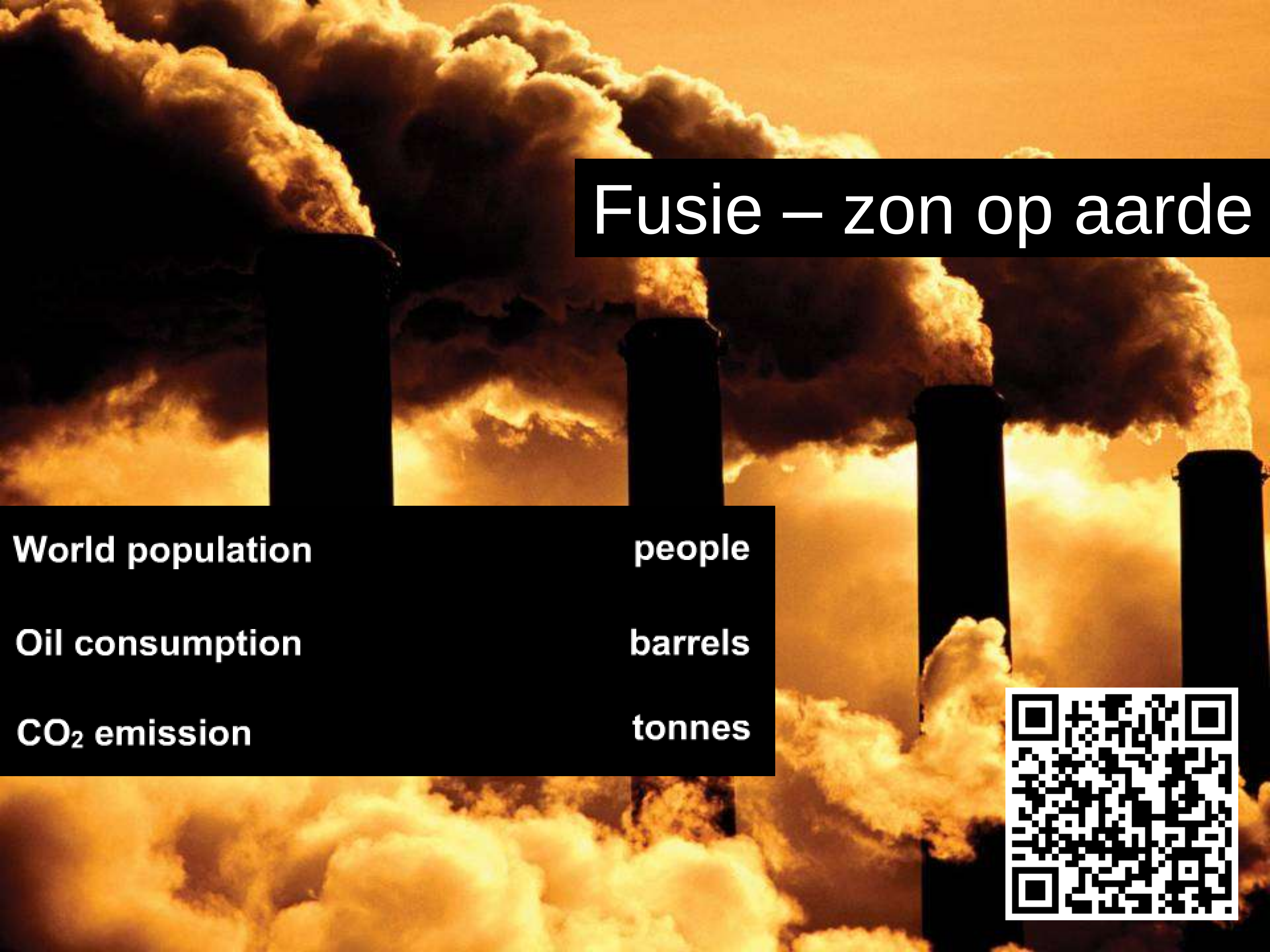
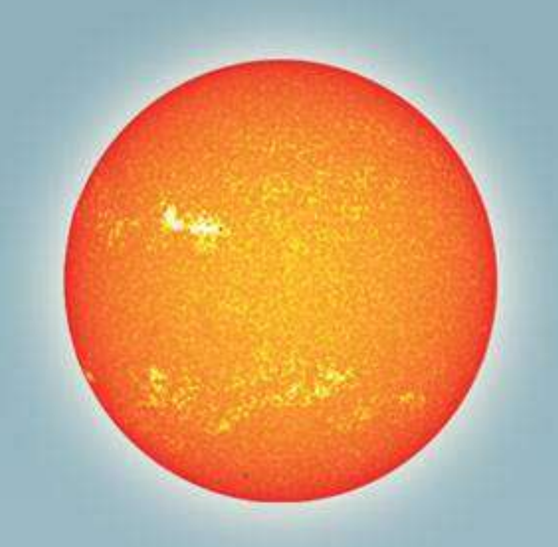
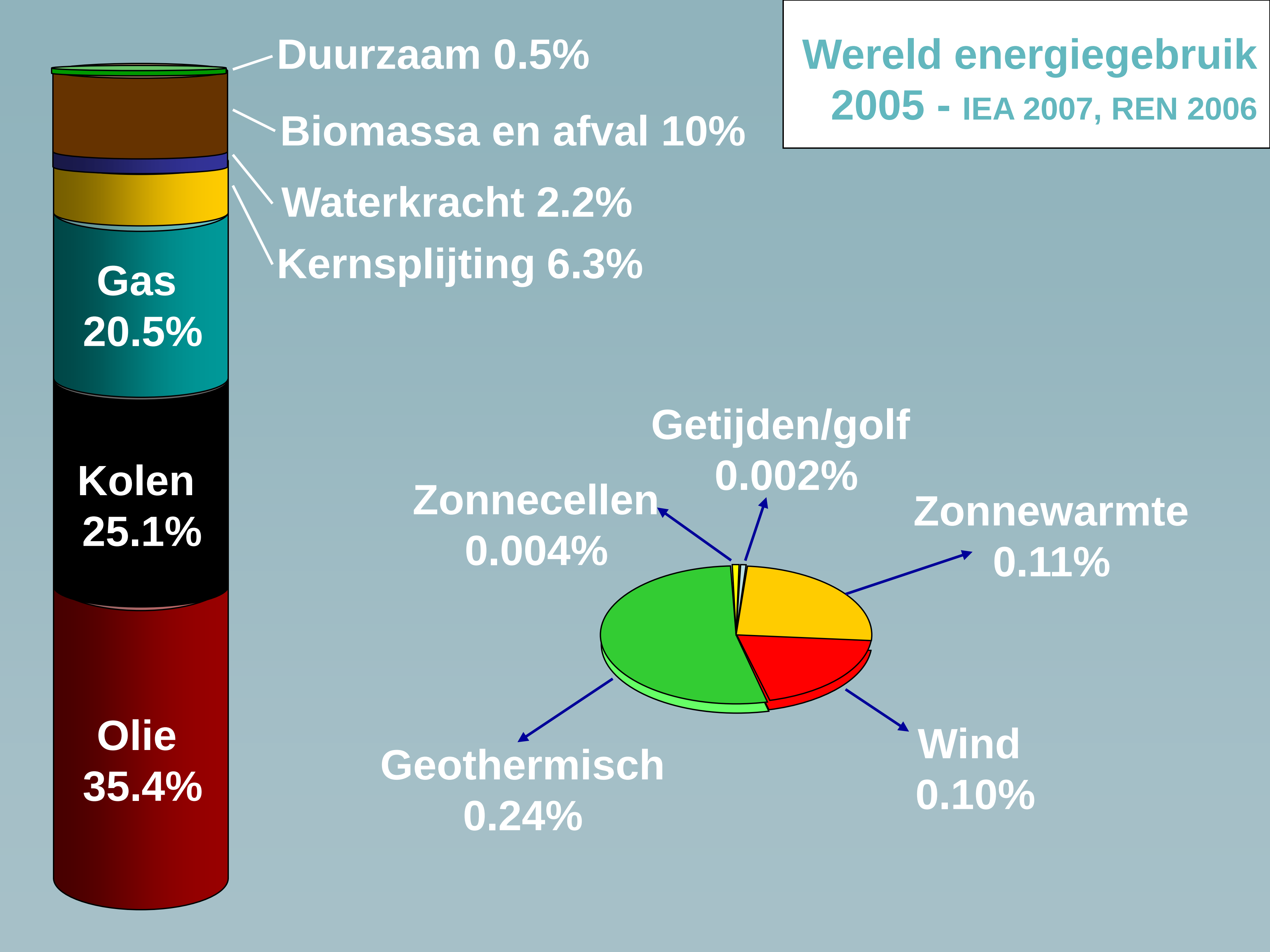

Fusie – zon op aarde
World population
people
Oil consumption
barrels
CO_2 emission
tonnes

Fusie
Van belofte naar realiteit



Tony Donné
FOM-Instituut DIFFER
TU Eindhoven

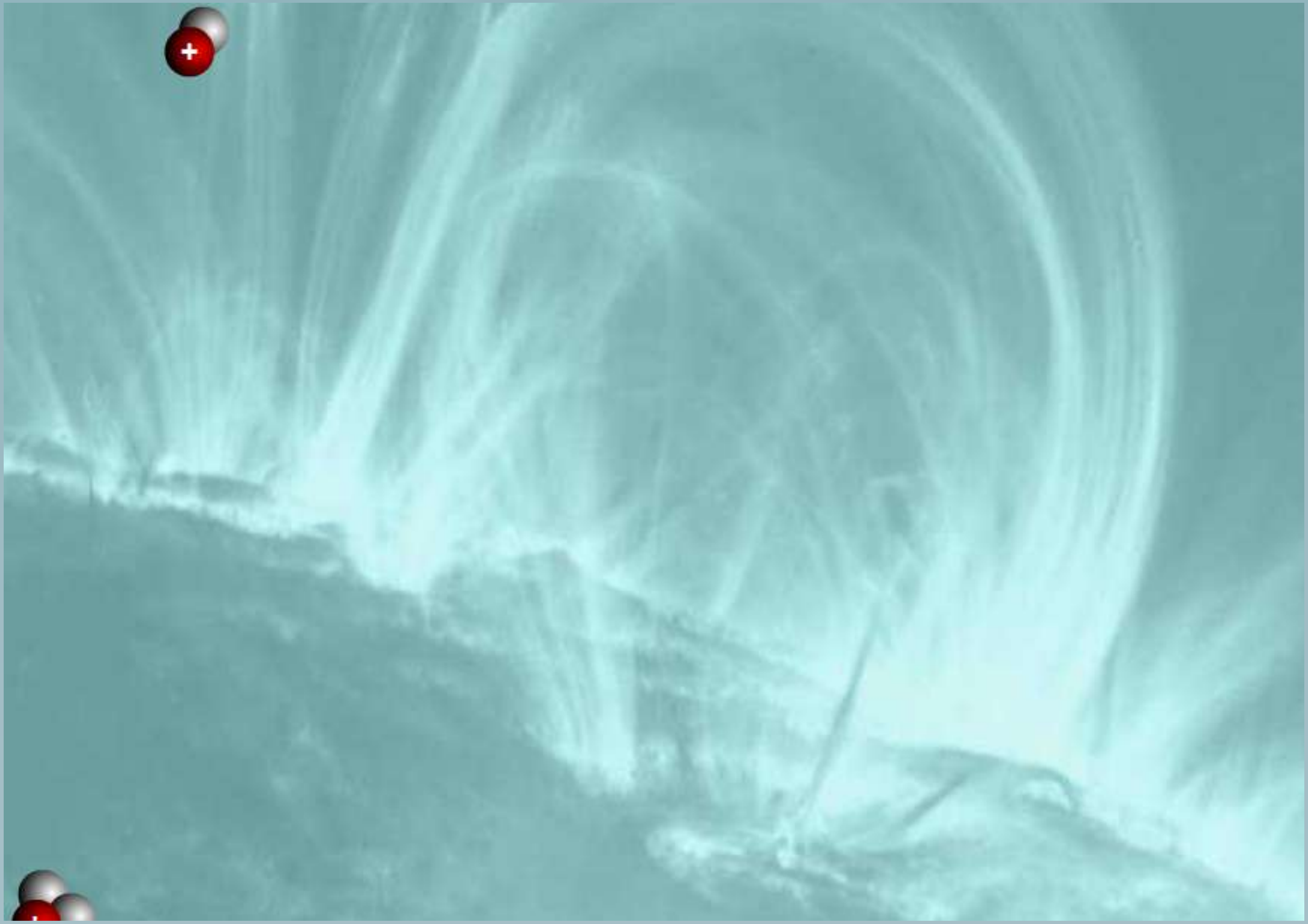
3-4-2013
KIVI NIRIAm Den Haagh


Wereld energiegebruik
2005 - IEA 2007, REN 2006
Duurzaam 0.5%
Biomassa en afval 10%
Waterkracht 2.2%
Kernsplijting 6.3%
Gas
20.5%
Kolen
25.1%
Olie
35.4%
Getijden/golf
0.002%
Zonnecellen
0.004%
Zonnewarmte
0.11%
Geothermisch
0.24%
Wind
0.10%

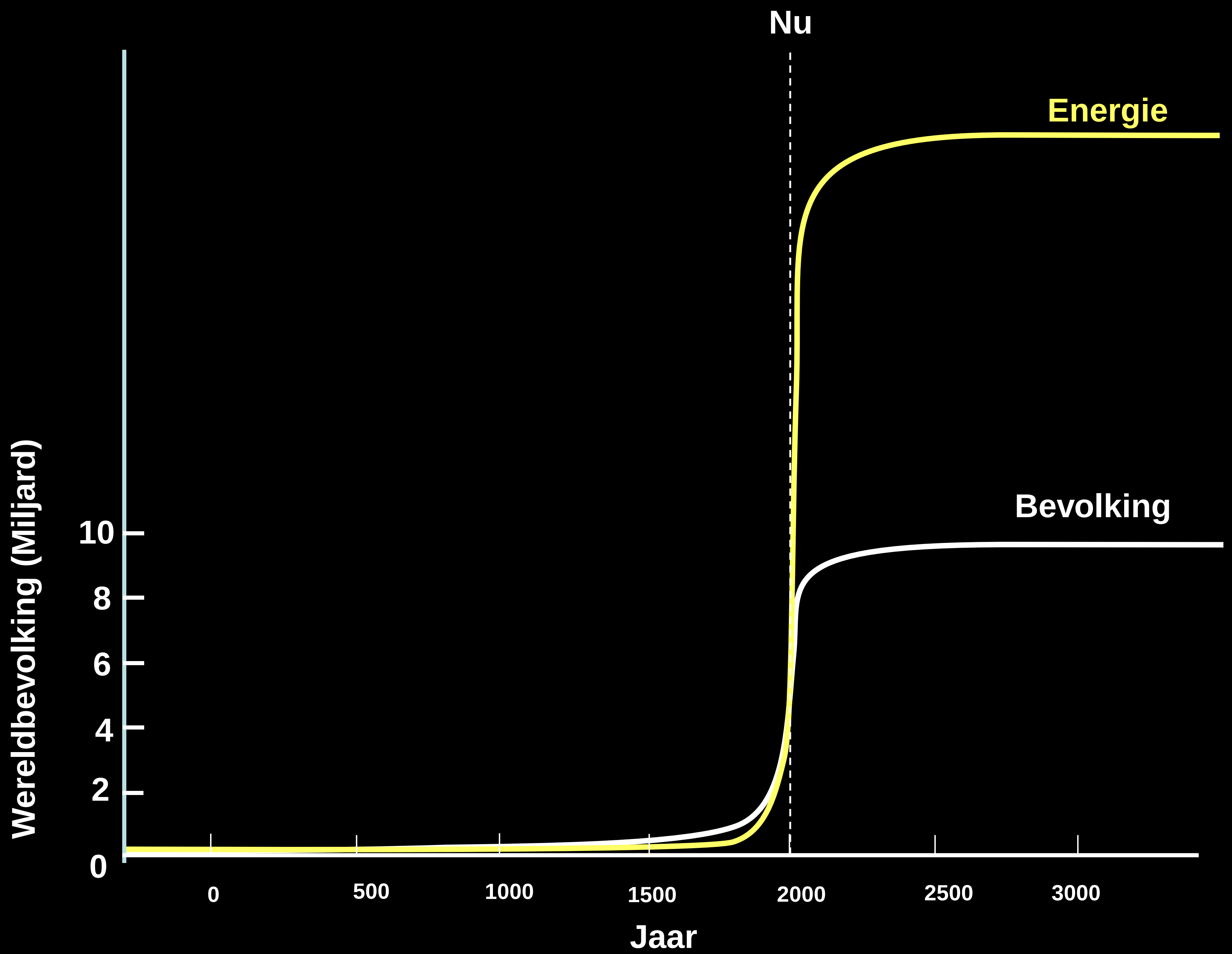
Kernsplijting

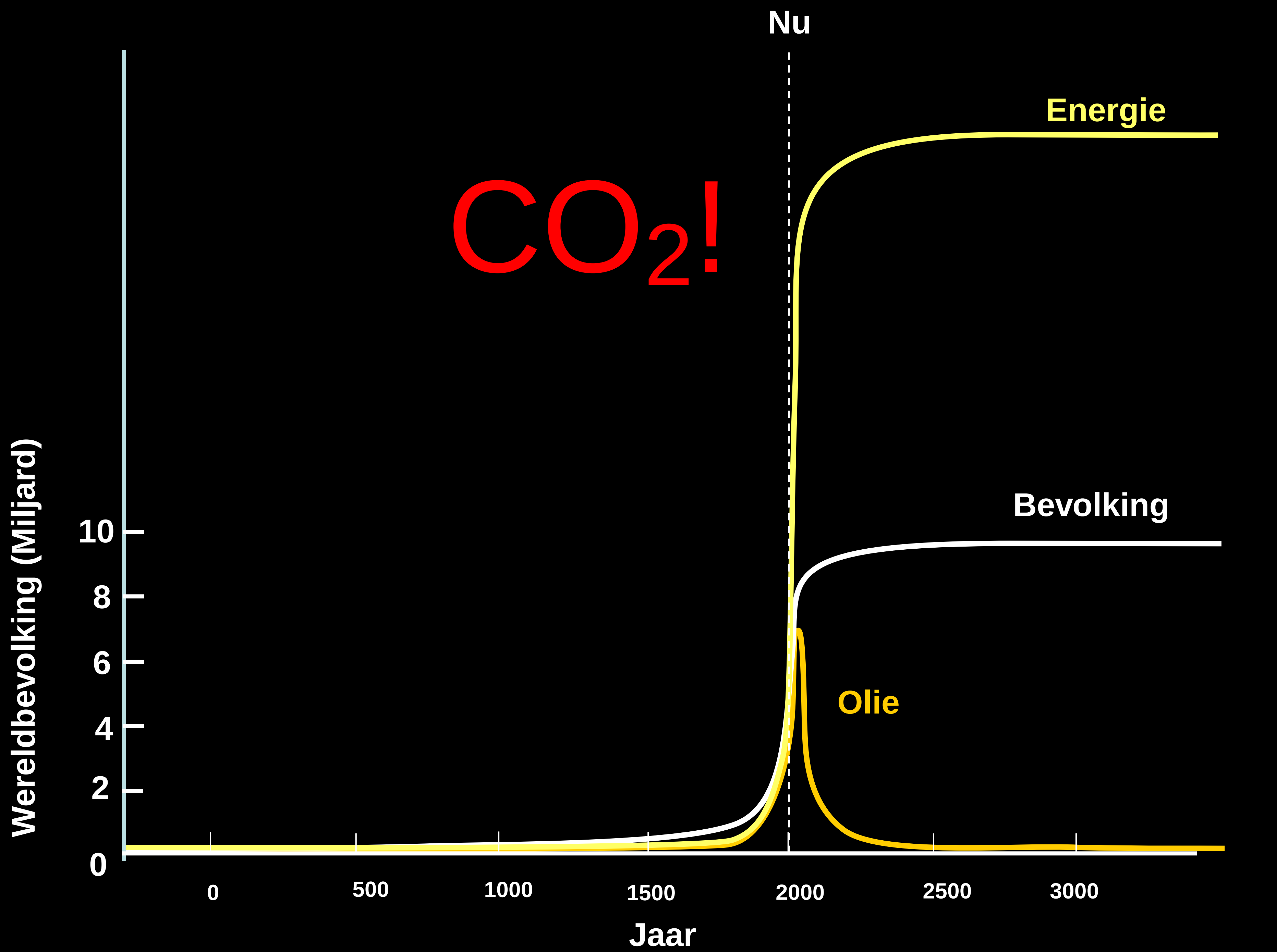
n + $^{235}U \rightarrow$ 3n + fragmenten

Fusie



deuterium + tritium → helium + neutron


Nu
Energie
Bevolking
Wereldbevolking (Miljard)
10
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
Jaar


Nu
Energie
CO_2!
Bevolking
Olie
Wereldbevolking (Miljard)
10
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
Jaar

Schone energie?

- Wind
- Zon
- Waterkracht
- Golfenergie
- Biomassa
- Kernsplijting
- Geothermisch
- CO_2-opslag


Europe, USA, Japan, China, Russia, S-Korea and India
willen fusie:
• Geen CO_2, schoon, veiligheid
• Brandstof alom voorradig
• Geen proliferatie issue
Nadeel... Fusie is onmogelijk

NASA

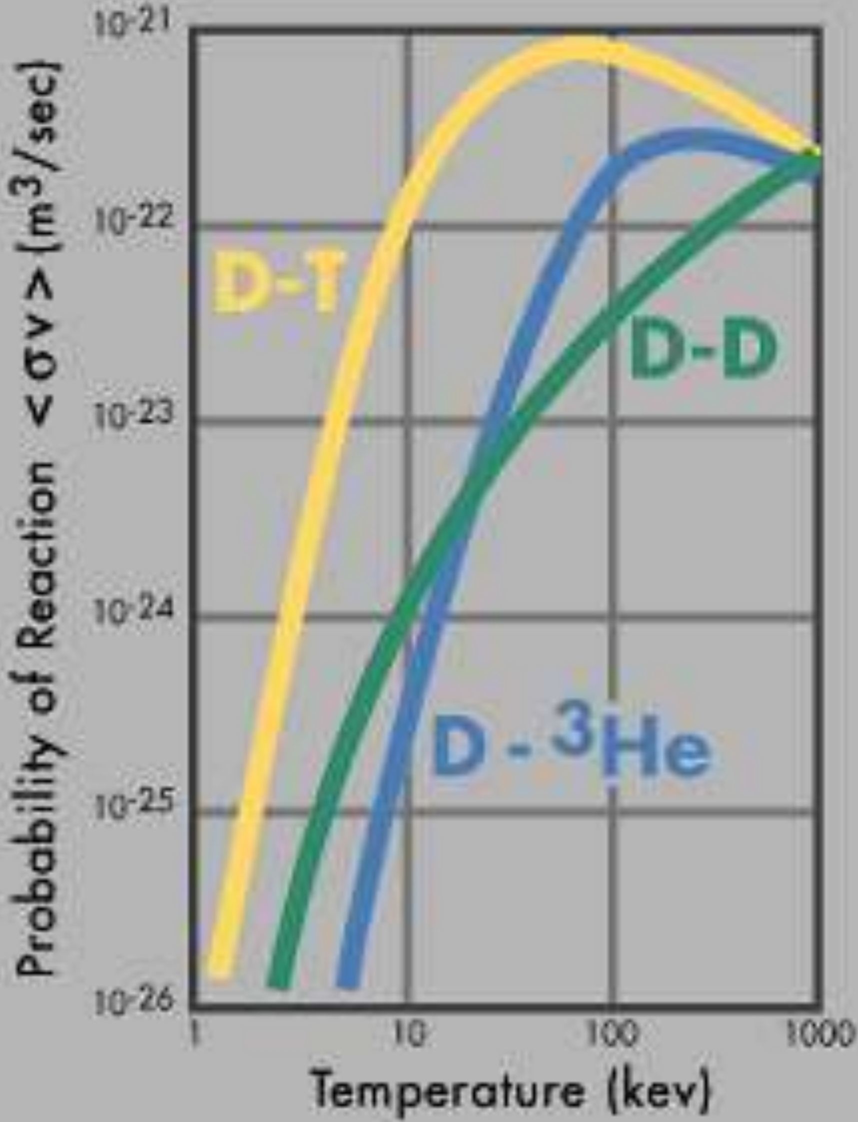
Europe, USA, Japan, China, Russia, S-Korea and India

willen fusie:

- Geen CO_2, schoon, veiligheid
- Brandstof alom voorradig
- Geen proliferatie issue

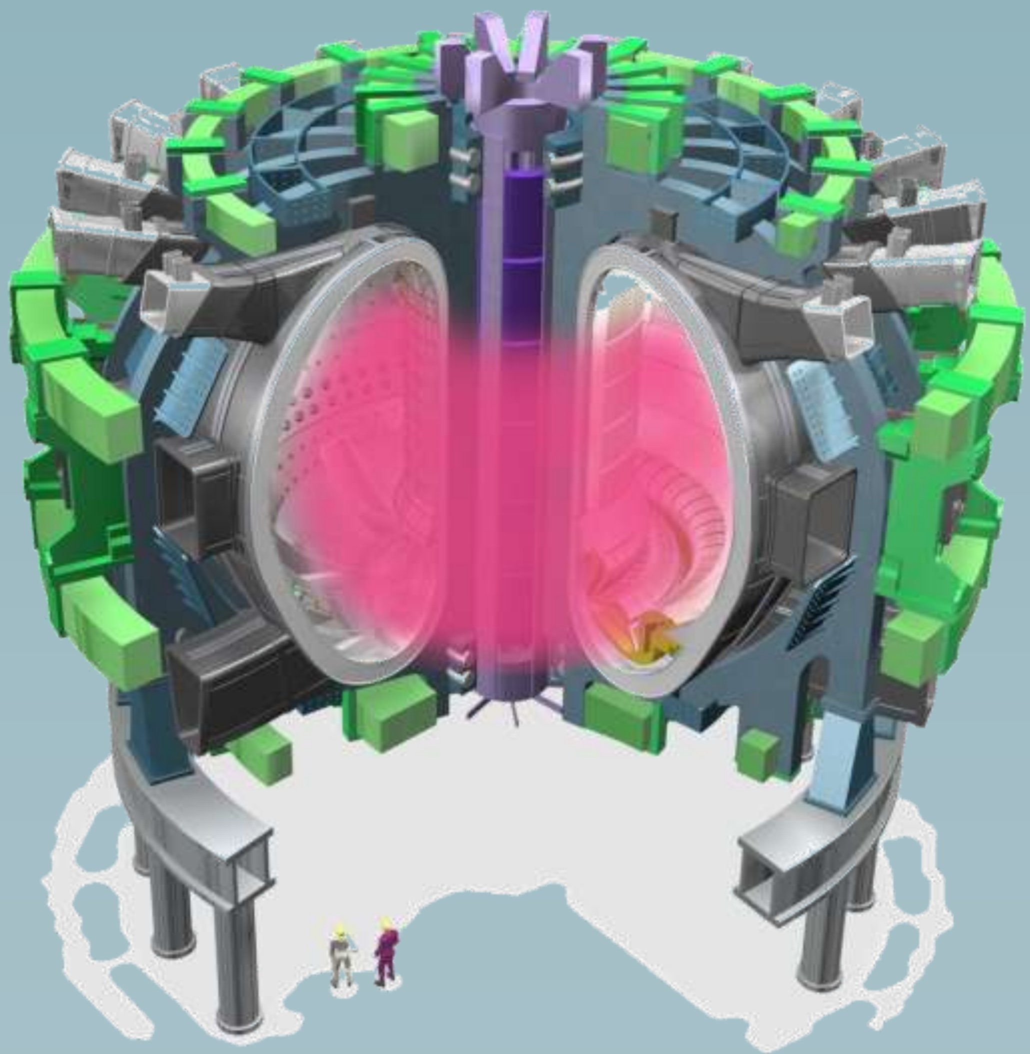
Nadeel... Fusie is moeilijk

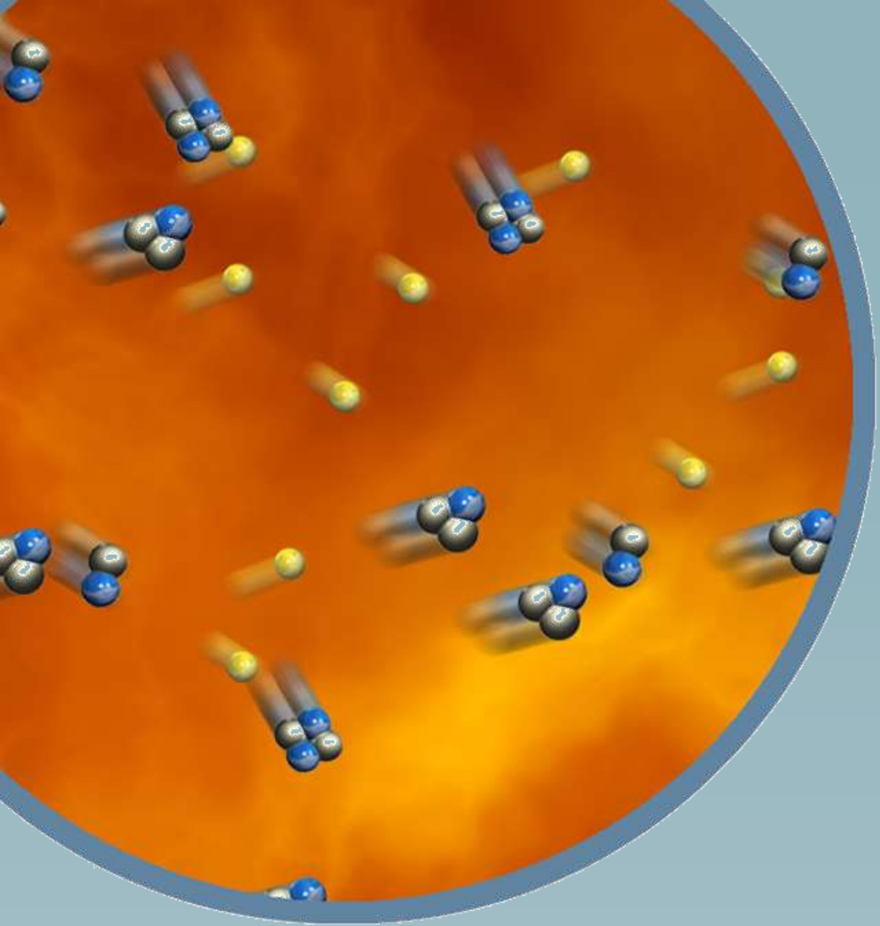
NASA



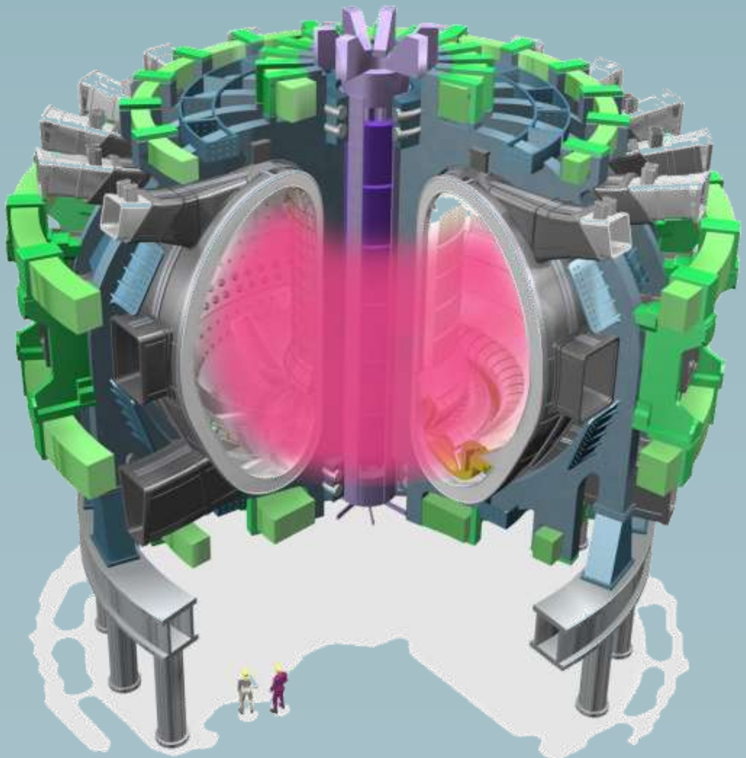
Probability of Reaction < σv > (m3/sec)
10-21
10-22
10-23
10-24
10-25
10-26
D-T
D-D
D - 3He
1
10
100
1000
Temperature (kev)

