EUROfusion

Fusion Electricity: A roadmap to the realisation of fusion energy

Tony Donné

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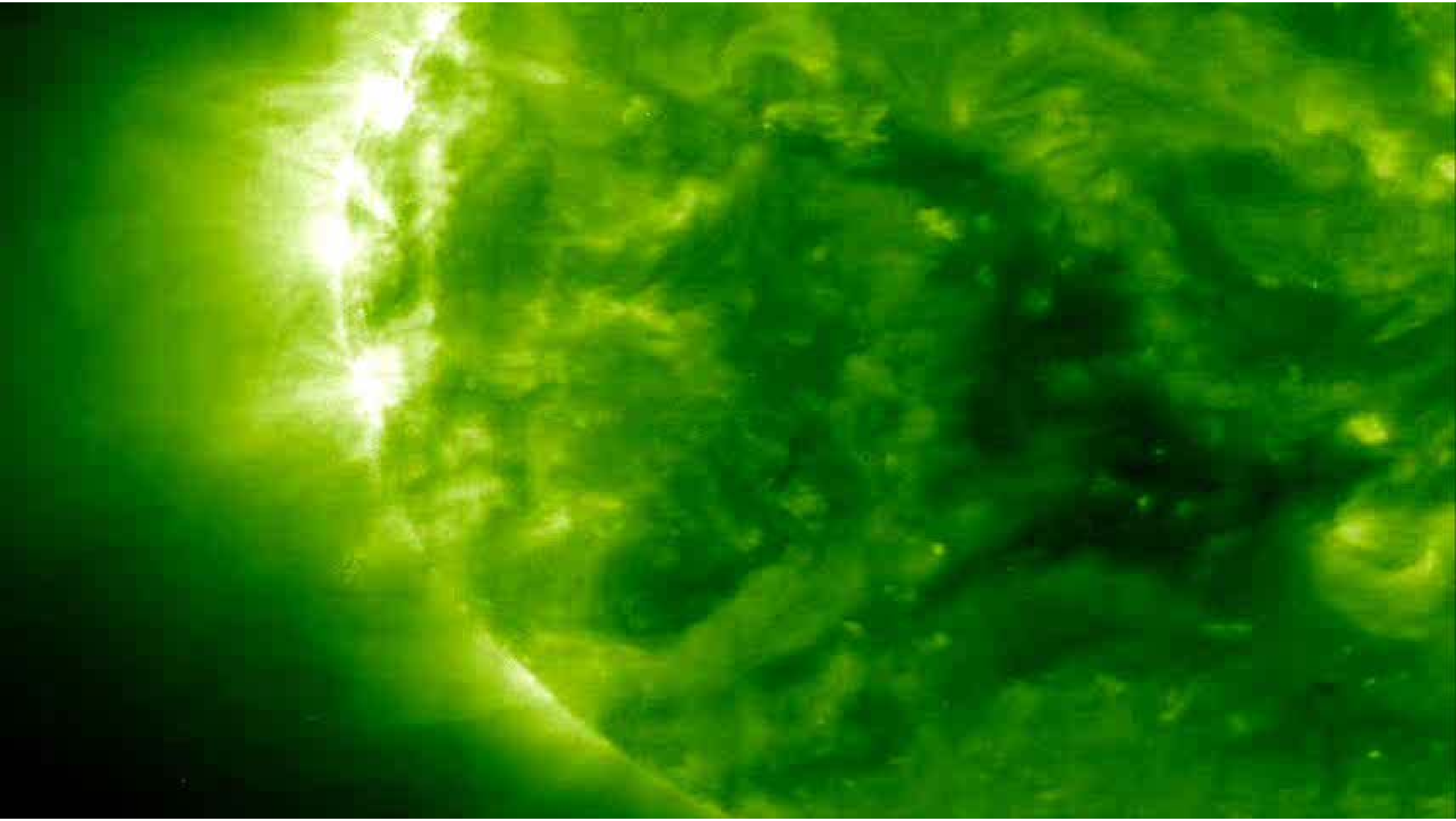
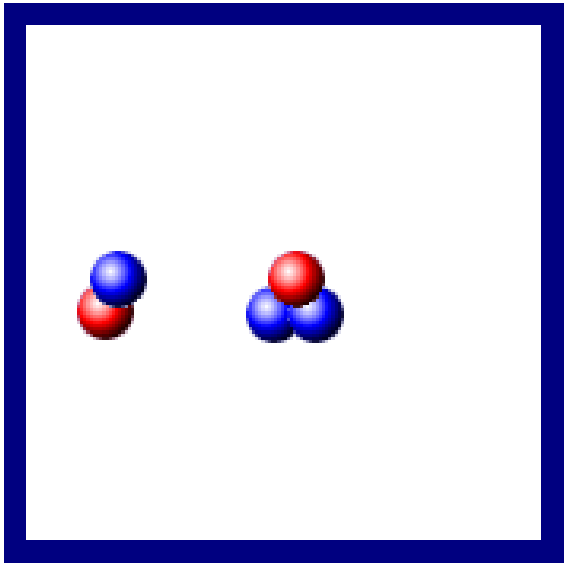
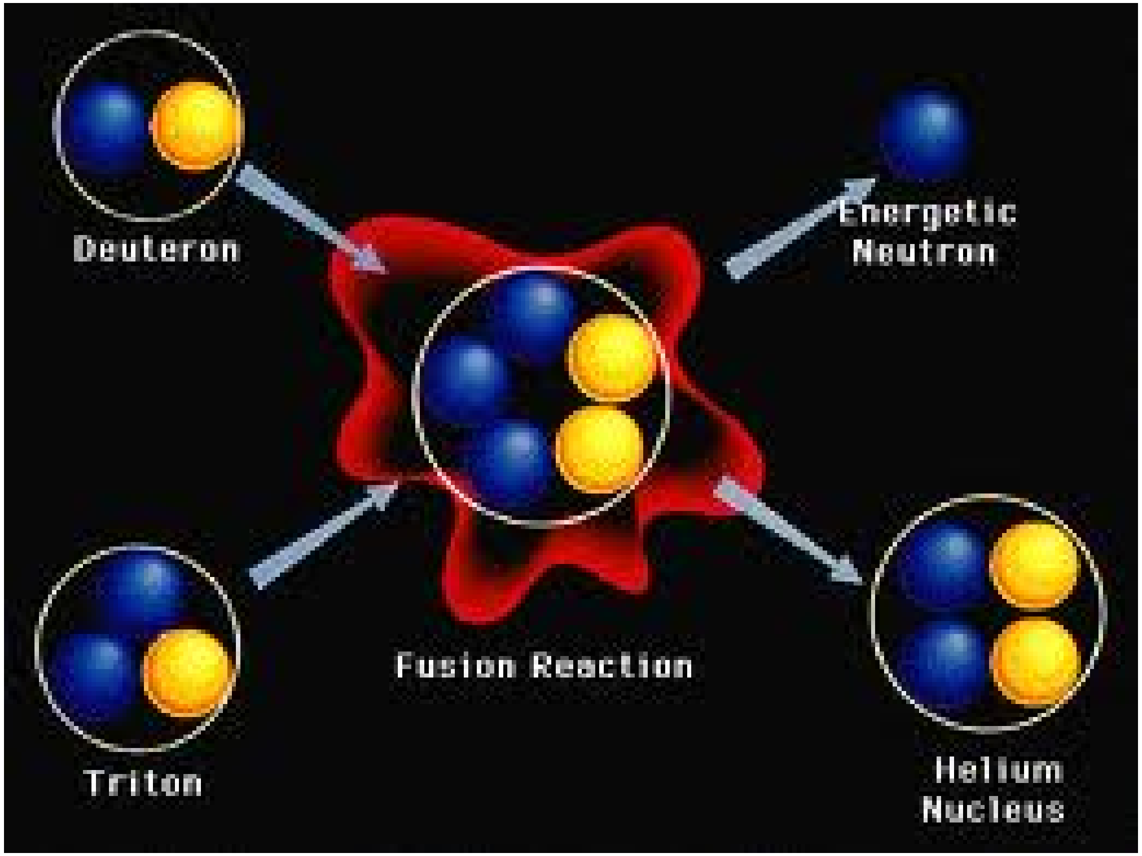
Fusion: the engine of the sun



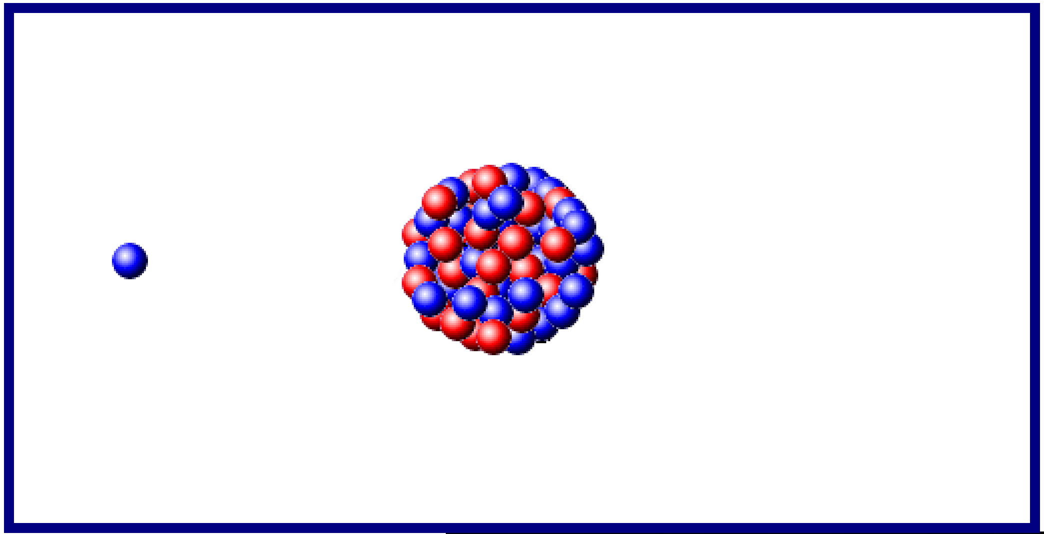
Source: NASA

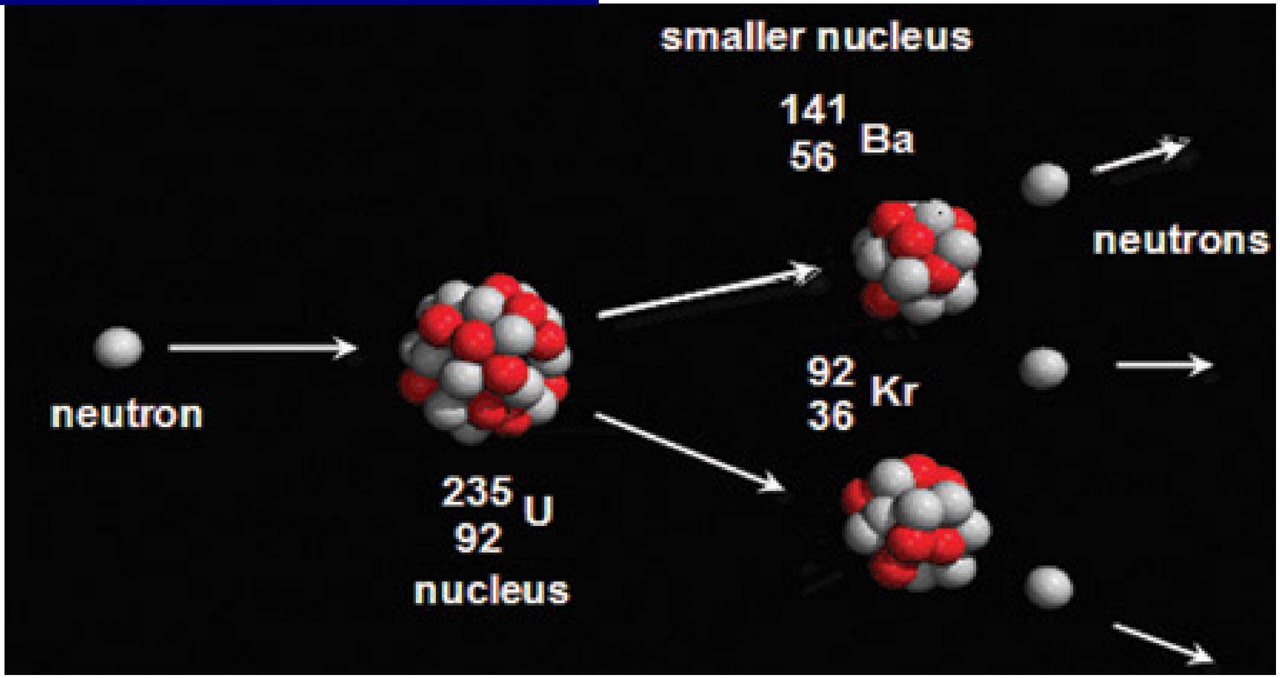
Nuclear Fusion



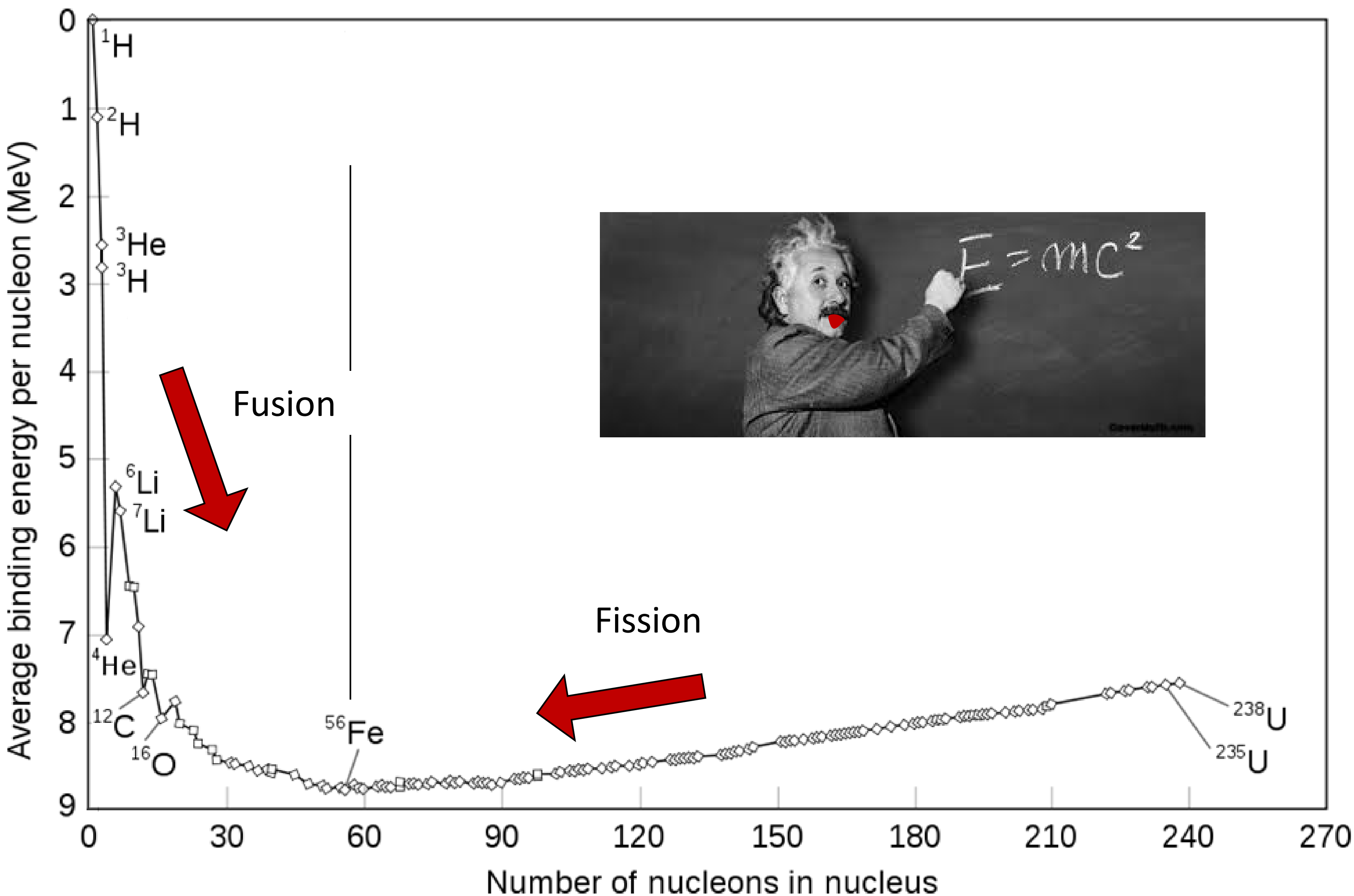


Nuclear Fission





$E = mc^2$


Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
210
240
270
1H
2H
3He
3H
6Li
7Li
4He
12C
16O
56Fe
238U
235U
Fusion
Fission
E = mc2

Europe, USA, Japan, China, Russia, S-Korea and India

want fusion:

- No CO_2 release, clean, safe
- Fuel abundantly available
- No proliferation issues

But...   Fusion is impossible

Source: NASA

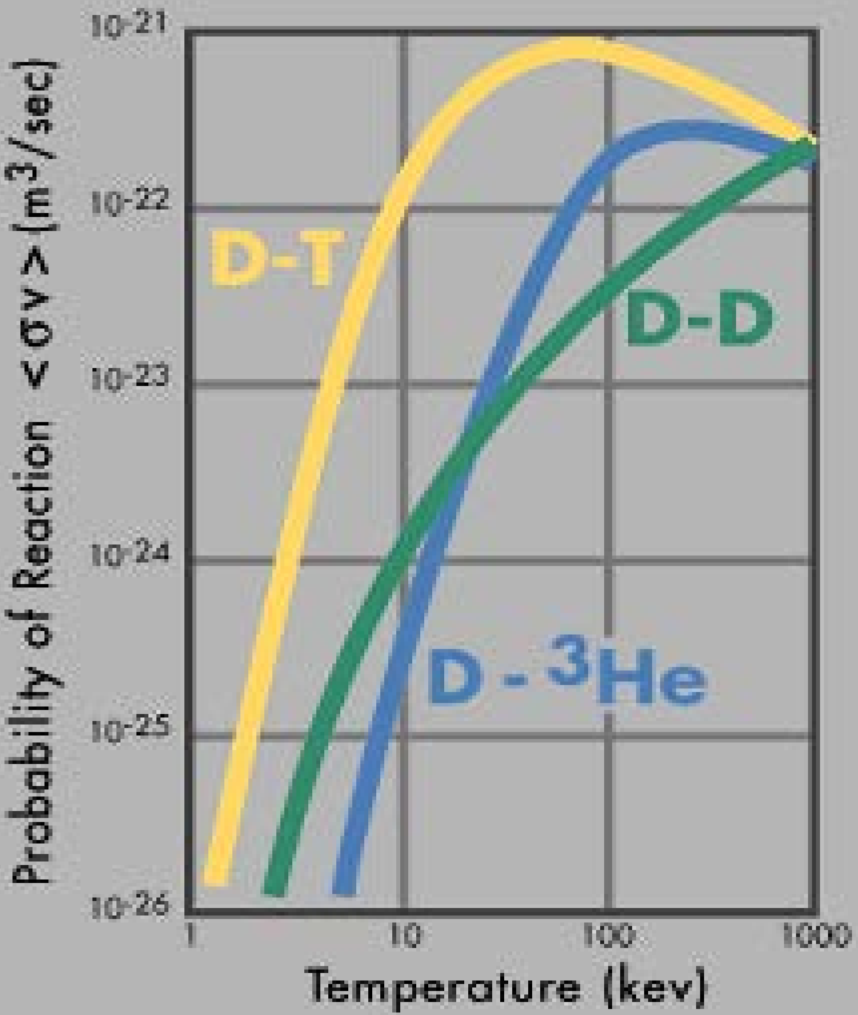
Europe, USA, Japan, China, Russia, S-Korea and India

want fusion:

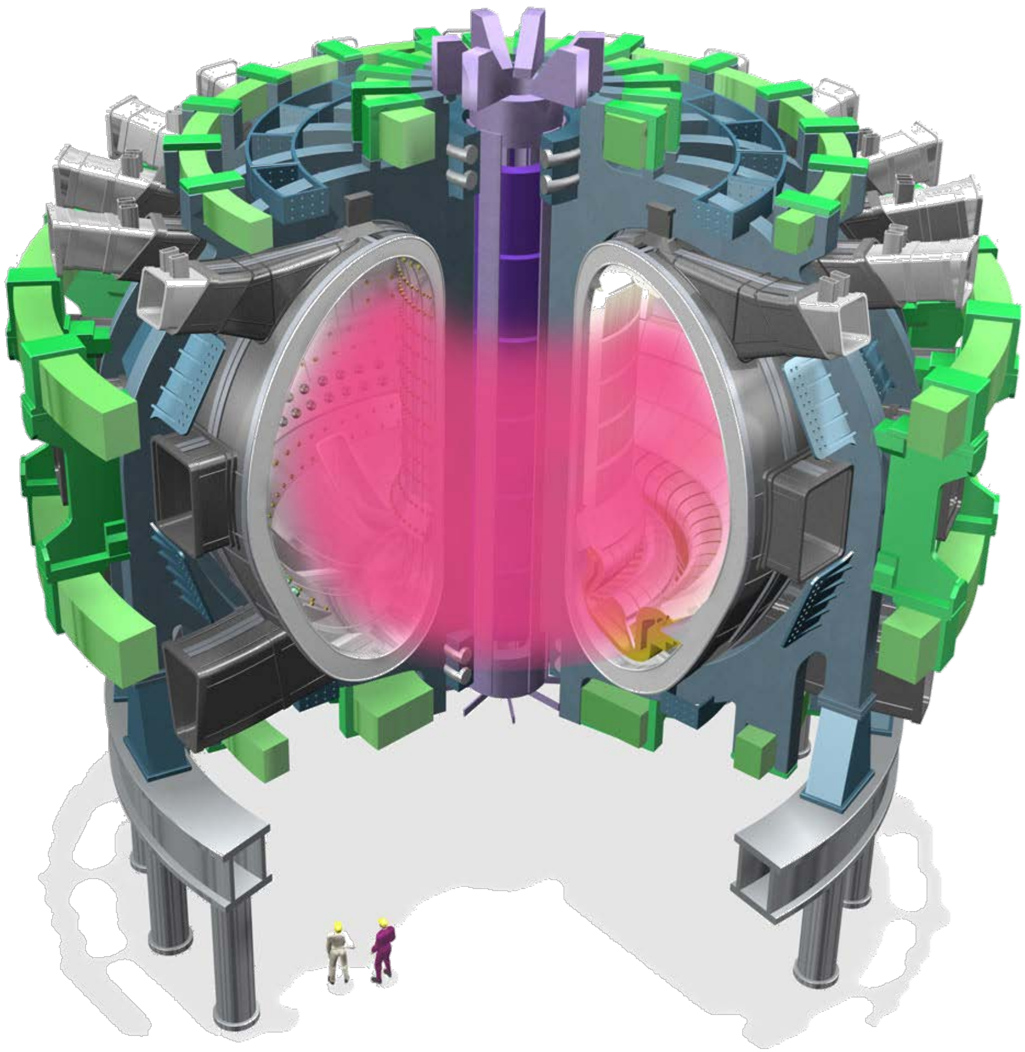
- No CO_2 release, clean, safe
- Fuel abundantly available
- No proliferation issues

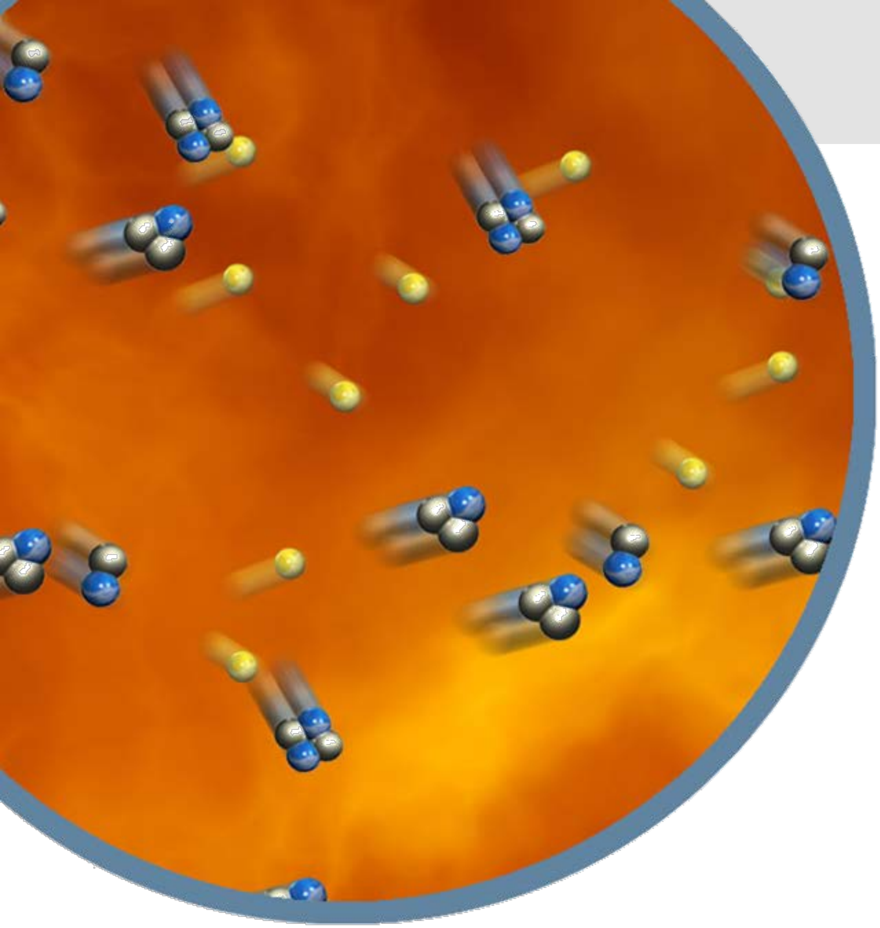
But... Fusion is difficult

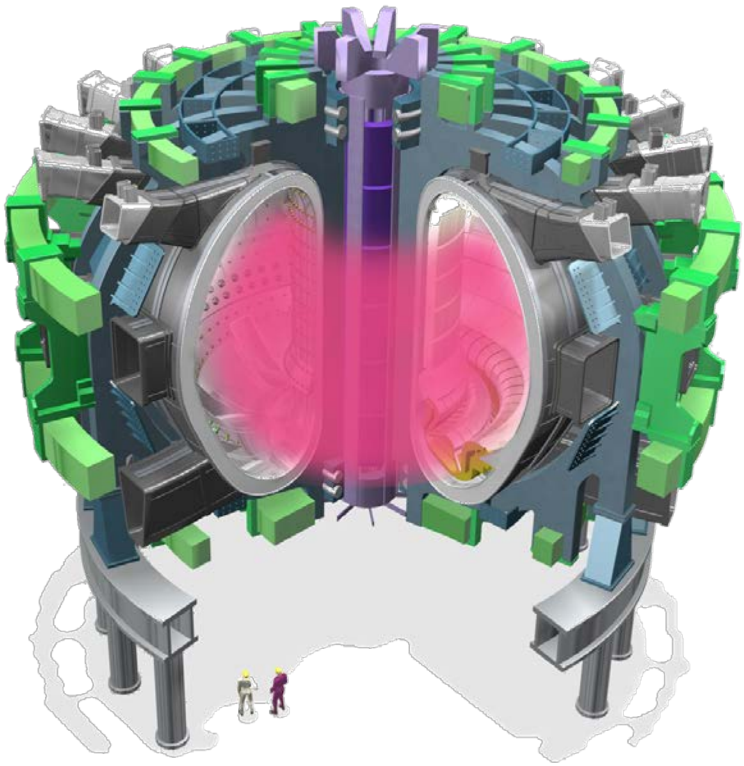
Source: NASA


10-21
10-22
10-23
10-24
10-25
10-26
Probability of Reaction <σv> (m3/sec)
D-T
D-D
D - 3He
1
10
100
1000
Temperature (kev)

