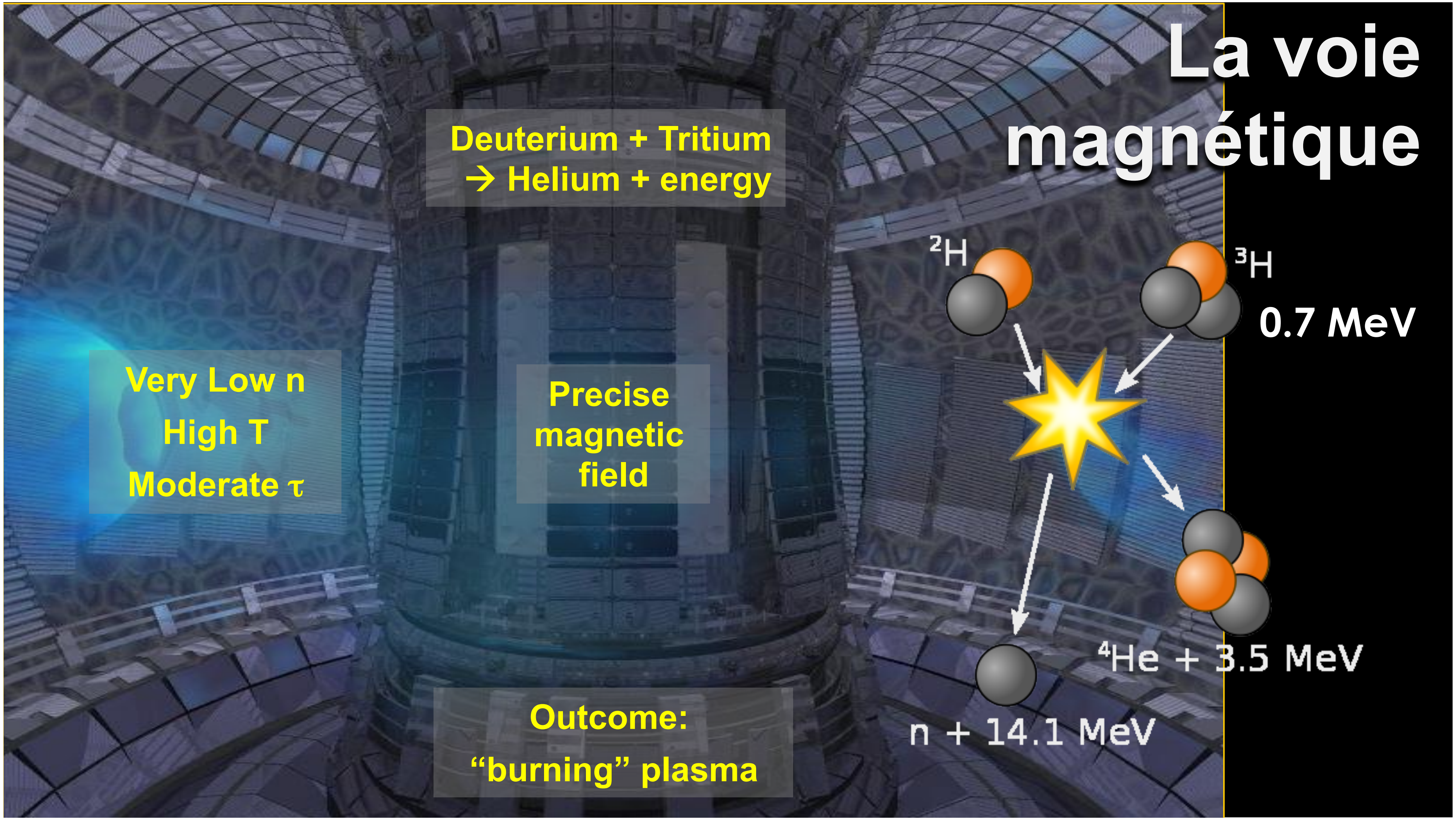
$$\Delta E = \Delta m c^2$$

Une infime perte de masse se traduit par une formidable libération d’énergie

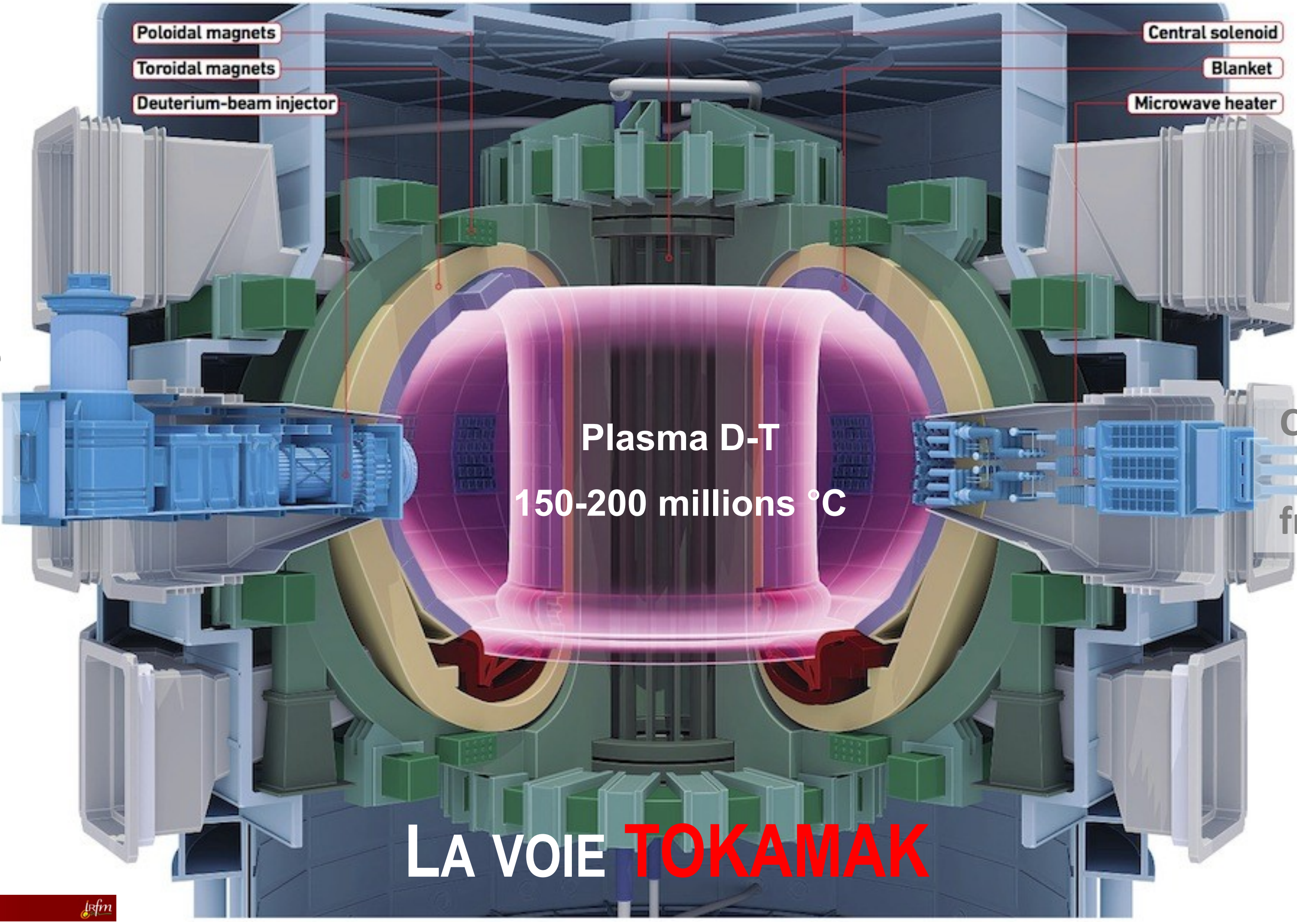

LES MÉCANISMES
DE LA FUSION



La voie inertielle
Deuterium + Tritium
→ Helium + energy
Very High n
Moderate T
Very Low τ
Outcome:
"burning" plasma
²H
³H
0.7 MeV
⁴He + 3.5 MeV
n + 14.1 MeV


La voie magnétique
Deuterium + Tritium
→ Helium + energy
Very Low n
High T
Moderate τ
Precise magnetic field
Outcome:
"burning" plasma
²H
³H
0.7 MeV
⁴He + 3.5 MeV
n + 14.1 MeV

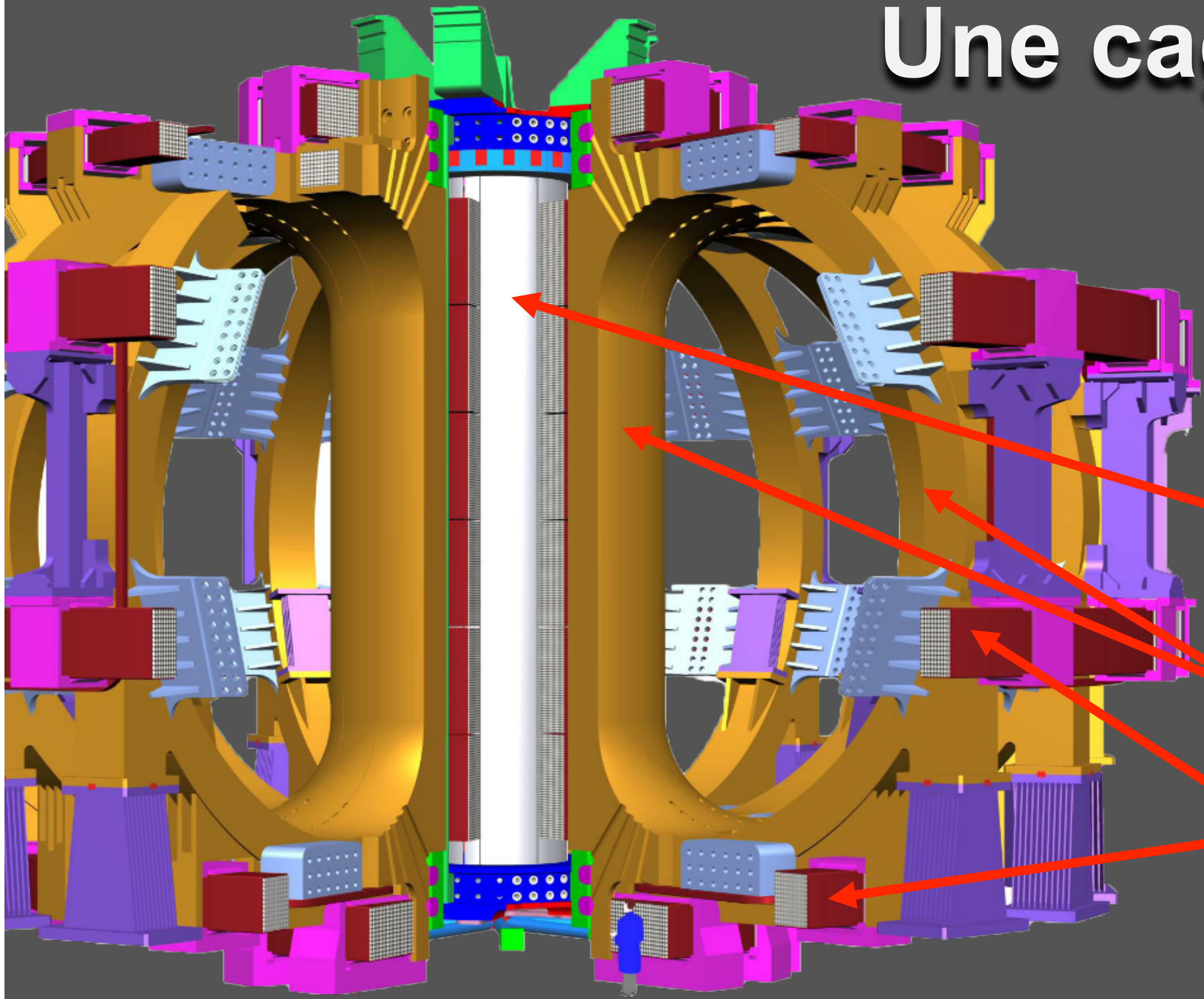
Chauffage par injection d'atomes rapides



