ITER and the development of nuclear fusion

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Do we need fusion ?

Personal opinion, for consideration by the audience

- Population explosion, especially in emerging economies
- The lion's share of world energy production is of fossil origin (80 - 90%)
  - Finite resources
  - Need a replacement: but only two classes left - nuclear and renewable
  - Climate effects due to CO_2
- Renewable energy (hydro, wind, solar, ...) must contribute, but:
  - Large fluctuations: day / night, summer / winter, storm / windless, ..
  - Low energy density: large installations and costs
  - Need for backup, storage and large interconnections
  - Not easy and will take time
- A broad energy mix is needed, and a correct public discussion
  in which no option is ruled out à priori
- In the current confused ‘discussion’ on our energy future
  fusion has an important role to play

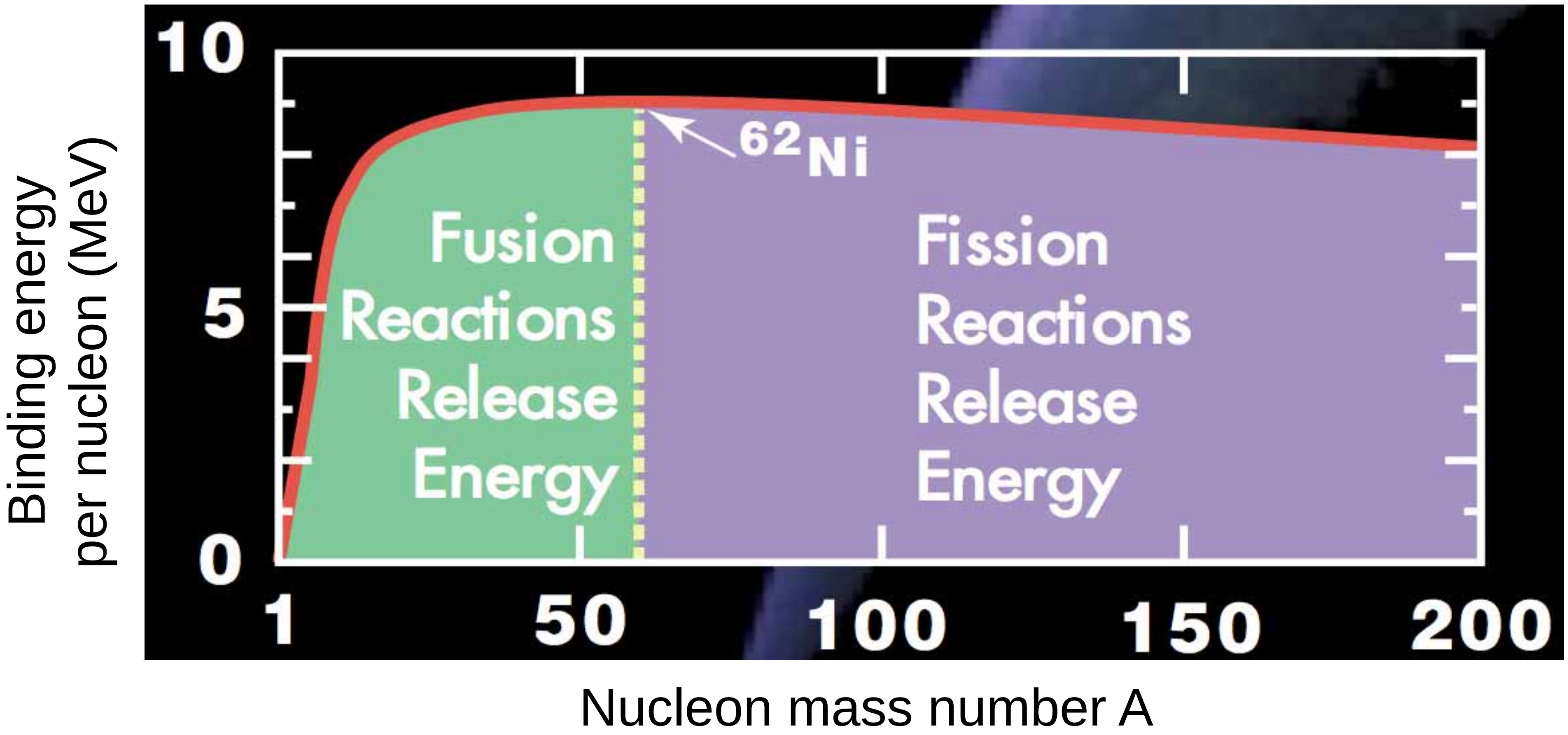
Outline

- Physics of fusion reactions
- Magnetic fusion research in Europe and the world
- ITER
- Planning a prototype fusion power plant
- Important technological advances in recent years
- Conclusions

PHYSICS OF FUSION REACTIONS

Energy gain in fusion reactions

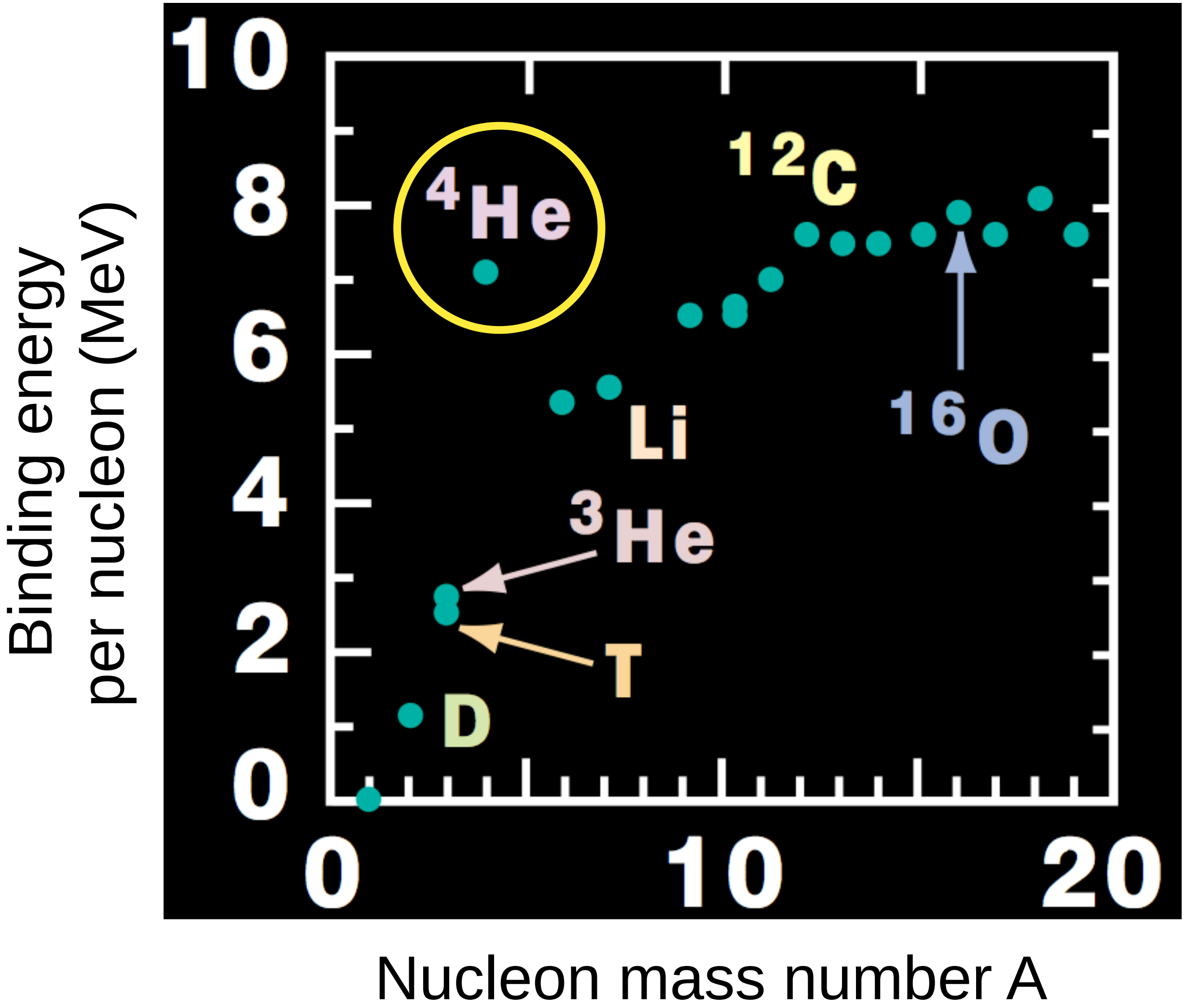
Results from the difference in binding energy between light nuclei and fusion products



Maximum at ~ ^{62}Ni : tremendous consequences for heavy stars

Energy gain in fusion reactions

^4He has a particularly large binding energy



Nucleus	Total Binding Energy (MeV)
D = ^2H	2.22457
T = ^3H	8.48182
^3He	7.71806
^4He	28.29567

Large gain in energy when ^4He is one of the reaction products

Some facts about our sun

Temperature at edge

From Stefan-Boltzmann law and measured Luminosity L

$$L = 4\pi\sigma R^2_{sun} T^4_{edge} \rightarrow \mathbf{T_{edge} = 5780K}$$

(σ = Stefan-Boltzmann constant $=5.670\times10^{-8}$ J m^{-2} K^{-1} s^{-1})

Temperature in centre:

Proton thermal energy in centre (= 3/2 kT) equal to potential energy from gravity per proton:

$$1.5k\, T_{centre} = Gm_p\, M_{sun}/R_{sun} \rightarrow \mathbf{T_{centre} = 15\,600\,000\ K}$$

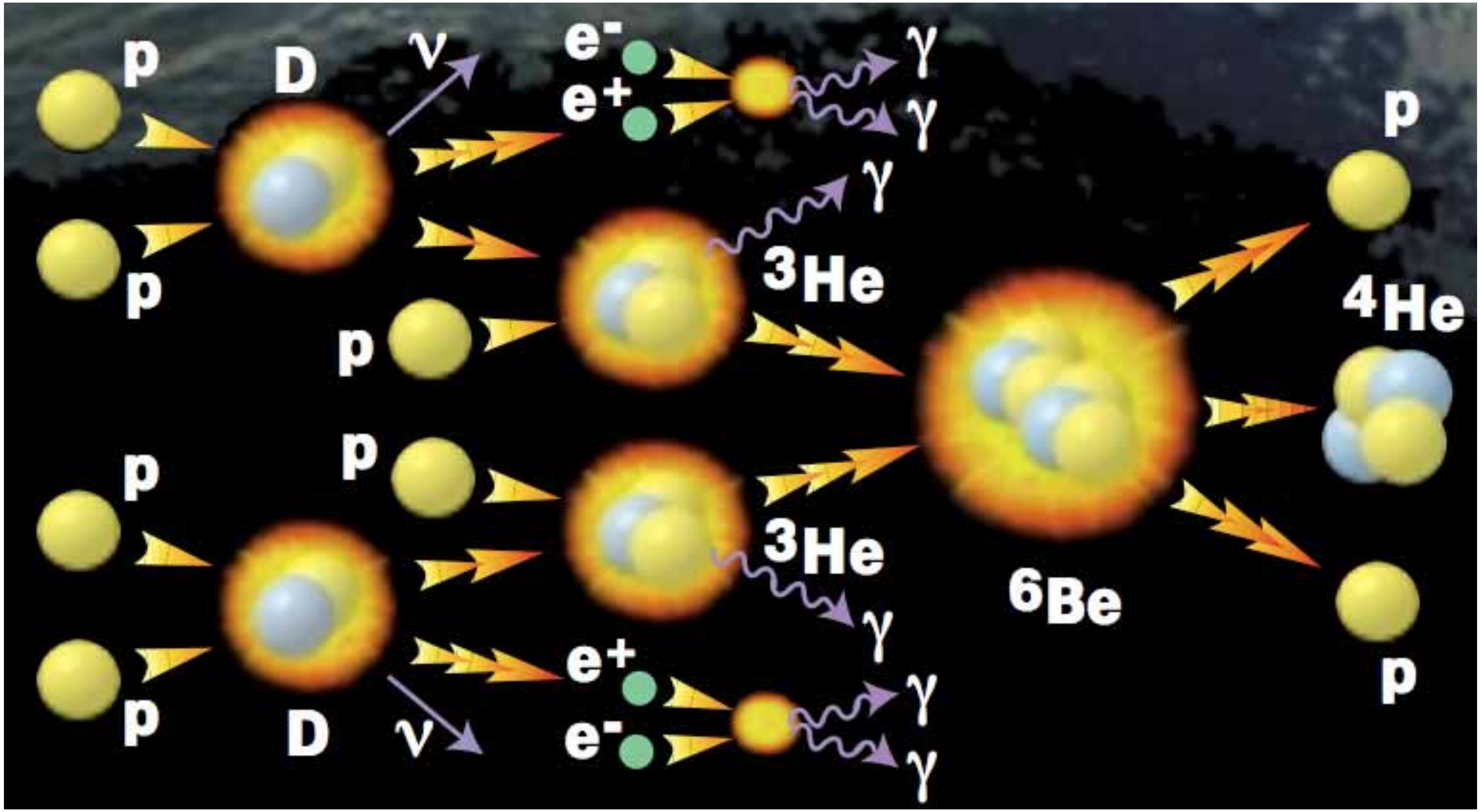
(G=gravitational constant=6.6726 10^{-11} Nm^{2}kg^{-2}

k=Boltzmann's constant=1.38 10^{-23} J K^{-1}

m_p = mass of proton = 1.6726 × 10^{-27} kg.

p-p reaction in the sun

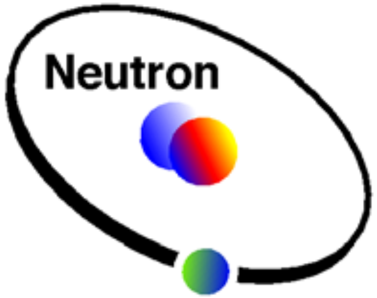
Conversion proton to neutron: inverse β-decay



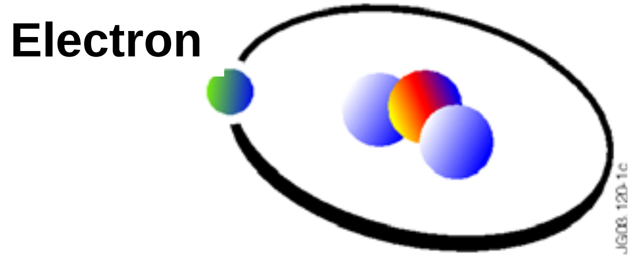
Very slow reaction (which is good for mankind....)

Sun : Every second : 4 million tonnes transformed → Energy

On earth: use deuterium and tritium



Deuterium ($^{2}_{1}H$) or D



Tritium ($^{3}_{1}H$) or T

Stable
Isotope

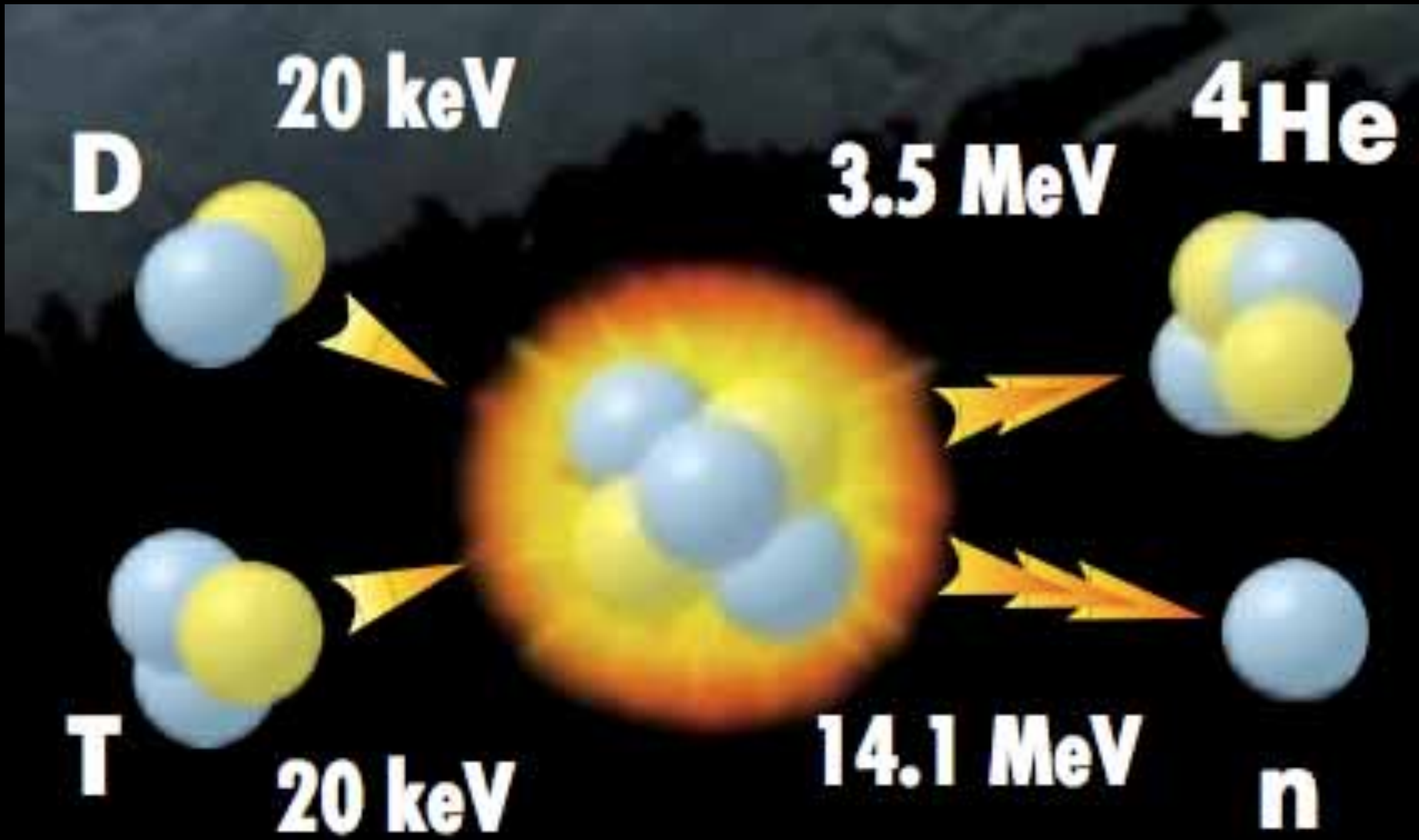
Artificial
Isotope
Half life
12.3 years

‘Easiest’ fusion reactions on earth

Fusion Reaction		Temperature Needed (in Million Degrees)	Reaction Energy (in keV)
D + T	^4He + n	100-200	17,600
D + ^3He	^4He + p	~700	18,300
D + D	^3He + n	~400	~4,000
	T + p	~400	~4,000

Extensive database on fusion reactions : http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

The 'simplest' fusion reaction on earth



Advantages of fusion

- Ash is ^4He
  - — no radioactivity
  - — chemically inert : no ozone depletion, no acid rain,...
  - — no greenhouse effect
  - ⇒ Excellent environmental compatibility

- Does not imply long term storage of radioactive waste
  - — part of fuel is active (tritium), but consumed in reaction
  - — choice of structural materials to reduce long lived activity
  - ⇒ Offers prospect to recycle radioactive waste in 1-2 generations

- Inherently safe
  - — malfunction of control system does not lead to runaway
  - — 'gas burner' : shutting down gas supply stops reactor
  - ⇒ Tchernobyl like accident EXCLUDED

- Inexhaustible
  - — fuel consumption is minimal, reaction releases lots of energy
  - ⇒ Energy source for thousands/millions of years