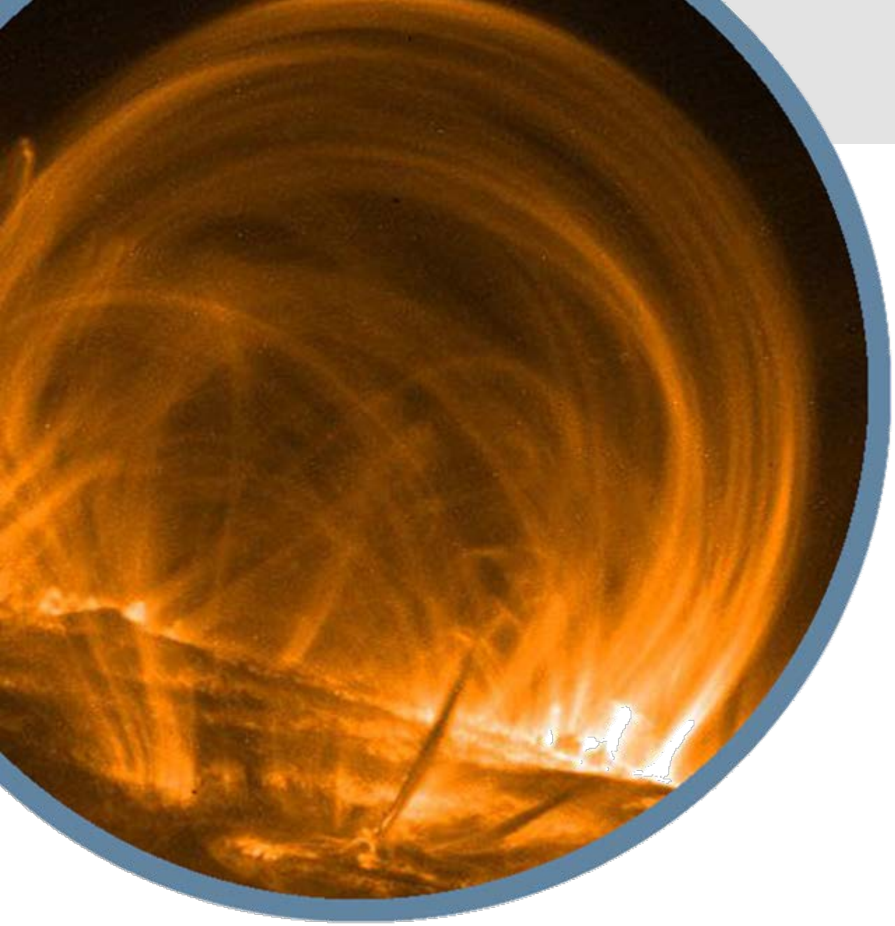
Challenges in Nuclear Fusion Research

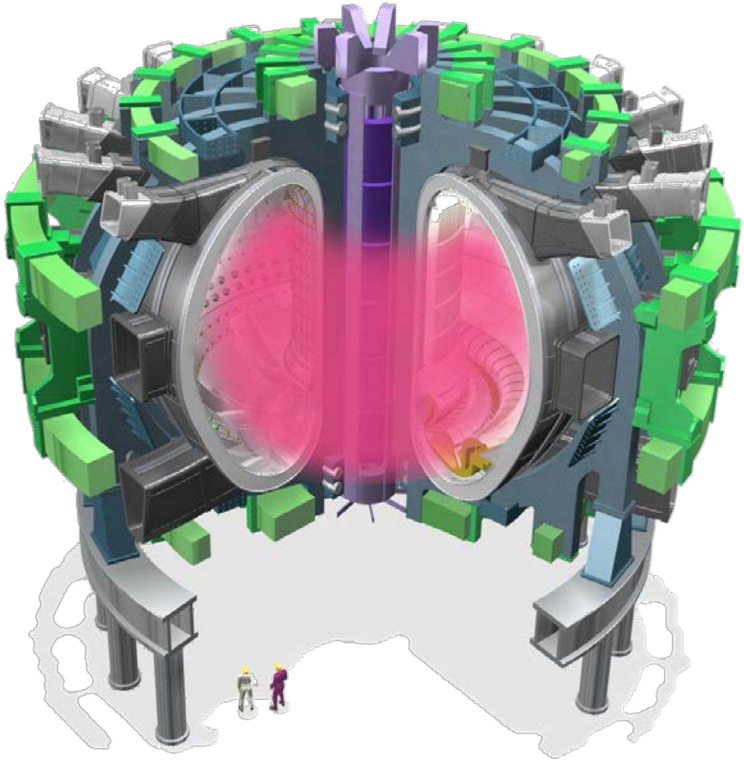




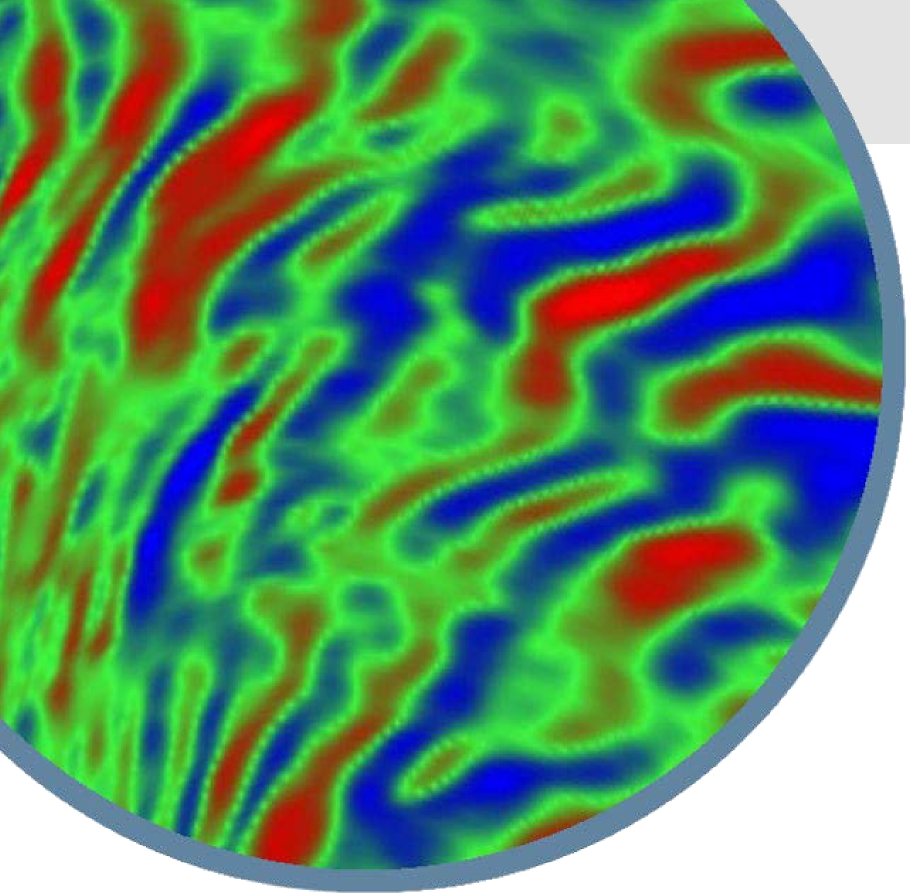


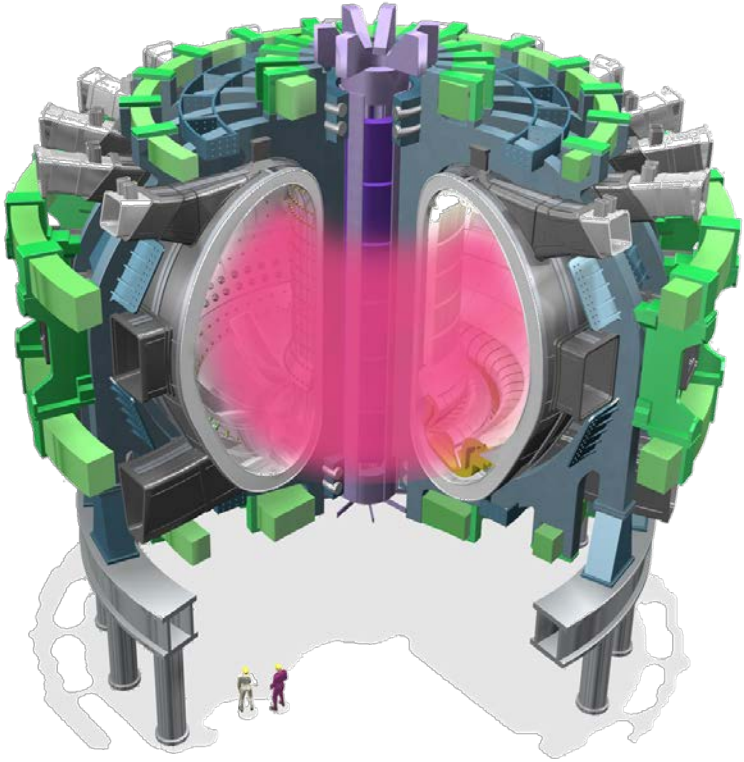
10× hotter than the sun



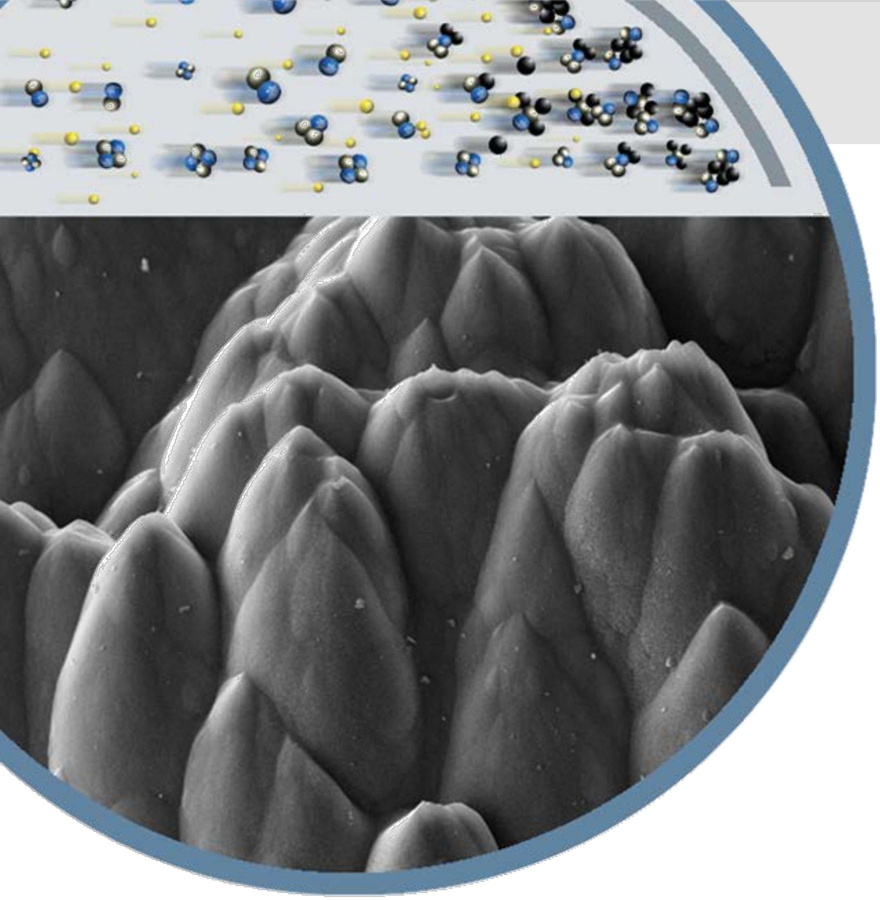


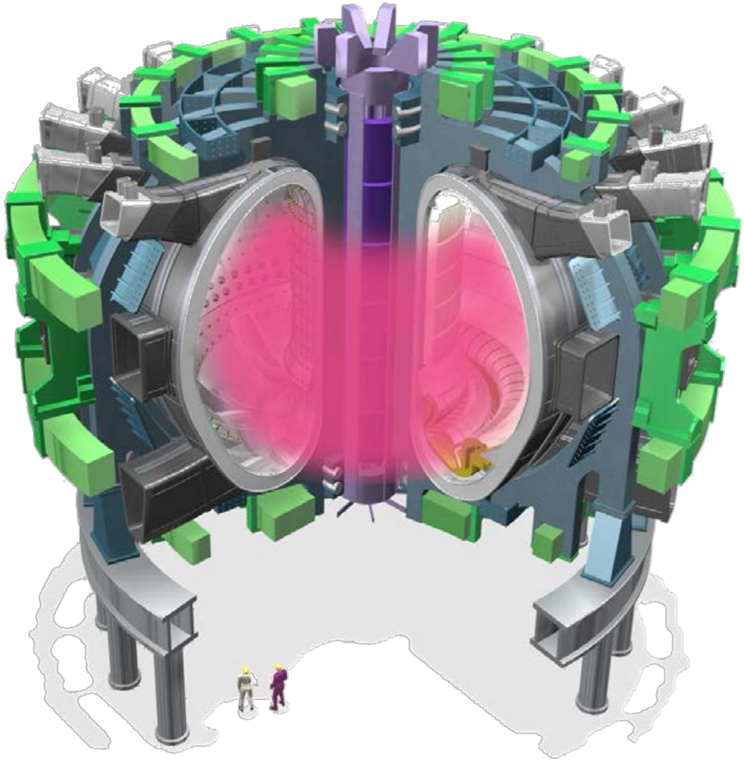
Harnessing solar flares



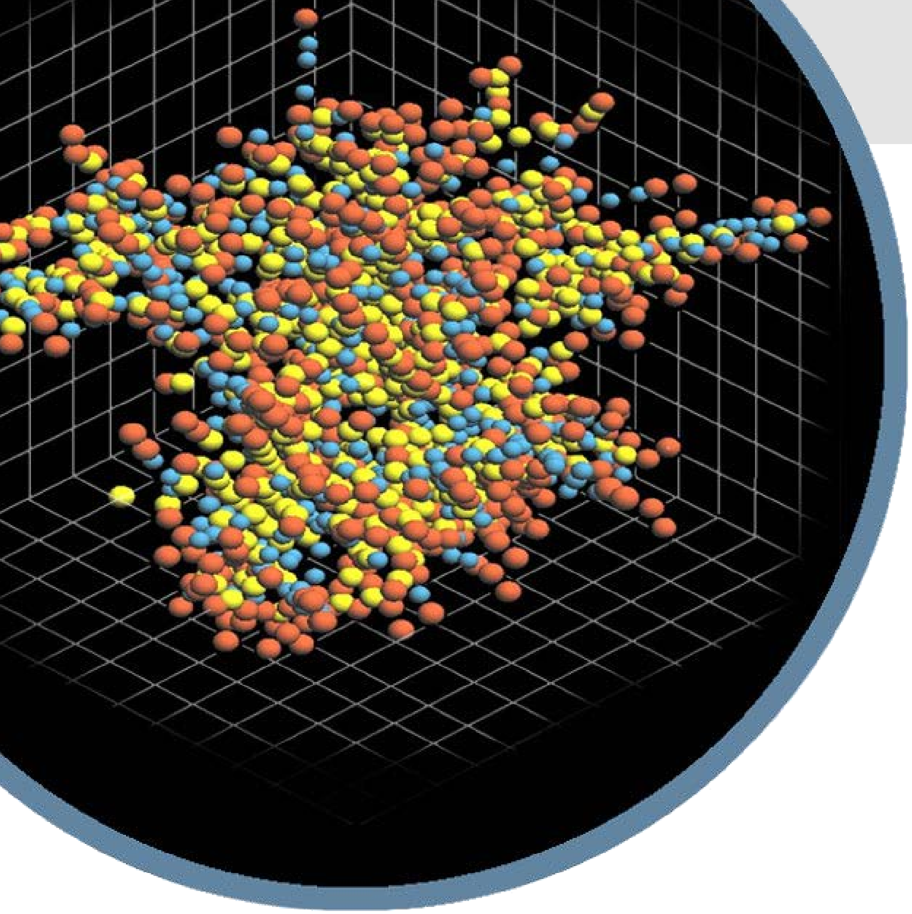


Thermal insulation: nearly perfect

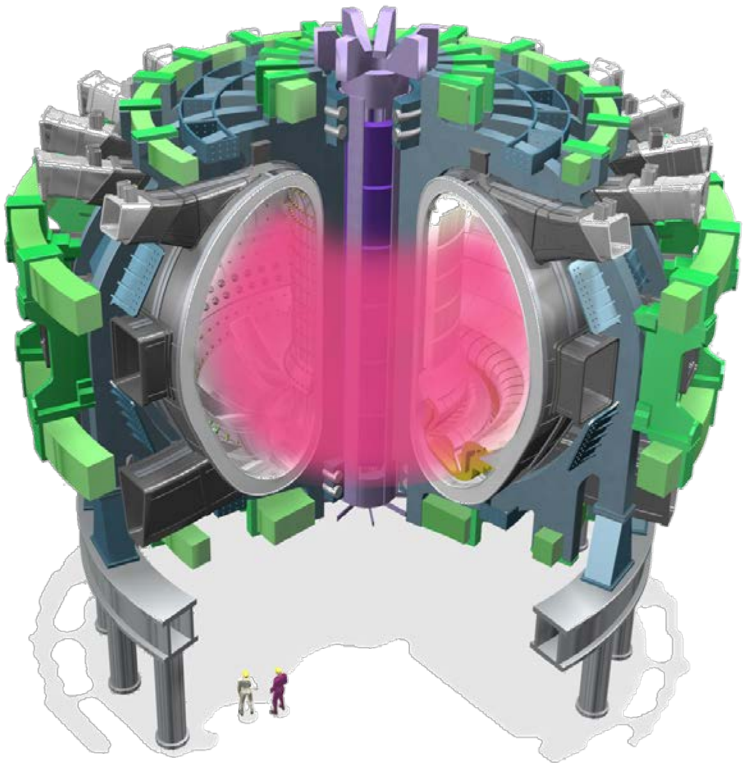


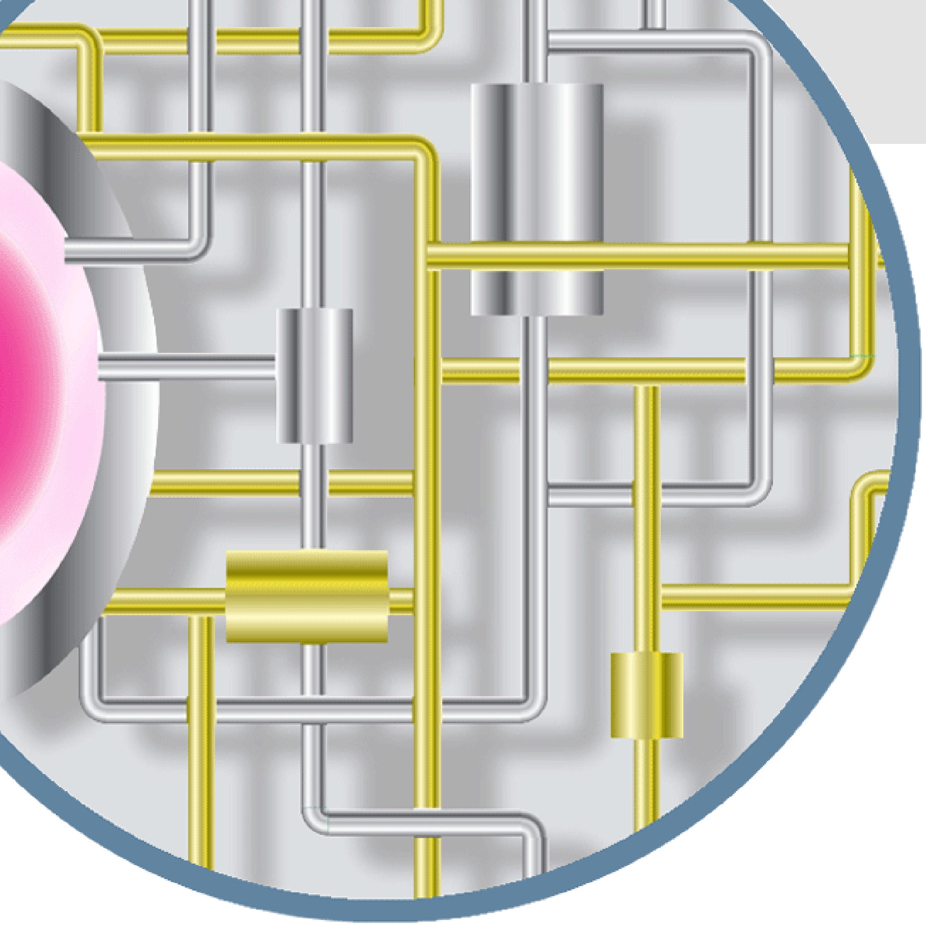


Materials one can lay on the sun

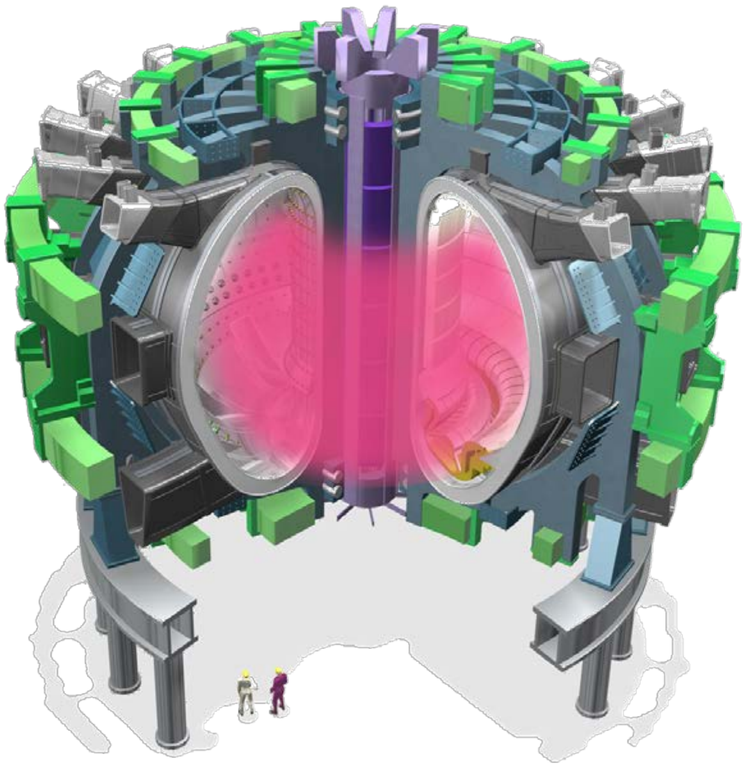


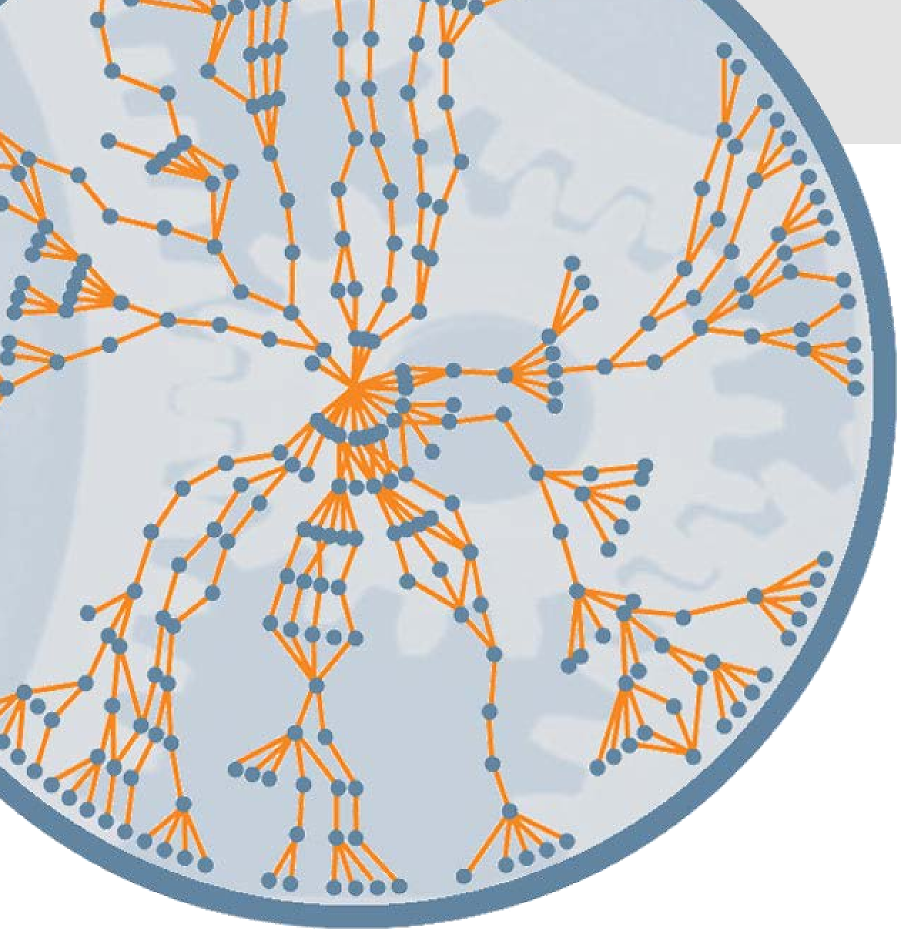
Bombardment of neutrons



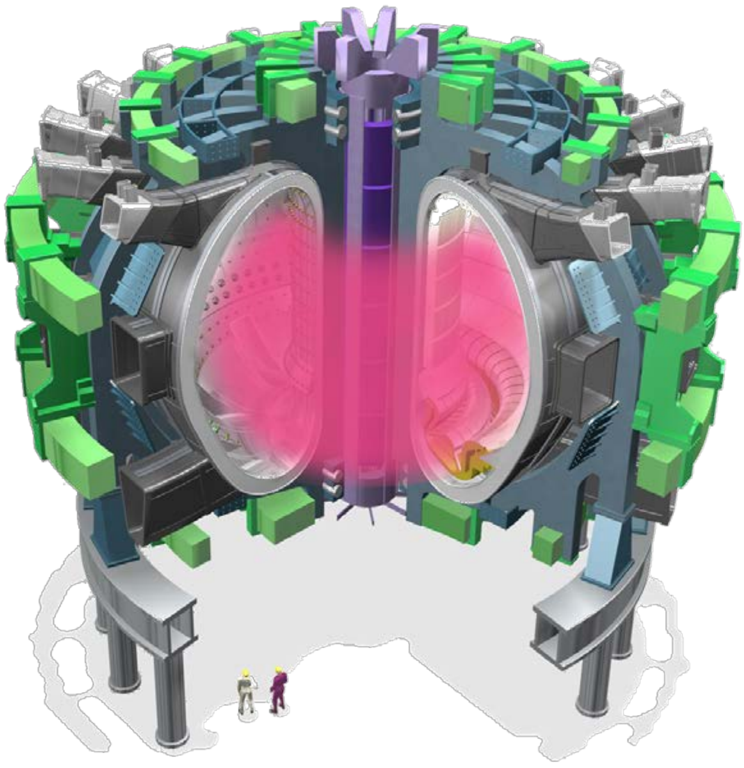


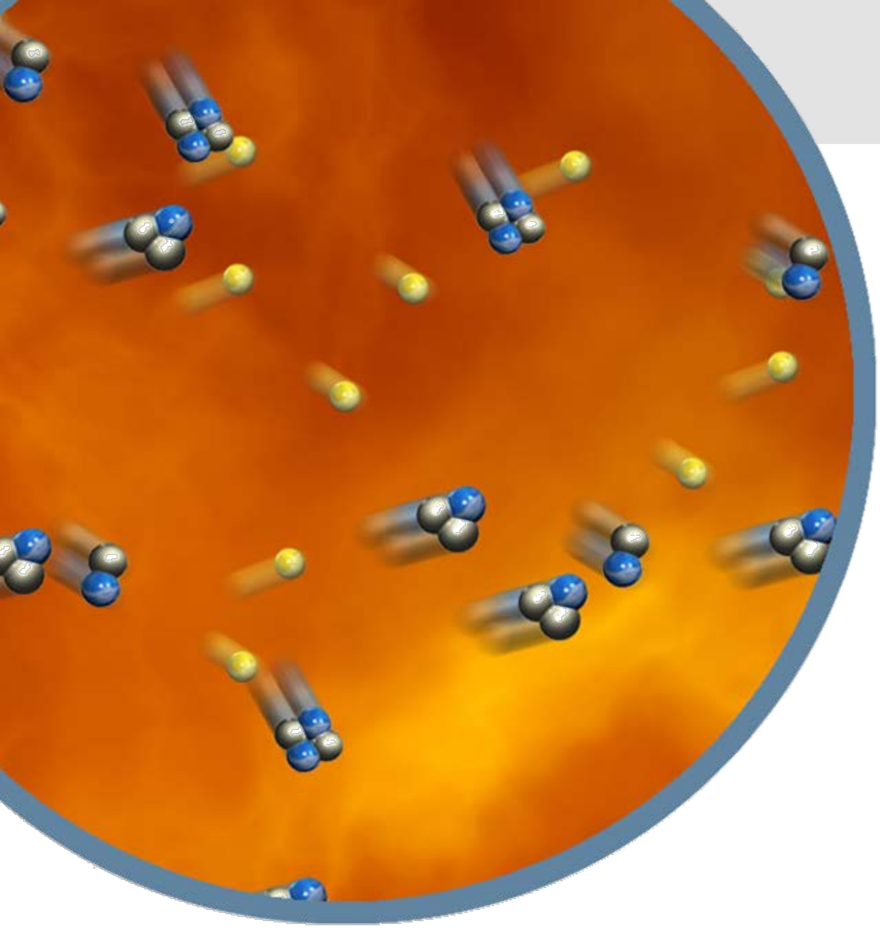
Fuel cycle
Tritium production

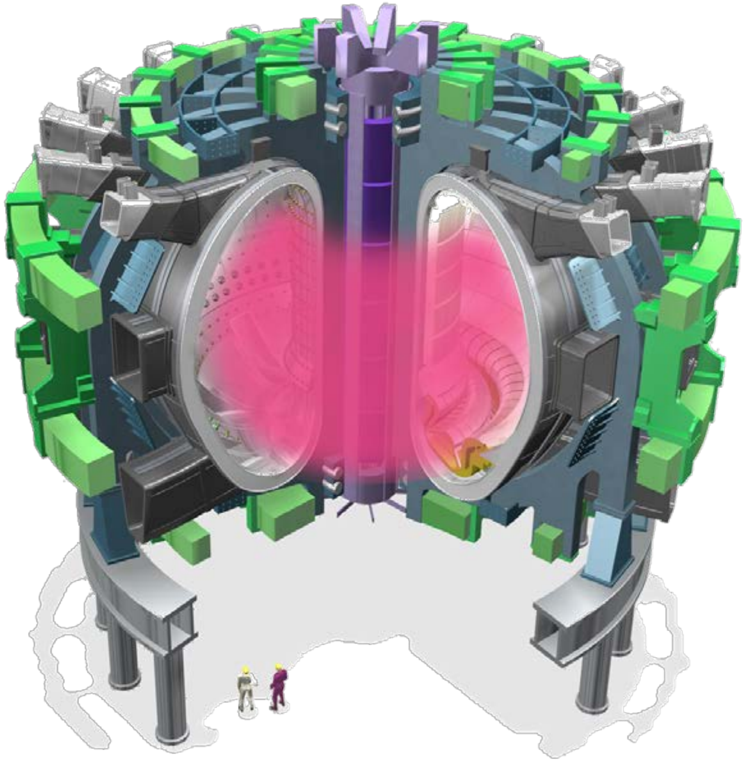




ITER: 34 countries
15.000.000 components



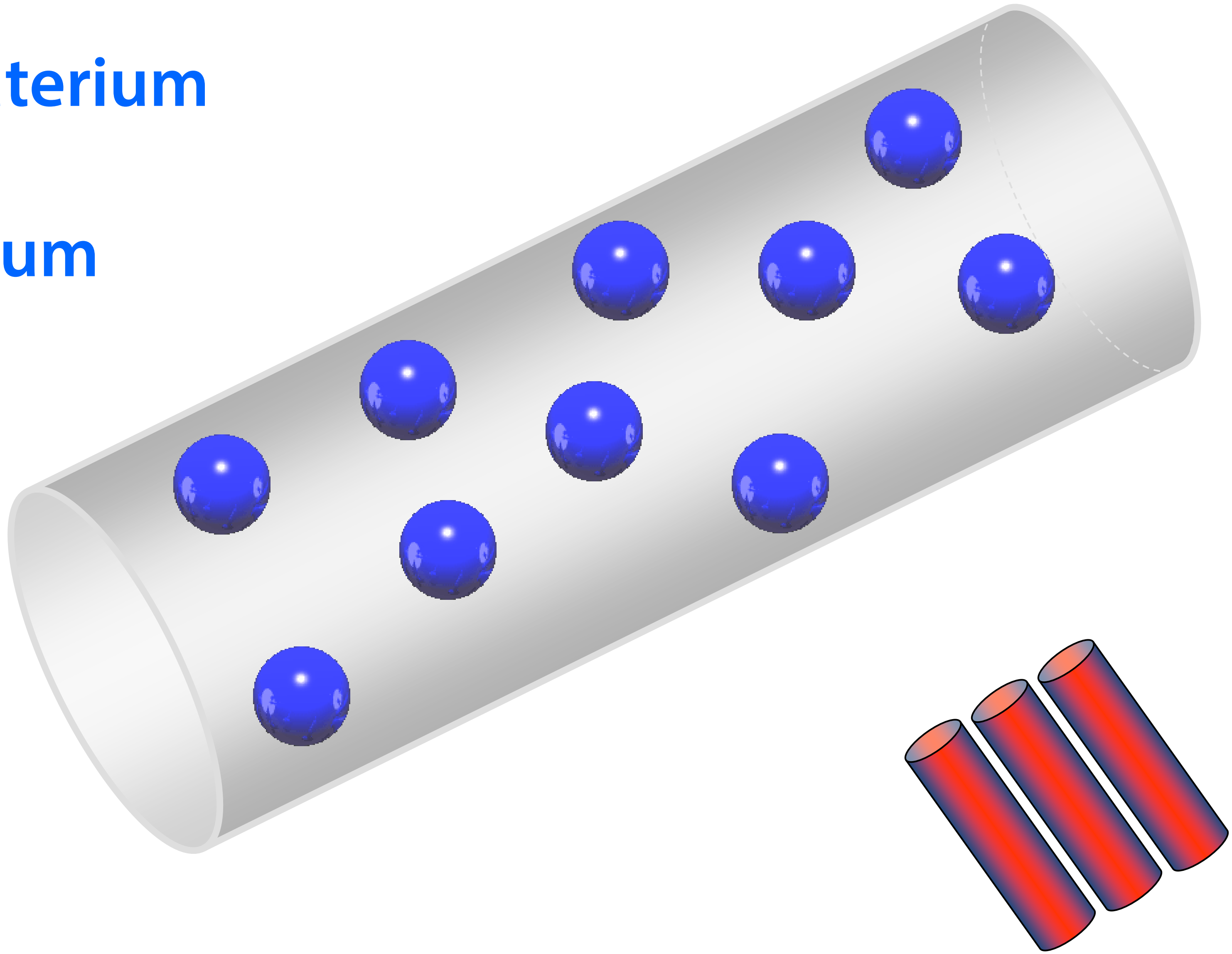




10× hotter than the sun

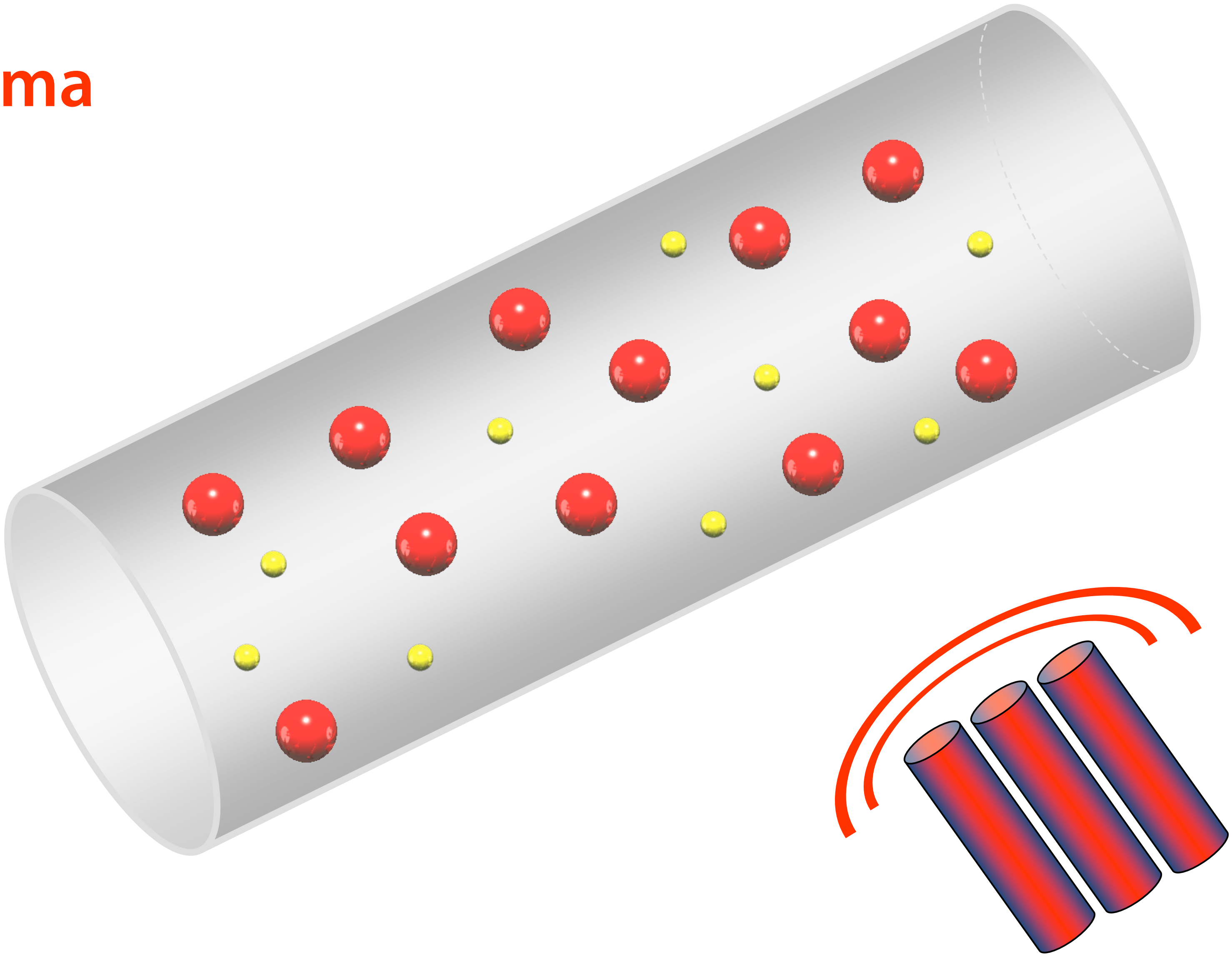
Making a plasma

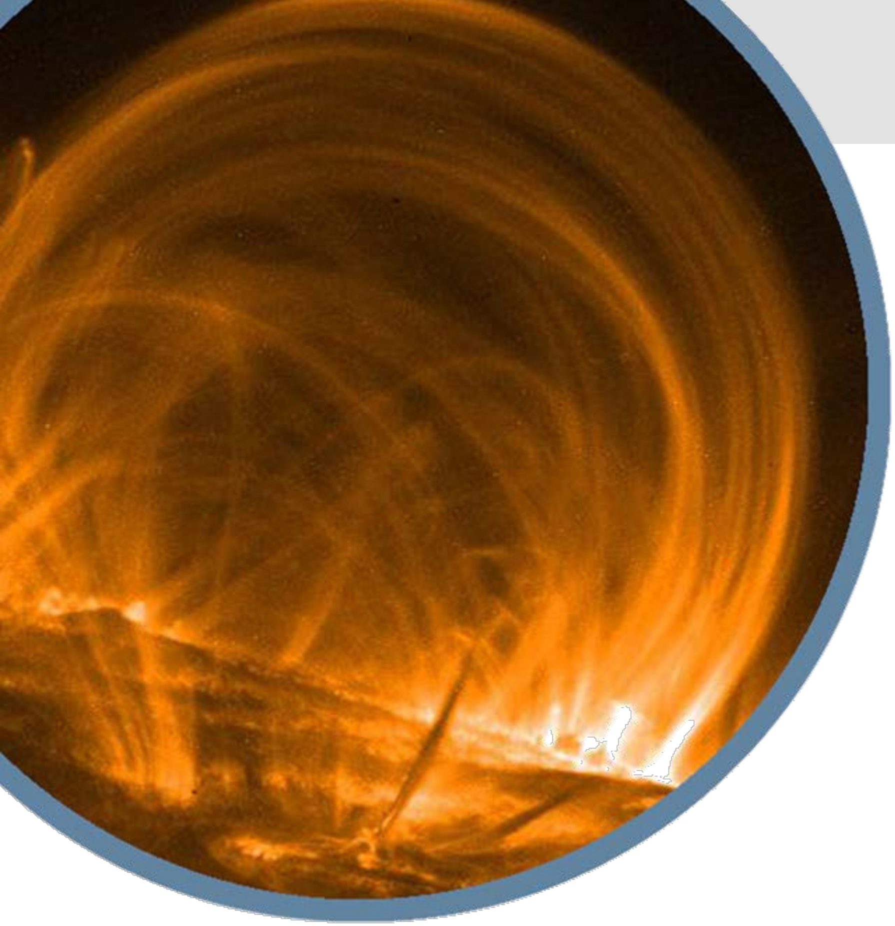
Deuterium
and
Tritium



Heating

Plasma





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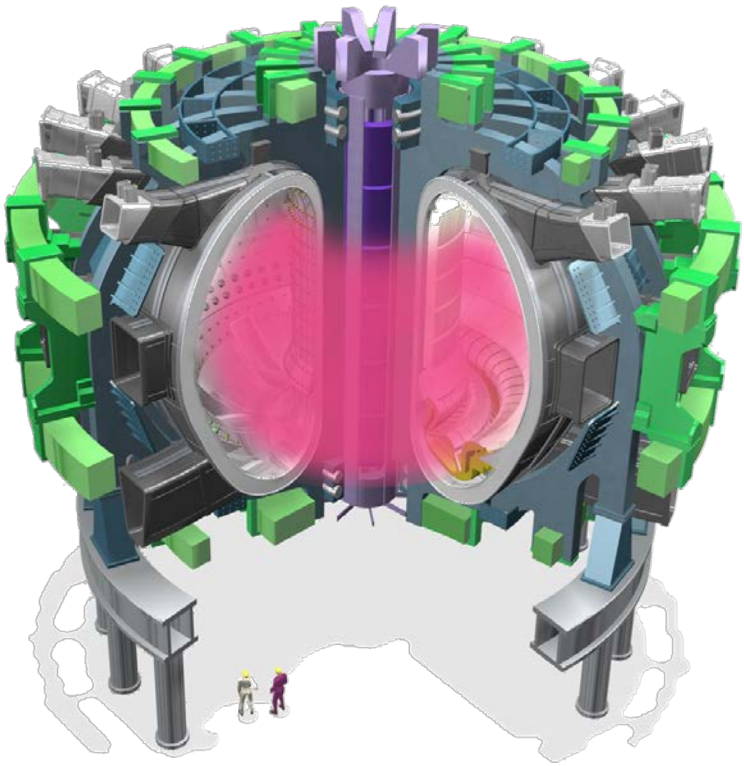
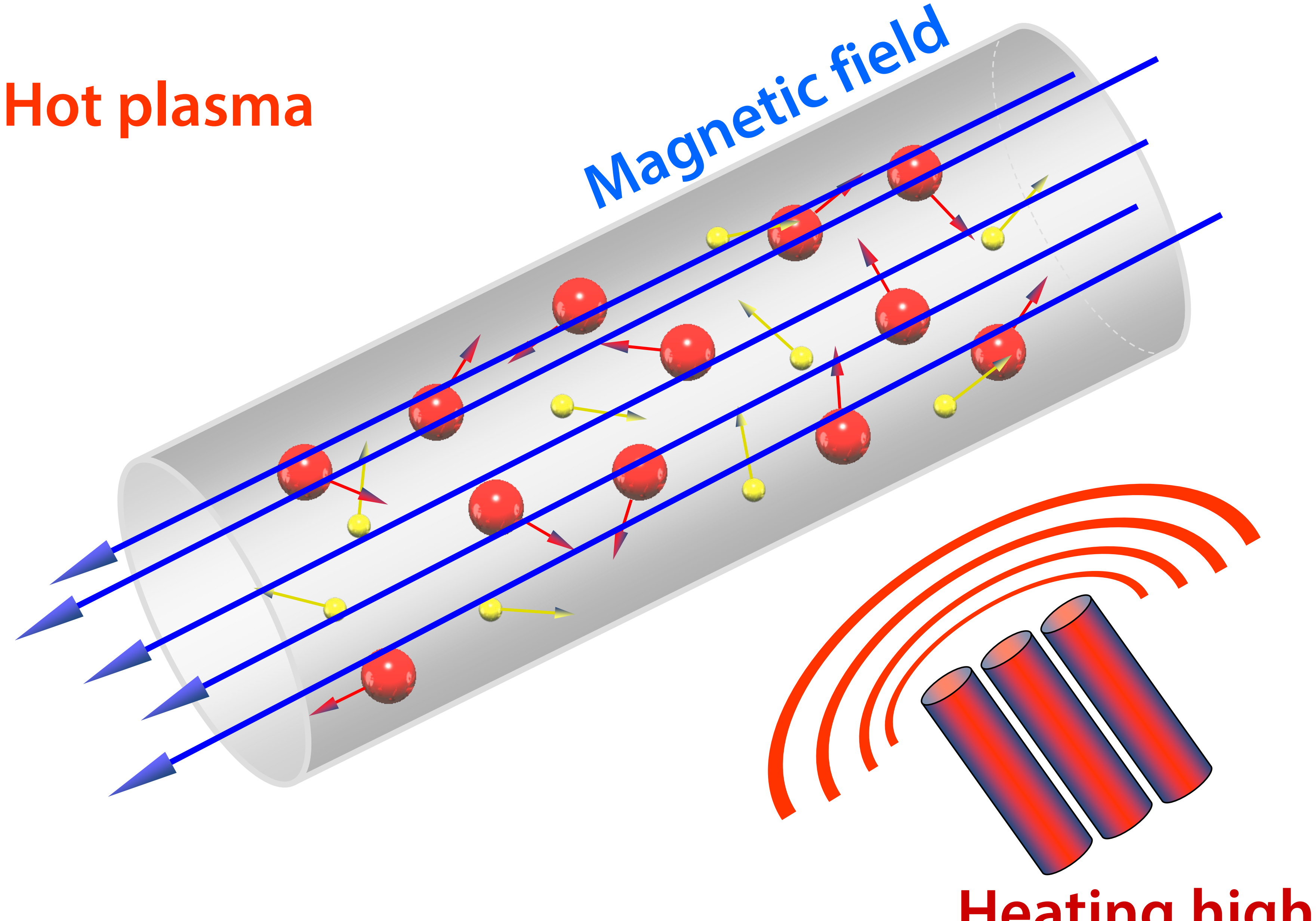
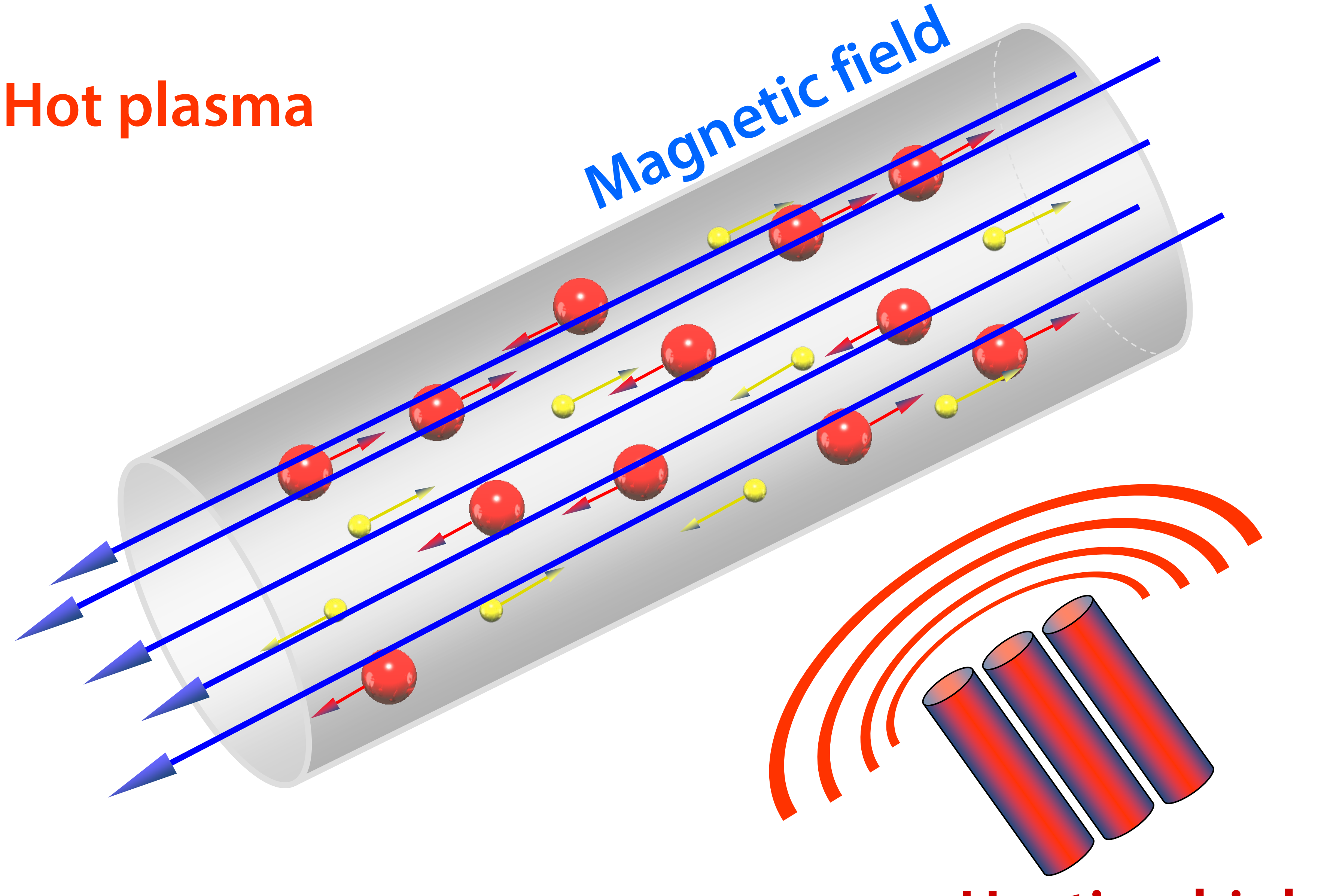


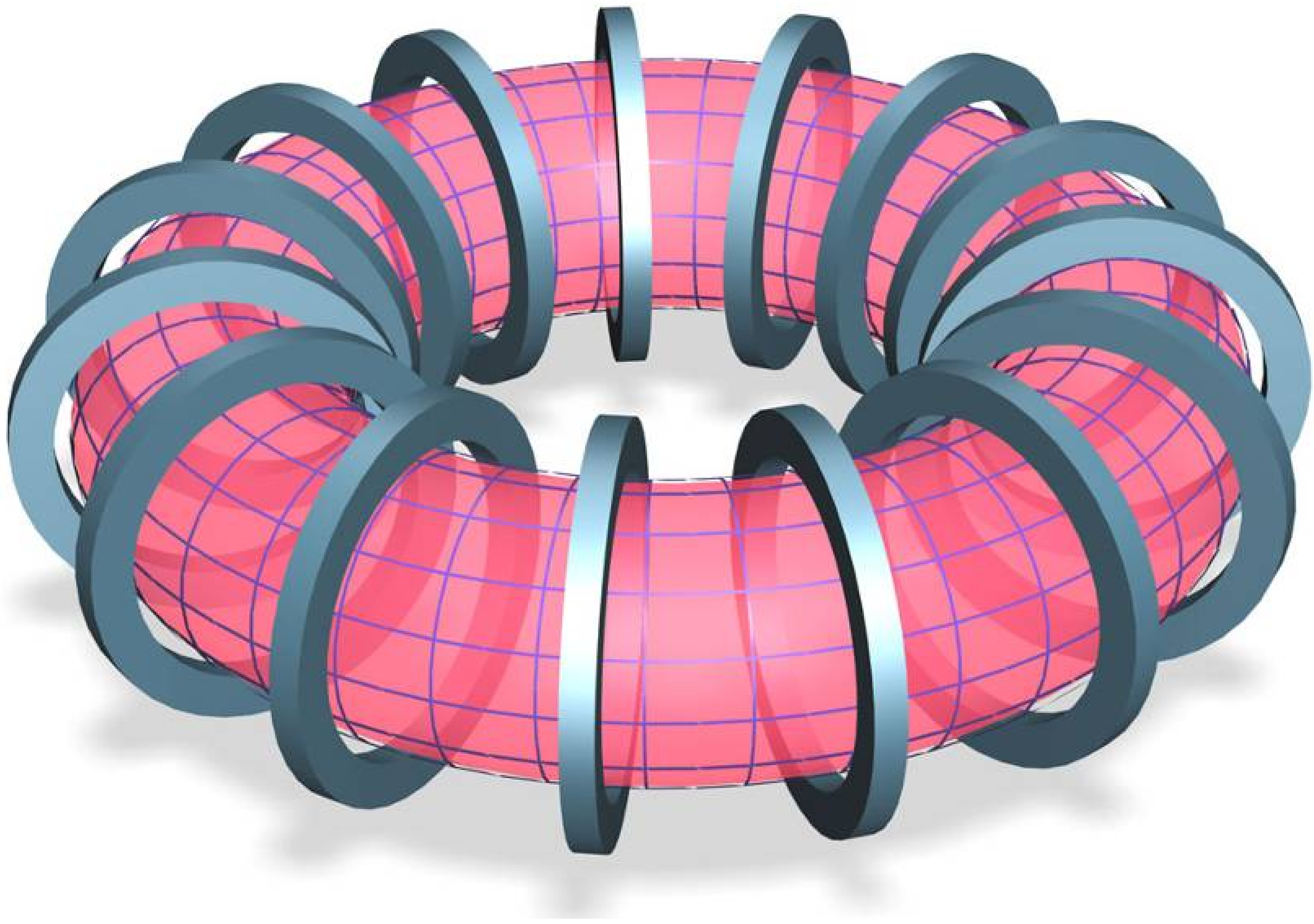
Confining a plasma



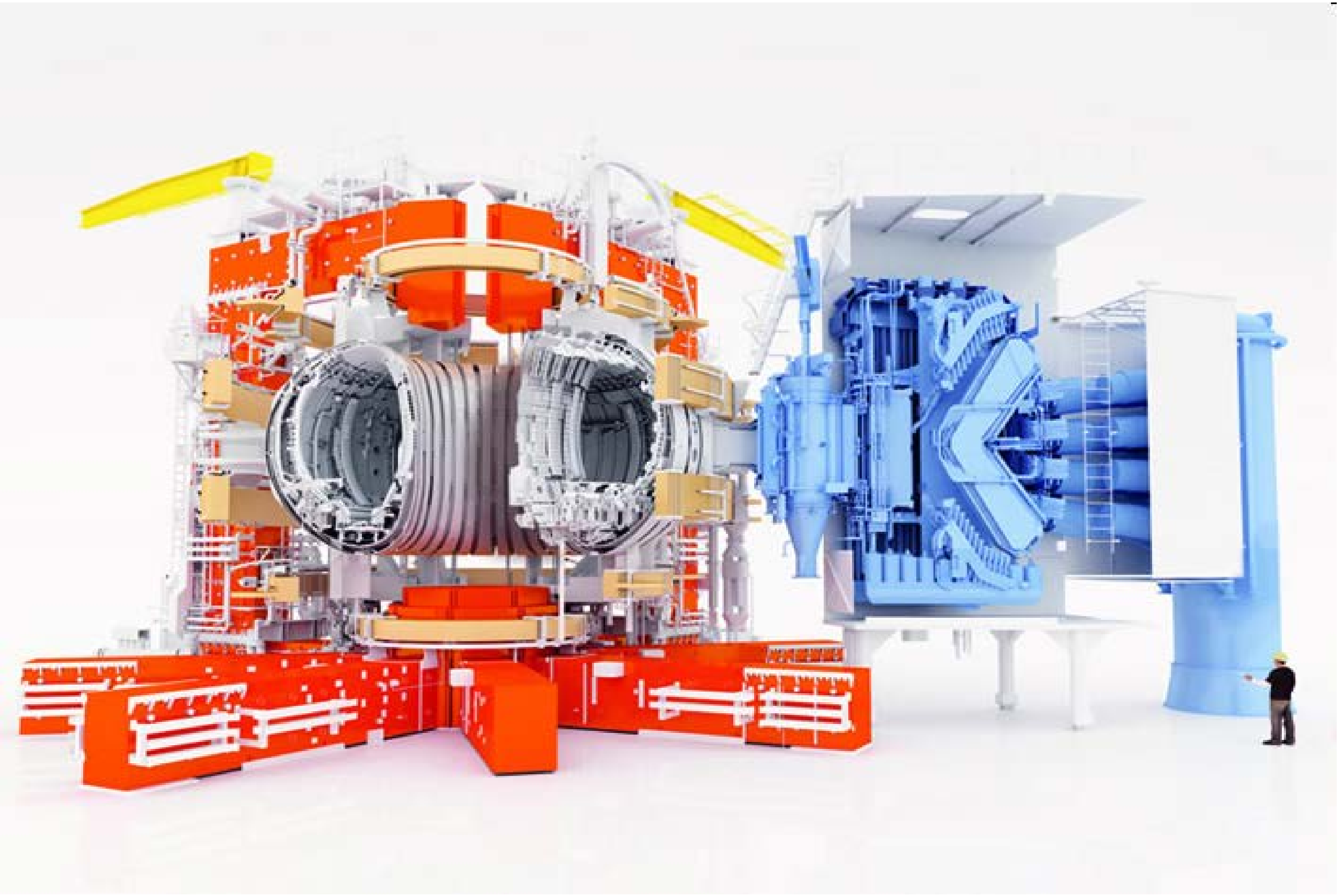
Confining a plasma



Best confinement in a torus

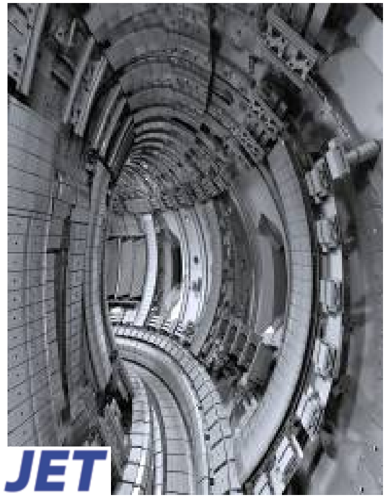


Plasma heating

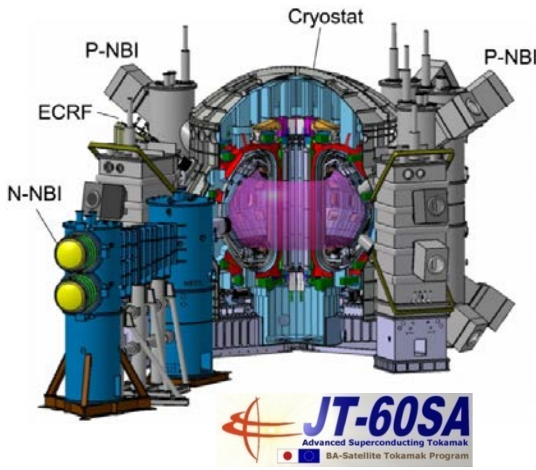


JET

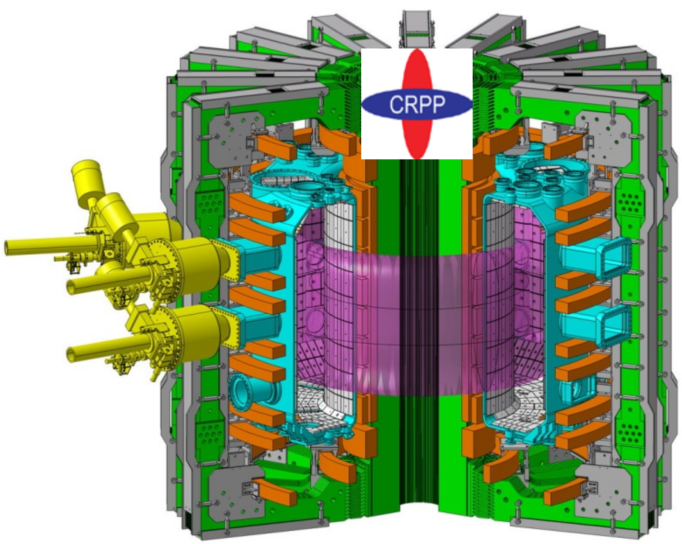
JET and Medium-Size Tokamaks (missions 1 & 2)