Chauffage radio-fréquence

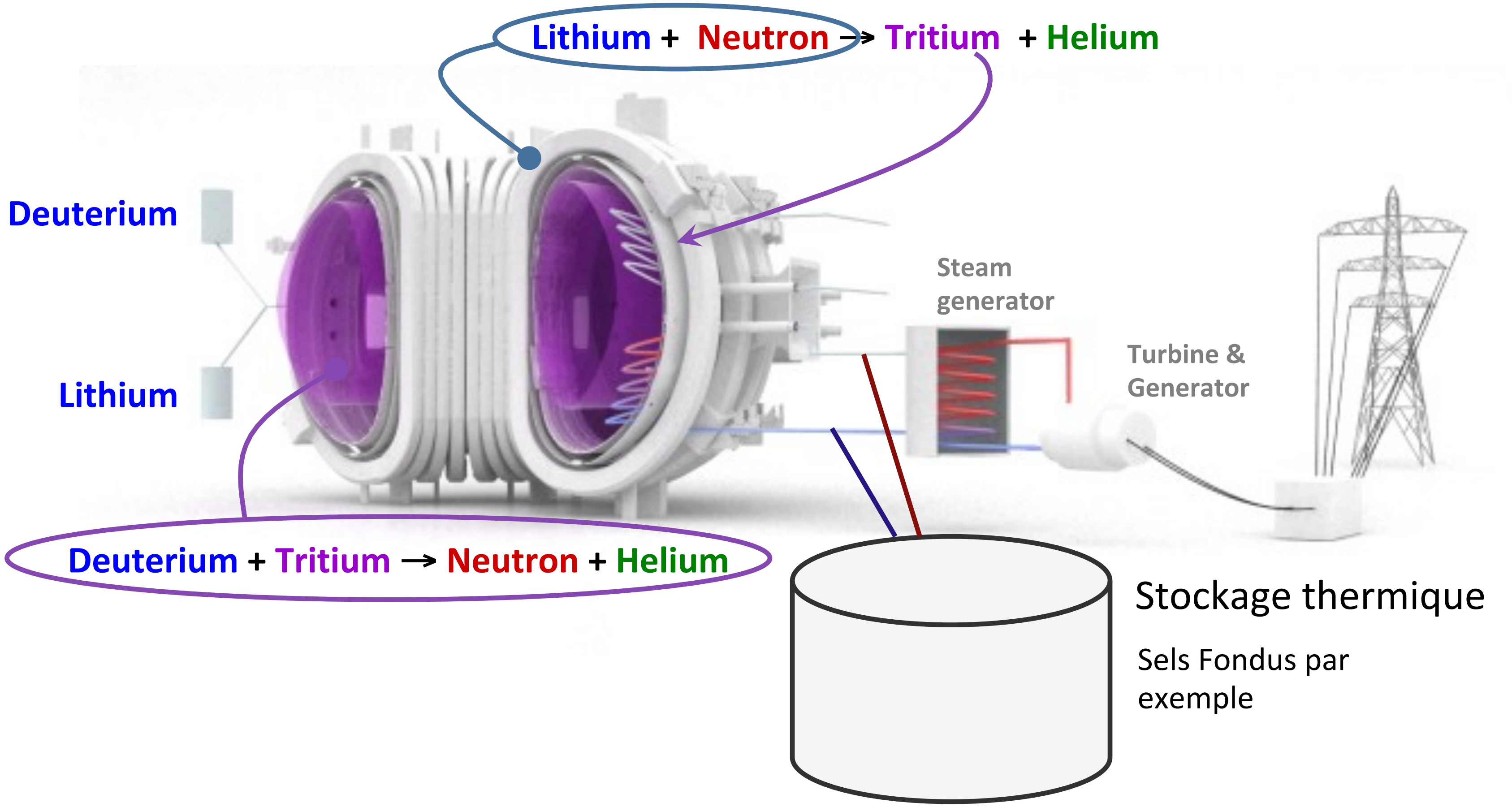
LA VOIE TOKAMAK

Une cage magnetique



Three main magnet systems:

- 1 Central solenoid
- 18 Toroidal Field Magnets
- 6 Poloidal Field Magnets



LE PRINCIPE DU RÉACTEUR

Les combustibles

Deutérium & Tritium, isotopes de l'hydrogène

Le lithium que contient la batterie d'un ordinateur portable et le deutérium de l'eau d'une demi-baignoire peuvent fournir 200,000 kilowatt/heures d'électricité.

Assez pour couvrir les besoins d'un Européen moyen pendant 30 ans.

- **Deutérium: 33 mg/m^3 – techniques d'extraction industrielle maîtrisées;**
- **Tritium: ITER expérimentera la production de tritium dans l'enceinte même de la machine par interaction neutron-lithium (modules tritigènes).**

UNE ENERGIE POTENTIELLEMENT ABONDANTE, PROPRE ET SURE

ABONDANCE

PROPRETÉ

SURETÉ

Les combustibles sont abondants et accessibles partout sur terre

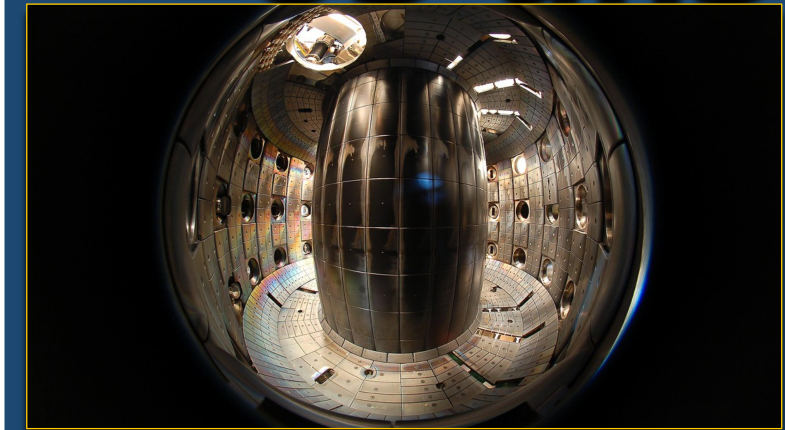
(1g D/T ⇔ 8 t pétrole)

La Fusion ne produit pas de gaz à effet de serre

La Fusion ne produit pas de déchets radioactifs à vie longue

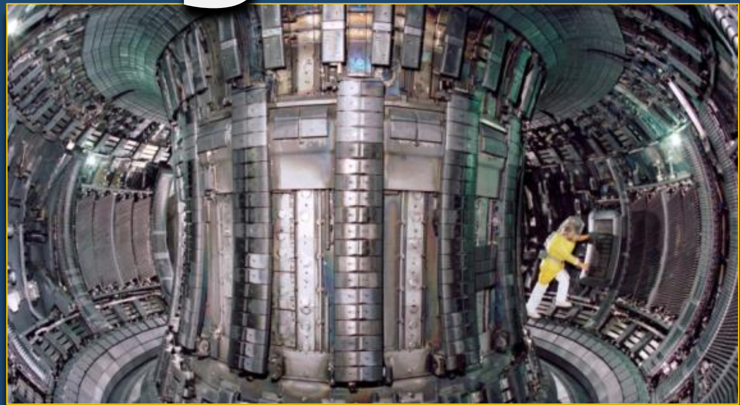
Un réacteur de Fusion ne peut pas devenir incontrôlable

65 ans de progrès



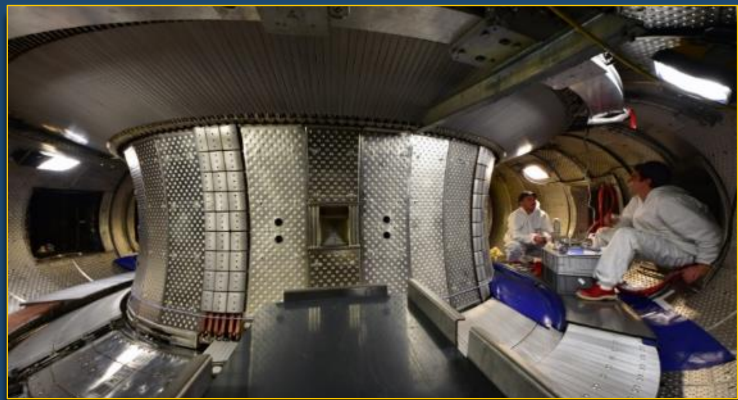
TCV – EPFL
Lausanne,
1992-présent

JET, Euratom,
1983-présent
(Opérations DT)



JT-60SA
Japon-UE
Mise en service
imminente

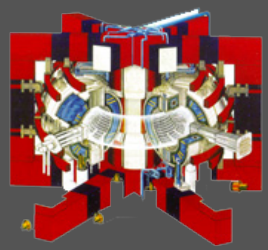
Tore Supra, CEA-Euratom
1988-présent
(devient WEST,
banc d'essai d'ITER)