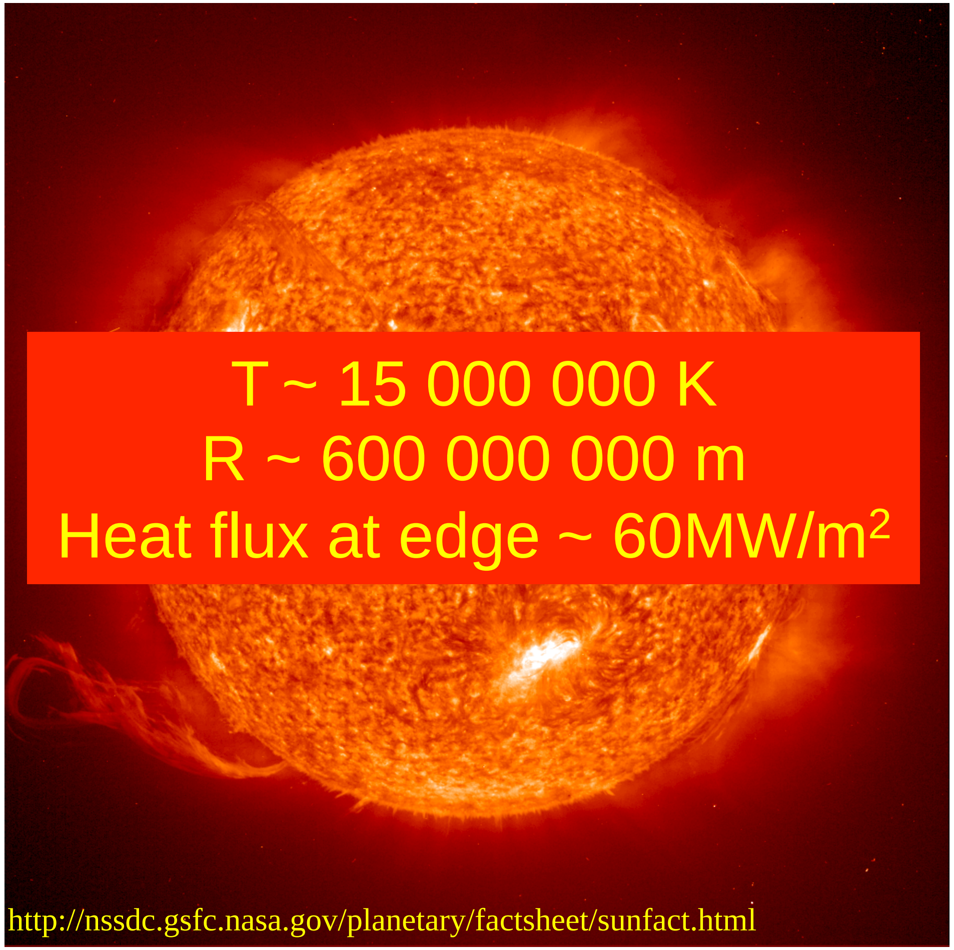
- Energy independence
  - — no geographical dependence for fuel
  - ⇒ Avoid geopolitical difficulties

MAGNETIC FUSION RESEARCH

IN EUROPE AND THE WORLD

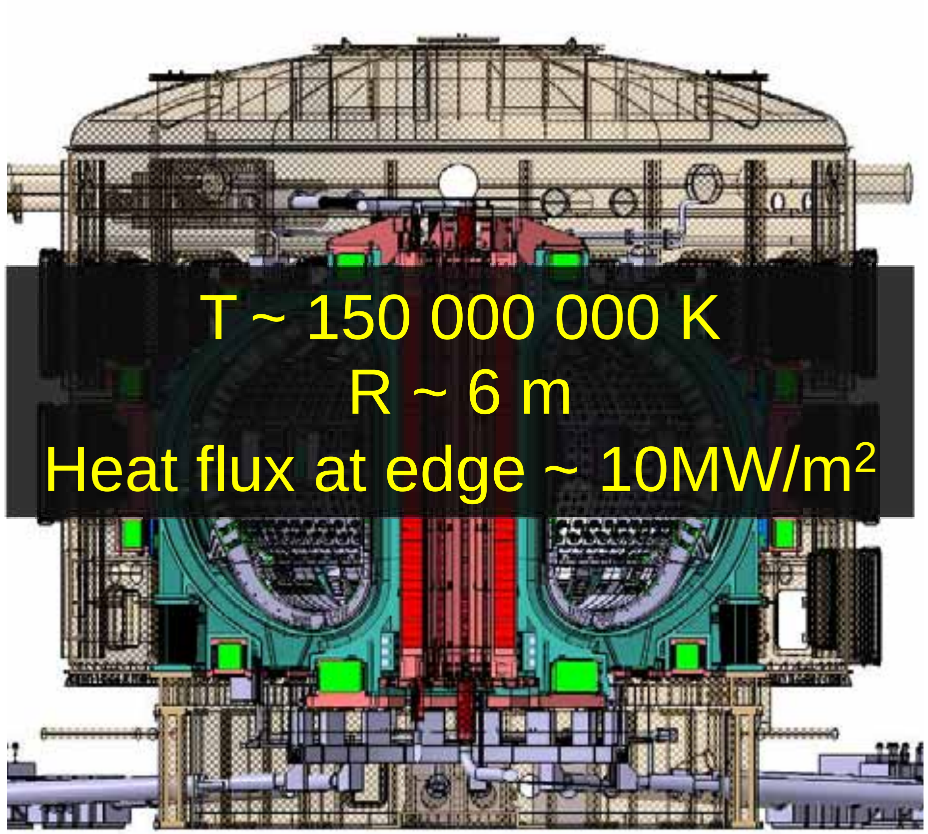
Magnetic Fusion – a real challenge

Sun



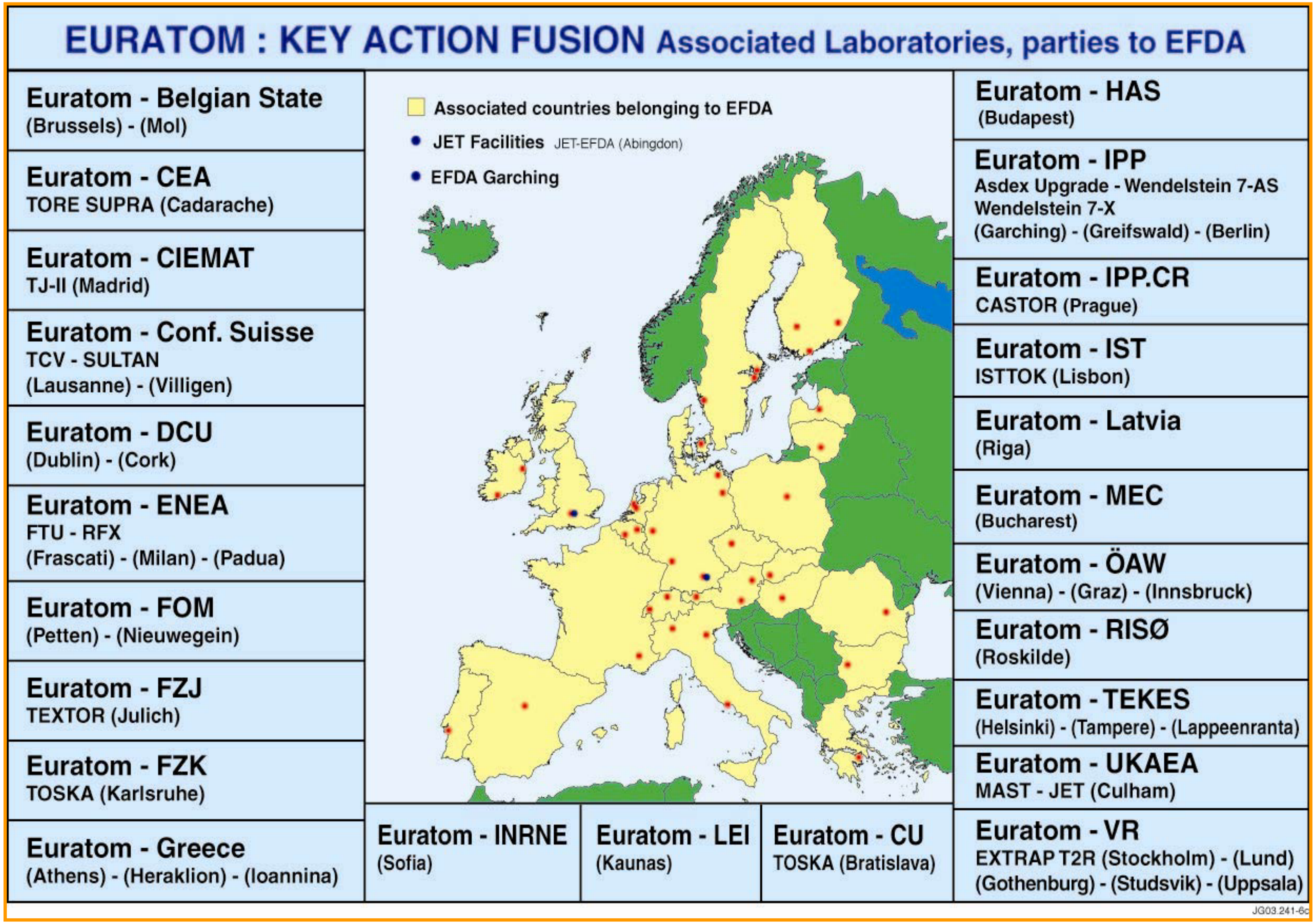
T ~ 15 000 000 K
R ~ 600 000 000 m
Heat flux at edge ~ 60MW/m^2

ITER (France, in construction)

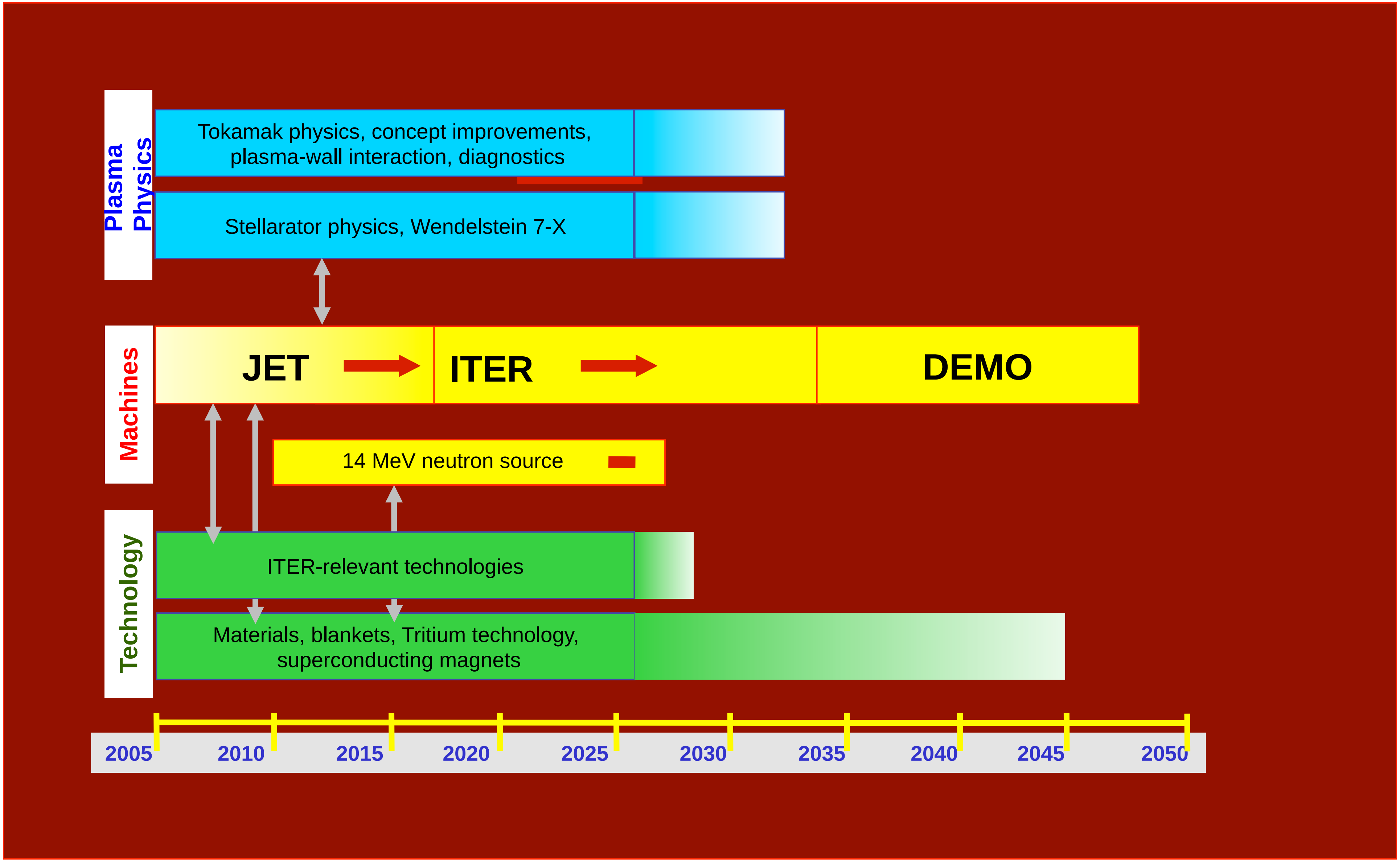


T ~ 150 000 000 K
R ~ 6 m
Heat flux at edge ~ 10MW/m^2

Fusion research in Europe

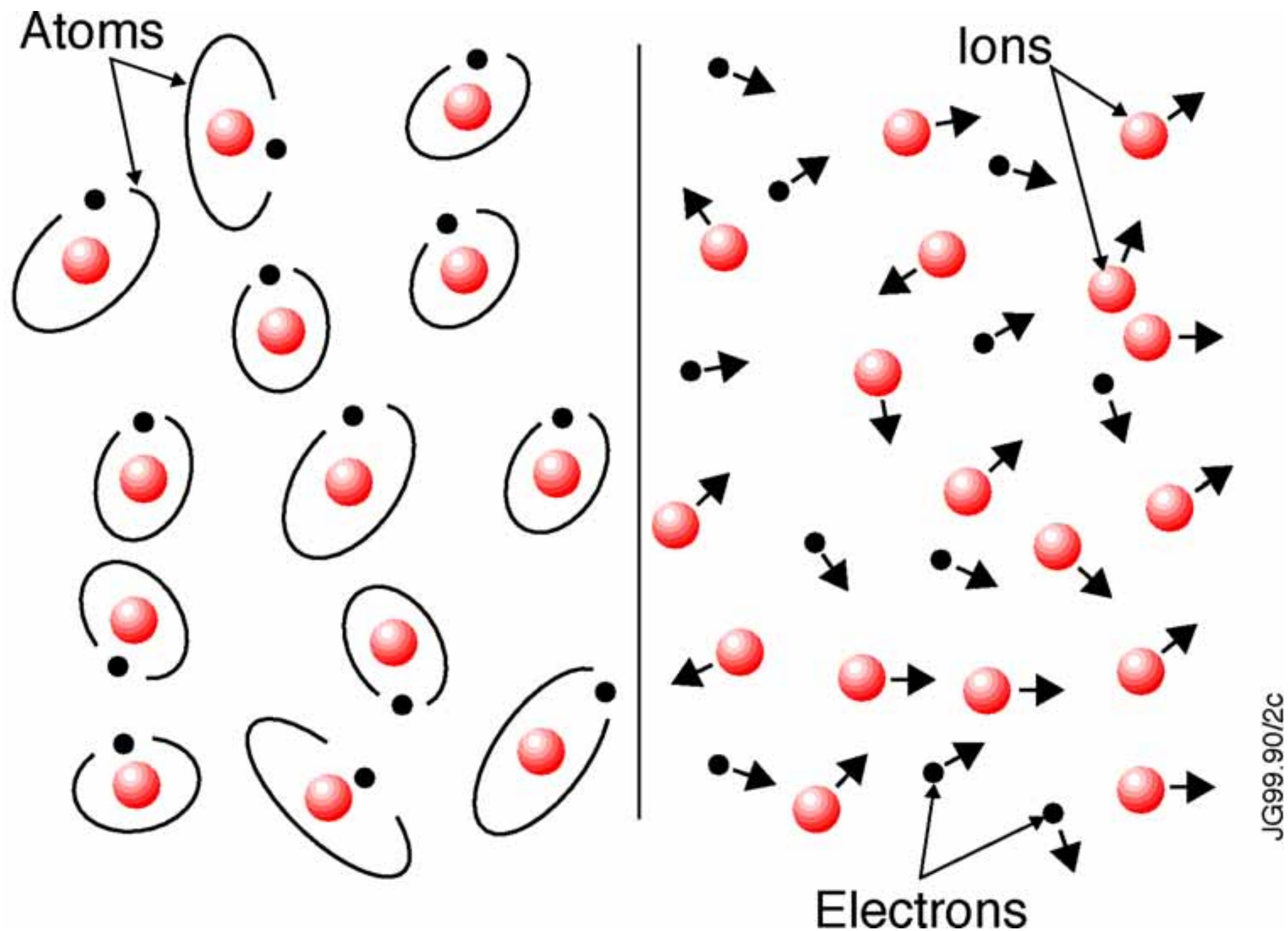


EU Fusion Roadmap



Principle of magnetic fusion

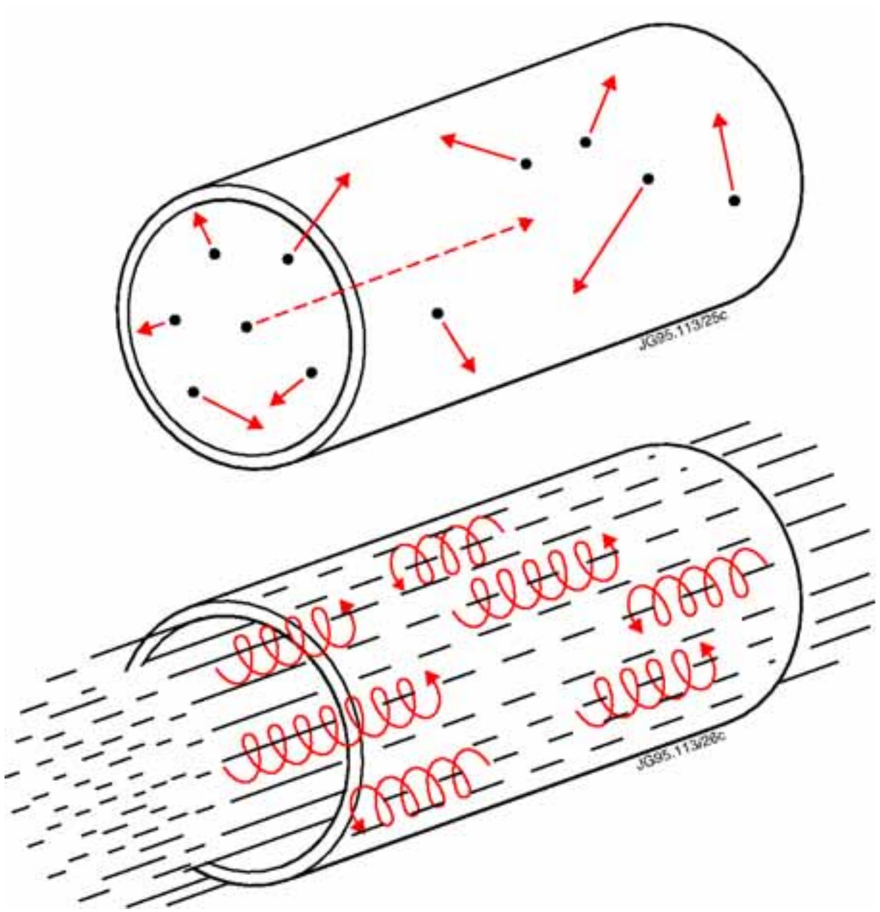
Neutral gas **Plasma**



Low temperature / High temperature

Principle of magnetic fusion

Charged particles 'stick' to magnetic field lines
(Lorentz force)