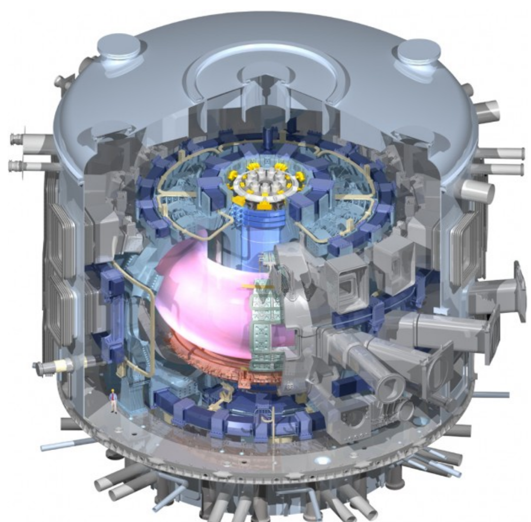
JET



AUG



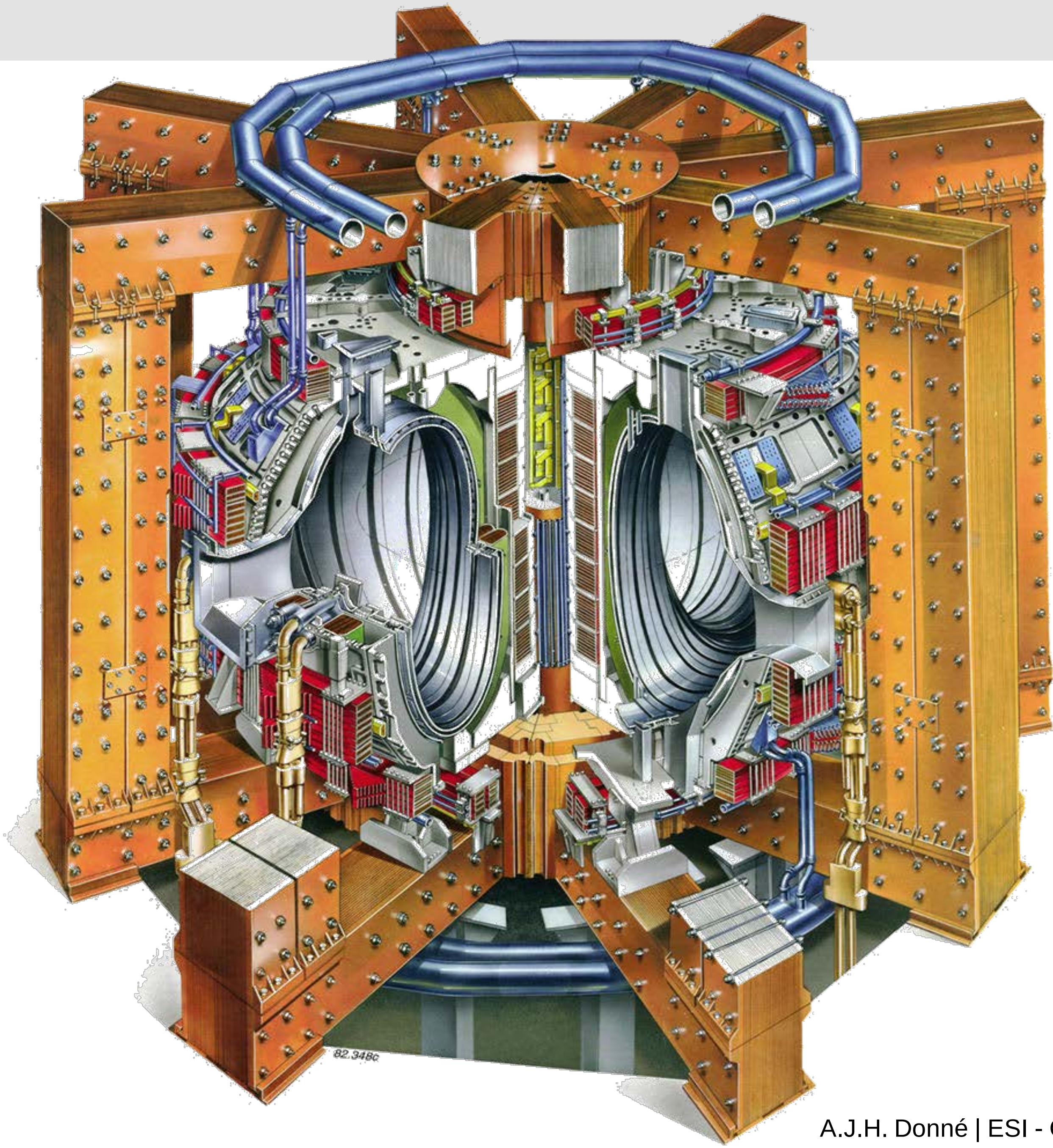
TCV



ITER

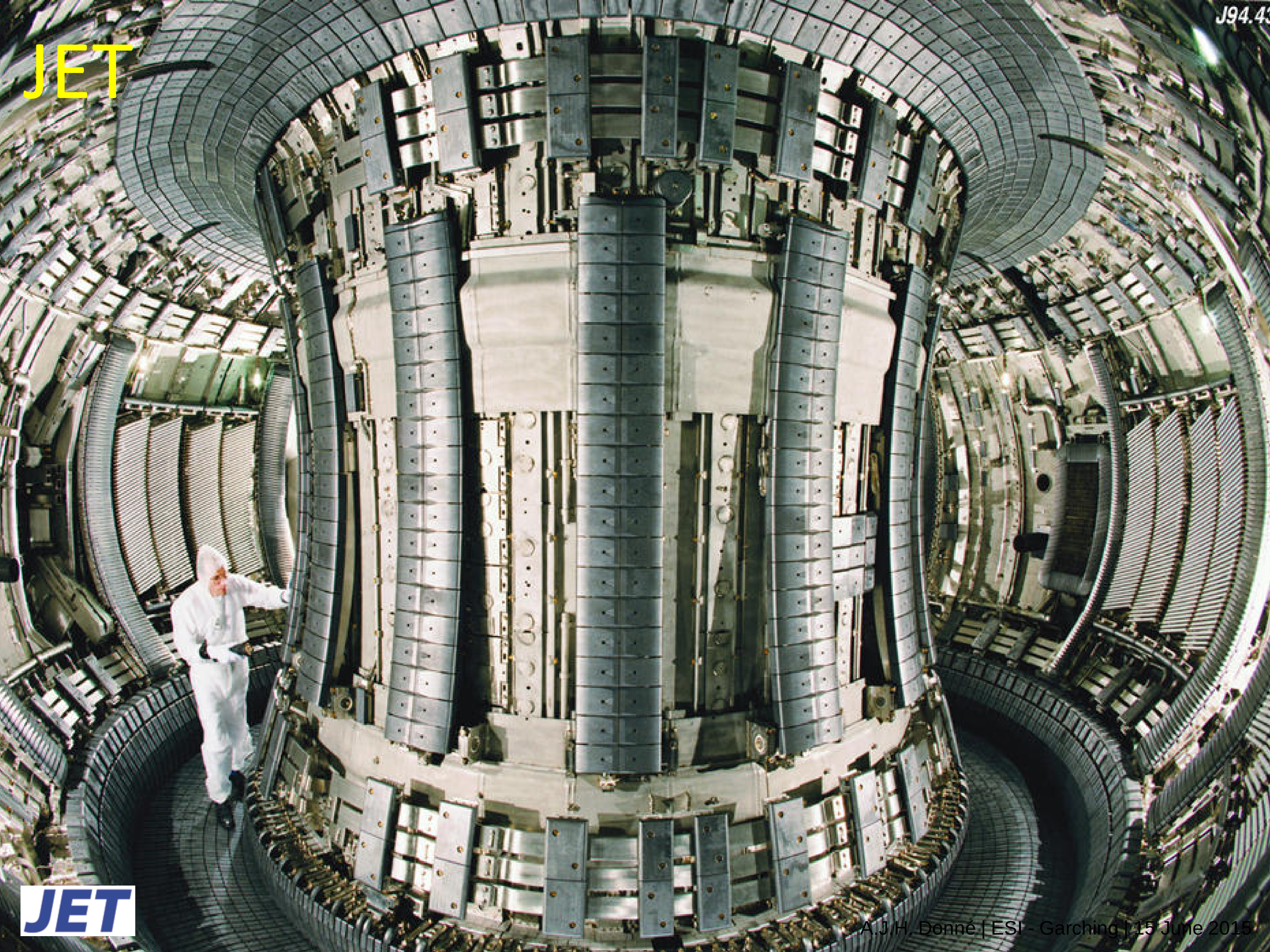
MAST Upgrade

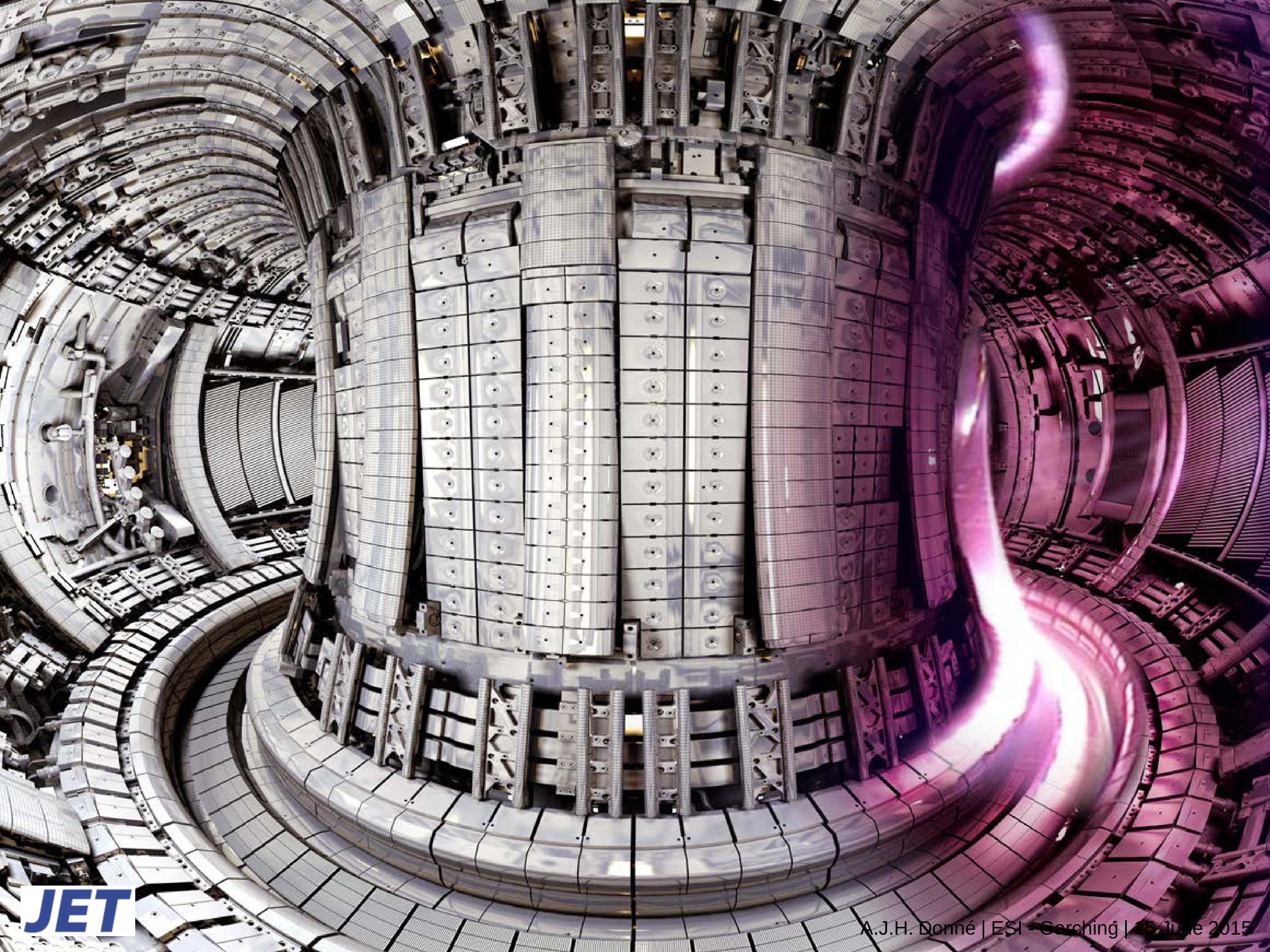
JET



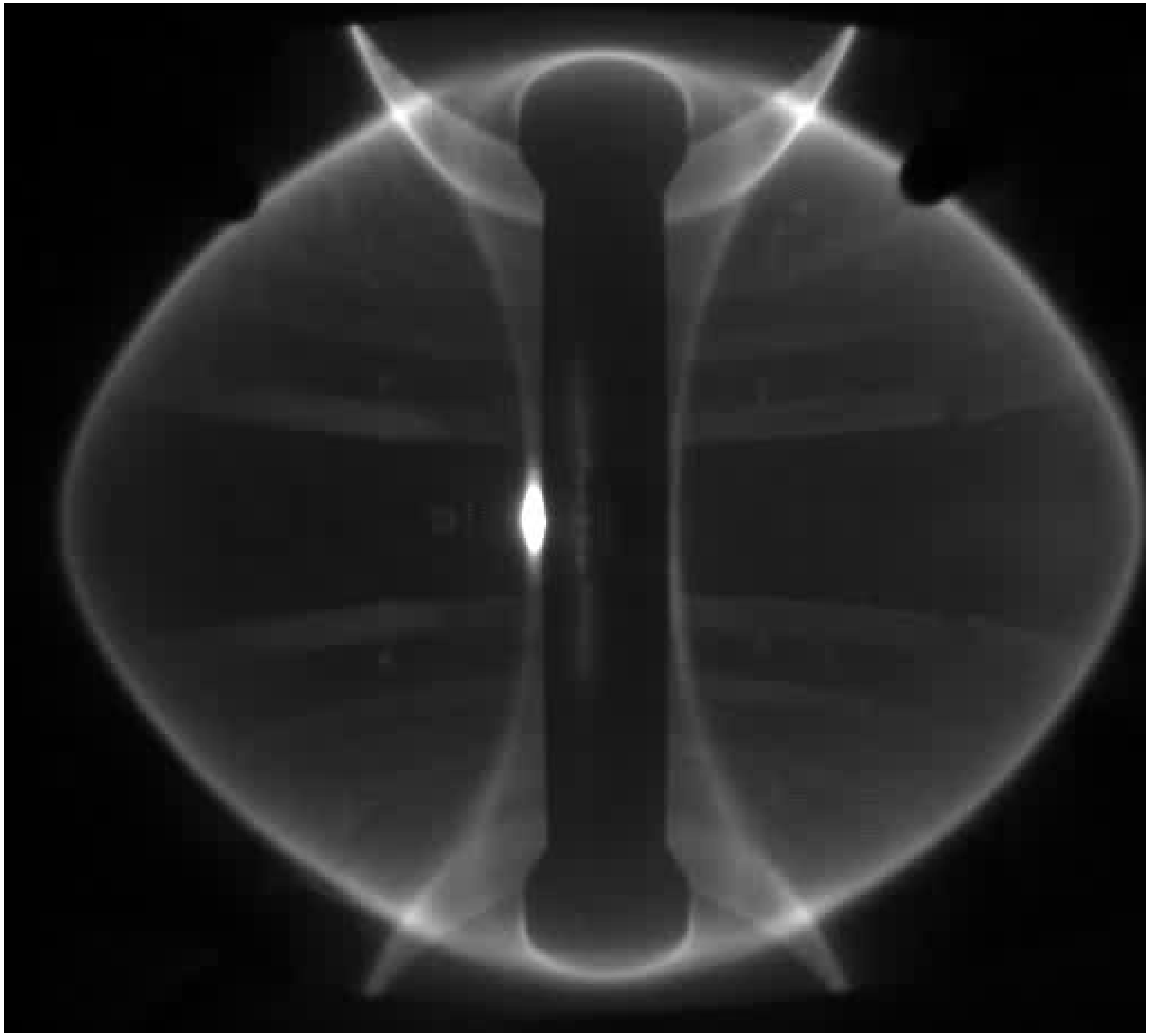
JET

JET



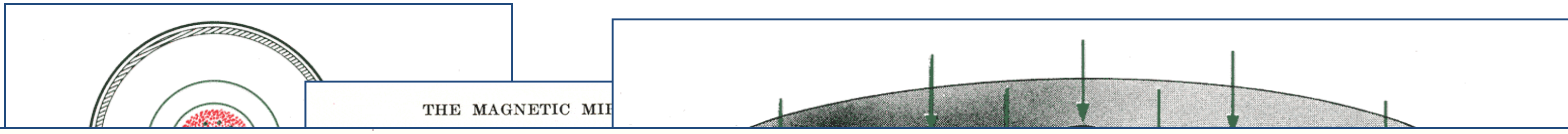


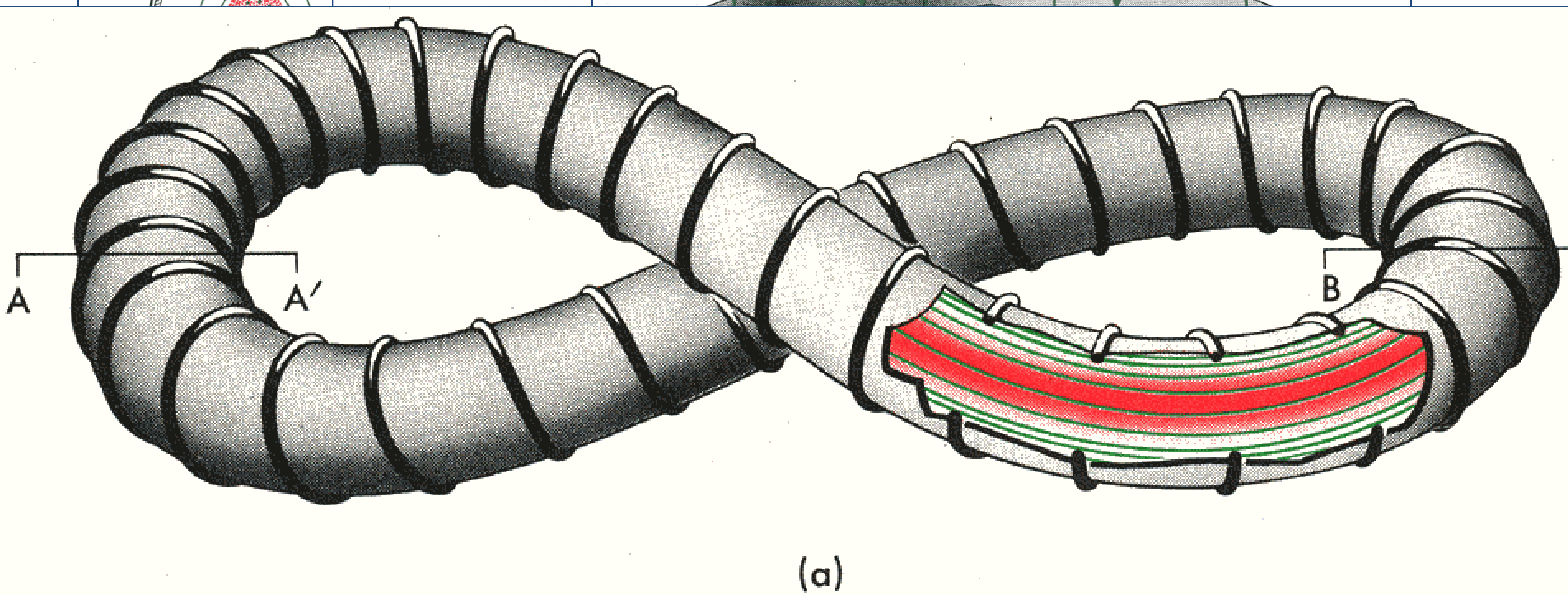
MAST (Culham, UK)

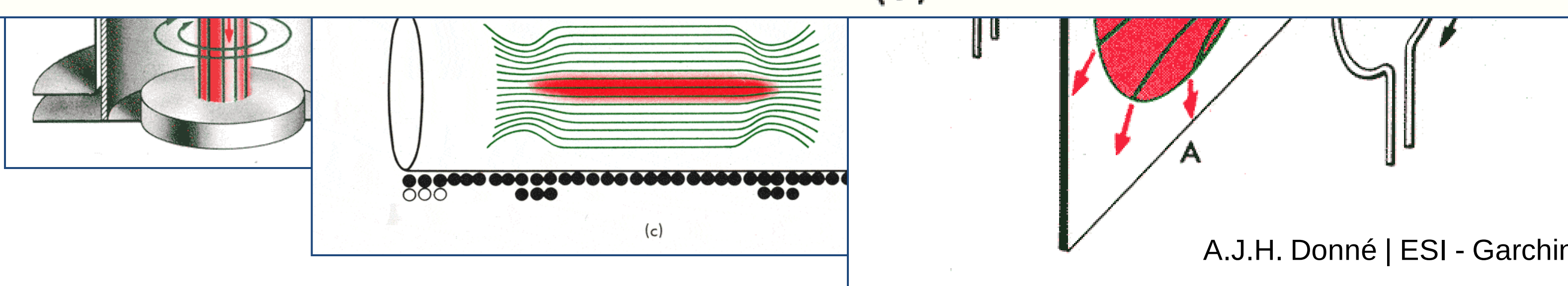


CCFE
CULHAM CENTRE FOR FUSION ENERGY

1960 1970 1980 1990 2000

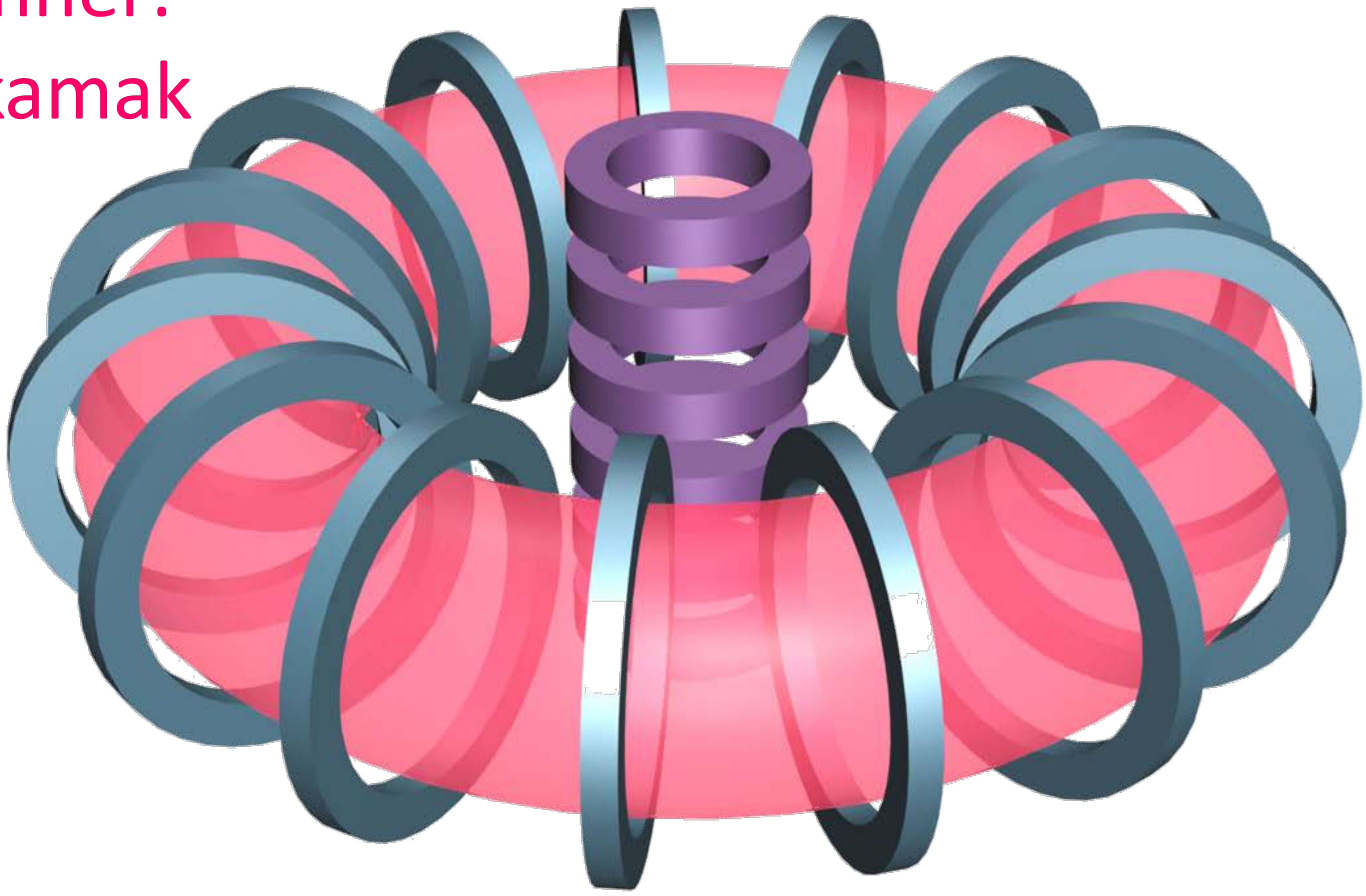






1960 1970 1980 1990 2000

The winner: the tokamak



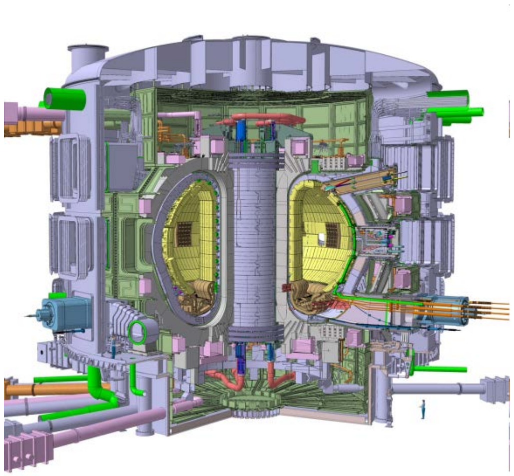
тороидальная **ка**мера с **ма**гнитными **к**атушками"
(***to**roidal'naya **ka**mera s **ma**gnitnymi **k**atushkami*)

Concept improvement continues

1960 1970 1980 1990 2000

Spherical Tokamak
(MAST, UK)

Progress in fusion

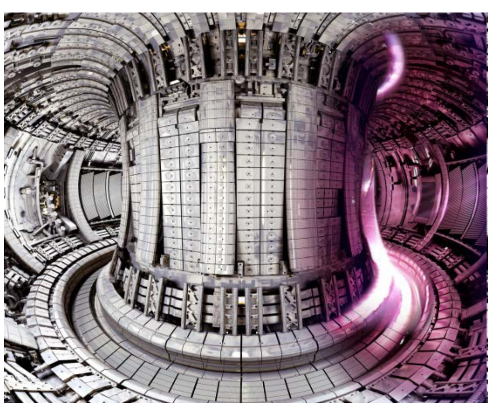


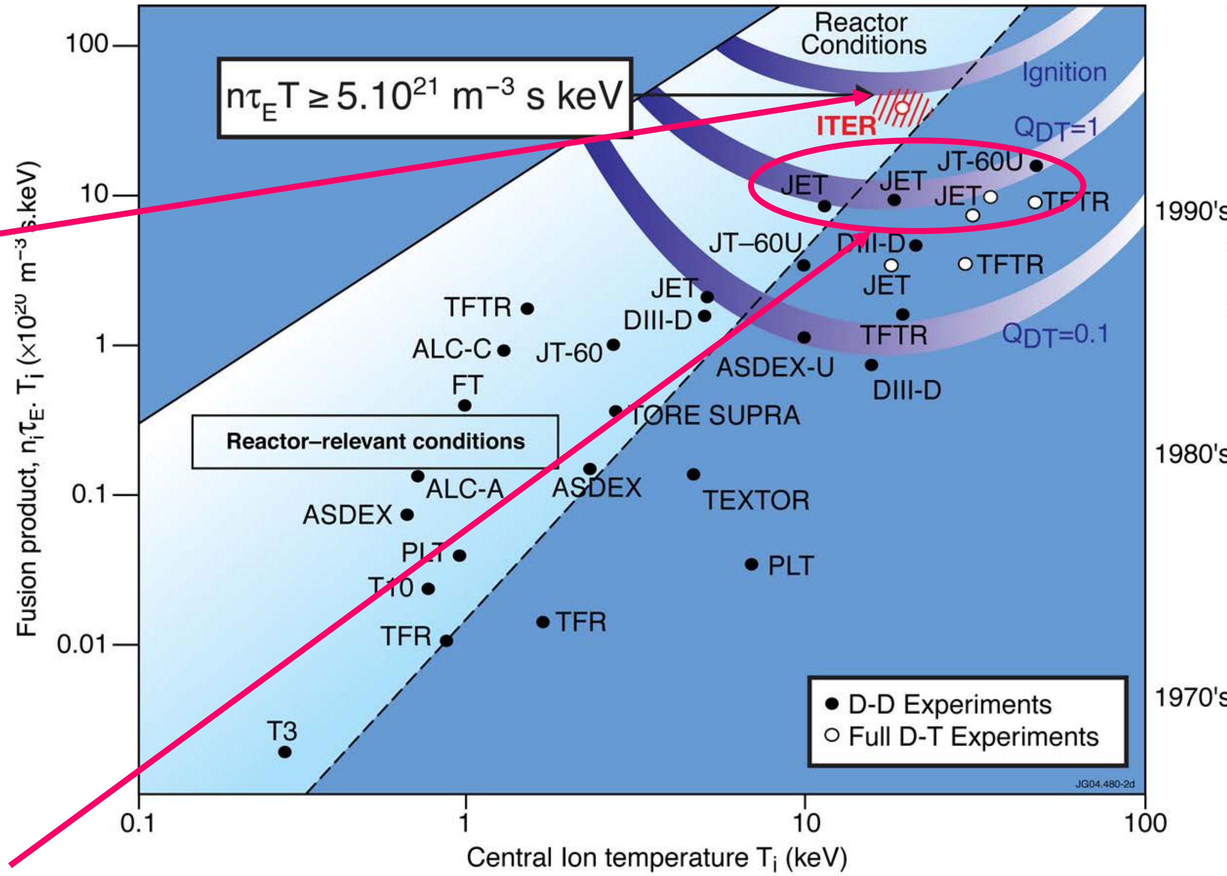
ITER

Nett power gain:

$P_{fusion} = 10 \times P_{in}$

Demonstration of technical principles



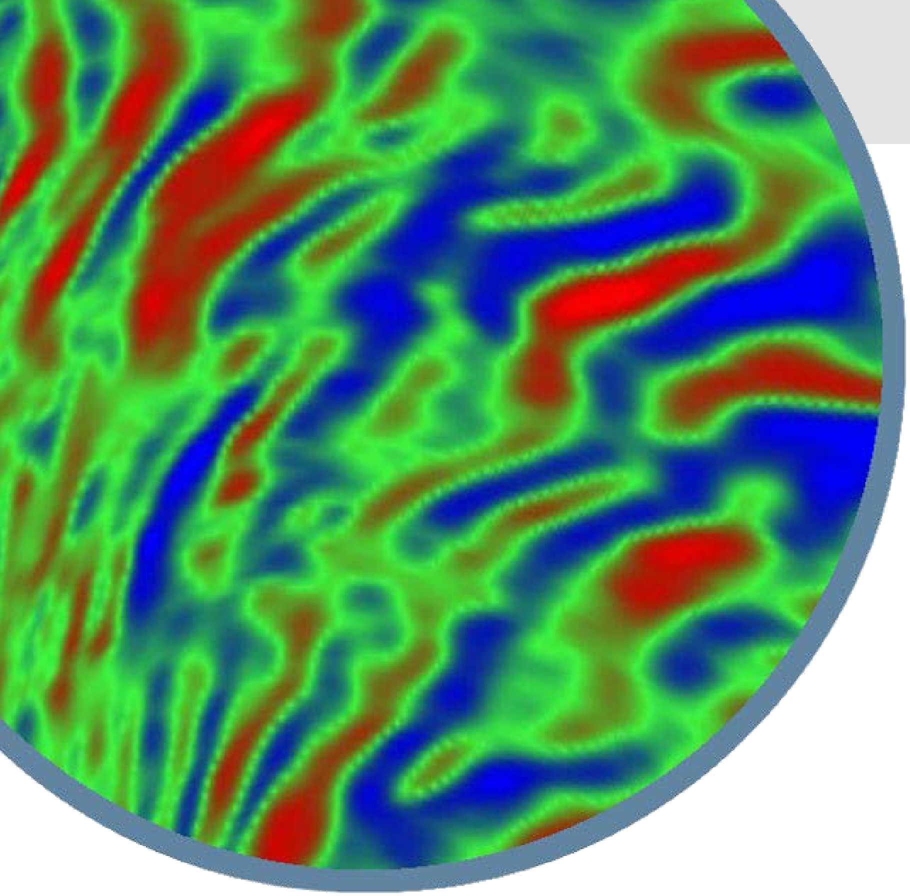


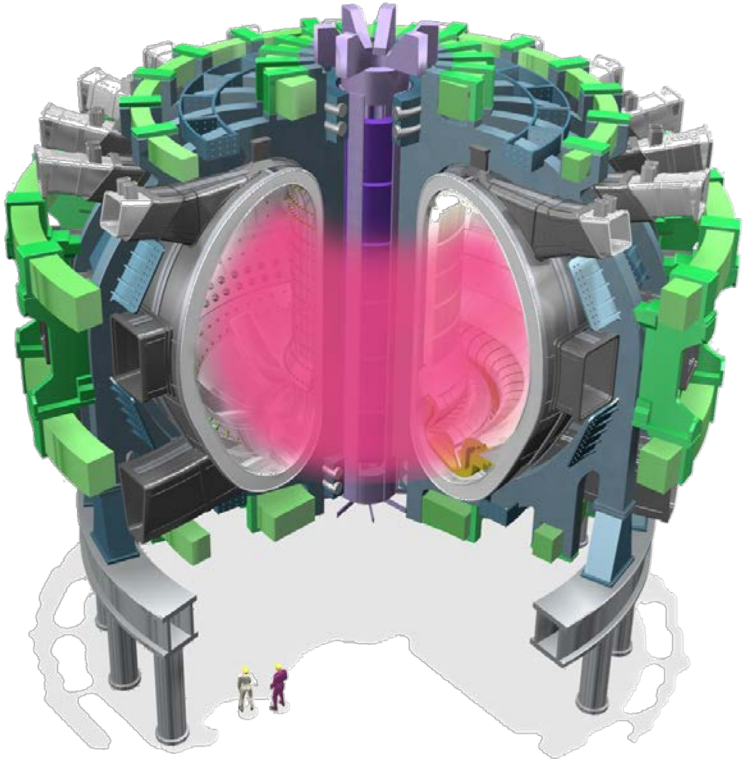
JET (and other machines)

Break-even:

$P_{fusion} = P_{in}$

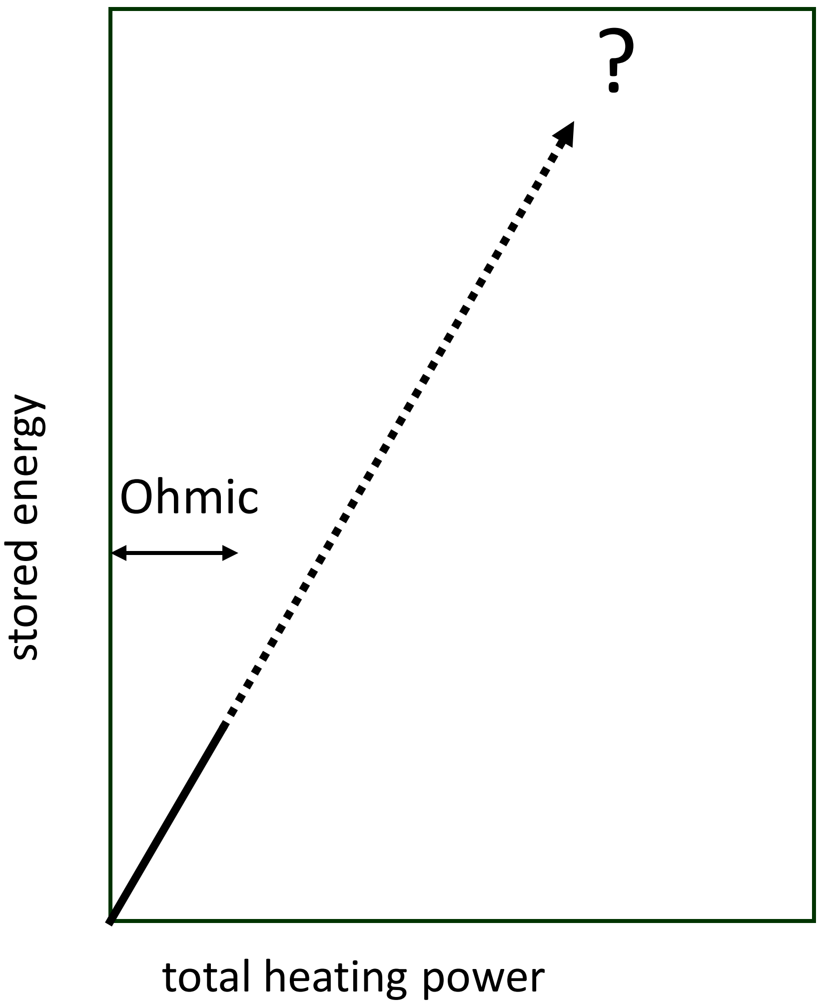
Emphasis on understanding the science

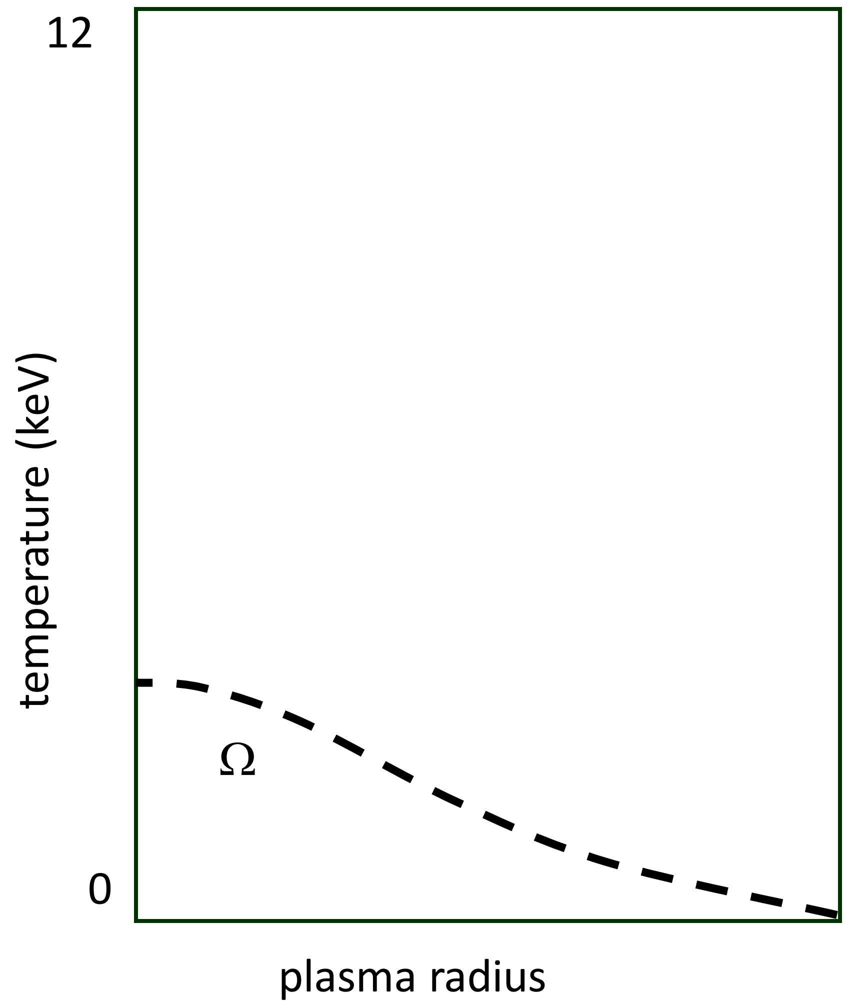




Thermal insulation: nearly perfect

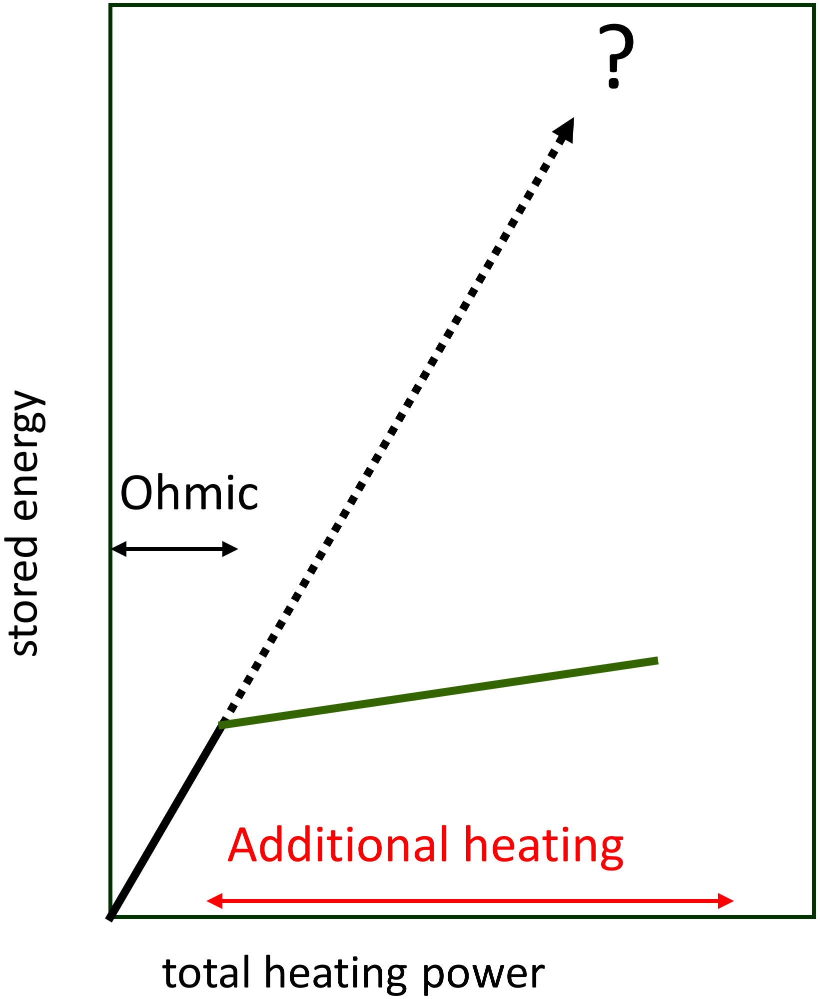
Ohmic heating: power coupled to confining magnetic field

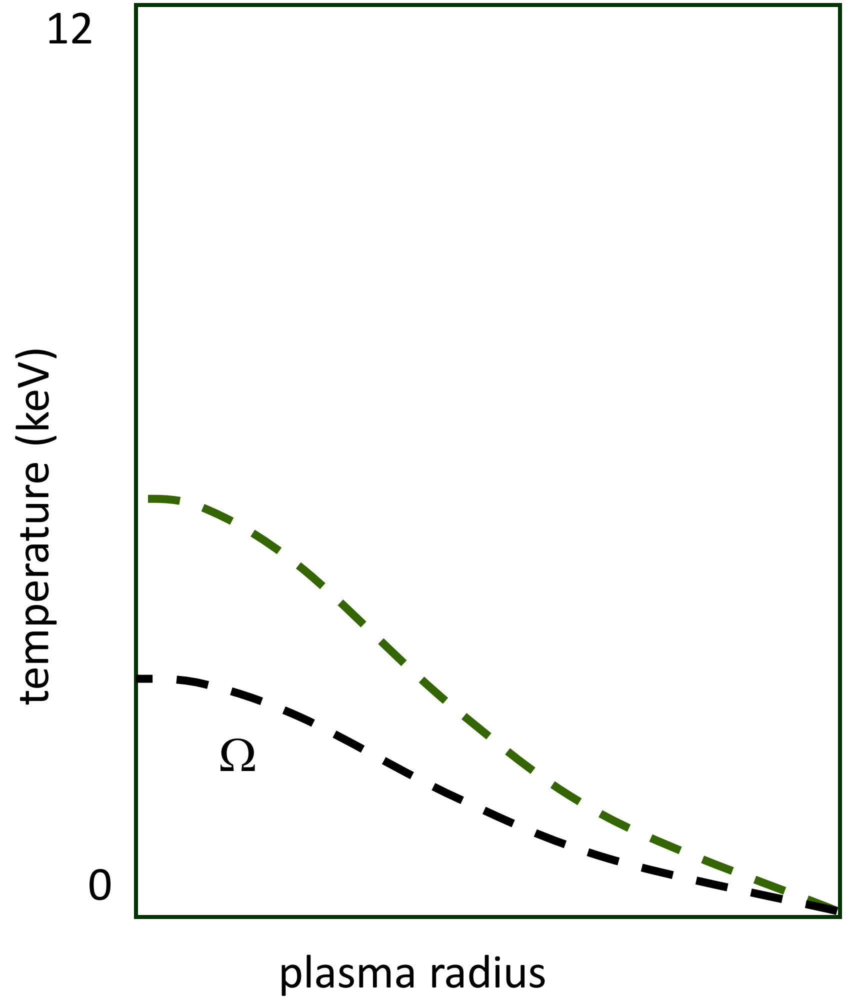




1960 1970 1980 1990 2000

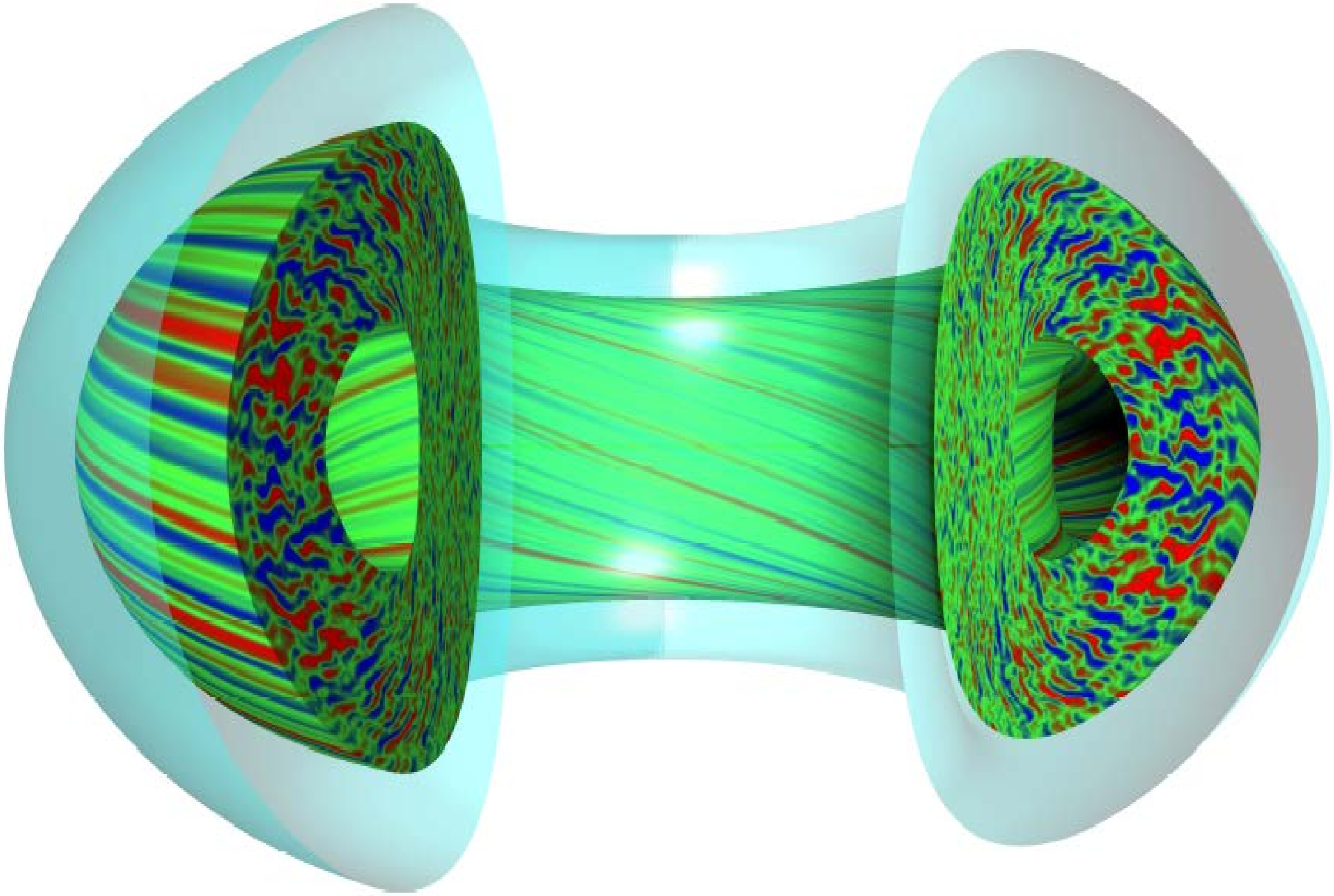
Additional heating: decouple heating & confining B-field



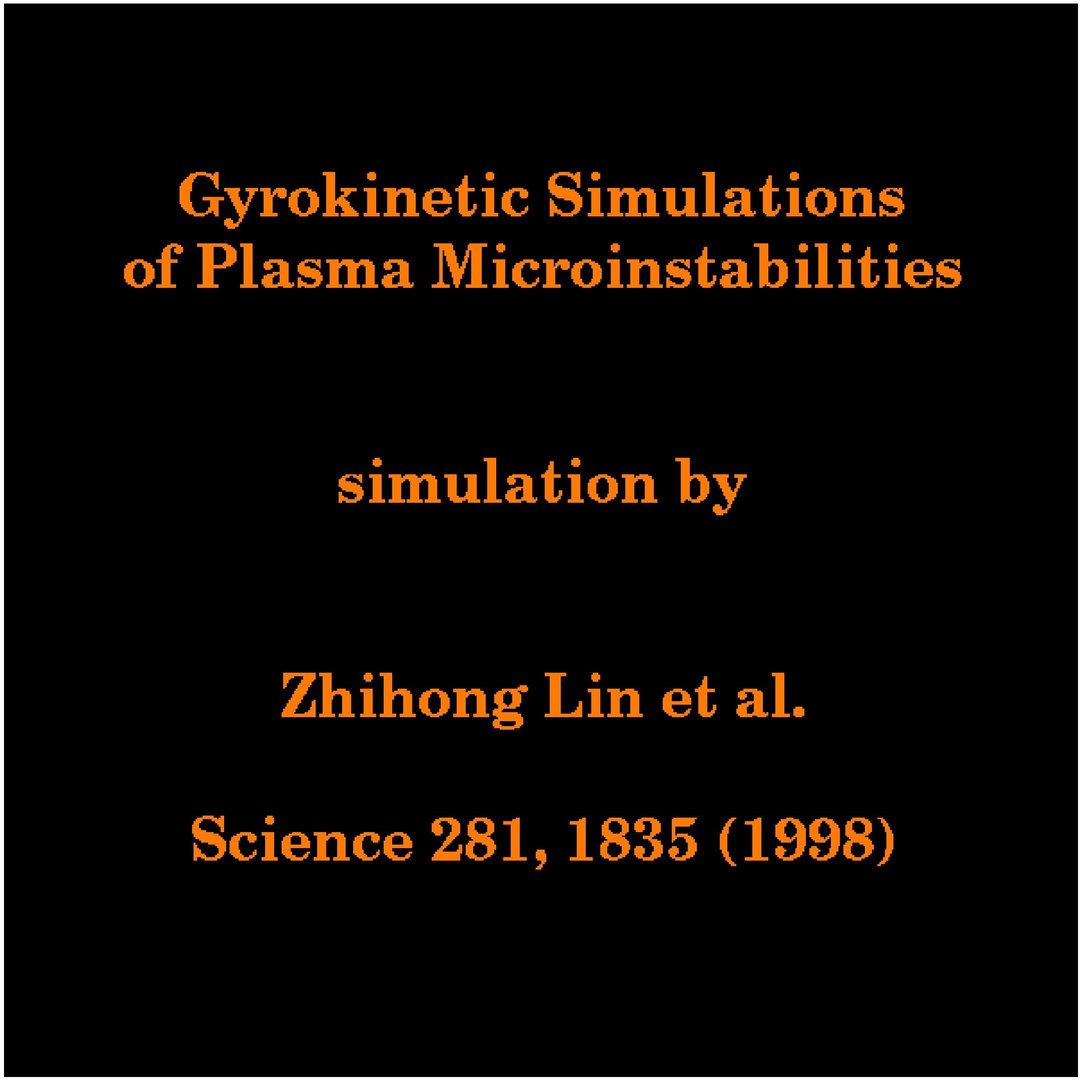


Gyro code; Jeff Candy

http://fusion.gat.com/comp/parallel/figures/supertorus-hi-2.jpg



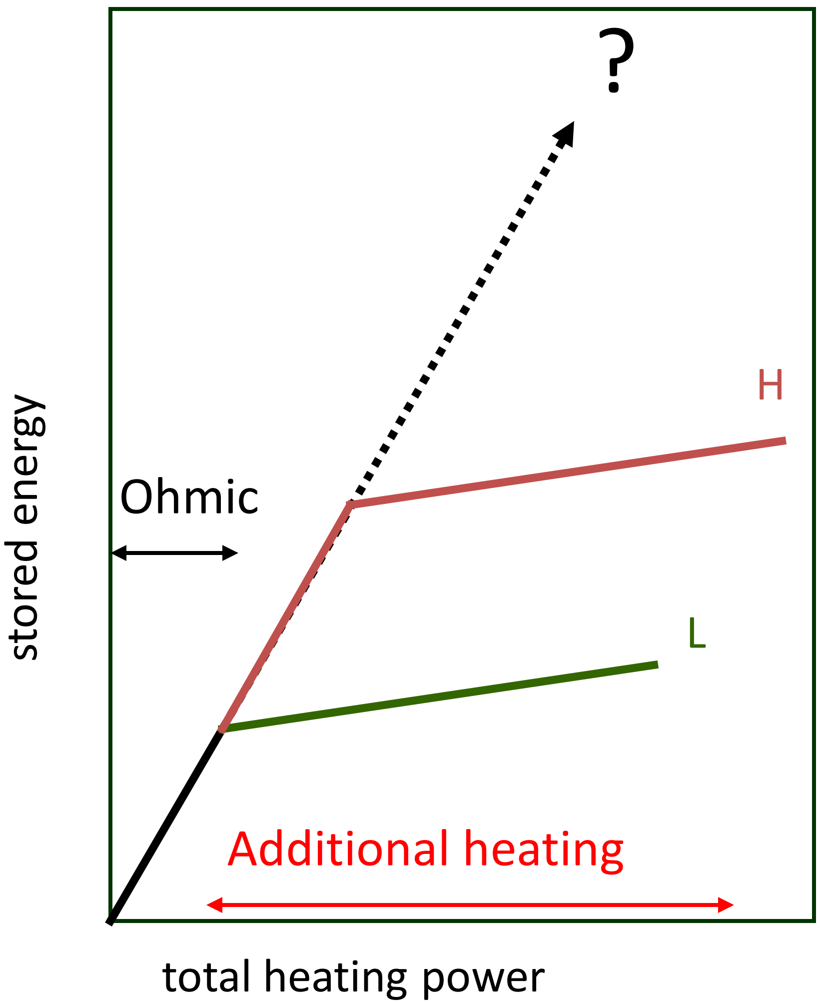
Hot plasmas have a rich structure

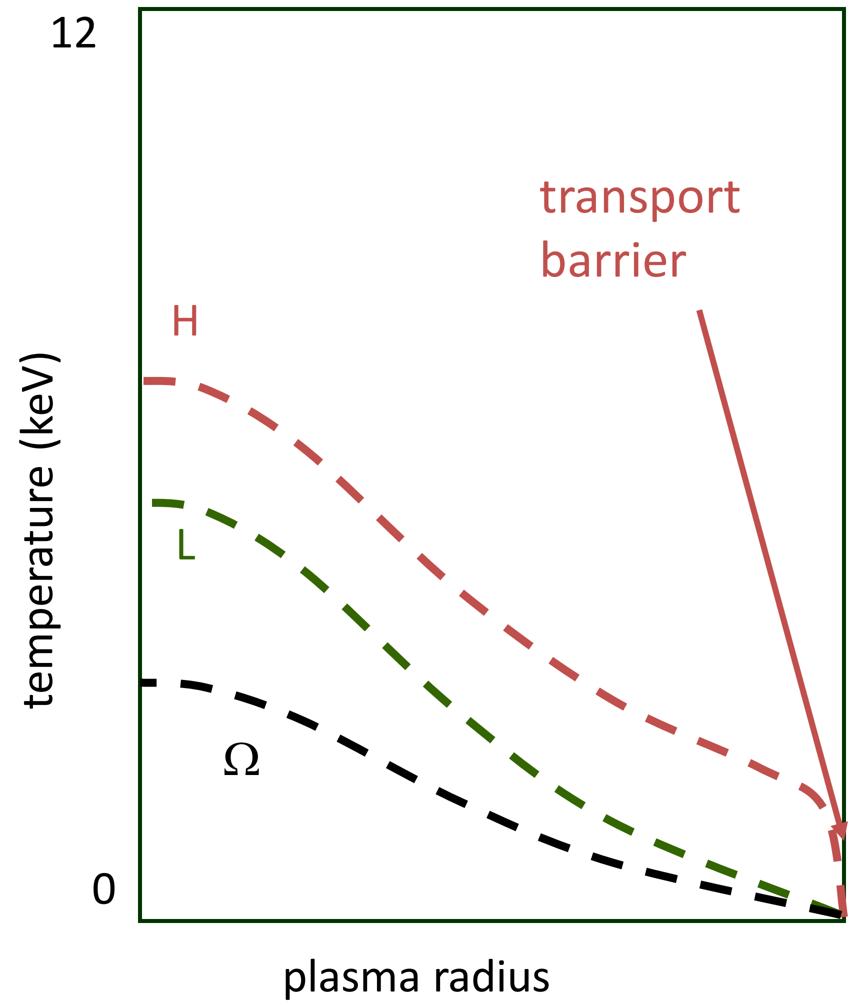


Fluctuations lead to reduced performance

1960 1970 1980 1990 2000

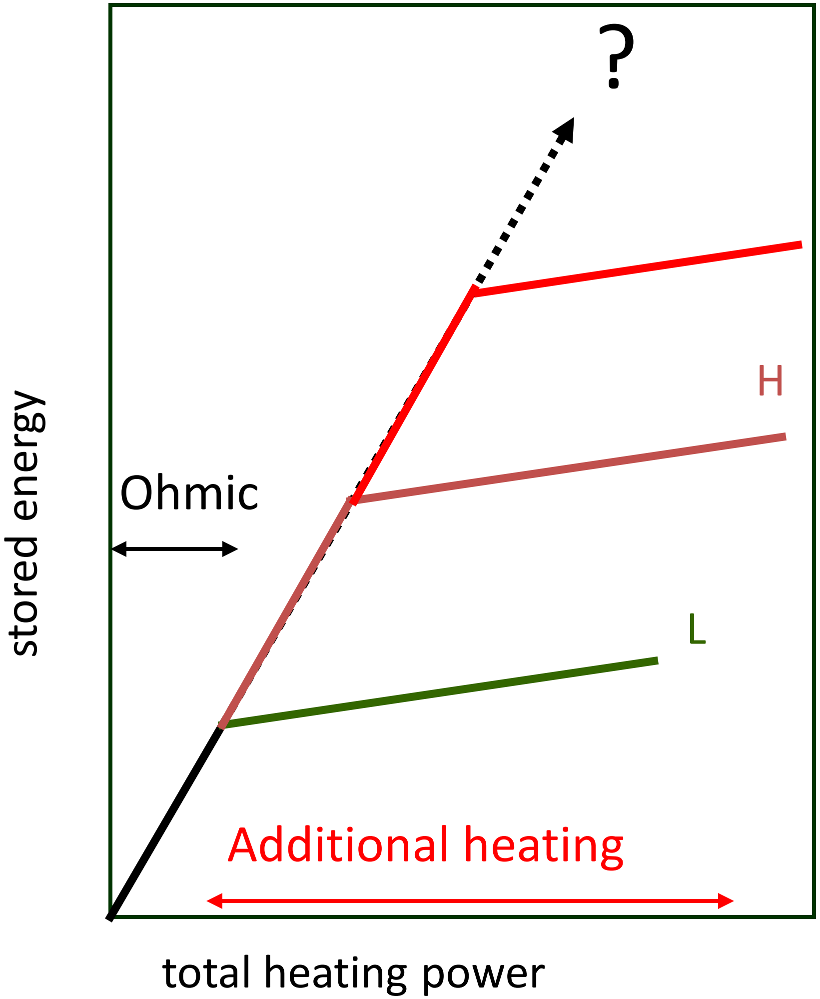
1982 ASDEX: discovery of high confinement mode (F. Wagner)