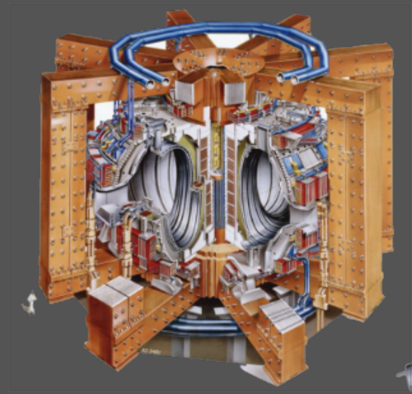


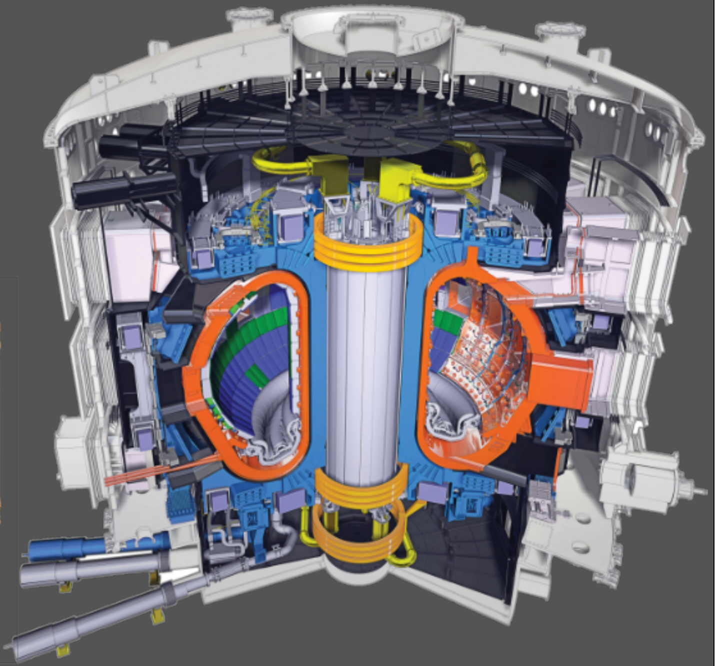
Size is important

Q - ratio of output over input – depends on:

- **Magnet strength**
- **Plasma density**
- **Plasma volume**







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

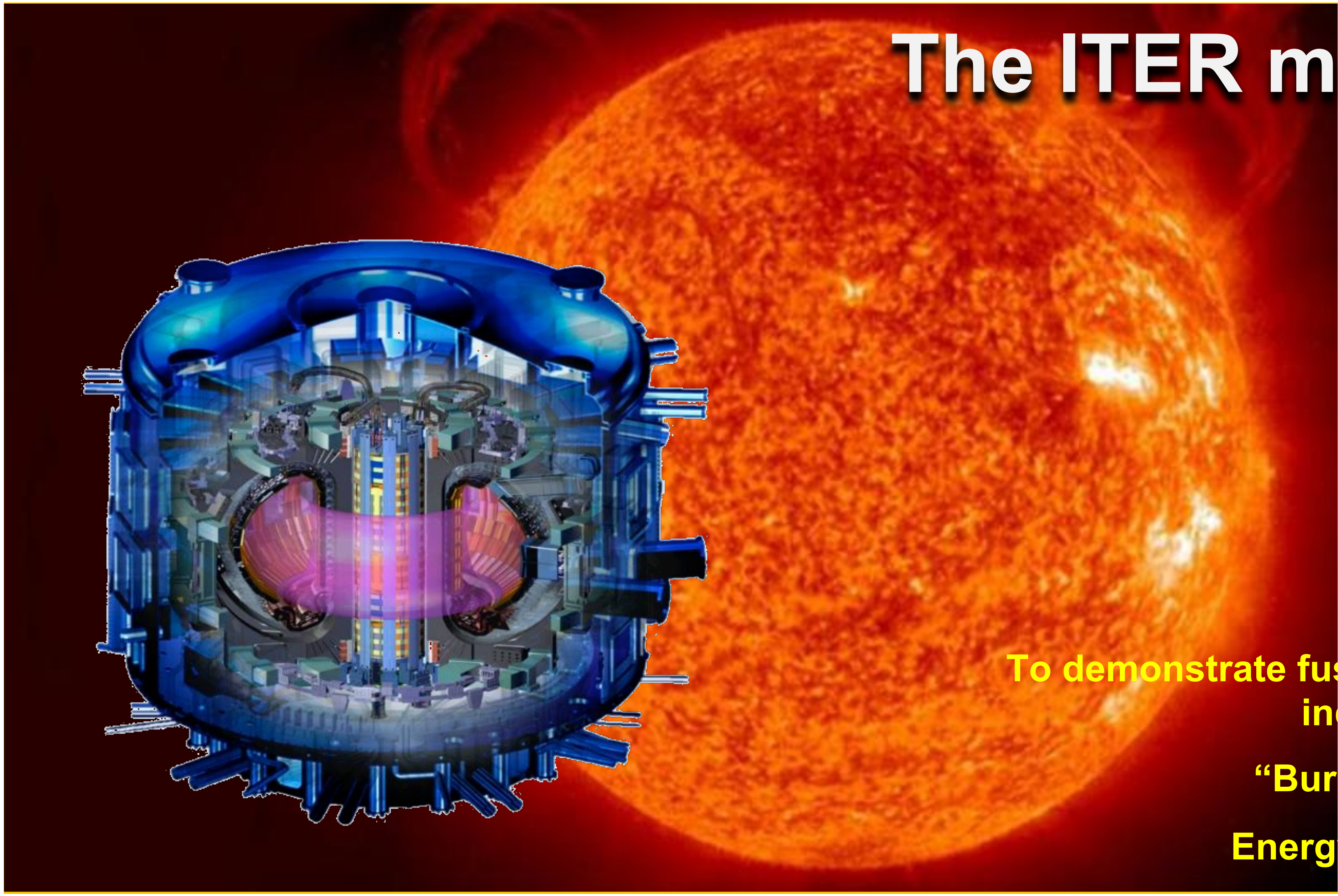
Progress on ITER Construction and Engineering

Dr Alain Bécoulet

on behalf of the ITER Team

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

The ITER mission



To demonstrate fusion power at industrial scale

“Burning” plasma

Energy Gain Q ≥ 10

The ITER narrative:

from idea to reality

November 1985

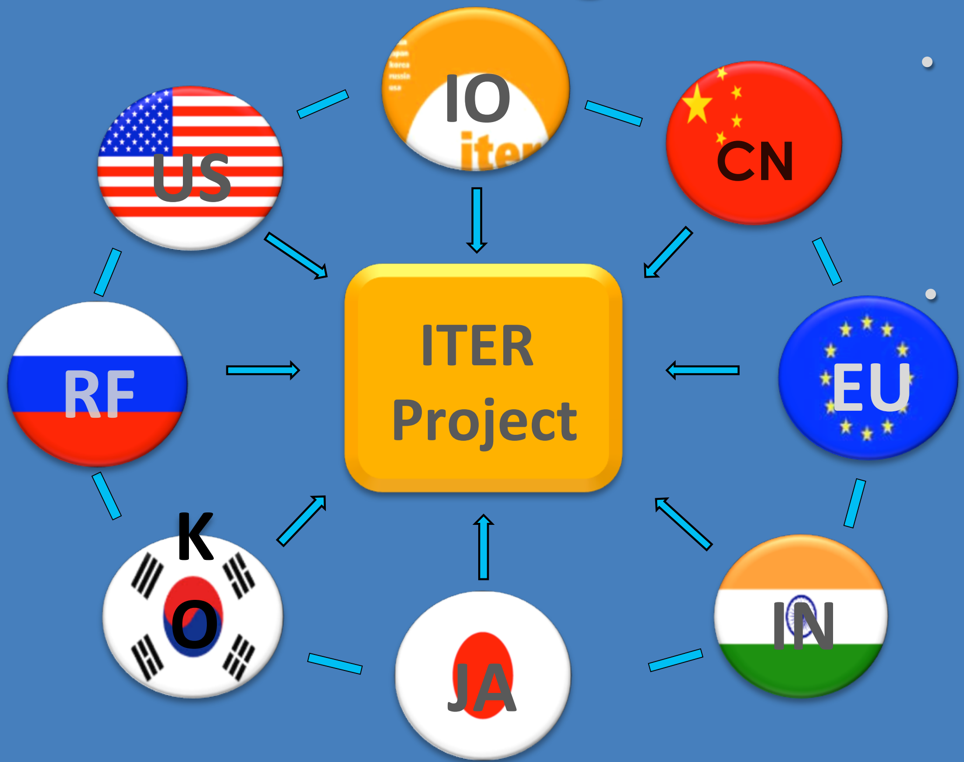
November 2006

August 2010

Today

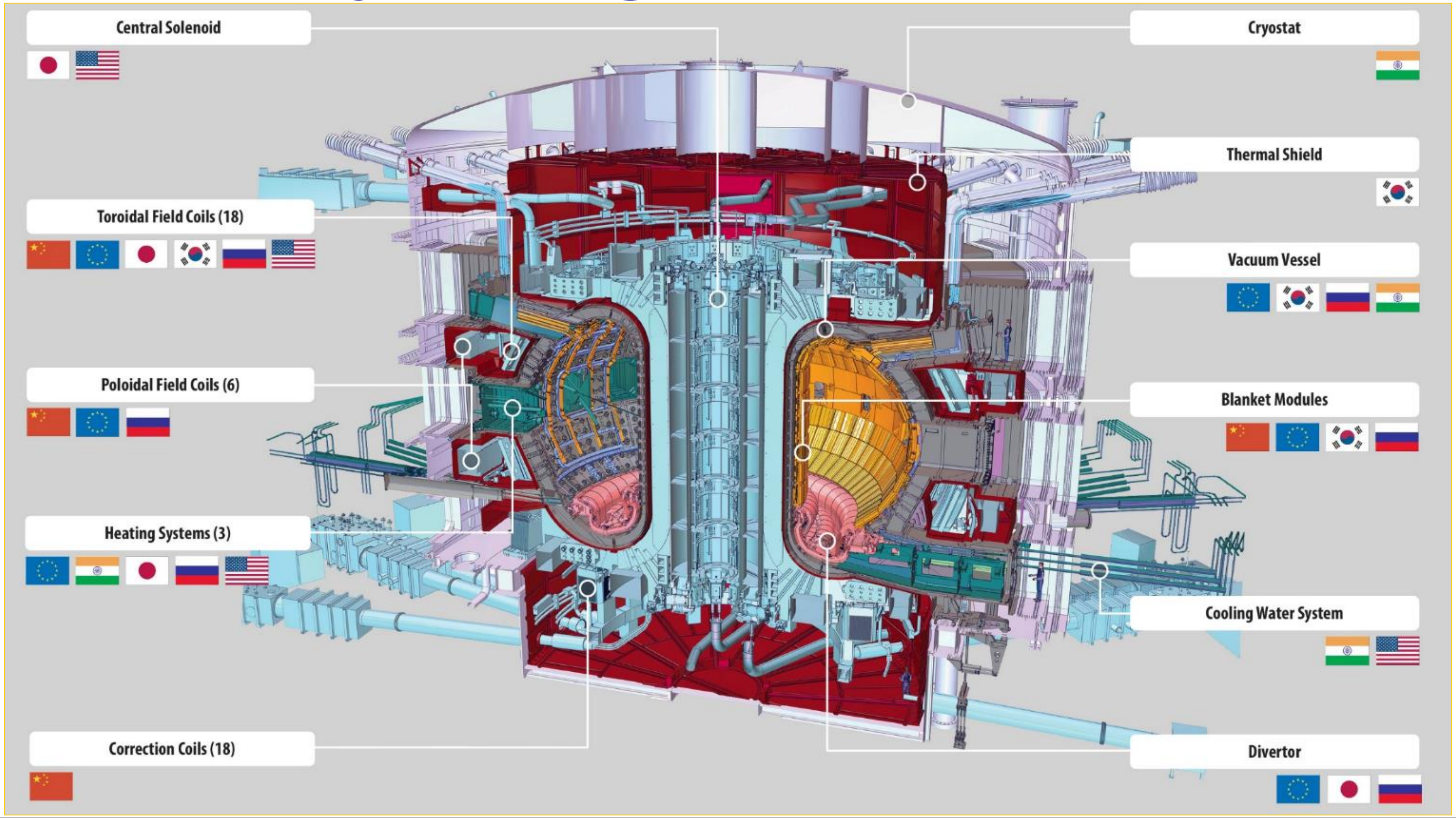
ITER: an integrated project:

ITER Organization & 7 Domestic Agencies

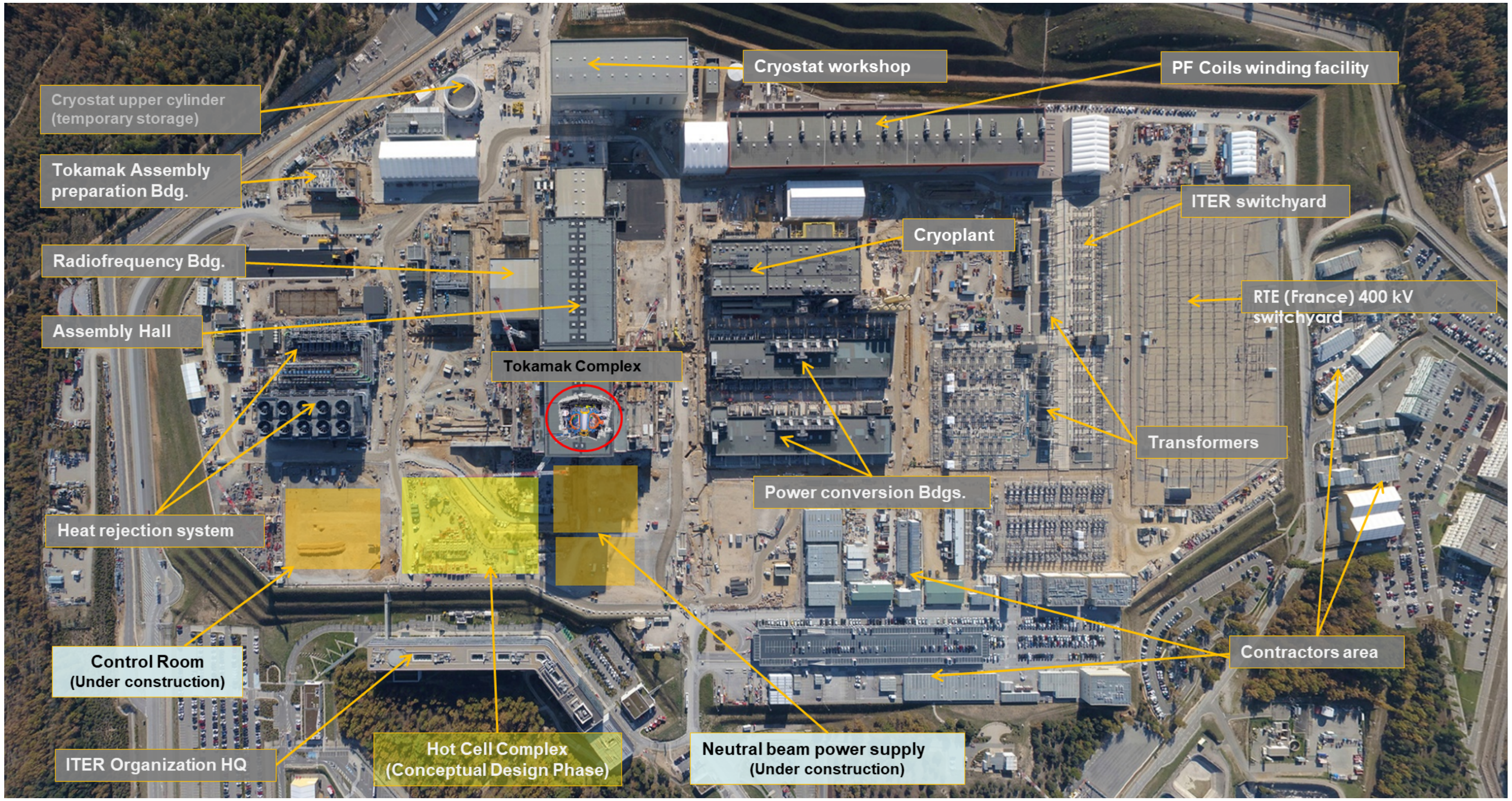


- Members contribute “in-kind” (80-90%)
  - Domestic Agencies offer contracts
  - Europe, as host, contributes ~45%
- Non-EU members contribute ~9% each

ITER Project Progress: A world-wide effort

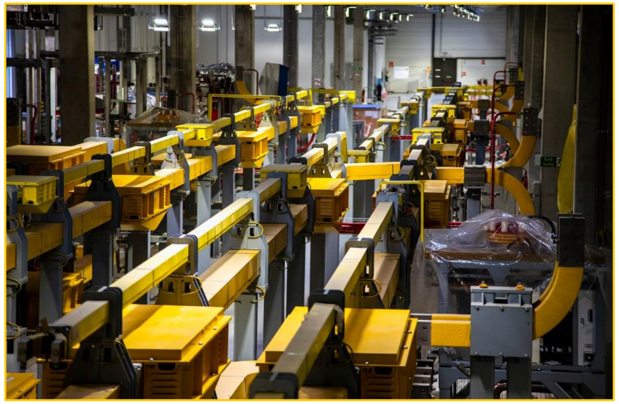


76% completed towards First Plasma milestone

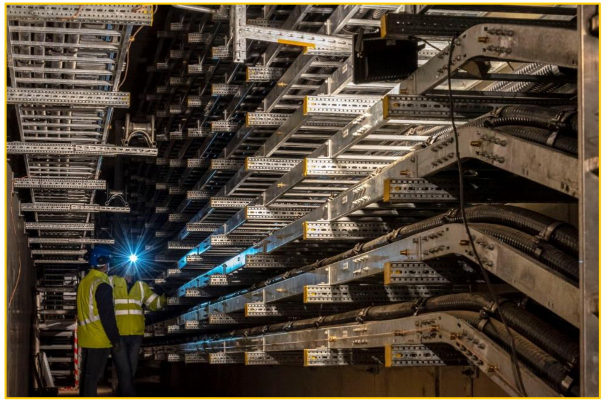


ITER Plant starting System Commissioning

Heat Rejection System



8 kms of busbars



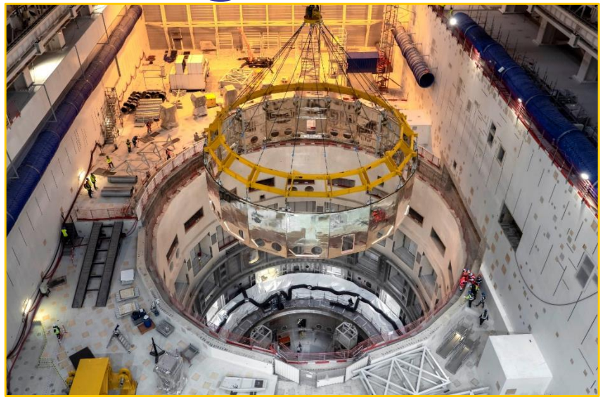
10 000 kms of cables

5000 tons of CryoPlant equipment

IO access to Control Bldg by Dec 2022

ITER Project Progress: ITER Assembly

Lower Cryostat in pit
base May 2020; lower cylinder August 2020

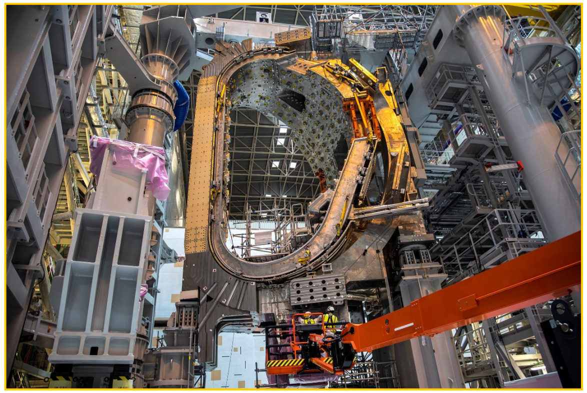


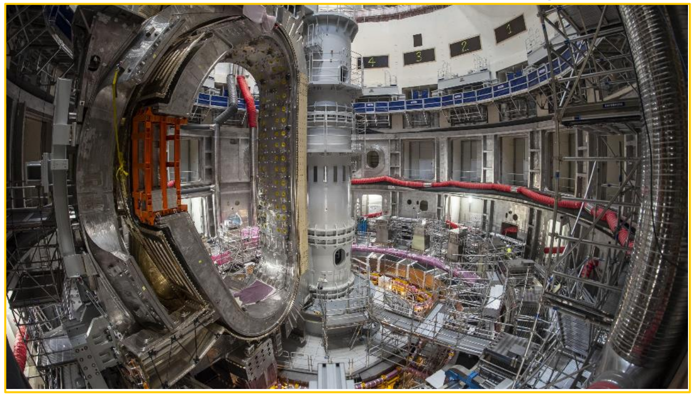
Low. Cyl. Thermal Shield in pit
Jan 2021