De 7 onmogelijkheden van fusie



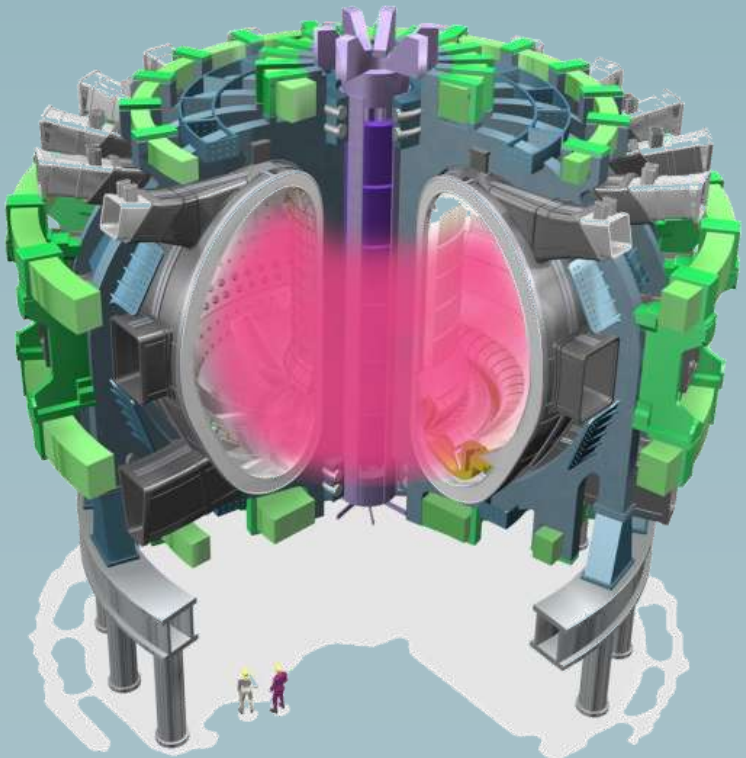


1

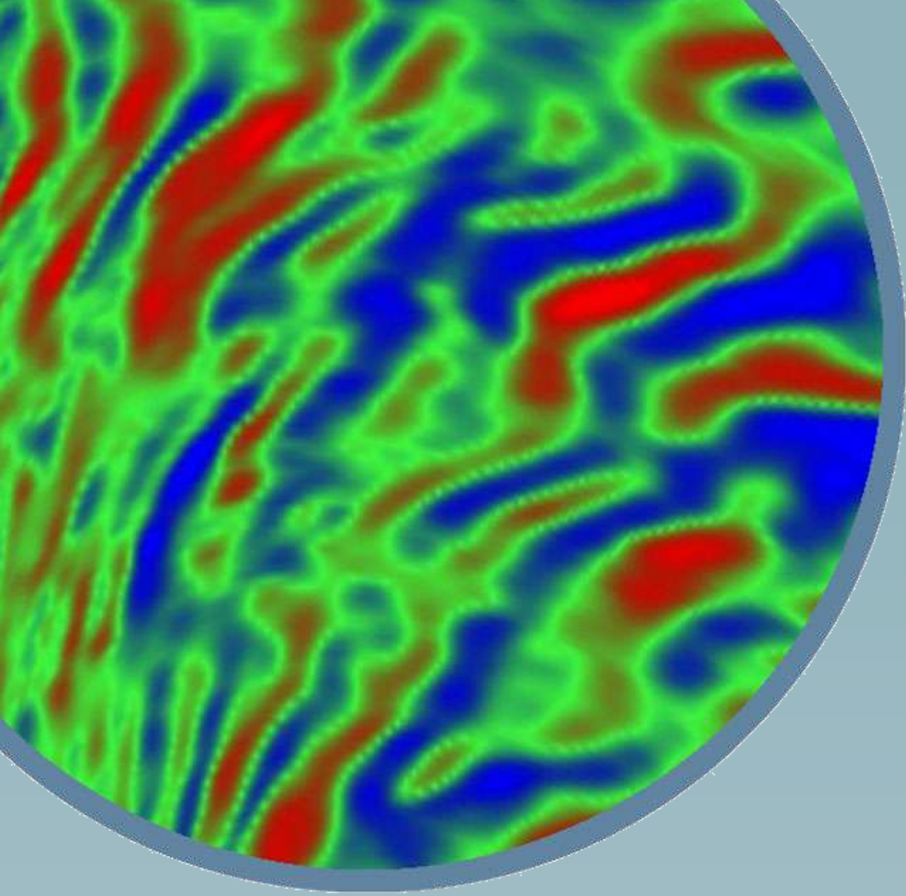


10× heter dan de zon

2



Zonnevlammen beheersen



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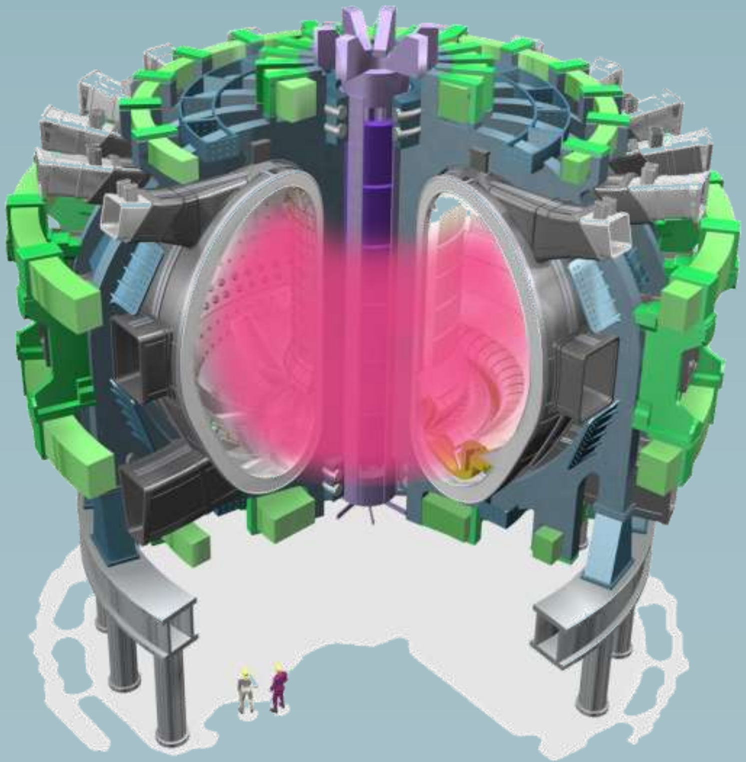
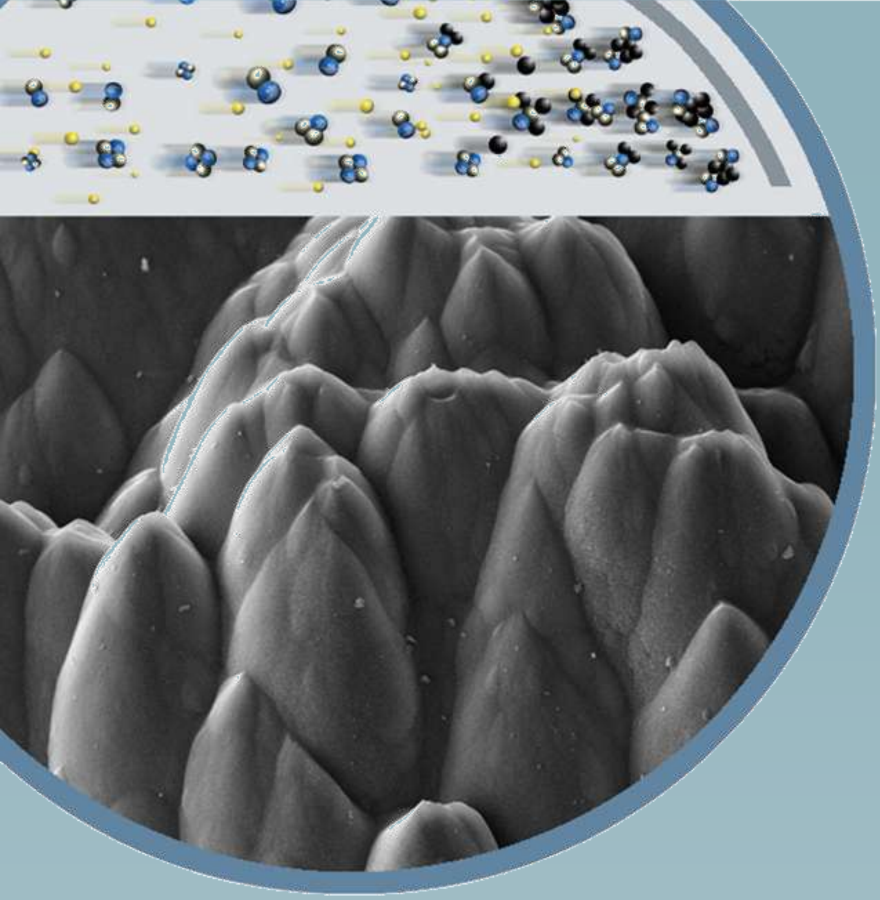


Thermische isolatie nagenoeg perfect



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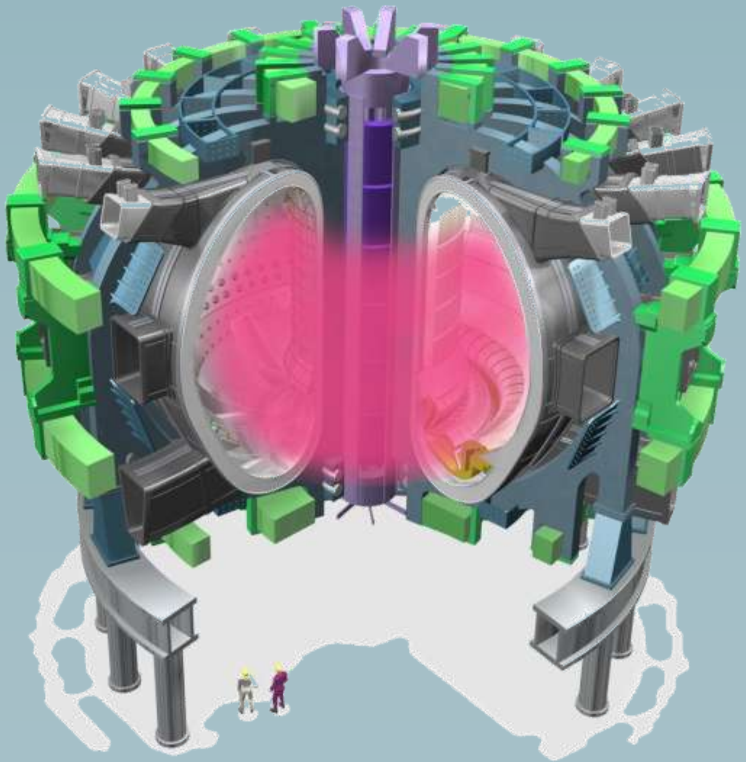
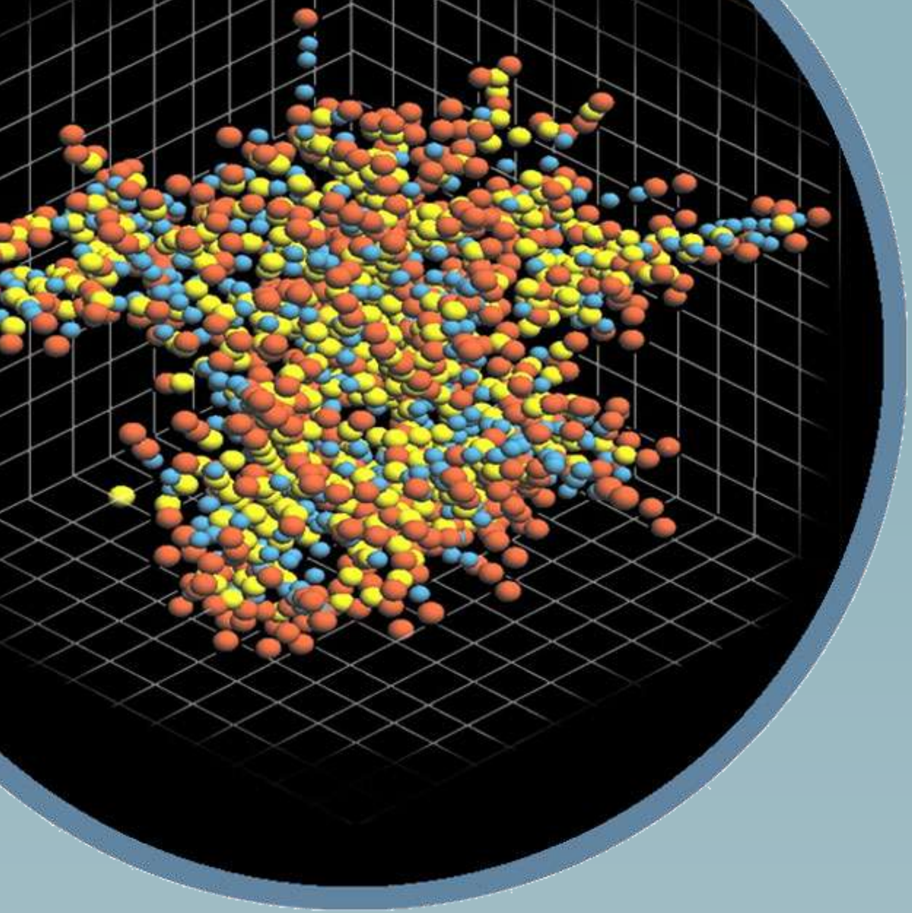


Materialen die je op de zon kunt leggen



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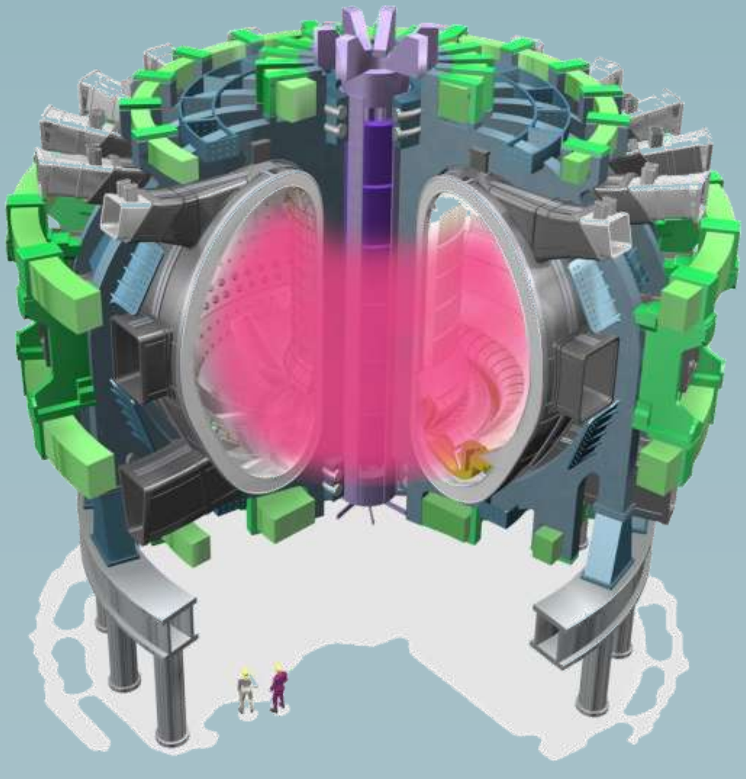
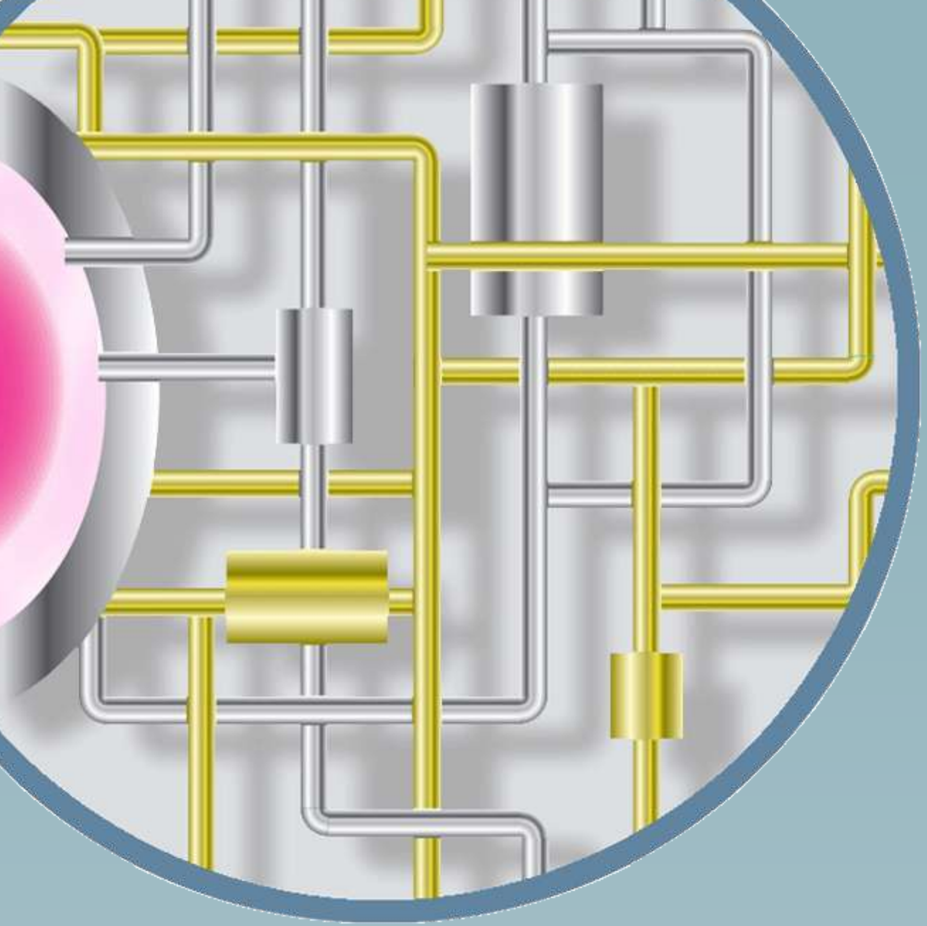


Bombardement van neutronen



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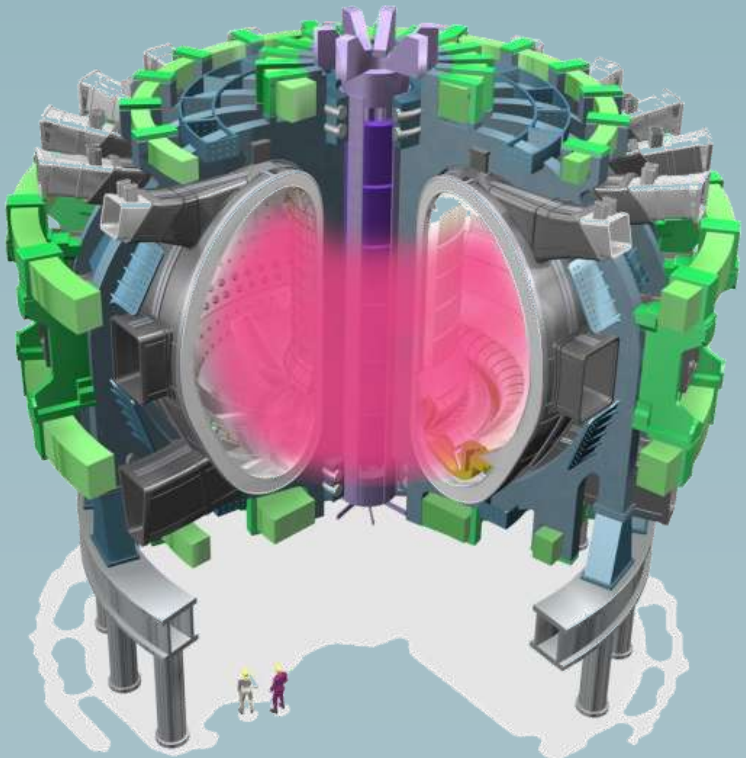
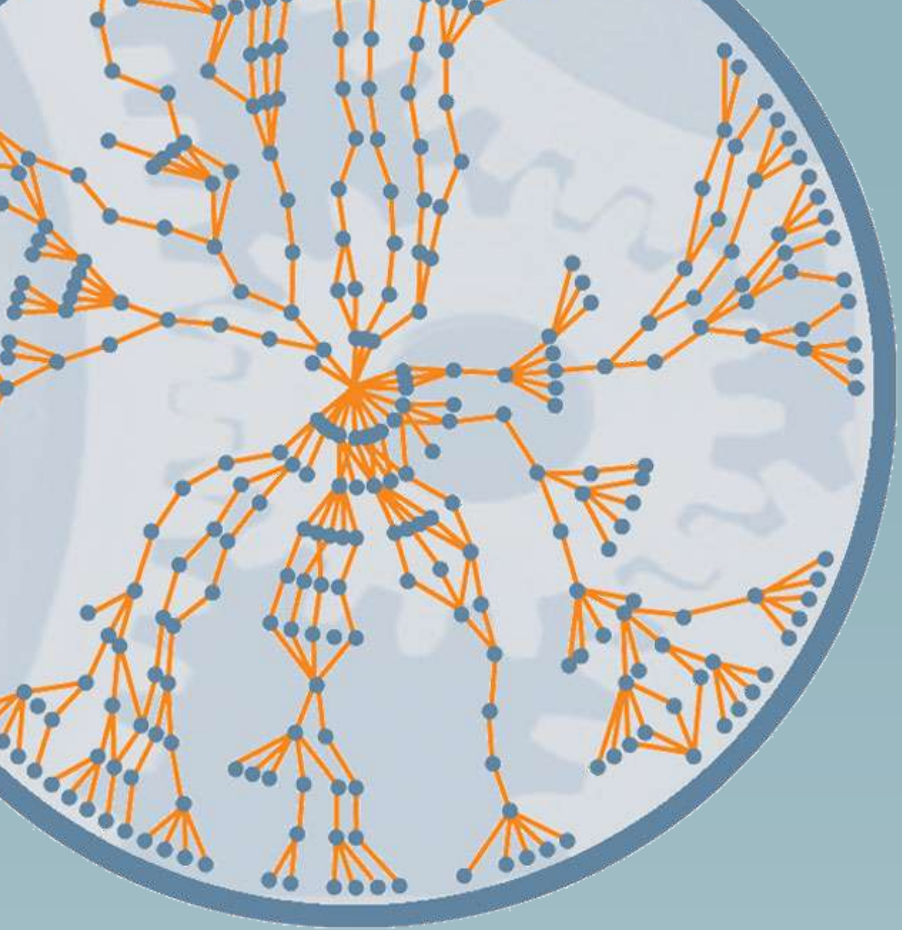
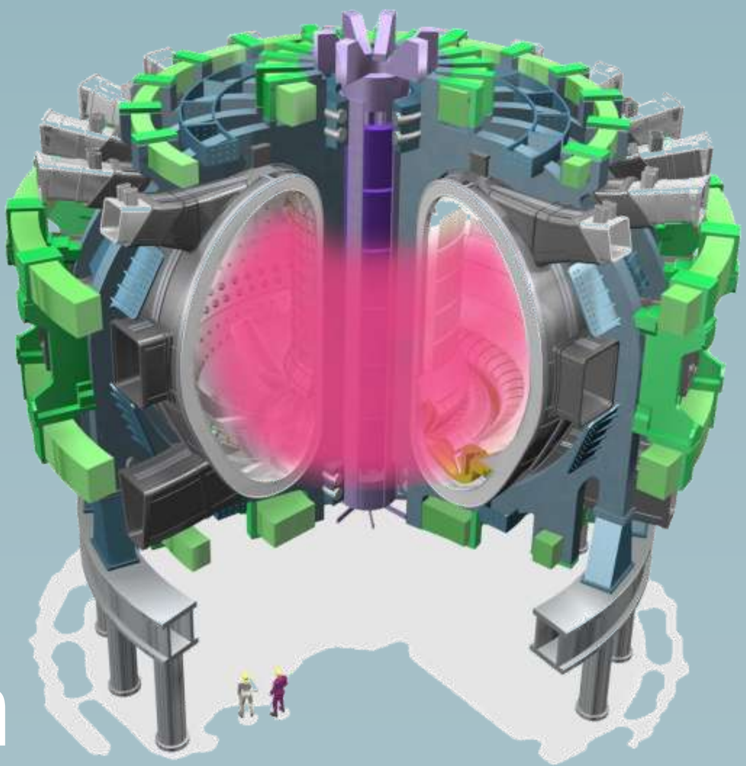
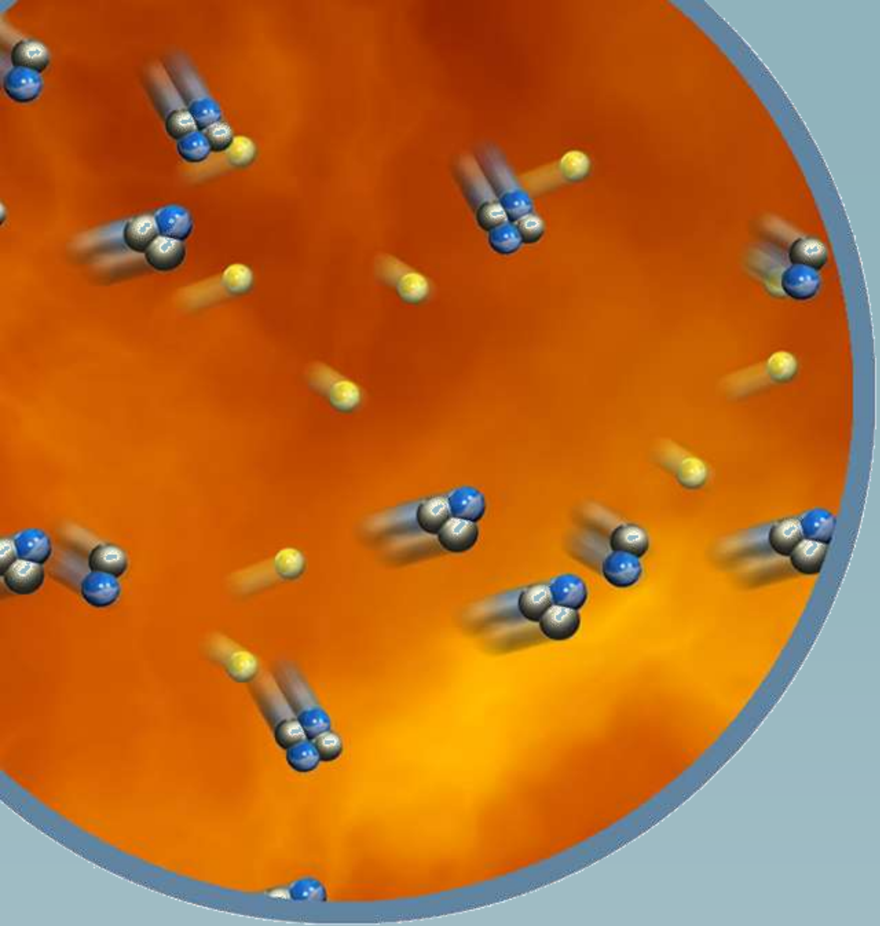