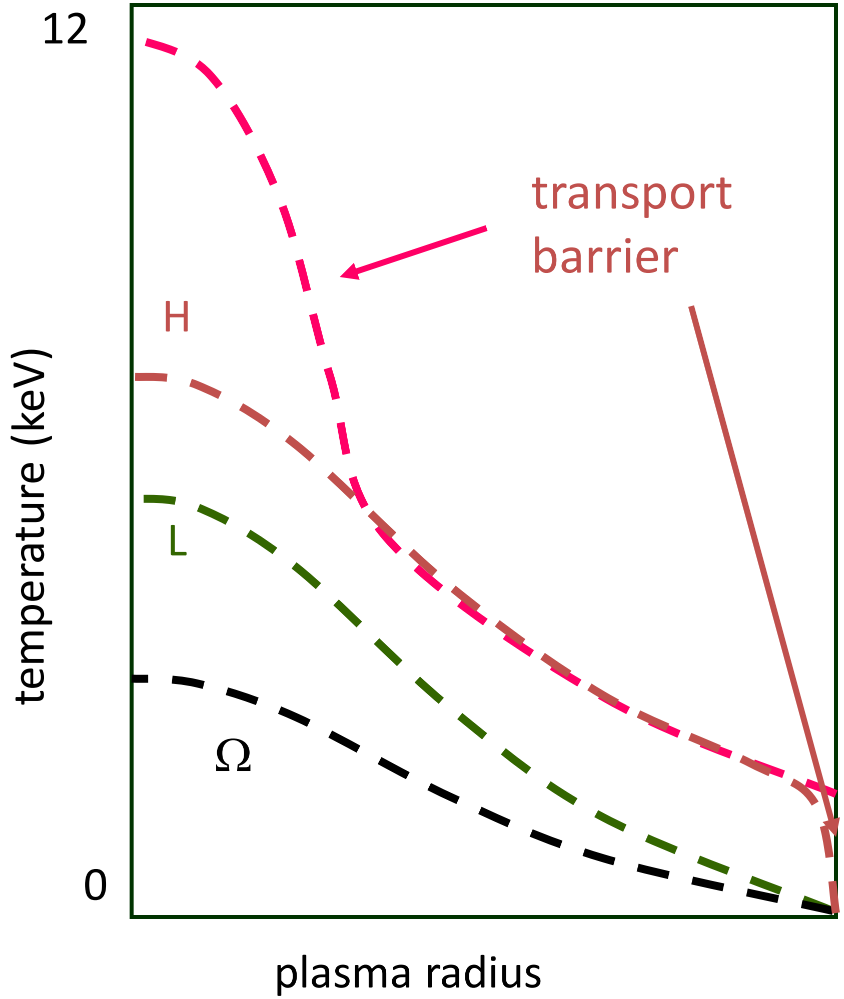




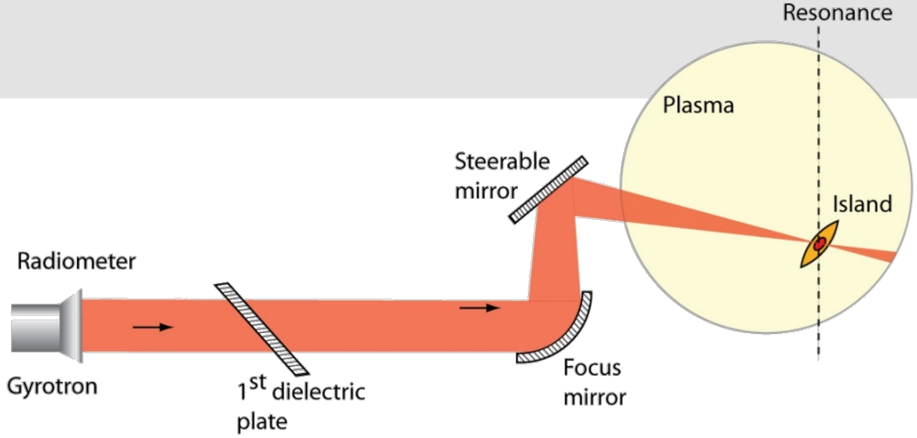
1960 1970 1980 1990 2000

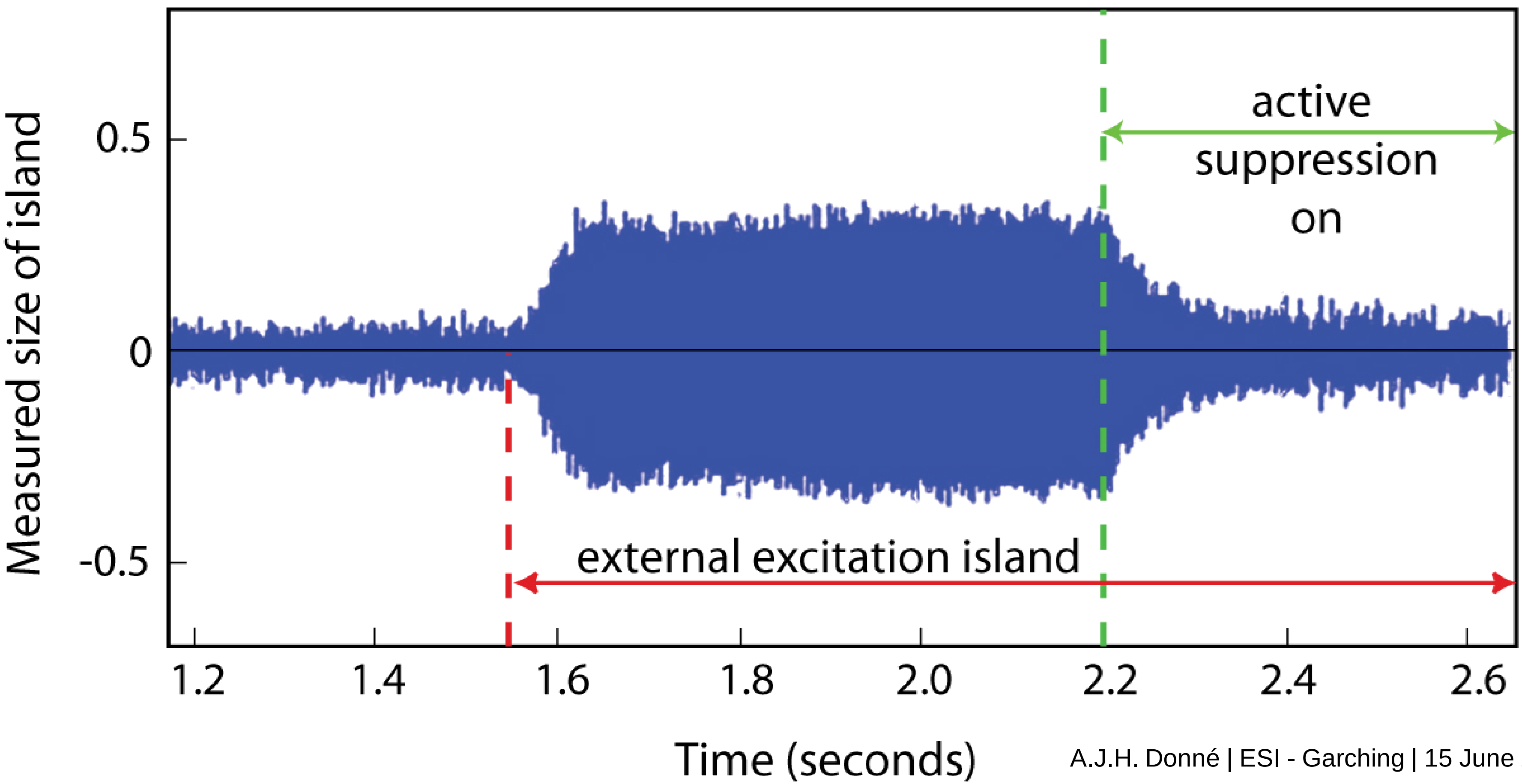
Discovery of internal transport barriers



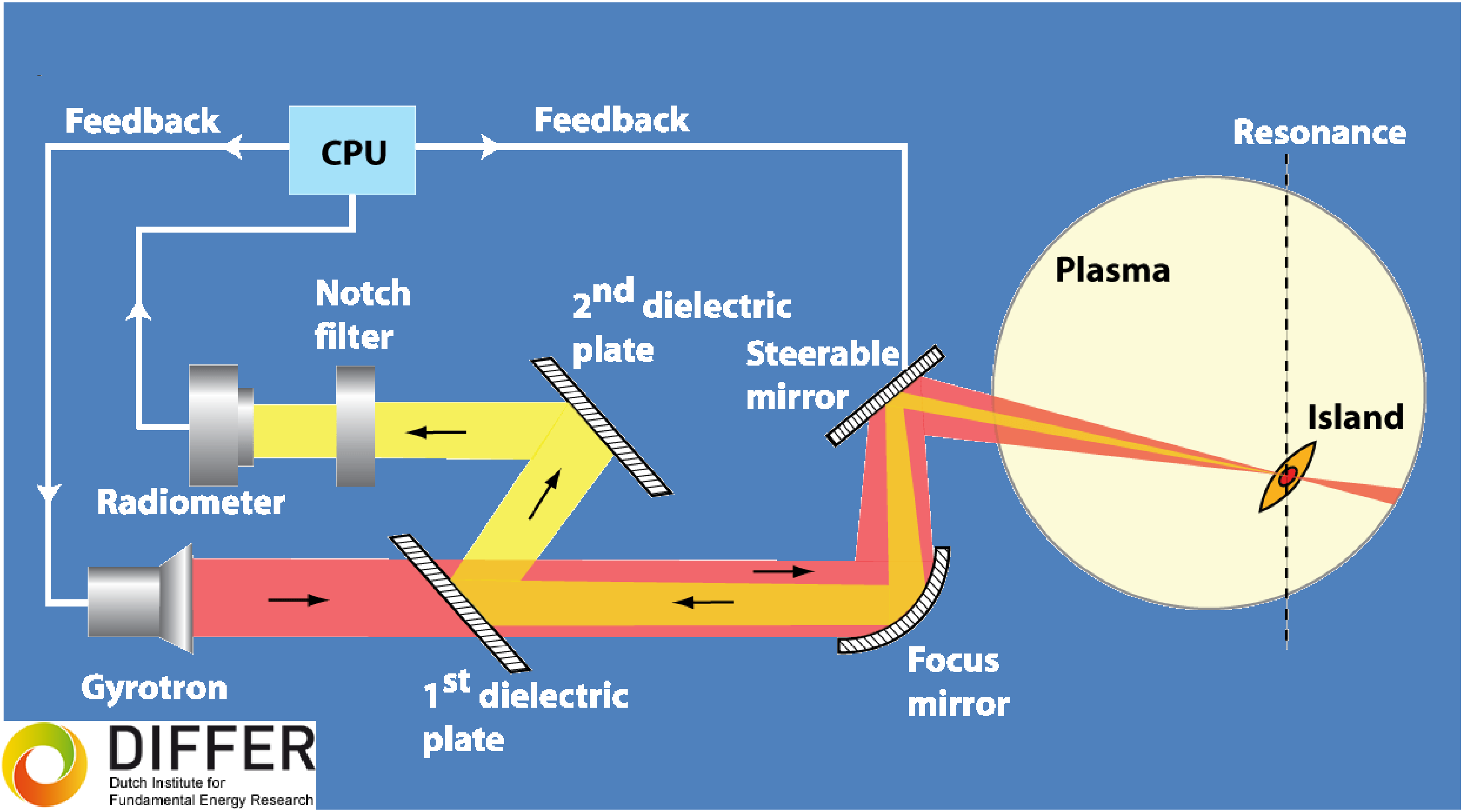


Turbulence control



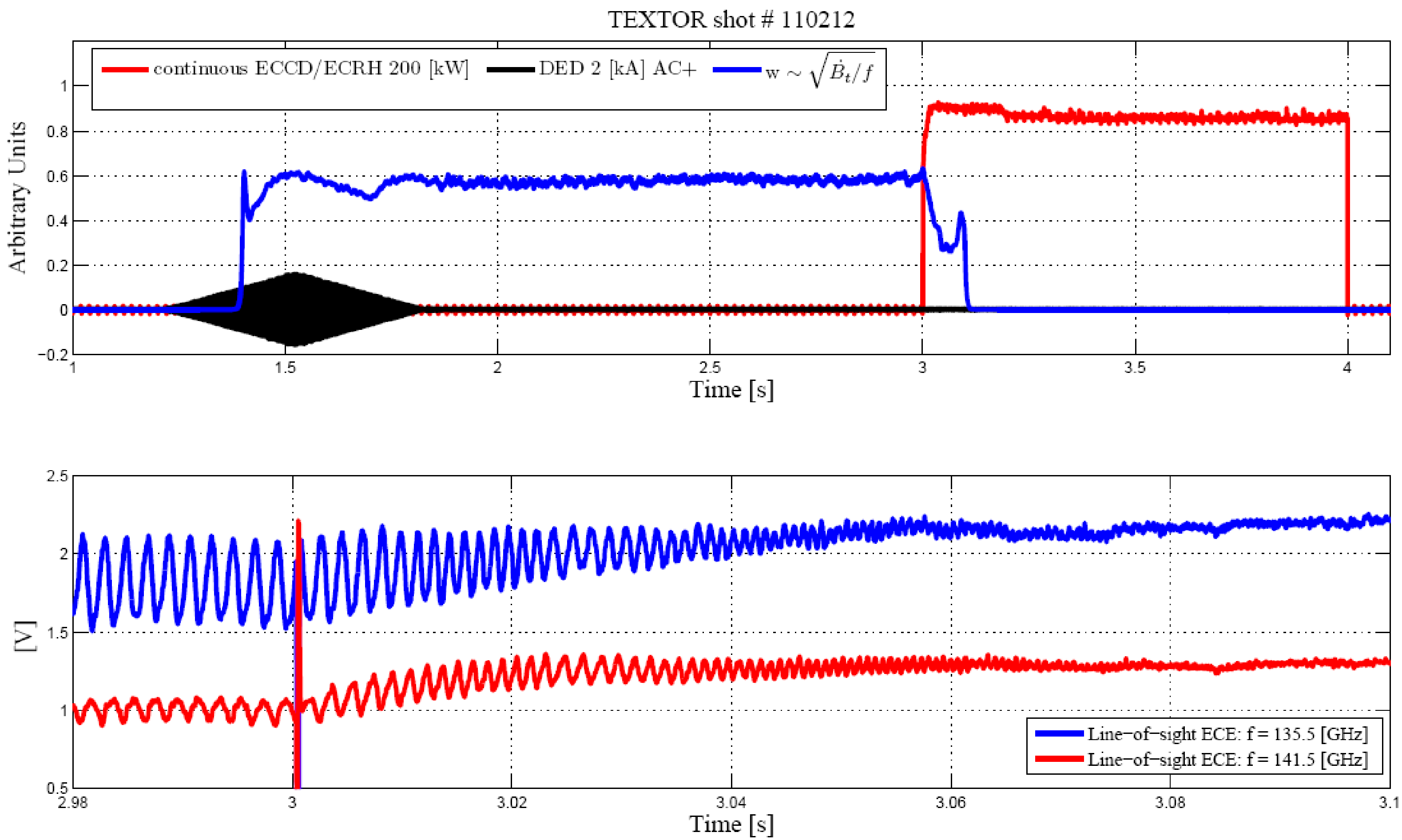


Turbulence control (Bart Hennen / Hans Oosterbeek)



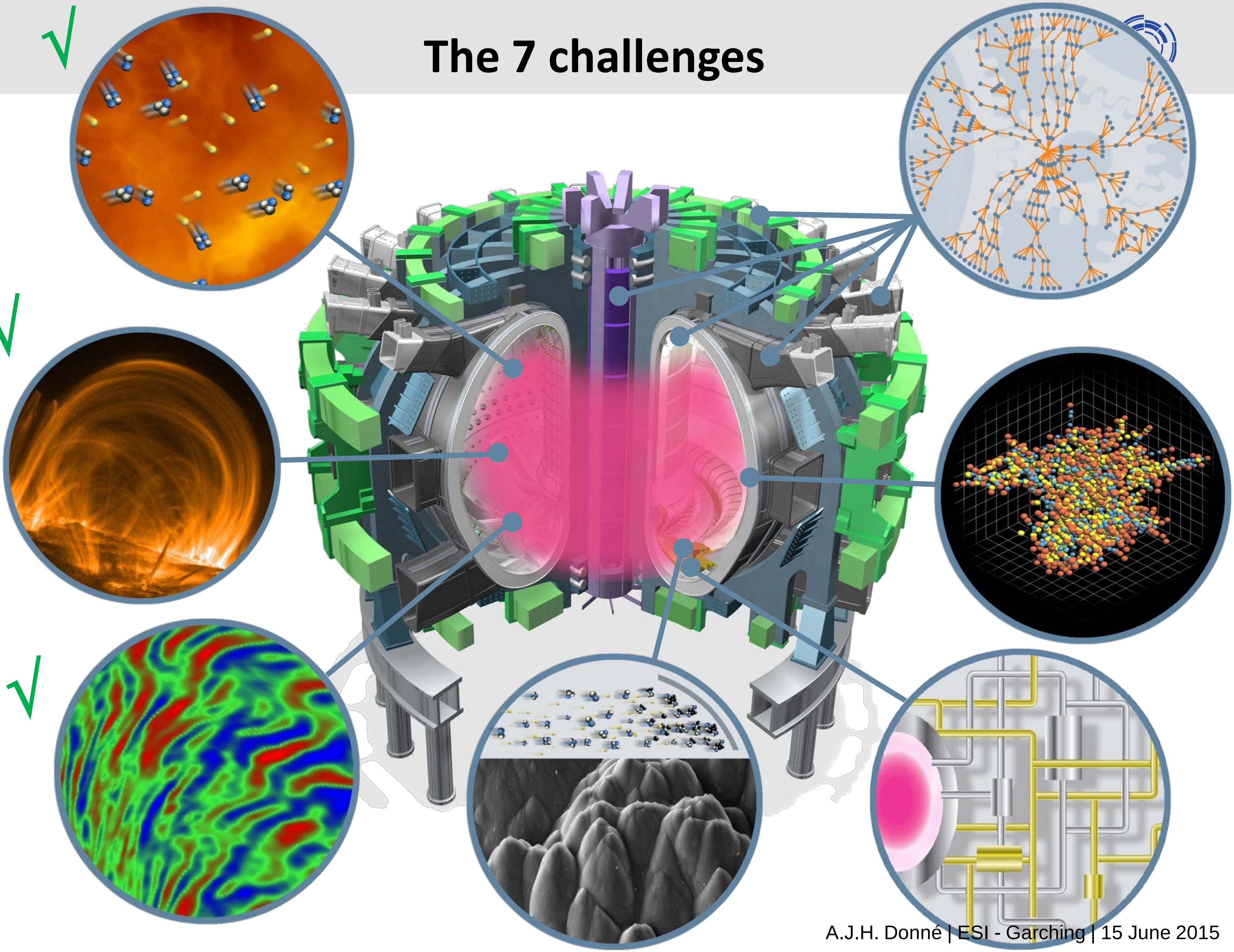
DIFFER
Dutch Institute for
Fundamental Energy Research

Excitation and suppression of an island in TEXTOR

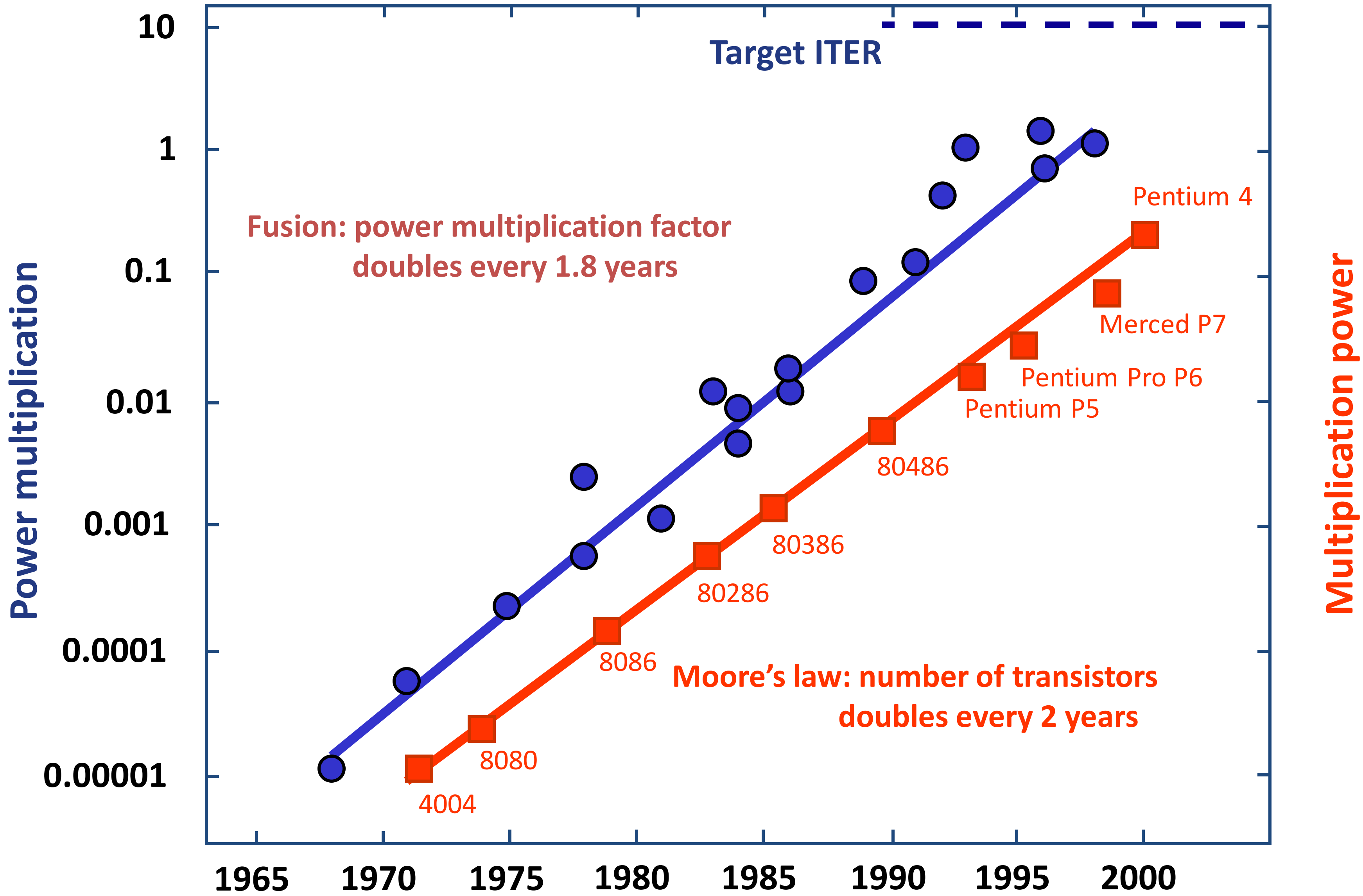


DIFFER
Dutch Institute for Fundamental Energy Research

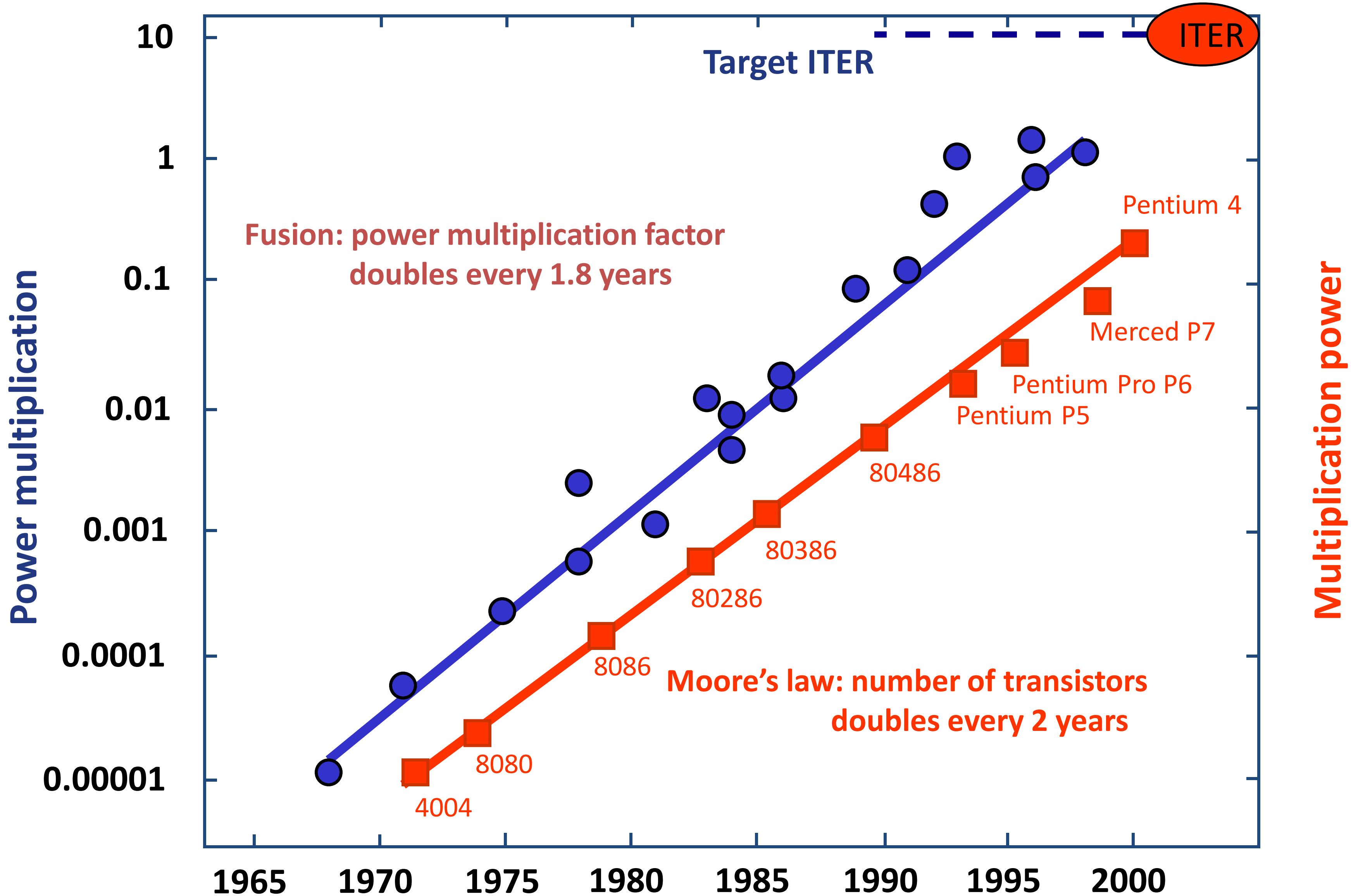
The 7 challenges

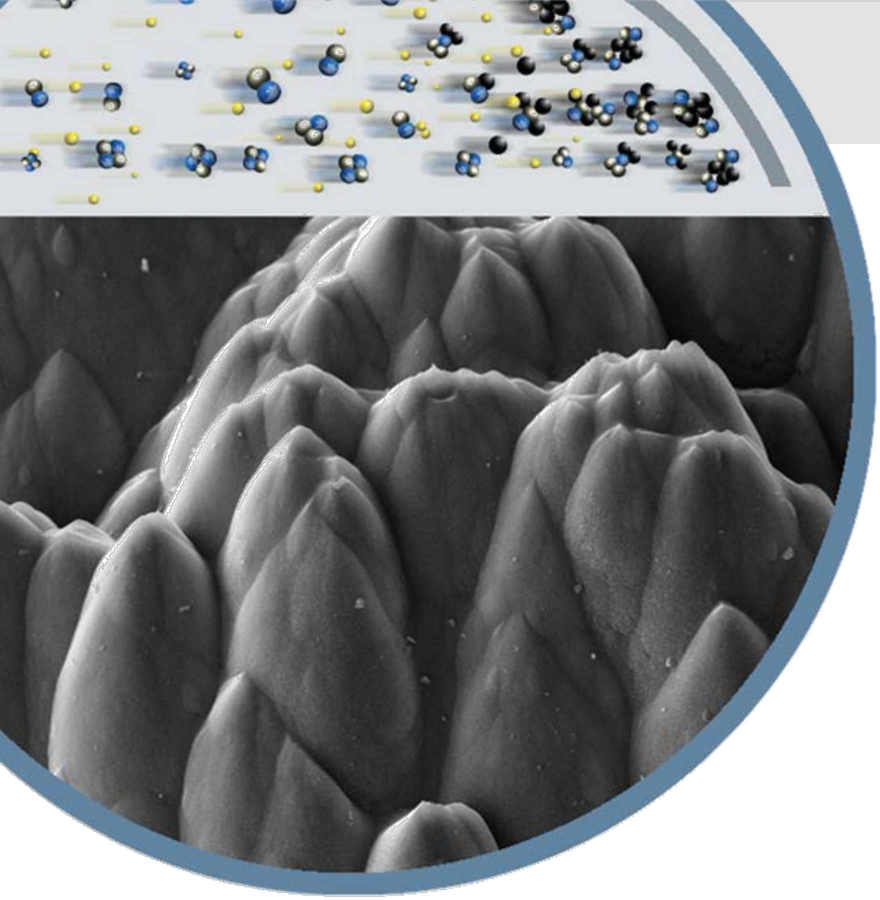


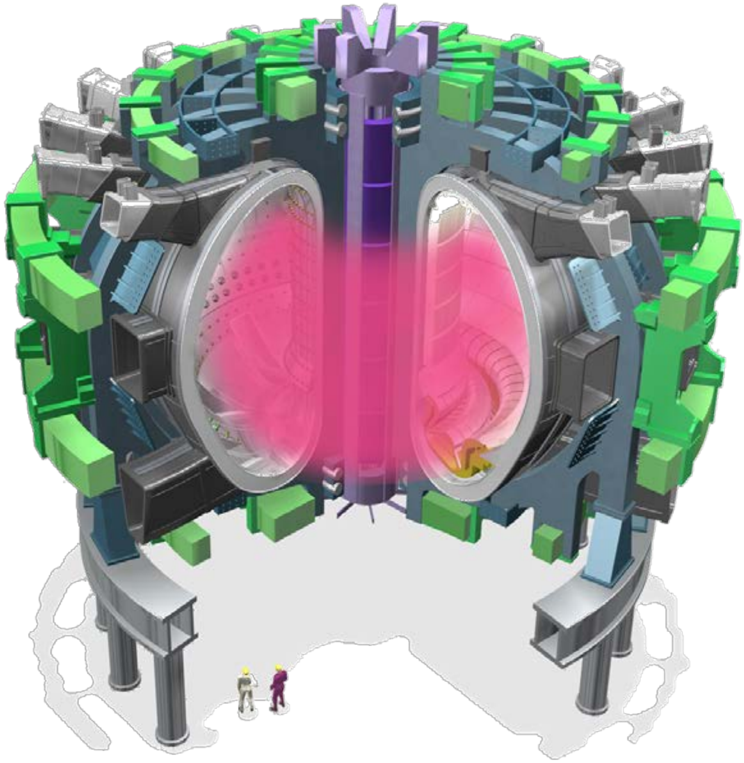
High T, magnetic confinement, turbulence control



High T, magnetic confinement, turbulence control





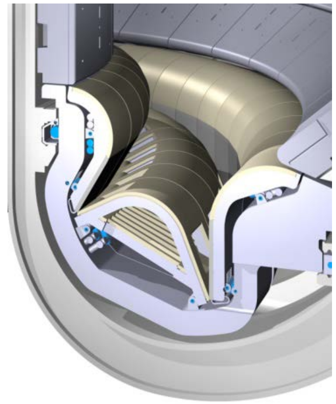


Materials one can lay on the sun

Thermal power loads

Rolls Royce Trent 900

ITER steady-state



ITER transients

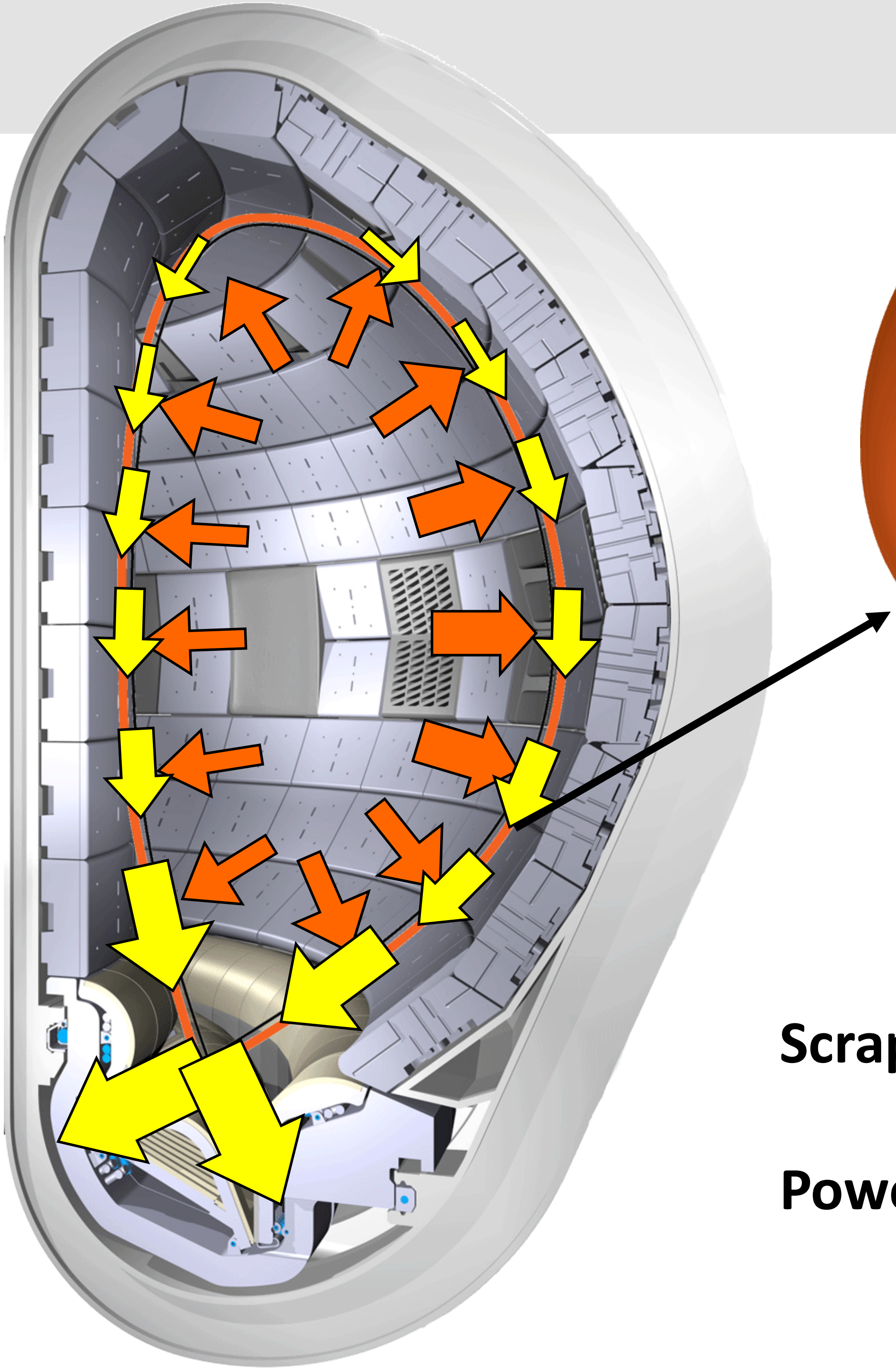
~1 <10 85 2000

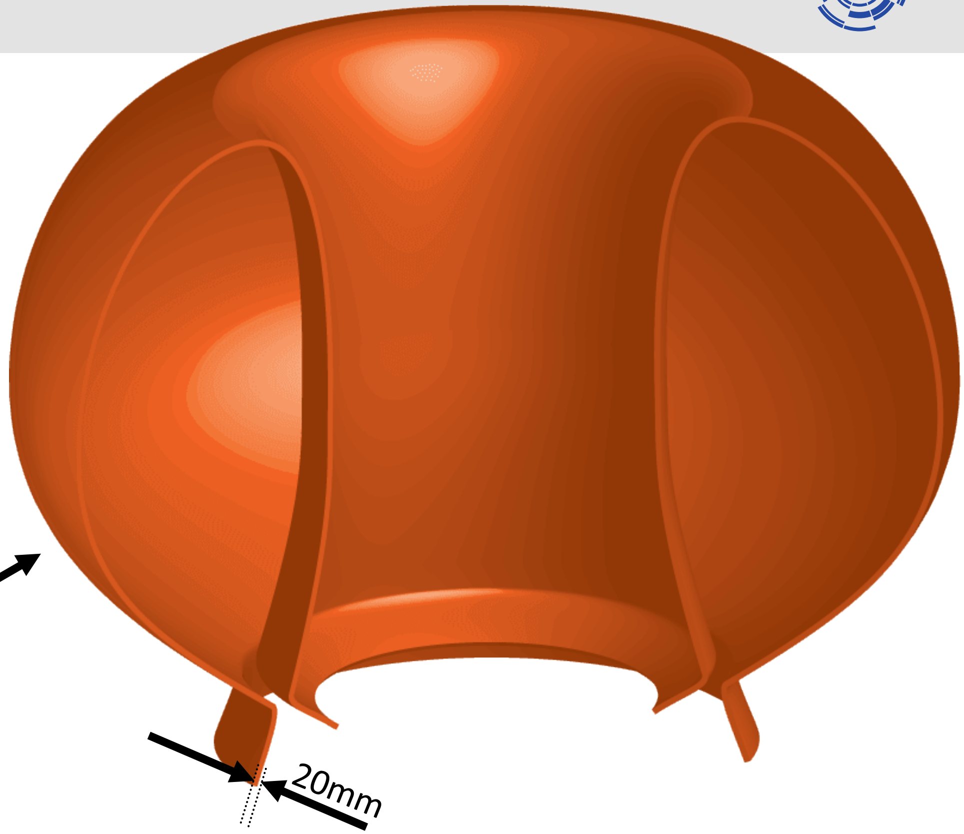
Power load [MW/m^2]

HWR

Re-entry vehicle

Ariane 5/Vulcain 2





Scrape-off layer ~ 2 cm thick

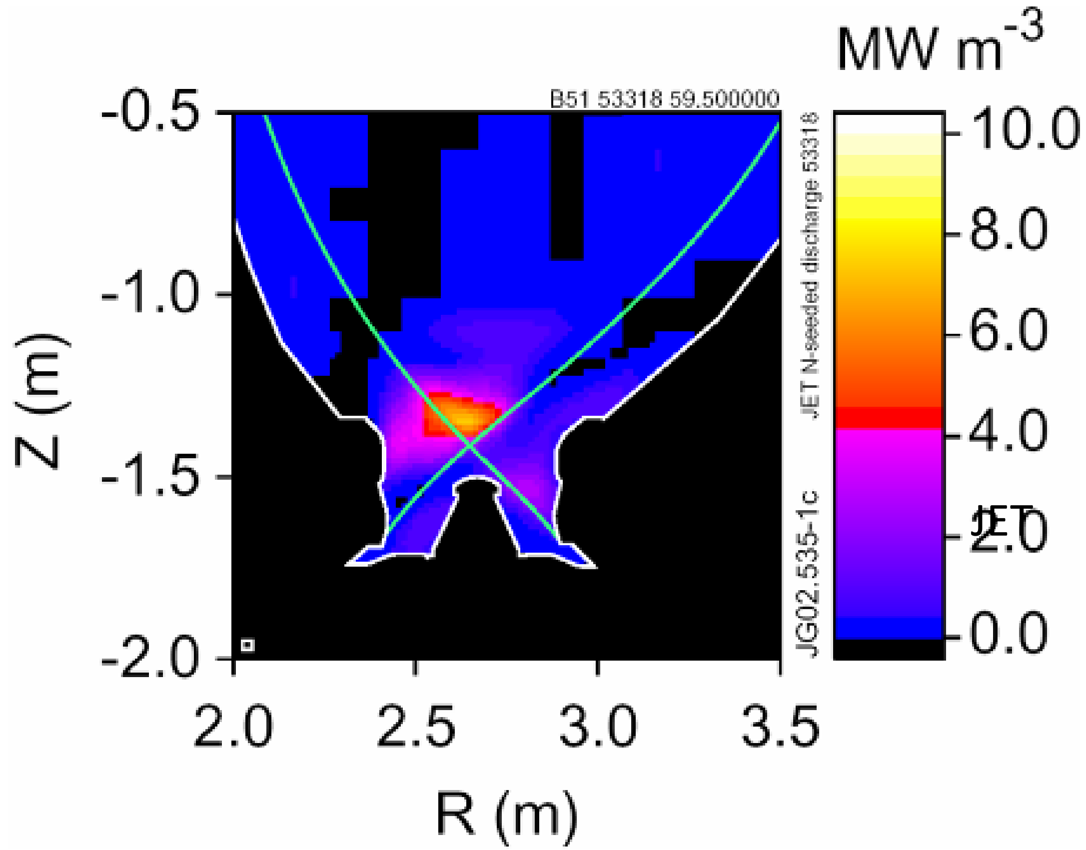
Power density 1 GW/m²

How to reduce the power loads of 1 GW/m²

Proper choice of the divertor geometry

Radiate >90% of the power away (uniform distribution)

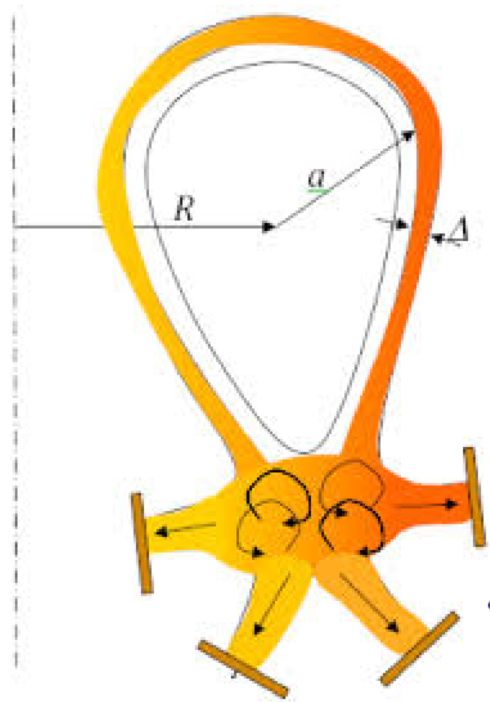
Decouple (detach) the plasma from the divertor (T<10 eV)

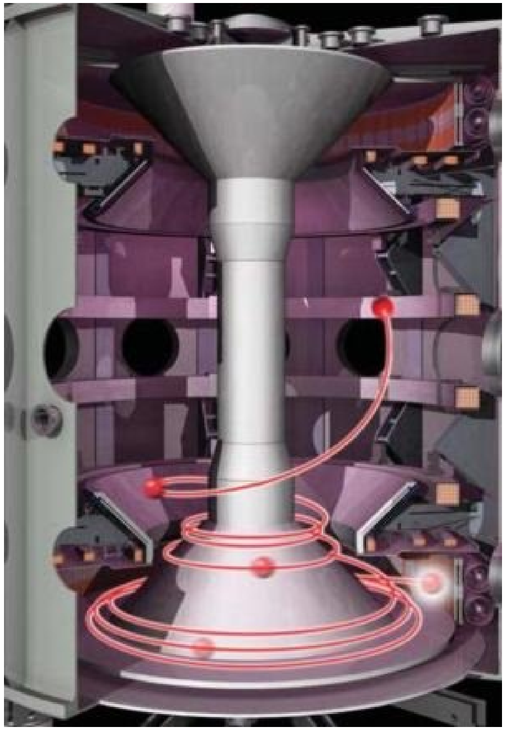


Heat Exhaust Research in Tokamaks

Research in alternative divertor solutions (Super-X, snowflake, liquid metal divertors)

Research in order to understand detached divertor conditions

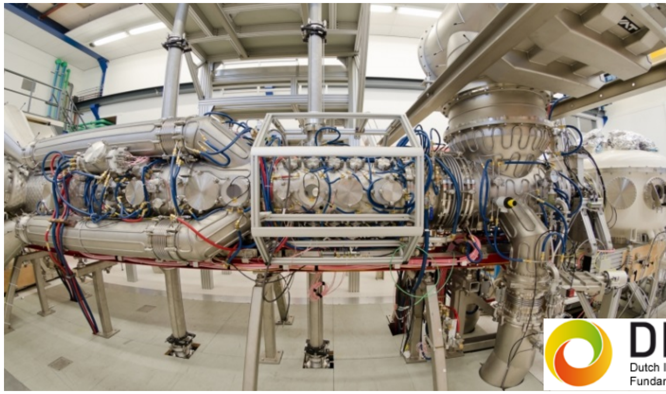


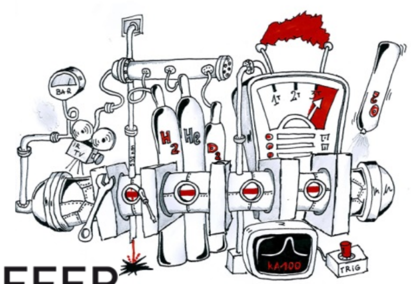


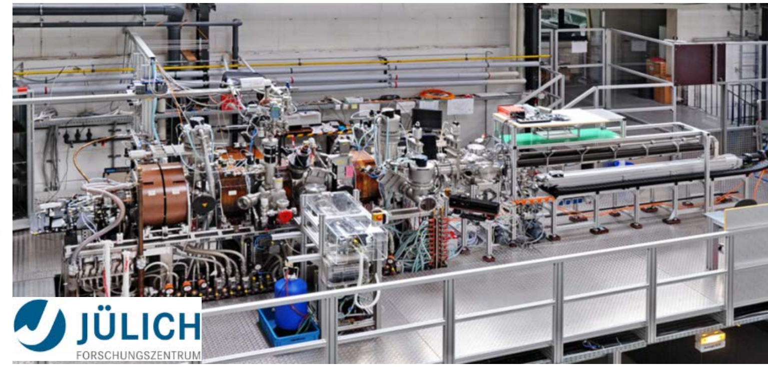
CRPP

CCFE
CULHAM CENTRE FOR FUSION ENERGY

Studying Plasma Facing Components (mission 2)



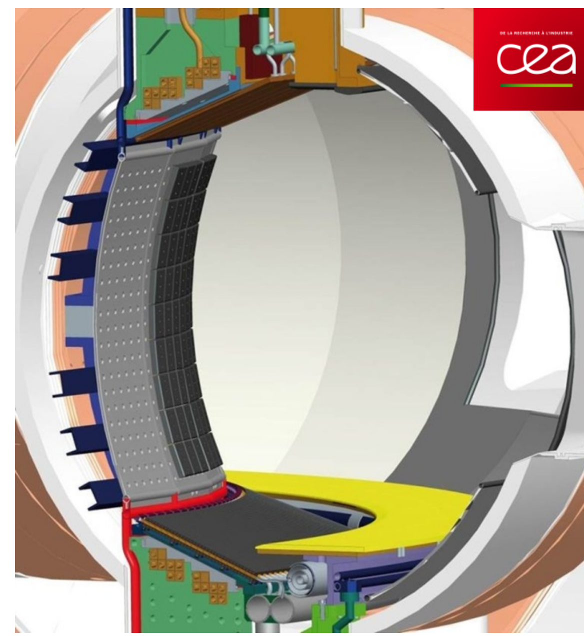




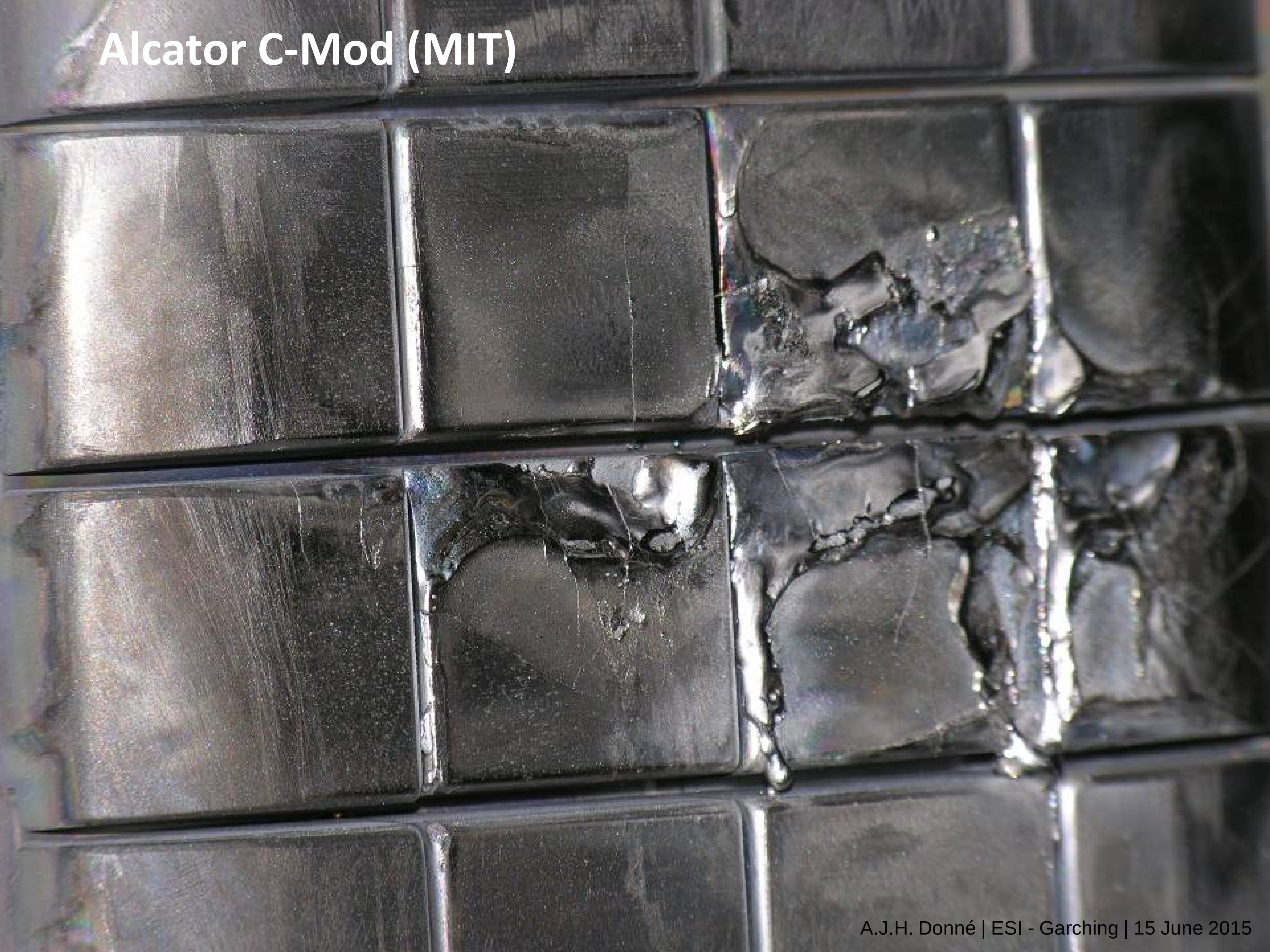
Magnum-PSI **Pilot-PSI** **PSI-2**

JUDITH-1/2

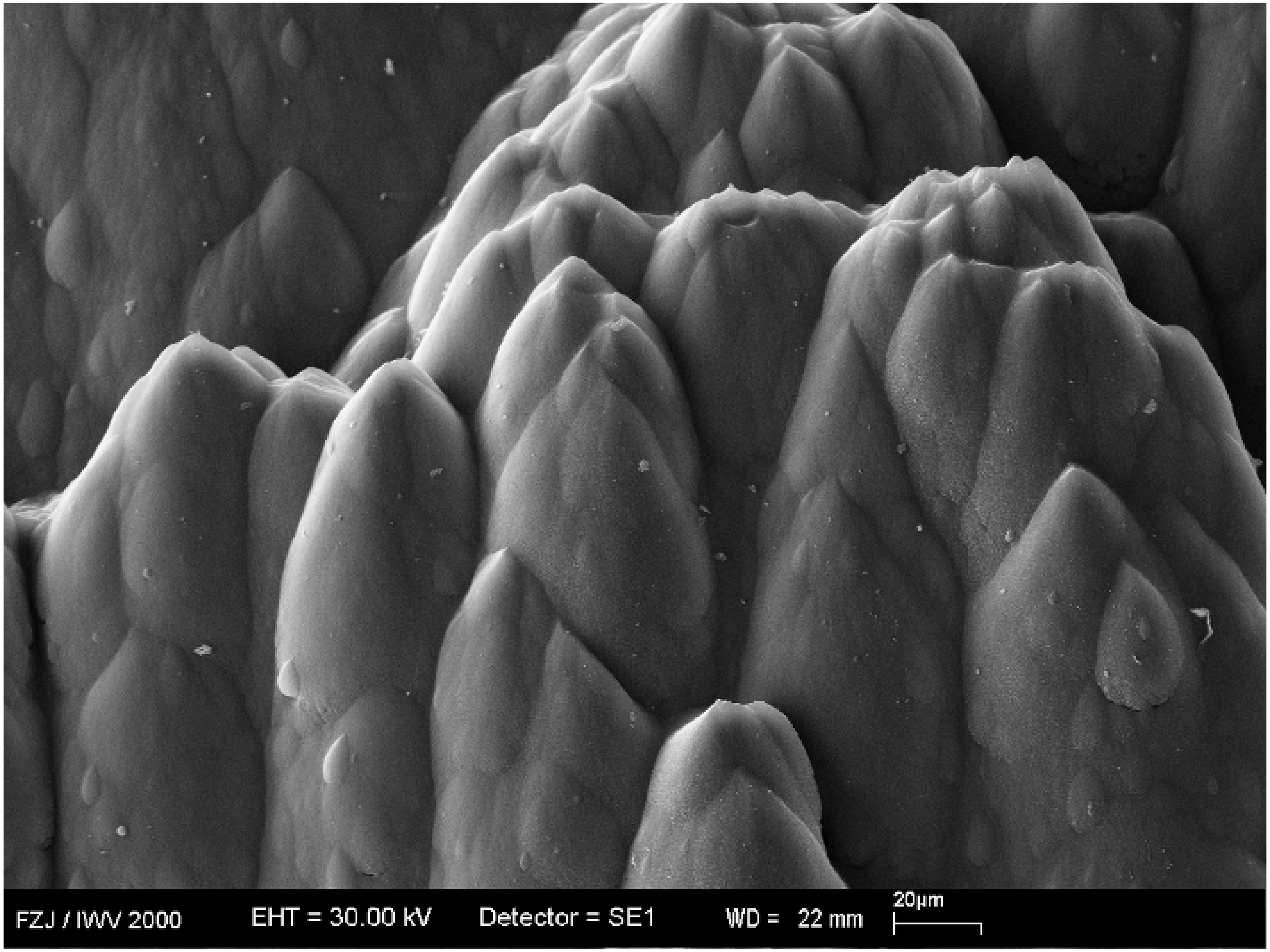
WEST



Alcator C-Mod (MIT)