First 2 Pol. Field coils in pit
PF6 April 2021; PF5 Sep. 2021

Sub-Sector Assembly

- *3 VV sectors on-site*
- *14 TF coils on site*

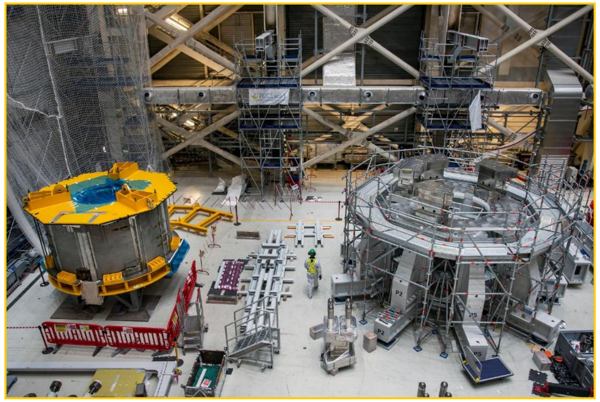




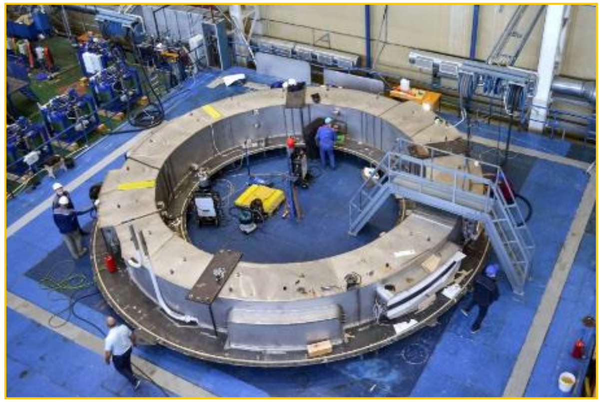
Tokamak Assembly

First sector module in pit ***14 May 2022***

ITER Project Progress: ITER Assembly



Central Solenoid
2 modules on-site (Sept & Dec 2021)



Poloidal Field Coil #1
Ready to be shipped Oct 2022

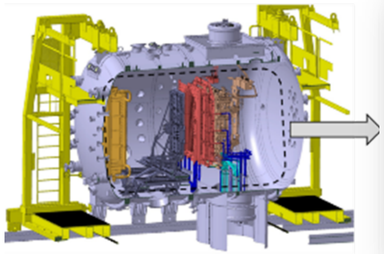
Magnetic Coil Feeders
1600 tons of equipment delivered

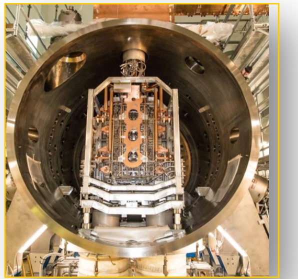
Poloidal field Coils # 2 to 6
- *6; 2-5 completed*
- *3 on test*
- *4 under completion*
- *6 & 5 in pit*

Cryostat
- *Completed*

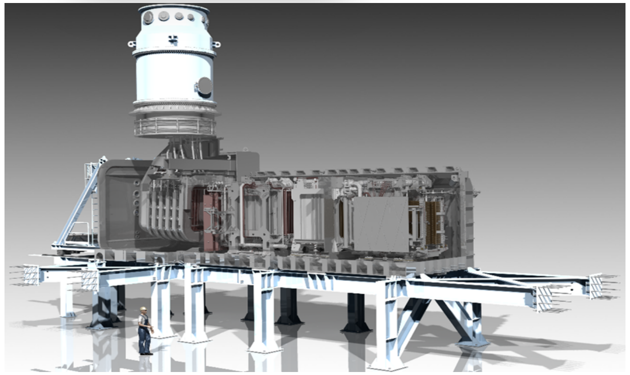
ITER Engineering: Neutral Beam H&CD

***SPIDER**: Optim. of the filter field; modif. of the driver material from Alumina to Quartz; modif. of the technology of the RF generators from oscillators to solid state amplifiers; …*



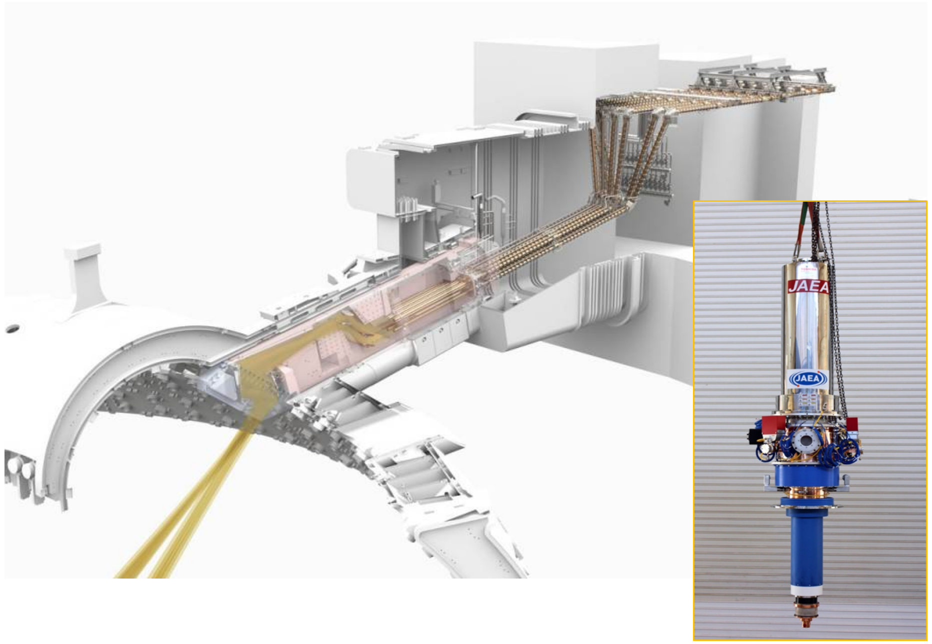


***MITICA**: under construction; integrated power tests on-going; Plasma operation of the injection will commence in 2025*



- ***2 Heating Neutral Beam Injectors and 1 Diagnostic Neutral Beam Injector***
- ***16.7 MW** (1MeV D0 or 0.87MeV H0) to the ITER plasma for up to 3600 s **per HNB***
- ***Final Design** stage; dependent on the resulting R&D underway in the Neutral Beam Test Facility (NBTF) in Padua*
  - ***SPIDER testbed** to optimize the Beam source of the HNB and DNB*
  - ***MITICA facility,** full-scale prototype of an HNB injector at 1 MV.*

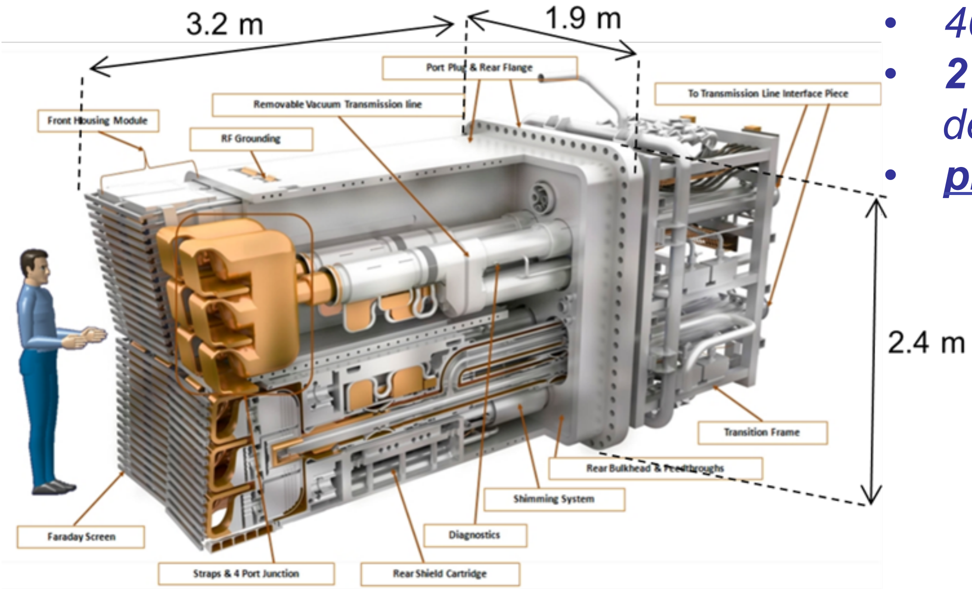
ITER Engineering: Electron Cyclotron H&CD



First **upper launcher** is required for FP and is to be delivered in 2026 (EU)
First stage of **EC plant controller** (EU) delivered and accepted on the ITER site

- ***20 MW of heating and current drive***
- *170 GHz for pulse lengths up to 3600 seconds*
- *24 gyrotrons, 12 matching high voltage power supplies, 24 transmission lines*
- ***8 MW*** *installed for the ITER first plasma campaign, providing* ***breakdown assist***
  - *8 Gyrotrons passed FAT (RF+JA)*
  - *2 sets of Power Supplies (+ 2 in FAT), and all the transformers and switchgears delivered (EU)*
  - *commissioning to start in* ***Q4/2022*** *allowing for the installation and commissioning of the first gyrotrons*
  - ***FP Transmission Lines*** *being prototyped (US) and testing at the FALCON facility in Lausanne from early 2023*

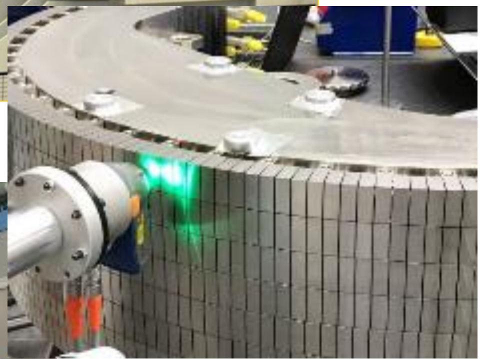
ITER Engineering: Ion Cyclotron H&CD



*1st ICRH Antenna delivery by **end of 2029**, followed by the second antenna **mid-2030***