Brandstofcyclus
Tritiumproductie

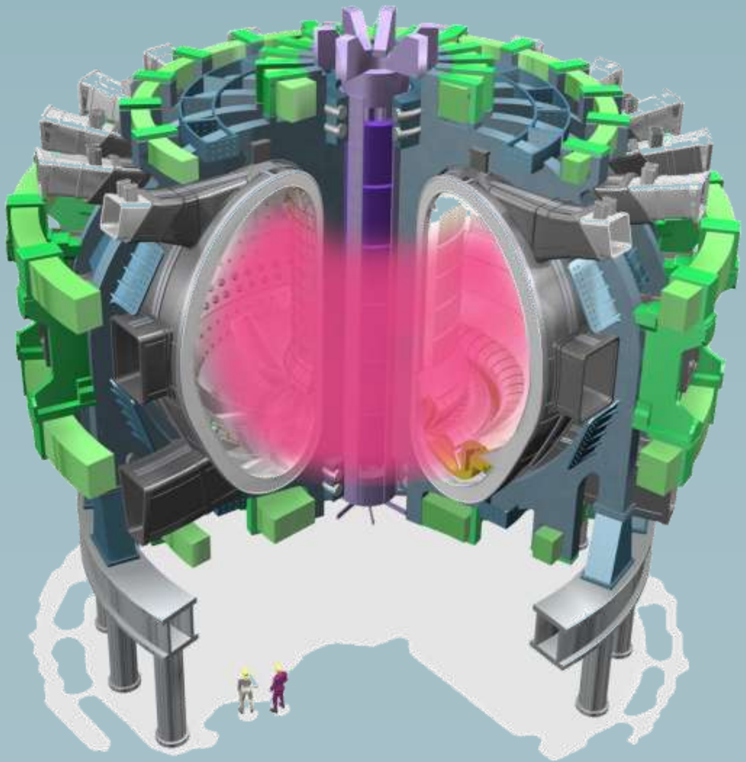




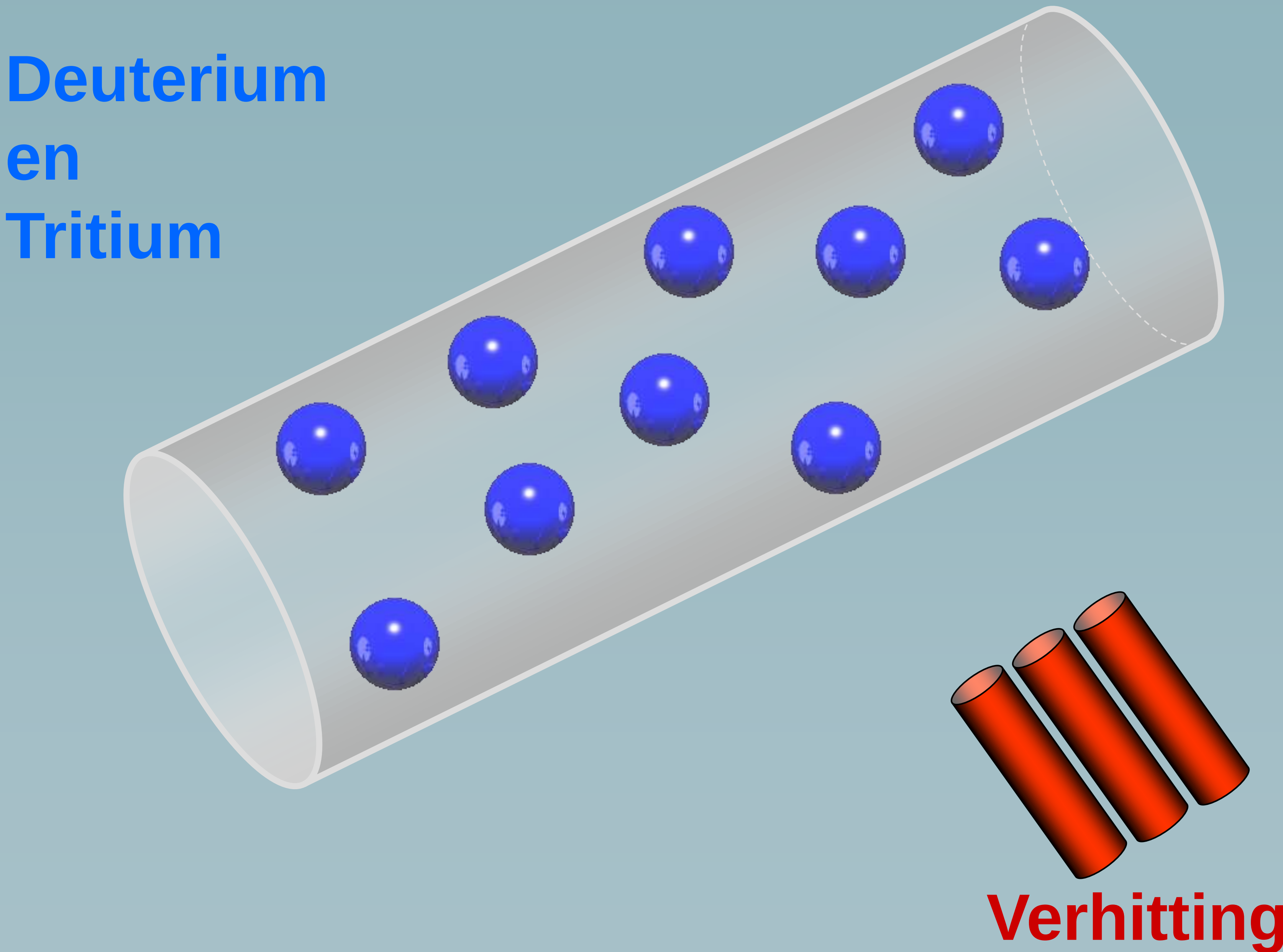
ITER: 34 landen
15.000.000 onderdelen



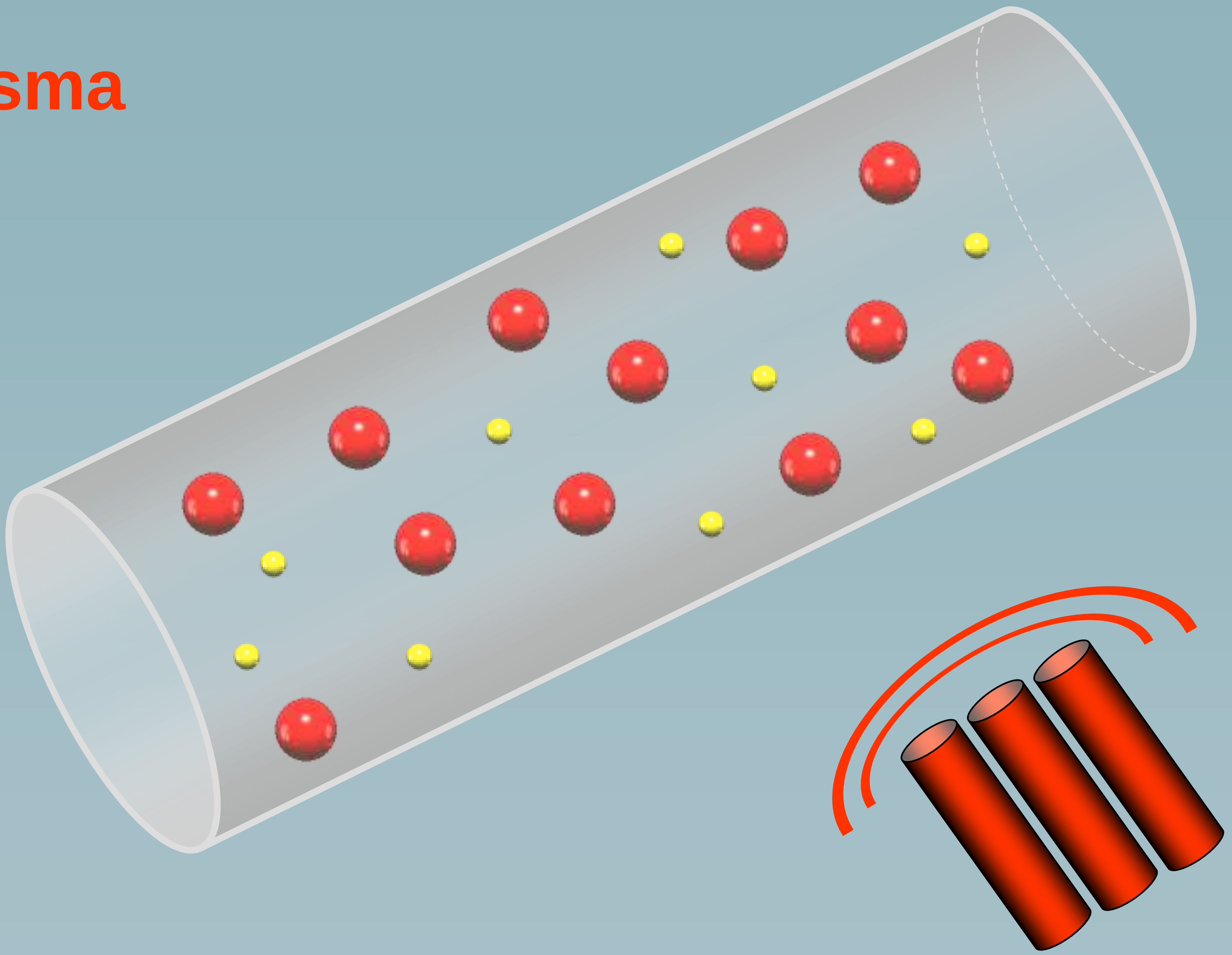
1



10× heter dan de zon

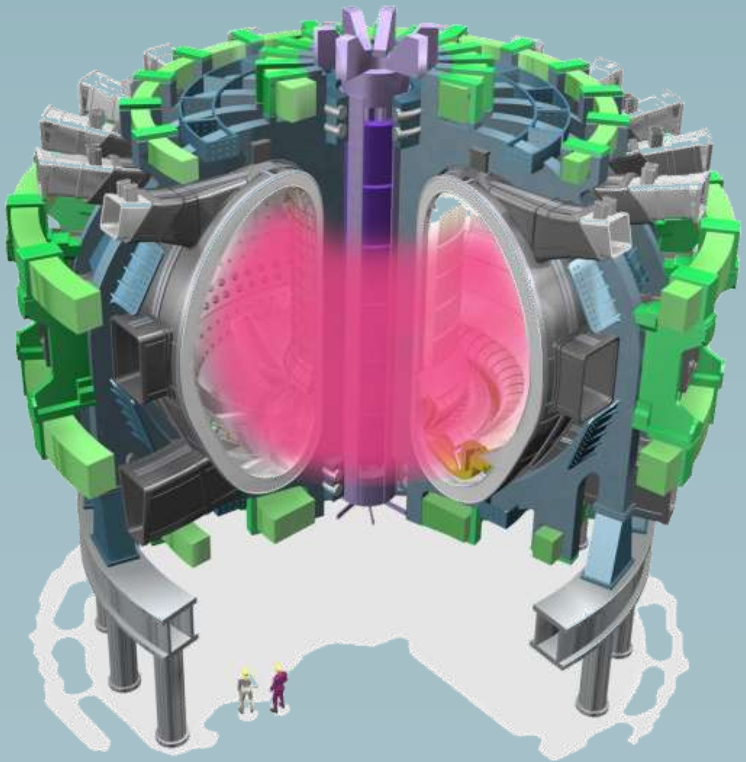

Deuterium
en
Tritium
Verhitting

Plasma

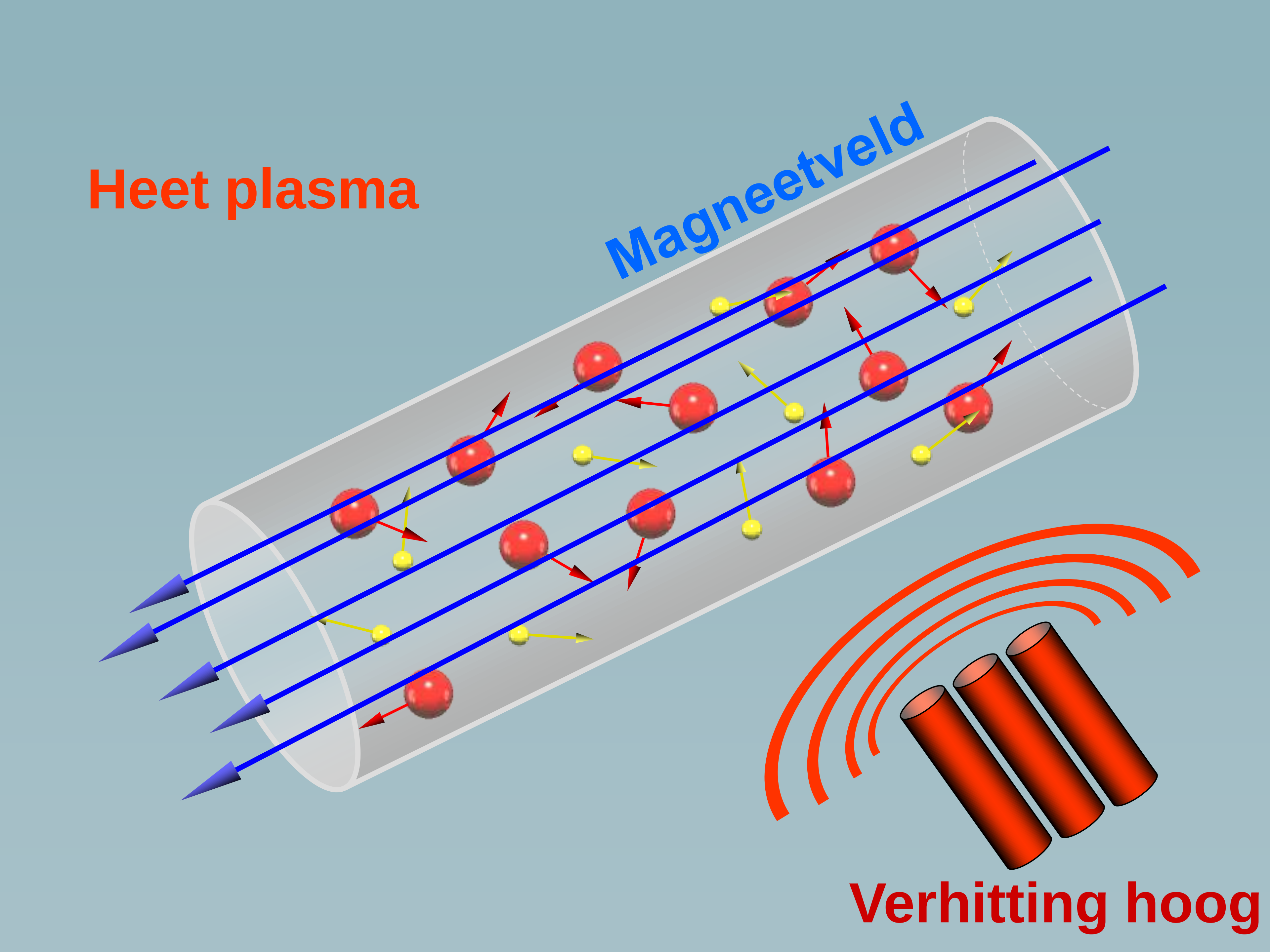


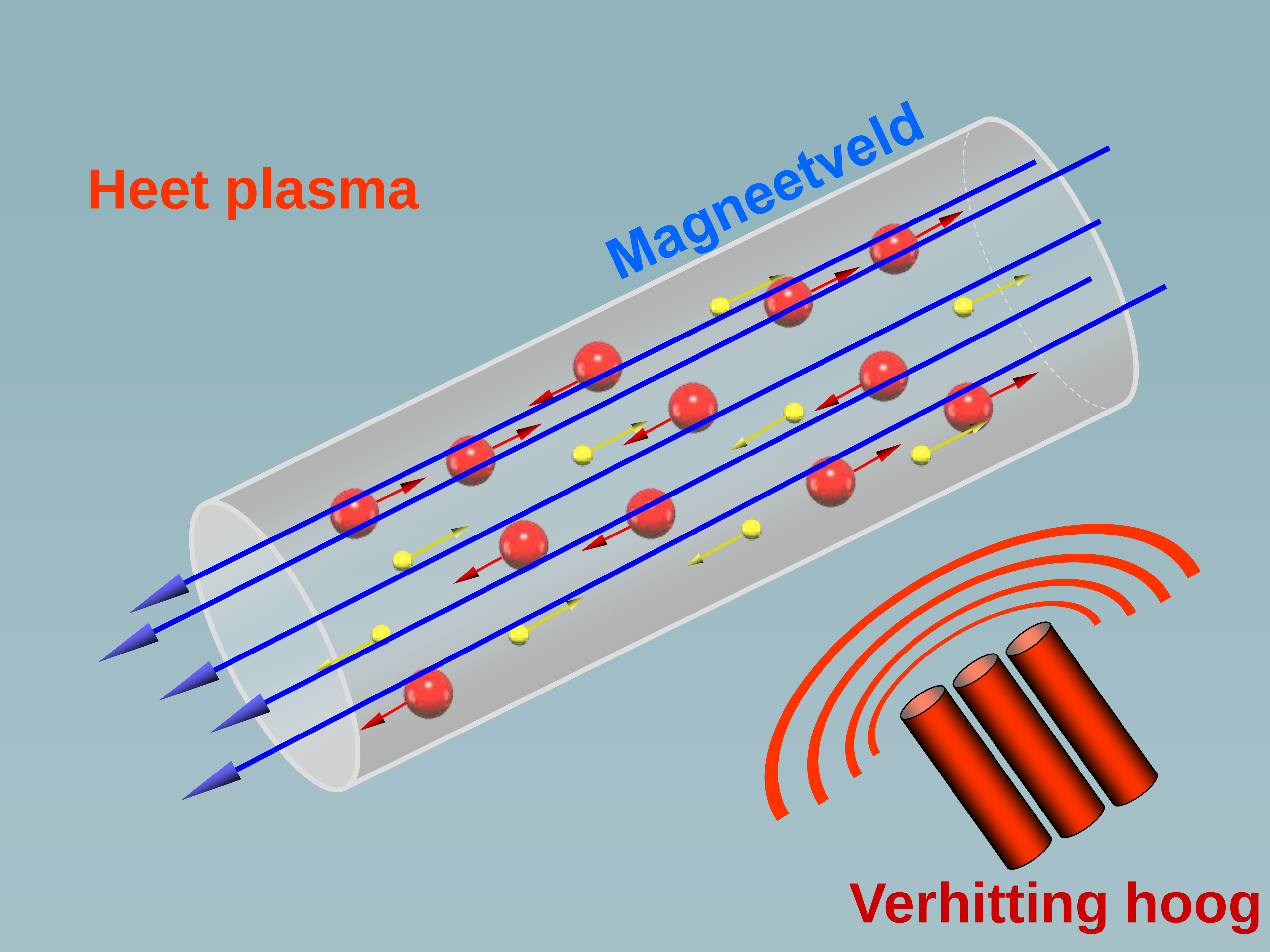
Verhitting aan

2



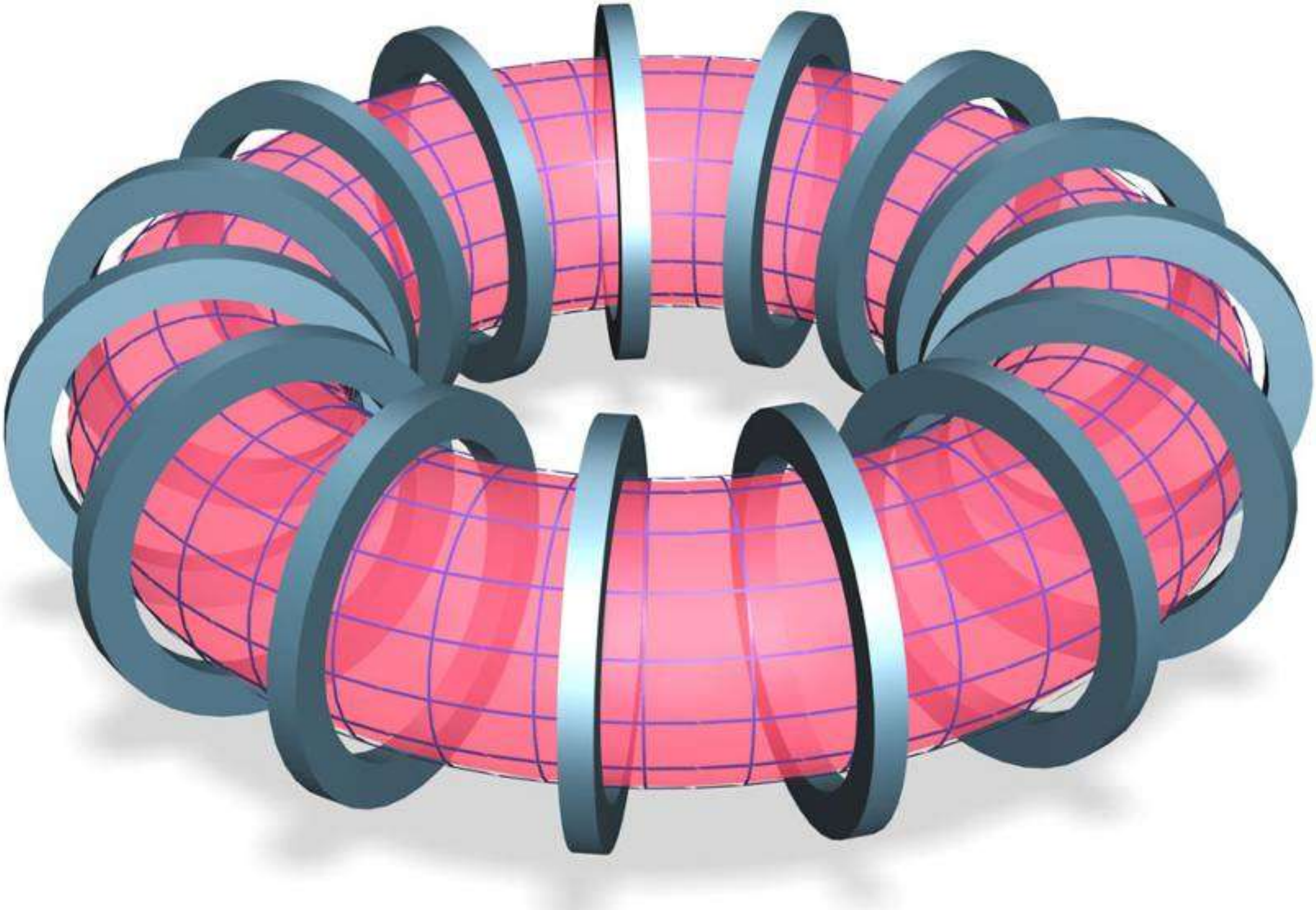
Zonnevlammen beheersen


Heet plasma
Magneetveld
Verhitting hoog

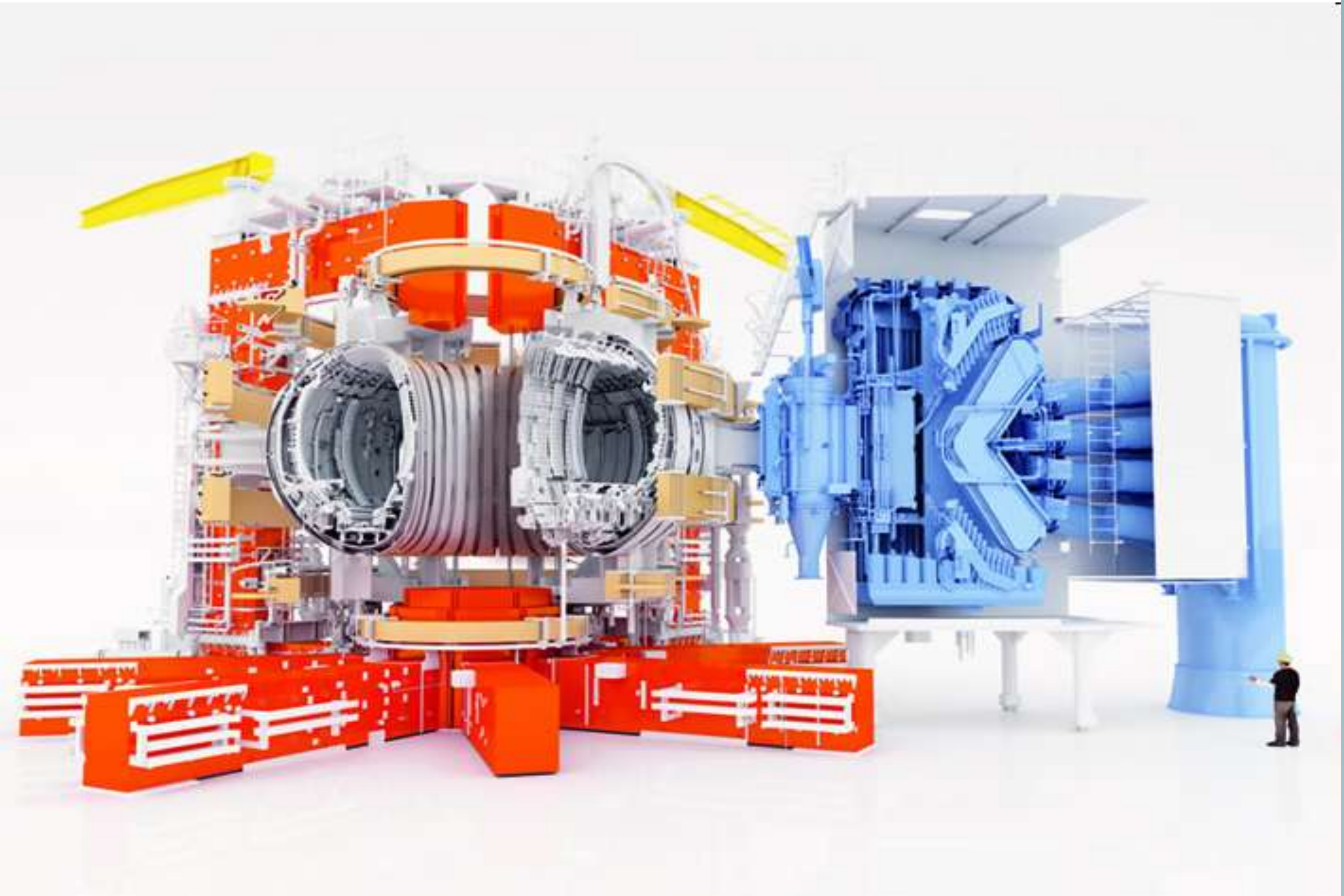


Heet plasma
Magneetveld
Verhitting hoog

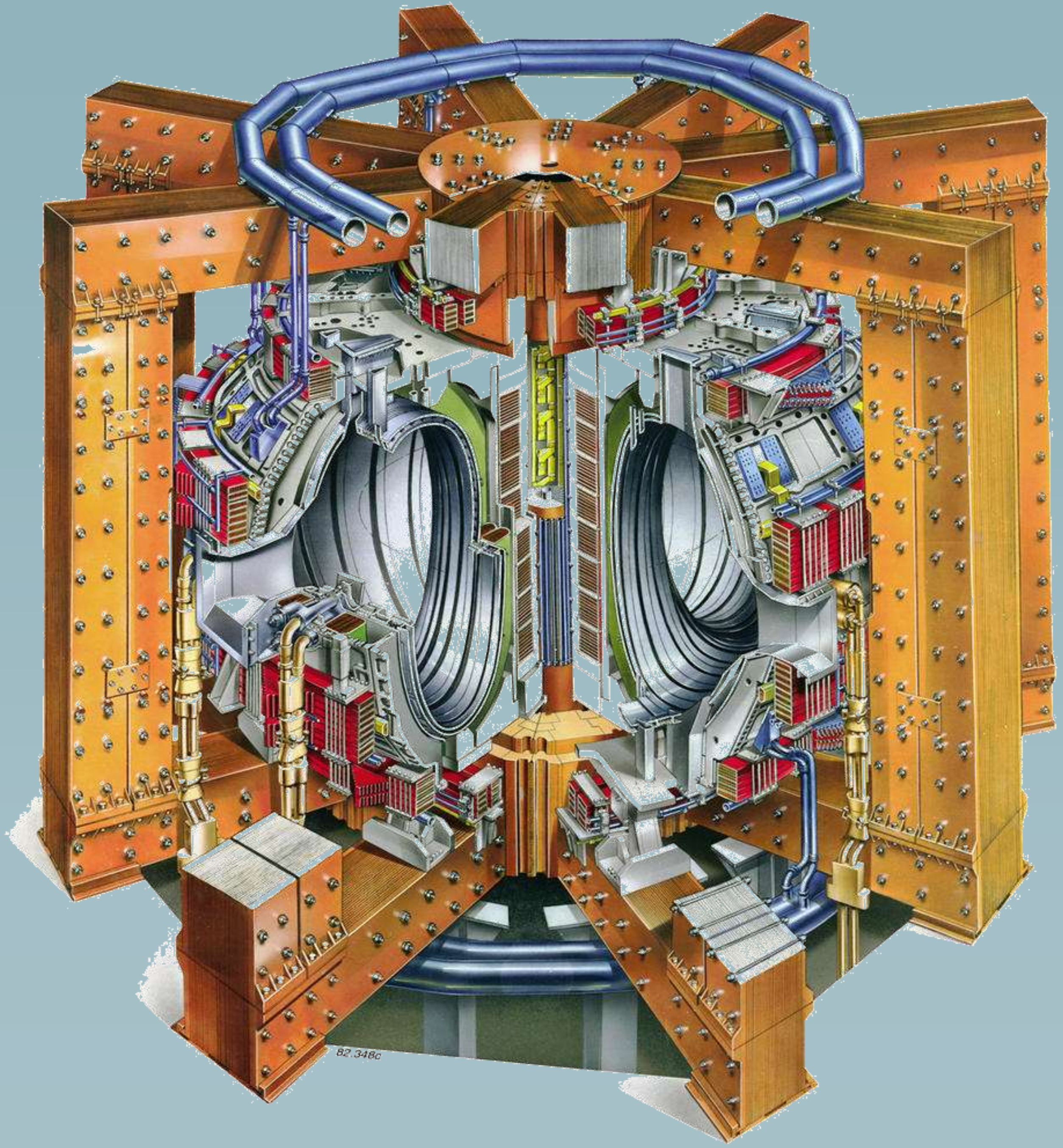
De Torus

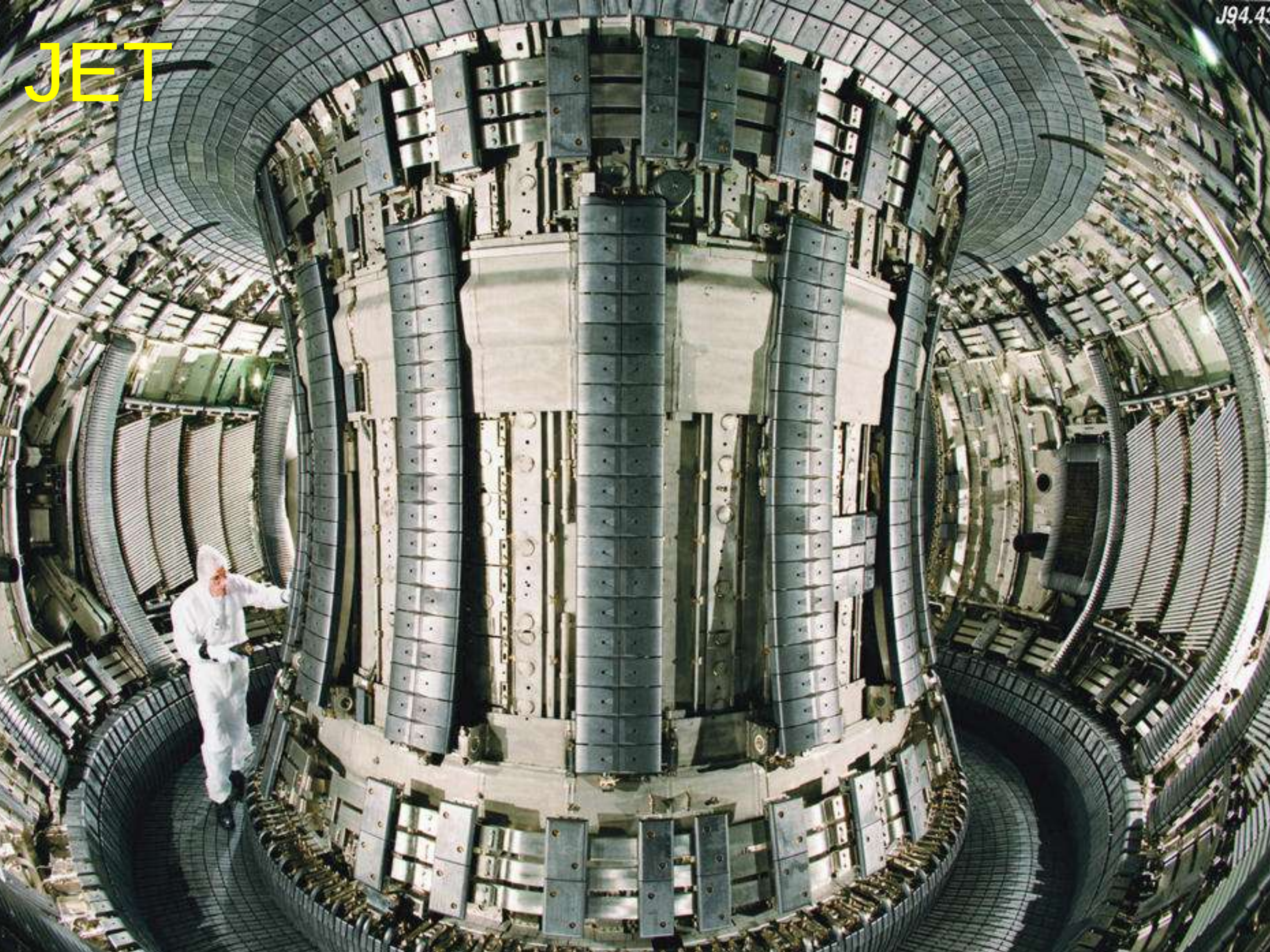


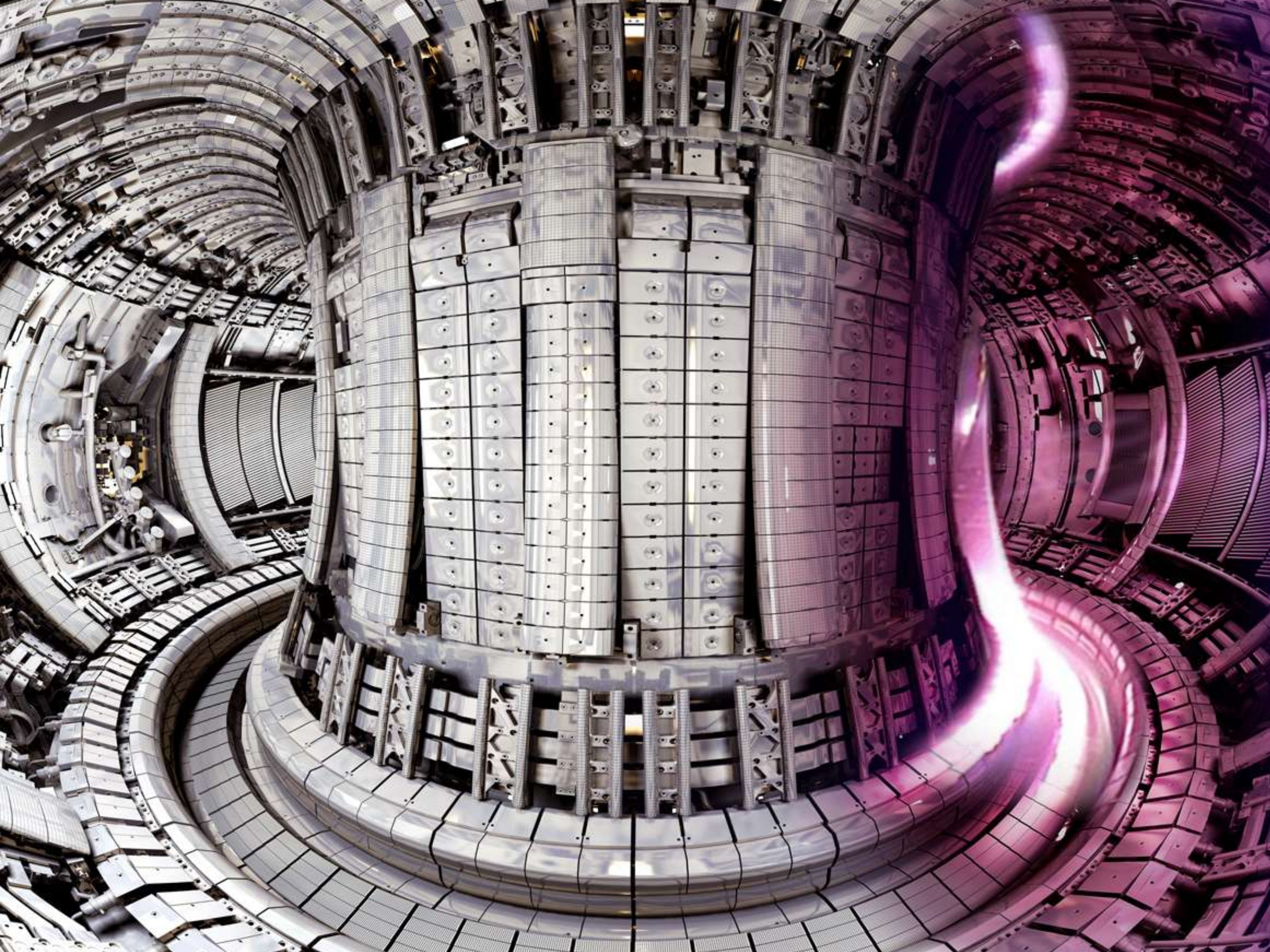
Plasma verhitting

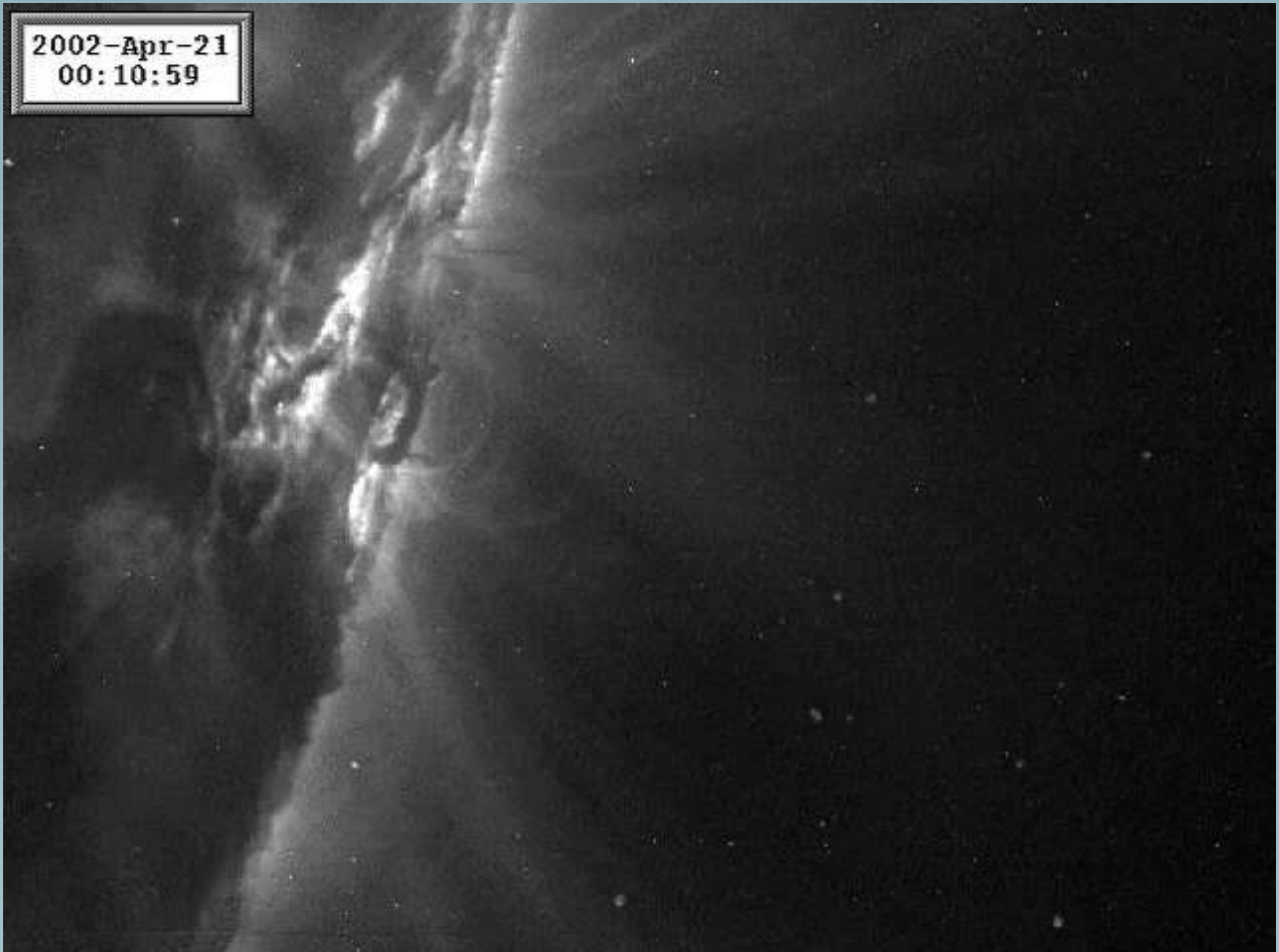


JET

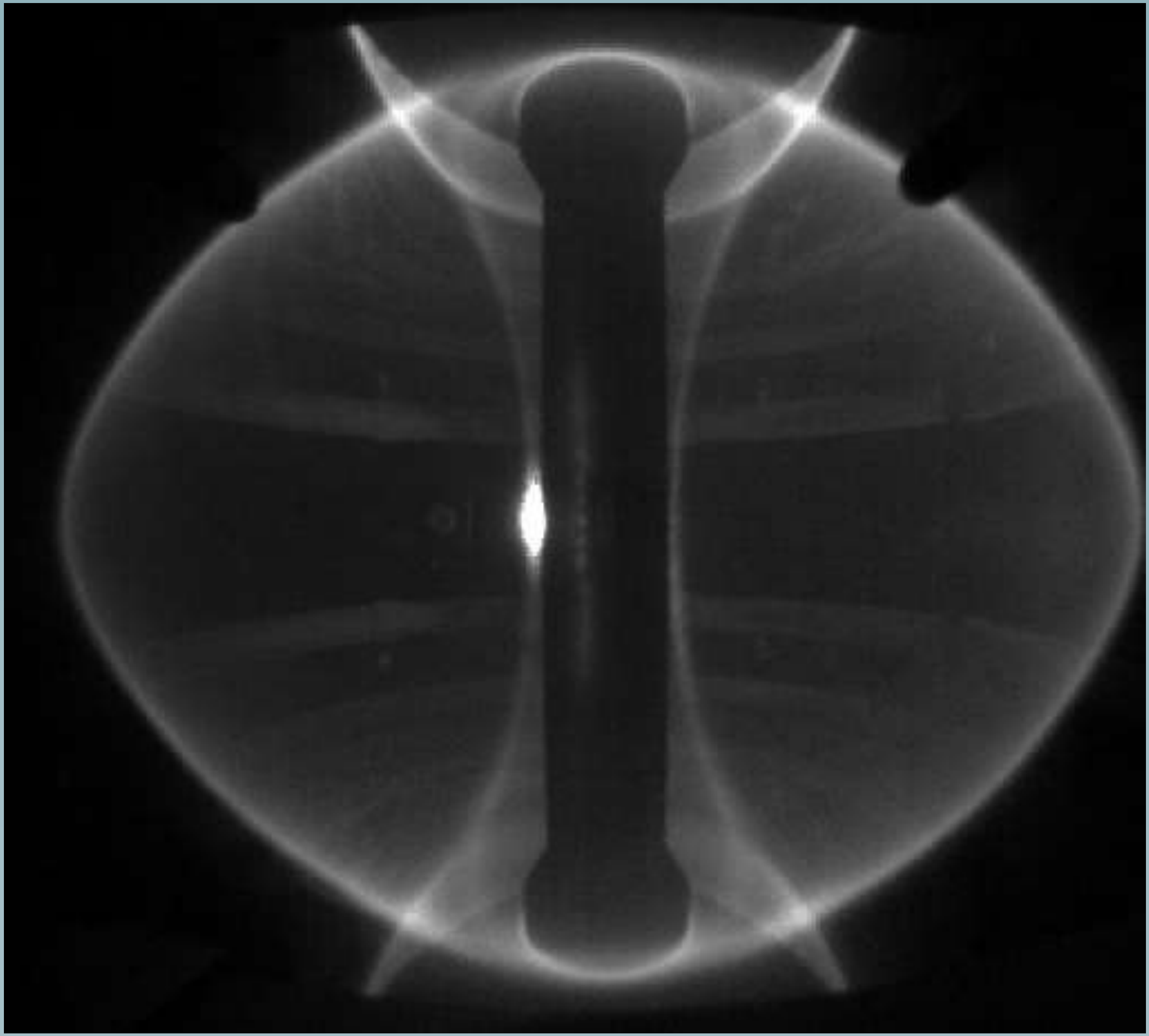



JET



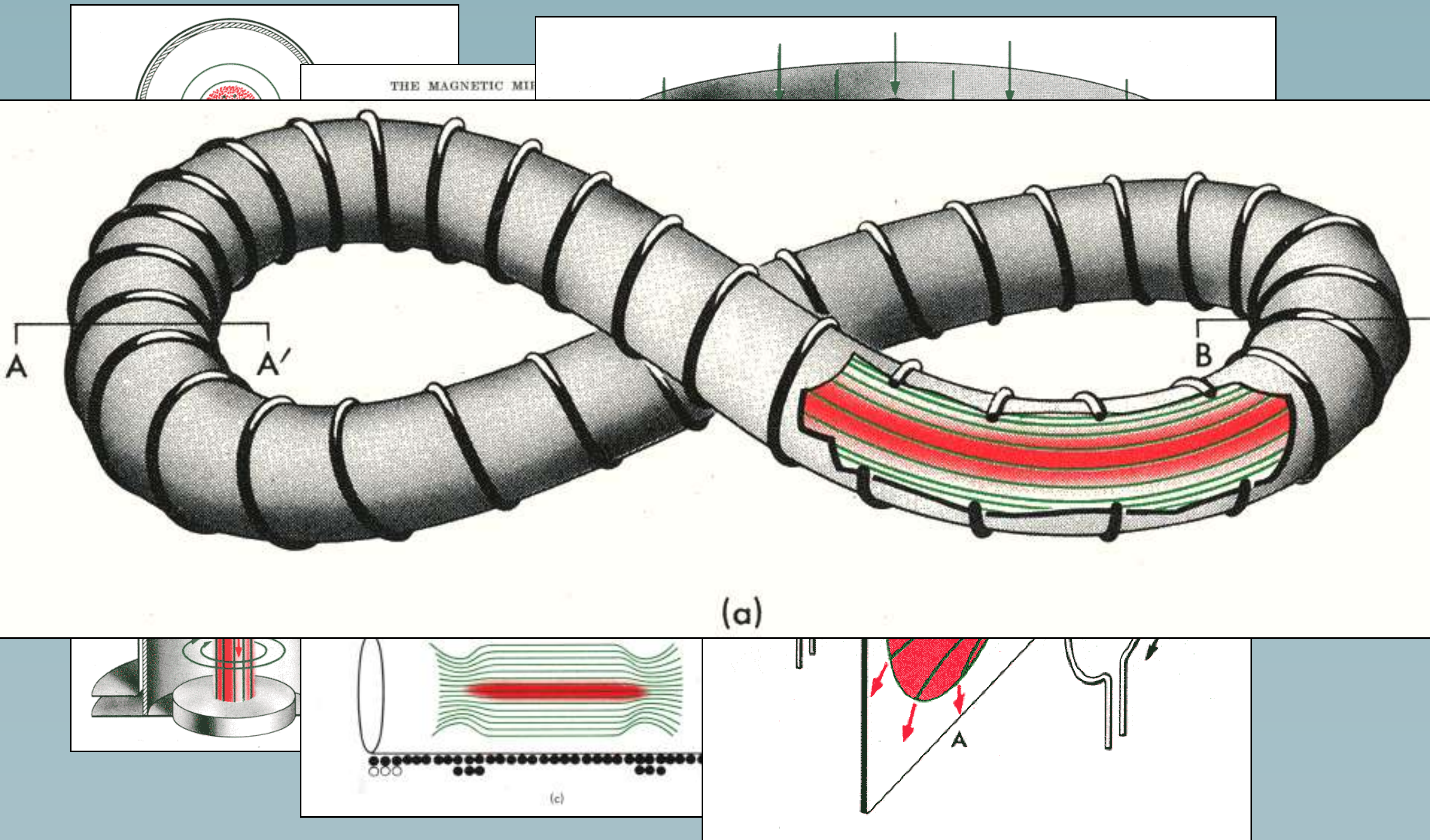

2002-Apr-21
00:10:59

MAST (Culham, UK)



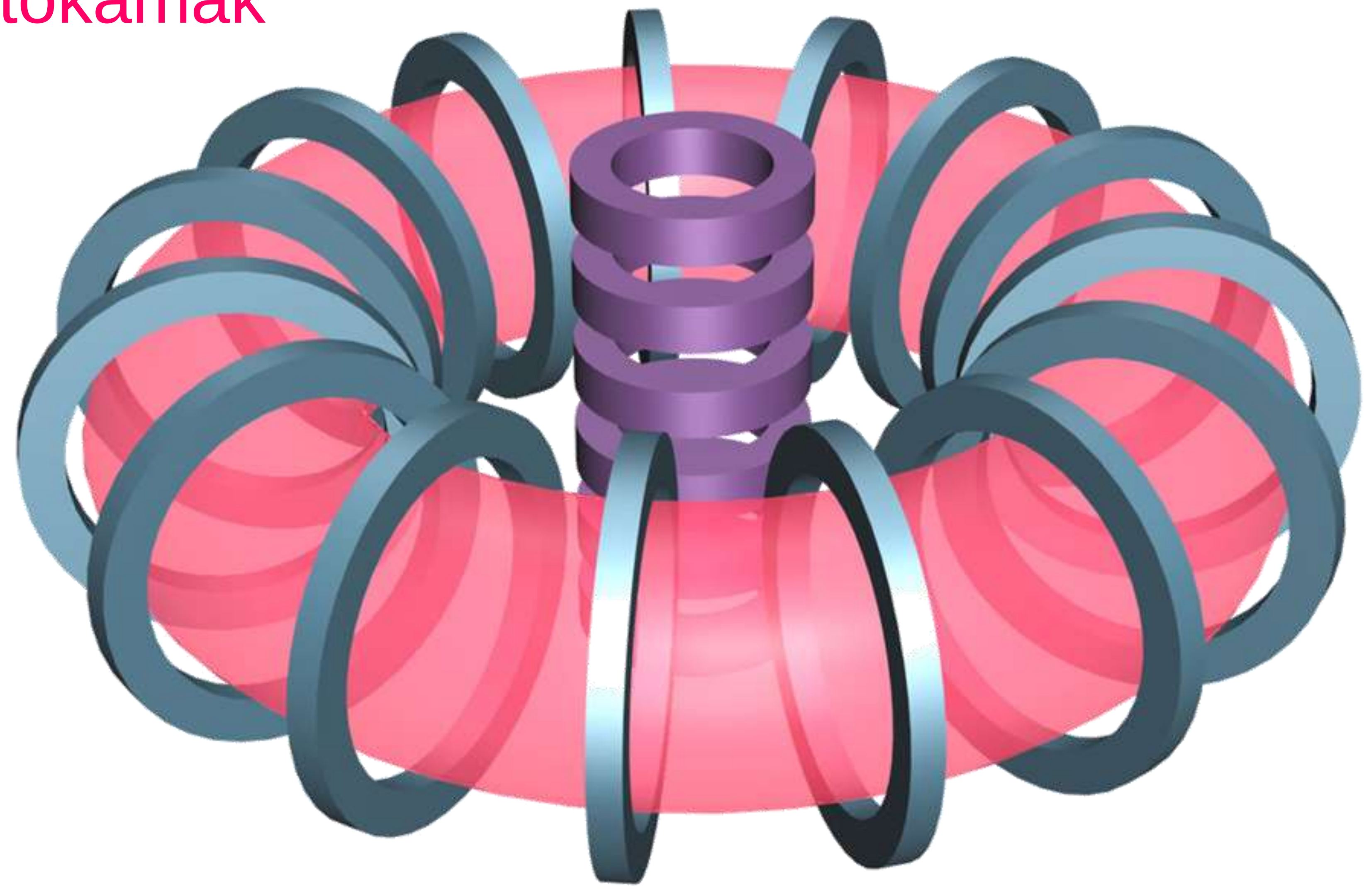
1960 1970 1980 1990 2000