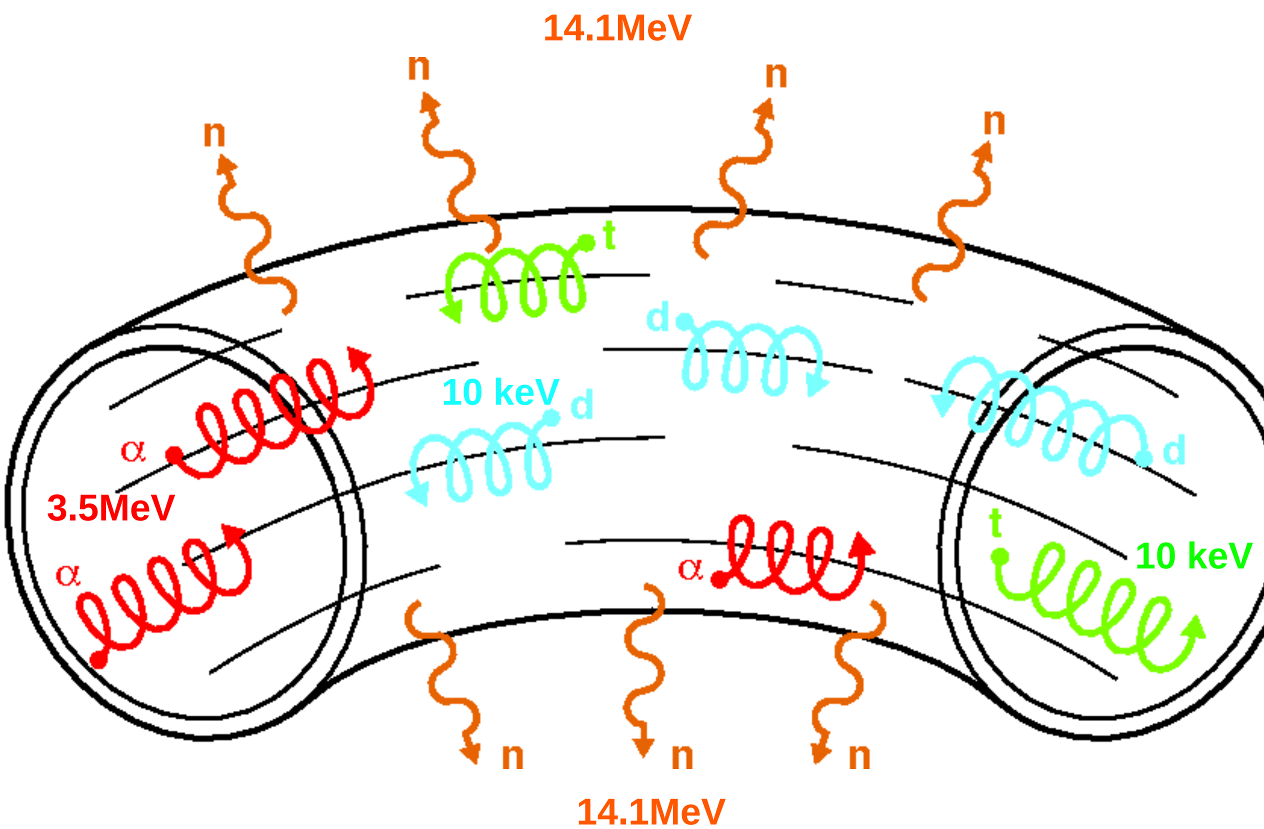
No magnetic field

With magnetic field

Closed system –> Toroidal Configuration
BUT needs **helical magnetic field** for stability

Final Configuration − Toroidal Configuration

Charged particles are confined
Neutrons (carrying 80% of the reaction energy) escape

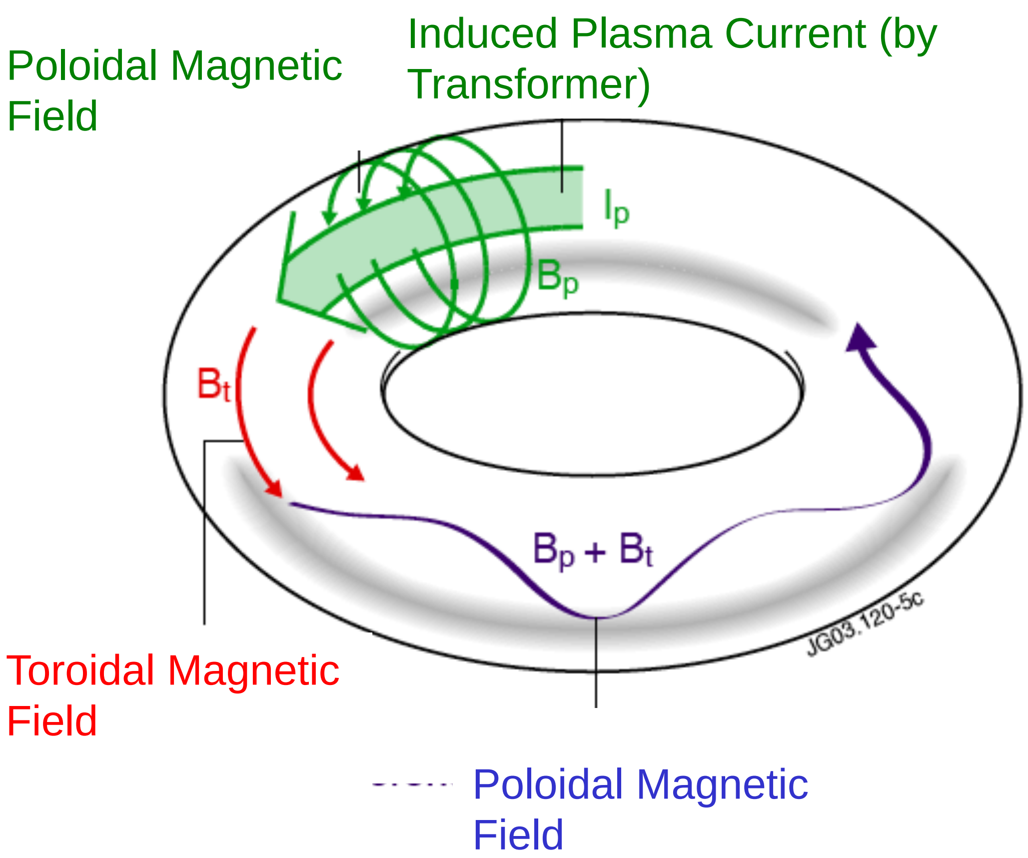


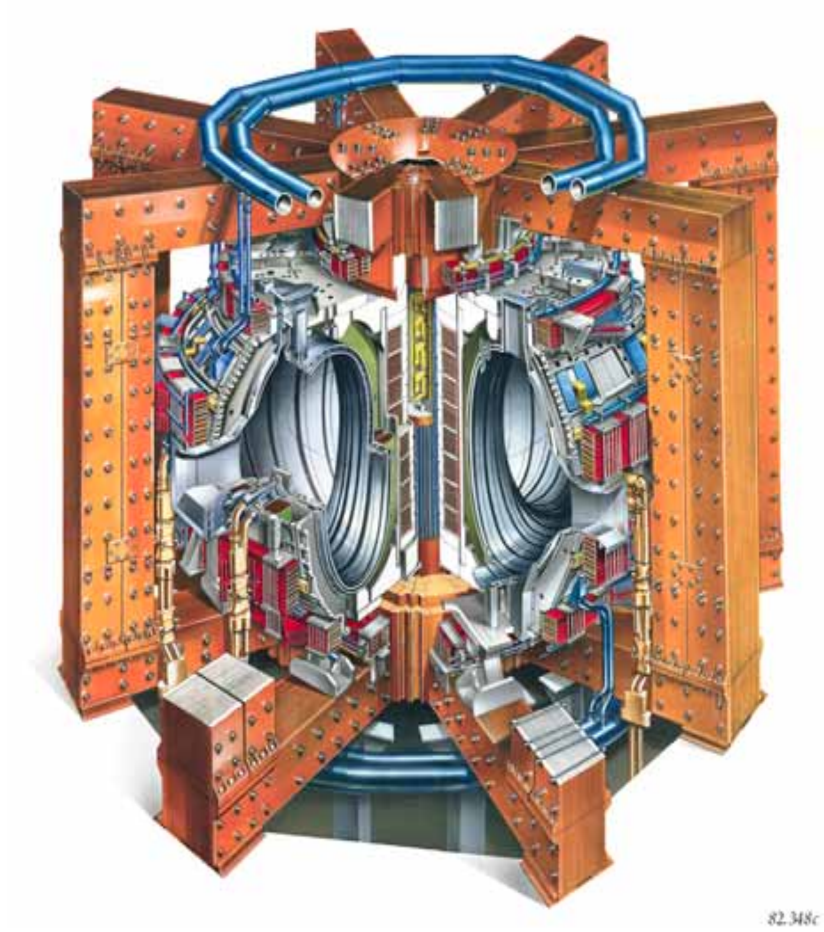
BUT need helical magnetic field for stability

Realizing a helical magnetic field : Option 1

Tokamak

Large current induced in plasma (~100kA - 10MA)

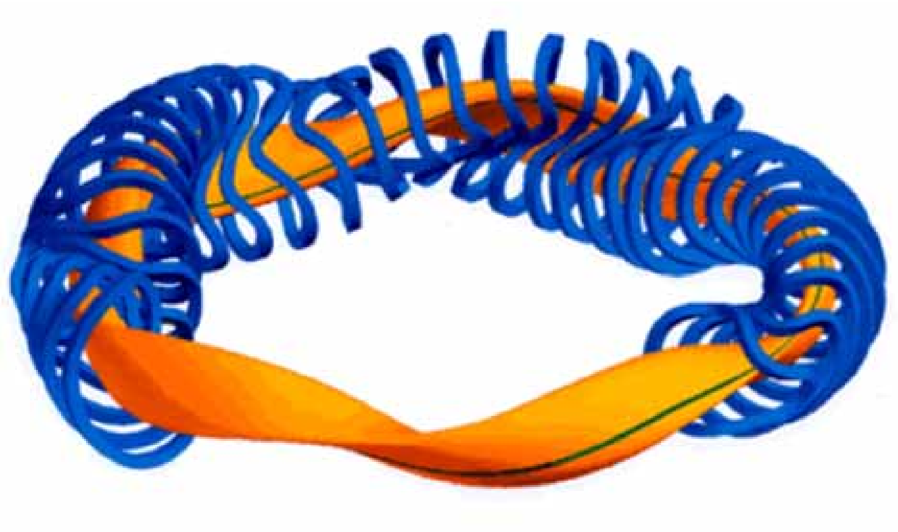


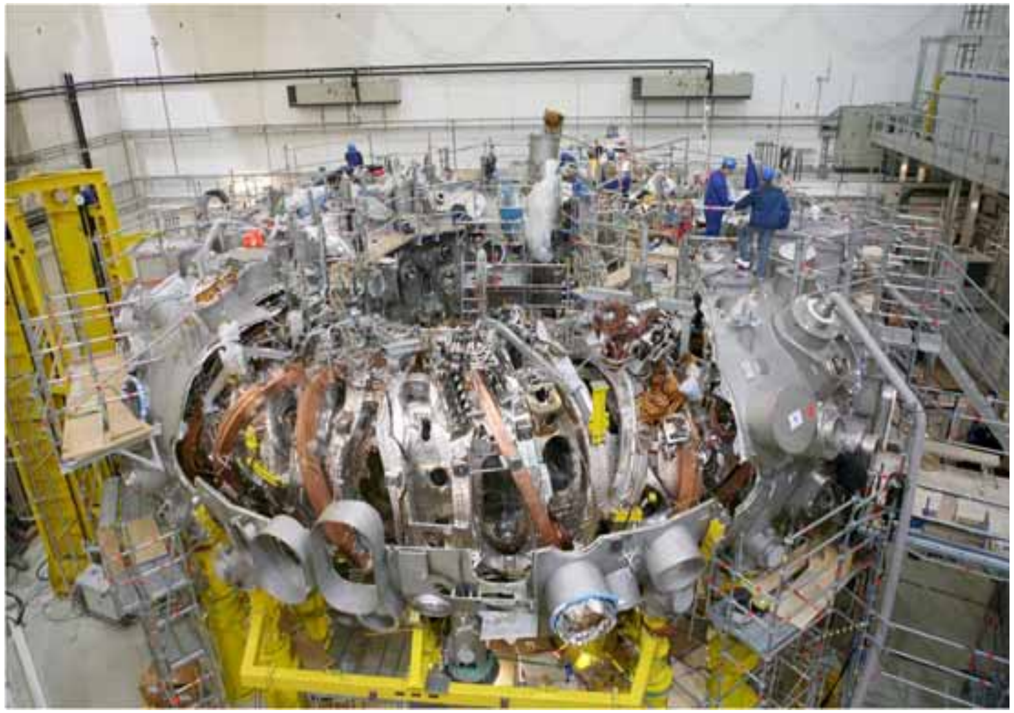


Realizing a helical magnetic field : Option 2

Stellarator

Complex 3D coils create directly a helical field





No plasma current

⇒ no transformer

⇒ continuous operation

Wendelstein 7-X
Max-Planck Institut, Greifswald

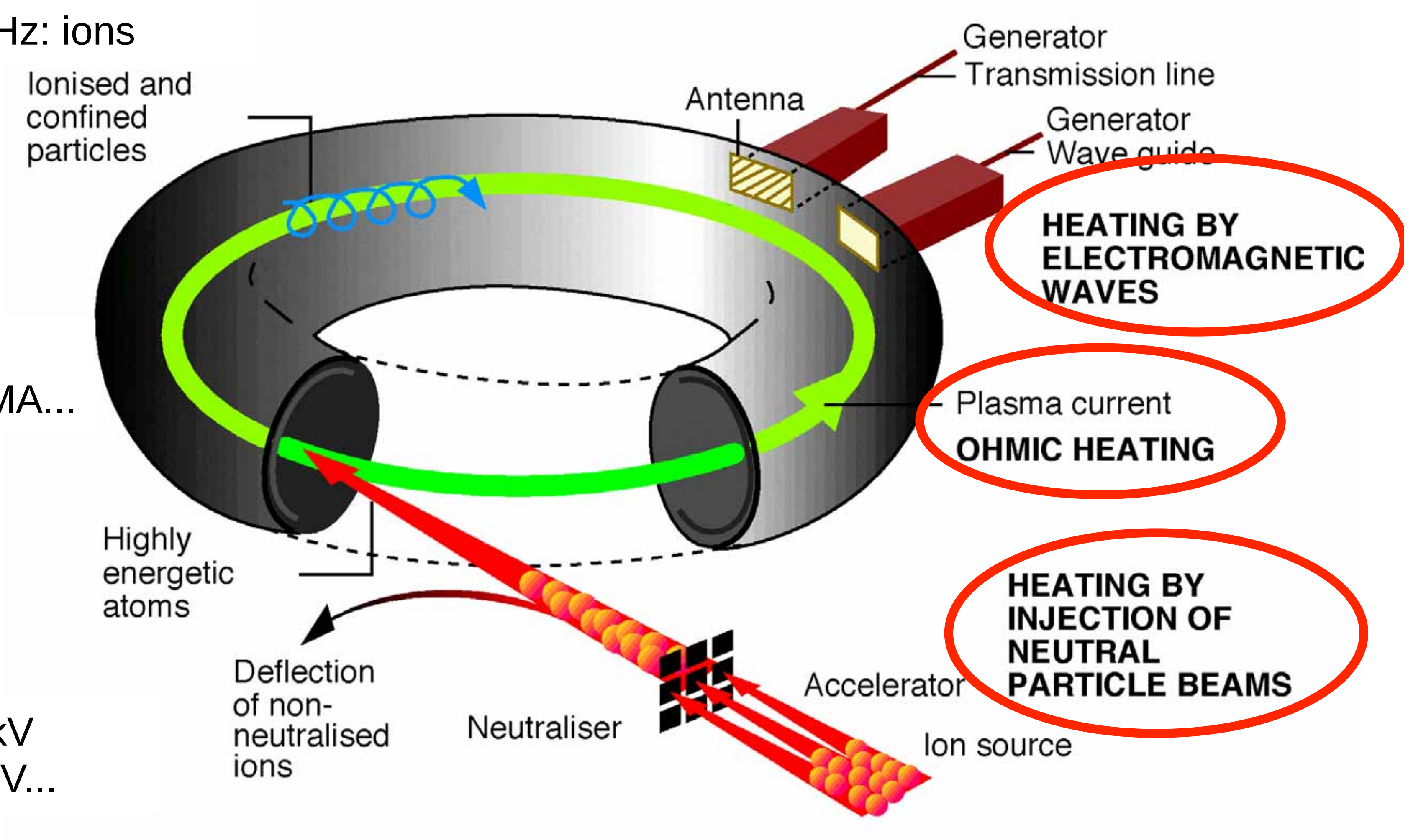
How to create the ultra high temperatures needed ?

In a future fusion reactor: α-particle heating

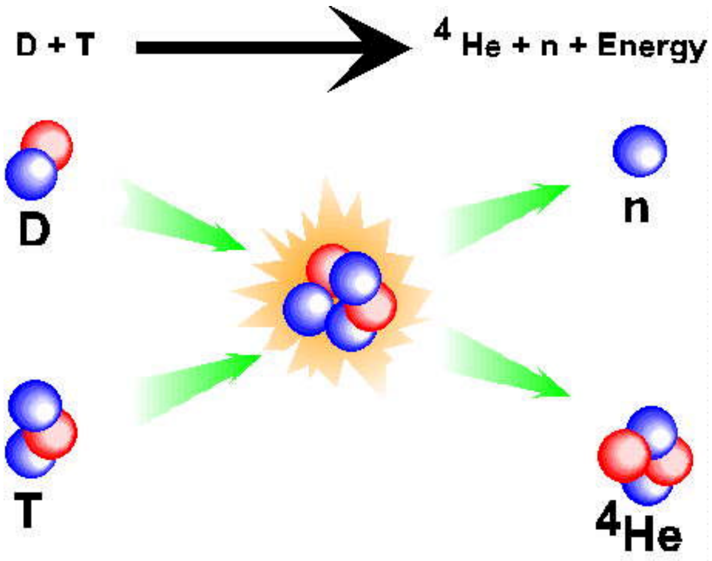
Cyclotron frequencies
~70-140GHz: electrons
~30-60 MHz: ions

JET: 5 MA
ITER: 15 MA...

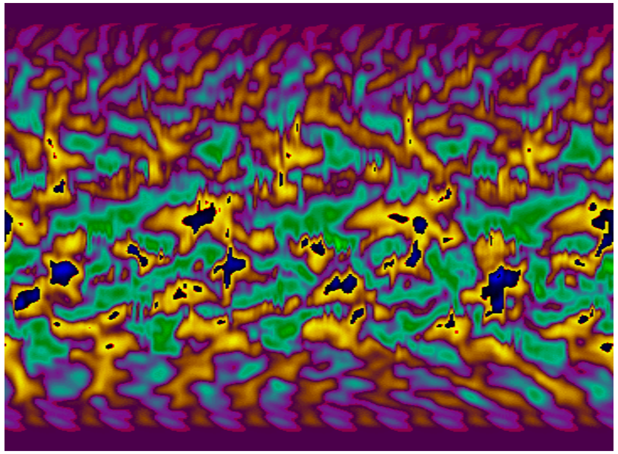
JET: 150 kV
ITER: 1 MV...