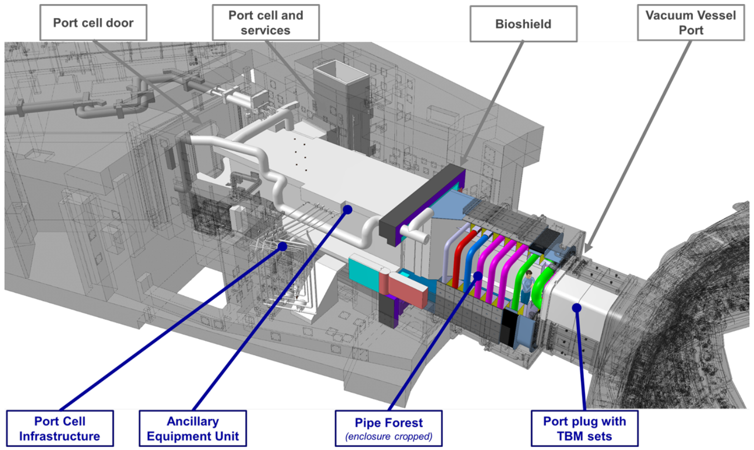
- ***<u>20 MW of heating and current drive</u>***
- *40-55 MHz for up to 3600 seconds*
- ***2 antennas** powered by 8 RF sources; final design to be completed early 2025*
- ***<u>prototypes manufacturing and testing</u>** needed*
  - *Front & Rear **RF Windows** test articles & functional prototypes*
  - ***Faraday screen** prototype, including representative bar material and dimensions*
  - ***RF module** & **quarter of IC Port Plug***
  - *RF module **metallic seal** prototype*
  - ***Strap** prototype (3D printed strap)*
  - *Port Plug **back flanges** with various connection to services*
  - ***Arc detection** devices prototype*

ITER Engineering: Divertor



- ***54 divertor cassette assemblies****, each including one Cassette Body and three Plasma-Facing Components, i.e. the inner and outer vertical targets, and the Dome*
- *series production of CBs have started (EU) in CNIM-SIMIC and Waltertosto;*
- *one prototype of* ***IVT*** *(EU) delivered to IO.*
- ***OVT*** *prototype is in manufacturing (JA)*
- ***Dome*** *prototype (RU) delivered to IO*
- *IO in charge of cassette* ***integration*** *and diagnostics/operational* ***instrumentation***

ITER Engineering: Tritium Breeding Modules

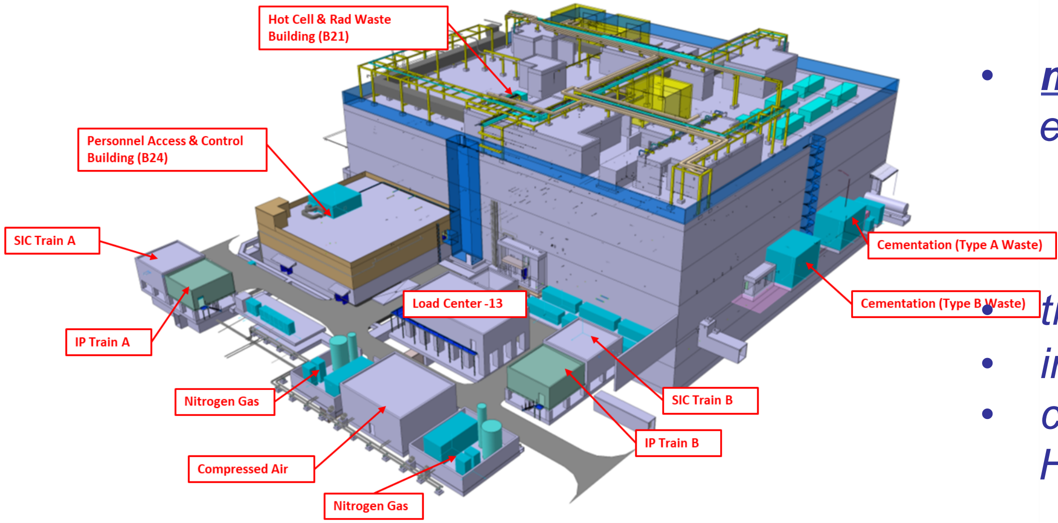


4 Test Blanket Systems planned to be operated in ITER *as "TBS initial configuration" covering the last ITER non-nuclear phase and the first two nuclear phase*

- *Water-Cooled Lithium Lead (WCLL) TBS, designed and procured by the EU;*
- *Helium-Cooled Ceramic Pebbles (HCCP) TBS, jointly designed, procured by Korea & EU;*
- *Water-Cooled Ceramic Breeder (WCCB) TBS, designed and procured by Japan;*
- *Helium-Cooled Ceramic Breeder (HCCB) TBS, designed and procured by China.*
- *The IO in charge of design and procurement of the infrastructures enabling to host the TBSs*

The design of all the four TBSs has reached the Preliminary Design stage

ITER Engineering: Hot Cell Facility

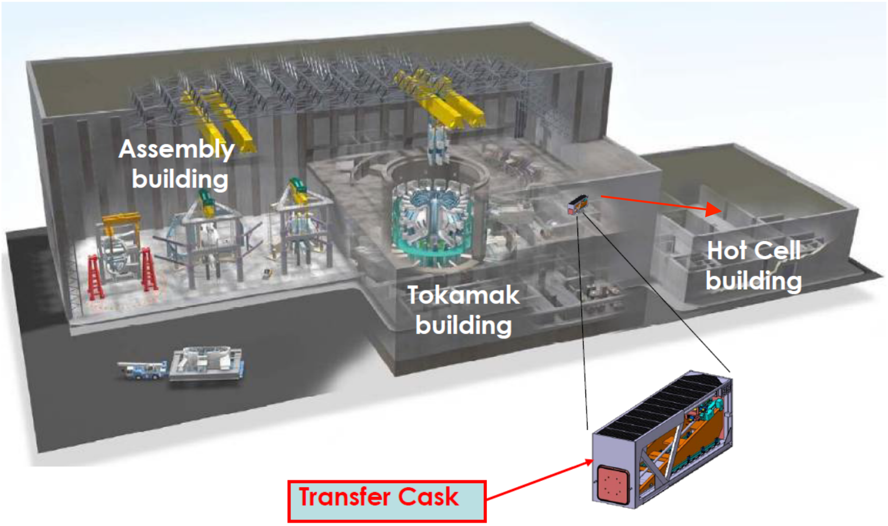


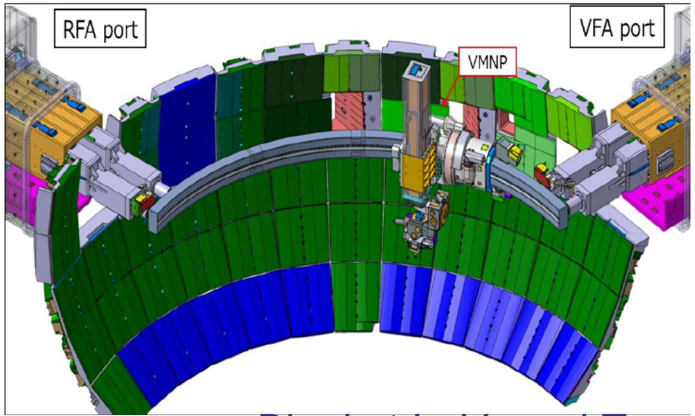
- ***maintain*** *activated and/or contaminated equipment*
  - *In Vessel Components,*
  - *Port Cell Equipment,*
  - *Tokamak Remote Handling equipment,*
- *treat and interim store* ***radioactive waste,***
- *import and export components and waste,*
- *control human ingress and egress to the Hot Cell and the Tokamak Complex.*

Present status

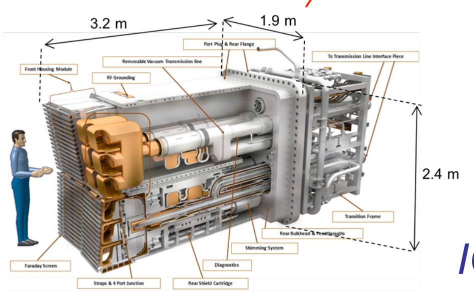
- *Conceptual Design Reviews (Facility & Bldg) under closure,*
- *ITER Council Action Plan on Project Requirement vs Cost Optimisation on-going,*
- *Decision to launch Preliminary Design expected end 2022:*
  - *PDR 2025*
  - *Operation start expected ~2032*

ITER Engineering: Remote Handling tools

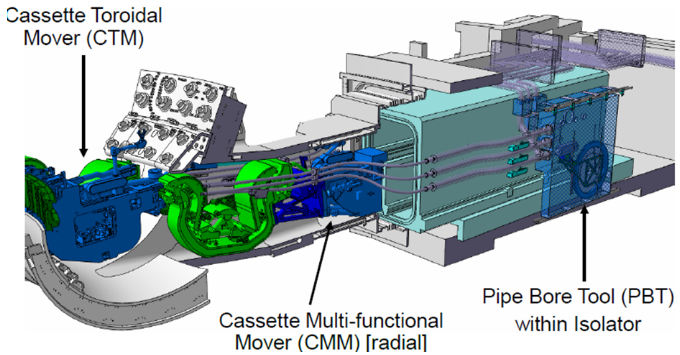




Blanket In-Vessel Transporter



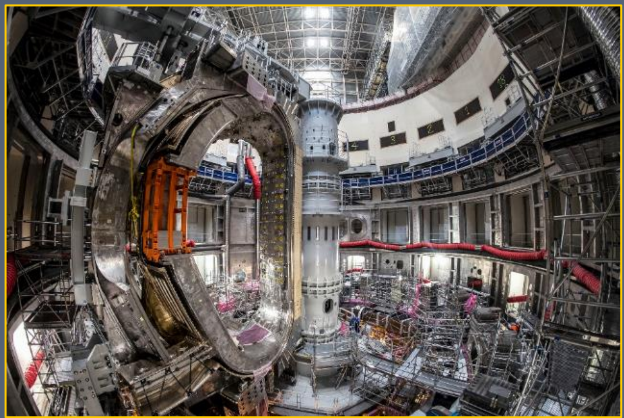
ICRH antenna

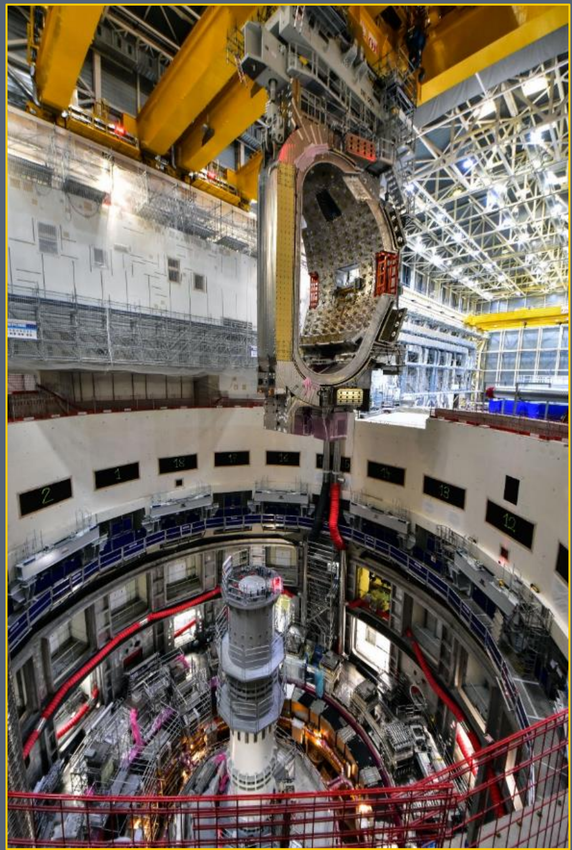


Divertor RH system


Addressing
Challenges
VV/TS repairs
FOAK/Covid delays
Regulatory relations
Offsetting future risks
Baseline update