Onderzoek aan magnetische opsluitingsconcepten



1960 1970 1980 1990 2000

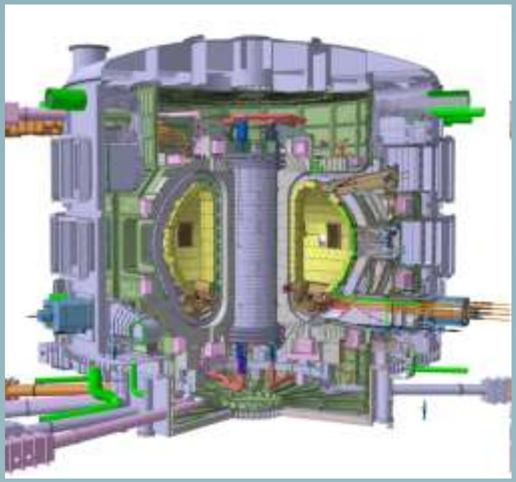
The winner: the tokamak

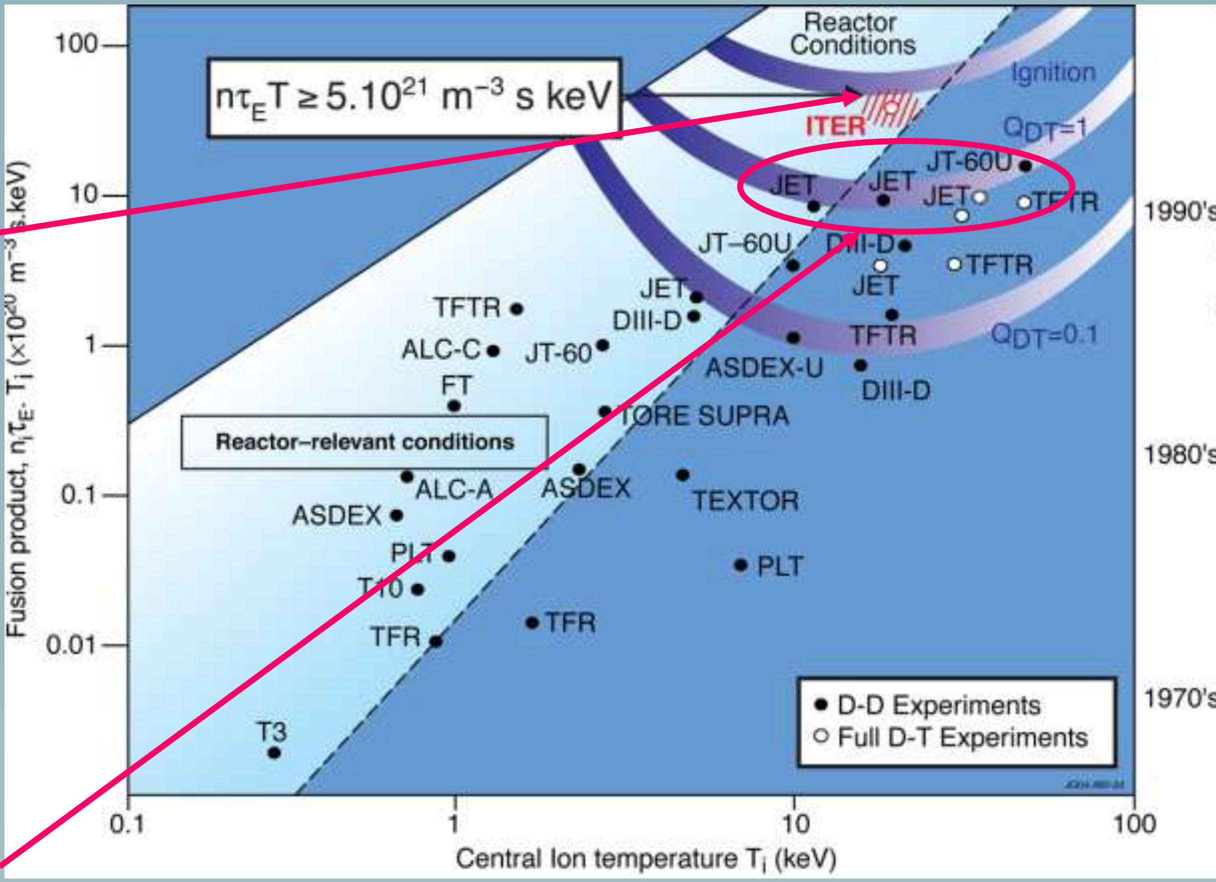


Conceptverbetering gaat door

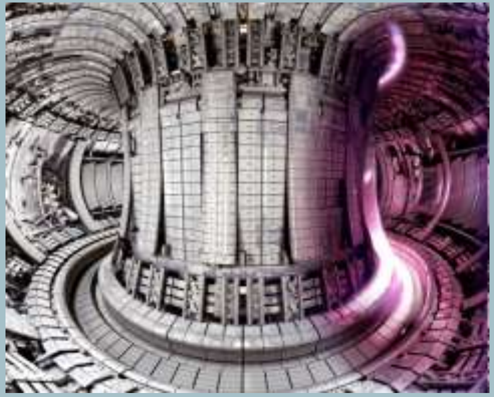
1960	1970	1980	1990	2000

Progress in fusion

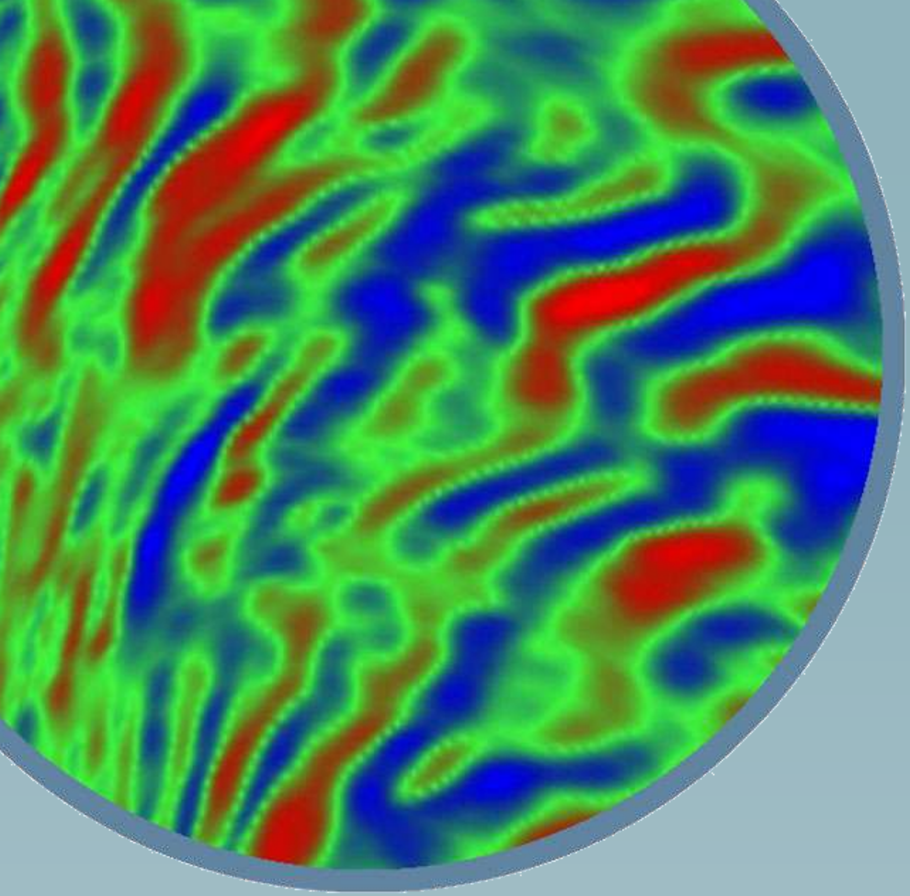




ITER
Nett energy gain:
$P_{fusion} = 10 \times P_{in}$
Demonstration of technical principles – new regime



JET (and other machines)
Break-even:
$P_{fusion} = P_{in}$
Emphasis on physics understanding



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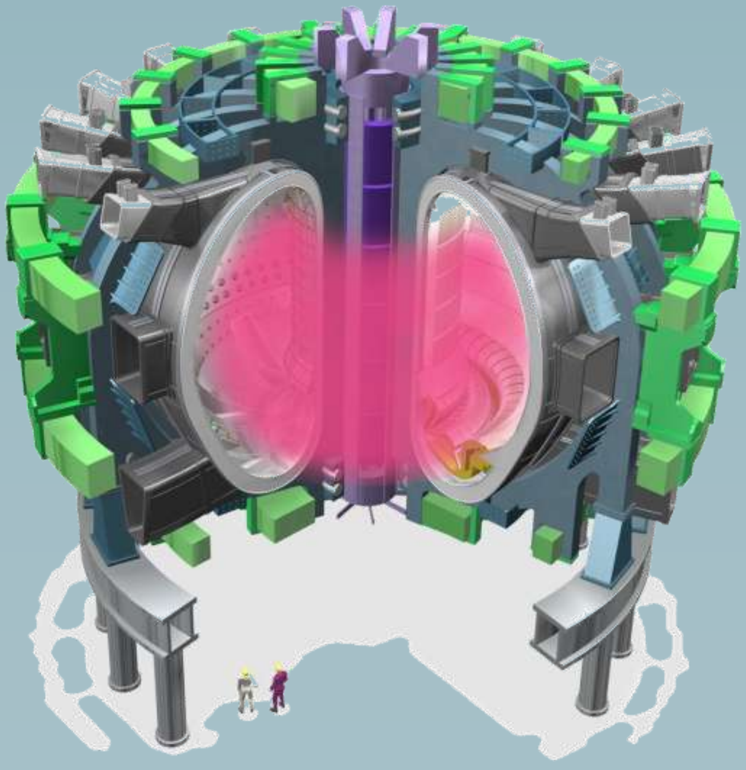
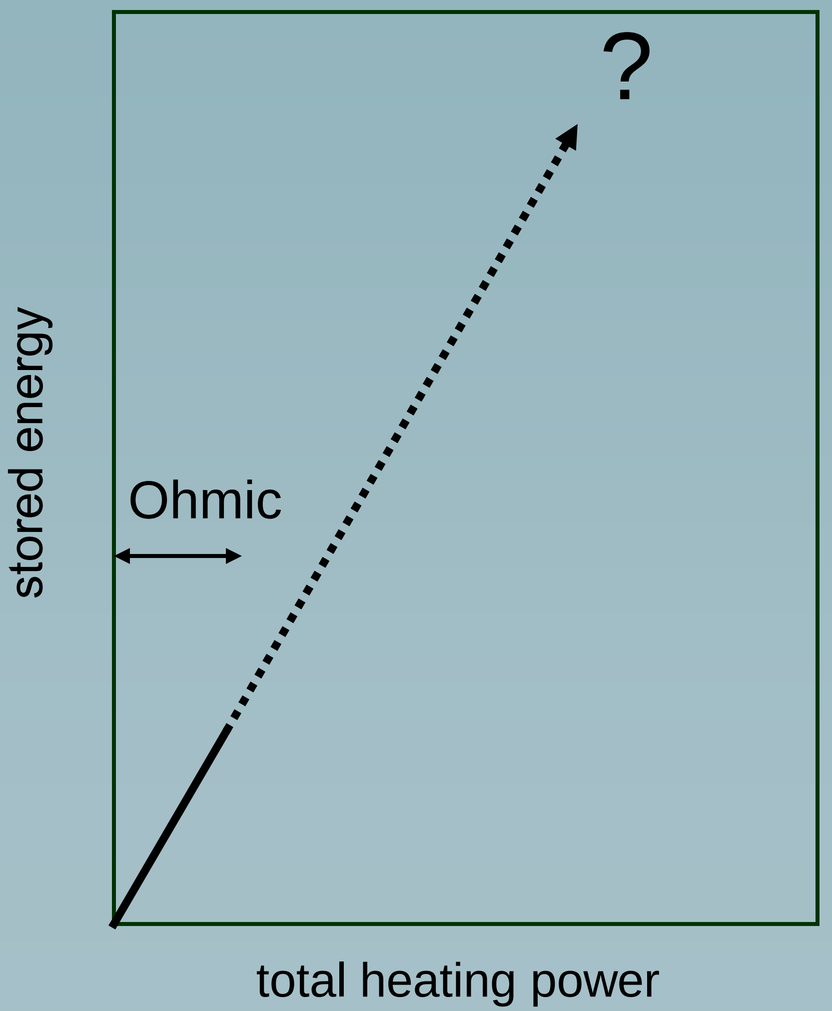
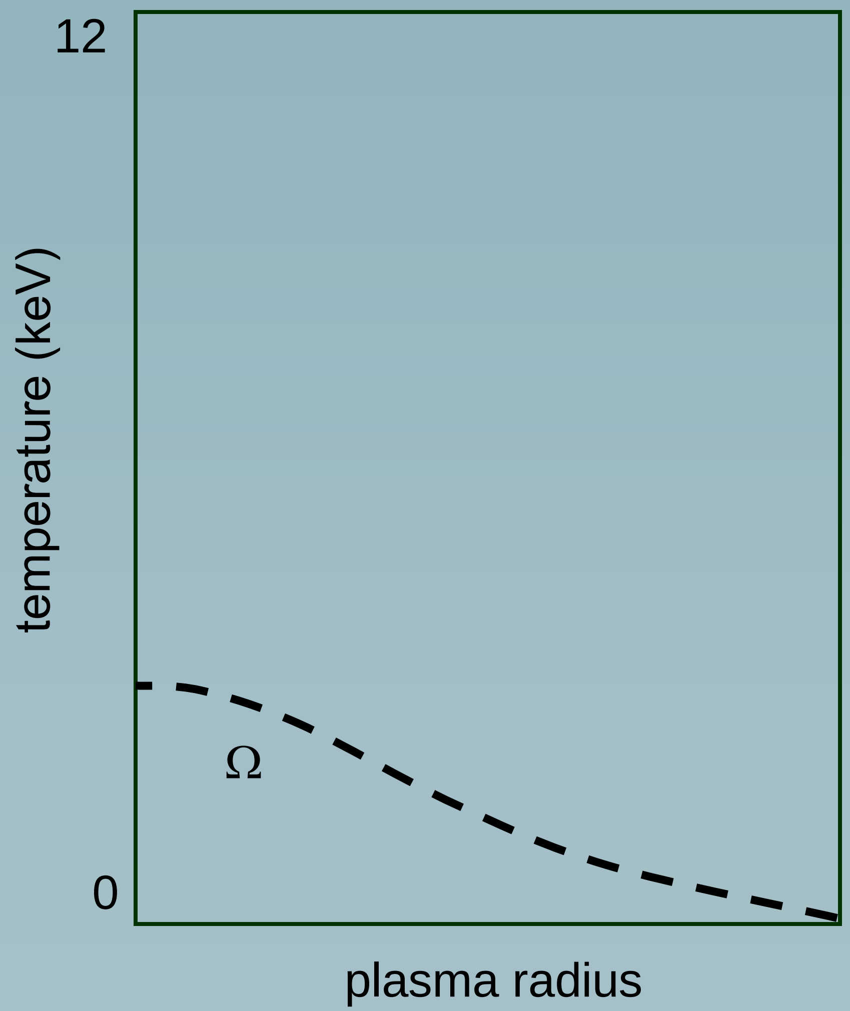


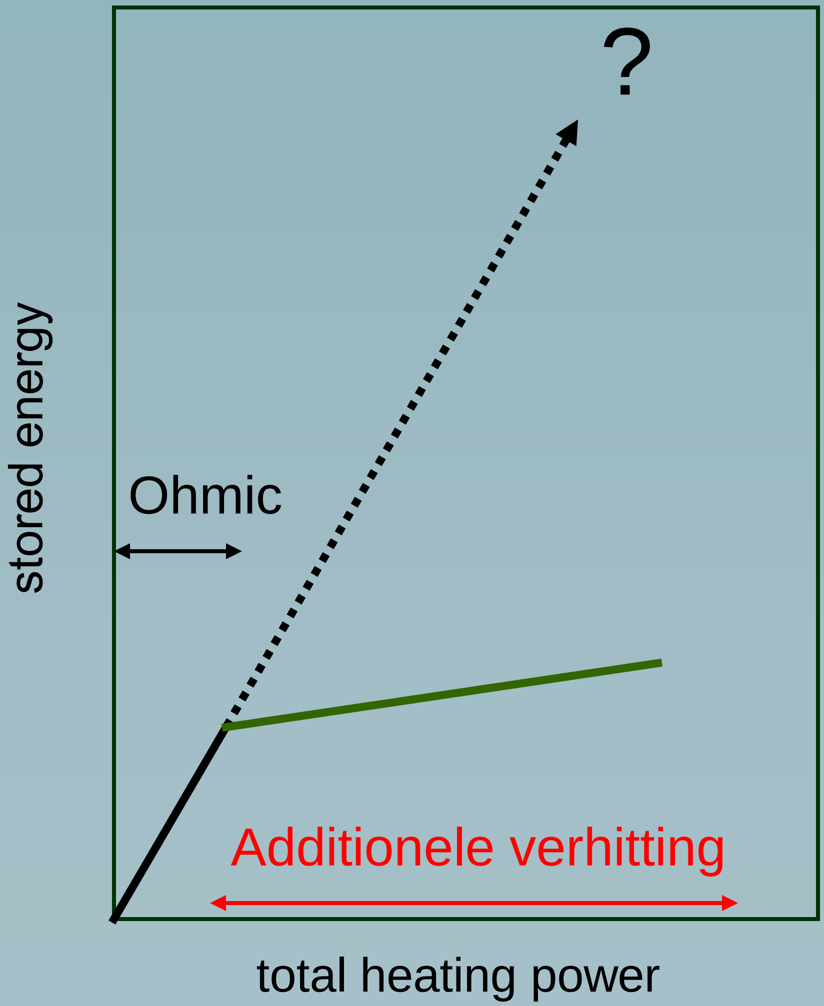
Thermische isolatie nagenoeg perfect

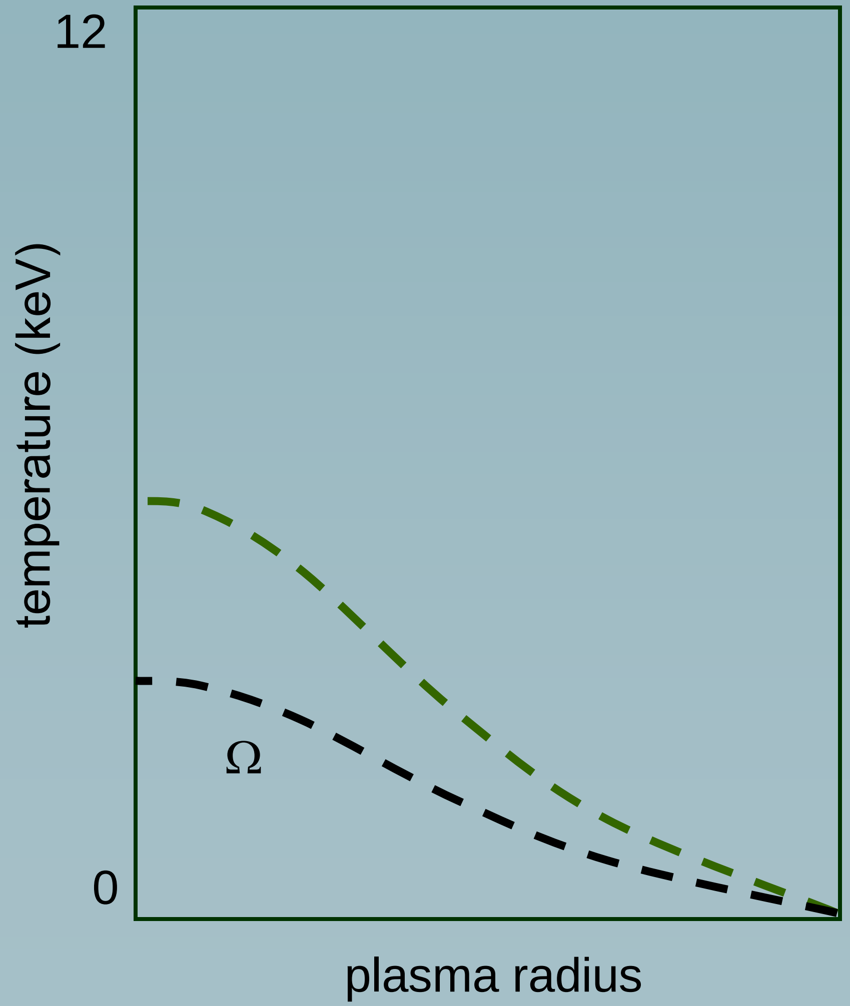
Ohmse verhitting: vermogen gekoppeld aan het opsluitende veld



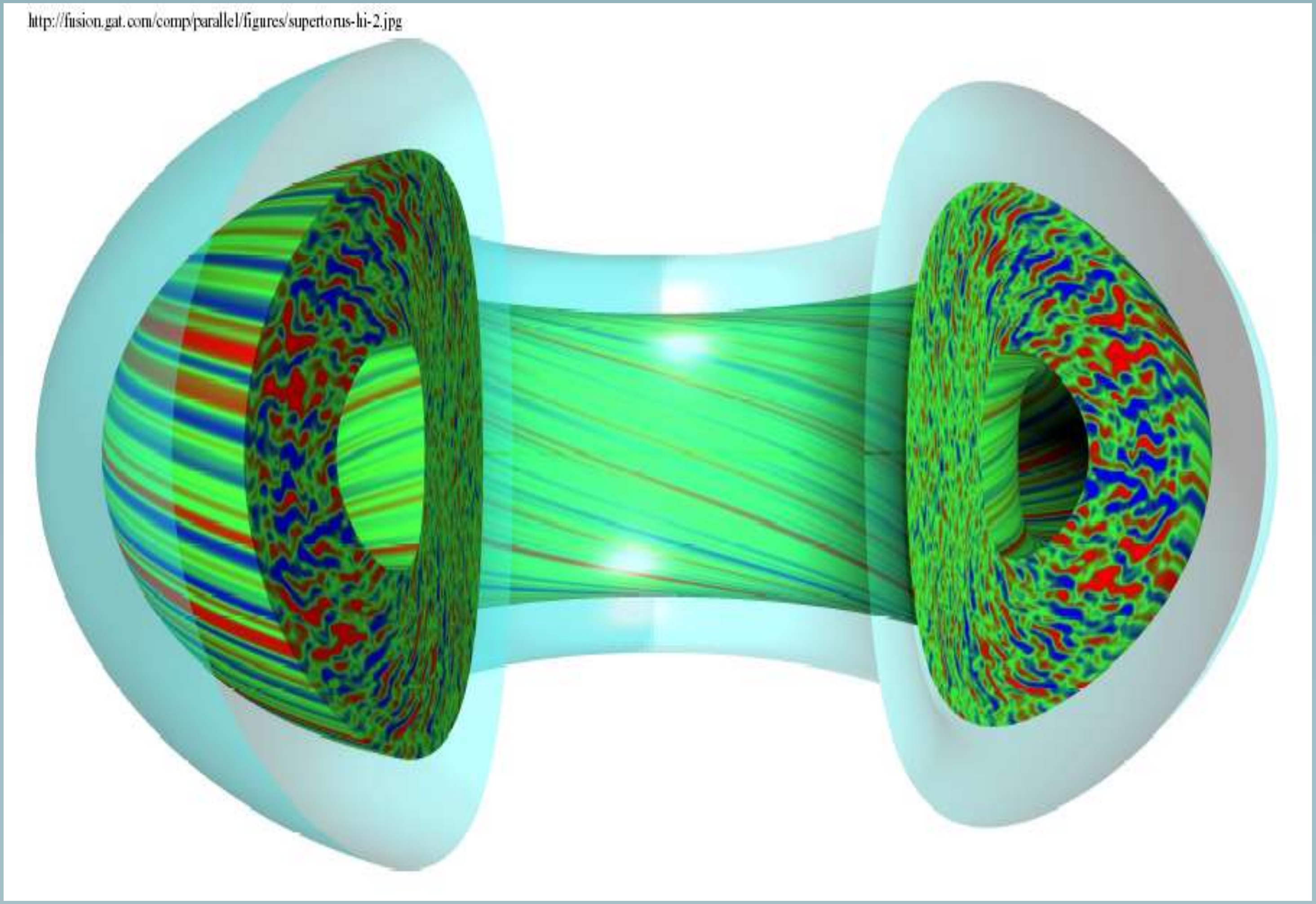


Additionele verhitting: ontkoppel verhitting & opsluitend B-veld





Gyro code; Jeff Candy (GA)