The main difficulty of magnetic fusion: keep a huge T gradient



- Two positive nuclei (D^+ and T^+) at short distance
  - — strong repulsion
  - EXTREMELY HIGH temperatures needed to bring the nuclei close enough together : ~200 000 000 K
- Special methods needed to heat and confine the fuel



- Very large gradient in temperature (~ 200 000 000K/m)
  - — gradients limited by turbulence
  - ⇒ TURBULENT medium : very complex physics

Characterizing progress – Power multiplication Q

$$Q = \frac{P_{fusion}}{P_{external\ heating}}$$

Breakeven Q=1

when $P_{fusion} = P_{external\ heating}$

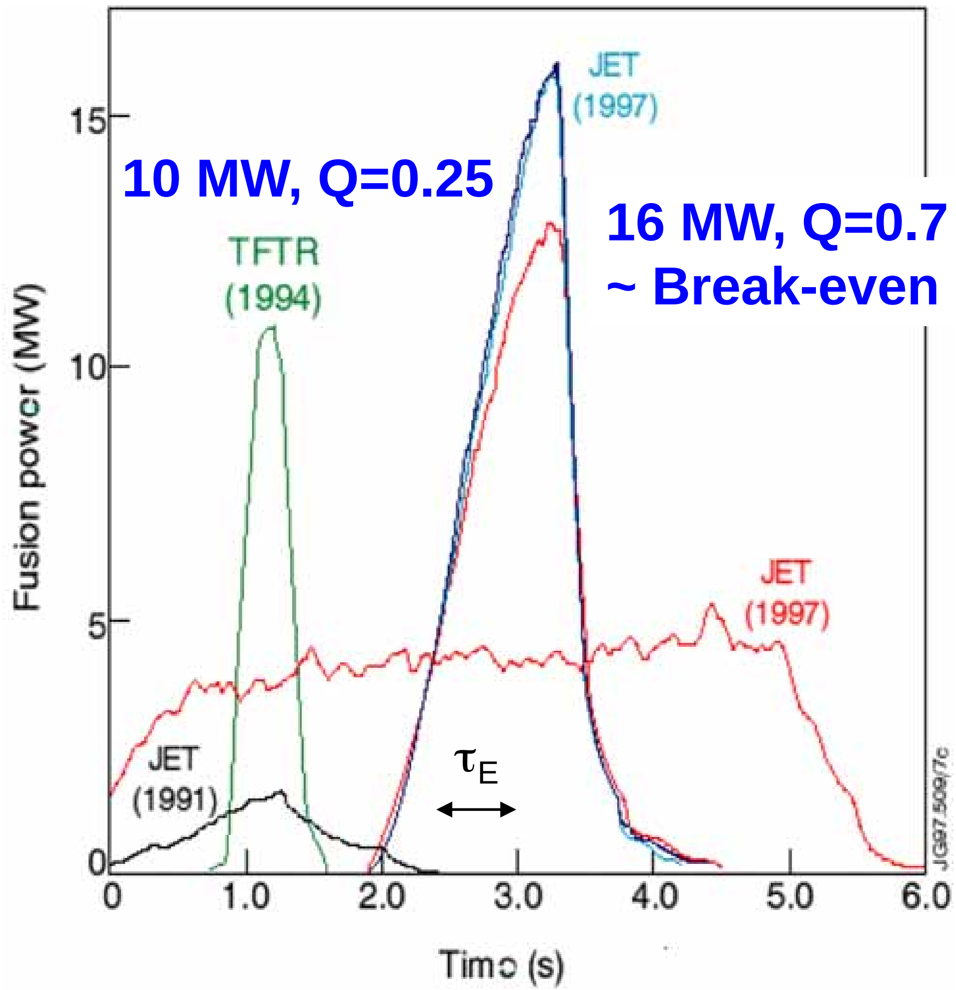
Ignition Q = ∞

when $P_{external\ heating} = 0$
No external heating needed
Self-sustained fusion reaction

Note:

Q characterizes the balance between fusion and external heating power **only**

It is **not** representative for the balance between total power consumption (magnetic fields, additional systems) and fusion power output



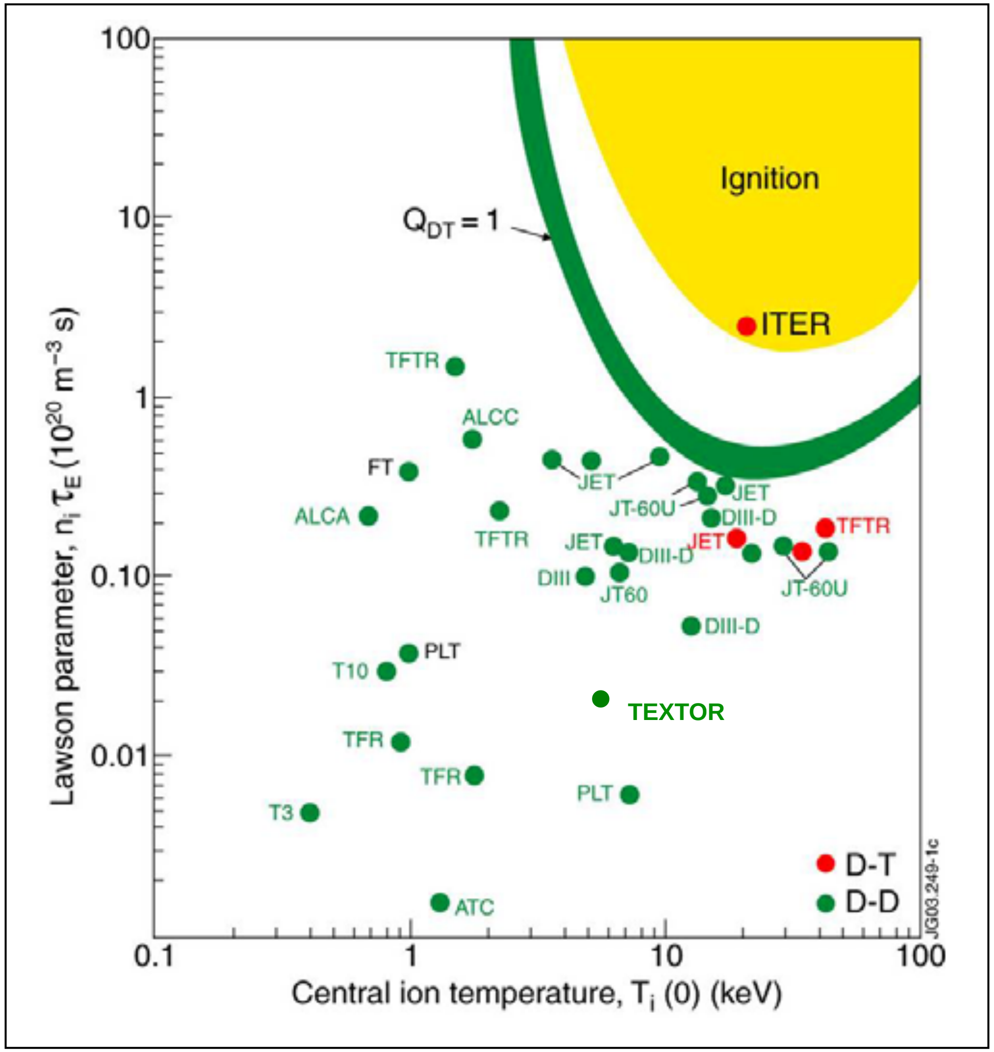
TFTR : Tokamak Fusion Test Reactor, Princeton, USA
JET : Joint European Torus, Culham, UK

Charcterizing progress – Lawson Criterion

Positive power balance in a reactor ➙ Condition on $n_i\ \tau_E$

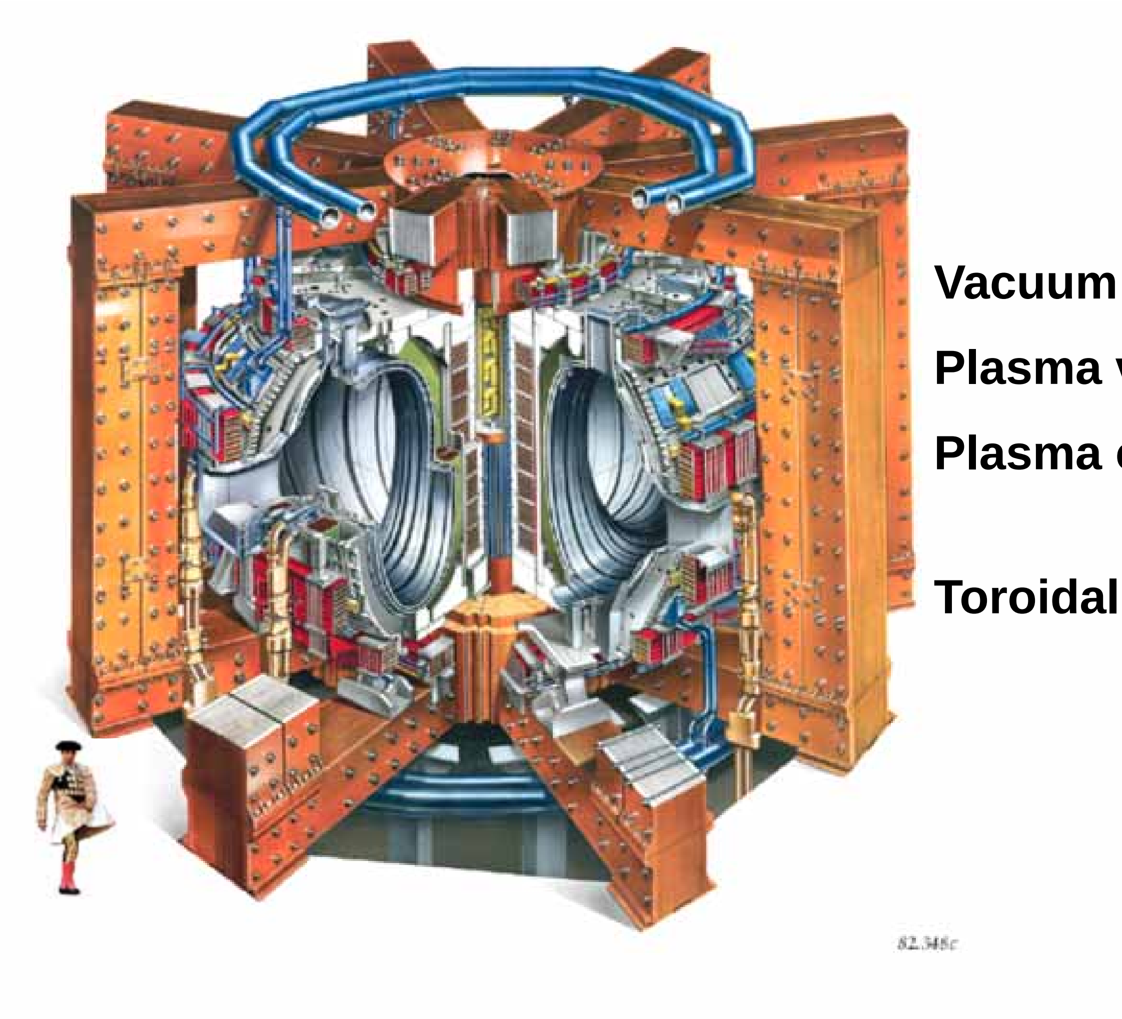
Present machines are close to produce fusion energy comparable with the energy required to sustain the plasma (breakeven : Q=1)

Next step devices (ITER) are expected to produce significantly more fusion energy than the energy required to sustain the plasma (Q=10 or larger)



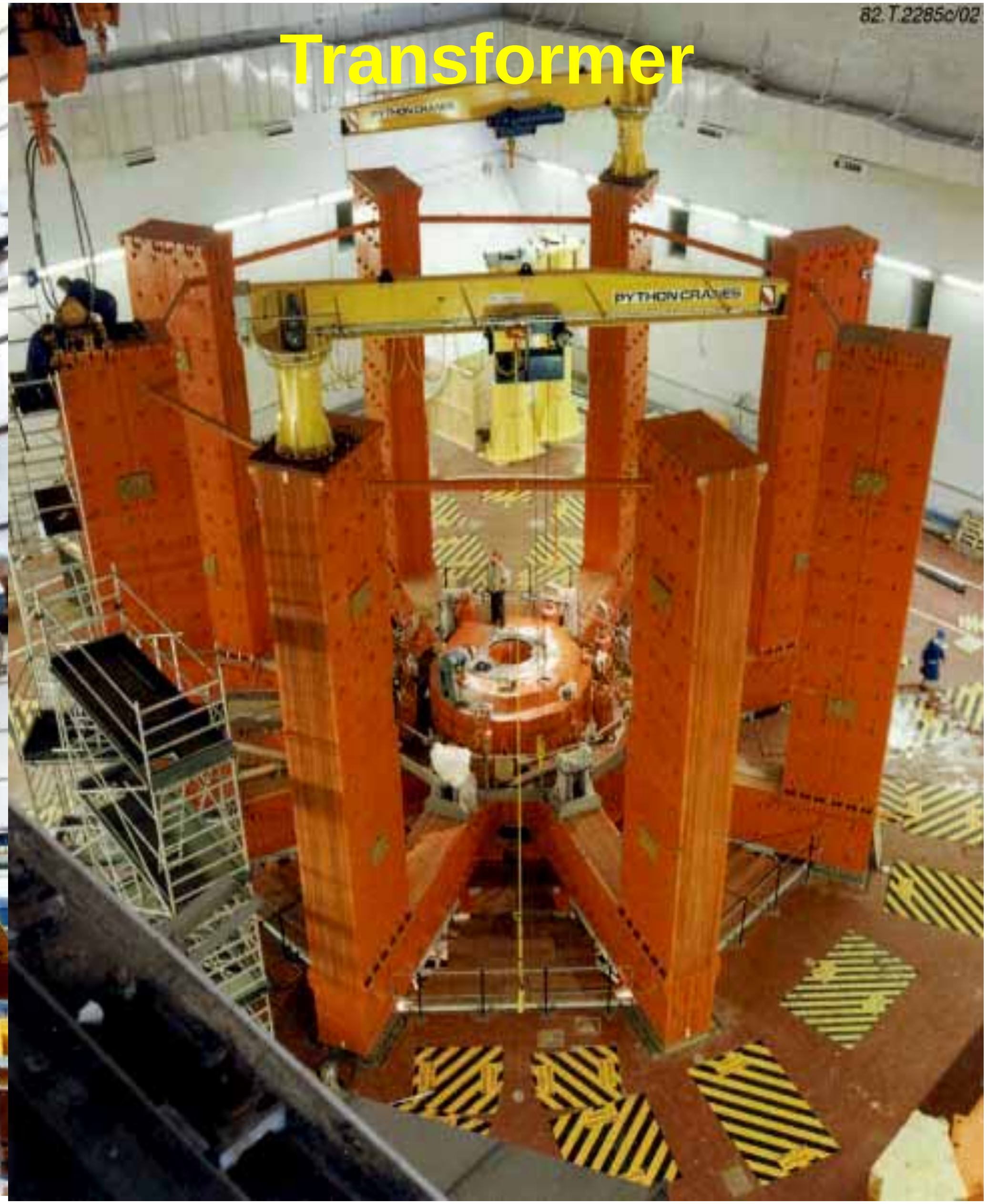
Largest operating tokamak: Joint European Torus (JET)

Common European Facility (Oxfordshire, UK)

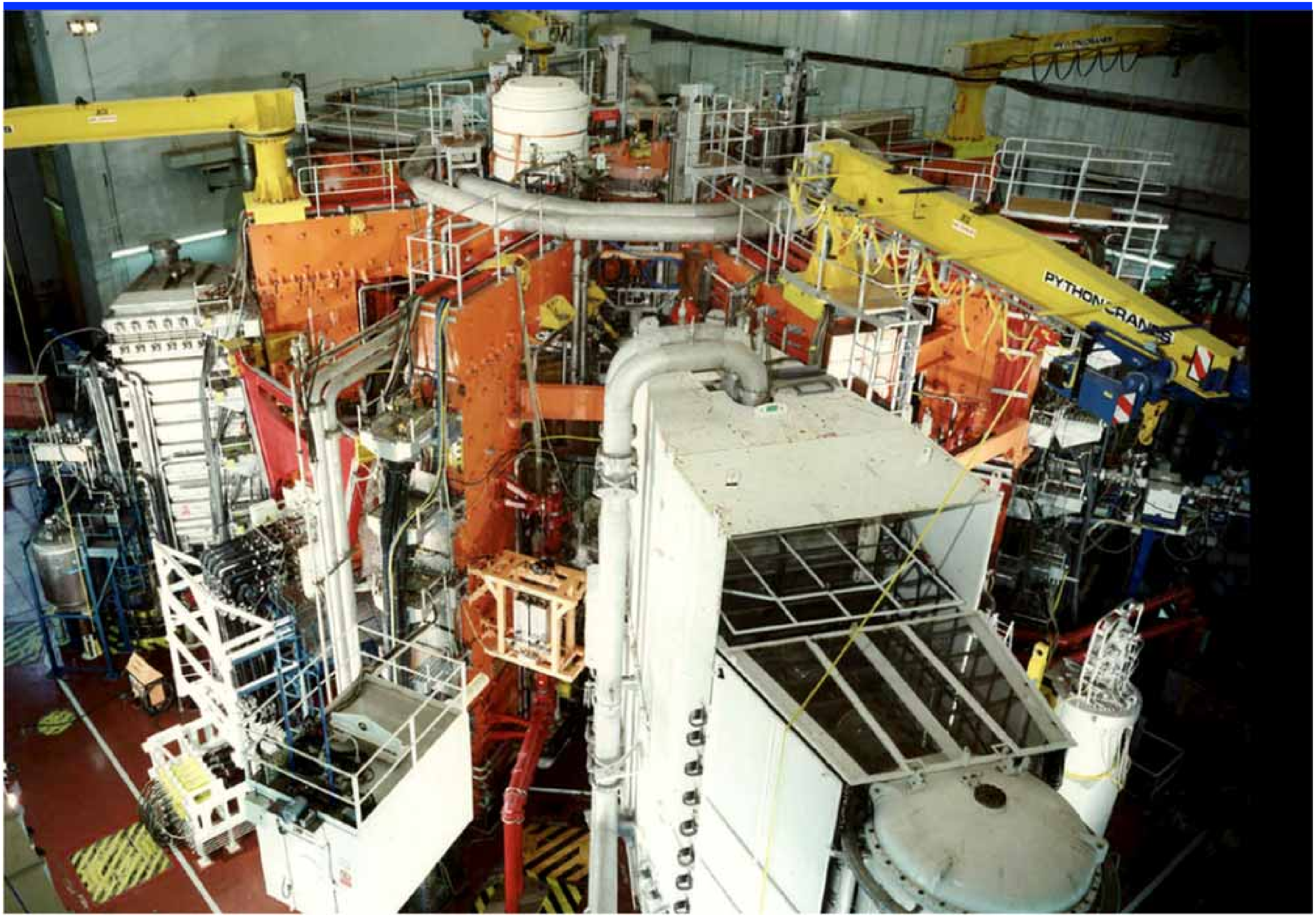


Vacuum vessel	**3.96m high x 2.4m wide**
Plasma volume	**80 m^3 - 100 m^3**
Plasma current	**up to 5 MA**
	in present (divertor) configurations
Toroidal magnetic field	**up to 4 Tesla**

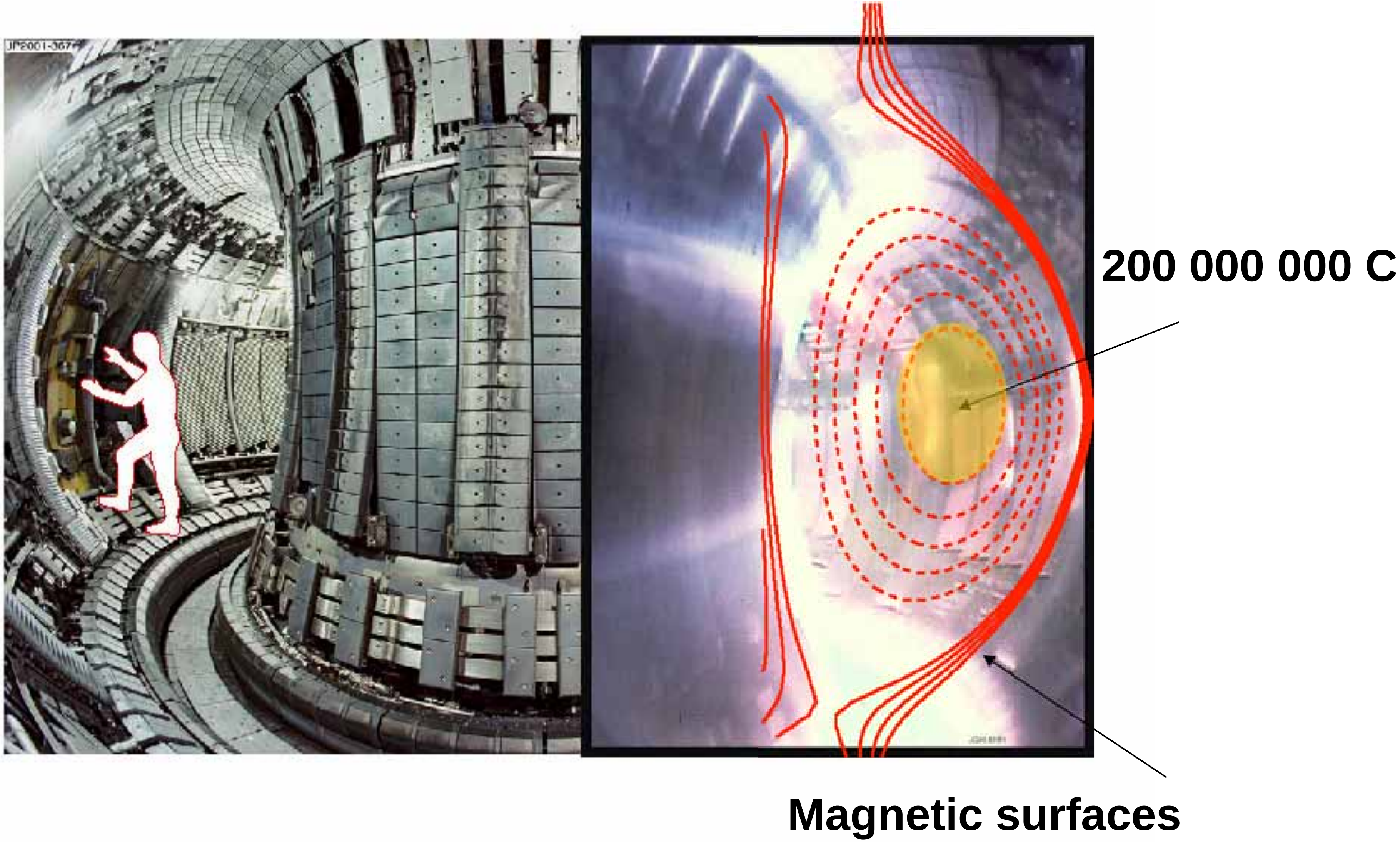
Dimensions of JET



Joint European Torus (JET)