Assembly status



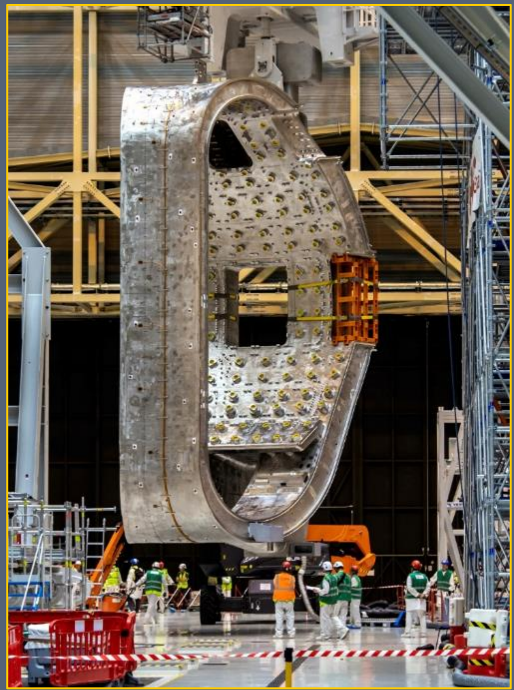


Vacuum vessel sector modules:

- Building blocks of the Tokamak (9 in total).
- Each is comprised of one 40° vacuum vessel sector, two toroidal field coils and a set of thermal shield panels.
- Problems have been identified in thermal shield cooling pipes (cracks) and in vacuum vessel sector field joints (dimensional non-conformities) that will require repairs

Challenges of FOAK components

Thermal Shields: stress corrosion identified in cooling pipes

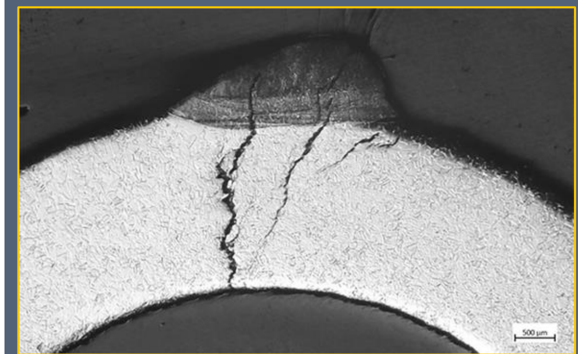


Vacuum Vessel Sectors: Dimensional non-conformities at field joint bevel

Issues have been investigated, and repair strategies initiated.

Lift, extract, and repair

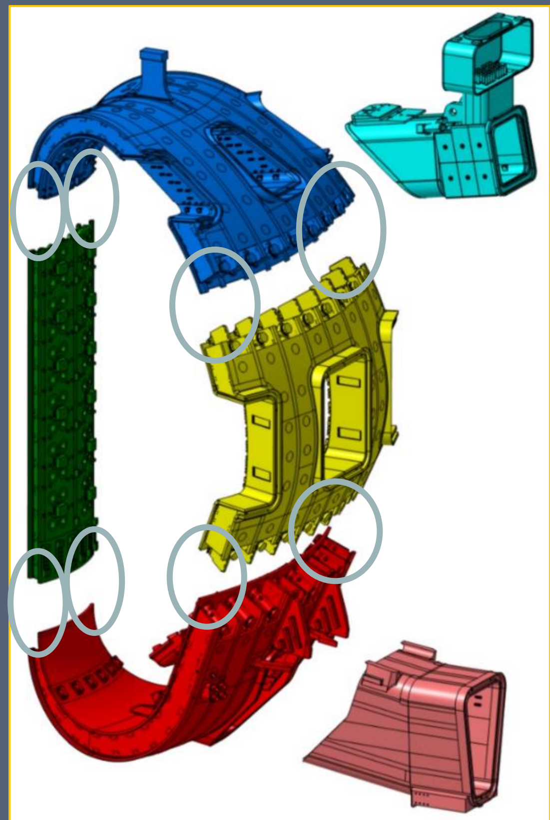
Thermal shield: actively-cooled component between the VV sectors and TF coils.



Cracks detected in TS cooling pipes

Cause: stress corrosion due to chlorine residues (design flaw)

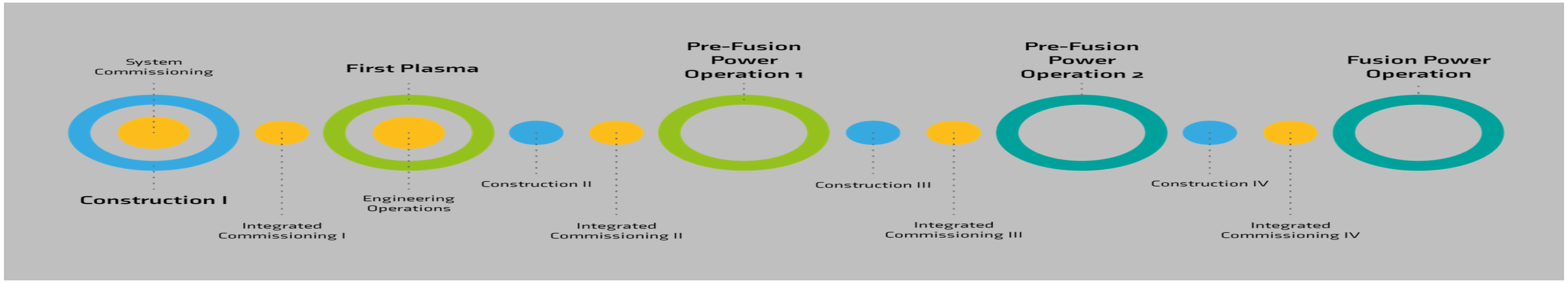
Decision: replace the pipes



Complex welding requirements on the four main sections of the VV sectors caused deviations.

These deviations affect the interface between sectors.

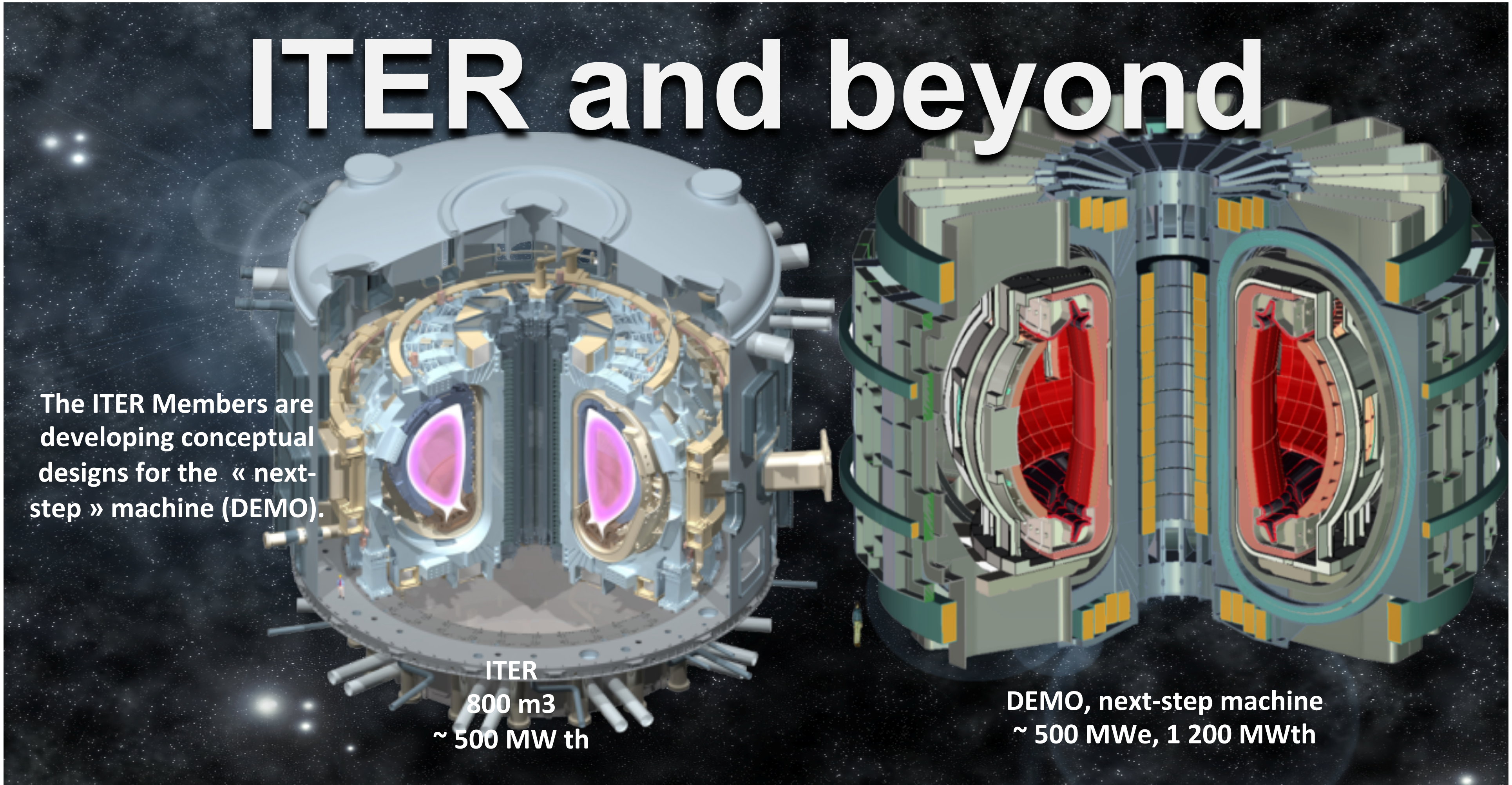
ITER Challenges and Way Forward



ITER presently faces challenges and delays linked to

- *External-cause delays (threats): Covid 19 pandemic and international situation*
- *Internal-cause delays (weaknesses): FOAK procurement and assembly*
- *Staged licensing process: tokamak assembly hold-point*
- *Management aspects, associated to the recent loss of Director General Bigot*