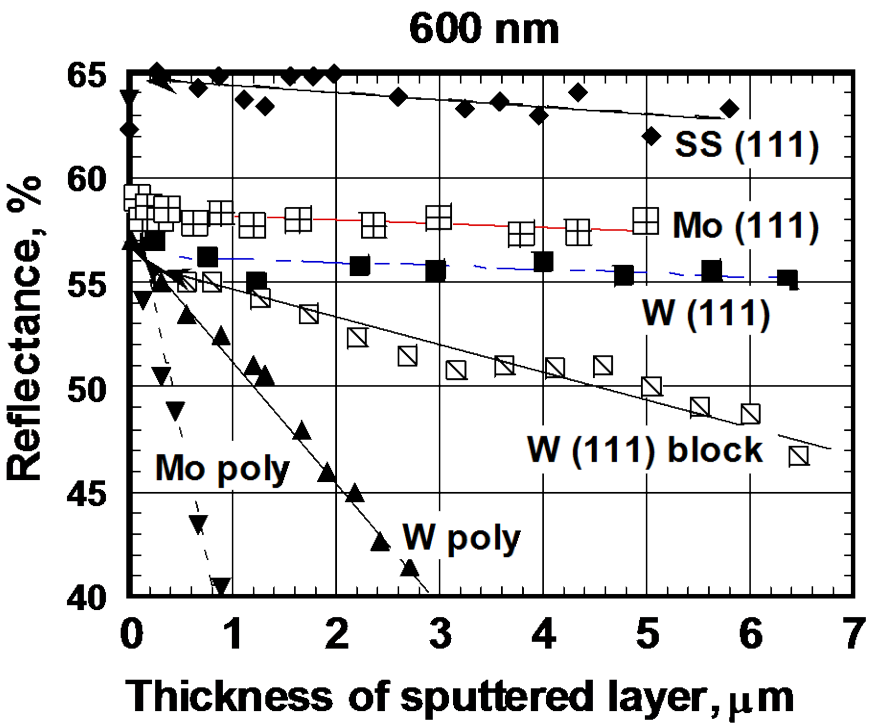
Deposition of carbon in TEXTOR



Erosion/redeposition

Reflectivity for eroded mirrors

V. Voitsenya, Rev. Sci. Instrum. 76 (2005) 083502.

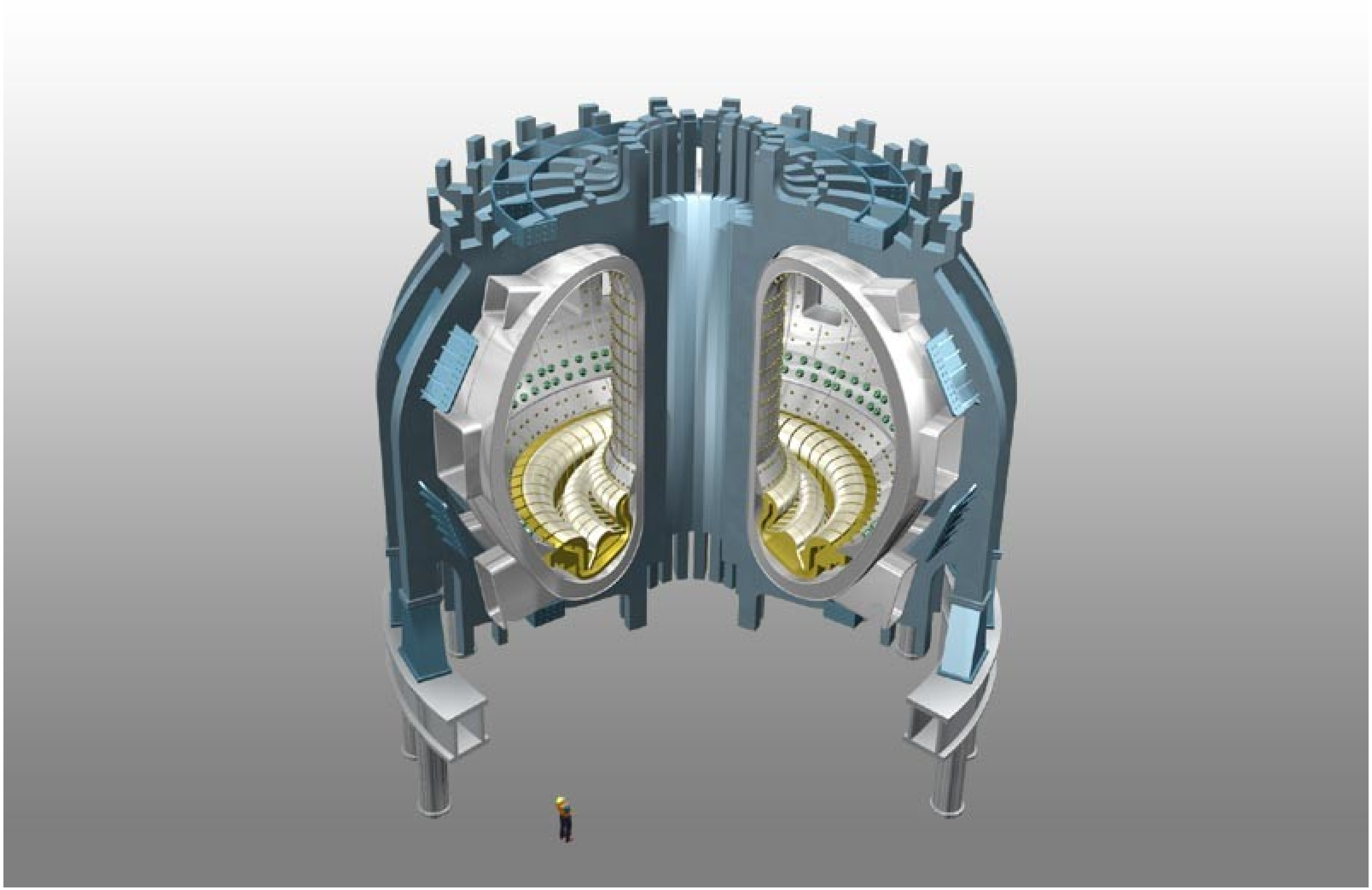


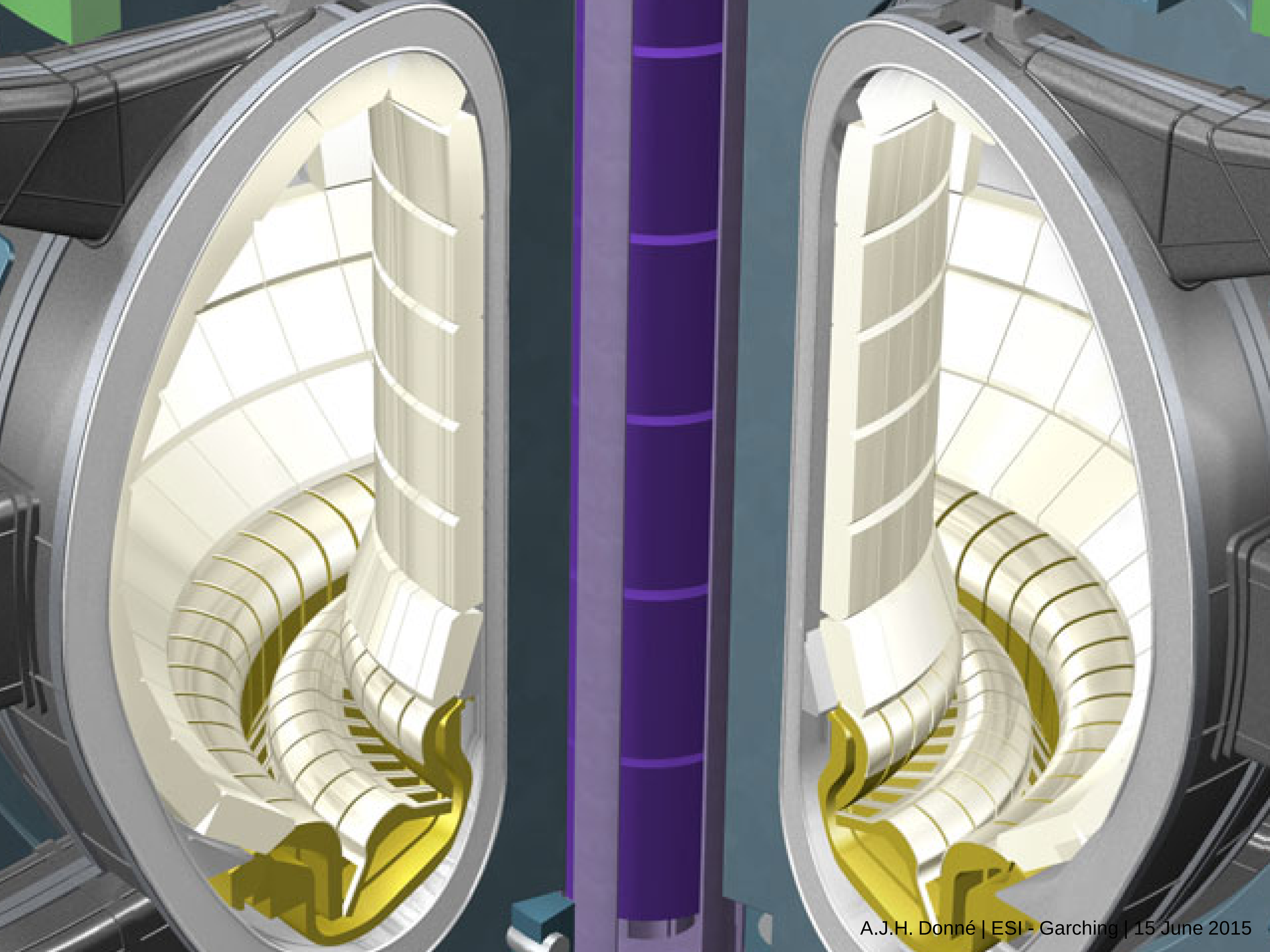
Material eroded away elsewhere can be redeposited on mirrors

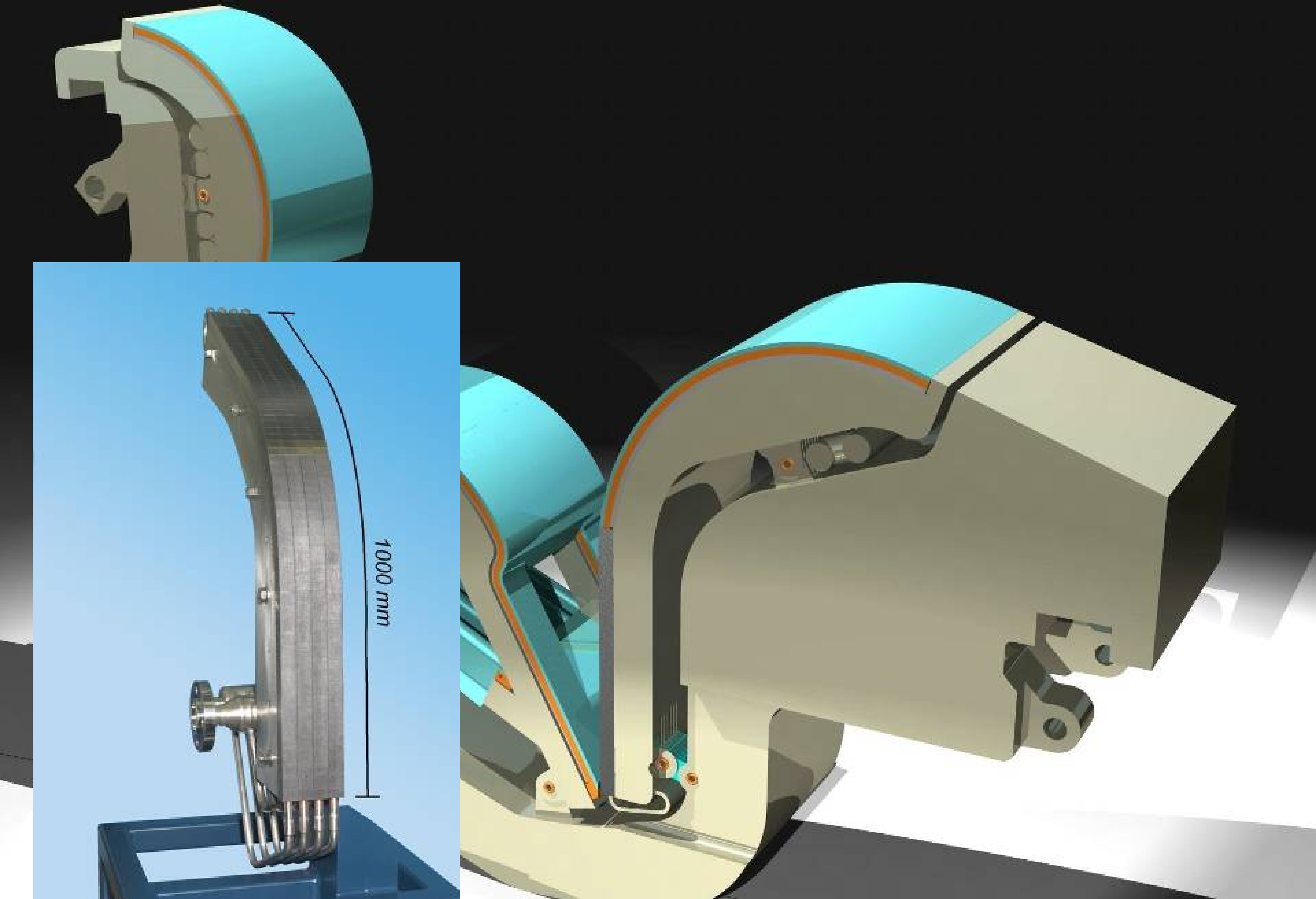
M. Rubel, 18th ITPA Diagnostics meeting

Courtesy: A. Litnovsky

Divertor

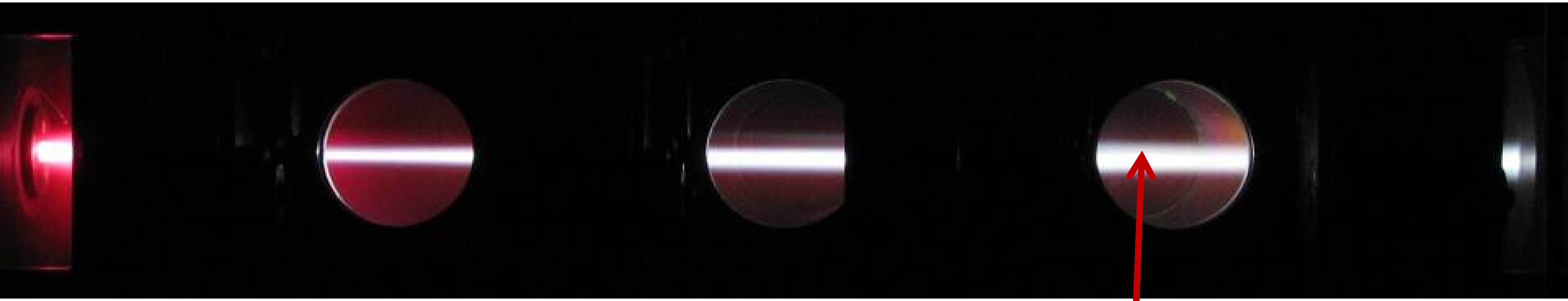





1000 mm

High-power linear divertor simulators

Pilot-PSI



10 - 30 MW/m^2

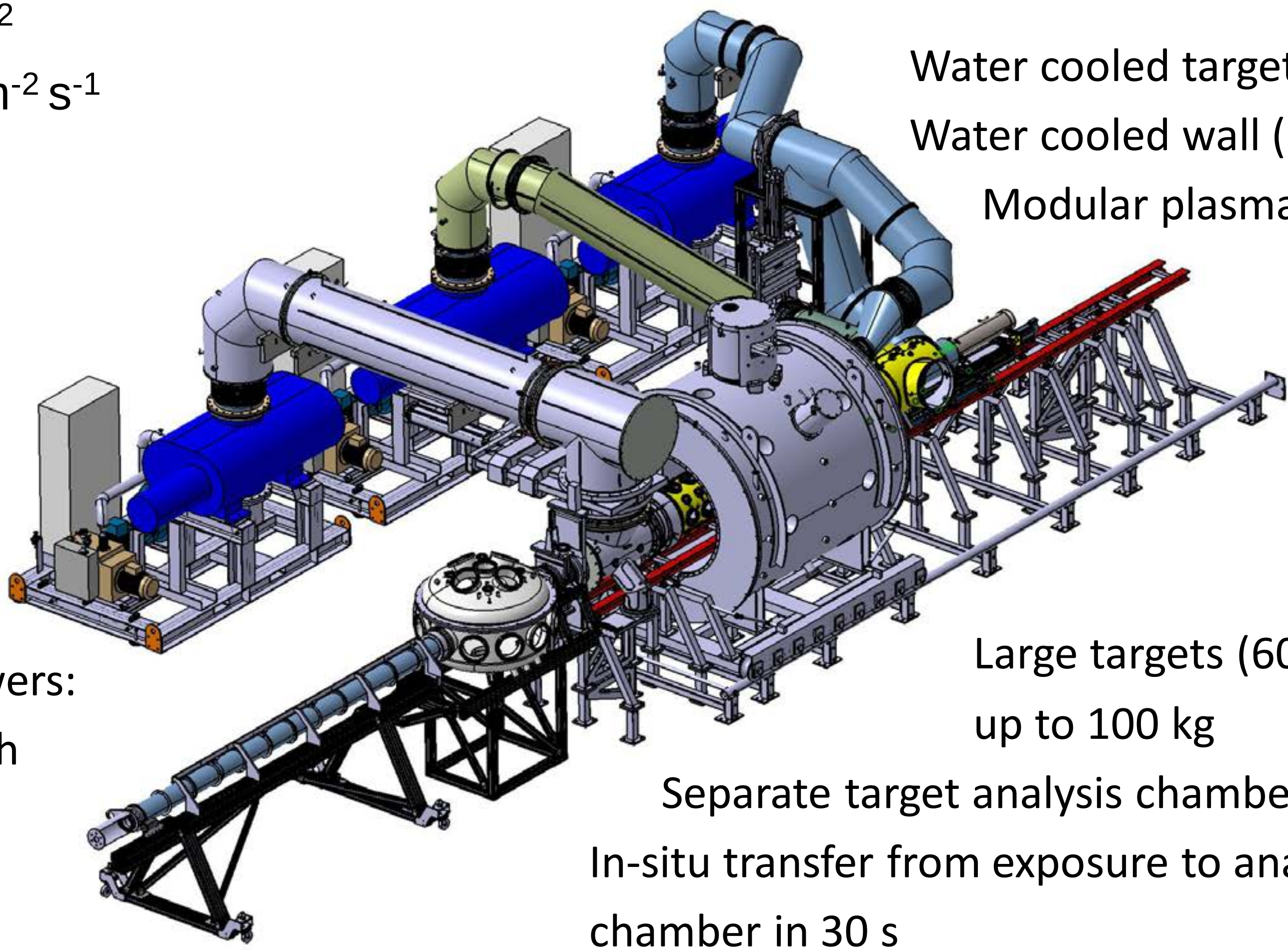
DIFFER
Dutch Institute for
Fundamental Energy Research

Magnum-PSI

First super-conducting linear plasma simulator: steady state 3T

10 MW/m^2

$\Gamma_D = 10^{24}$ m^{-2} s^{-1}



Water cooled target (100 kW)

Water cooled wall (50 kW/m^2)

Modular plasma source

Roots blowers:

60000 m^3/h

Turbo:

4400 l/s

Large targets (60 x 12 cm)

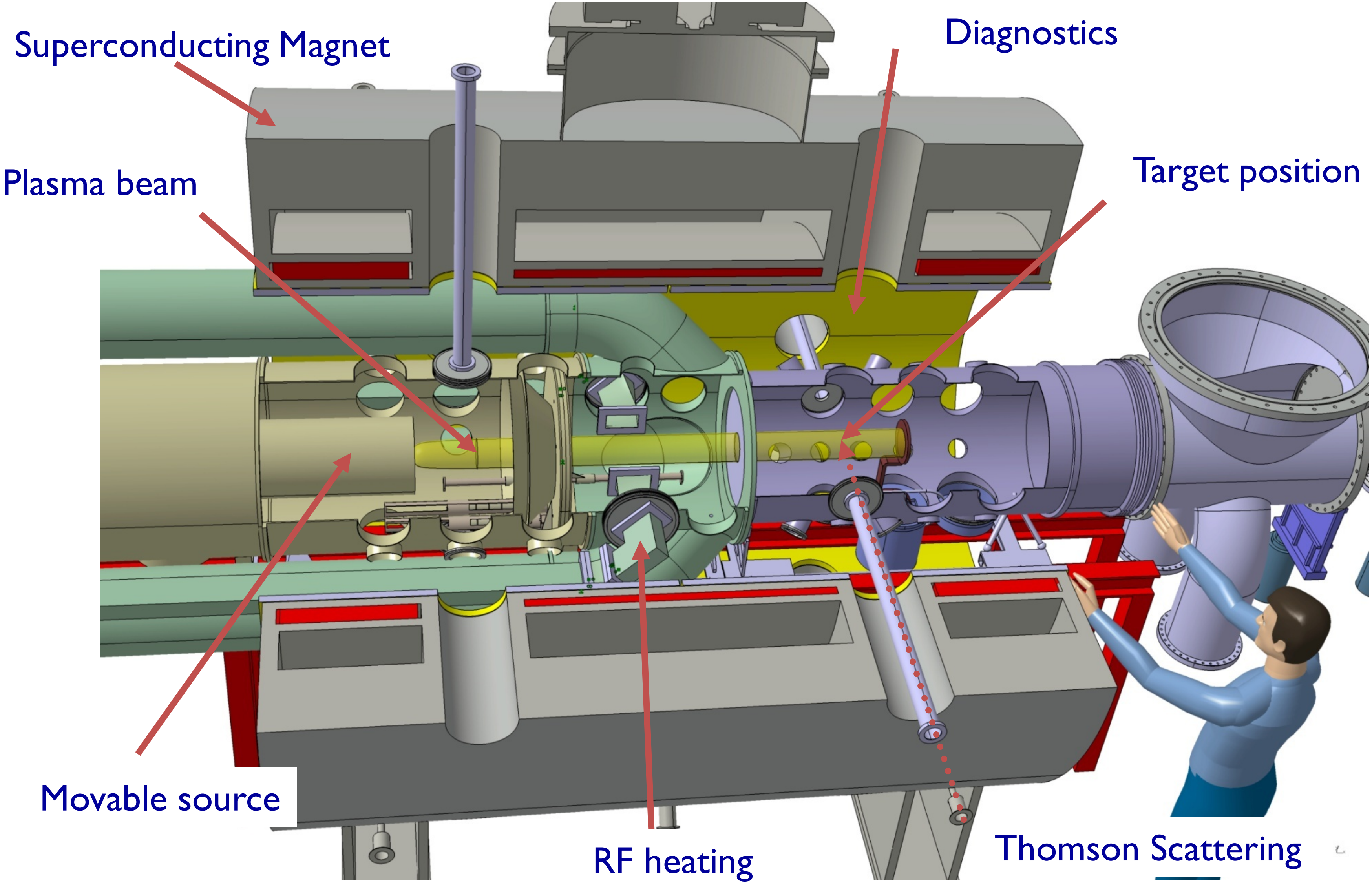
up to 100 kg

Separate target analysis chamber

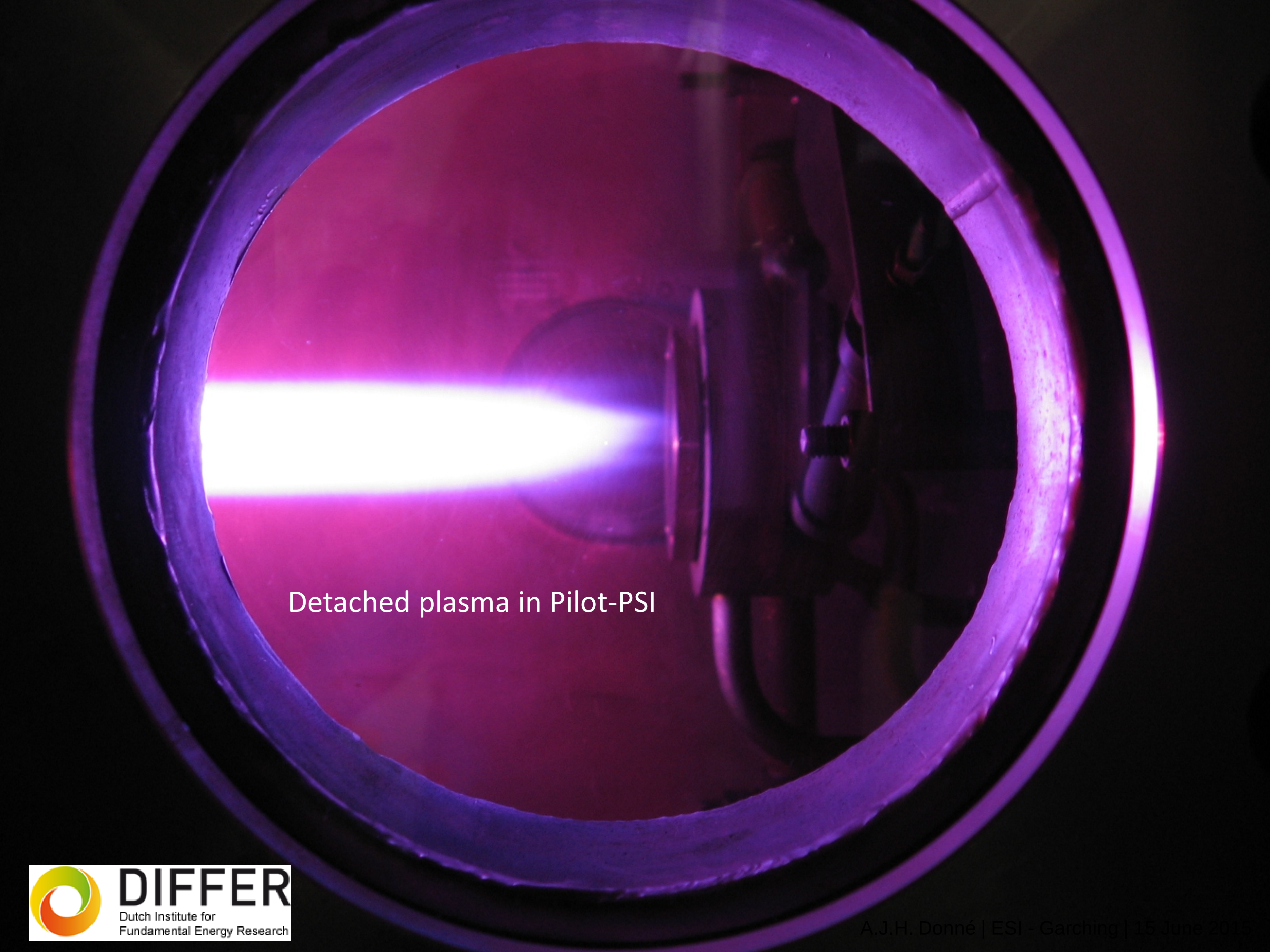
In-situ transfer from exposure to analysis chamber in 30 s

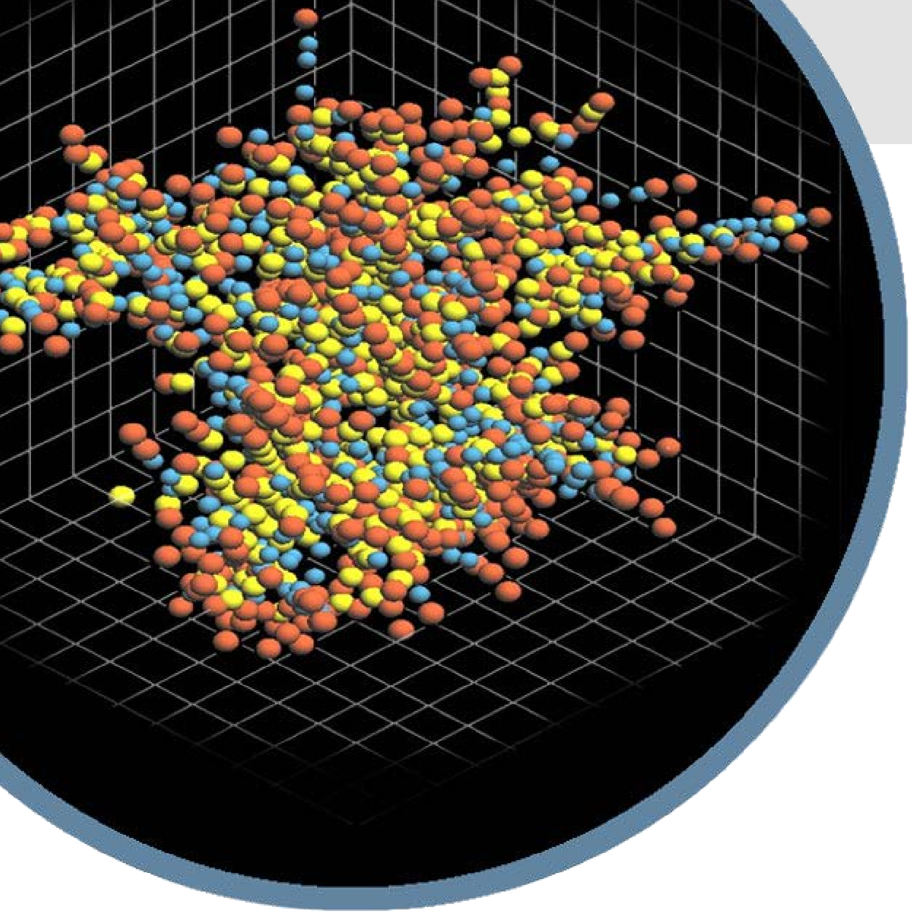
DIFFER
Dutch Institute for Fundamental Energy Research

Magnum-PSI

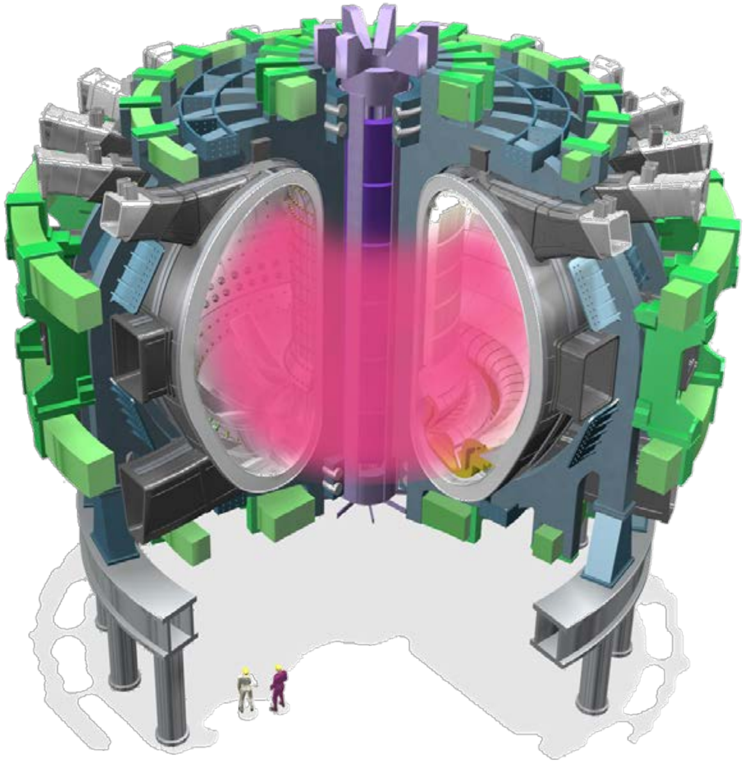


DIFFER
Dutch Institute for
Fundamental Energy Research

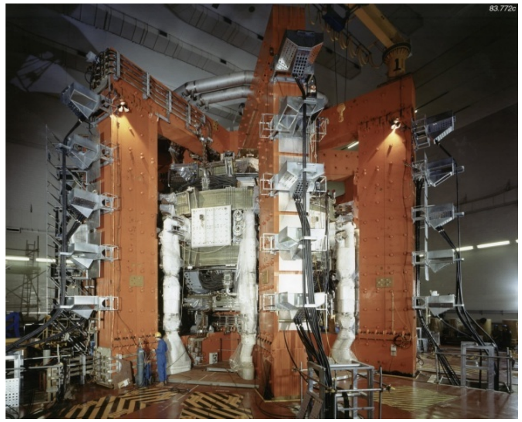

Detached plasma in Pilot-PSI

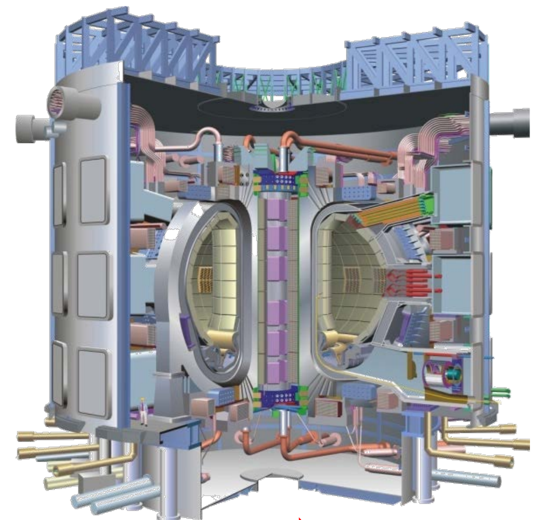


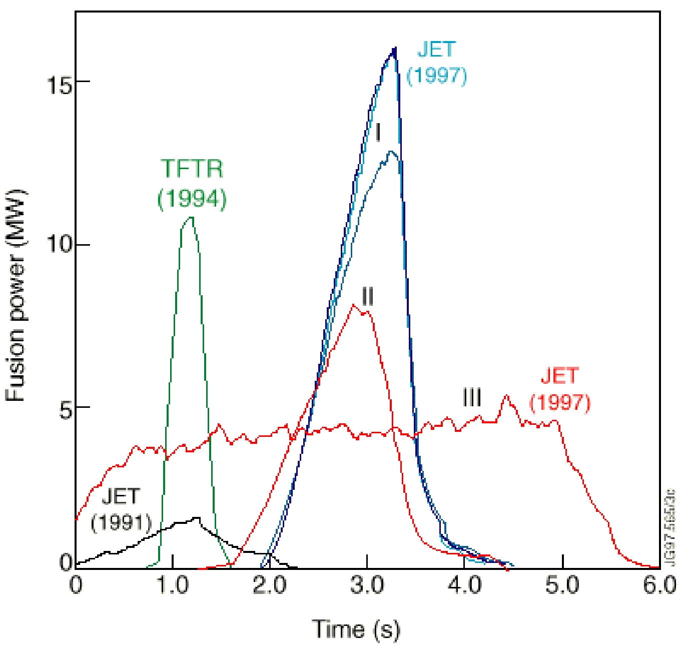
Bombardment of neutrons



High particle fluxes





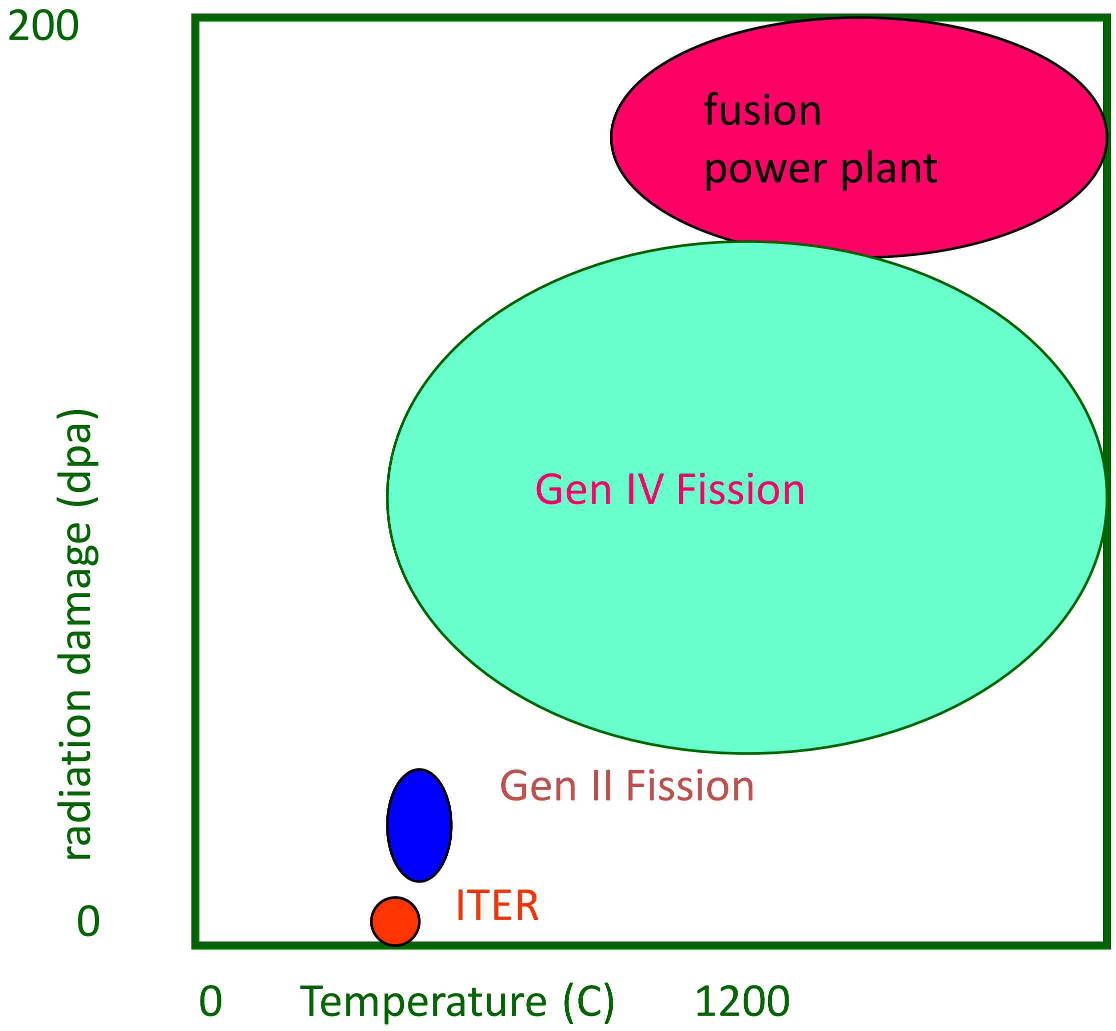


50 × higher ion flux

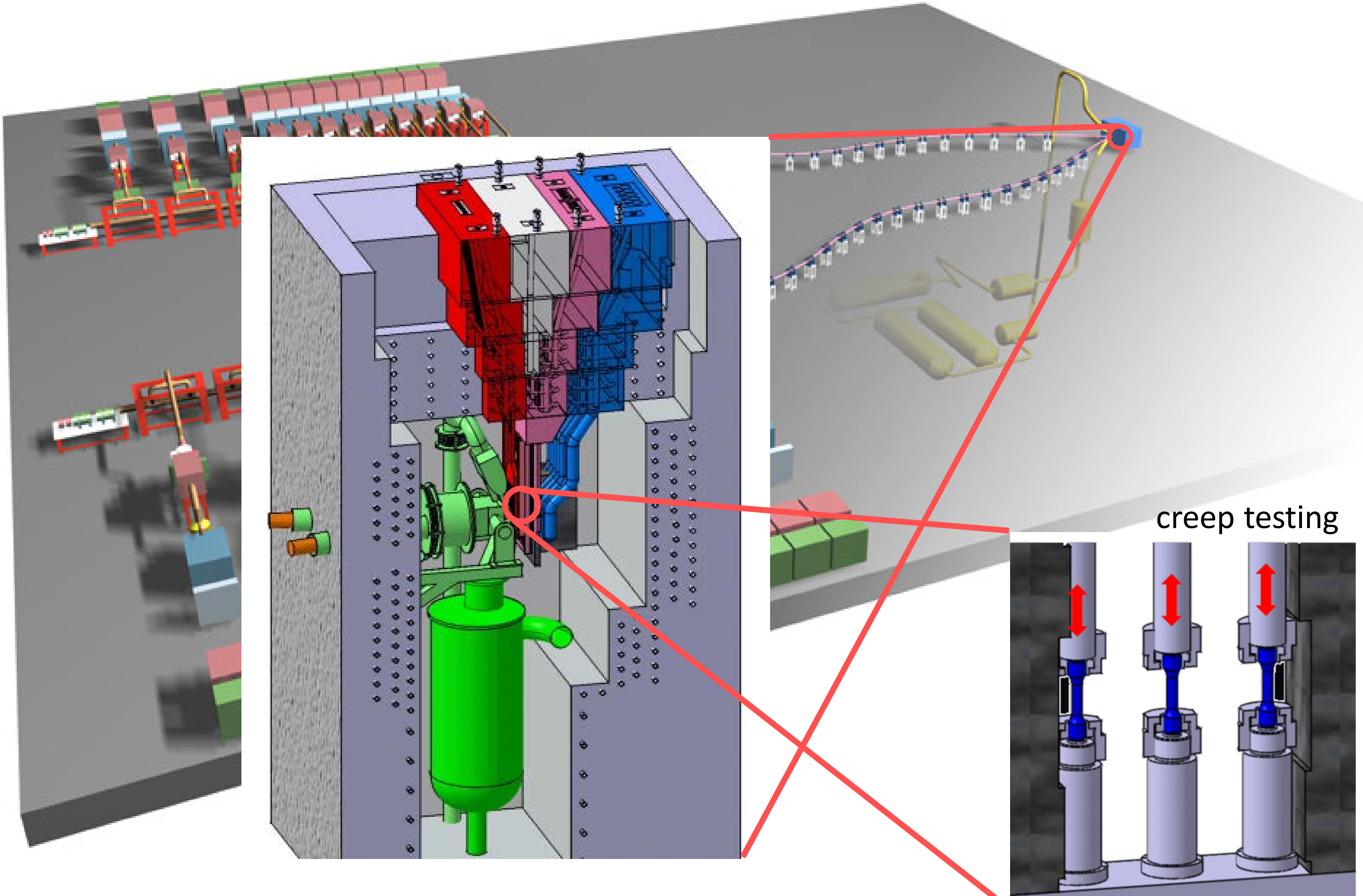
5000 × higher ion fluence

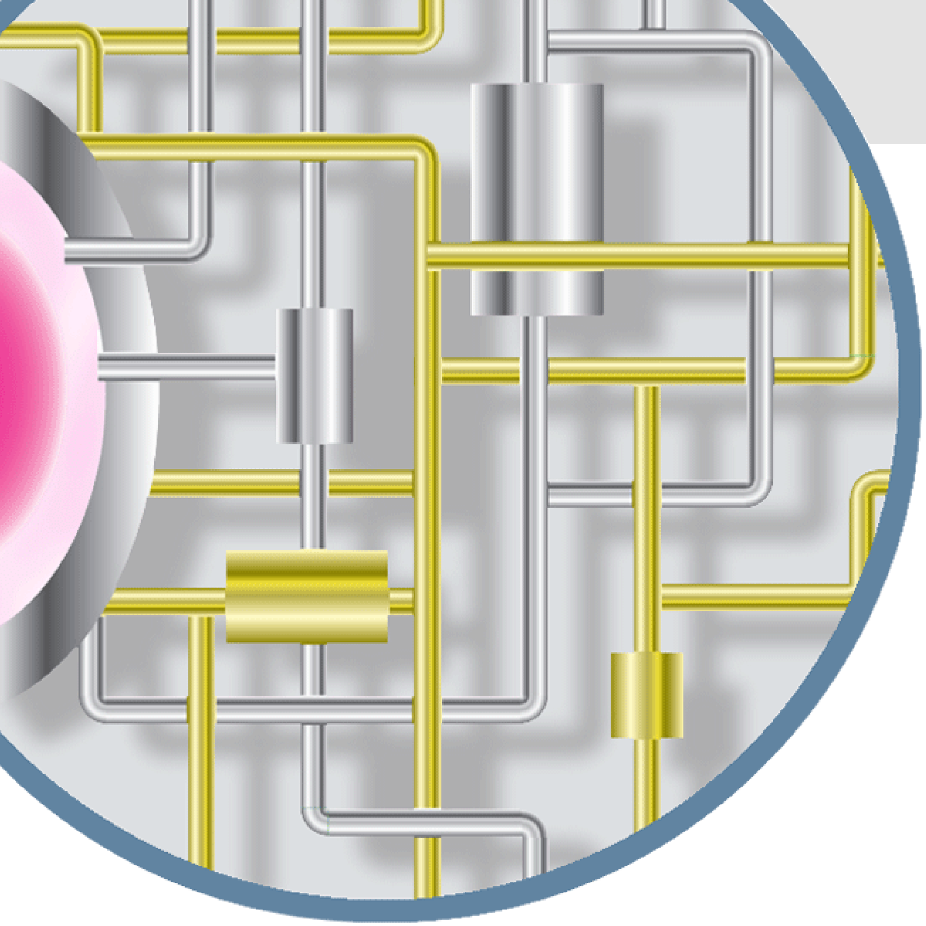
> 10^5 × higher neutron fluence

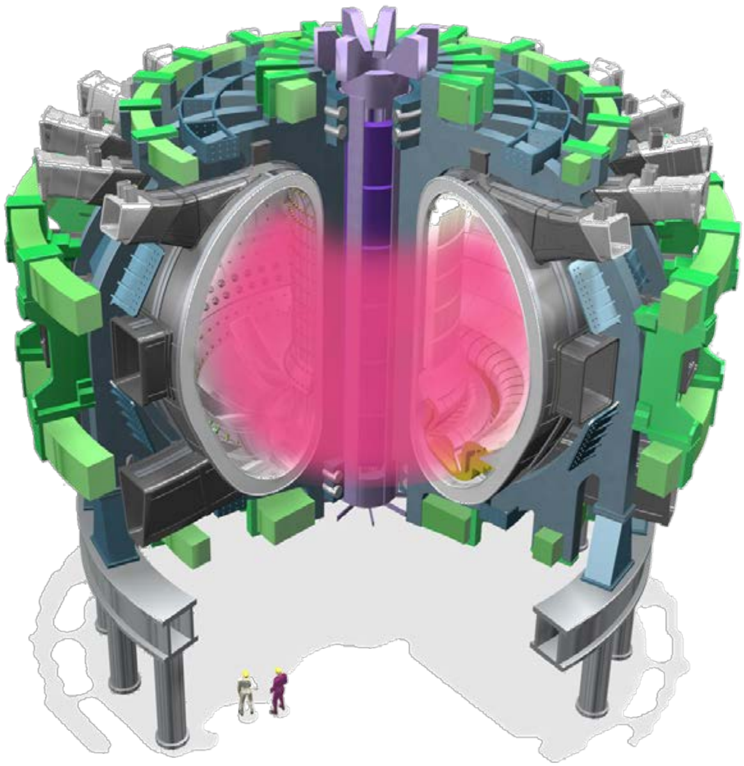
Neutron resistant materials (mission 3)