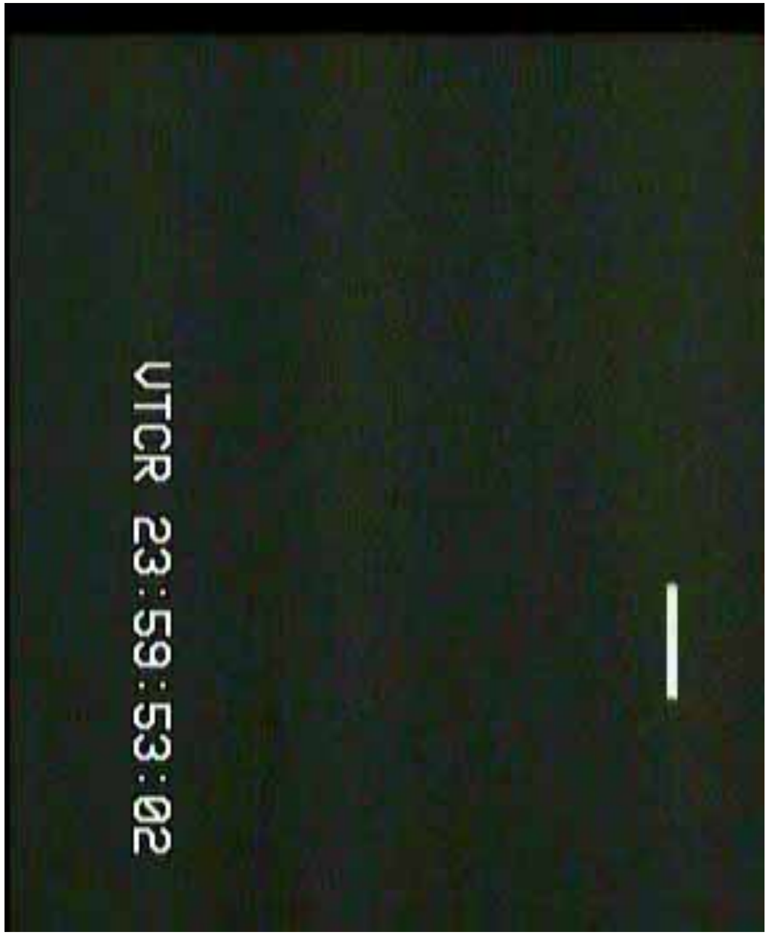


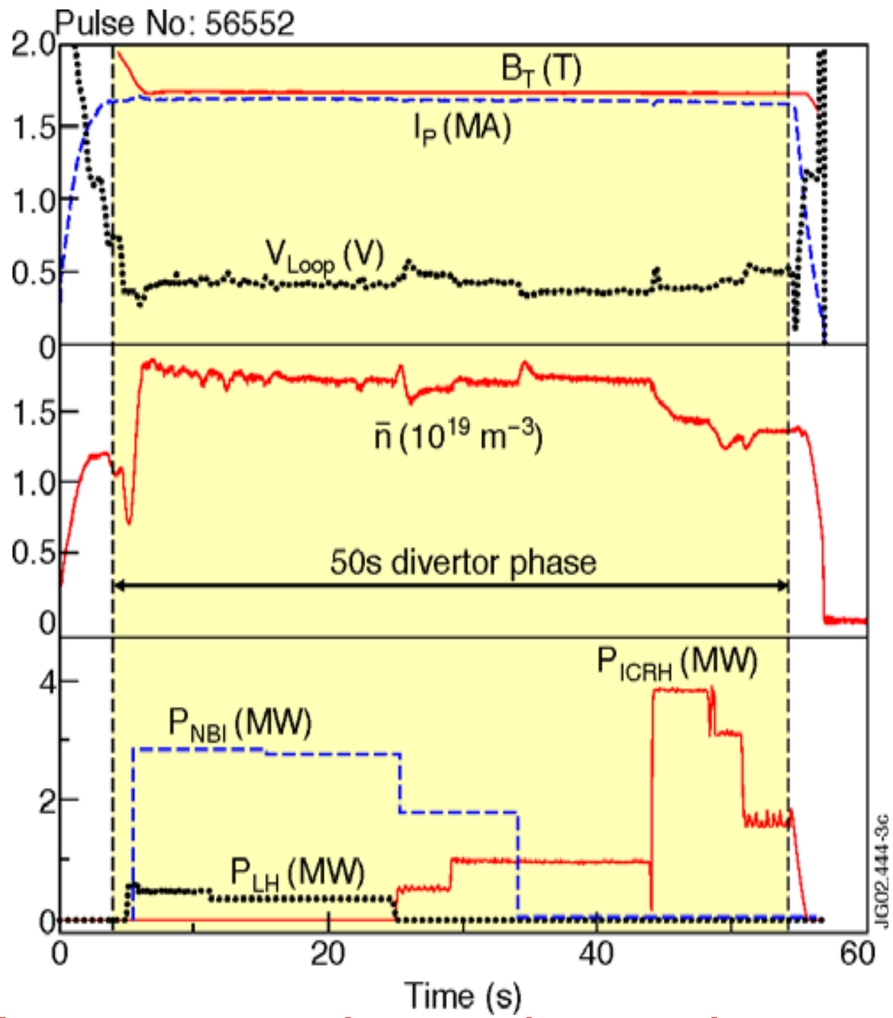
Inside of JET with and without plasma



Example of long pulse in JET

Long (1 min) JET Plasmas in ITER configuration





Also : Tore Supra (France): 6min30s, LHD (Japan): 30min

ITER

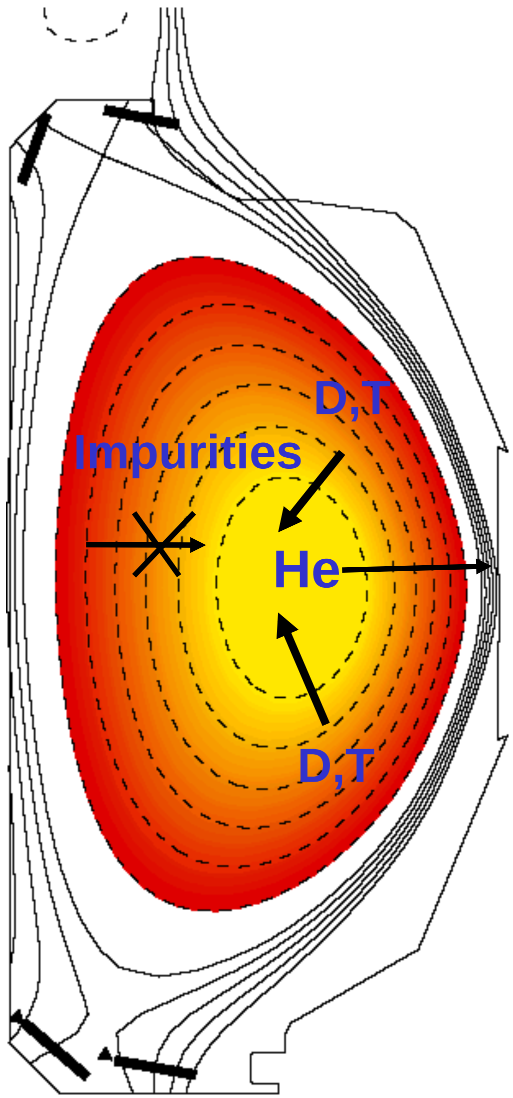
International Thermonuclear Experimental Reactor
(in construction in Cadarache, France)

From JET to ITER

***ITER = International Thermonuclear Experimental Reactor**

ITER should show us how to maintain the fusion 'fire' !

Important questions waiting for an answer



Physics

• Clean plasma centre needed
 — He must disappear quickly (…but not too quickly…)
 — Low level of other impurities

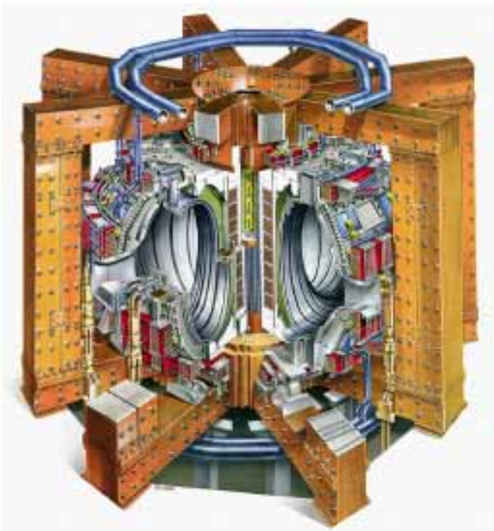
• High fusion reactivity :
— Ensure a good flow of D and T to the plasma center

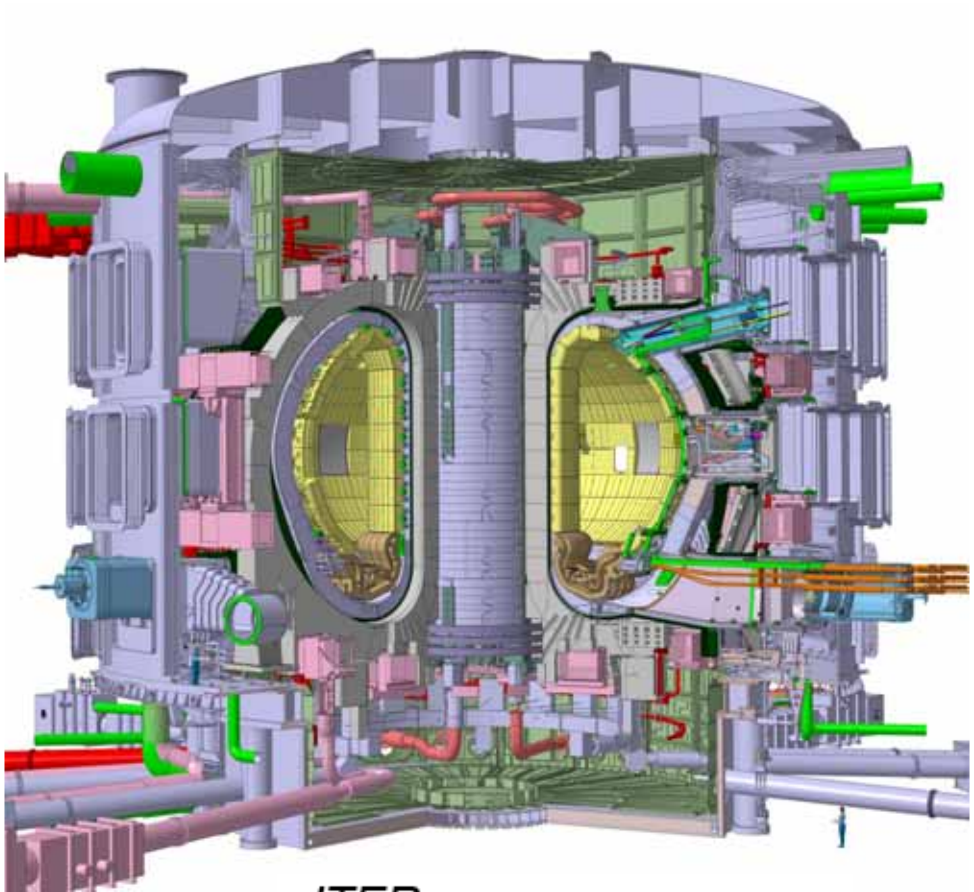
• Stable plasma:
— Suppress instabilities

Technological

• Check first wall properties
• Check T breeding techniques

ITER : ~ 2x larger than JET

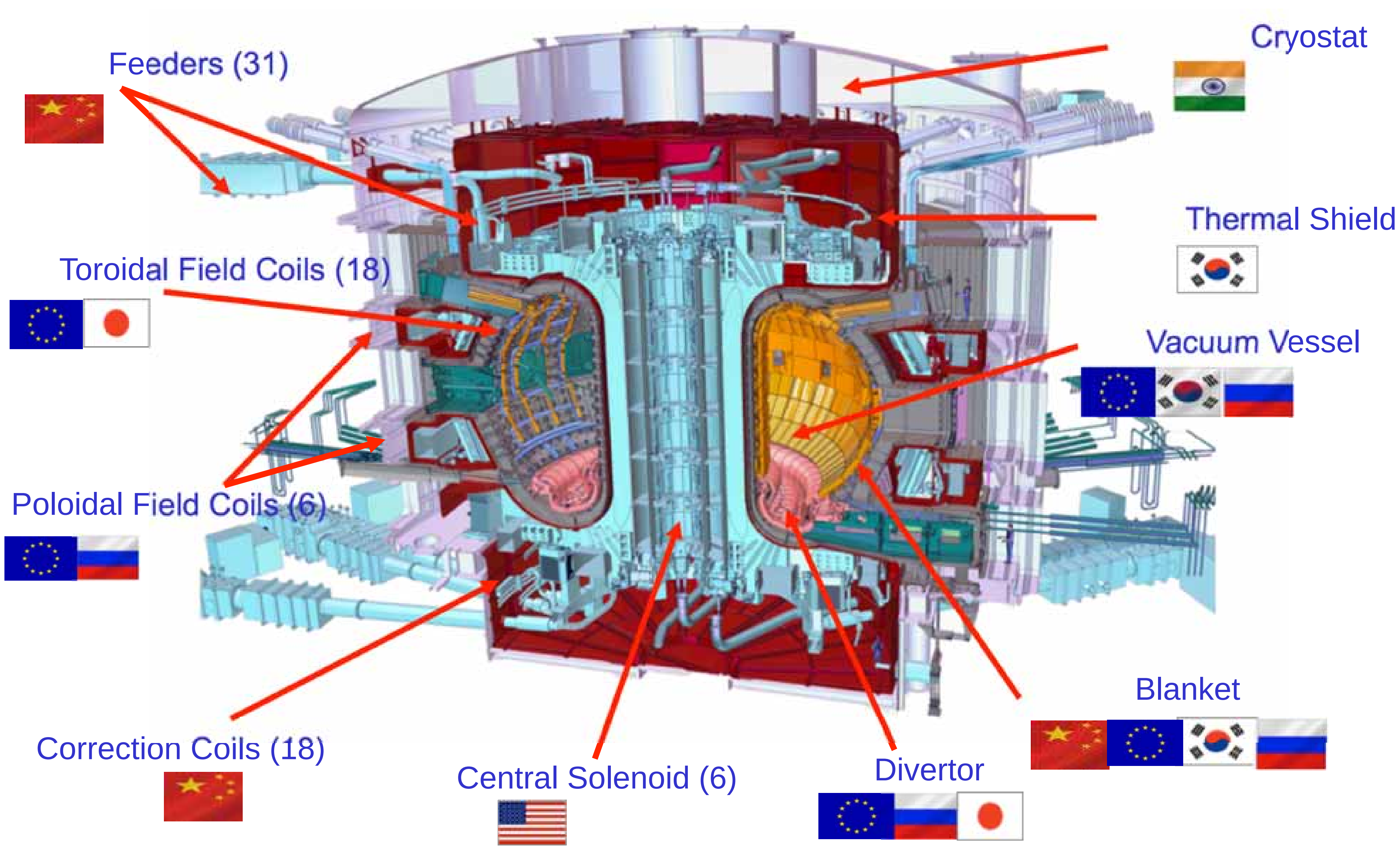




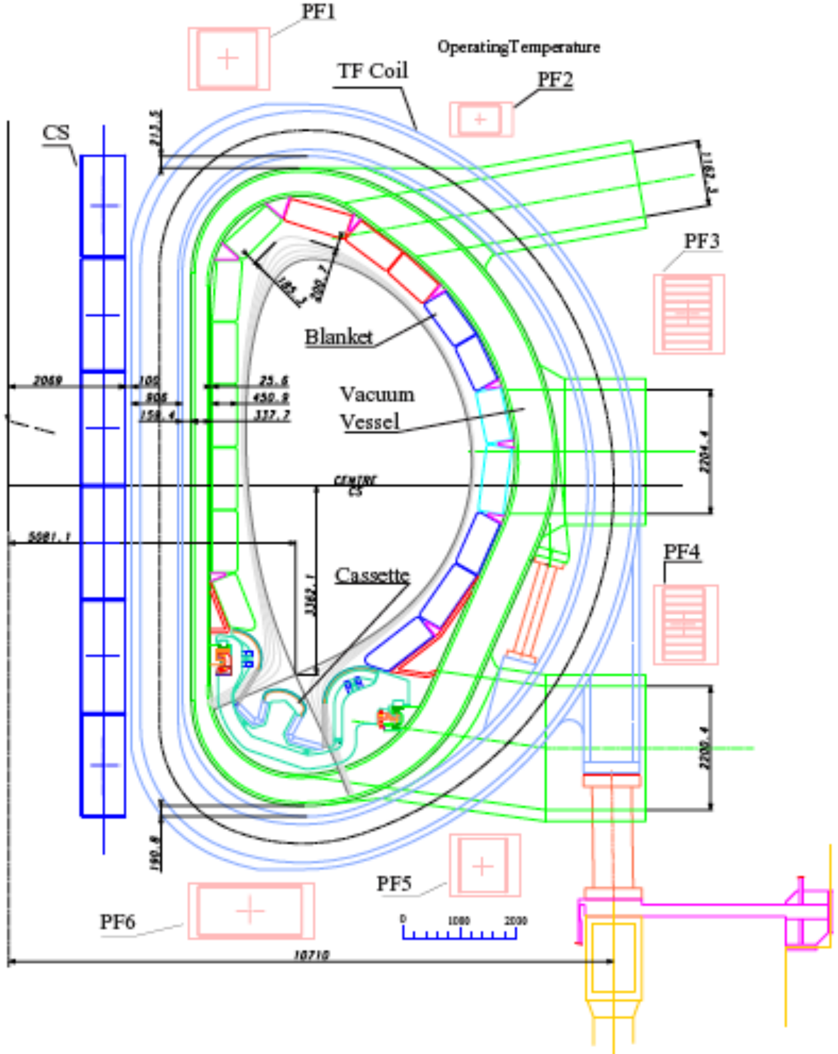
JET	
V_{plasma}	$80\ m^3$
P_{fusion}	~16 MW 2s
t_{plasma}	~30 s