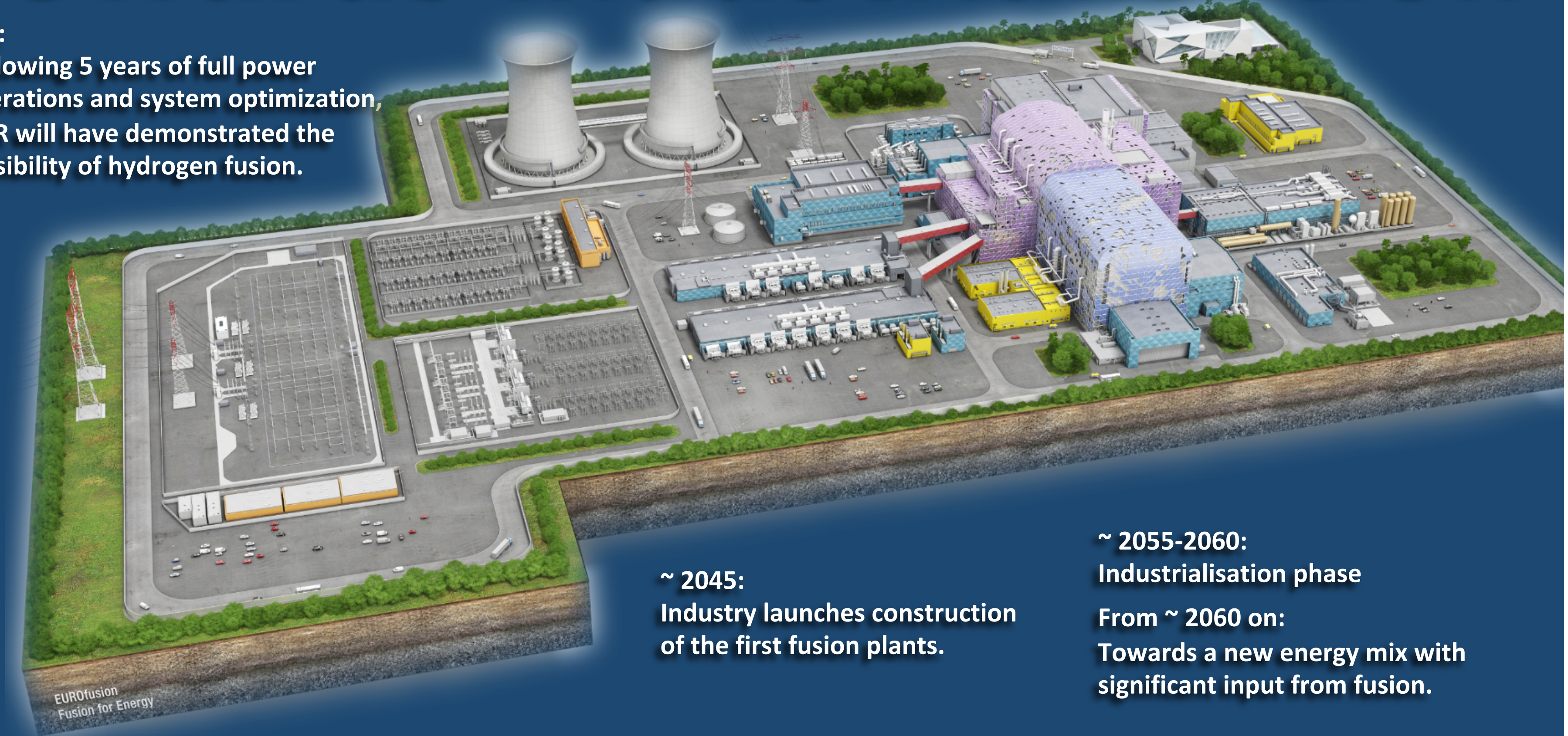
The 7 ITER Members and the IO are now working <u>as one ITER team</u> on a rebaselining of the ITER Project, under the governance of the ITER Council.


ITER and beyond
The ITER Members are developing conceptual designs for the « next-step » machine (DEMO).
ITER
800 m3
~ 500 MW th
DEMO, next-step machine
~ 500 MWe, 1 200 MWth

Towards industrialisation

~ 2040:

- Following 5 years of full power operations and system optimization, ITER will have demonstrated the feasibility of hydrogen fusion.

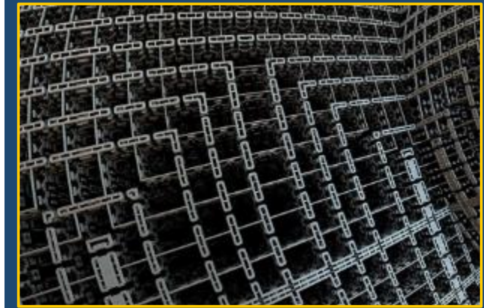


~ 2045:
Industry launches construction of the first fusion plants.

~ 2055-2060:
Industrialisation phase

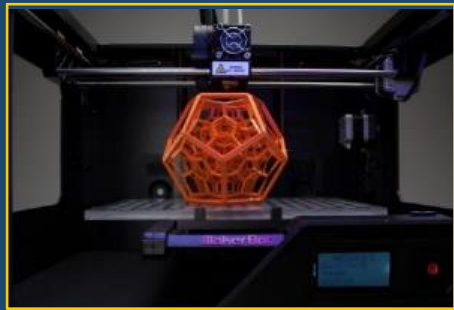
From ~ 2060 on:
Towards a new energy mix with significant input from fusion.

Innovation & spin offs

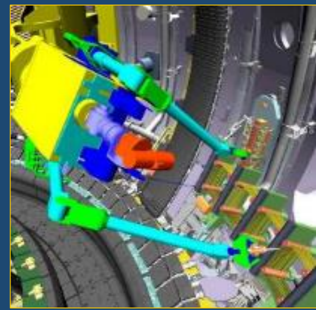


High technology filters

Medical magnetism



3D printing for complex shapes

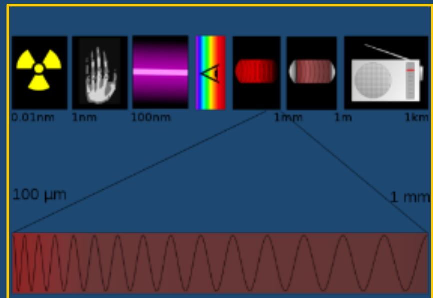


Robotics in extreme environments

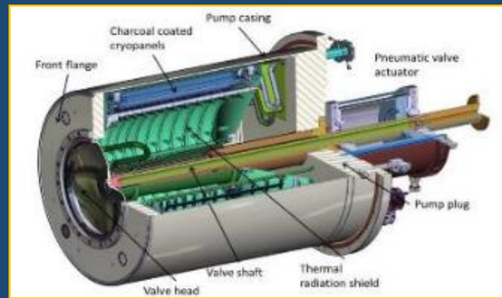
Etc.

Power electronics

Explosive forming



Ultra high-speed transmission



Cryopumps – Vacuum systems

Private initiatives

Recent development of private initiatives, essentially in the anglo-saxon world and sometimes in collaboration with academia add credibility to the fusion option.

By exploring new and sometimes original avenues, some of these start-ups contribute to fundamental knowledge and technical developement.

ITER and the fusion community are attentive to these developments, as they can benefit to fusion as a whole.

However, the laws of physics are the same for all, and some projects and announcements lack credibility

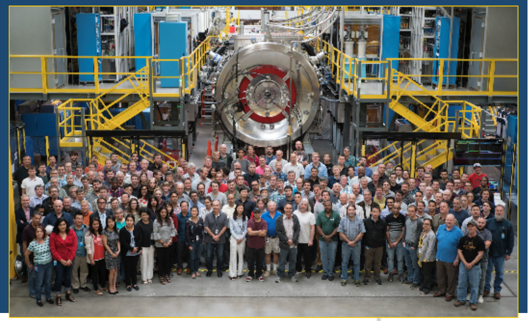
General Fusion, Canada

Helion Energy, US

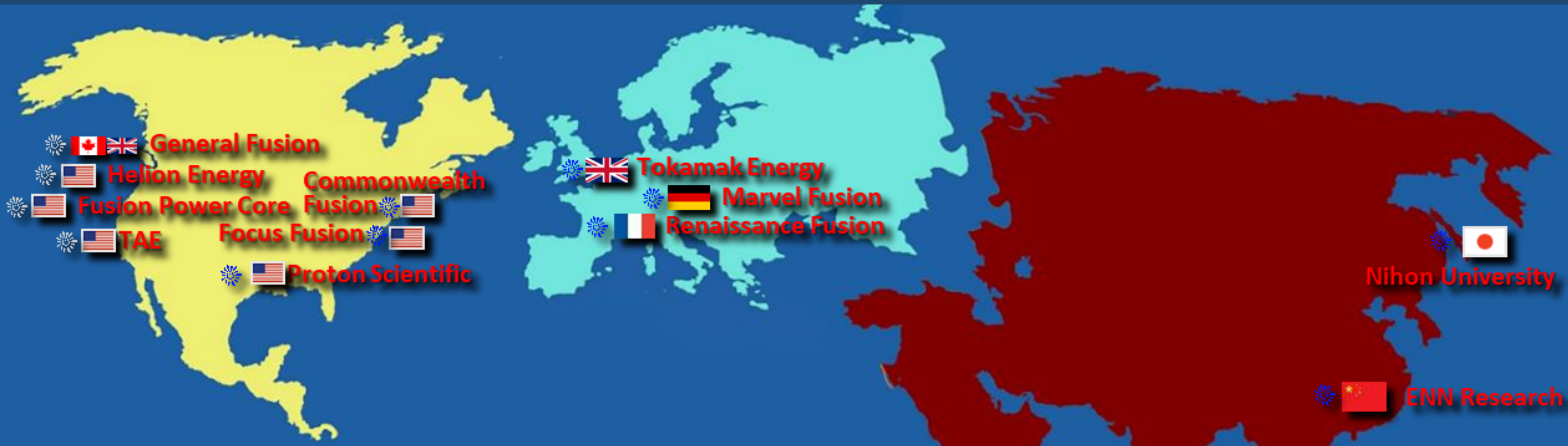
Commonwealth Technologies, US

Tokamak Energy, UK

TAE Technologies, US



Private Initiatives



Private Initiatives

- **10 programmes :**
  - ✓ 2 tokamaks
  - ✓ 1 laser/inertial
  - ✓ 7 alternative concepts
- **14 projects :**
  - ✓ 3 tokamaks
  - ✓ 1 Stellarator/Heliotron
  - ✓ 3 laser/inertial
  - ✓ 7 alternative concepts

ITER at COP26

ITER Director-General Bernard Bigot chairs High-Level Panel discussion at COP26 on 12 Nov 2021

For the first time on stage at a COP conference

Fusion definitely relevant for a low-carbon energy future.

En Mémoire du

Dr. Bernard Bigot

ITER Director-General, 2015-2022

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