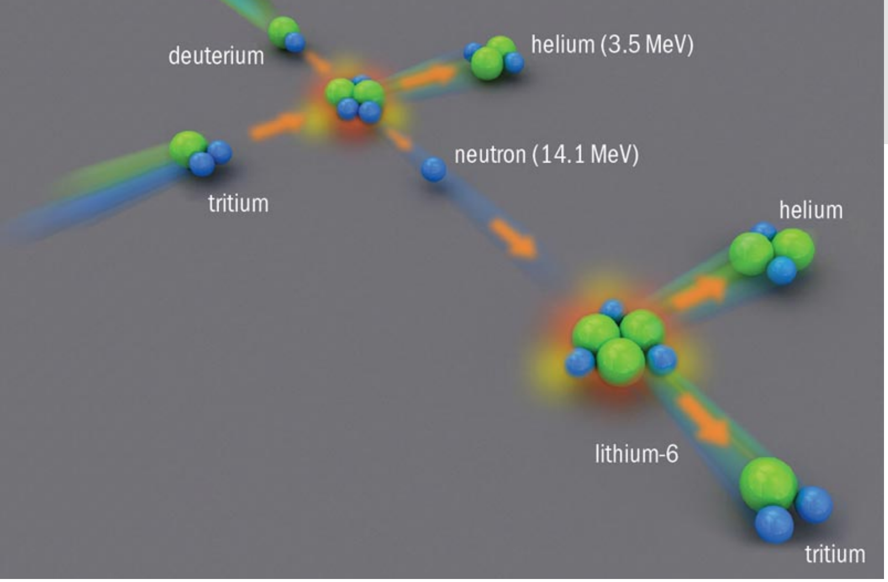
IFMIF - International Fusion Materials Irradiation Facility



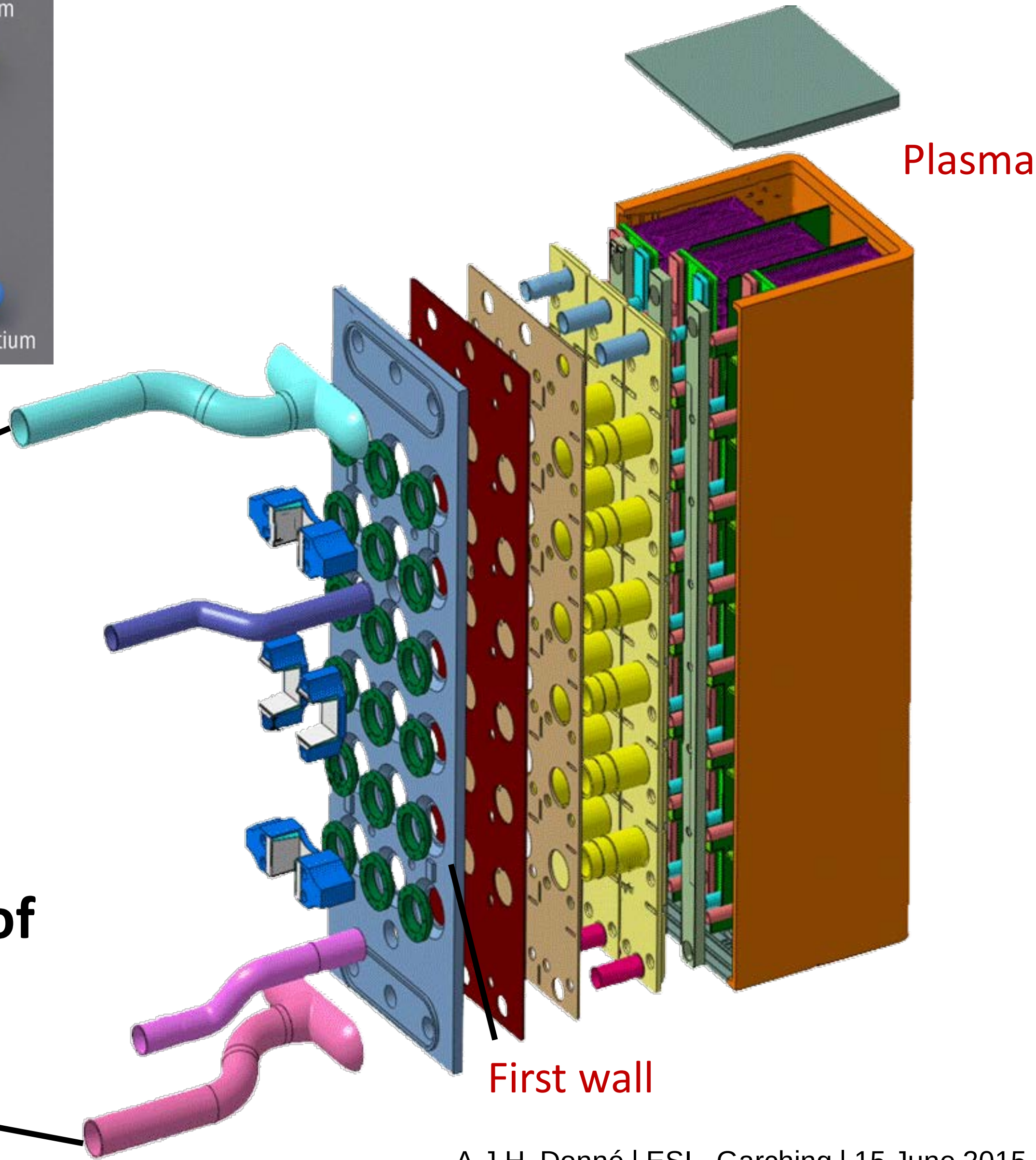




Fuel cycle
Tritium production

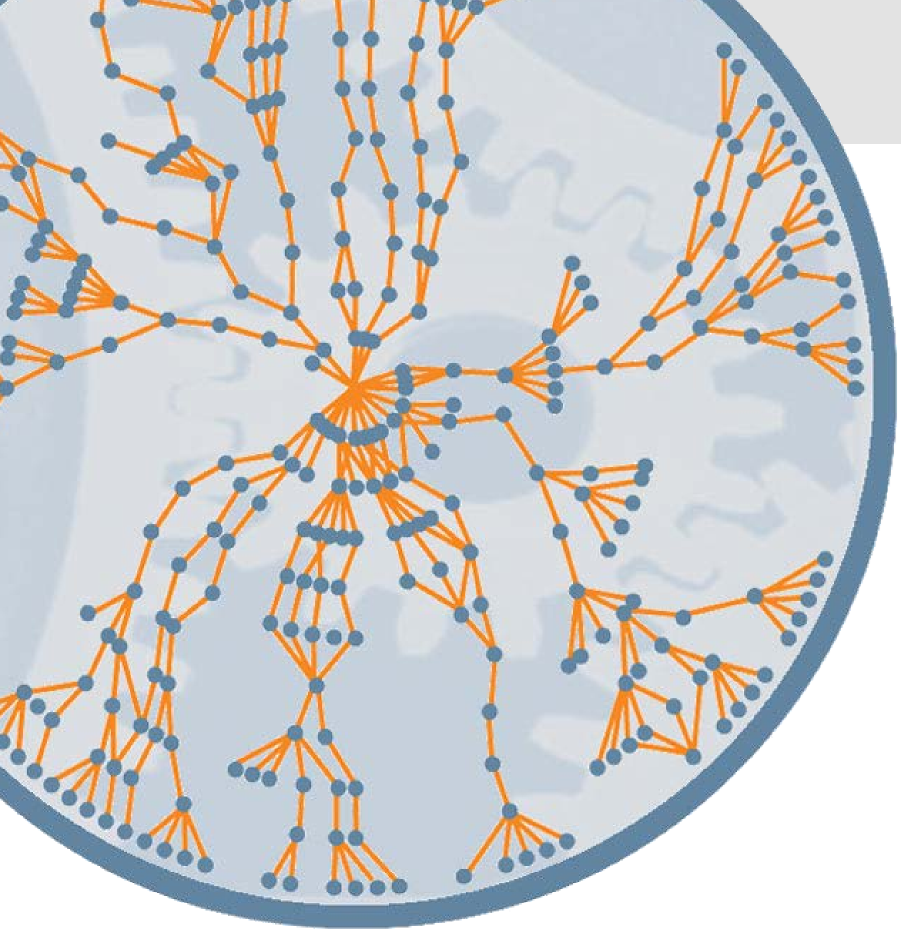


(mission 4)



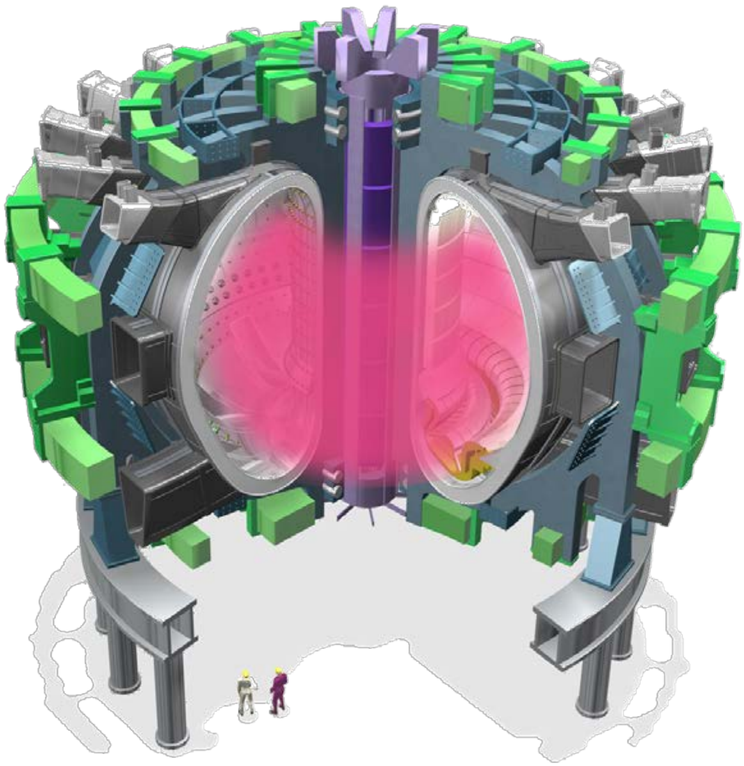
Tritium must be used at least 1000 × without being lossed

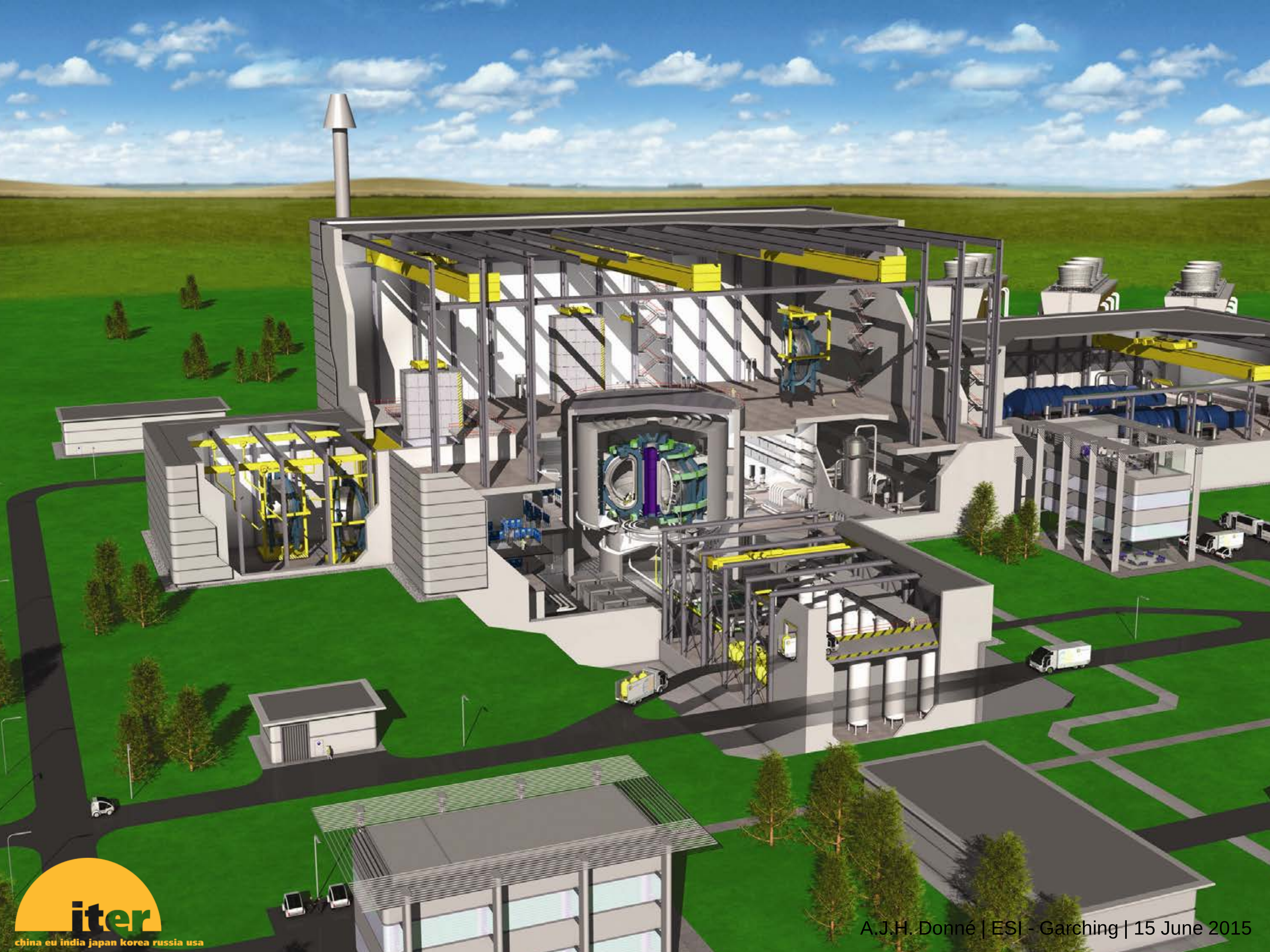
(each fusion reaction in the plasma must lead to creation of a new tritium atom in the blanket)

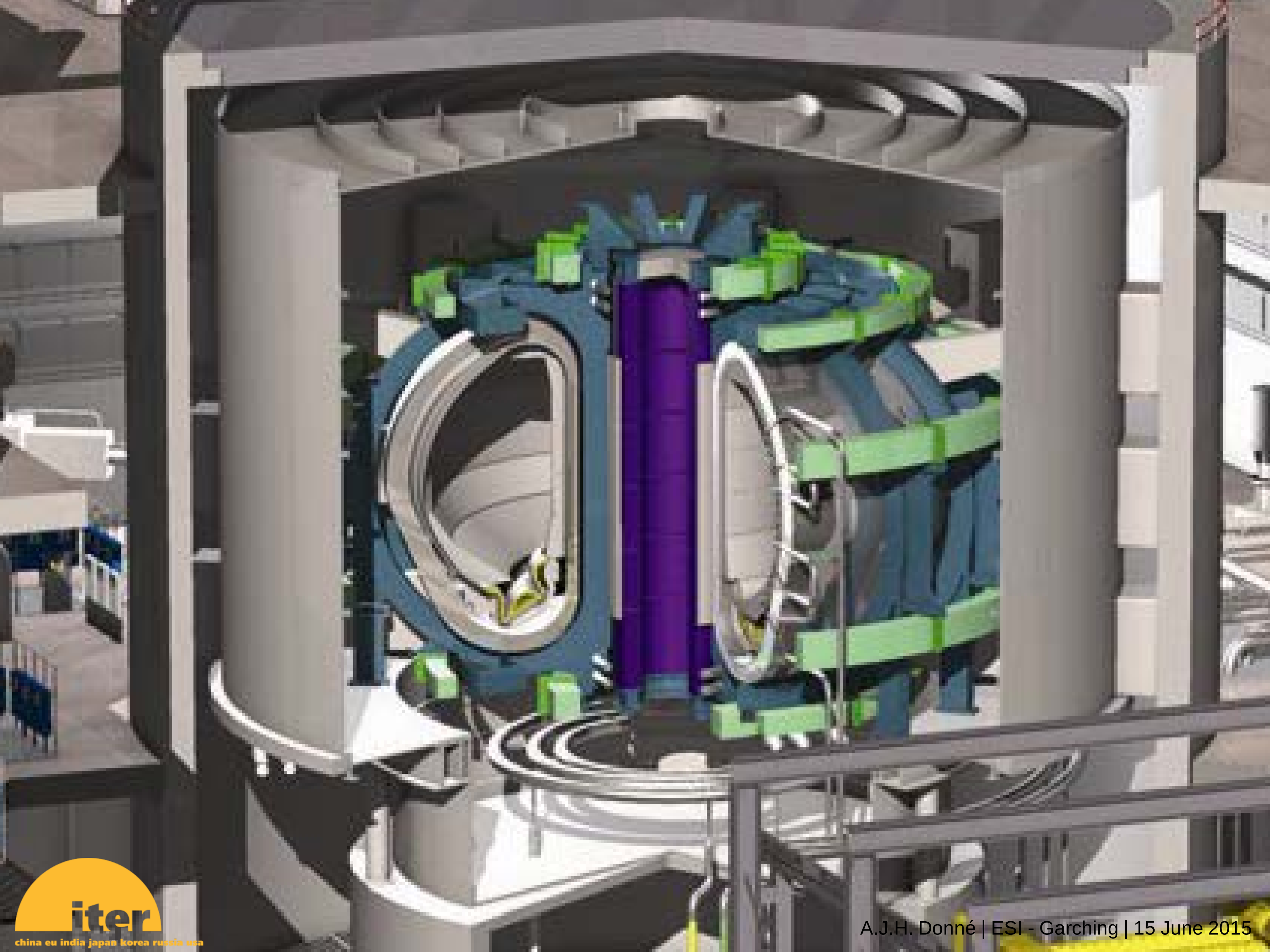


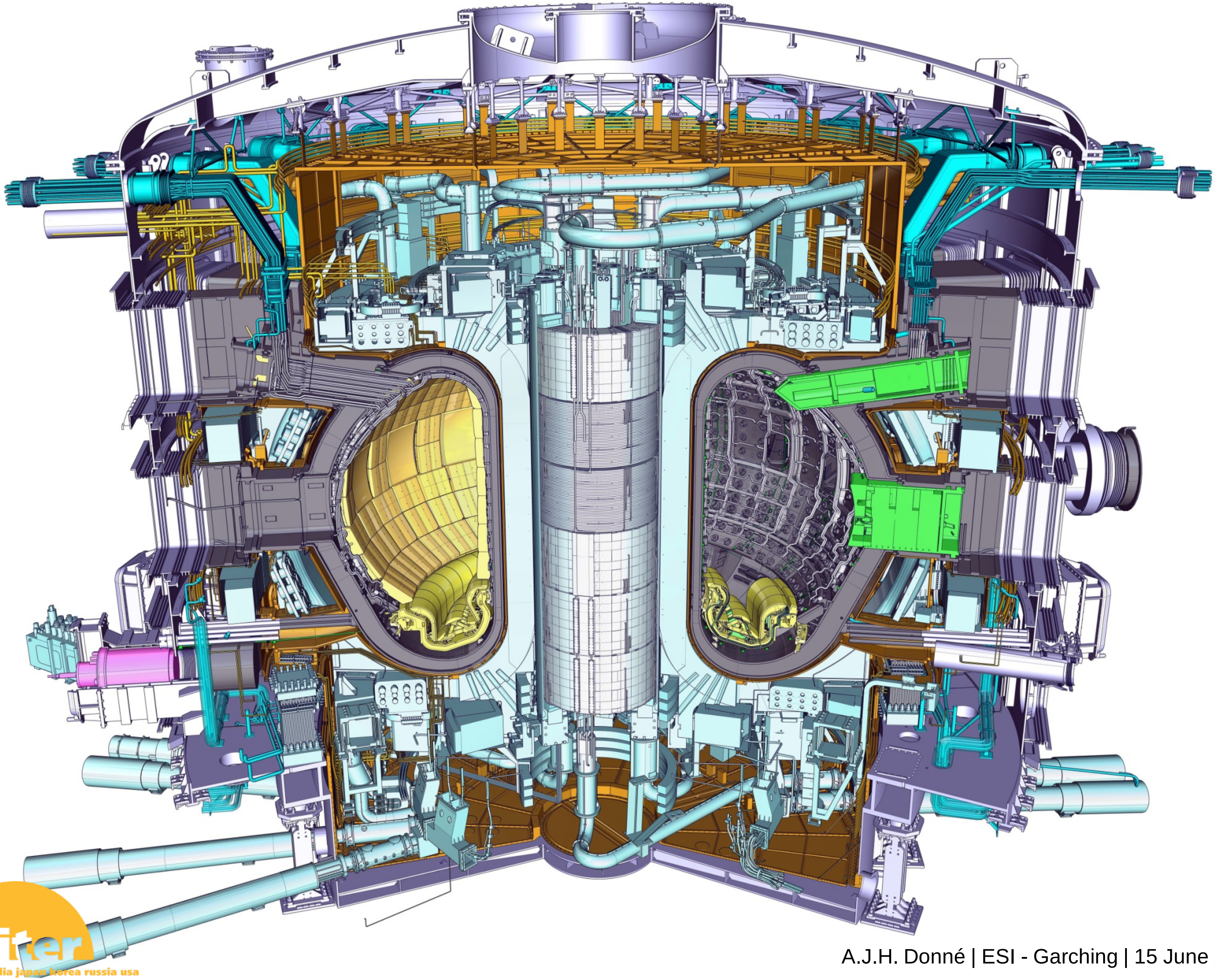
ITER: 34 countries

15.000.000 components




iter
china eu india japan korea russia usa





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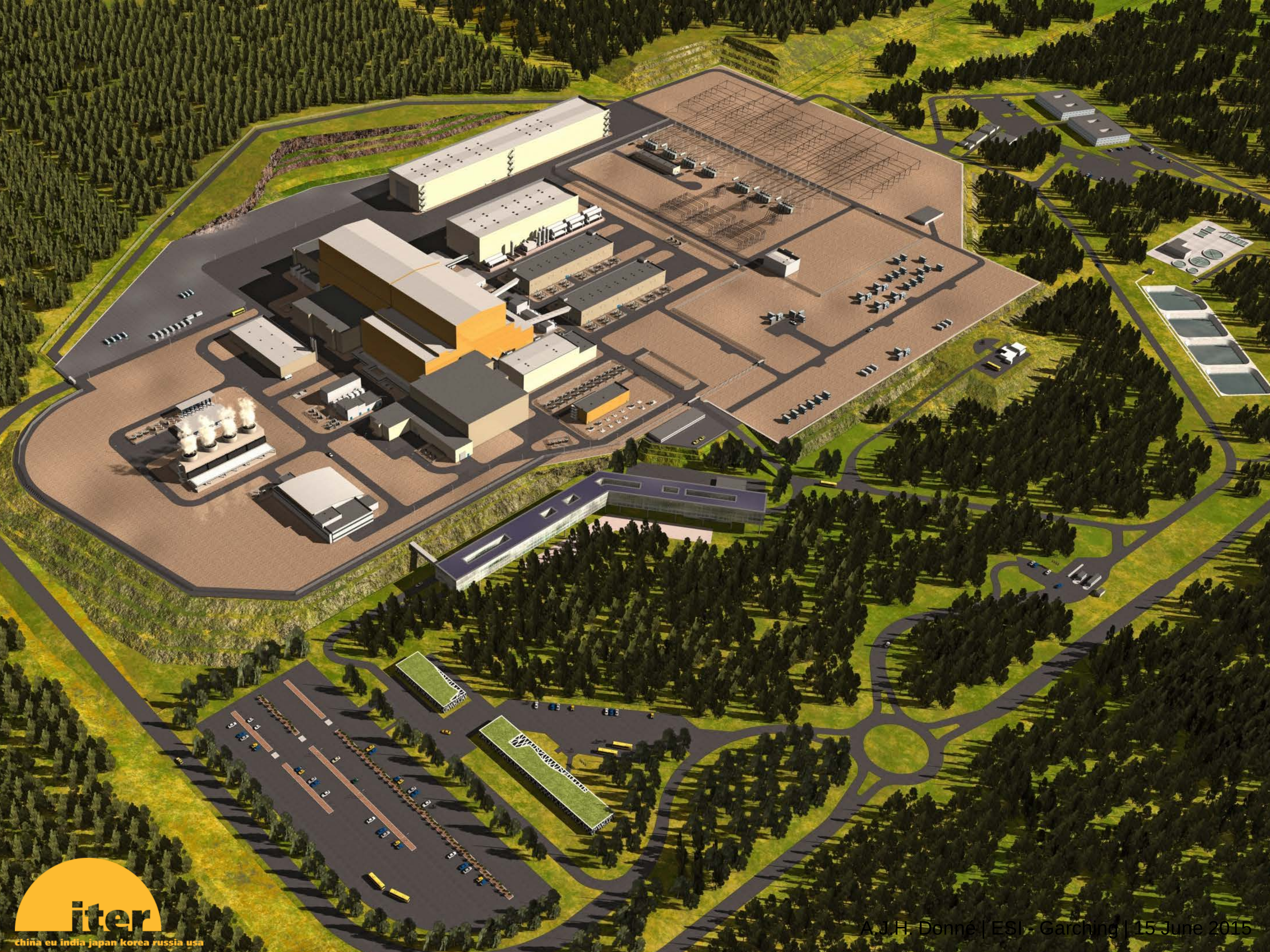
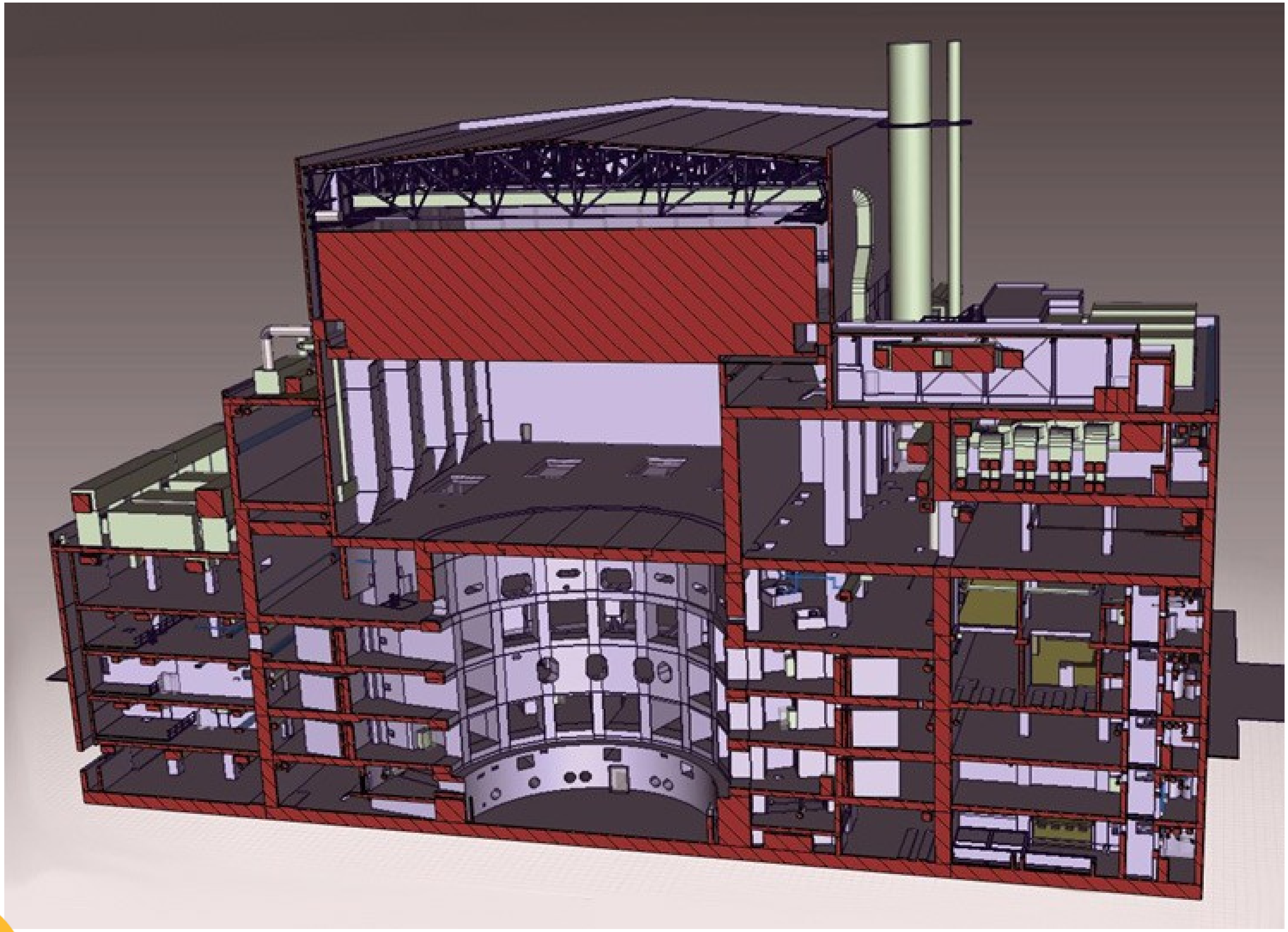
china eu india japan korea russia usa



ITER Tokamak building



ITER 2011: building has started

ITER Headquarters opened in Oct. 2012

Building for winding poloidal field coils

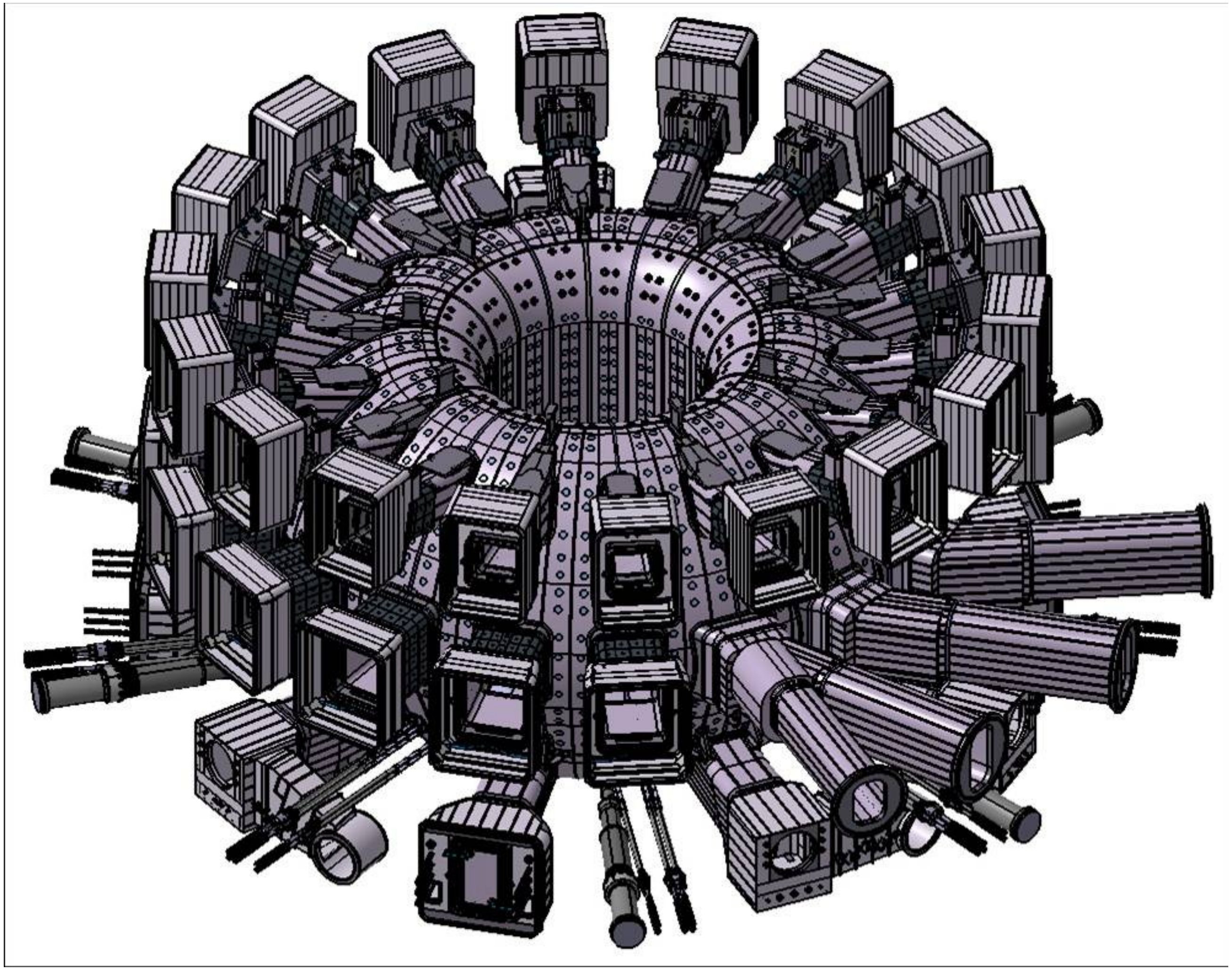
483 Seismic insulation pads

483 Seismic insulation pads

Preparation for laying the ground floor

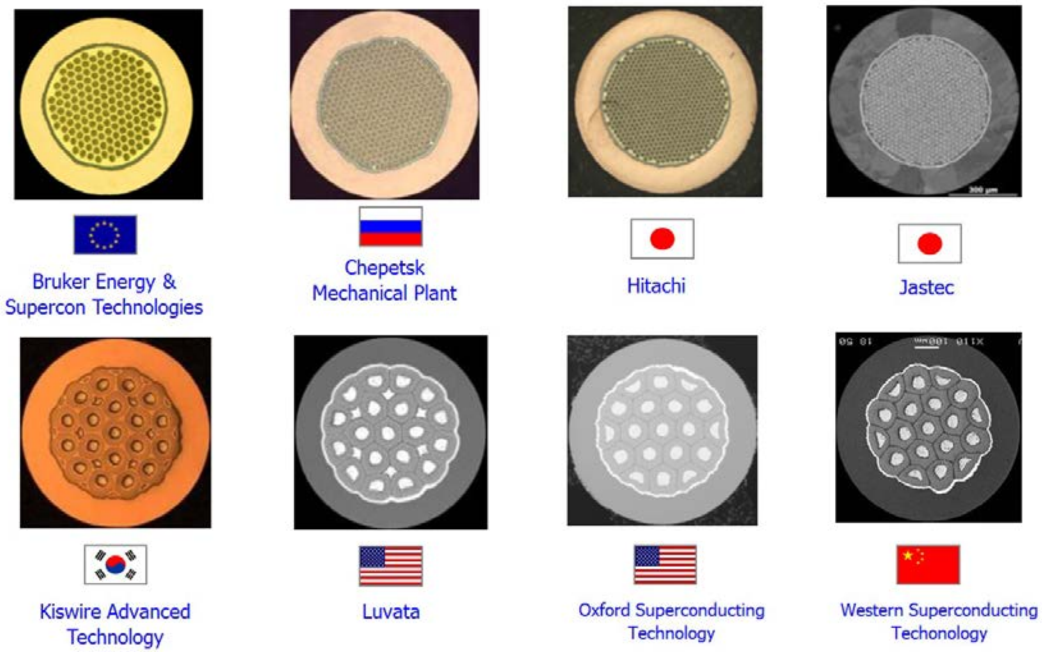
china eu india japan korea russia usa

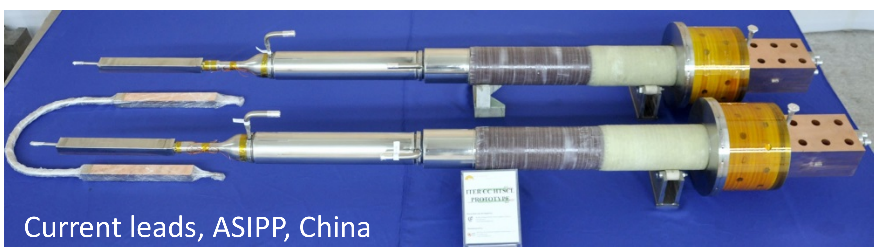
ITER vacuum vessel: more heavy than the Eiffel tower



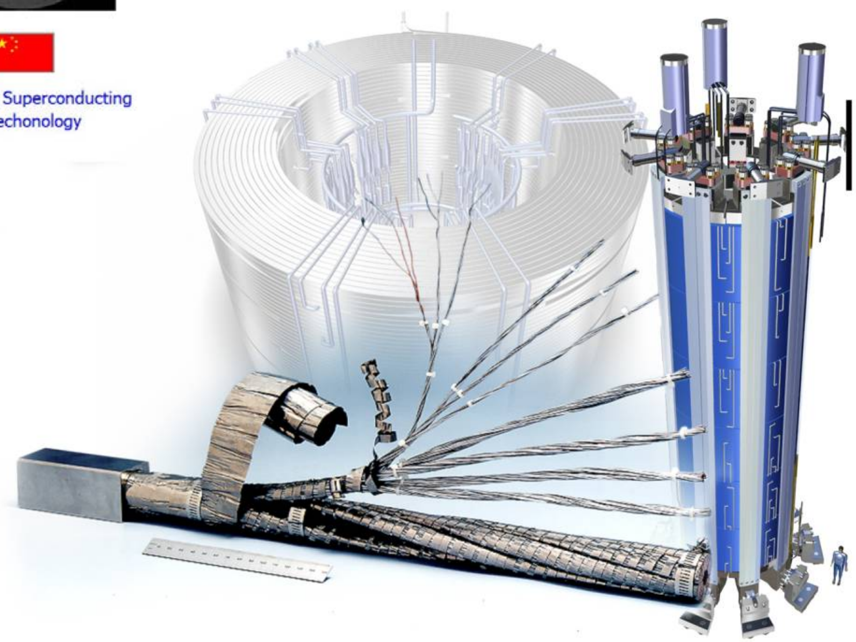
iter
china eu india japan korea russia usa

Superconducting cables



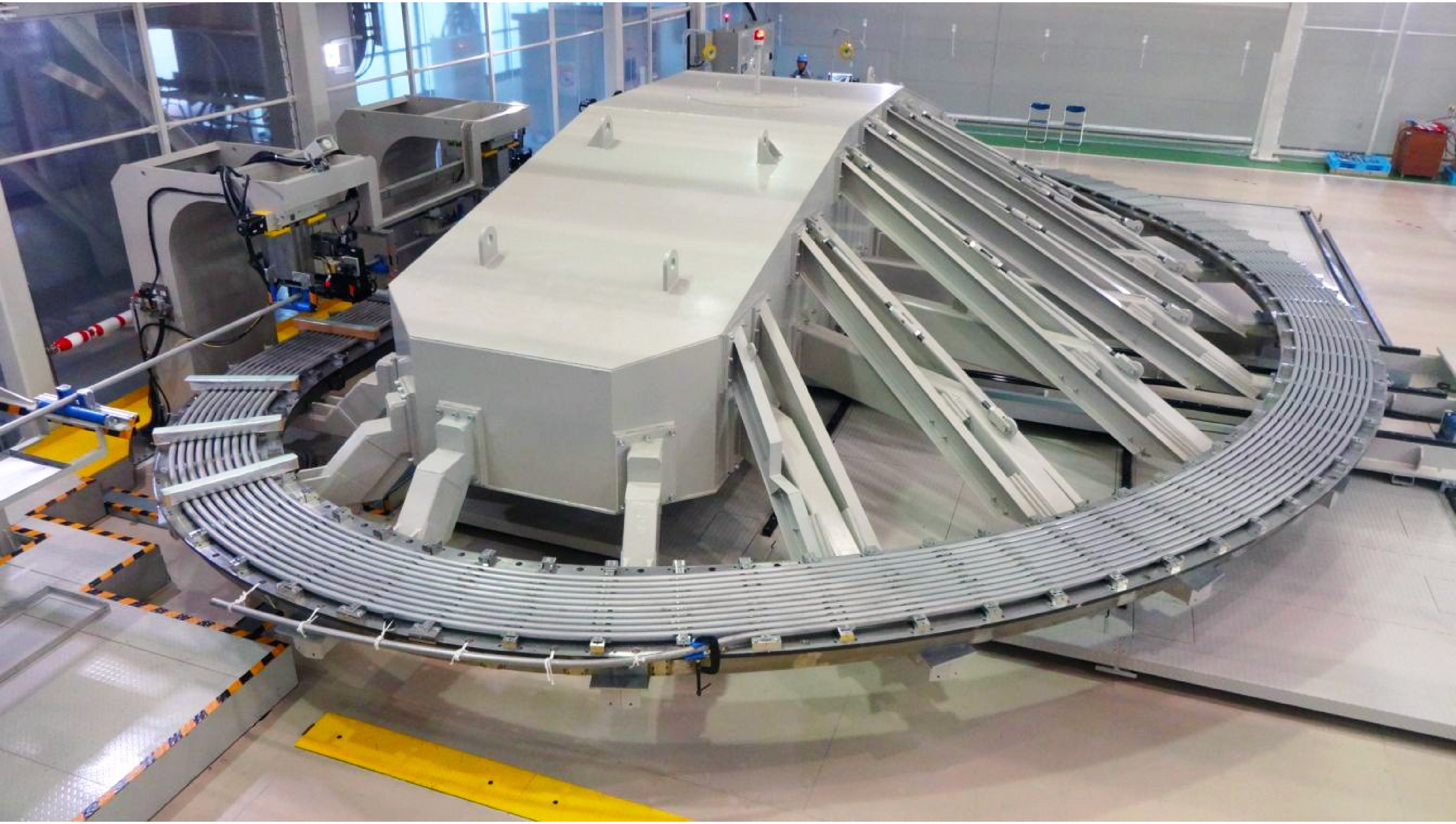


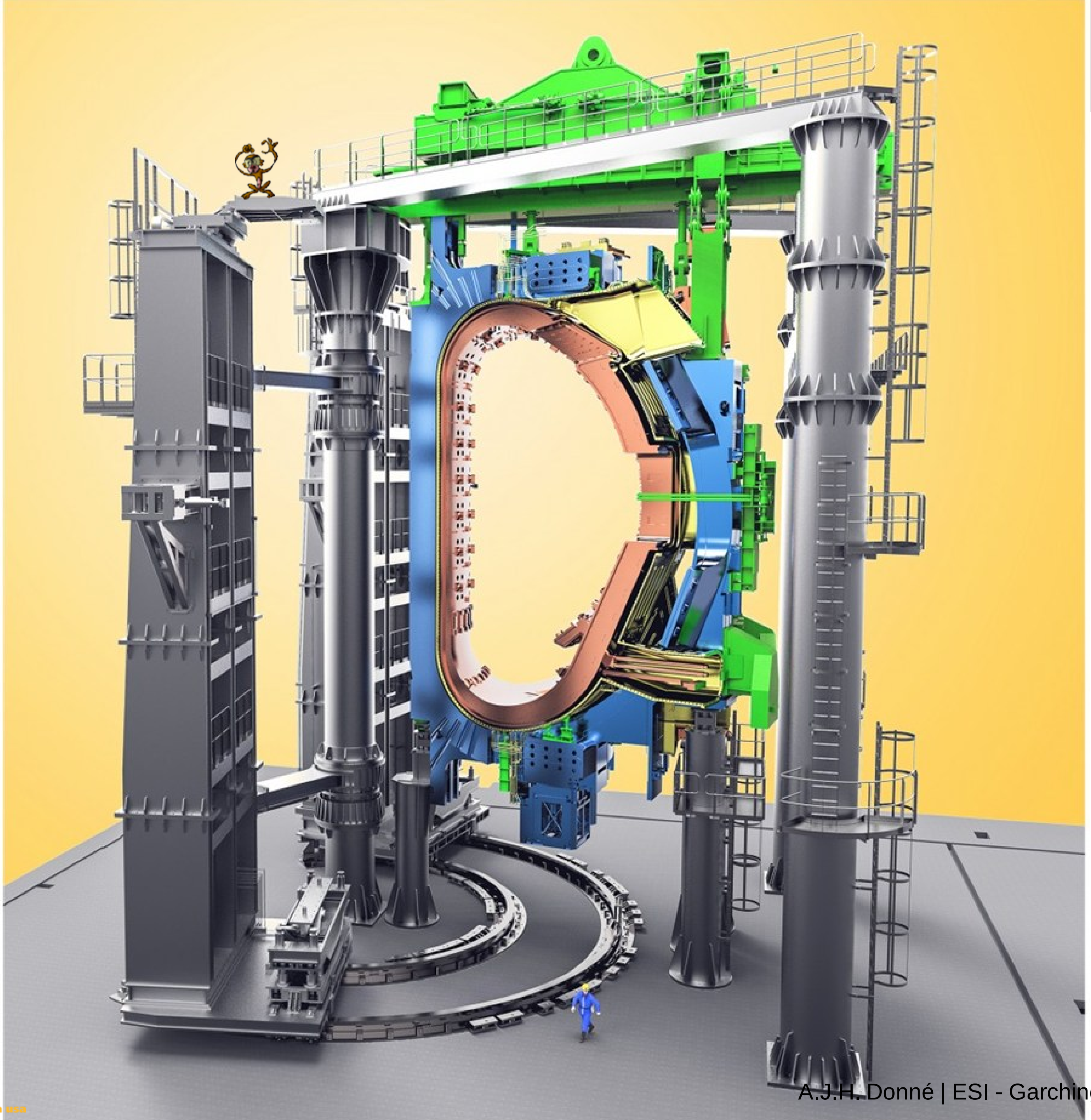
Current leads, ASIPP, China



Radial plates for the toroidal field coils

Winding the toroidal field coils





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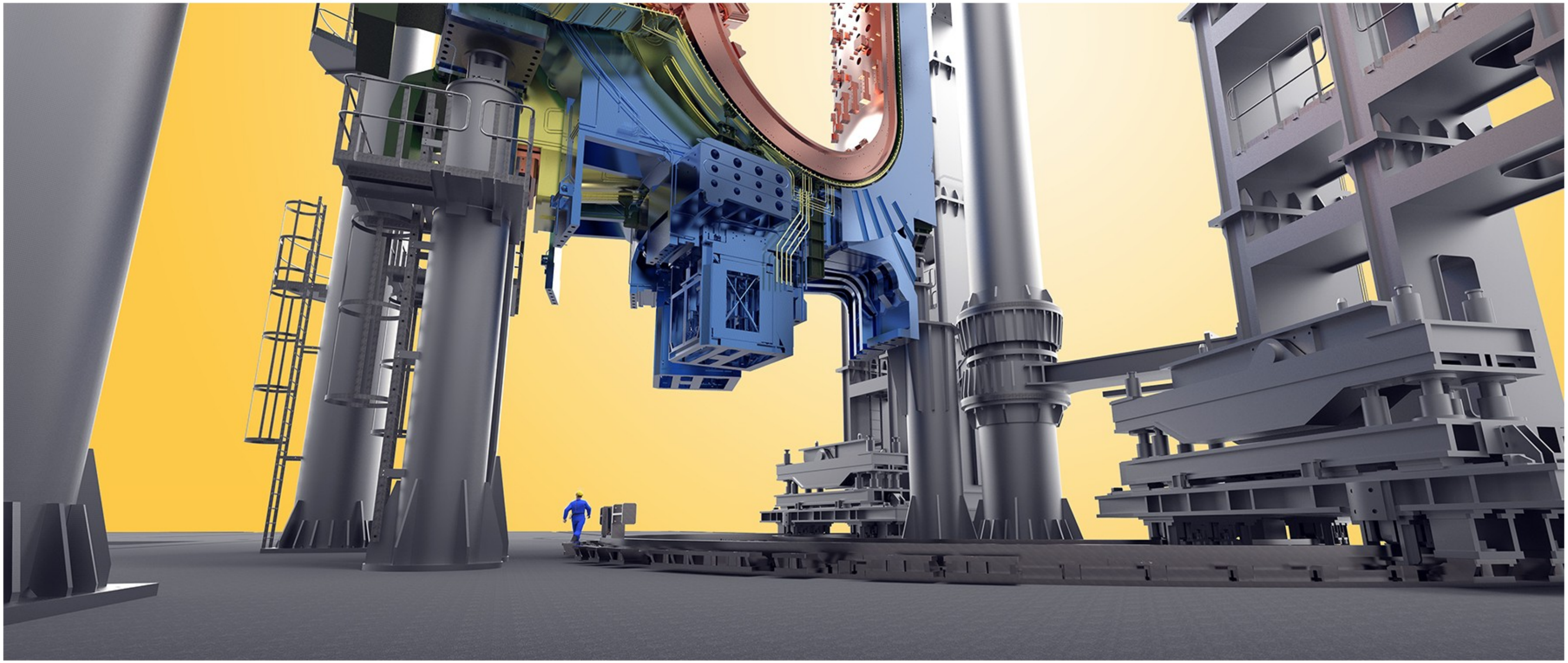
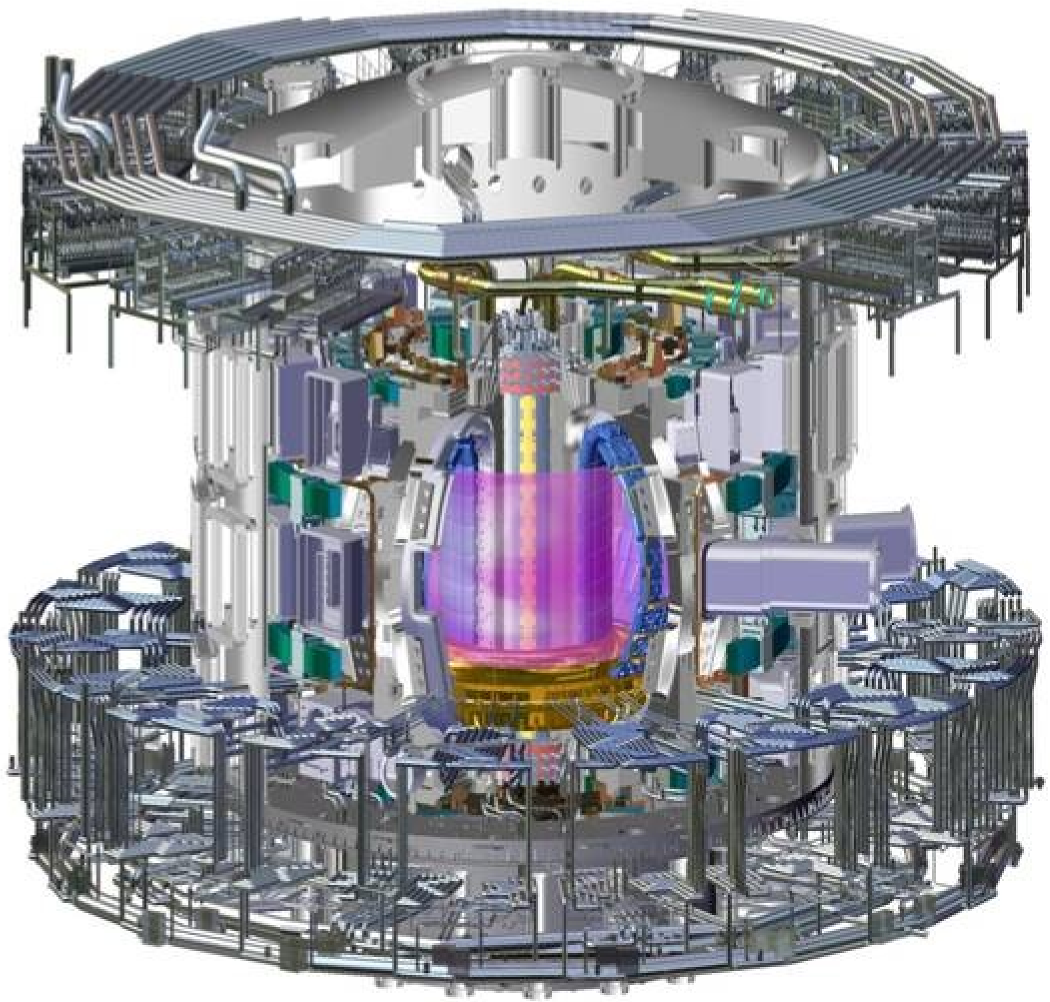
china eu india japan korea russia usa