ITER	
V_{plasma}	$830\ m^3$
P_{fusion}	~500 MW 500s
t_{plasma}	~400 s

Construction of ITER – A complex international endeavour



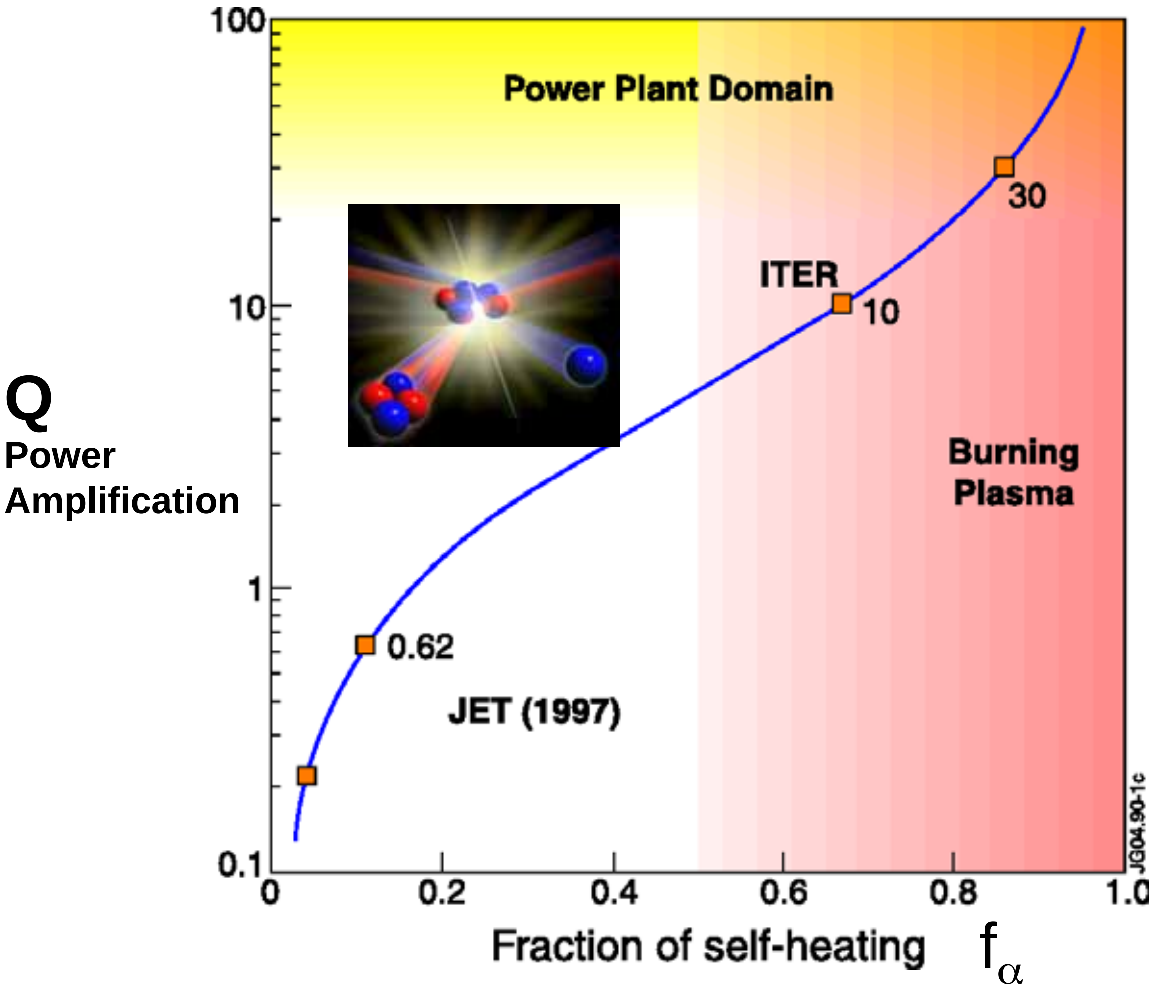
ITER Design Parameters



	ITER
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3T
Elongation / triangularity	1.85 / 0.49
Fusion power amplification	≥ 10
Fusion power	~500 MW
Plasma burn duration	300-500 s

ITER is not just ‘big science’

BUT crucial for scientific progress



$f_\alpha = Q / (Q+5)$

Fraction of plasma self-heating by fusion born α-particles

$Q > 10 \;\; \rightarrow \;\; f_\alpha > 2/3$

With ITER, for the first time:
fraction of alpha particles similar to fusion reactor plasma

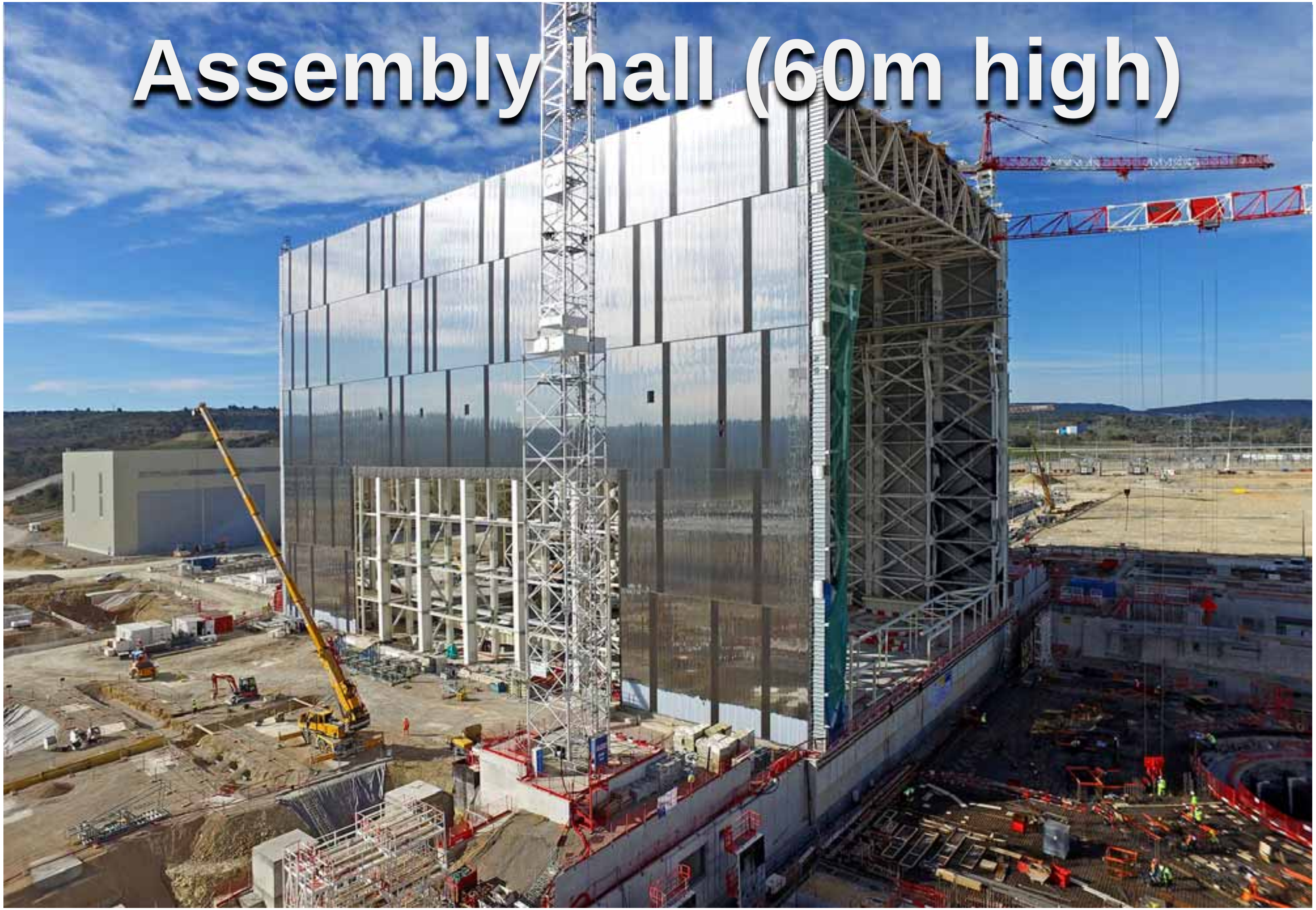
Six years of steady and important progress in Cadarache

April 2014

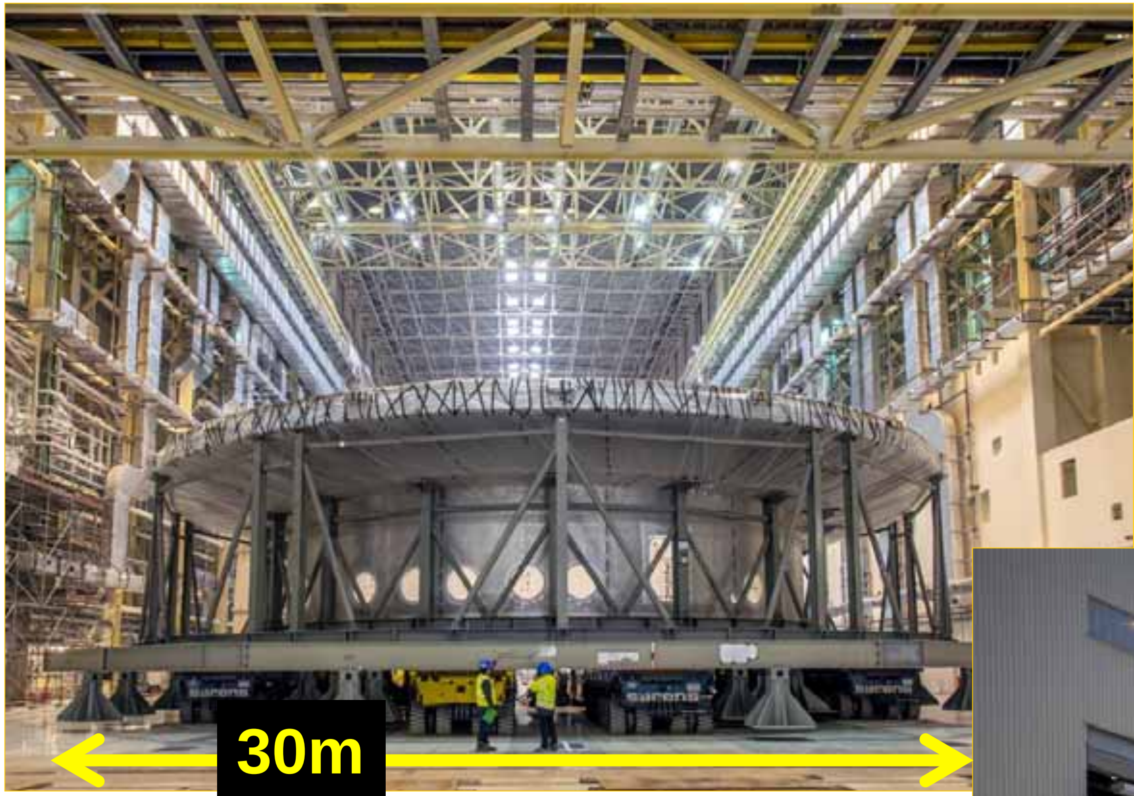
June 2020

More than 75% of the installation's civil works are now completed.

Assembly hall (60m high)



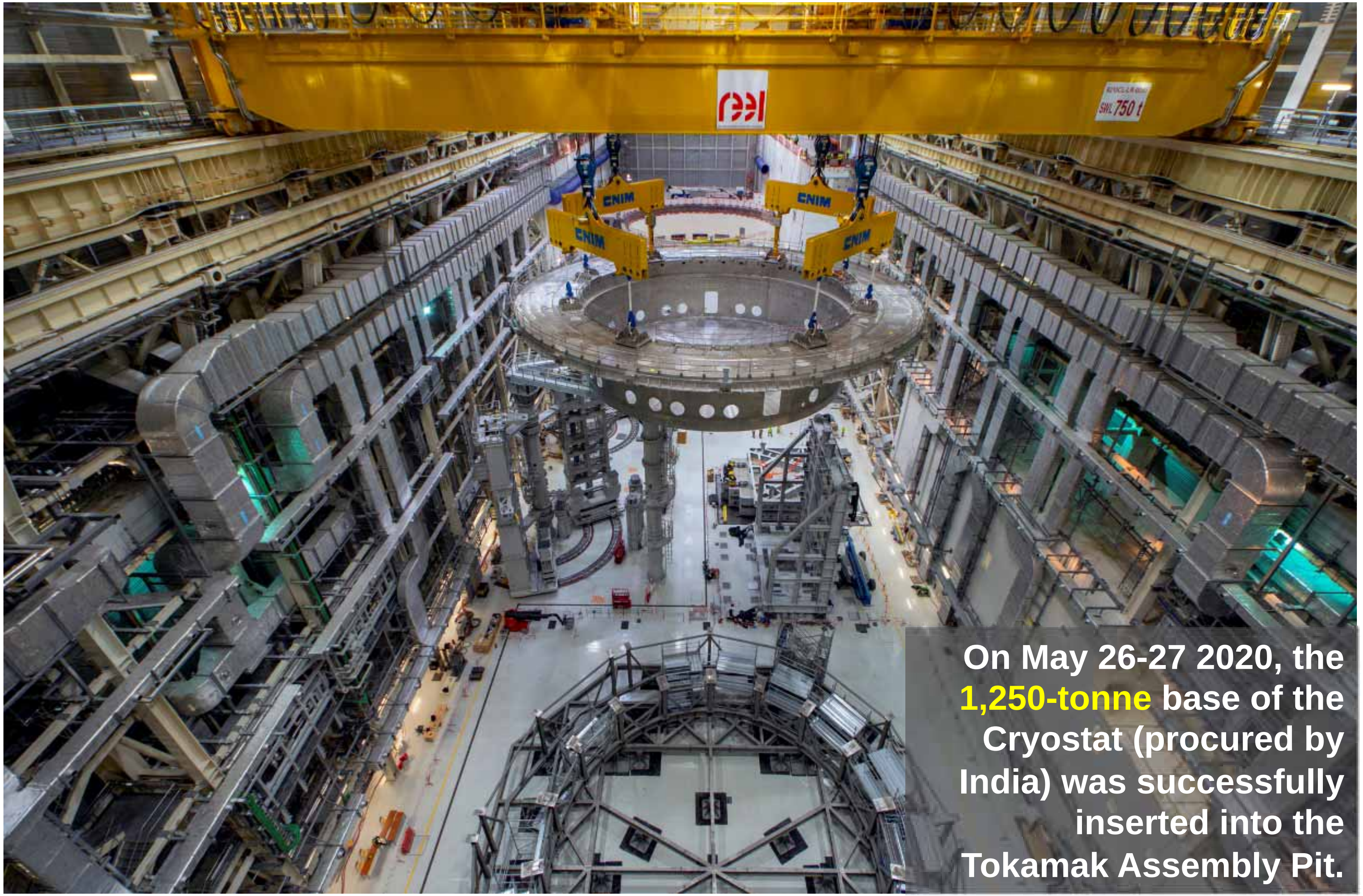
ITER's construction progress (2020)



Cryostat Base in Assembly Hall, April 2020

Cryostat Upper Cylinder emerging to go into storage, April 2020

A very important milestone (May 2020)



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

On-site fabrication of poloidal field coils (up to 24m diameter)

PF Coil #5 ready for cold testing,
June 2020

PF Coil #2 ready for resin
impregnation, June 2020

Manufacturing and delivering of components at high speed

Most recent magnet feeder delivered to ITER site

Last cryostat segments ready for delivery

Five vacuum vessel sectors in fabrication, with completion rates from 62% to 81%

Seven additional toroidal field coils in fabrication

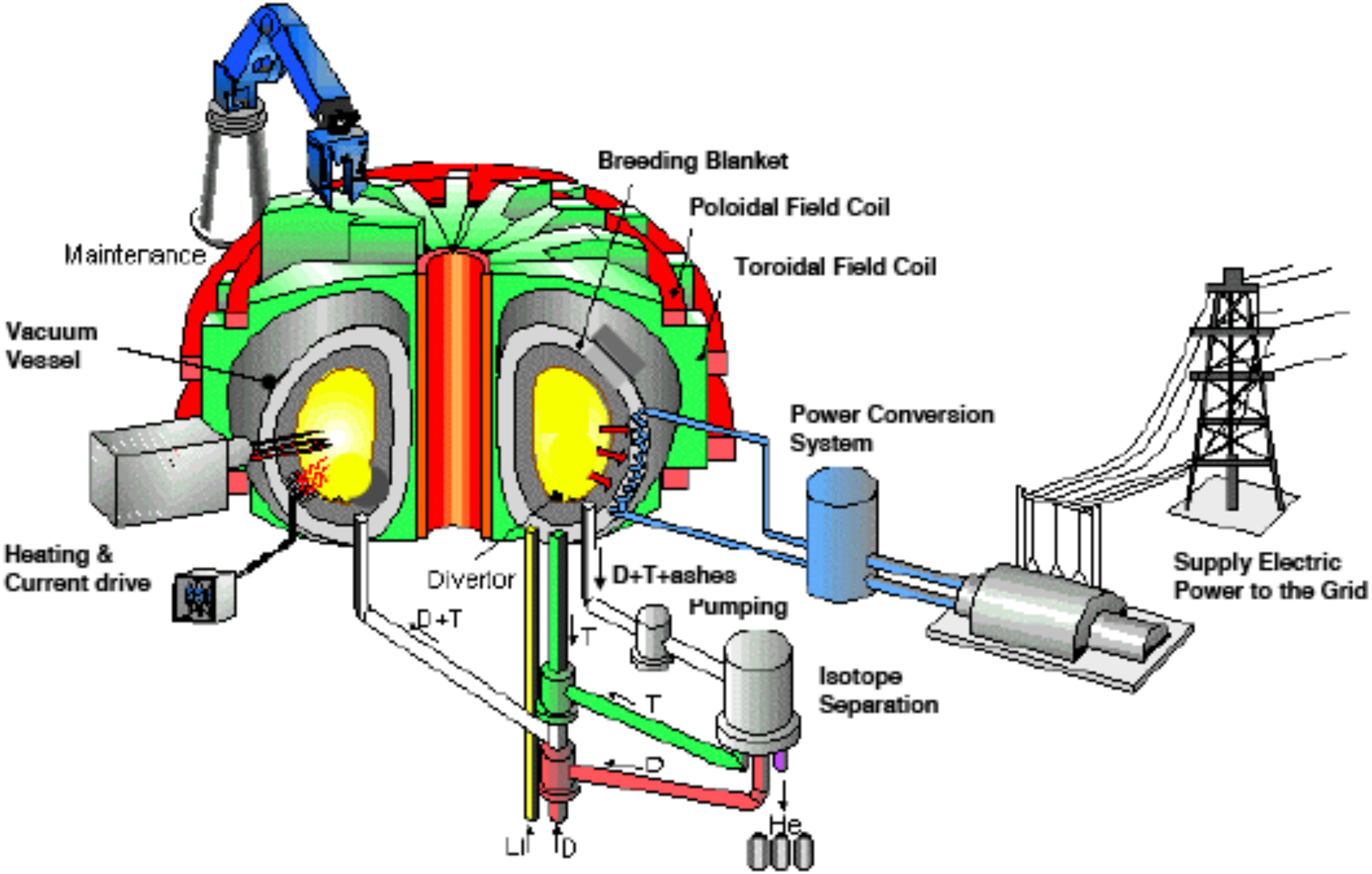
FUSION REACTOR STUDIES

DEMO – Europe
(Demonstration Fusion Reactor)

CFETR – China
(China Fusion Engineering Test Reactor)

A future fusion power plant

A ‘conventional’ one but with a ‘fusion’ oven



Fuel cycle integrated in the plant
D and Li externally supplied, T breeding from Li-n reactions

A FEW EXAMPLES OF THE
TECHNOLOGICAL PROGRESS OF THE LAST YEARS
IN FUSION RESEARCH

- **First wall consisting of Be and W**
- **20MW RF antenna for ITER – LPP/ERM-KMS, Brussels**
- **Progress towards D^0 particle beam at 16.5 MW, 1 MeV, 3600s**
- **140GHz sources at 1 MW for 30 min: world record**
- **125mA D^+ beam at 5 MeV: world record**

Which first wall for ITER/DEMO ?