Hete plasma's hebben een rijke structuur

Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

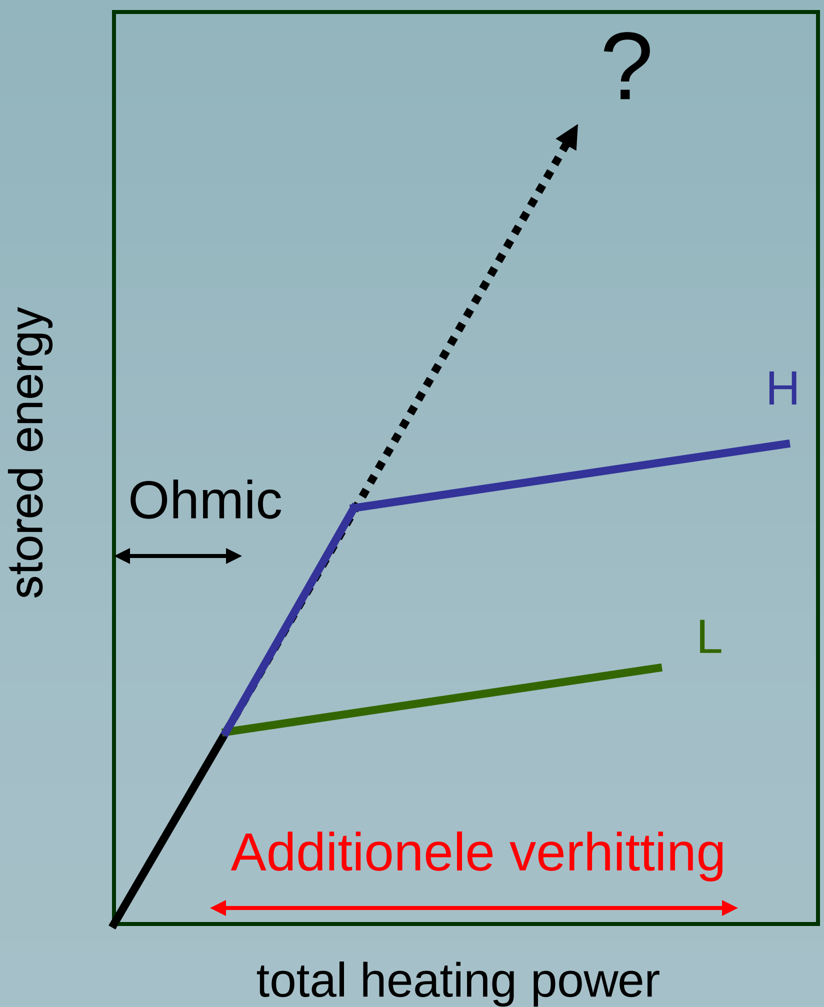
Science 281, 1835 (1998)

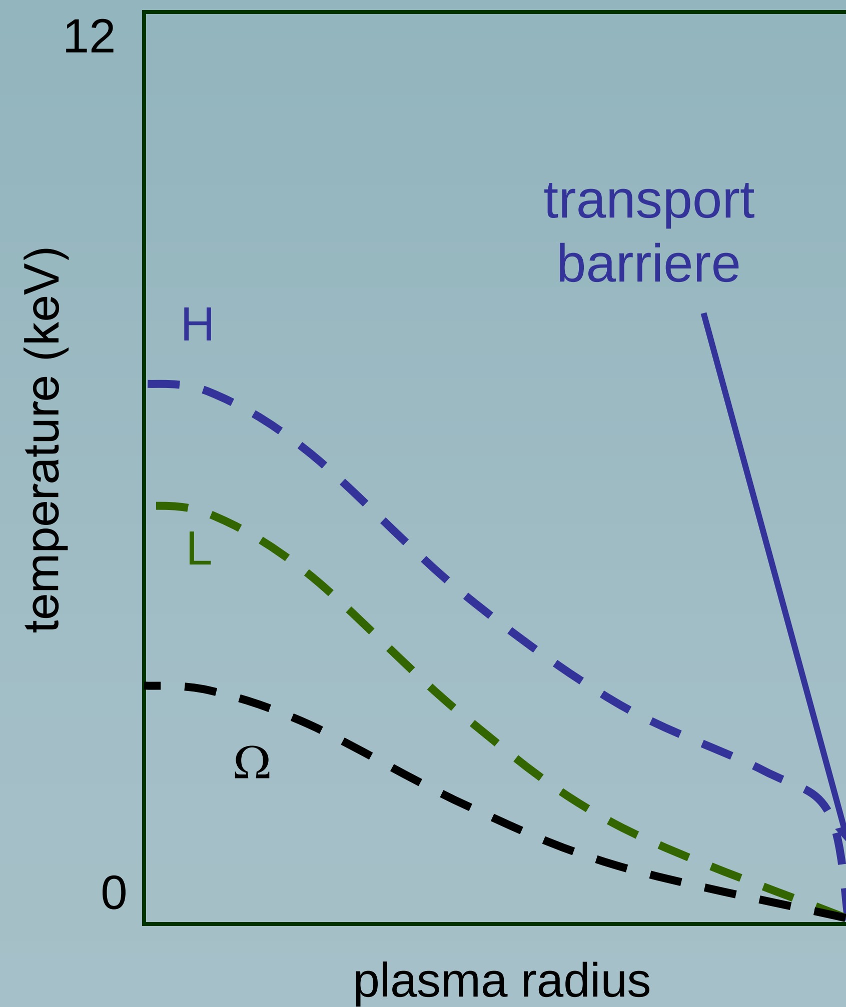
Transport door plasma fluctuaties

Lagere performance

1960 1970 1980 1990 2000

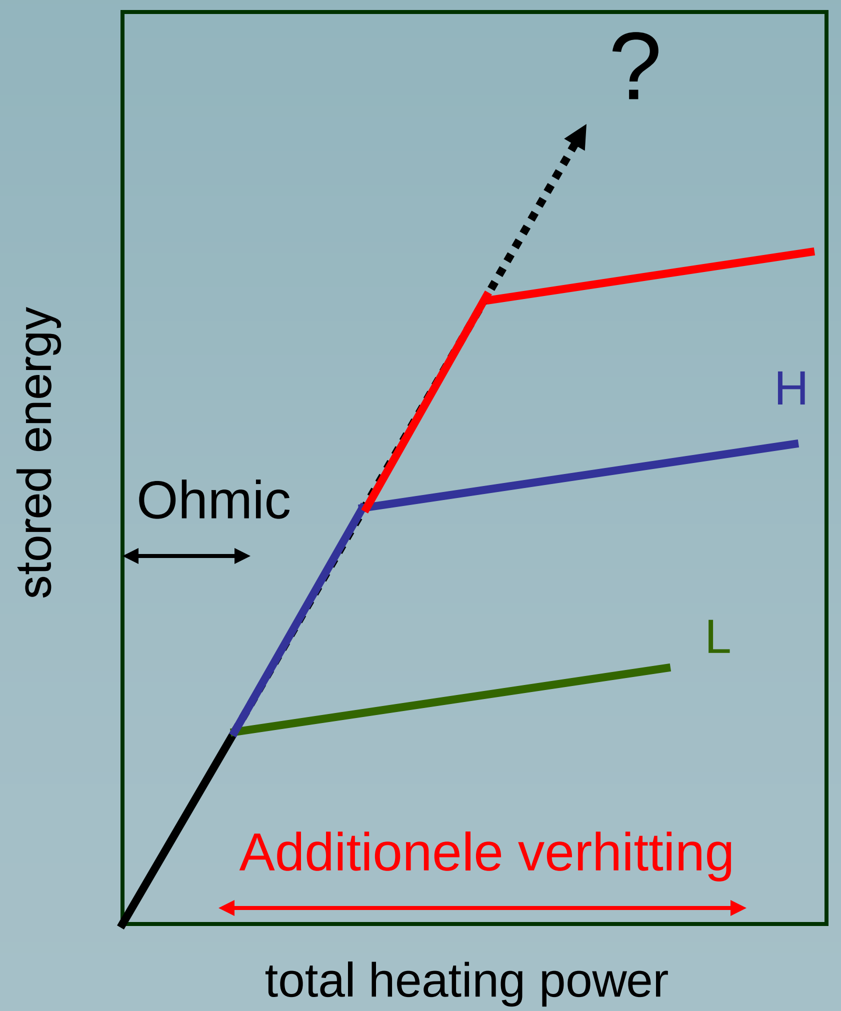
1982 ASDEX: ontdekking van high confinement mode.

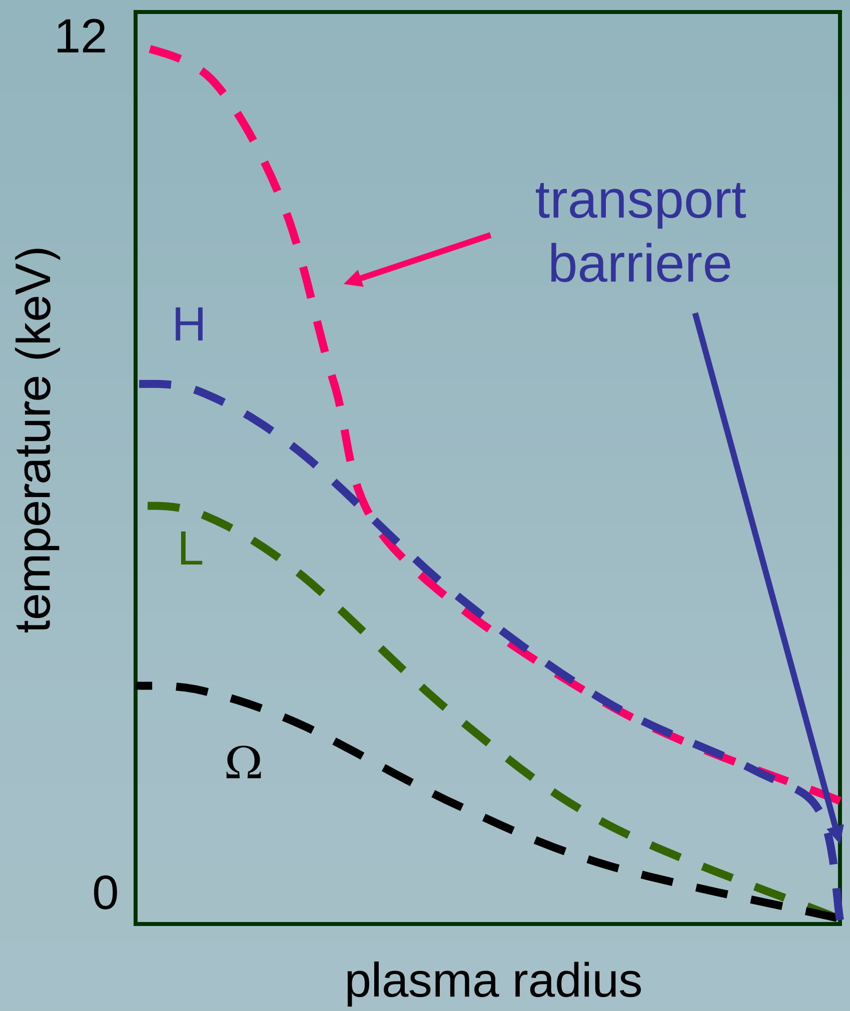




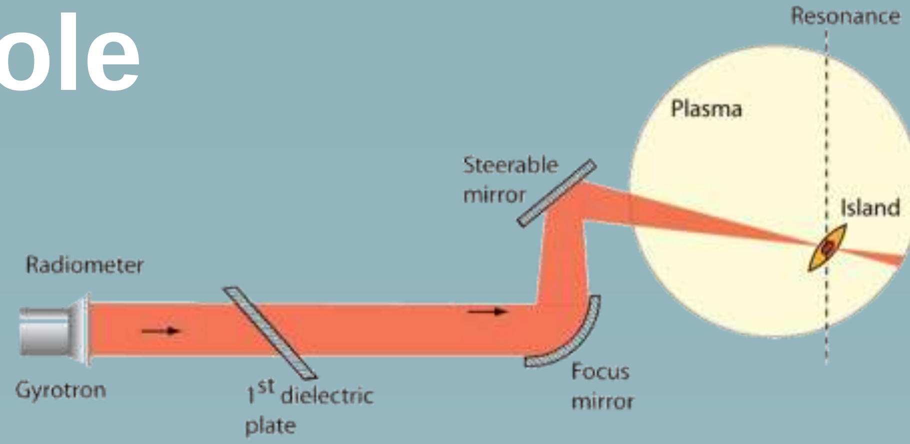
1960 1970 1980 1990 2000

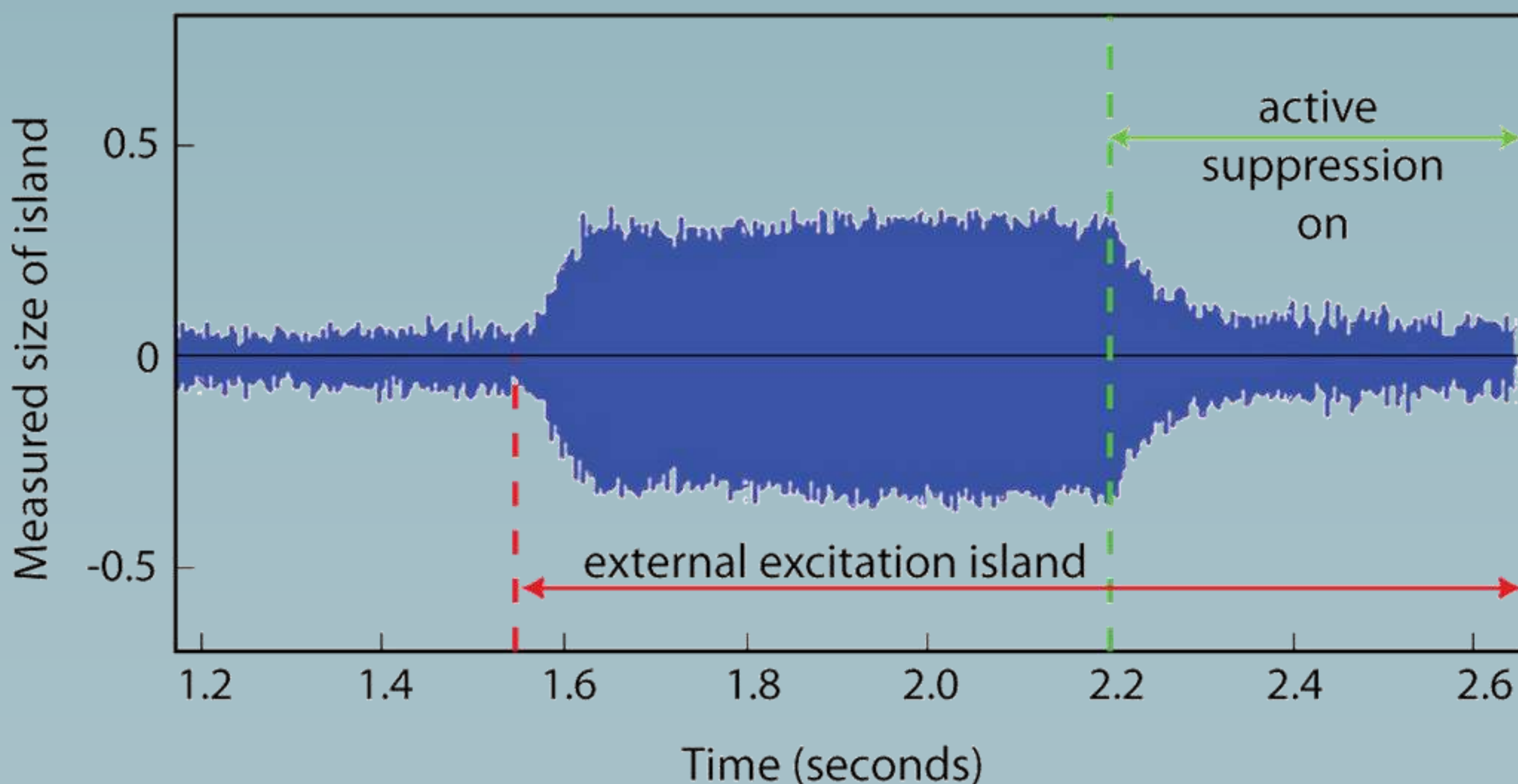
Ontdekking van interne transport barrieres