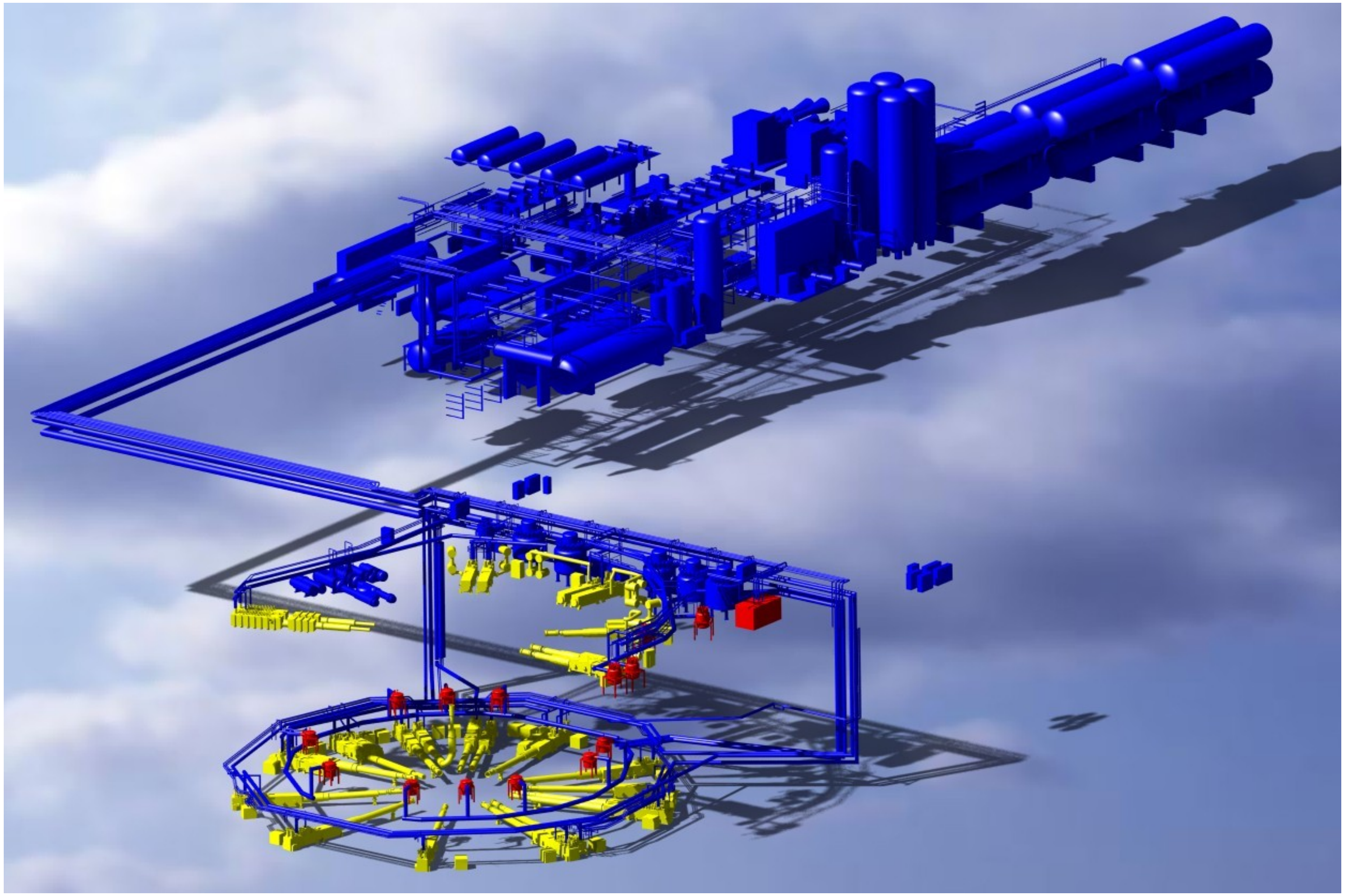


china eu india japan korea russia usa

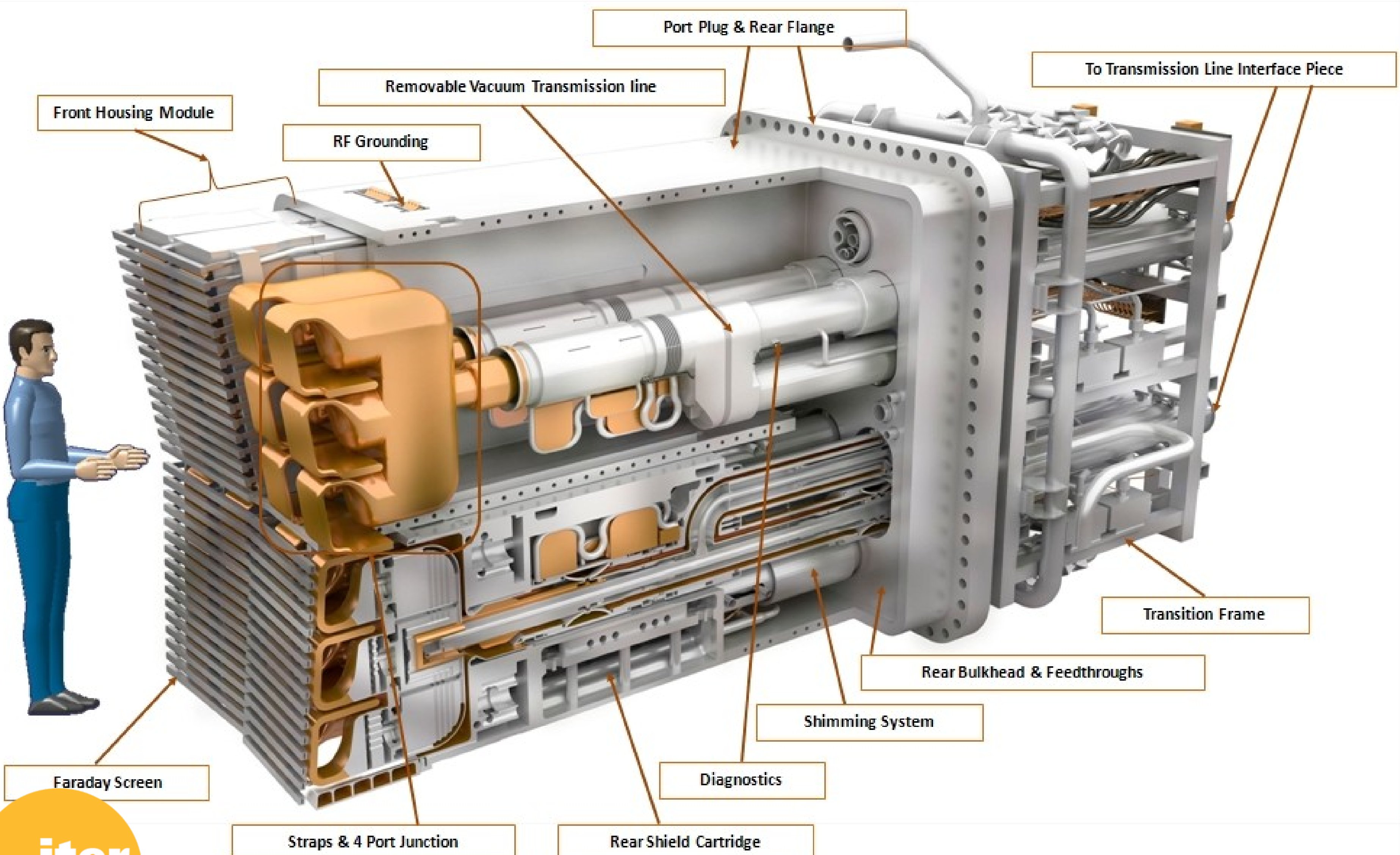
Cooling system



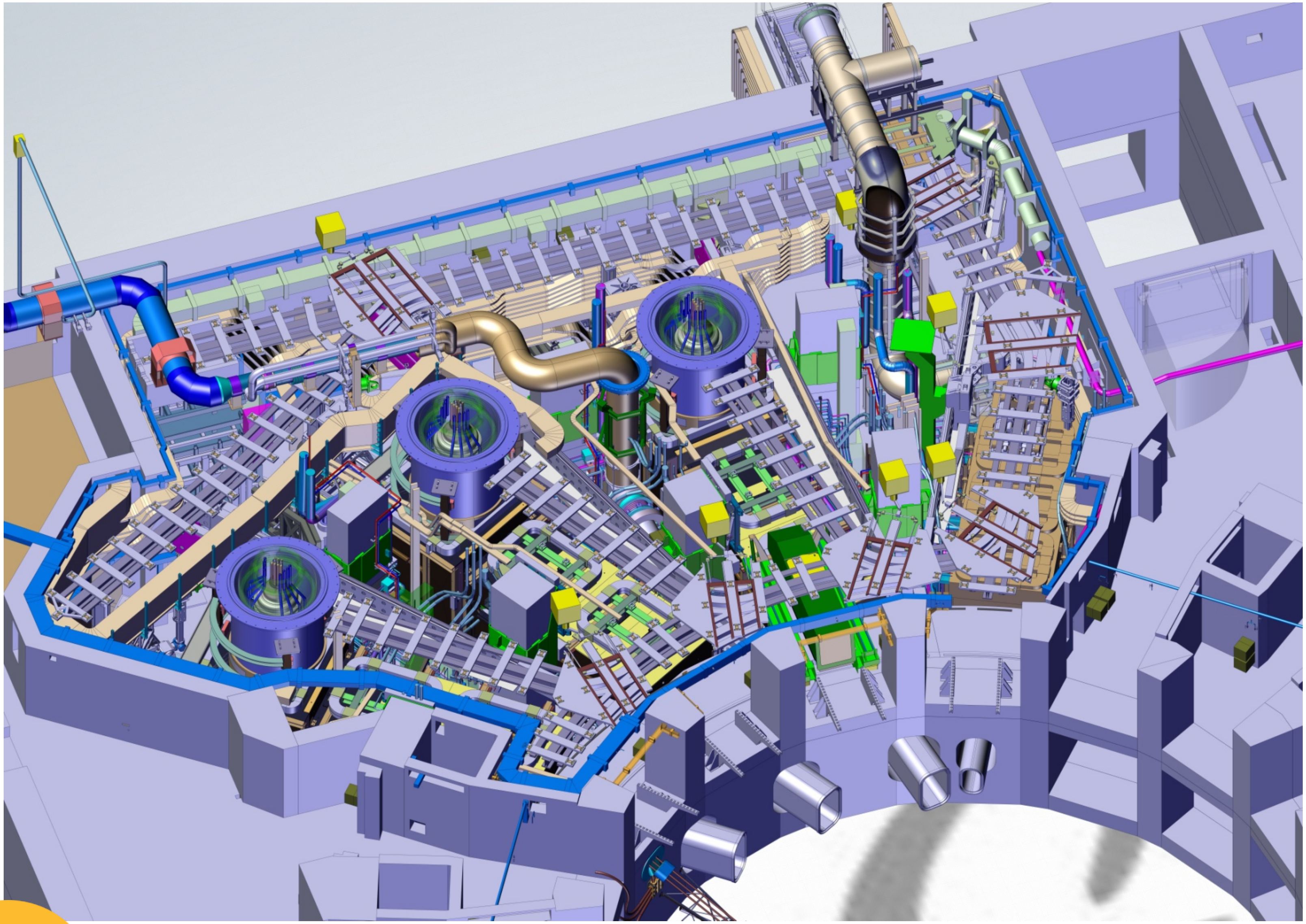
Cryogenic system



IC H&CD Antenna SYSTEM



Neutral Beam Heating



Transportation of heavy loads

iter
china eu india japan korea russia usa

Transportation of heavy loads

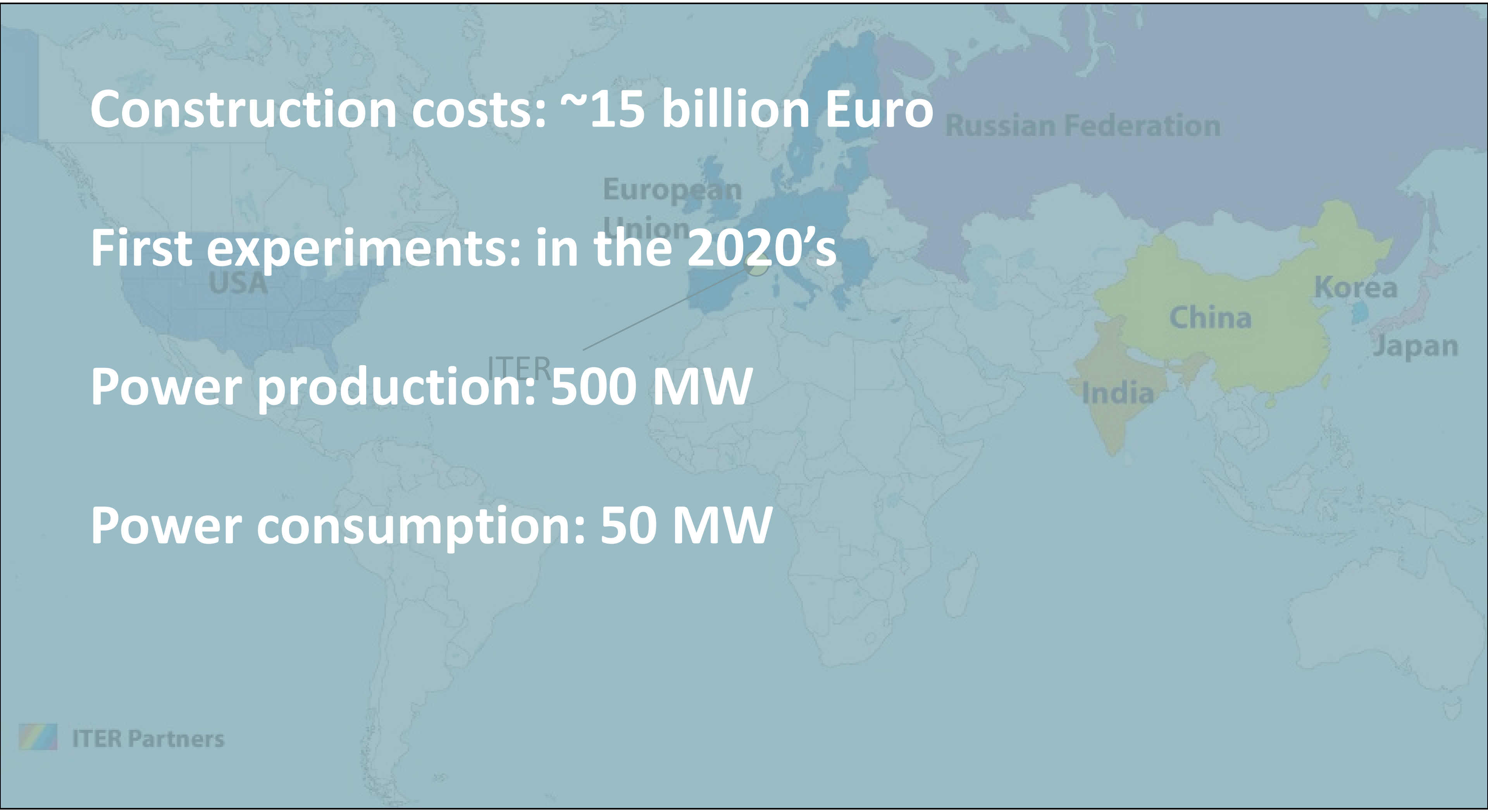
ITER is a world wide project

Construction costs: ~15 billion Euro

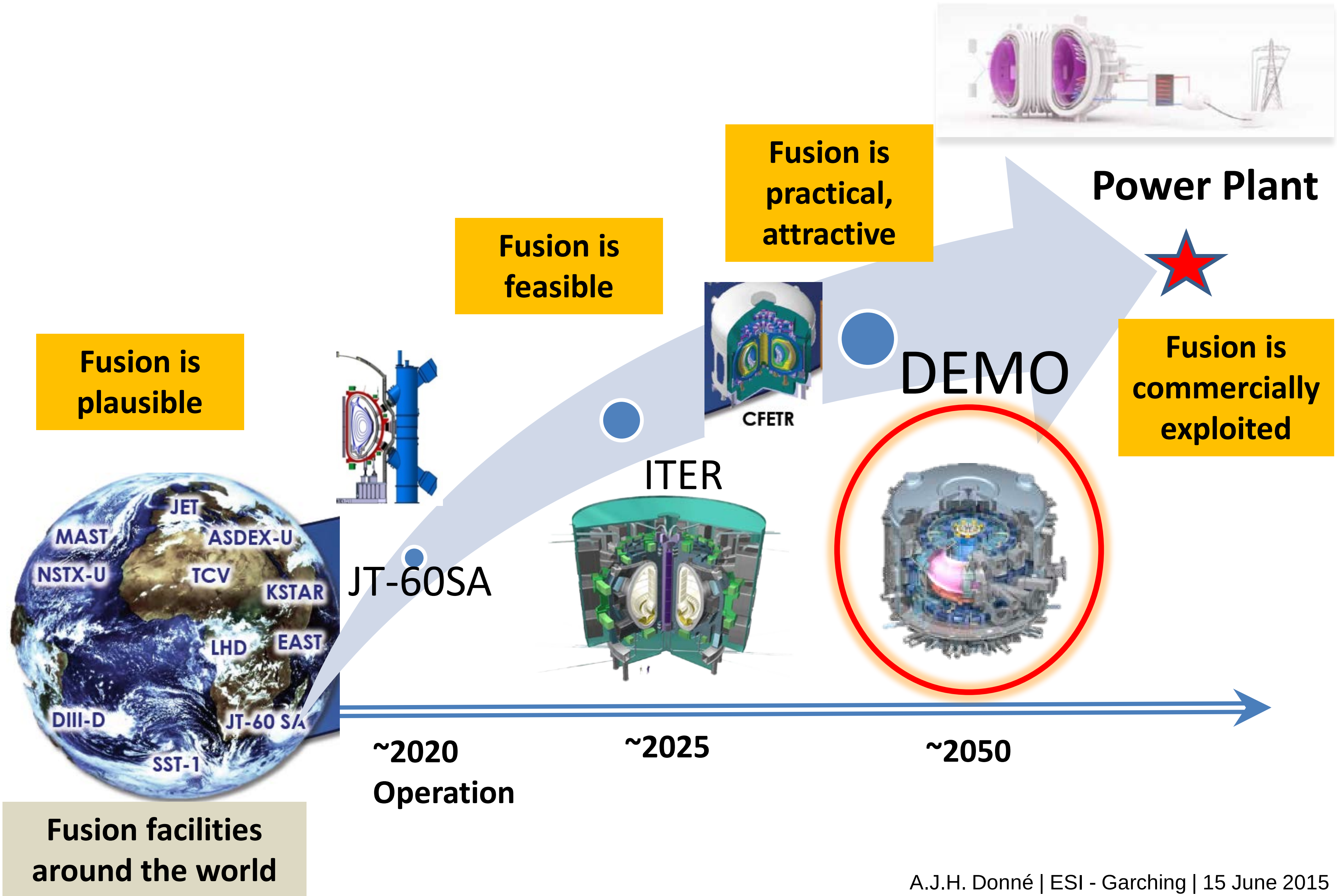
First experiments: in the 2020's

Power production: 500 MW

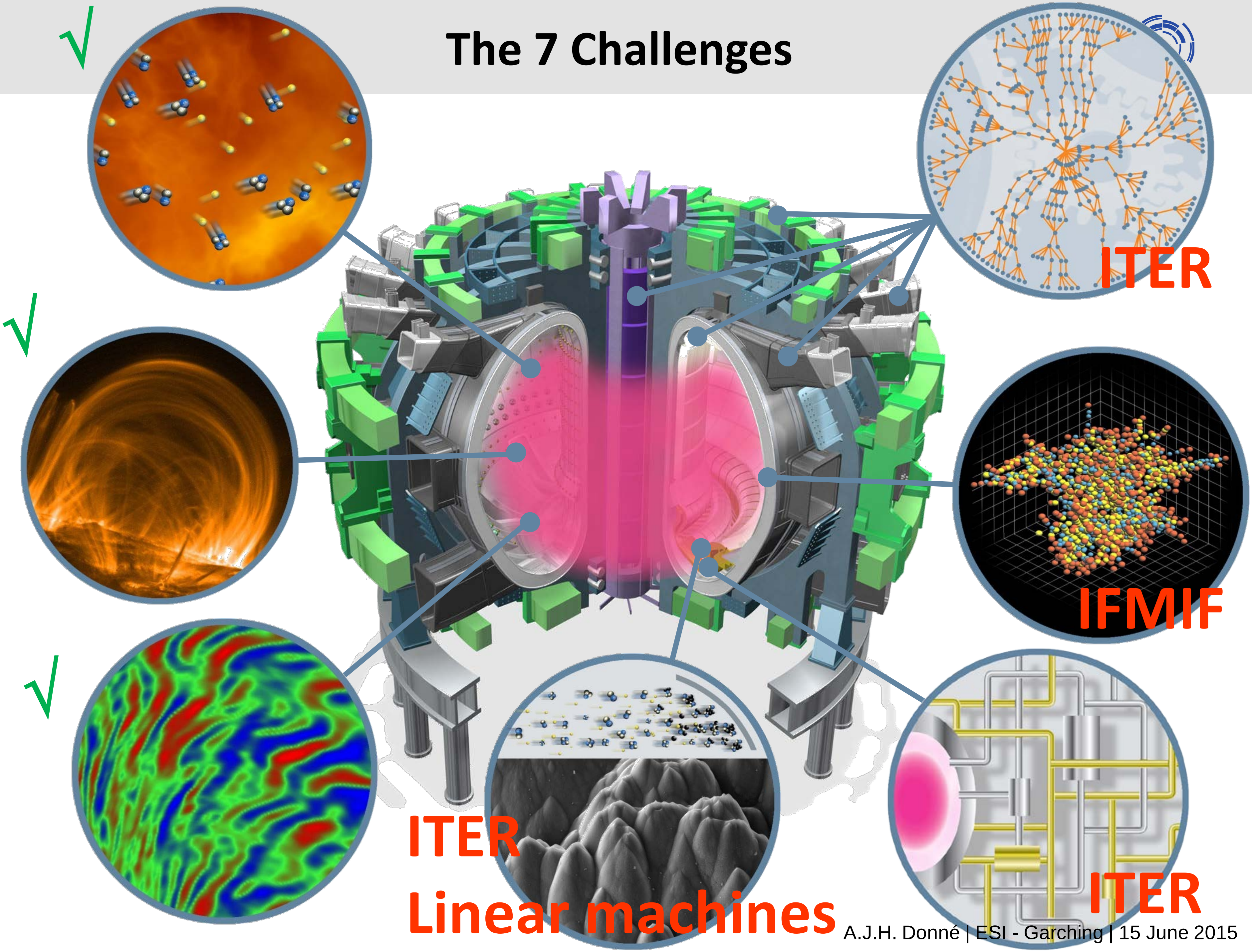
Power consumption: 50 MW



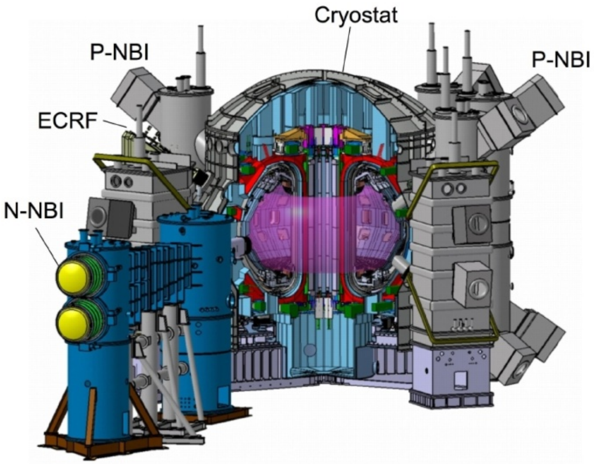
Roadmap towards fusion electricity

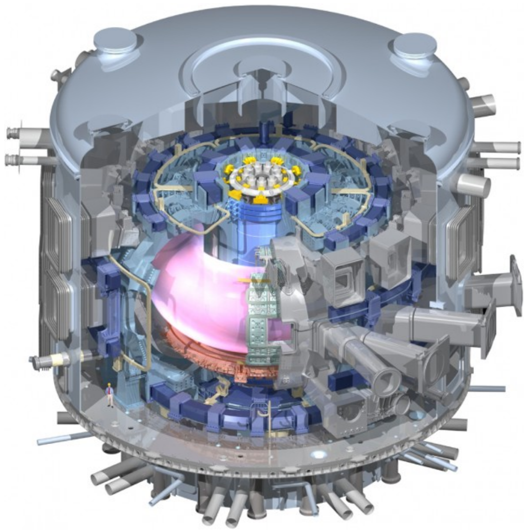


The 7 Challenges



1: Plasma Regimes of Operation





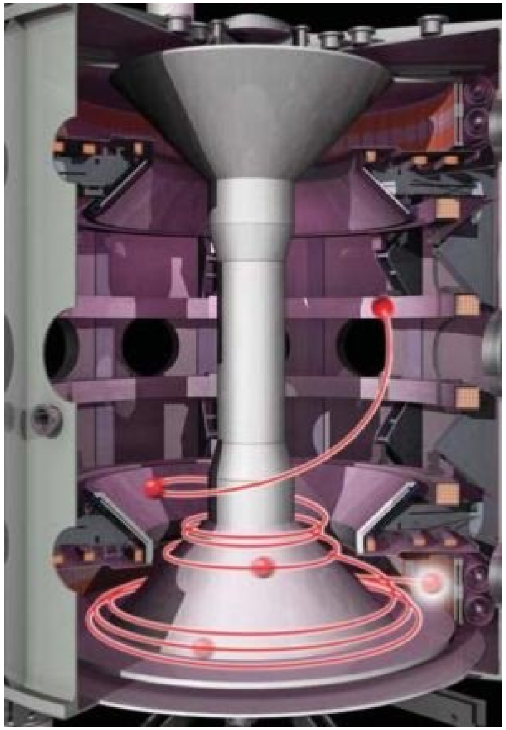
High fusion performance by reducing energy losses by turbulence and by controlling plasma instabilities.

To achieve acceptable power depositions in the divertor, radiate as much as possible power from the plasma without having adverse effects on the performance

Develop active methods the state of divertor detachment

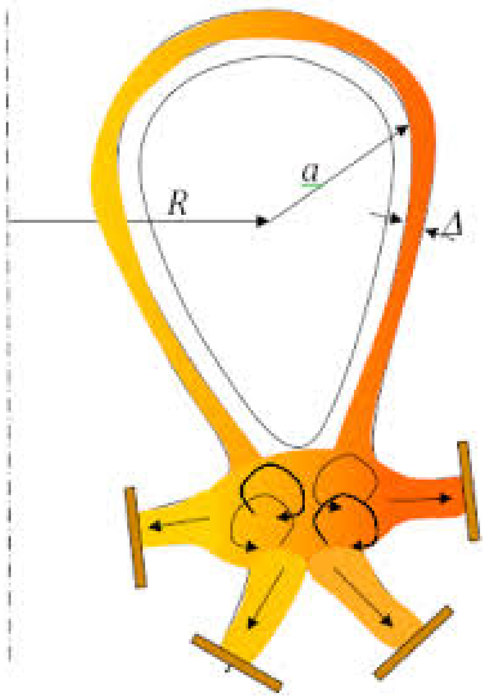
Try to achieve steady state conditions

Main devices:
JET, ASDEX, JT-60SA, ITER



Research in alternative divertor solutions (Super-X, snowflake, liquid metal divertors)

Research in order to understand detached divertor conditions



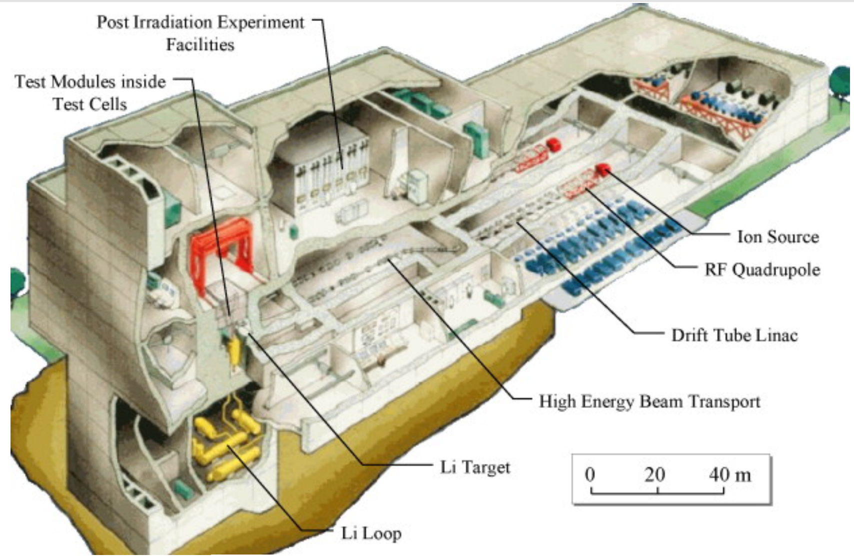
Research to find more robust materials

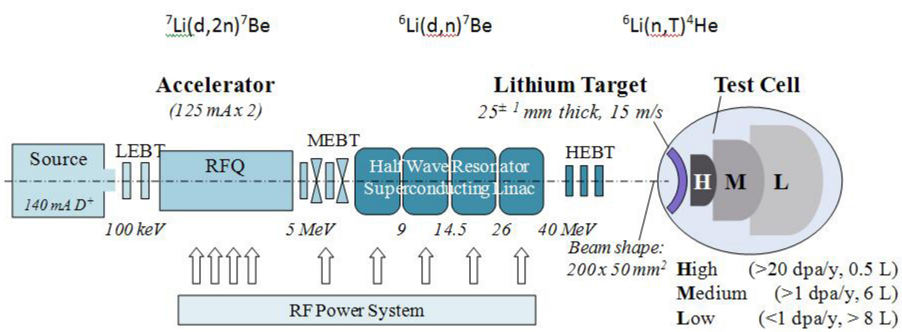
Main devices:
MAST, TCV,
Linear devices
Potentially a
Divertor Test Tokamak

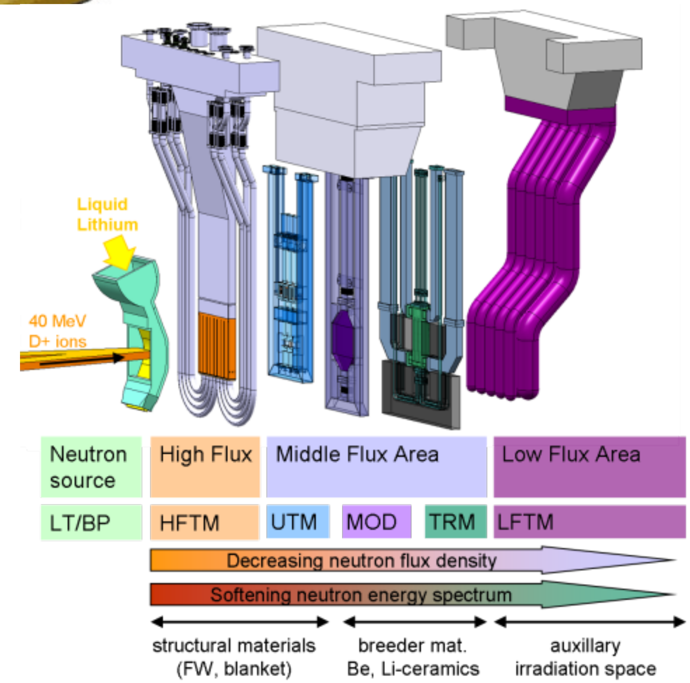
3: Neutron Resistant Materials

Full characterization of the baseline materials for DEMO:
EUROFER as structural material
Tungsten as Plasma Facing Component
Copper-alloys for cooling

Expand the operational range of these materials (e.g. EUROFER has an operational range of 350 – 550 °C



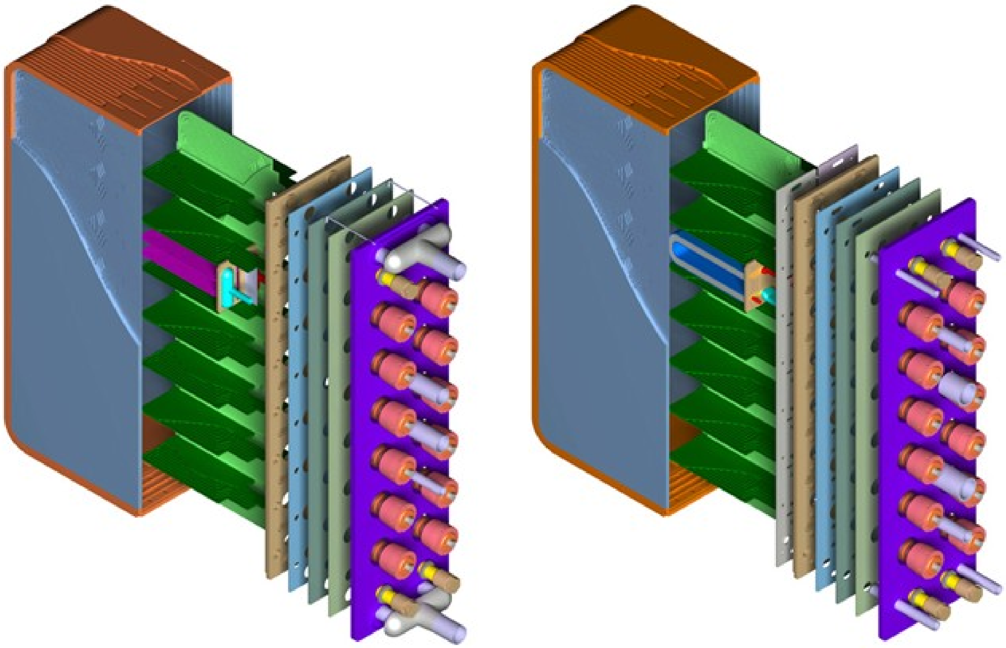




Main devices: IFMIF, Early Neutron Source, Irradiation facilities

4: Tritium self-sufficiency

Main question is whether a fusion reactor can produce enough tritium for its own fuel supply



Research concentrated on Two test blanket modules in ITER

Research in extraction of tritium from the blankets

Main devices (on ITER):

- TBM based on eutectic Pb-16Li and TBM on ceramic material; both using He as coolant
- Possibly also research in water-cooled Pb-16Li

5: Intrinsic safety features

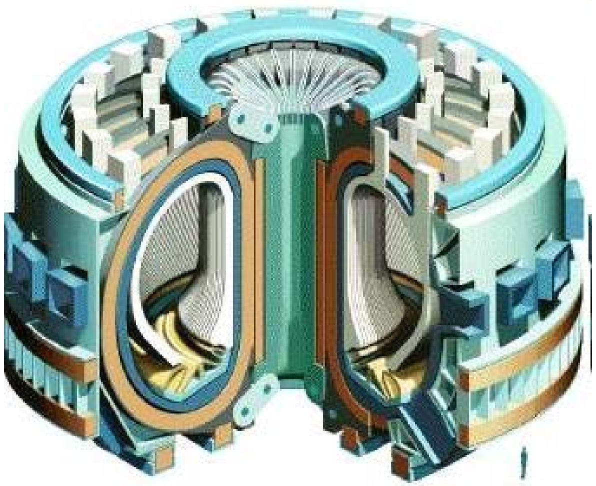
A relatively small mission to study the specific nuclear licensing procedures for DEMO and to study how the amount of radioactive waste can be reduced as much as possible.

Differences between ITER and DEMO in this respect are the much higher neutron and tritium fluences

Main device: ITER

6: Integrated DEMO design and system development

Find ways to reduce degradation of superconducting cables under continuously changing loads



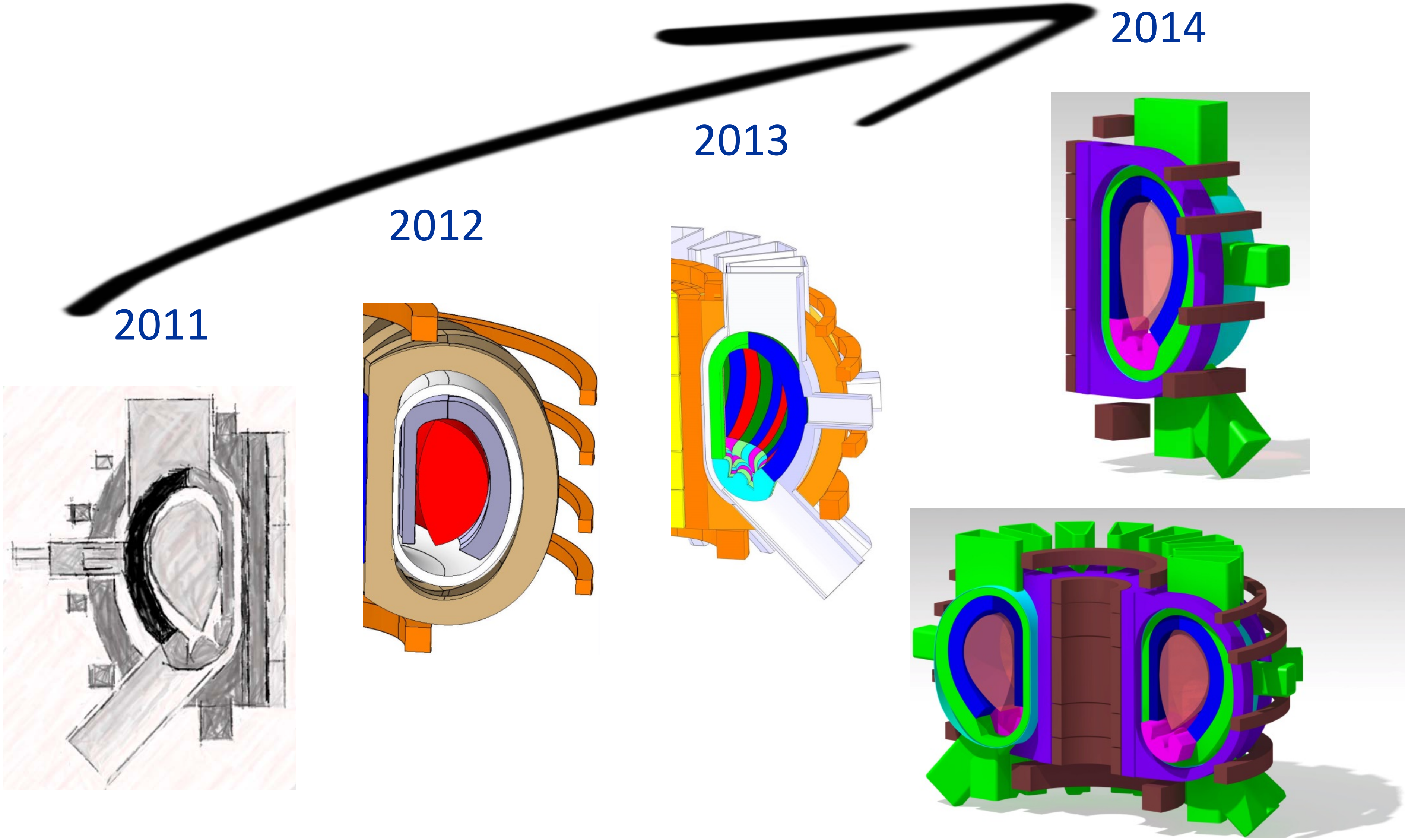
Study application of high T_c superconductors

Increase gyrotron frequencies for ECRH and ECCD to ~230 GHz

Optimize remote handling and remote maintenance strategies

Develop control strategies for underdiagnosed plasmas

6.1 Evolution of the DEMO CAD geometry



7: Competitive cost of electricity

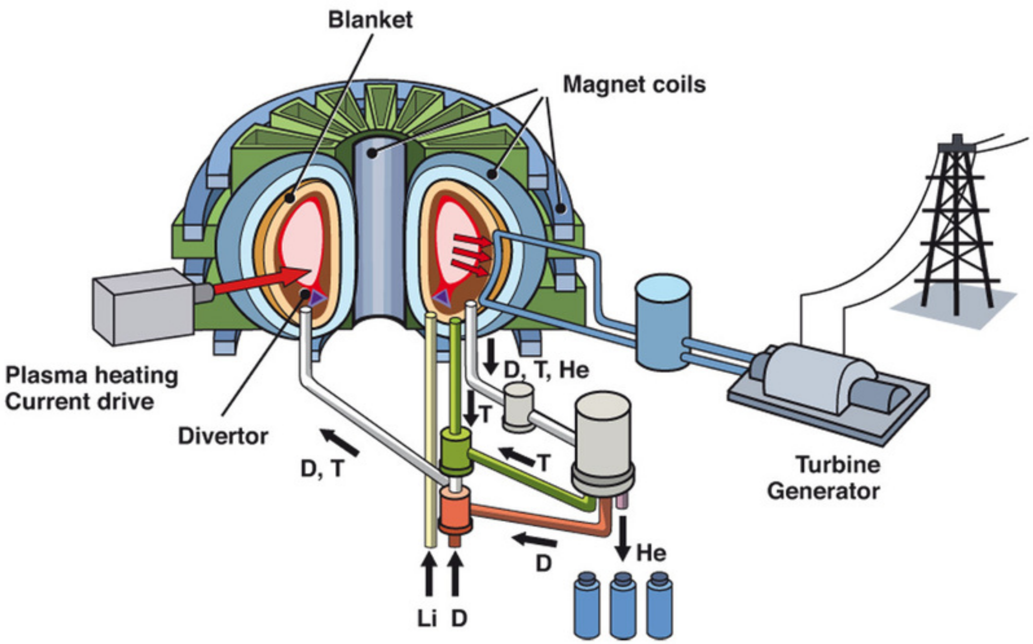
Which impact do design choices for DEMO have on the ultimate price of electricity:

Cheap and straightforward design solutions

Components with long life-expectancy

High machine availability

High temperature superconductors?

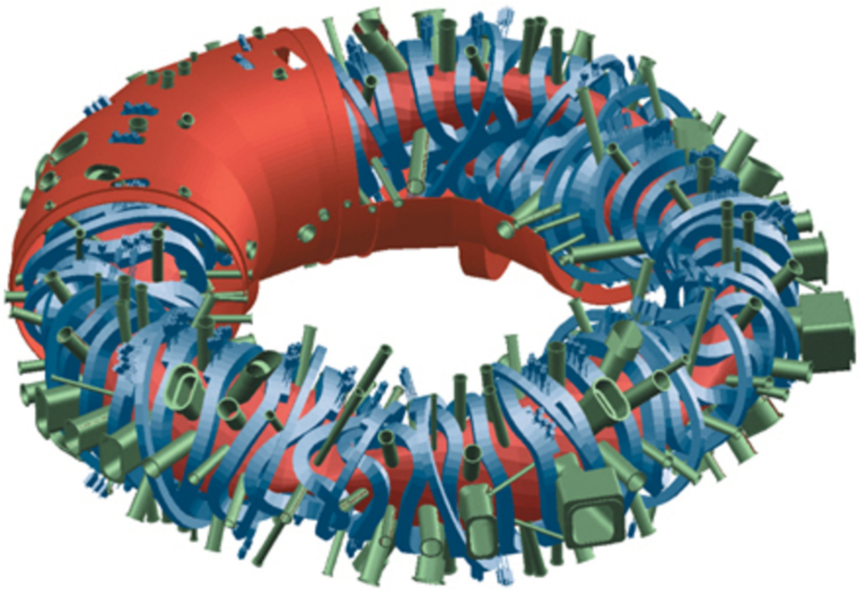


8: Stellarator

Stellarators are behind tokamaks performance wise

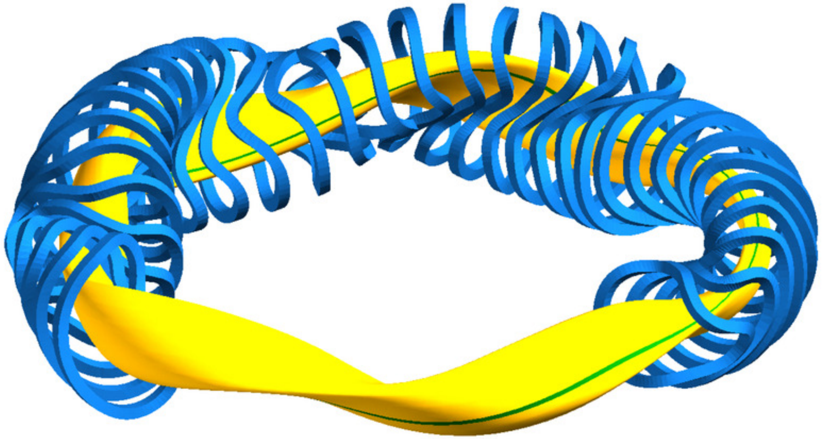
Stellarators are technically complicated

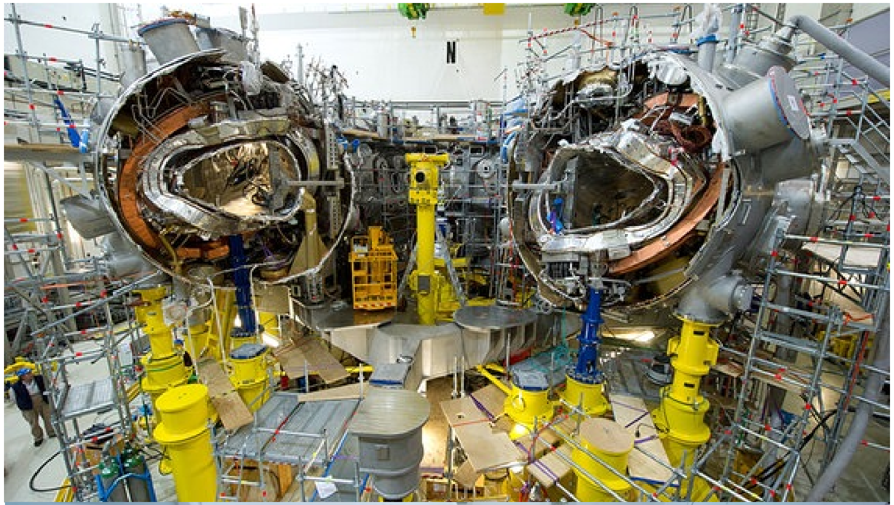
But, stellarators are by definition stable and steady state and they offer a number of important advantages for a fusion reactor

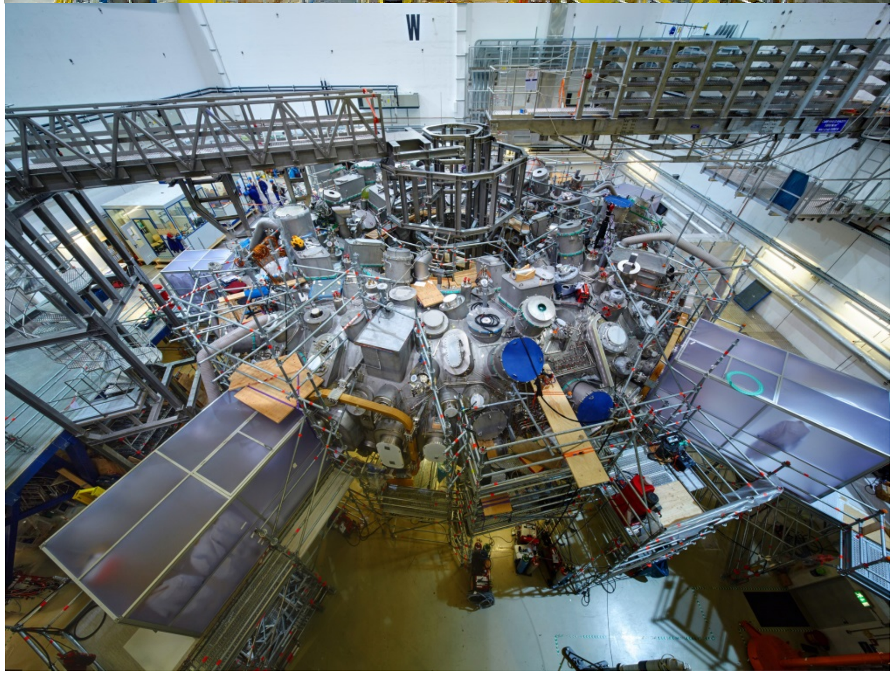


Main device: Wendelstein 7-X

8.1 Stellarator







Wendelstein 7-X

First operation in 2015


The End

Questions:

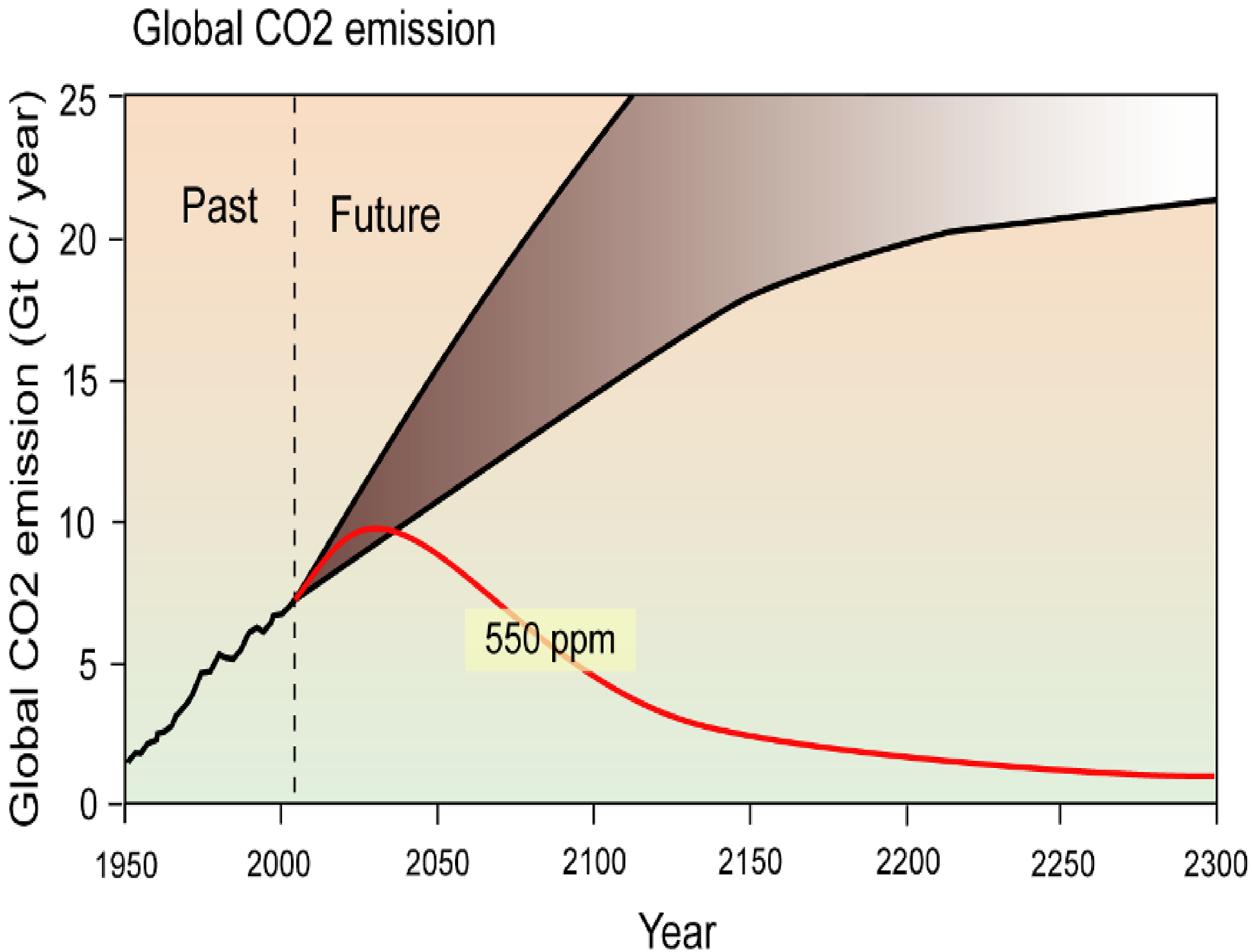
Safety

When do we have fusion and how expensive?