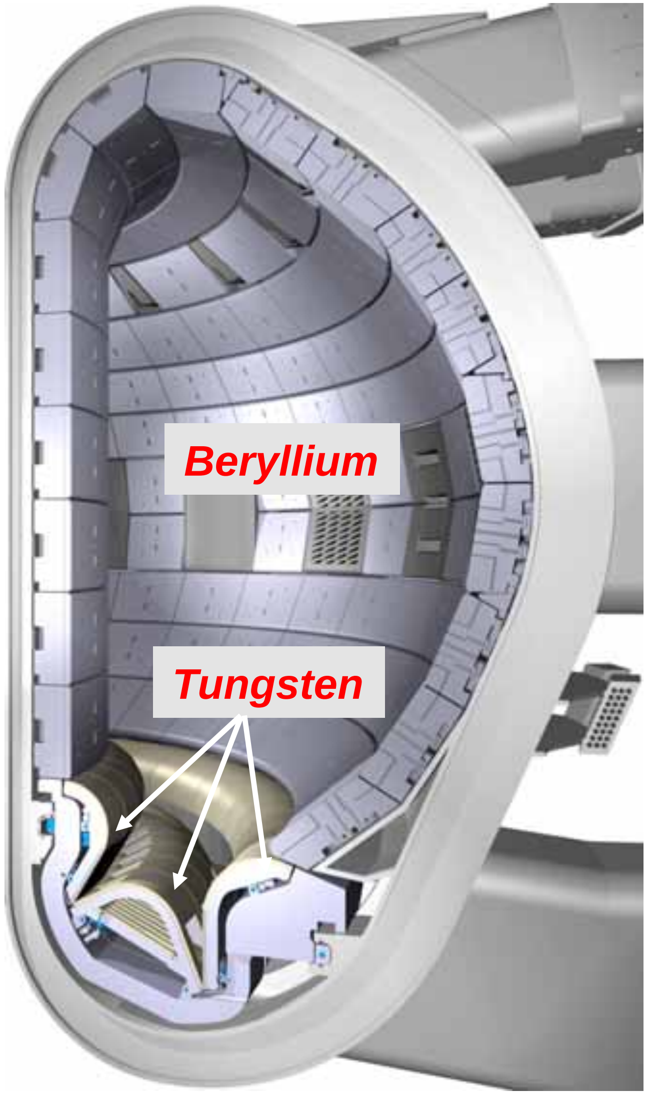
Graphite has been used in last 20 years to optimise plasma requirements

- High temperature : no melting, only sublimation at T~ 3000C
- Easy plasma operation/performance
- Resistance against power transients and operational failures

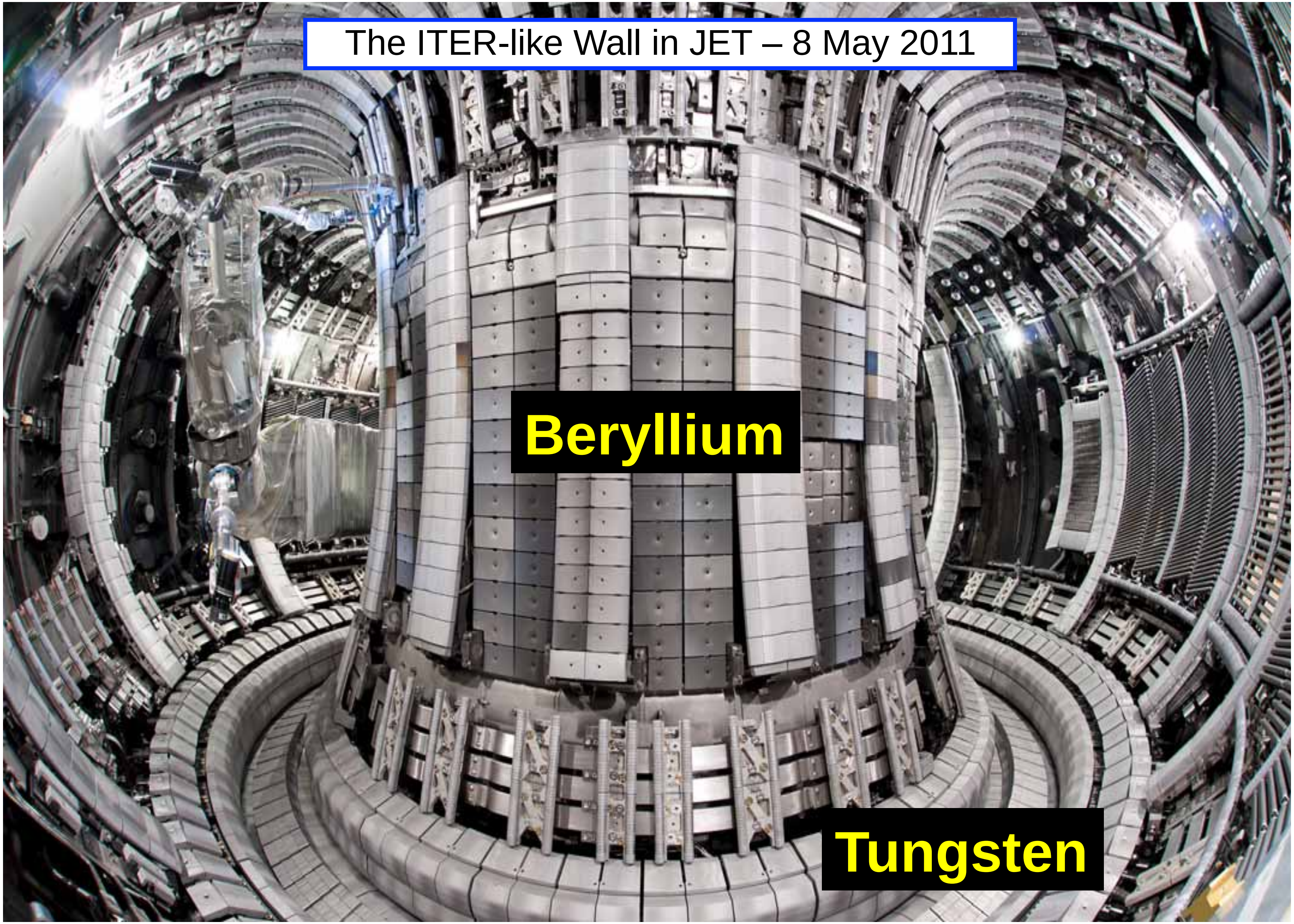
Not suitable for power reactor because of additional requirements

- Lifetime (low erosion) (DEMO)
- Low T uptake (ITER)
- Neutron compatibility (DEMO)

Combination Be/W for ITER/DEMO !



- **Beryllium (Be) ?**
  - \+ Reduced T retention in vacuum chamber
  - \+ Low Z
  - \- But rather low melting point : 1287 C
- **Tungsten (W) ?**
  - \+ Strongly reduced retention
  - \+ High melting point : 3422 C
  - \- But high Z : very low concentration tolerable
- **Solution: combination Be + W (succesfully tested on JET)**
  - Minimise use of W
  - Only there where it cannot be avoided : divertor


The ITER-like Wall in JET – 8 May 2011
Beryllium
Tungsten

A FEW EXAMPLES OF THE TECHNOLOGICAL PROGRESS OF THE LAST YEARS IN FUSION RESEARCH

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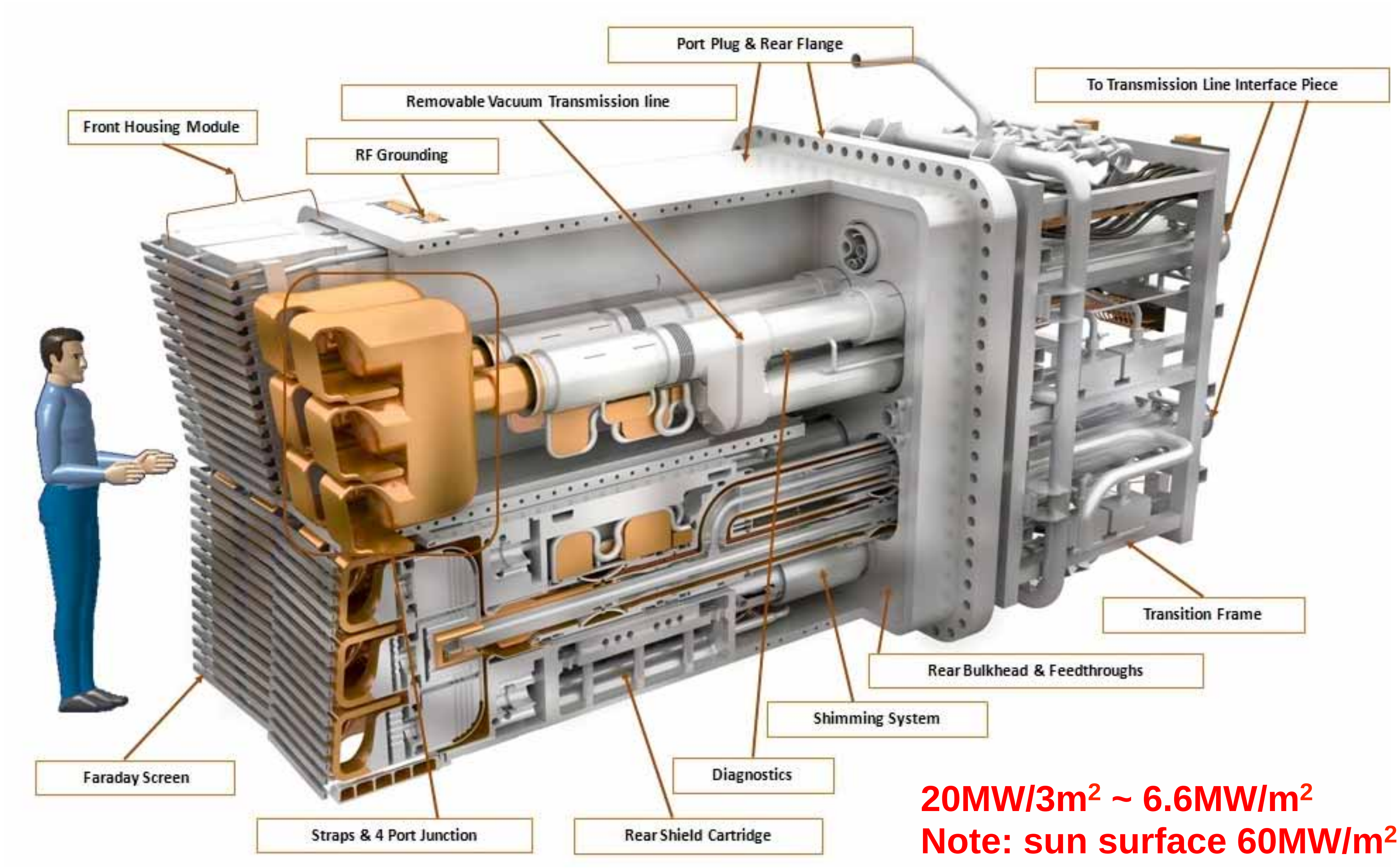
RF Heating antenna's for ITER (40-55MHz, 2x20MW)

Developed by LPP/ERM-KMS, Belgium
in collaboration with UKAEA and CEA-France



$20MW/3m^2 \sim 6.6MW/m^2$
Note: sun surface $60MW/m^2$

LPP/ERM-KMS, Brussels
recognized worldwide for its RF heating antenna expertise

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Contribution of LPP/ERM-KMS to the modern developments of ICRH antenna systems☆

A. Messiaen*, J. Ongena, P. Dumortier, F. Durodié, F. Louche, R. Ragona, M. Vervier

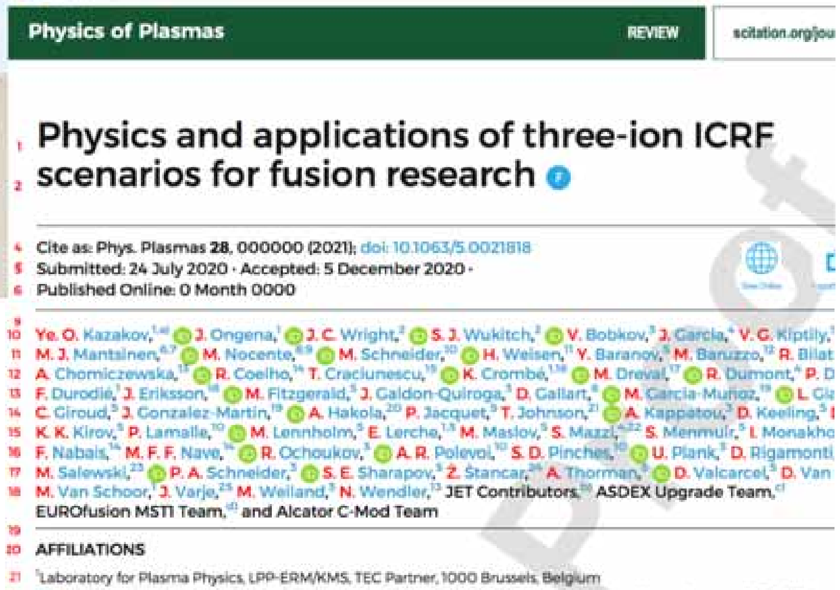
Laboratory for Plasmaphysics, Ecole Royale Militaire—Koninklijke Militaire School, Partner in the Trilateral Euregio Cluster, Brussels, Belgium

Research in LPP/ERM-KMS, Brussels awarded by American Physical Society in 2018

"for experimental verification, through collaborative experiments, of a **novel and highly efficient ion cyclotron resonance heating scenario for plasma heating** and generation of energetic ions in magnetic fusion devices"

APS/EPS Landau-Spitzer Award
2 LPP/ERM-KMS + 2 MIT colleagues

Recent "Featured Review" paper published


Physics of Plasmas REVIEW scitation.org/jou

Physics and applications of three-ion ICRF scenarios for fusion research

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Ye. O. Kazakov, J. Ongena, J. C. Wright, S. J. Wukitch, V. Bobkov, J. Garcia, V. G. Kiptily,
M. J. Mantsinen, M. Nocente, M. Schneider, H. Weisen, Y. Baranov, M. Baruzzo, R. Bilat
A. Chomiczewska, R. Coelho, T. Craciunescu, K. Crombé, M. Dreval, R. Dumont, P. D
F. Durodie, J. Eriksson, M. Fitzgerald, J. Galdon-Quiroga, D. Gallart, M. Garcia-Munoz, L. Gi
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F. Nabais, M. F. F. Nave, R. Ochoukov, A. R. Polevoi, S. D. Pinches, U. Plank, D. Rigamonti
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EUROfusion MST1 Team, and Alcator C-Mod Team

AFFILIATIONS

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A FEW EXAMPLES OF THE TECHNOLOGICAL PROGRESS OF THE LAST YEARS IN FUSION RESEARCH

- First wall consisting of Be and W
- 20MW RF antenna for ITER – LPP/ERM-KMS, Brussels
- Progress towards D^0 particle beam at 16.5 MW, 1 MeV, 3600s
- 140GHz sources at 1.5 MW for 30 min: world record
- 125mA D^+ beam at 5 MeV: world record

Neutral Beam Test Facility in Padua (August 2013)

SPIDER and MITICA

NBTF
Neutral Beam Test Facility (Padova, Italy)

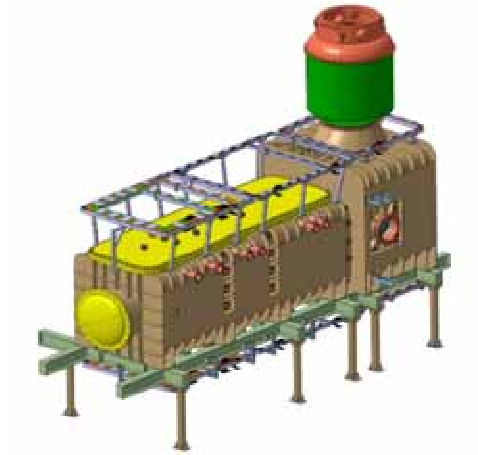
SPIDER:
Most powerful negative ion source in the world

MITICA:
Most powerful negative beam accelerator in the world

Full prototype of the ITER Neutral Beam Injector

SPIDER
Source for the Production of Ions of Deuterium Extracted from RF plasma

40A D^- beam, 2 years operation



MITICA
Megavolt ITER Injector & Concept Advancement

1MV Accelerator; 1.2MVcommissioned

SPIDER

A FEW EXAMPLES OF THE TECHNOLOGICAL PROGRESS OF THE LAST YEARS IN FUSION RESEARCH

- **First wall consisting of Be and W**
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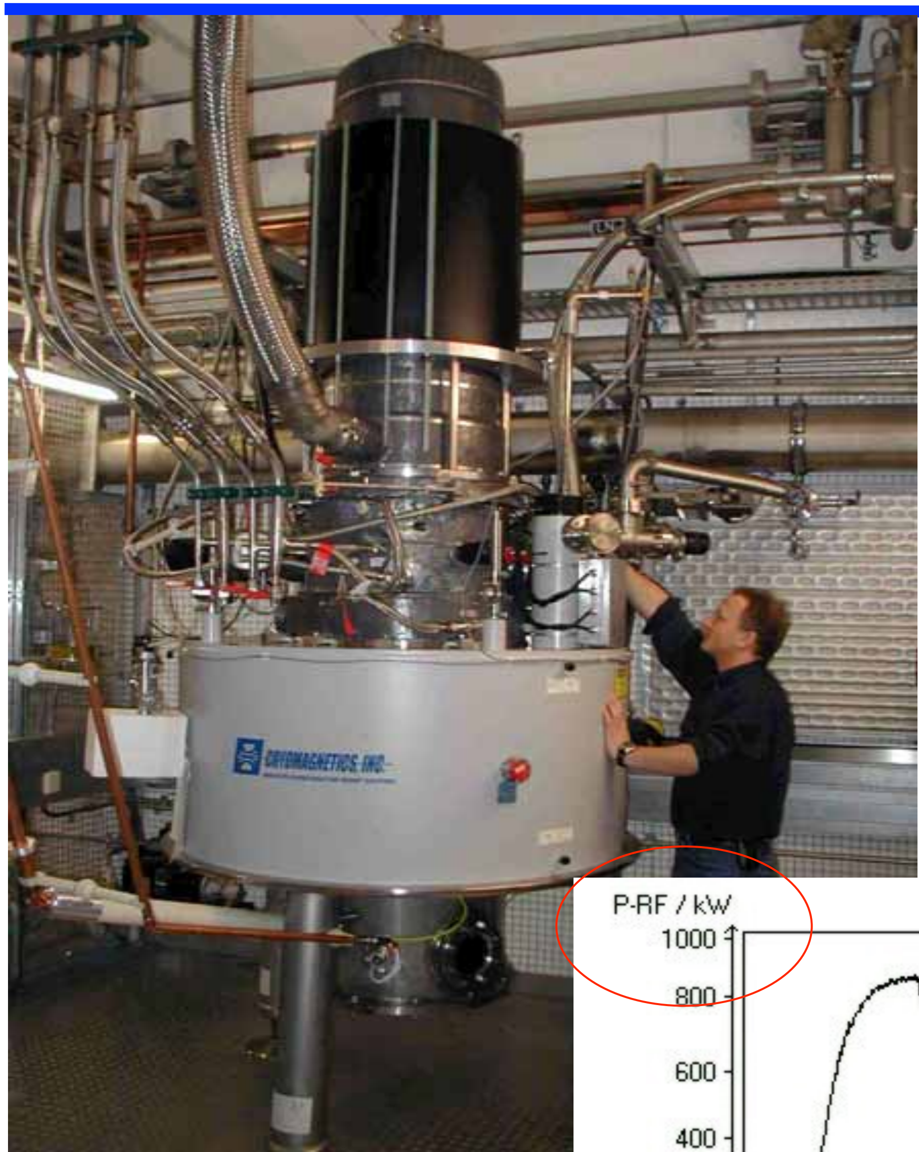
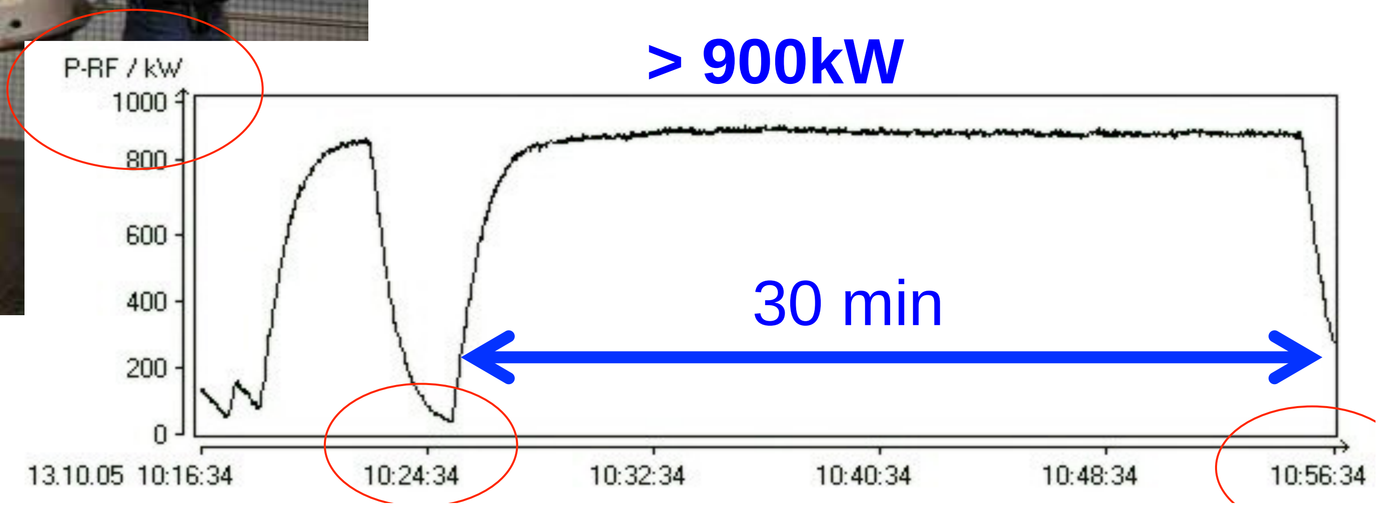
Development of 1MW 140GHz sources, 30 min CW



World record, but ...