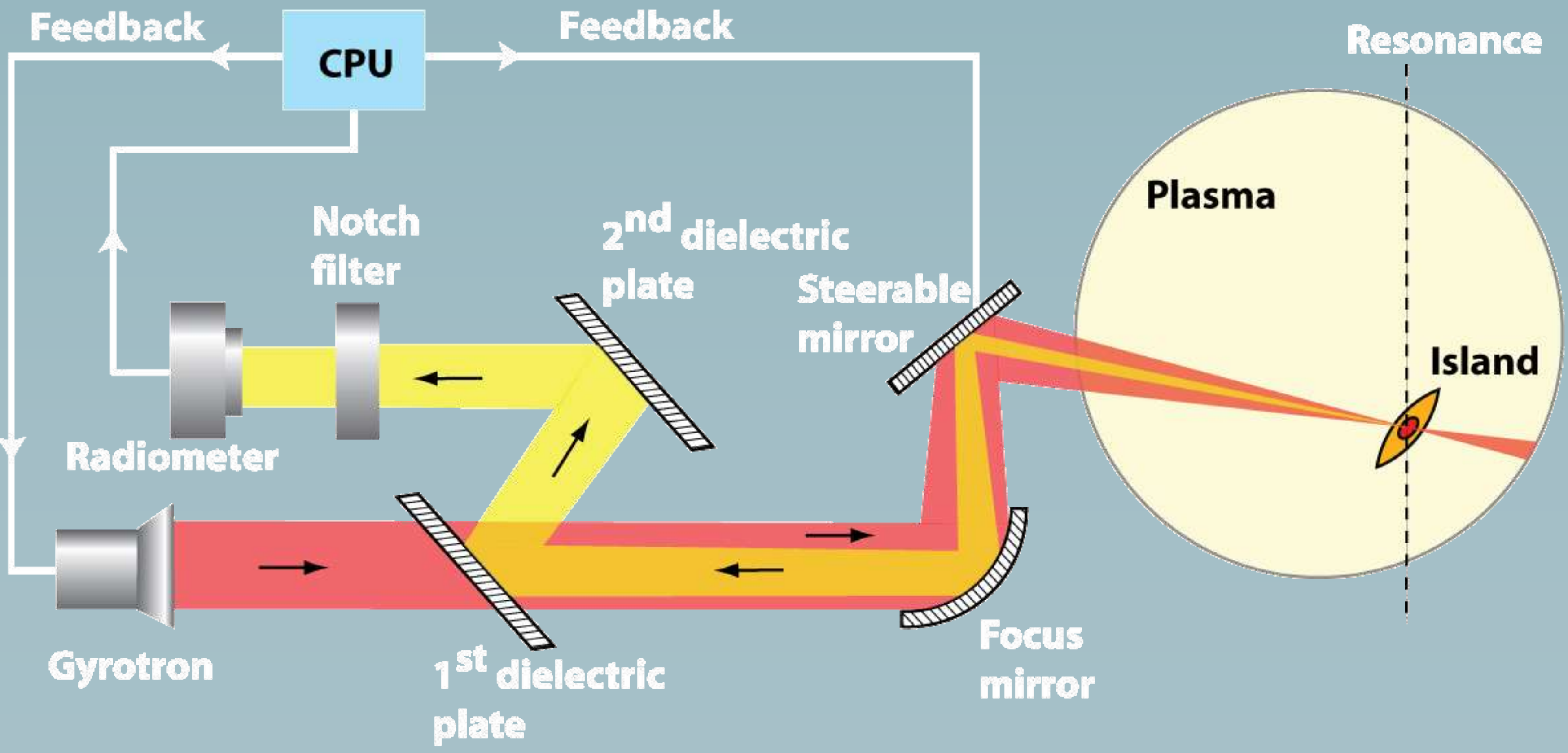
Turbulentie controle



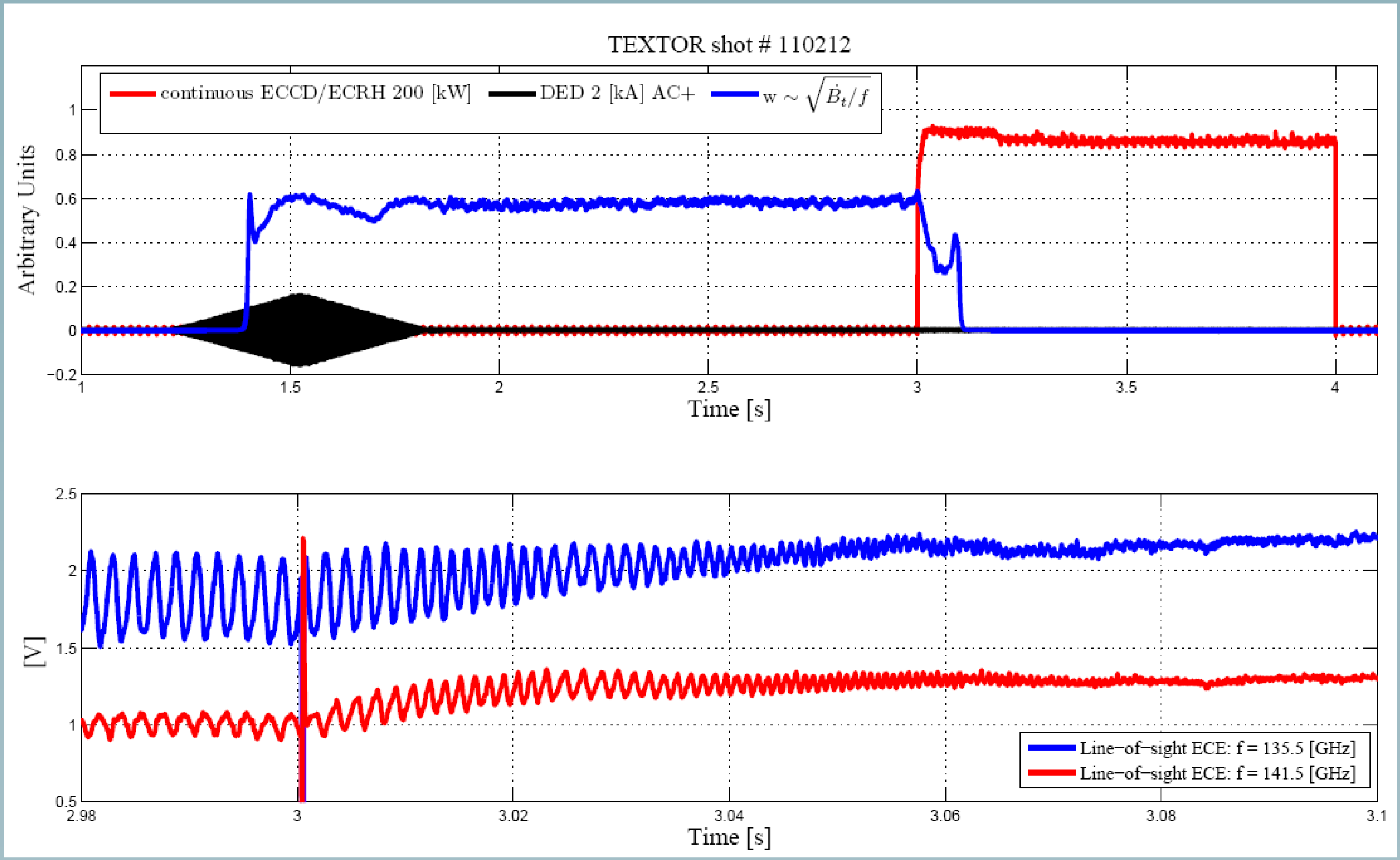


Turbulentie controle

Bart Hennen

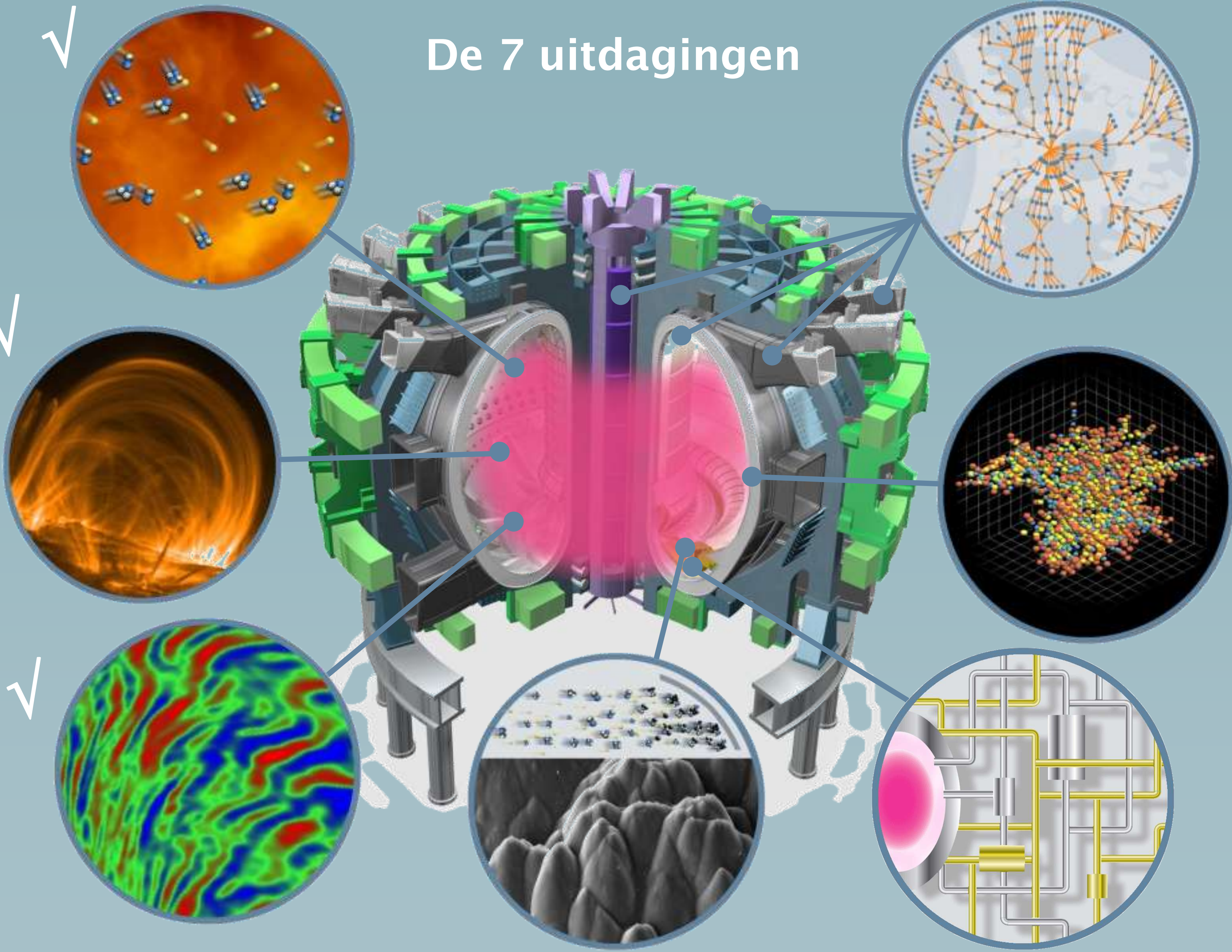


Turbulentie controle

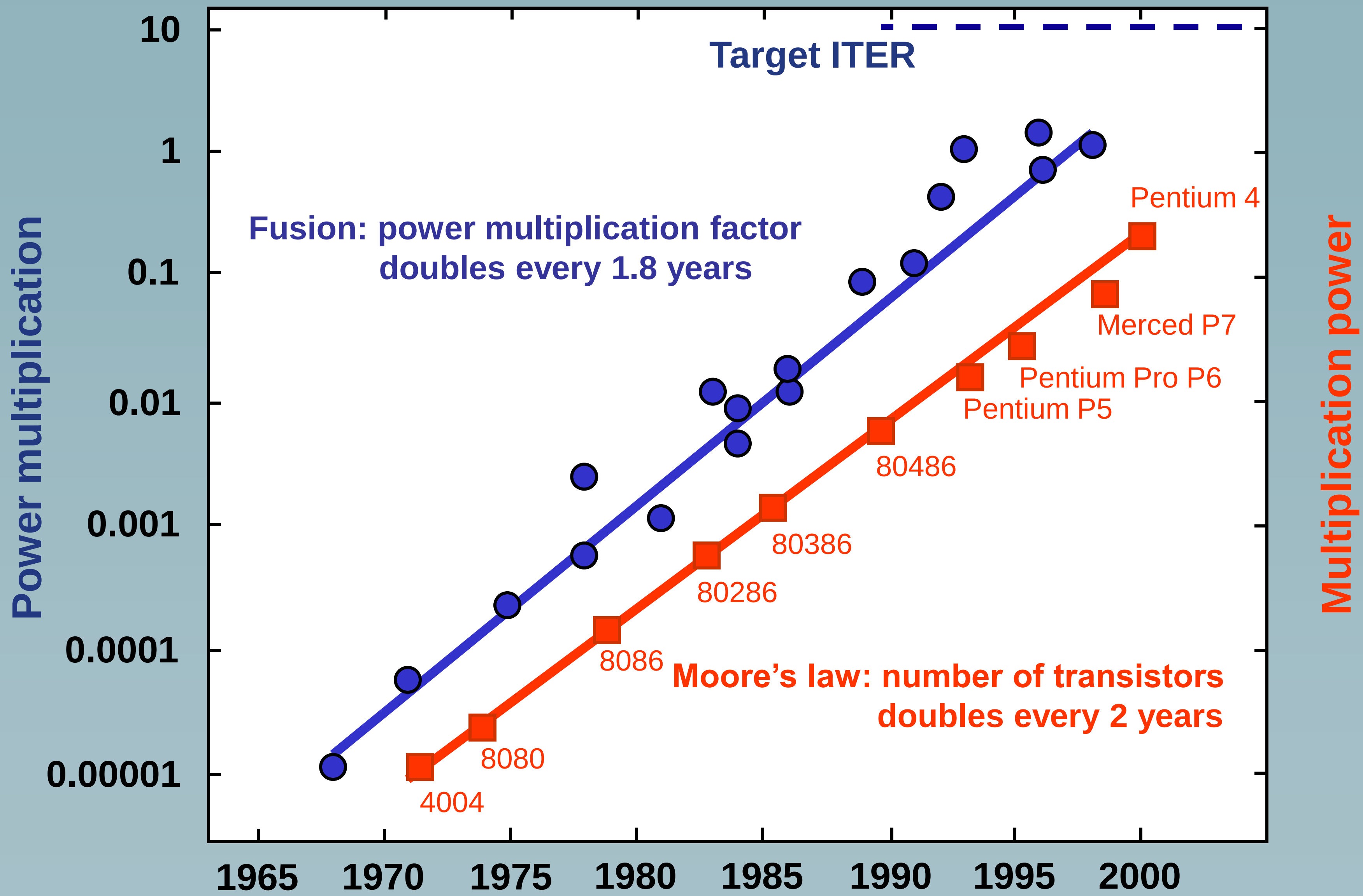


Excitatie en onderdrukking van een instabiliteit

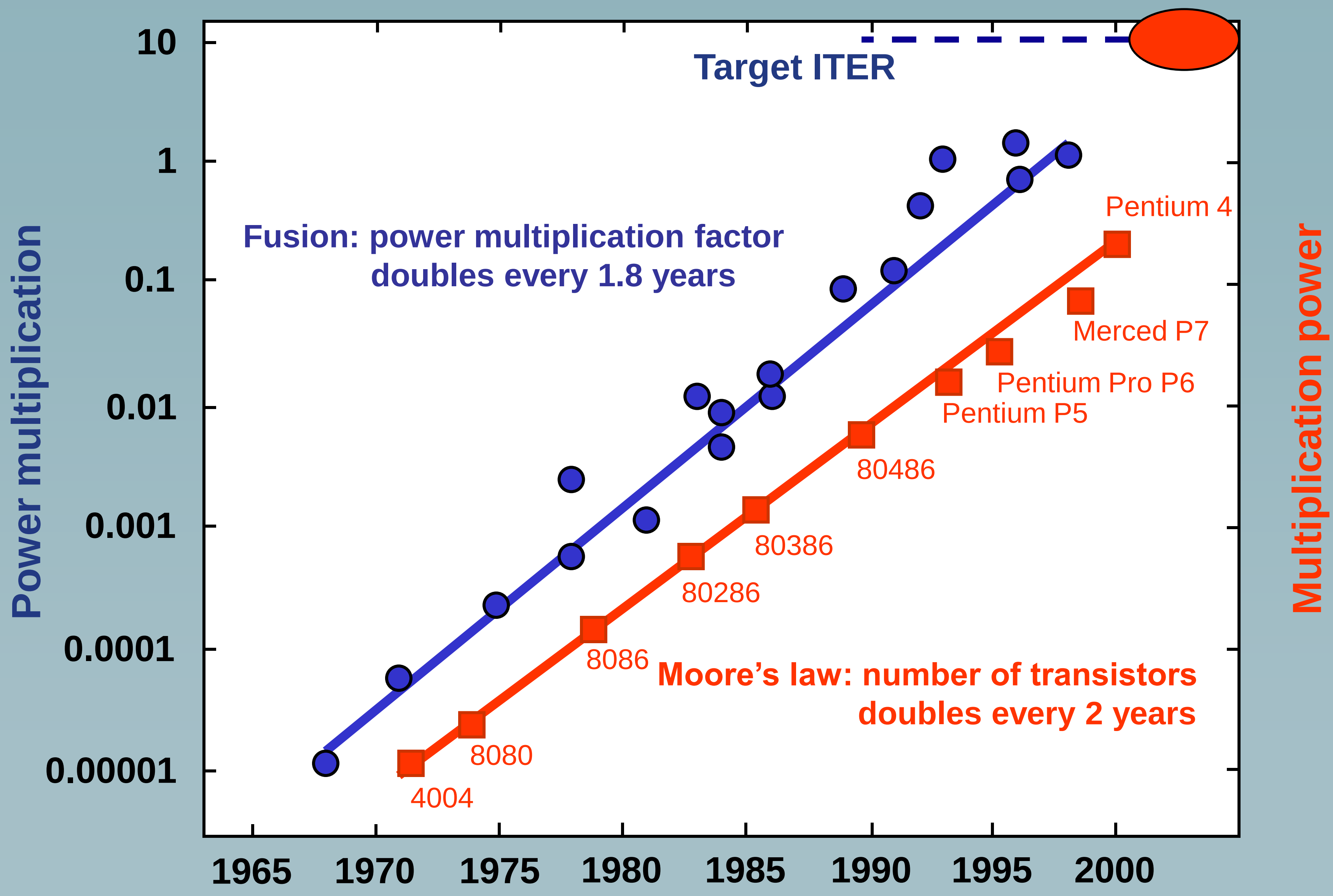
De 7 uitdagingen

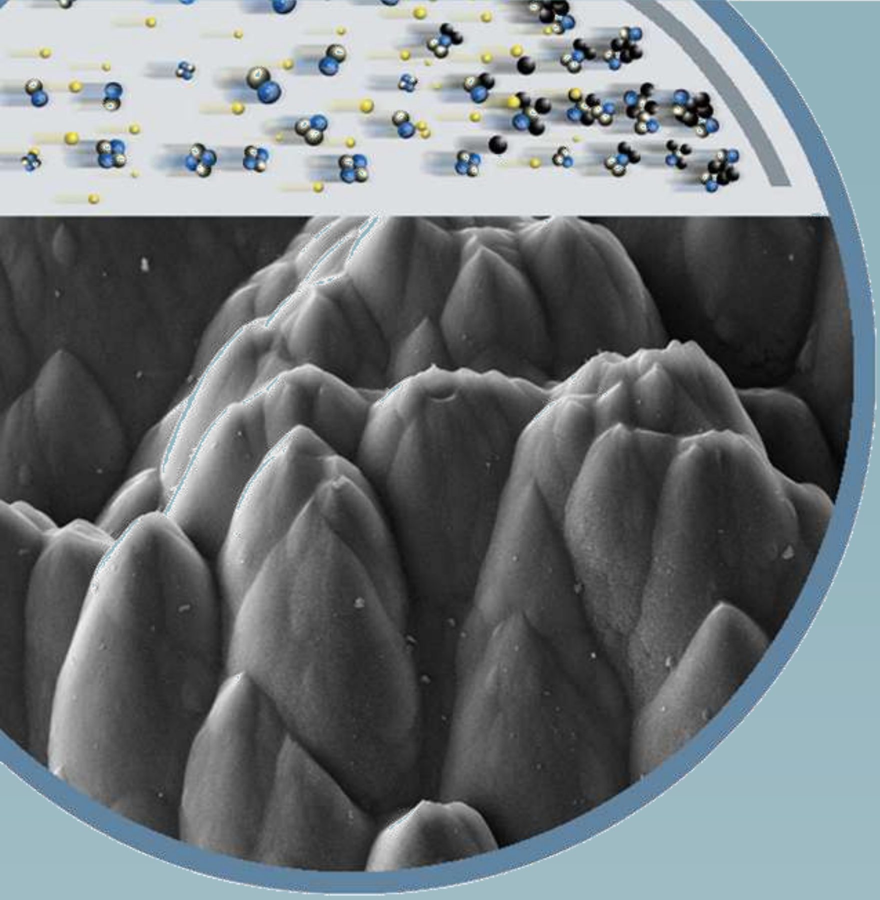


Hoge T, stabiele opsluiting, goede thermische isolatie



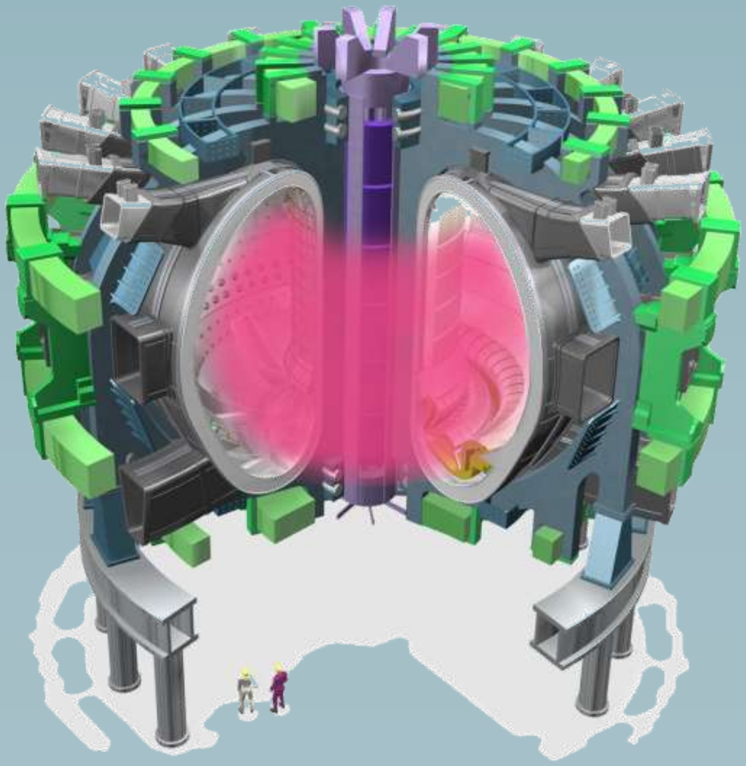
Hoge T, stabiele opsluiting, goede thermische isolatie





4

Materialen die je op de zon kunt leggen



Thermische belasting

Rolls Royce Trent 900

ITER steady-state

ITER transients

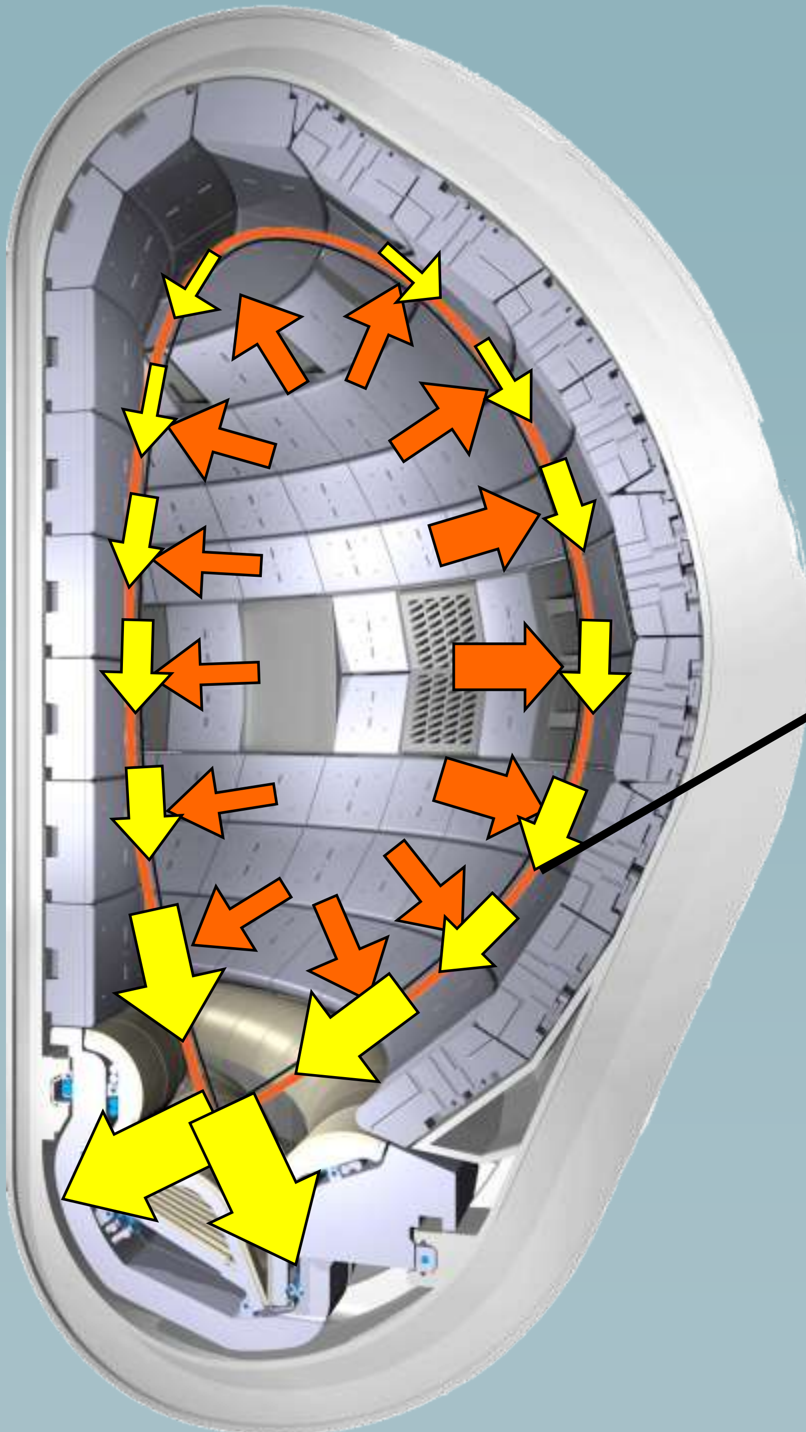
~1 <10 85 2000

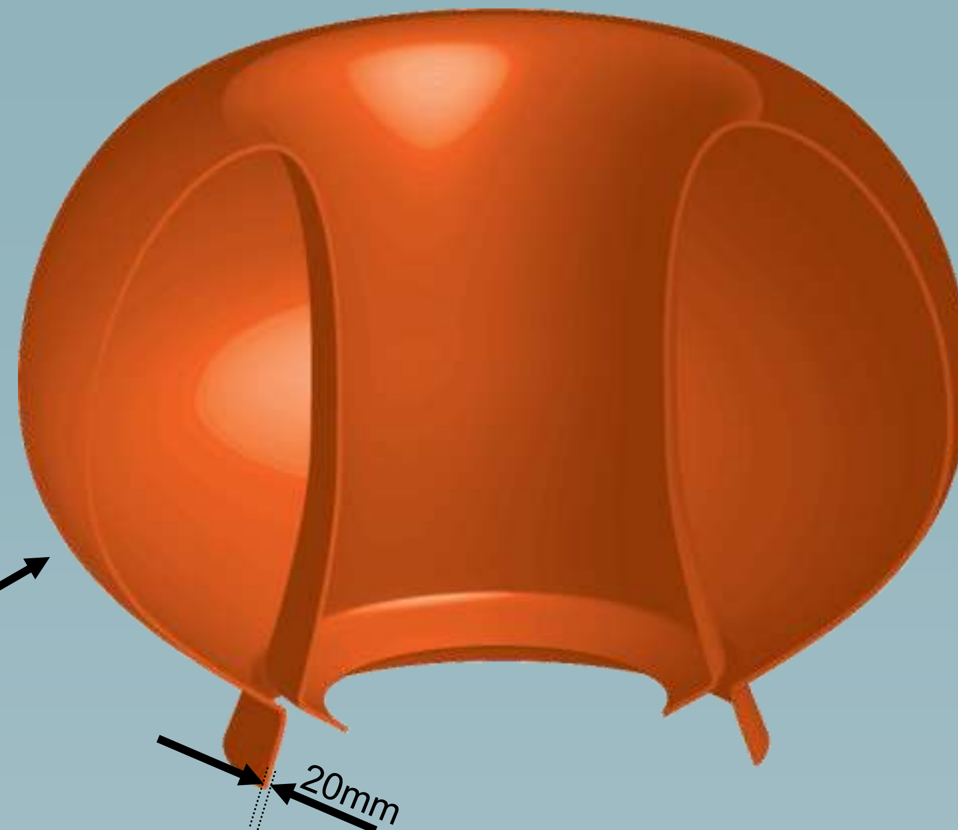
Power load [MW/m^2]

HWR

Re-entry vehicle

Ariane 5/Vulcain 2





Scrape-off laag ~ 2 cm dik

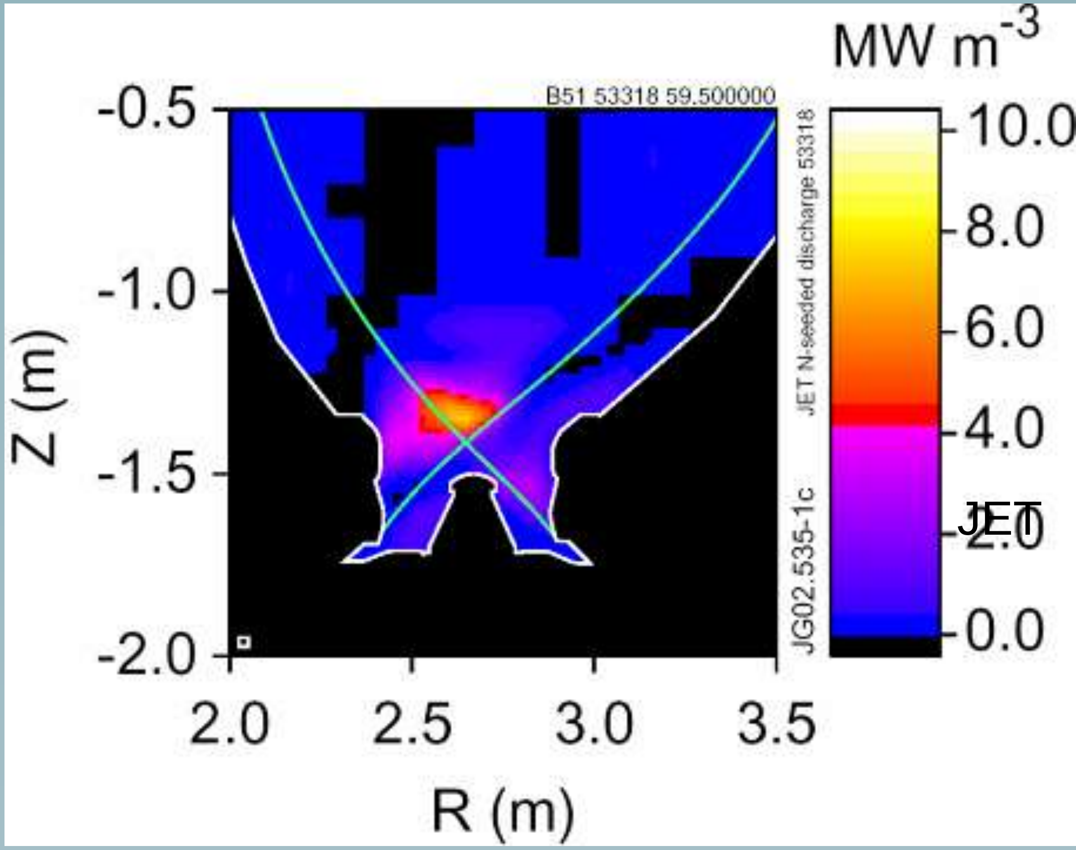
Vermogensdichtheid 1 GW/m^2

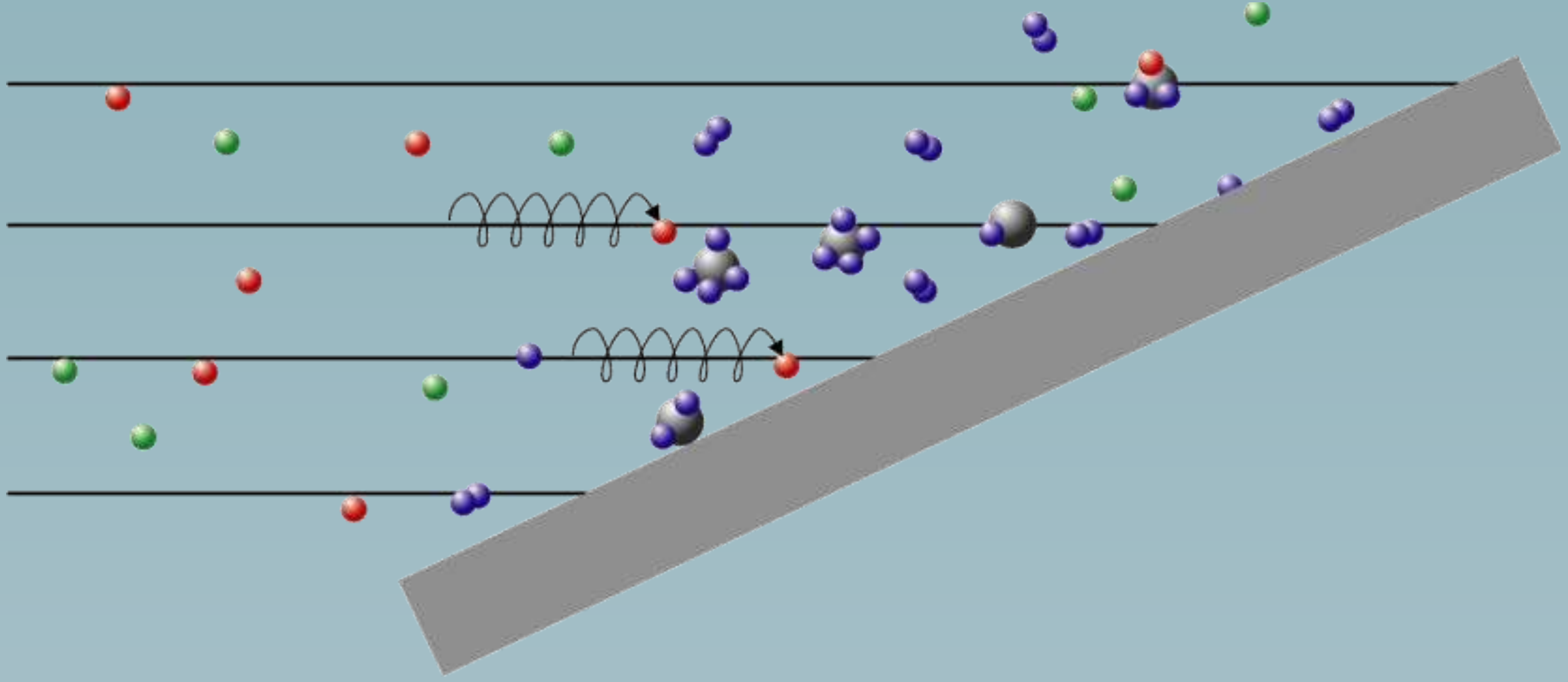
Hoe kan 1 GW/m² worden gereduceerd tot hanteerbare waarde?

Keuze van de geometrie van de divertor

Straal 90% van het vermogen weg

'Ontkoppel' het plasma in de divertor (T<10 eV)





Plasma wand materialen: vele uitdagingen

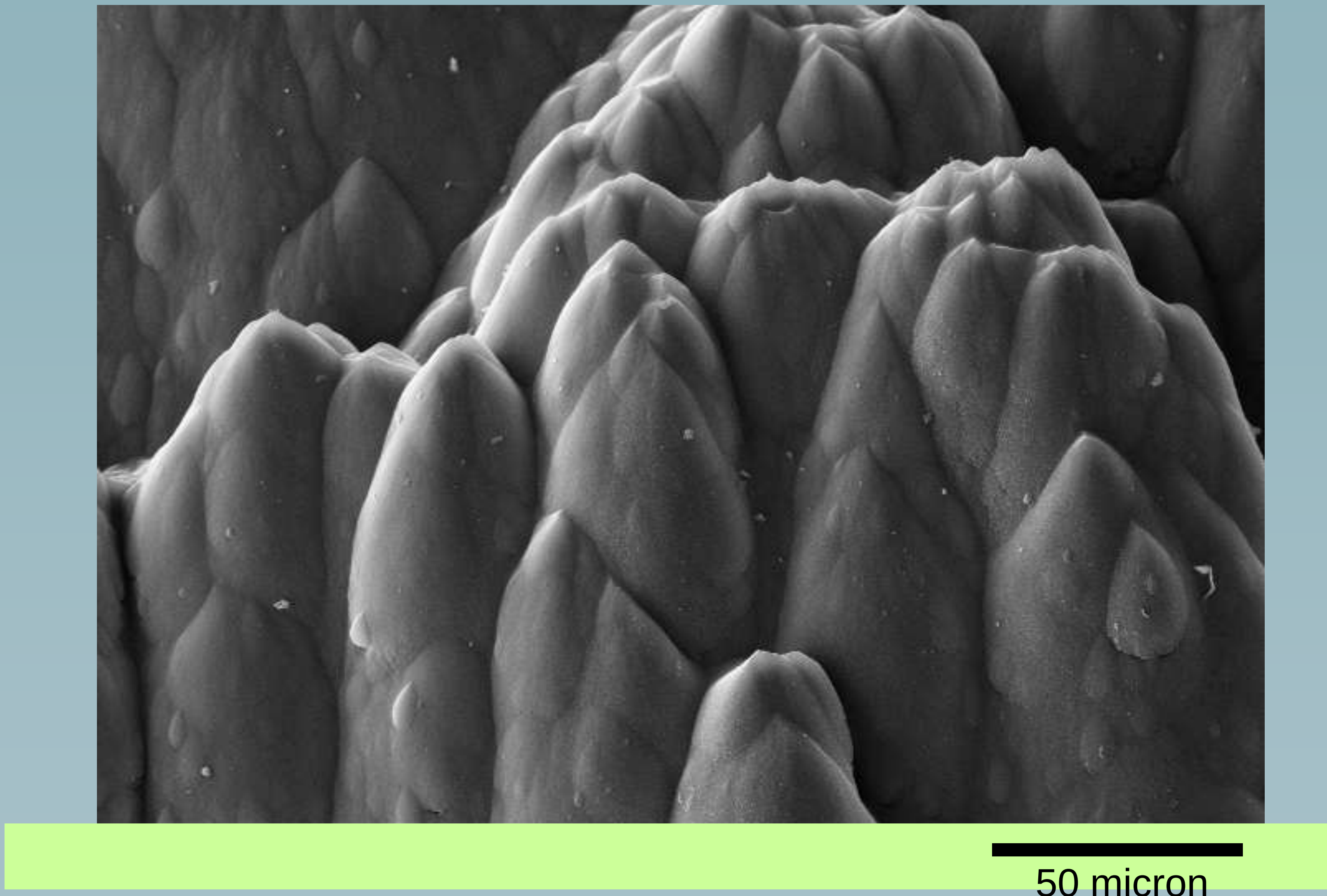
- Erosie
- Redepositie
- Tritium retentie
- Smelten
- Plasmavervuiling

Materiaalkeuze: Koolstof, Wolfraam, Beryllium.

Belangrijke randvoorwaarden: neutron fluentie activatie


Alcator C-Mod (MIT)

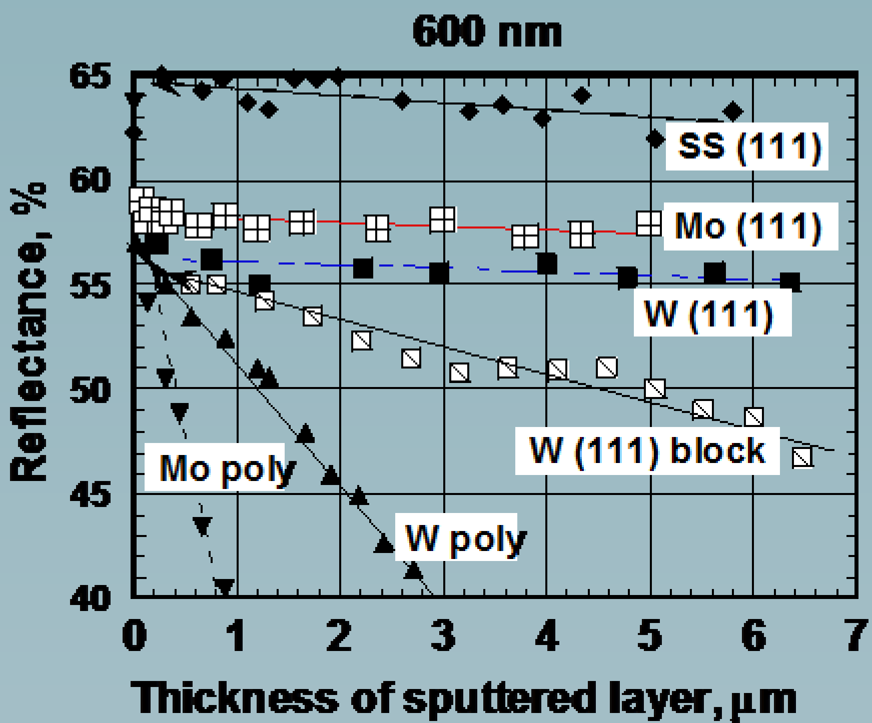
Depositie van koolstof in TEXTOR (FZ-Julich)



Erosie/redepositie

Reflectivity for eroded mirrors

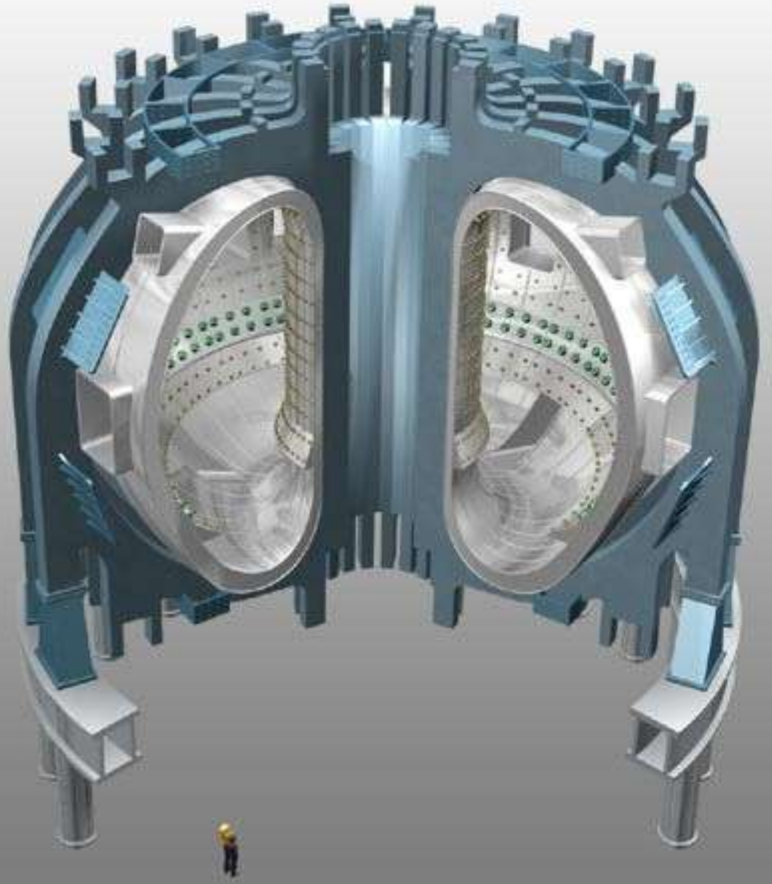
V. Voitsenya, Rev. Sci. Instrum. 76 (2005) 083502.

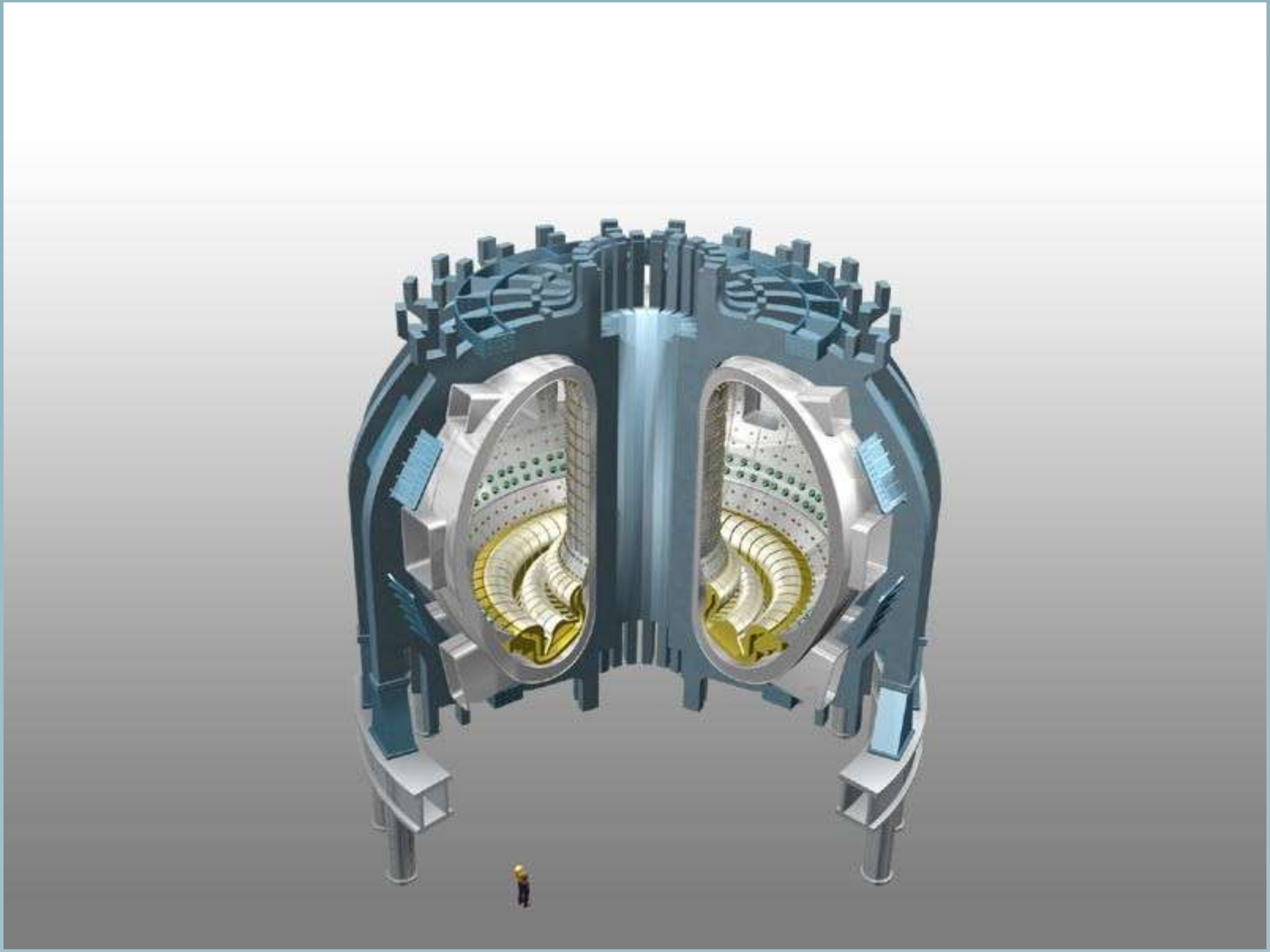


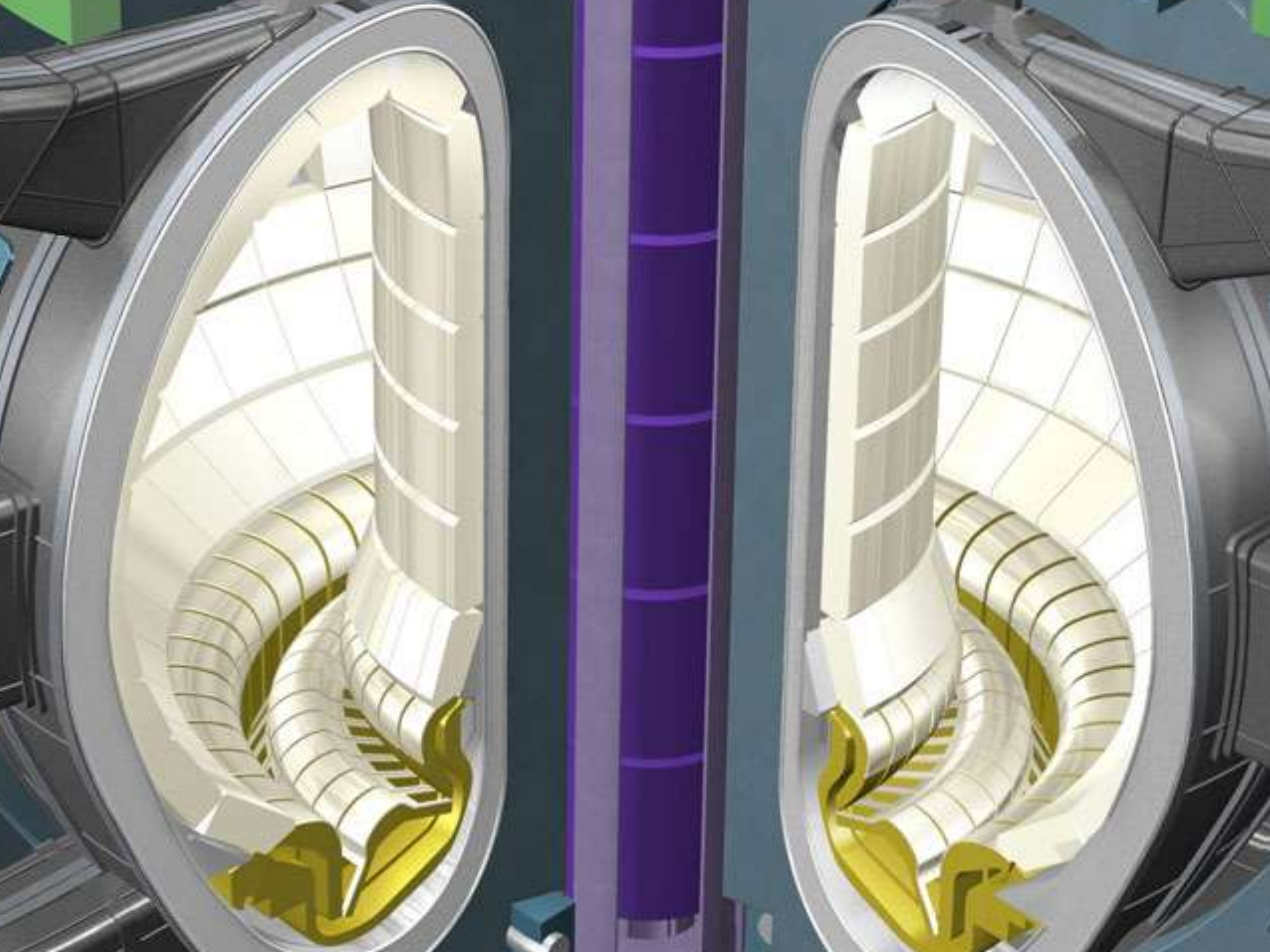
Material eroded away elsewhere can be redeposited on mirrors