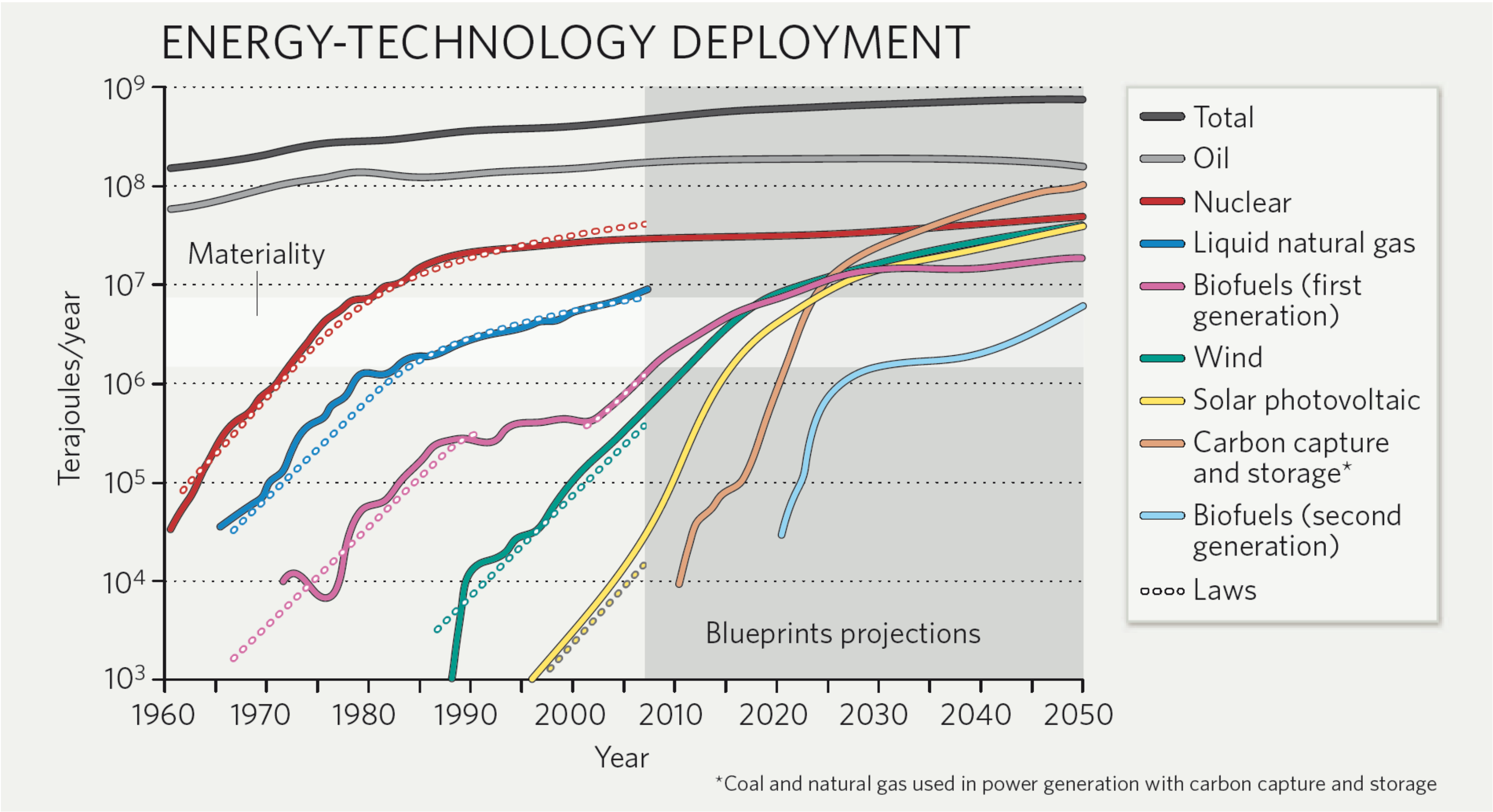
Other forms of fusion

Economy – what determines the cost

Does fusion come in time?

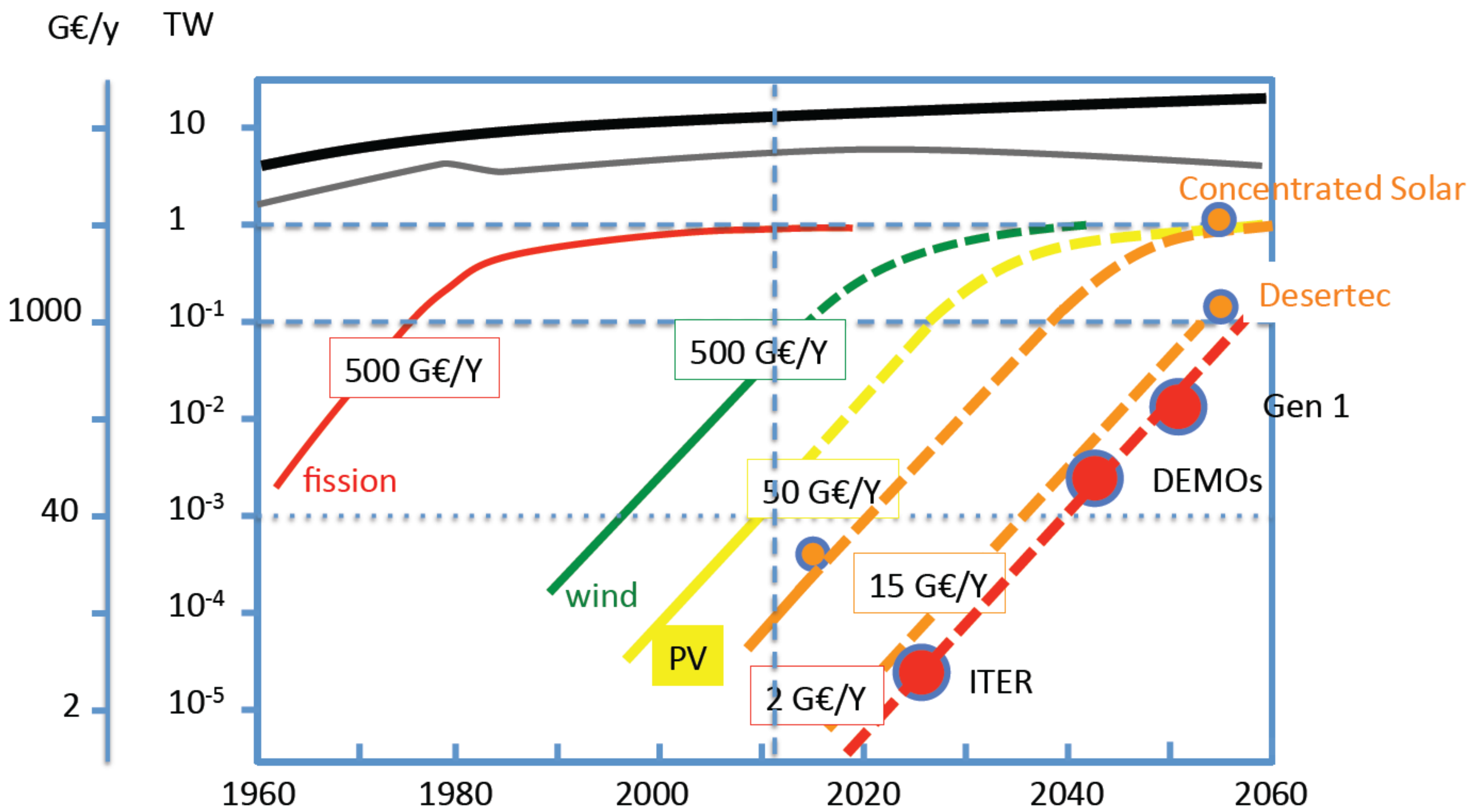


Growth of various energy sources



(G.J. Kramer, Nature 2009)

Fusion compared to other sources



(courtesy: N.J. Lopes Cardozo)

Safety

Fusion is no chain reaction

Fuel for only a few seconds

Safety

Deuterium and helium
are not radioactive

No transport of radioactive fuels
during reactor operation

No long-living nuclear waste

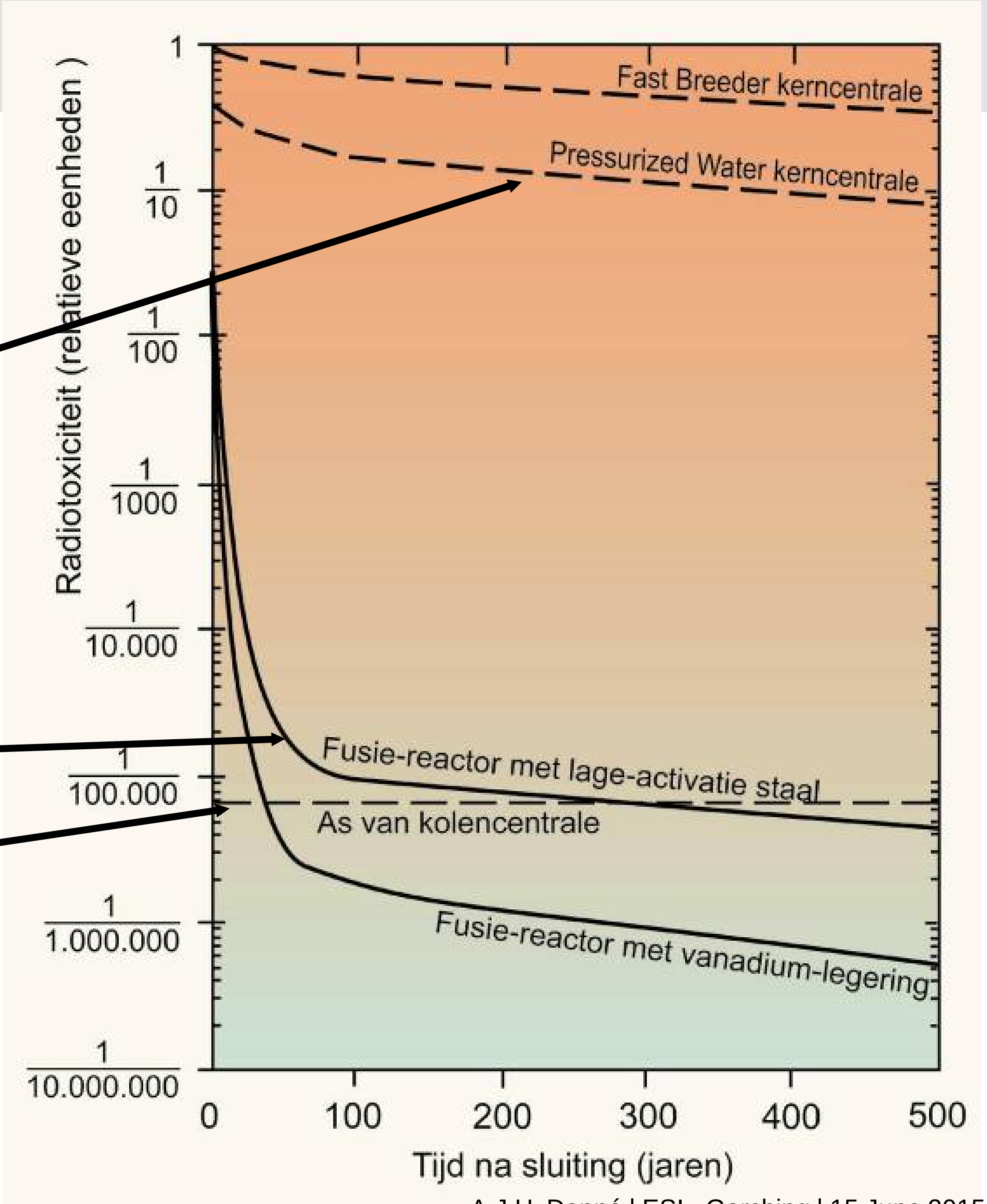
No emittance of green house gases

Nuclear waste

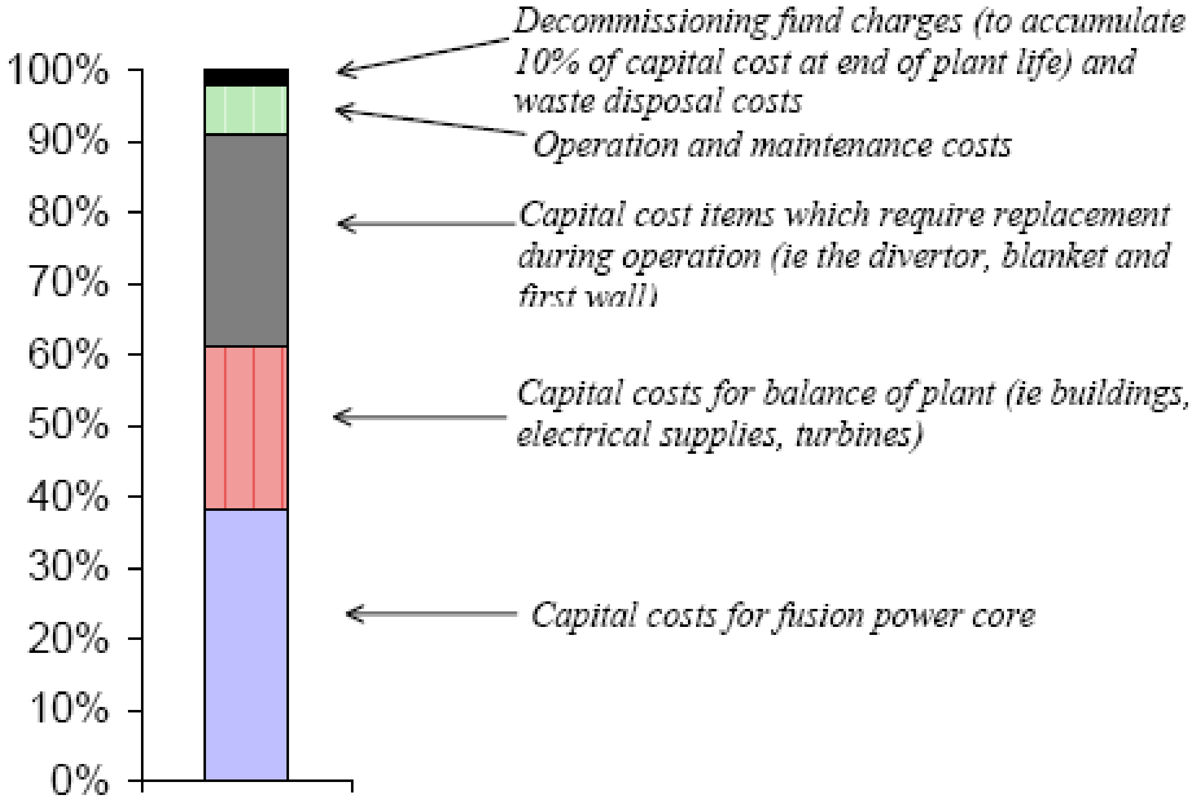
Nuclear fission

Nuclear fusion

Coal ash

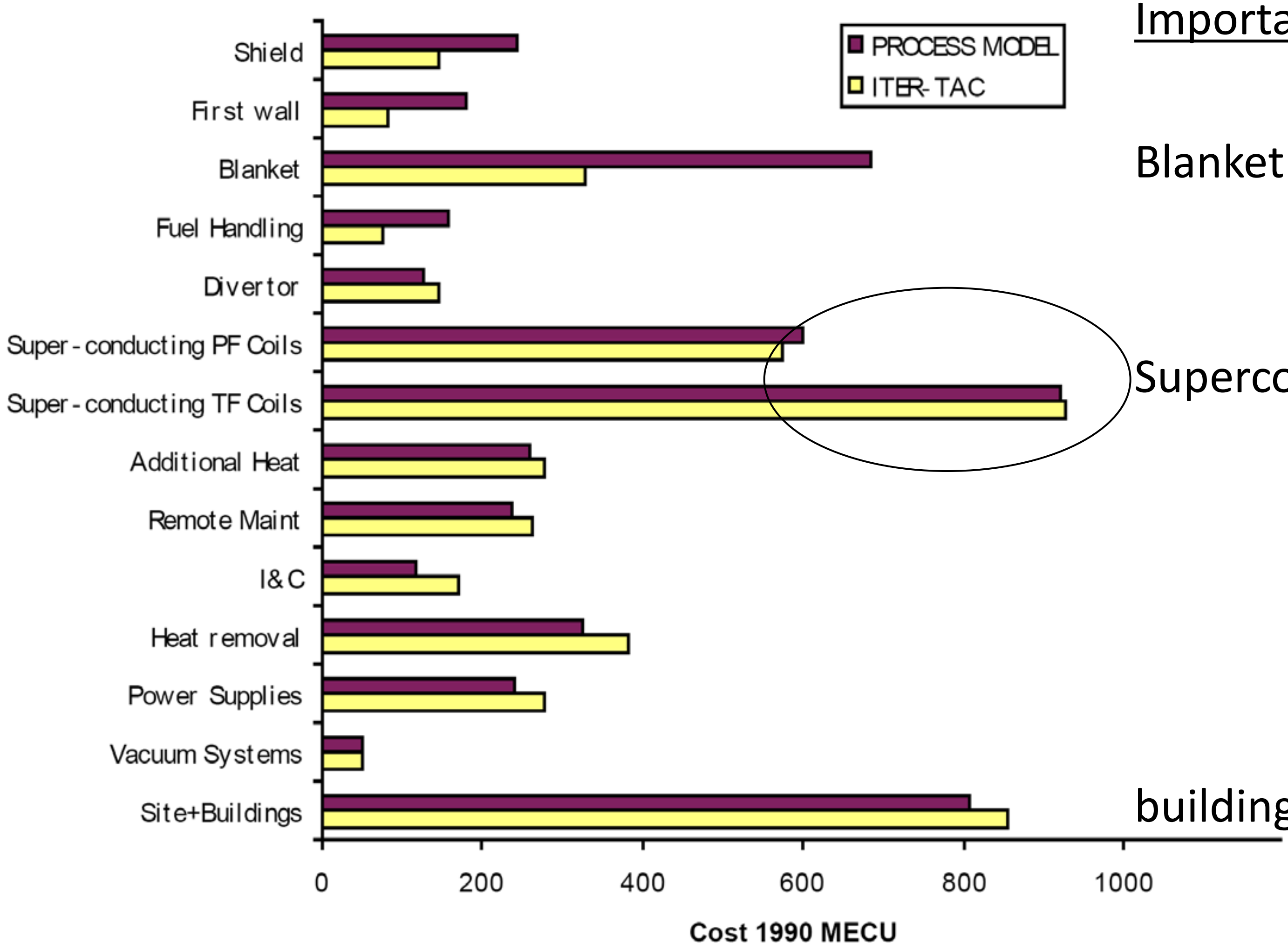


Economy: costs components



Fuel makes up only **0.5%** of the total costs!

Economy: Costs of the components



Important costs:

Blanket

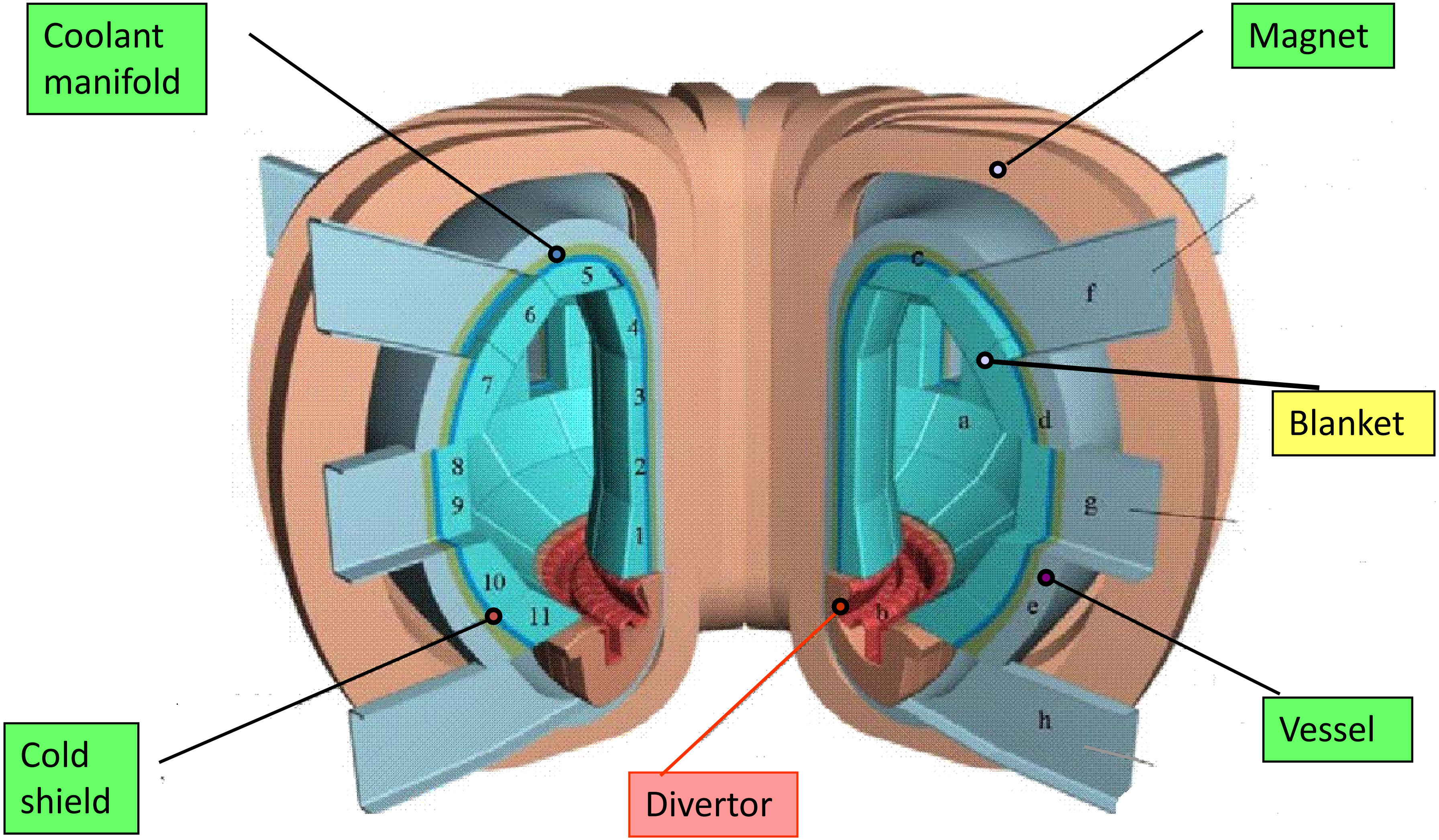
Superconducting coils

buildings

Permanent

5-6 year

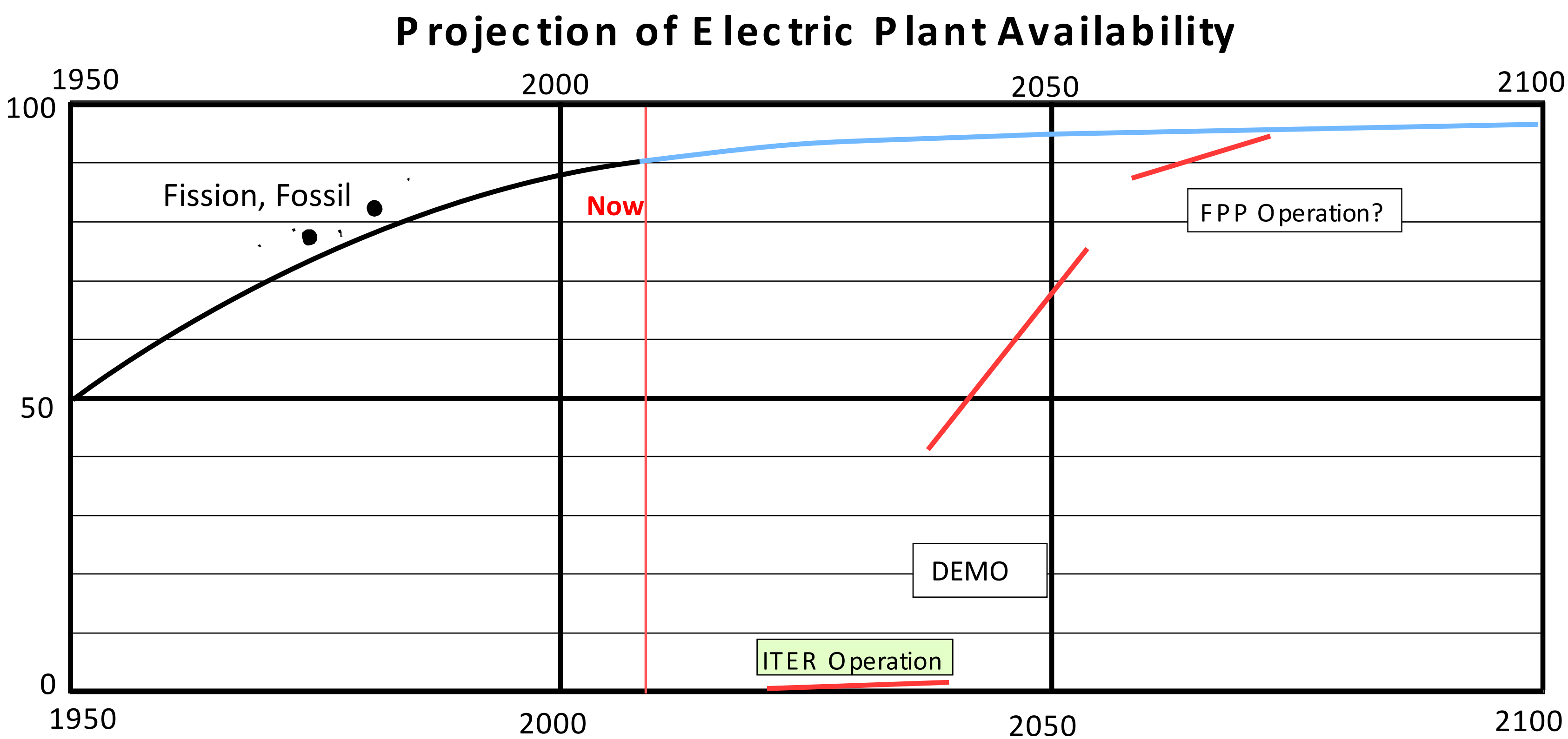
2 year



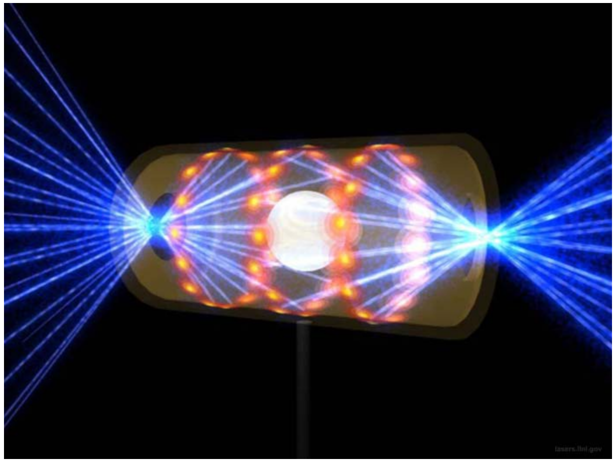
(Power Plant Conceptual Study)

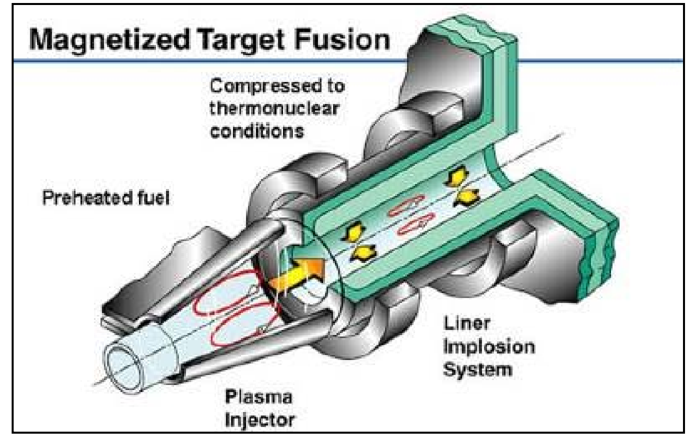
Economy: availability

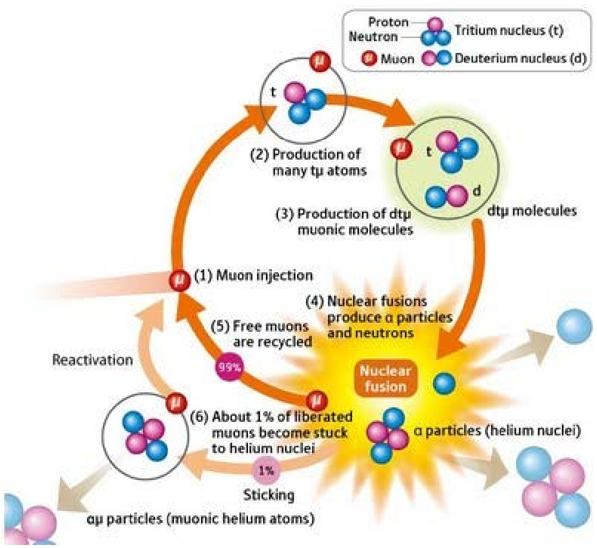
Availability should grow in going from ITER via DEMO to the Fusion Power Plant



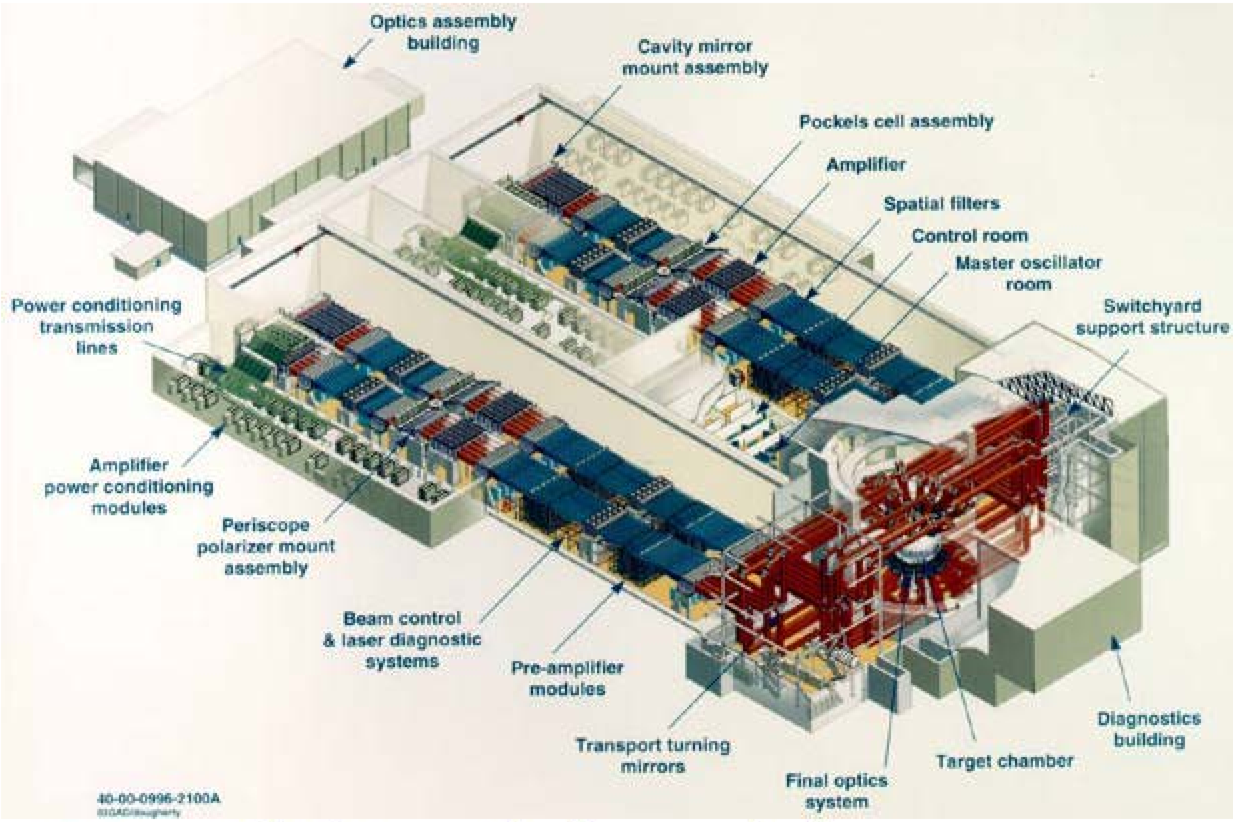
Other forms of fusion

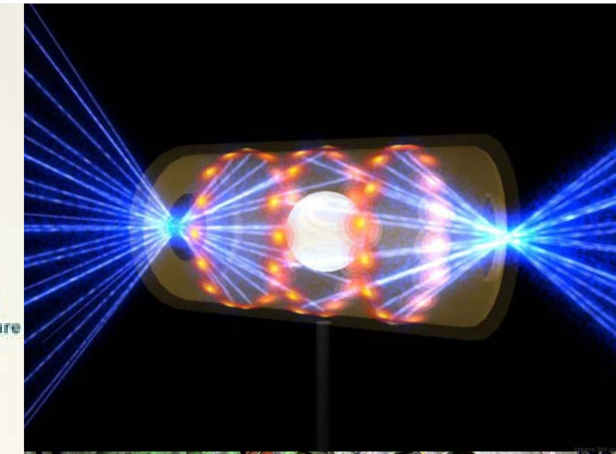


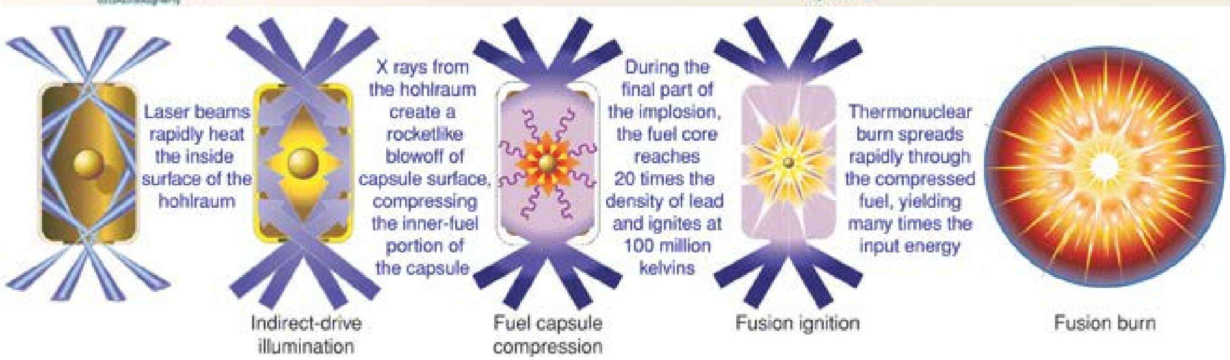




Inertial confinement fusion

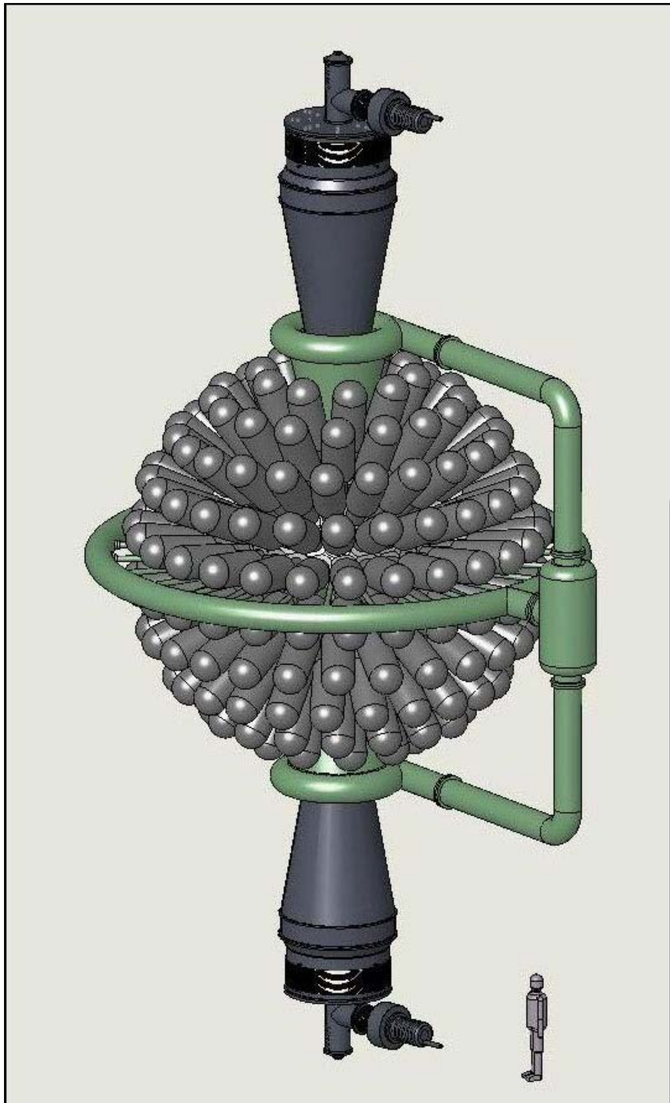


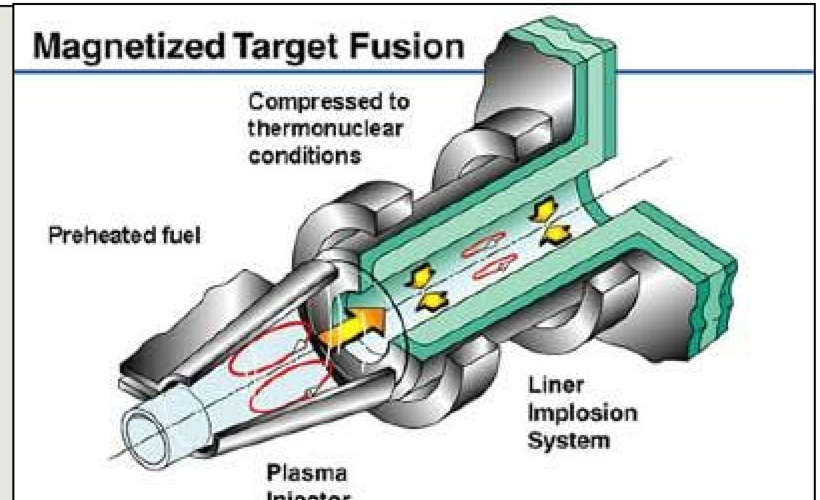


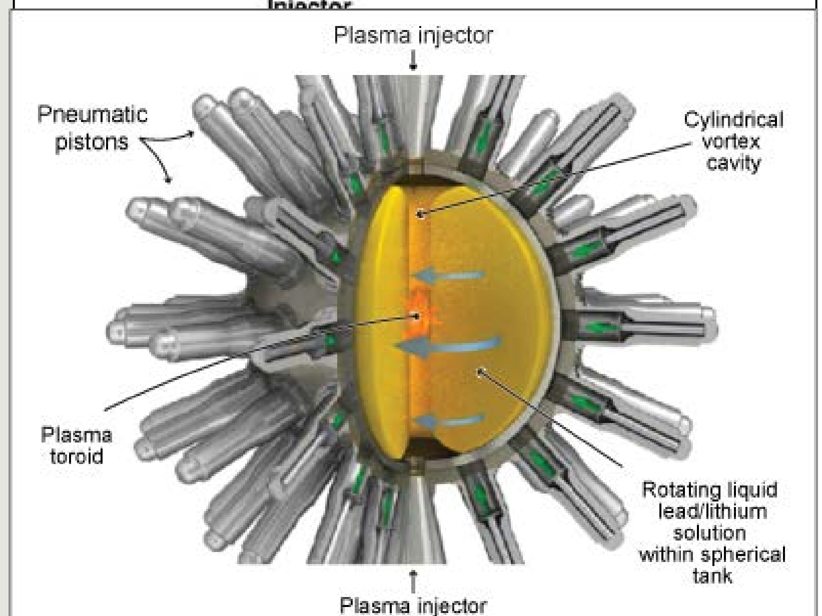


(Courtesy: NIF)

Acoustic Magnetic Target Fusion

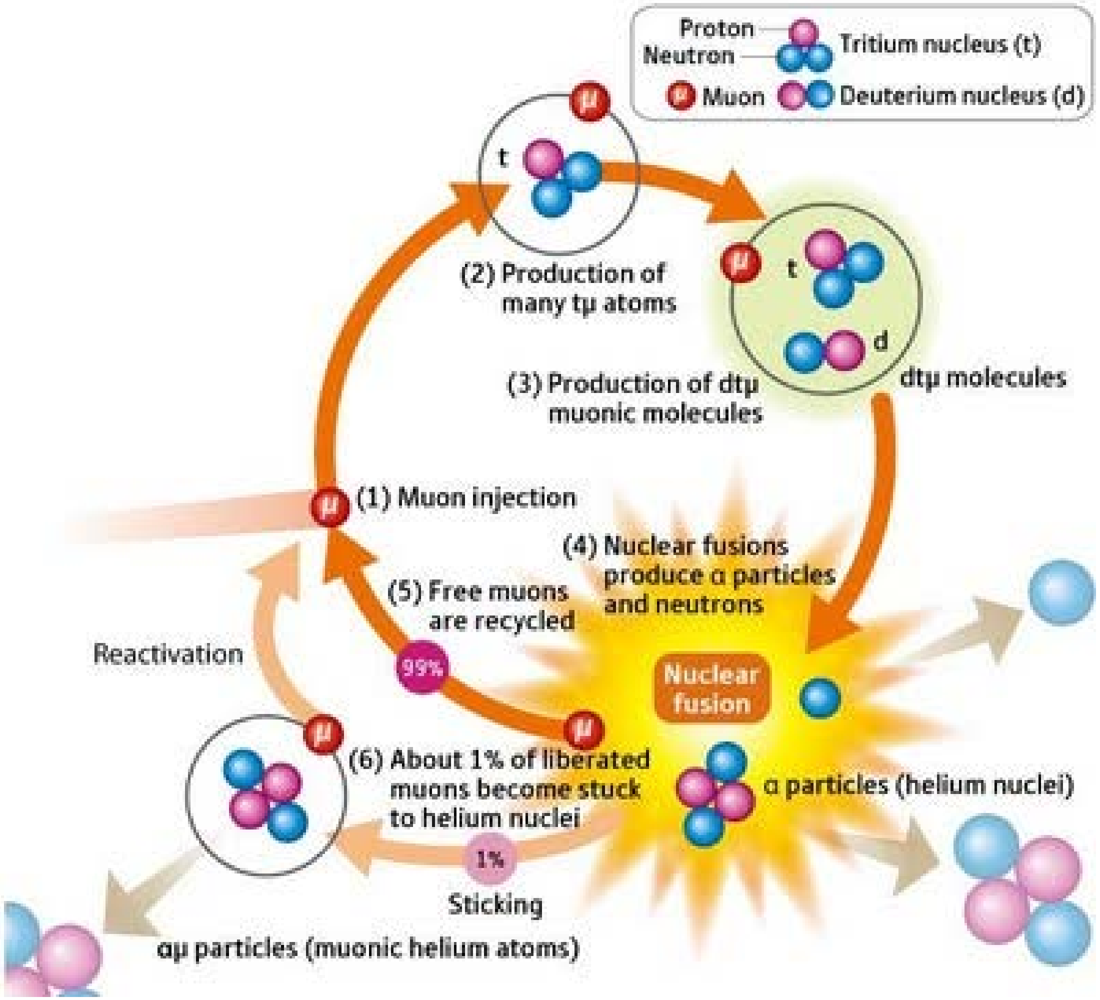




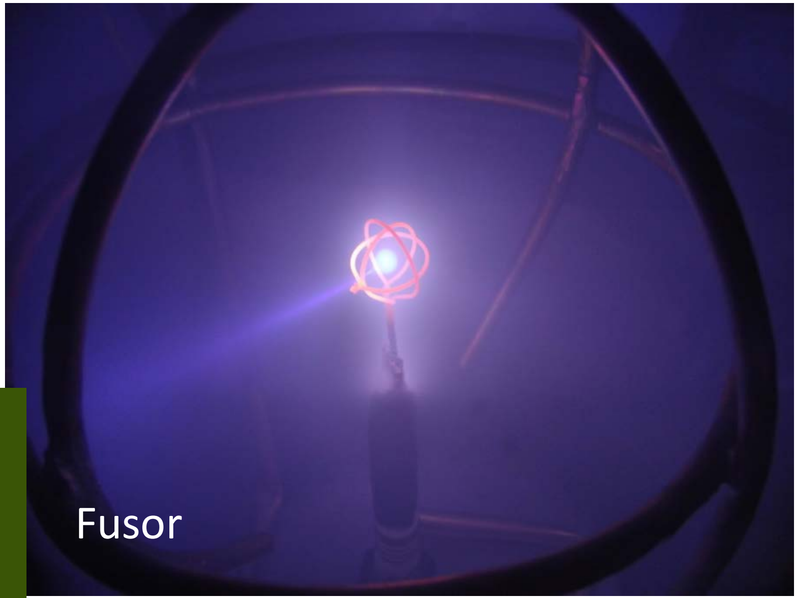


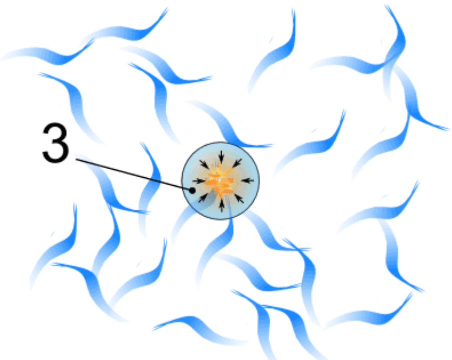
(Courtesy: General Fusion)

Muon-catalysed fusion



Confusion





3 When top of wave reaches the bubble starts implosion. Vapours are quicky pressed and heated so fusion may occur.

http://fusion.srubar.net