Higher power gyrotrons in development : 1.5MW



A FEW EXAMPLES OF THE TECHNOLOGICAL PROGRESS OF THE LAST YEARS IN FUSION RESEARCH

- First wall consisting of Be and W
- 6.6MW/m^2 RF antenna for ITER (20MW/3m^2) – LPP/ERM-KMS
- Progress towards D^0 particle beam at 16.5 MW, 1 MeV, 3600s
- 140GHz sources at 1 MW for 30 min: world record
- 125mA D^+ beam at 5 MeV: world record

Which device for fusion materials research ?

- Fission reactors ? NO **too low neutron energy**
- Spallation sources ? NO **too high neutron energy**

A dedicated device is needed

IFMIF = International Fusion Materials Irradiations Facility

40 MeV D^+ on 25mm liquid Li sheet (10MW, 2 x 125 mA D+ accelerator)

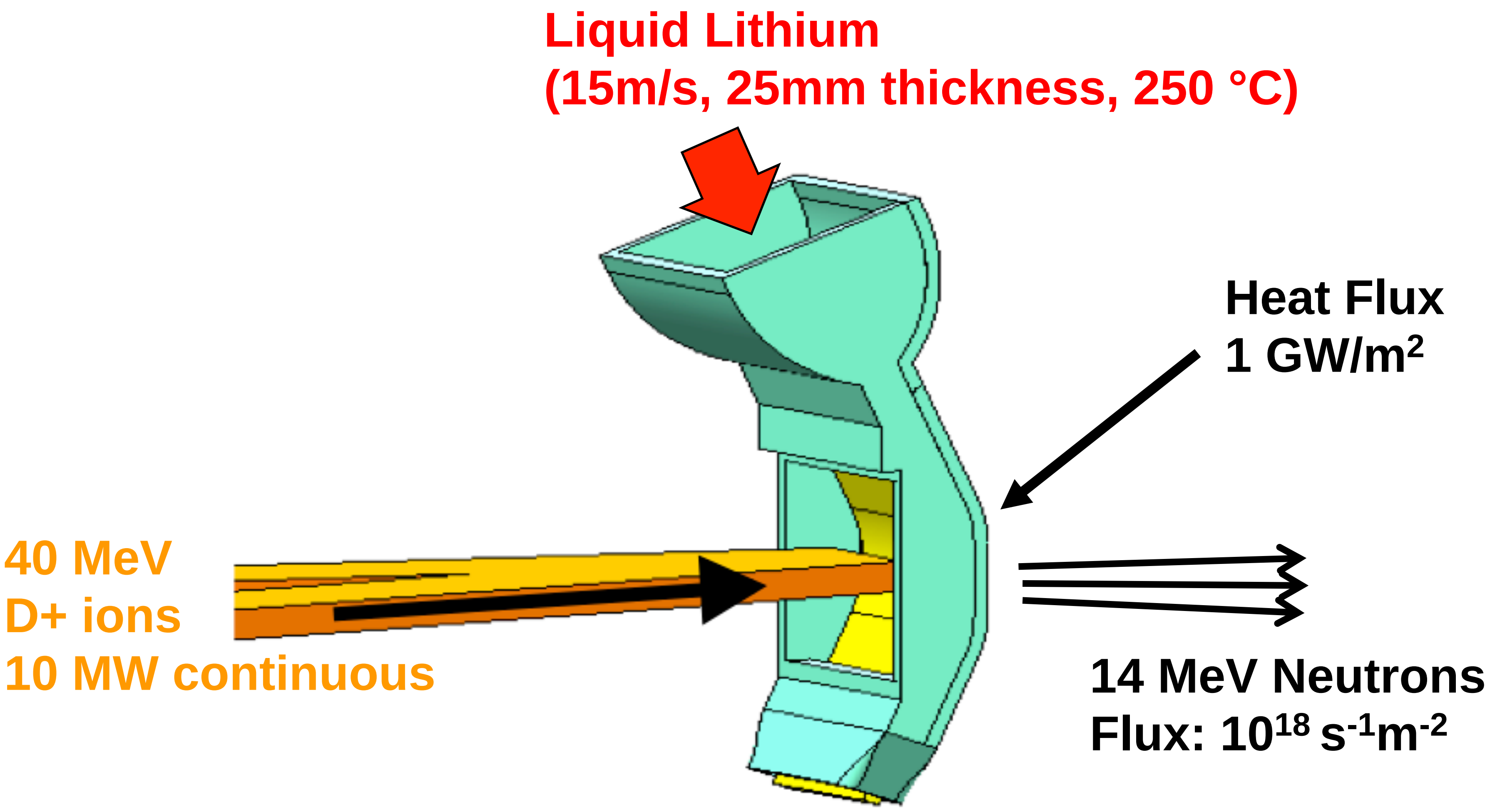
Smaller version: DONES = DEMO Oriented Neutron Source

40 MeV D^+ on 25mm liquid Li sheet (5MW, 125 mA D+ accelerator)

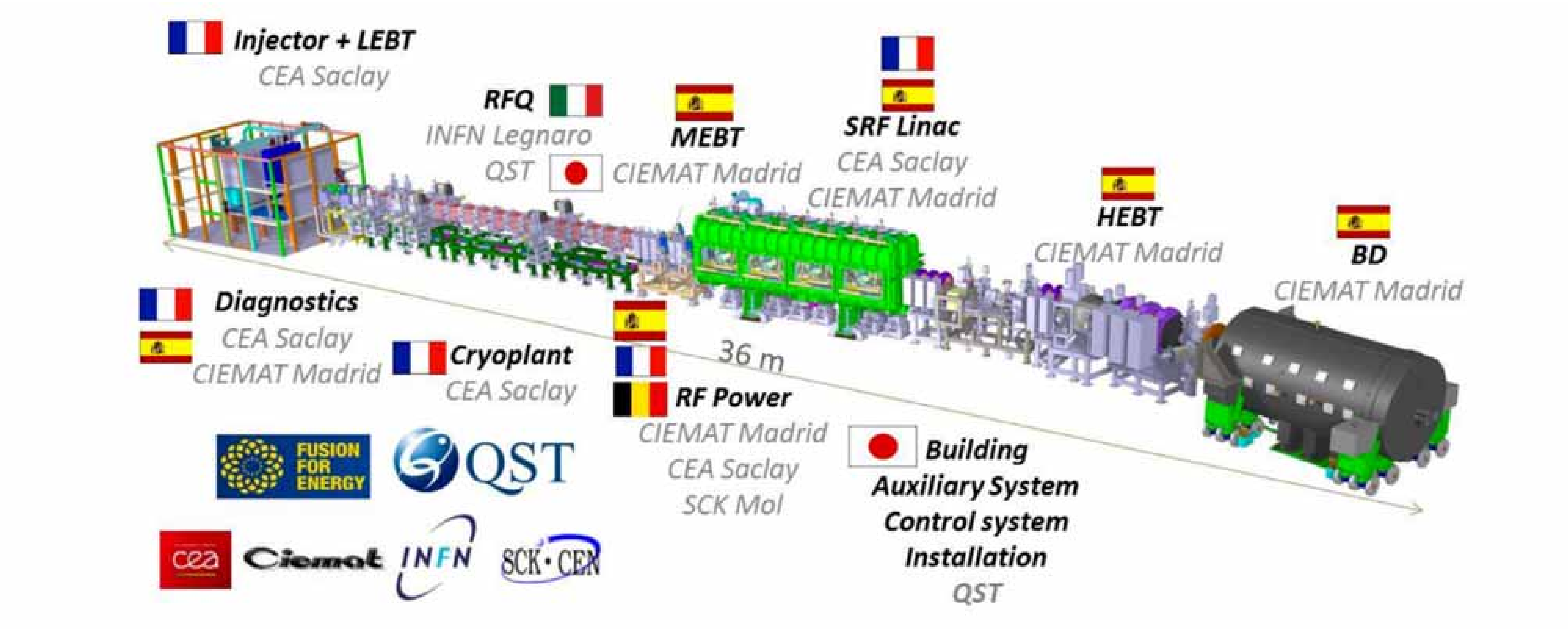
- Accelerator driven source of neutrons
- Neutrons from stripping ${}^{nat}Li(d,xn)$ reactions with peak at 14 MeV

→ ${}^{7}Li(d,n){}^{8}Be$, ${}^{6}Li(d,n){}^{7}Be$, ${}^{7}Li(d,n\alpha\alpha)$,
${}^{7}Li(d,np){}^{7}Li$, ${}^{7}Li(d,nn){}^{7}Be$, ${}^{7}Li(d,nd){}^{6}Li$,…

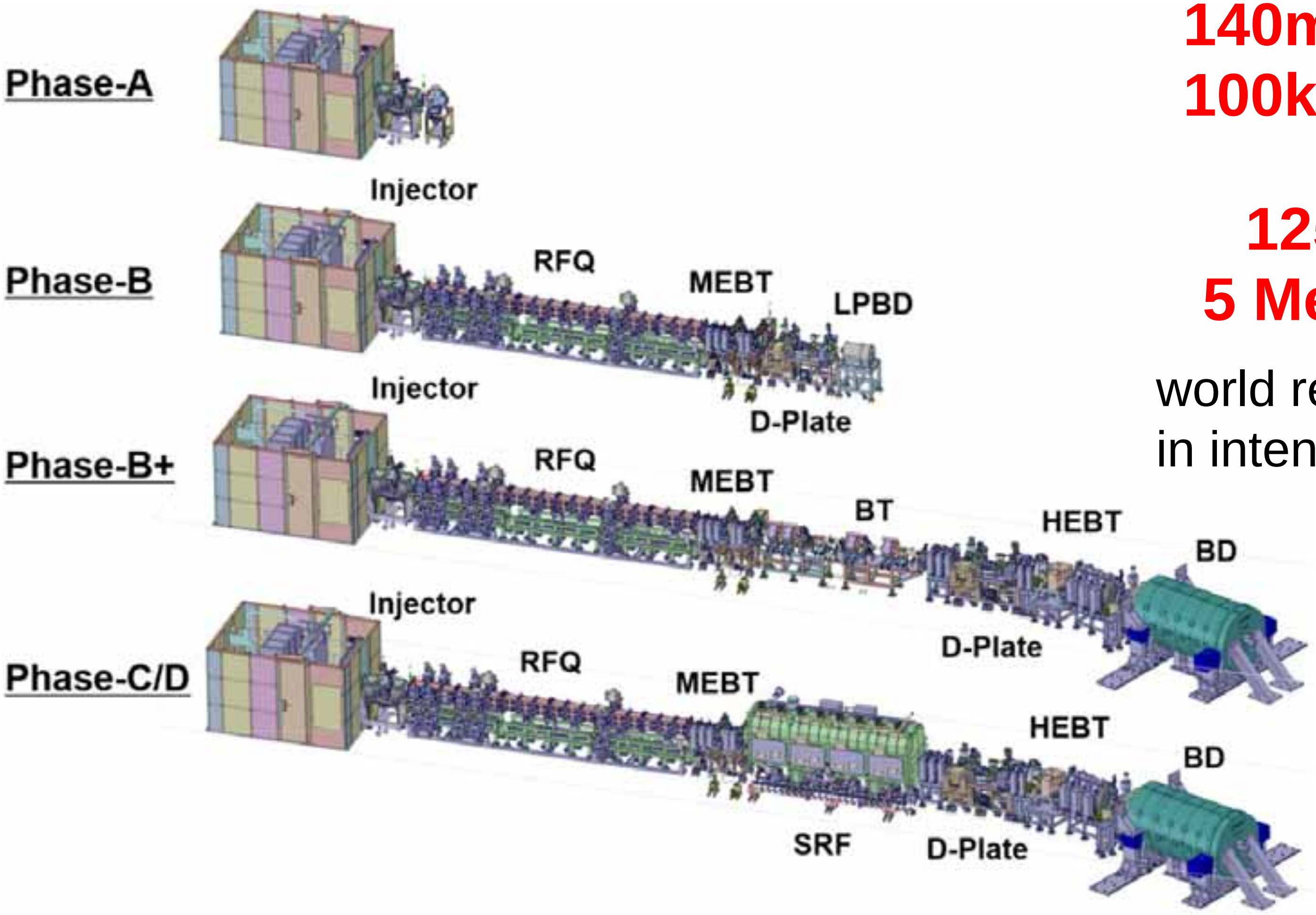
IFMIF: Principle



Linear IFMIF Prototype Accelerator : LIPAc
Many EU countries involved, including Belgium



Development phases of the world's most powerful LINAC



140mA
100keV, H+
2016:ok

125mA
5 MeV, D+
2019:ok

world record deuteron beam
in intensity and energy

125mA
9 MeV, D+ pulsed

2021-2014

125mA
9 MeV, D+ CW

LIPAc – Nov 2016

Latest results of LIPAc

Fusion Engineering and Design 153 (2020) 111503

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

ELSEVIER

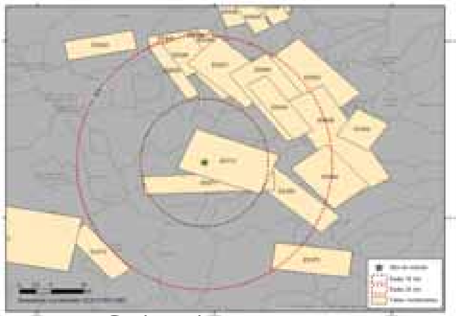
Validation of the Linear IFMIF Prototype Accelerator (LIPAc) in Rokkasho

Keitaro Kondo[a,*], Tomoya Akagi[a], Fernando Arranz[b], Nicolas Bazin[c], Luca Bellan[d], Benoit Bolzon[c], Beatriz Brañas[b], Philippe Cara[e], Yann Carin[f], Jesus Castellanos[b], Stephane Chel[c], Michele Comunian[d], Hervé Dzitko[f], Takashi Ebisawa[a], Alberto Facco[d], Enrico Fagotti[d], Daniel Gavela[b], Dominique Gex[f], Francesco Grespan[d], Roland Heidinger[f], Yosuke Hirata[a], David Jimenez[b], Antti Jokinen[f], Atsushi Kasugai[a], Juan Knaster[e], Kohki Kumagai[a], Saerom Kwon[a], Sunao Maebara[a], Alvaro Marchena[b], Alvaro Marqueta[f], Jacques Marroncle[c]

K. Kondo et al., Fusion Engineering and Design 153 (2020) 111503

Preparation in Spain for the fusion materials research lab

DONES-PRIME and DONES-UGR

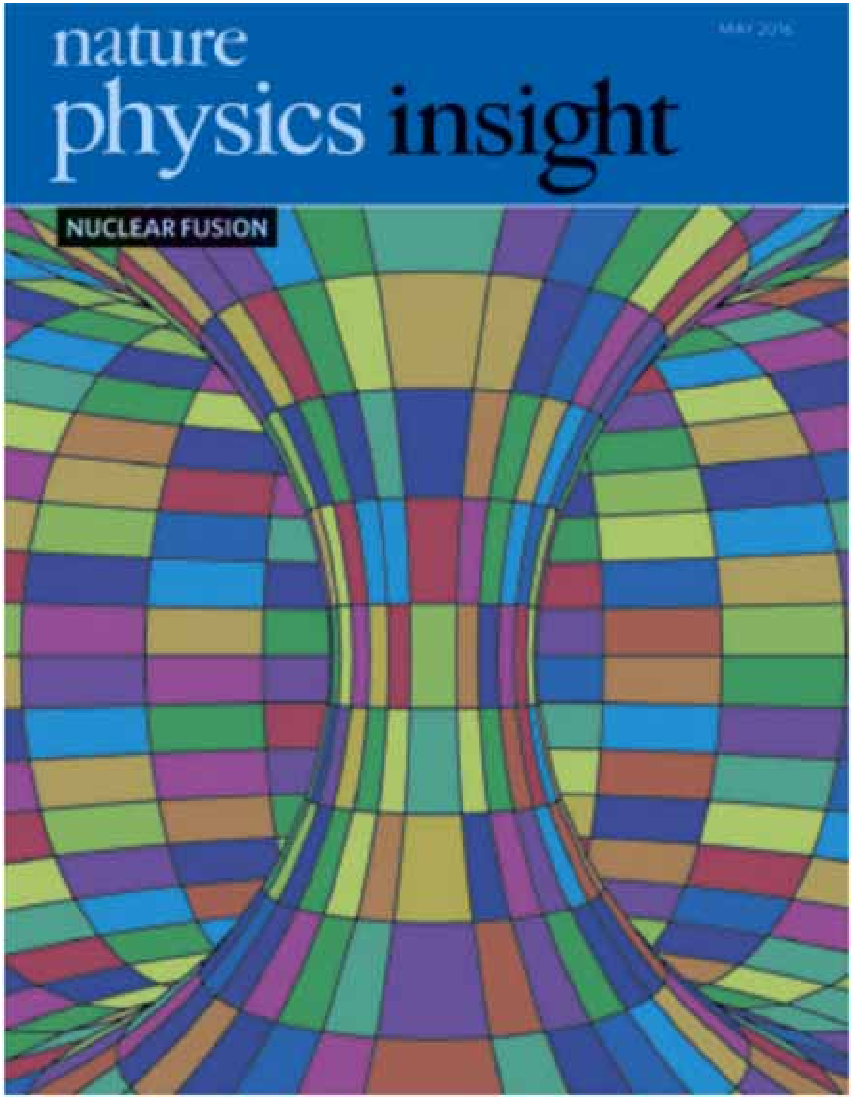


Seismic map

- **Main objectives**: to support the proposal to built the facility as soon as possible and to assure a fast start of the project
- Technical objectives:
  - Full detailed characterization of the site (geotechnical, seismic, radiological, meteorological,…
  - Construction of first buildings
  - Initial steps for a Project Office (around 10-12 people in 20-21)
  - Specific training program (around 20-30 people)
  - Construction of some specific prototypes and medium size facilities

Granada – Spain: Site for DONES

Latest status in fusion research



Nature Physics,
May 2016

"Insight Section"
On nuclear fusion

66 pages of
last minute info on:

- -Magnetic fusion
- -Inertial fusion
- -Fusion materials research
- -Computational advances

http://www.nature.com/nphys/journal/v12/n5/index.html


Fusion: a necessary option for the future
More information:
http://www.iter.org