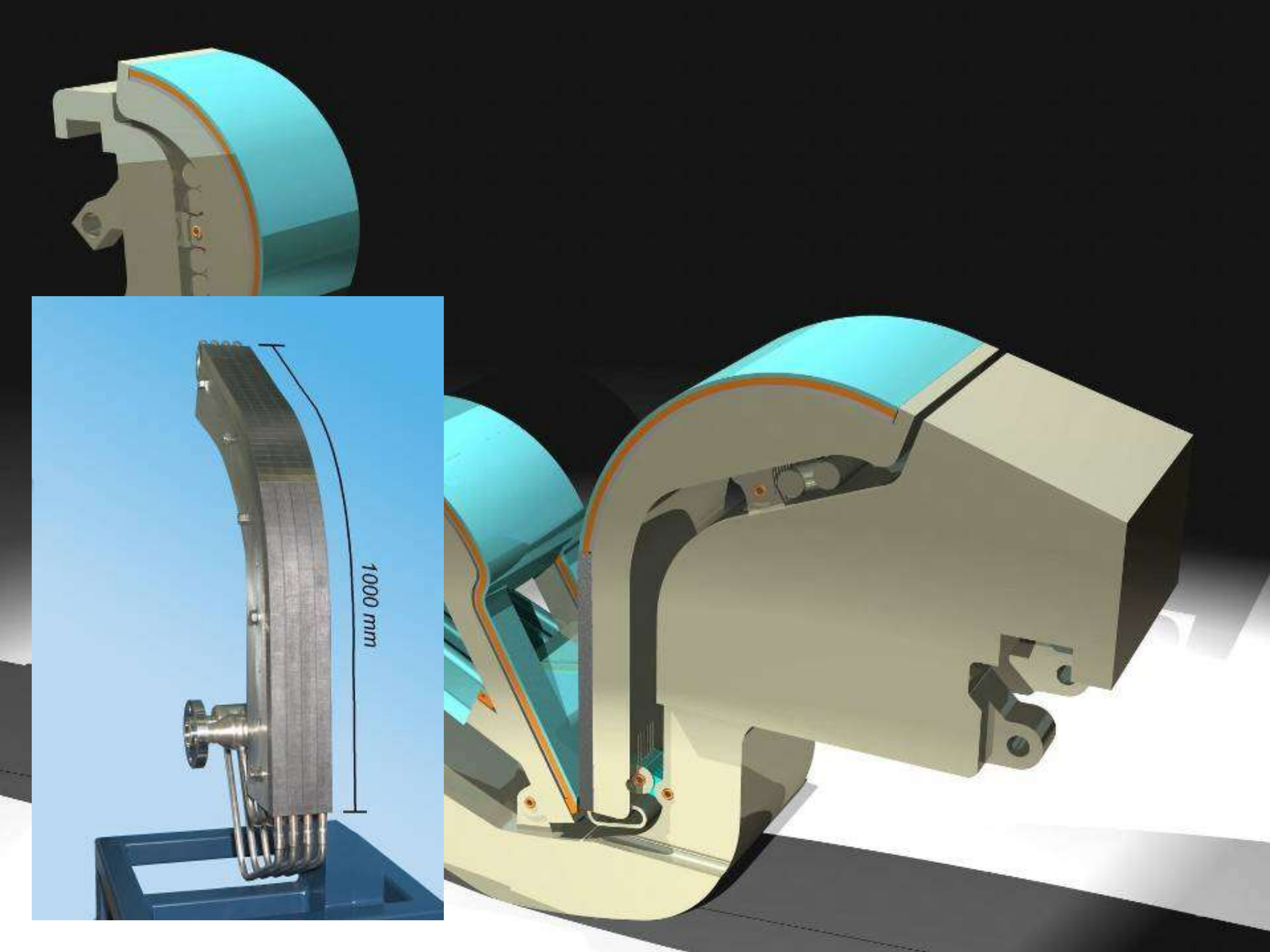
M. Rubel, 18th ITPA Diagnostics meeting

Courtesy: A. Litnovsky





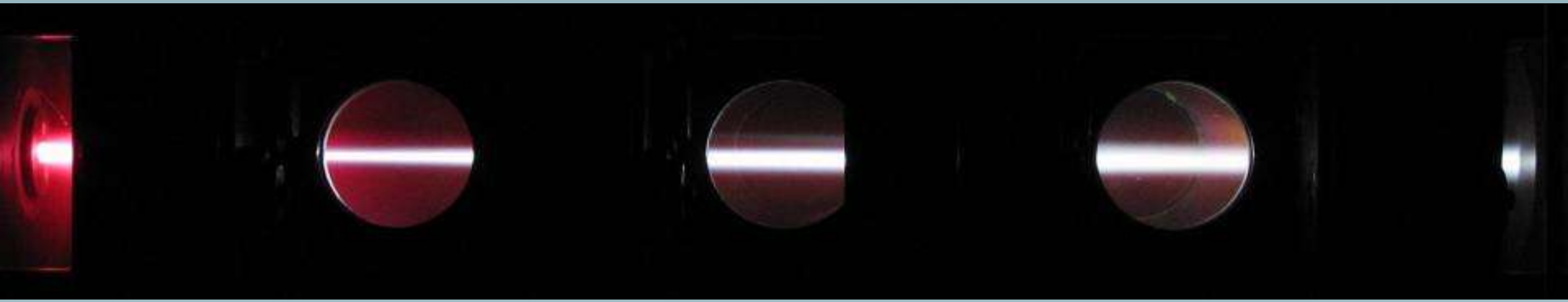


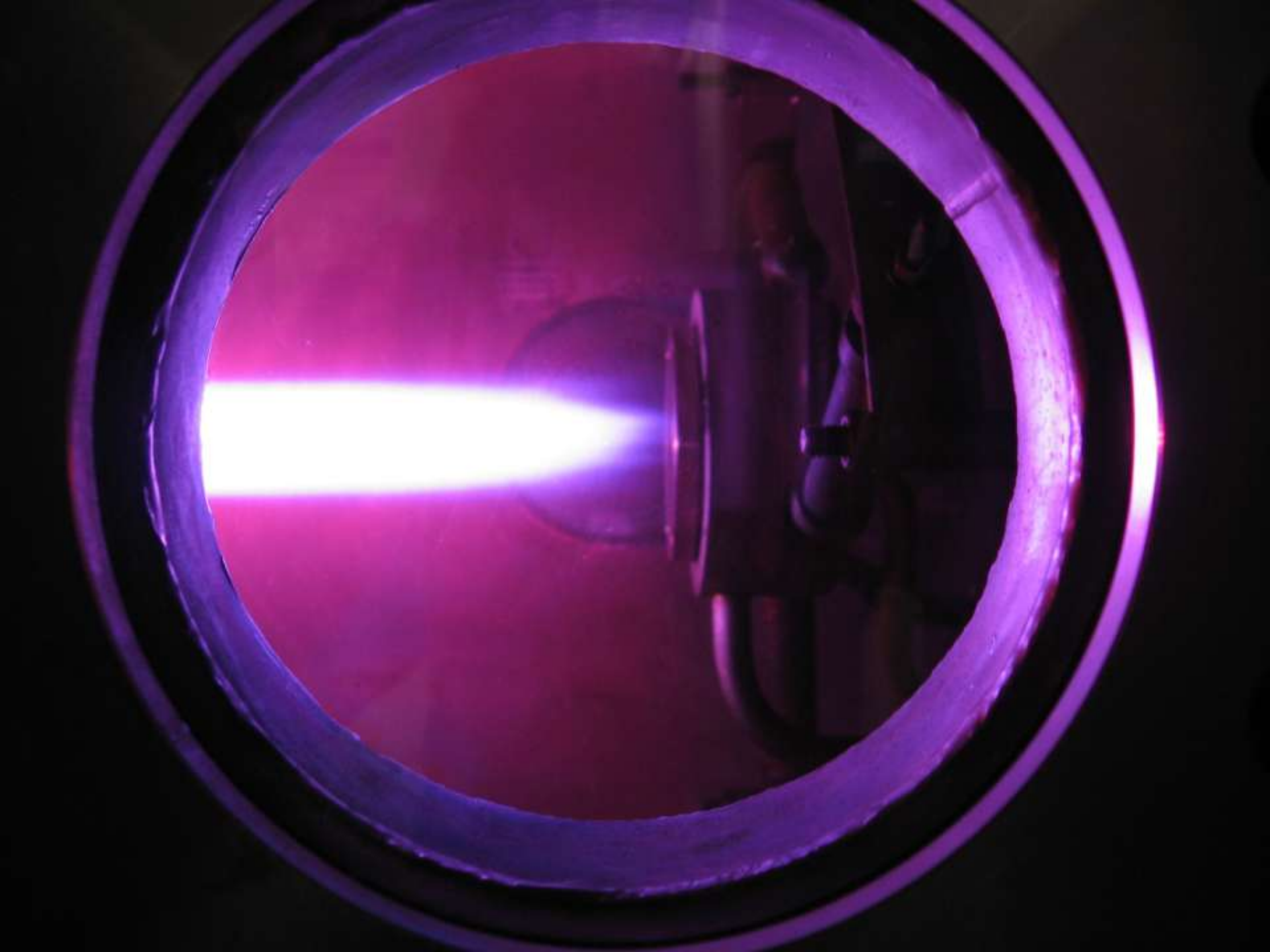

1000 mm

High-power linear plasma generators at FOM (NL):

operationeel: Pilot-PSI

In aanbouw: Magnum-PSI





MAGNUM-PSI

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

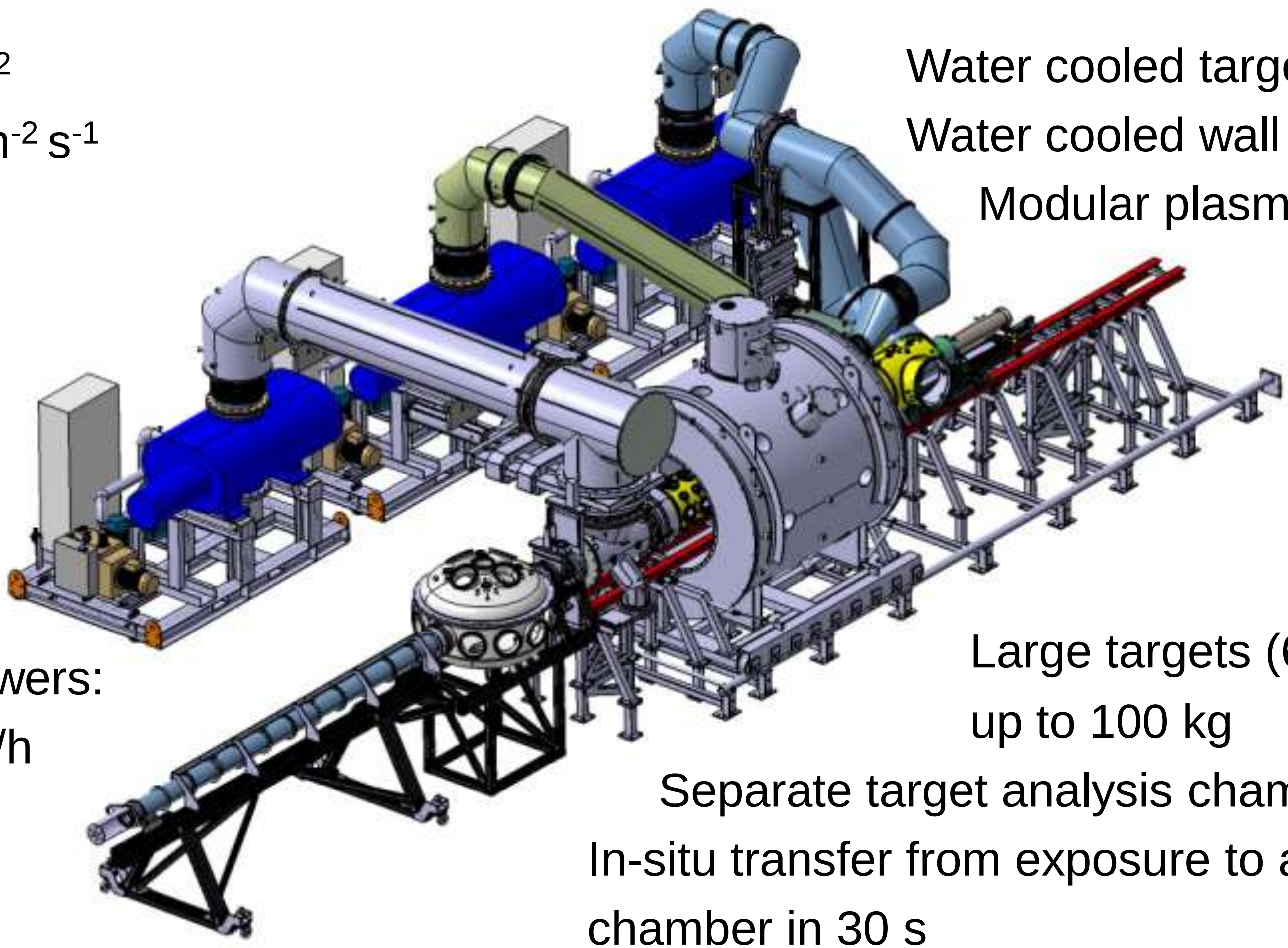
10 MW/m^2

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

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

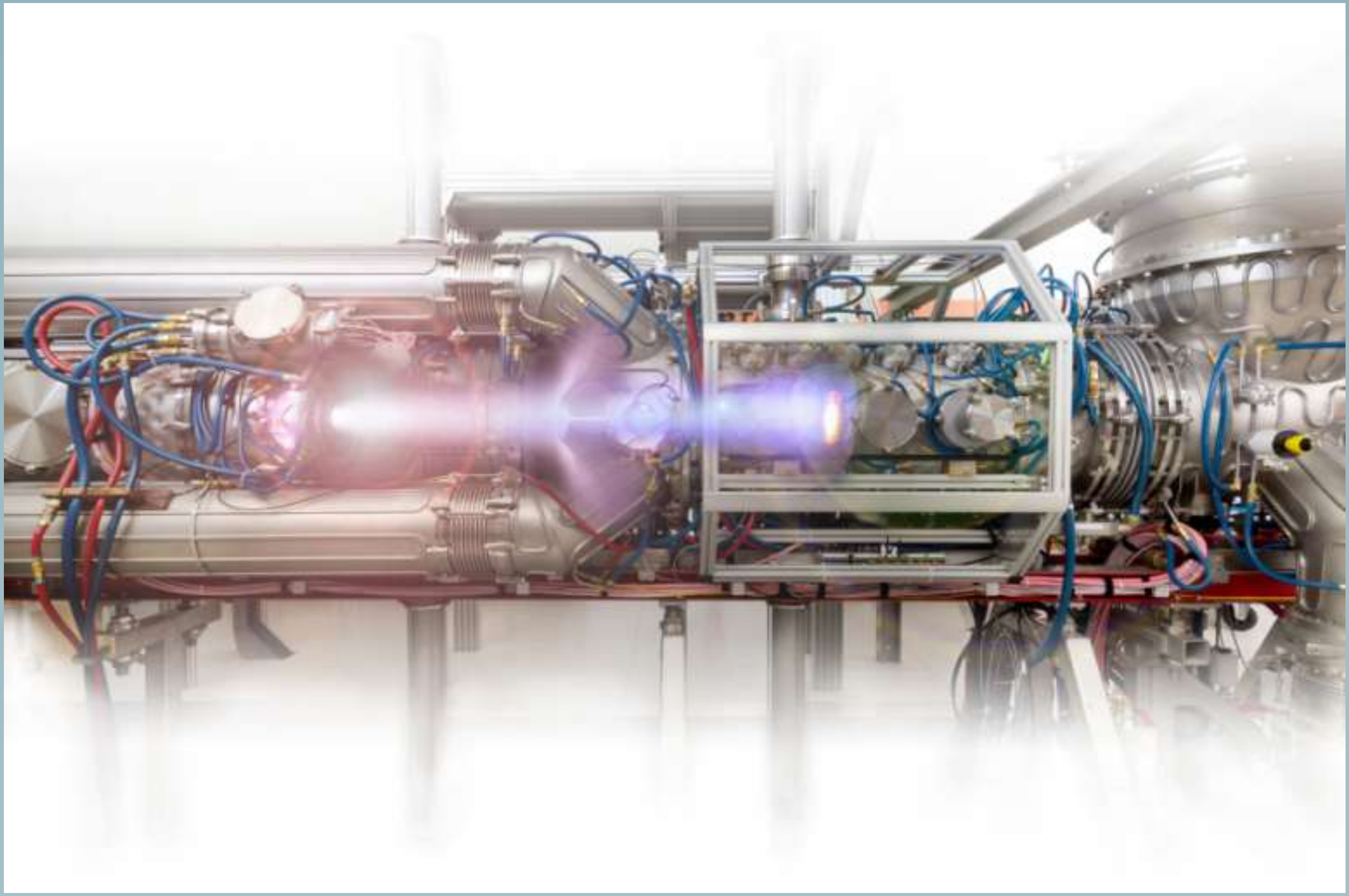
Large targets (60 x 12 cm)

up to 100 kg

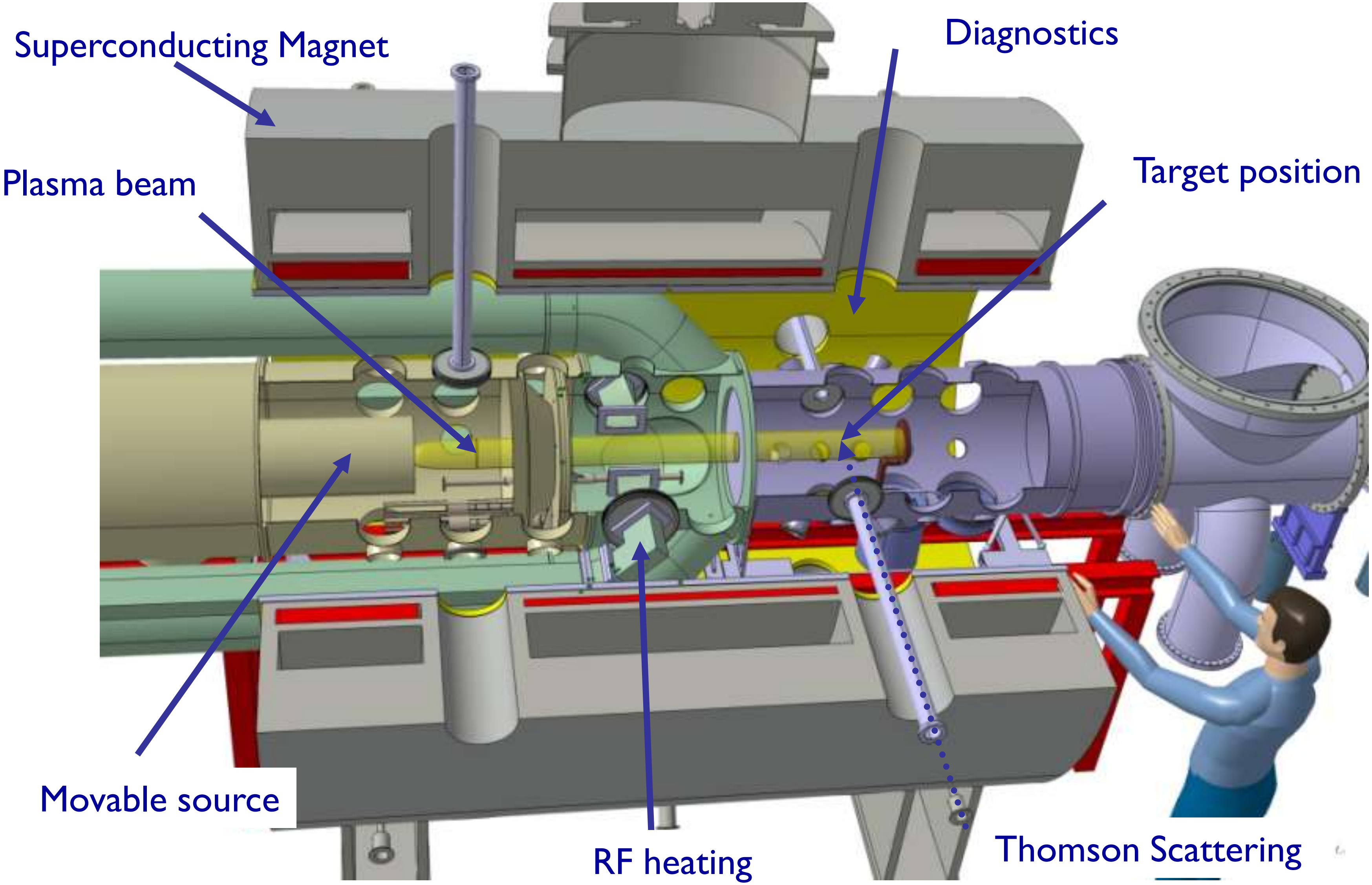
Separate target analysis chamber

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

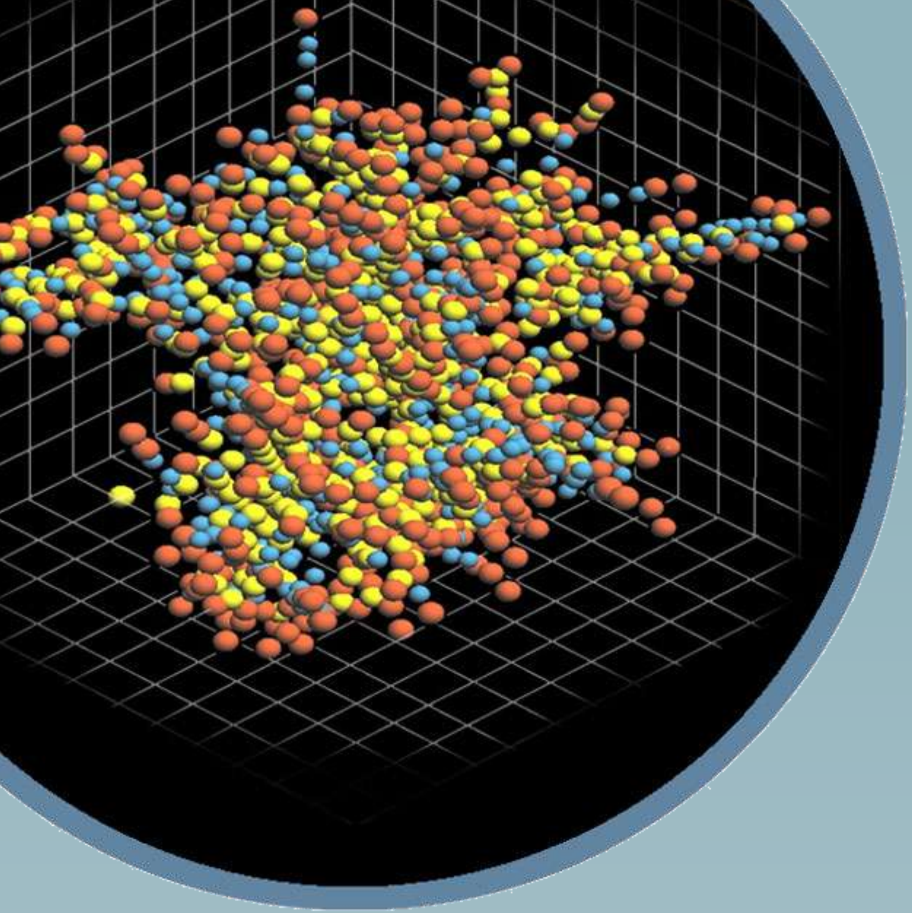
MAGNUM-PSI



MAGNUM-PSI



Superconducting Magnet
Diagnostics
Plasma beam
Target position
Movable source
RF heating
Thomson Scattering



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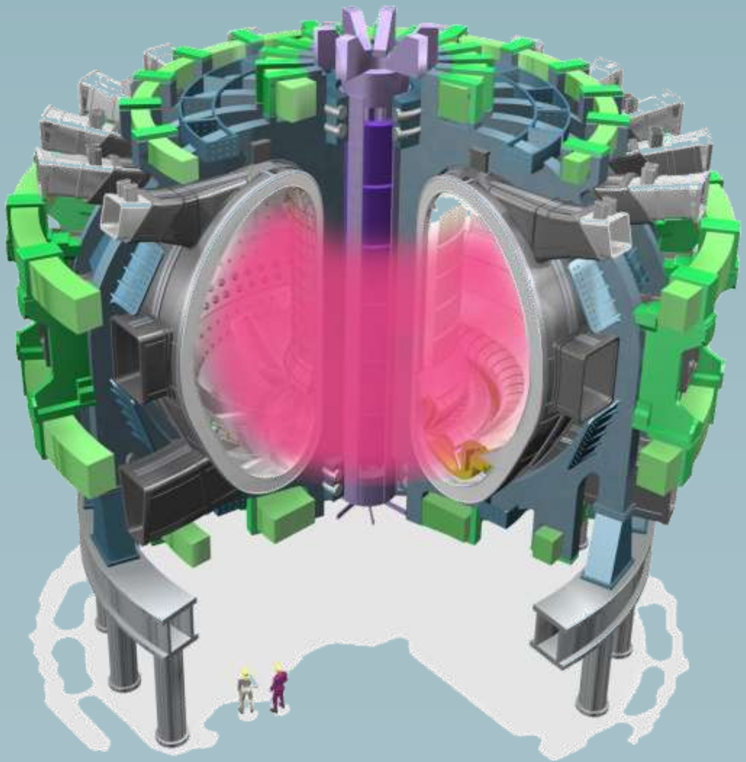
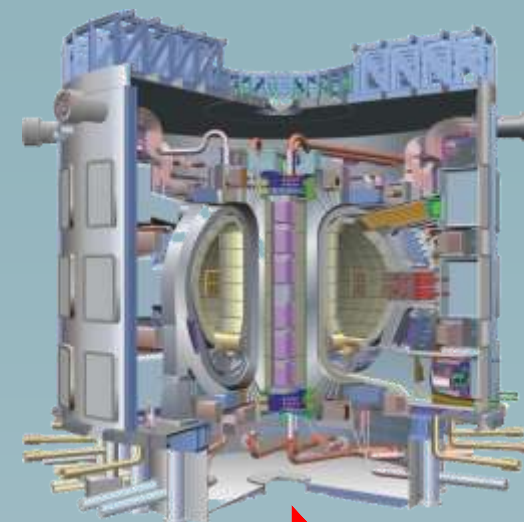


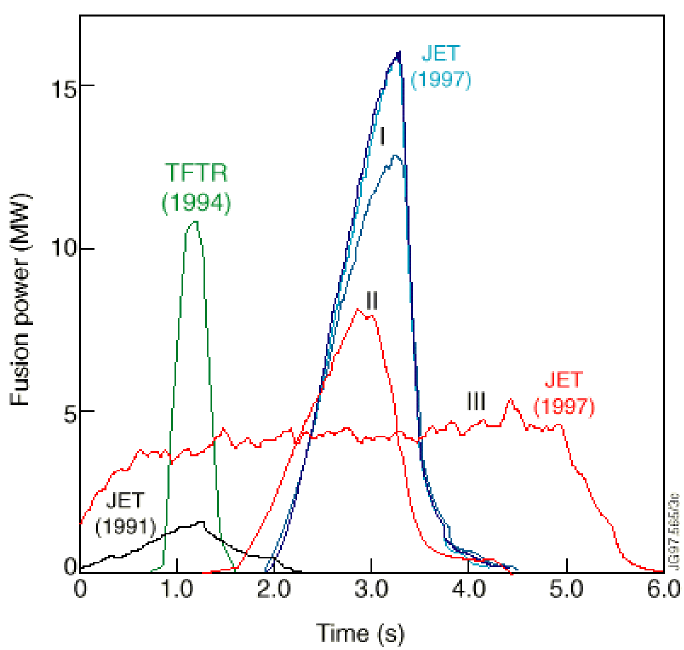
Bombardement van neutronen

Hoge deeltjesfluxen

JET

ITER





50 × hogere ionenflux

5000 × hogere ionenfluentie

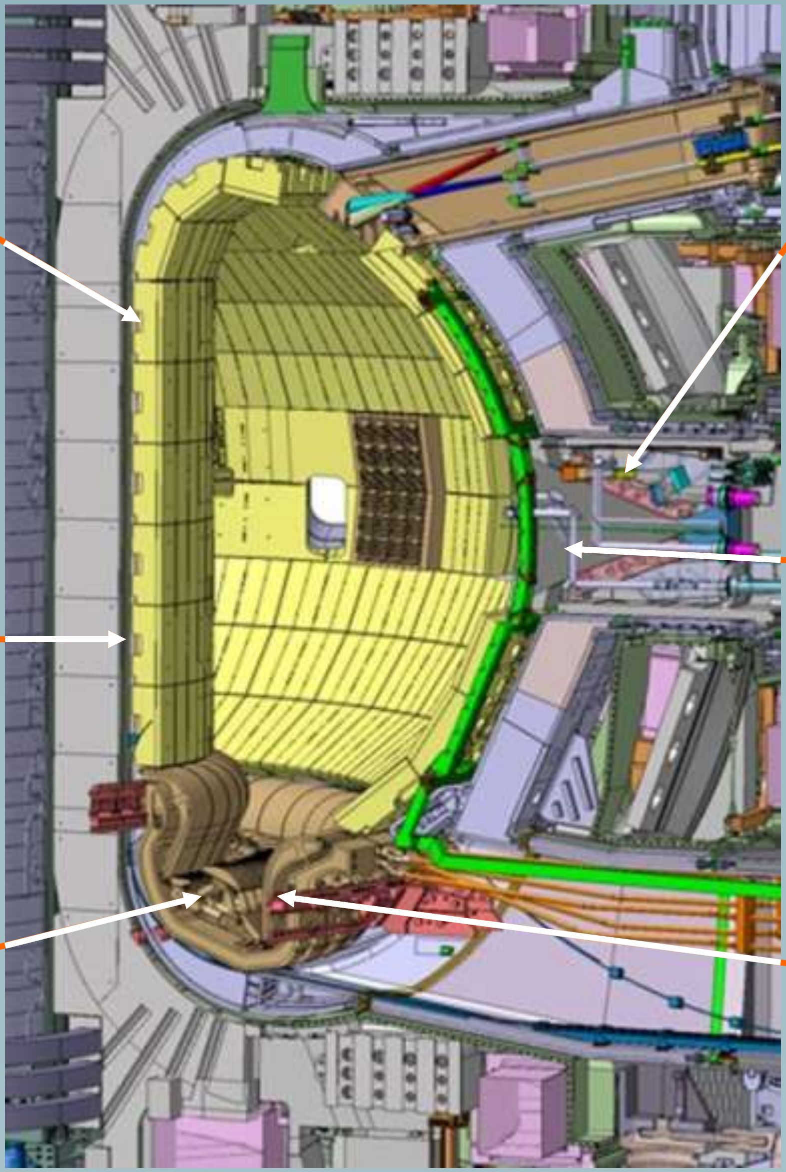
> 10^5 × hogere neutronenfluentie

Nieuwe fenomenen voor diagnostieken

Magnetic coils
- Radiation Induced Conductivity (RIC)
- Radiation Induced Electric Degradation (RIED)
- Radiation Induced Electromotive Force (RIEMF)

Bolometers
- RIC
- Nuclear Heating
- Sputtering
- Contact degradation
- Differential swelling and distortion

Pressure gauges
- RIC
- RIED
- Filament aging



Neutron cameras
- Noise due to γ-ray, proton, α
- Radiation damage on solid state detectors

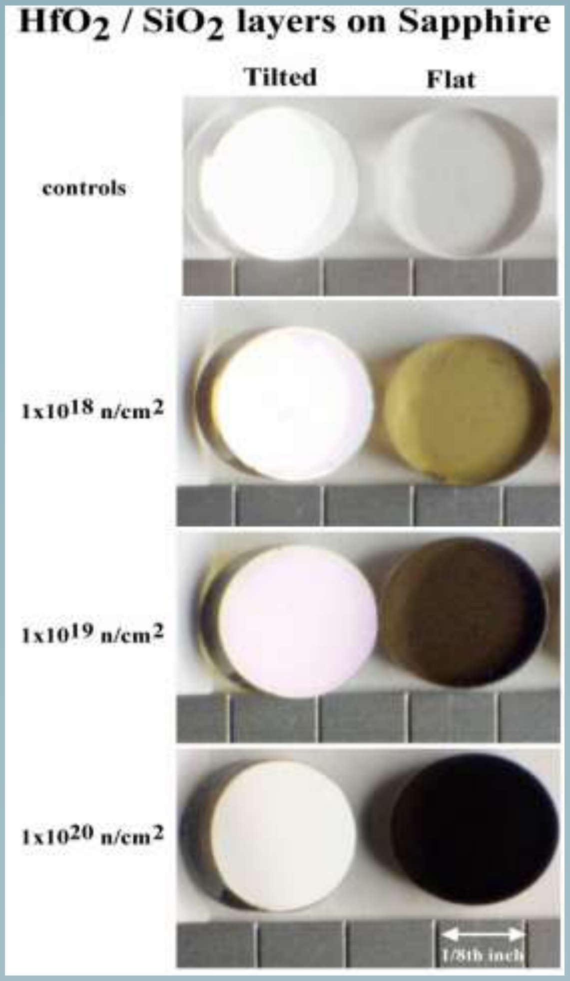
Optical diagnostics
Mirror
- Deposition, erosion
- Swelling, distortion

Window
- Permanent transient absorption
- Radioluminescence
- Swelling, distortion

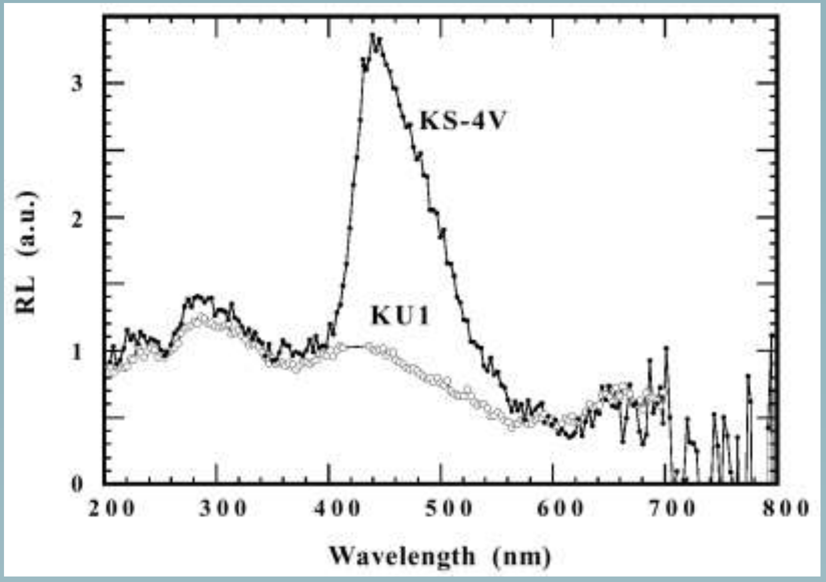
Impurity monitoring
Mirror and windows
- same as above

Fibers
- Permanent transient absorption
- Radioluminescence

Stralingsgeinduceerde absorptie en emissie



Stralingsgeinduceerde Absorptie (RIA) door neutronenstraling



Stralingsgeinduceerde Emissie (RL or RIE) van twee typen quartz fibers in gammastralingsveld van 700 Gy/s

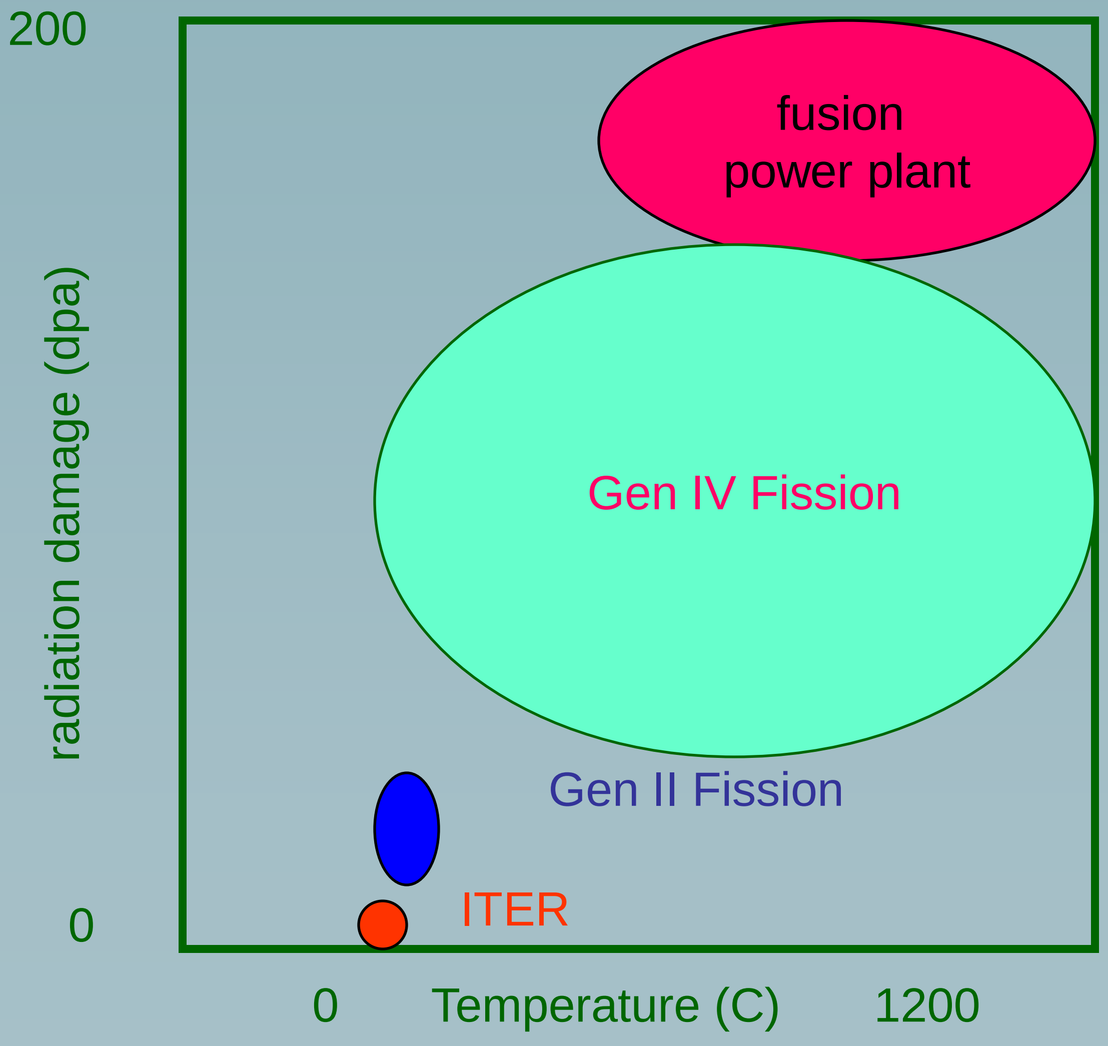
Refractieve componenten kunnen niet dicht bij plasma worden gebruikt

Transmutatie

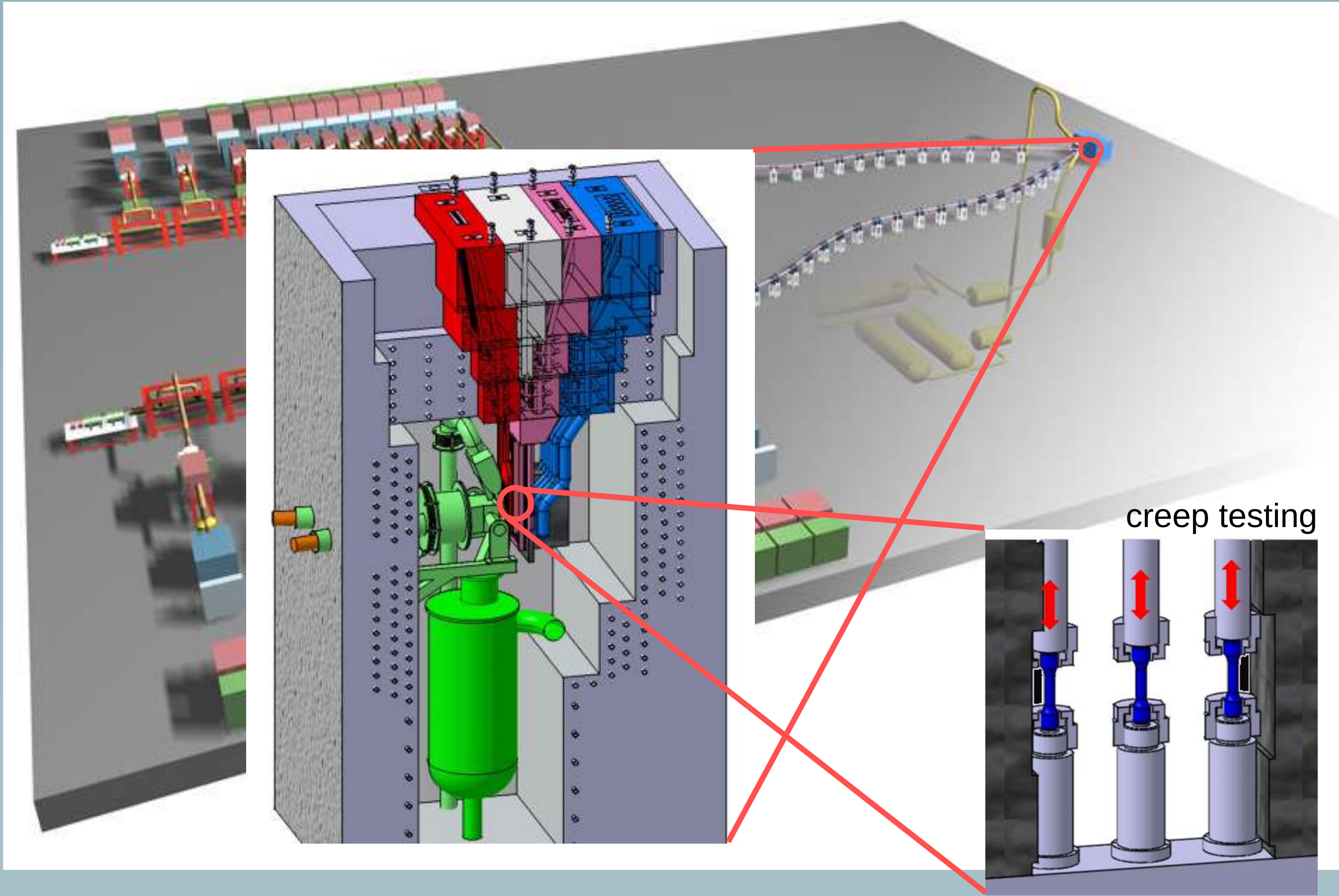
Transmutatie was een issue voor weerstands-bolometers met Au meanders (transmutatie naar Hg)

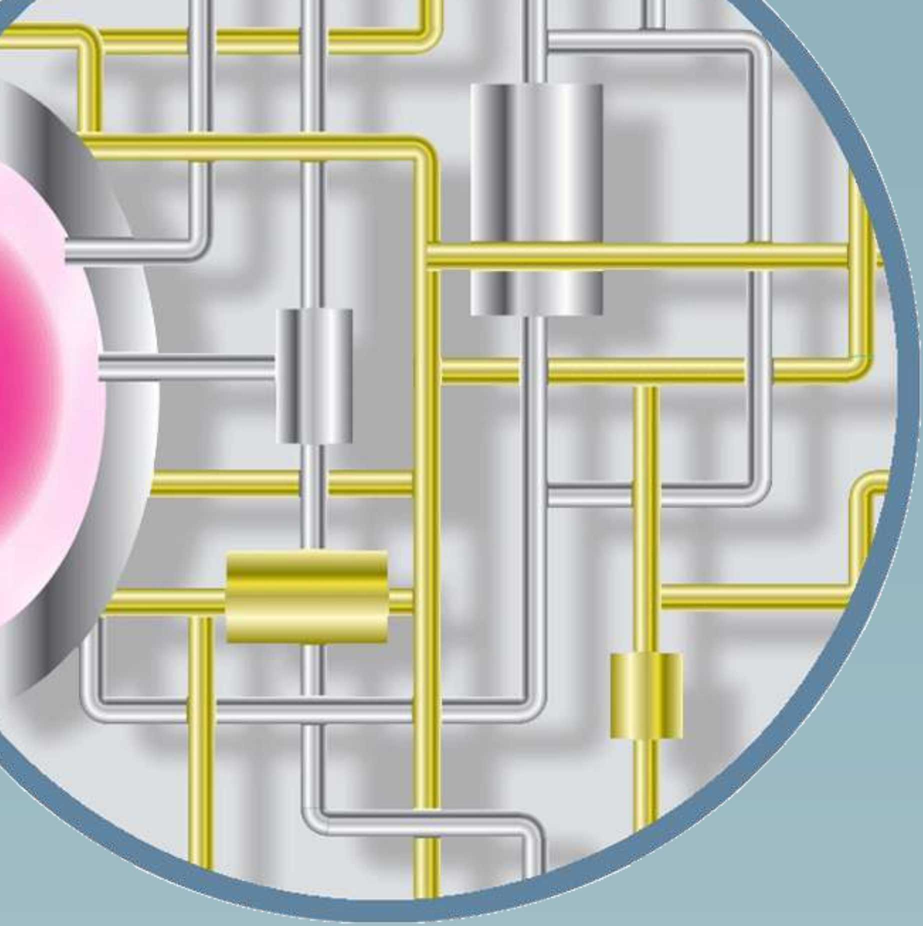
Goede resultaten met Pt meanders

Materiaalontwikkeling



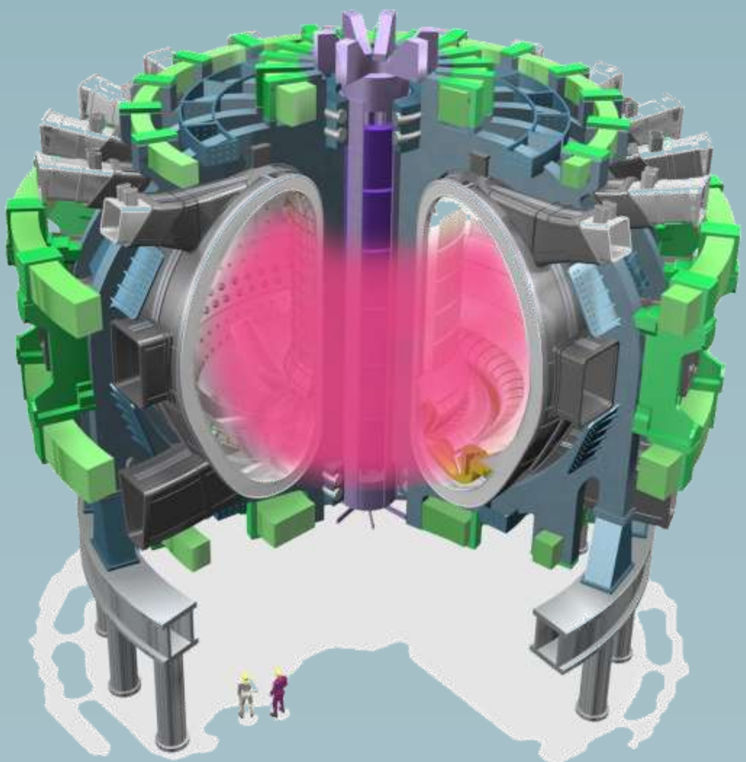
IFMIF - International Fusion Materials Irradiation Facility

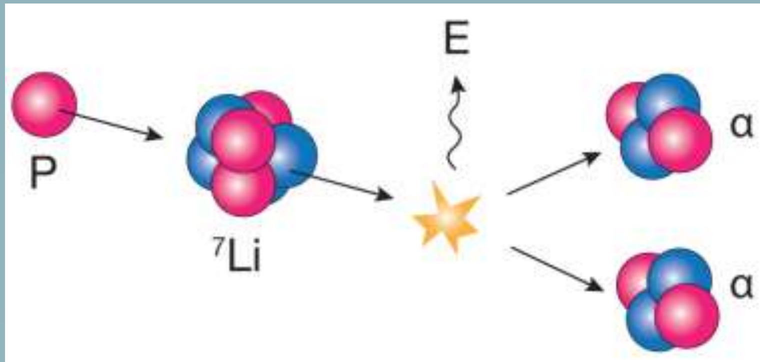




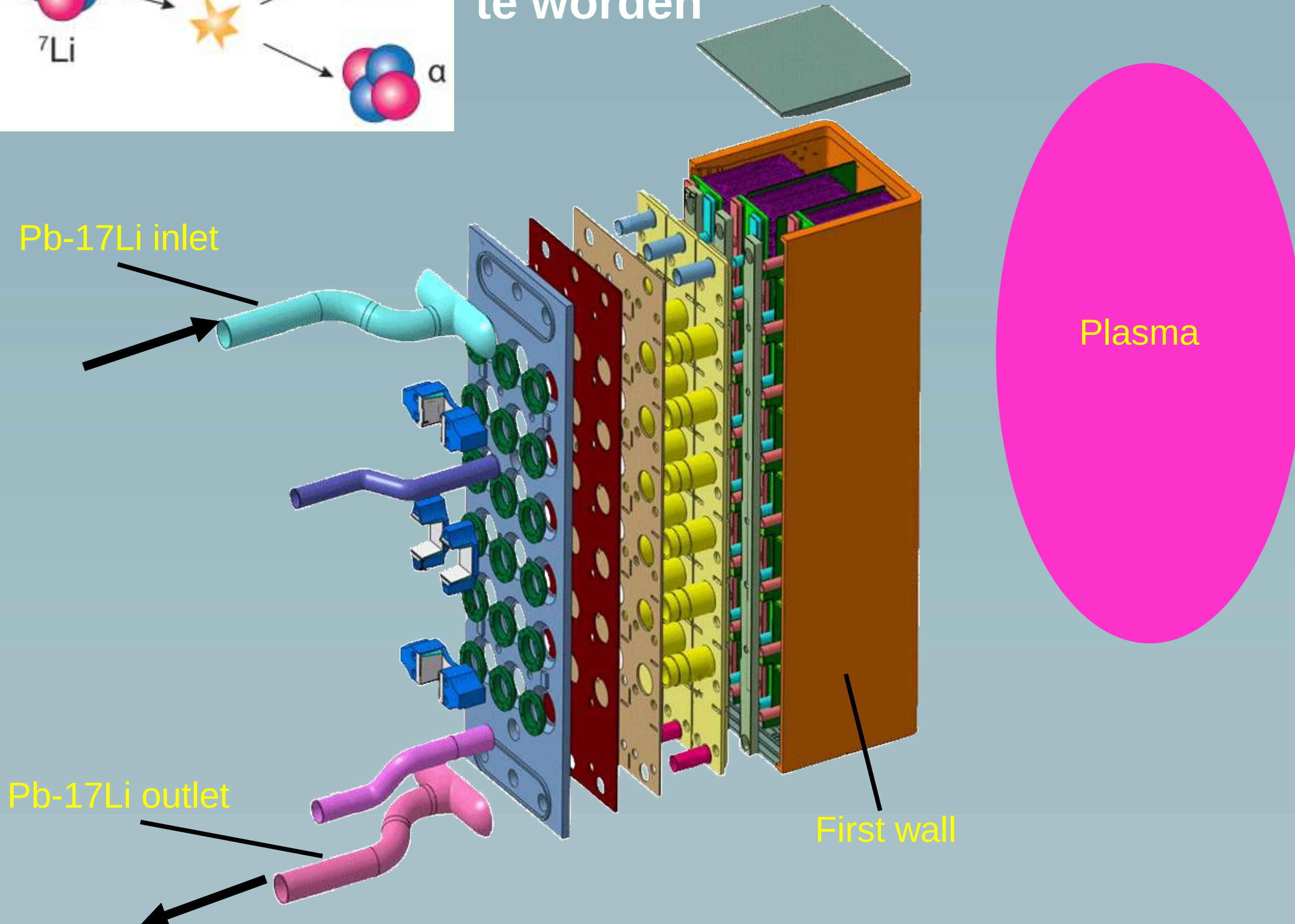
6

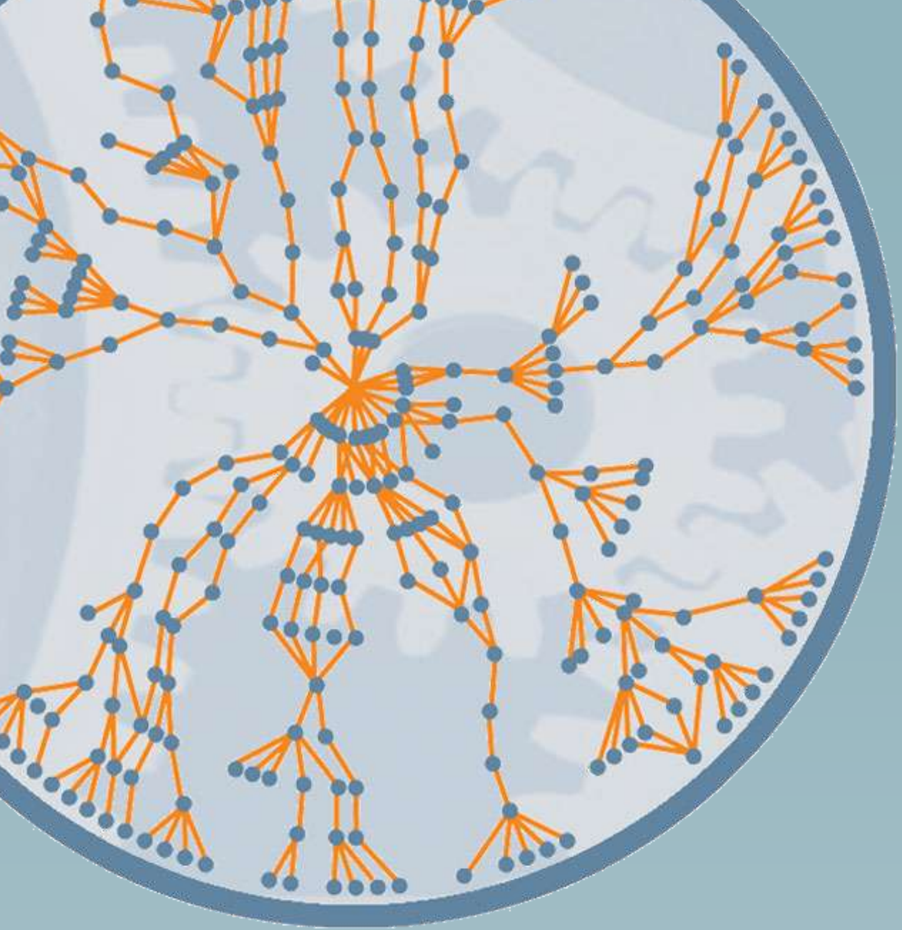
Brandstofcyclus Tritiumproductie



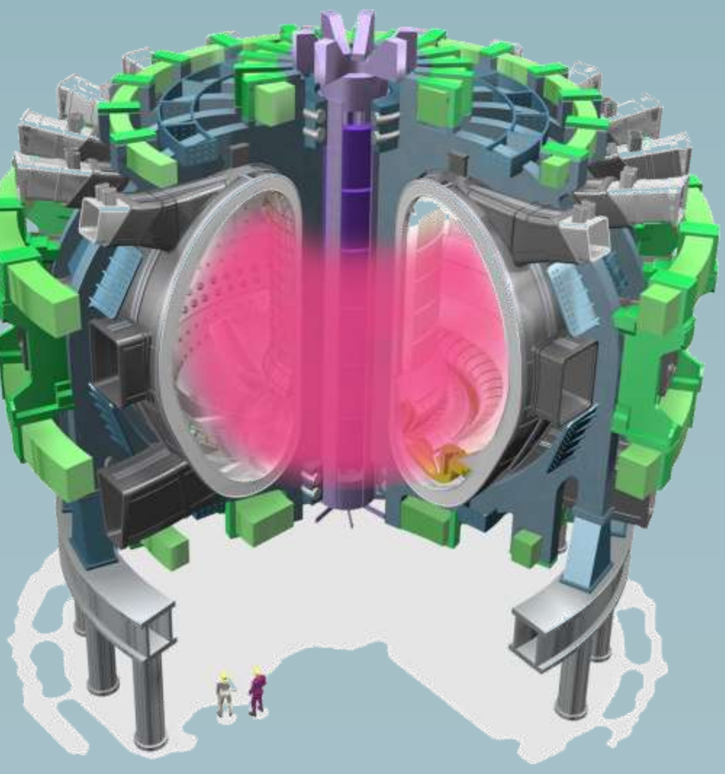


Tritium moet minstens 1000 × worden gebruikt zonder gevangen te worden



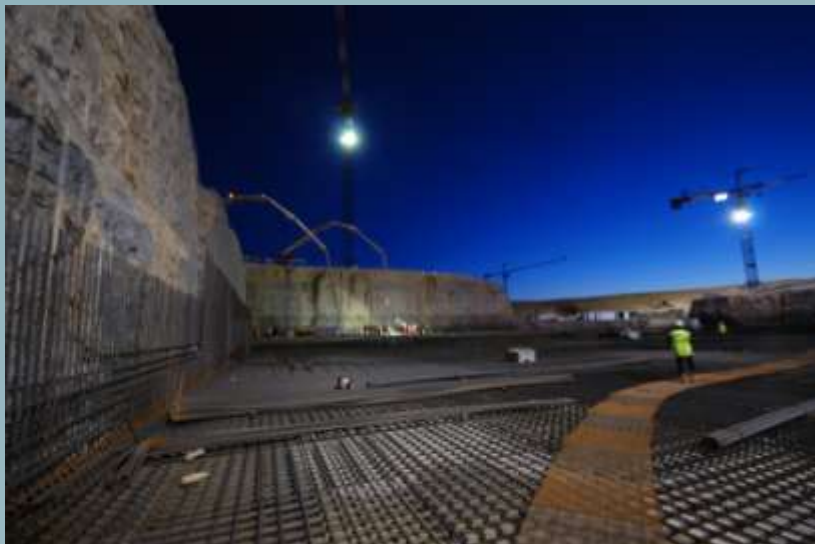


7



ITER: 34 landen
15.000.000 onderdelen

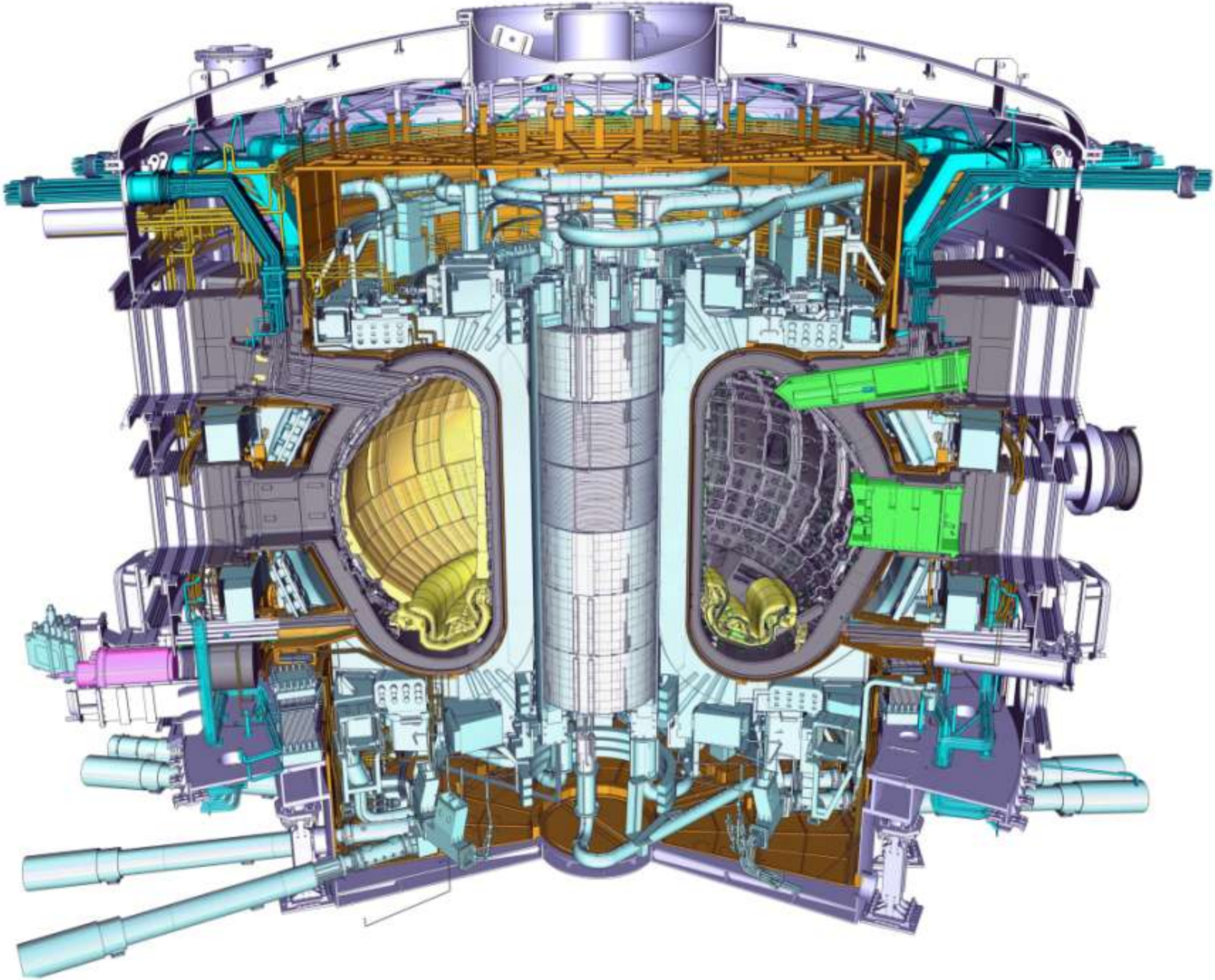
ITER in 2011 - bouw is onderweg



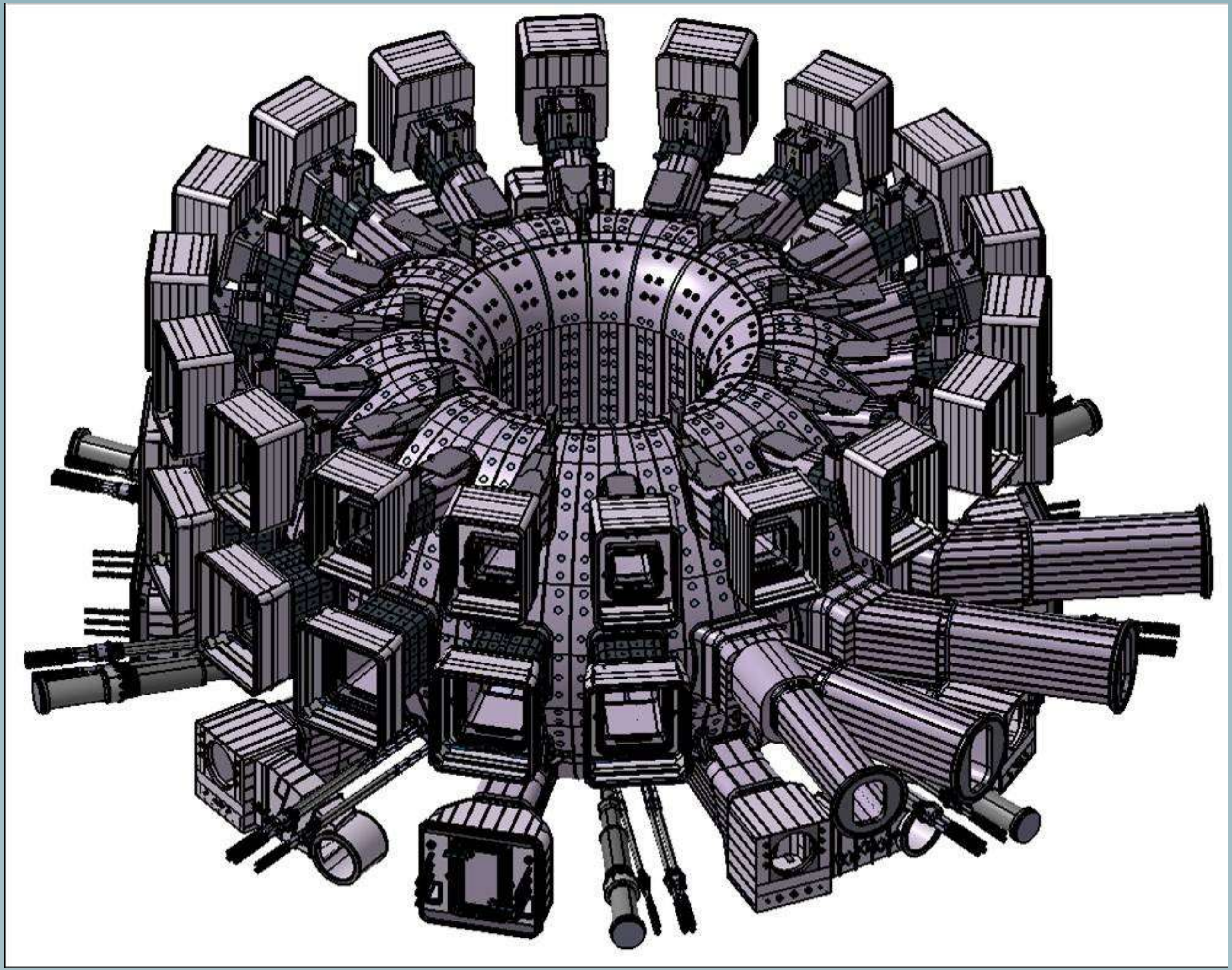

Seismic Isolation Pads

Poloidal Field Coil Winding Facilicity Building

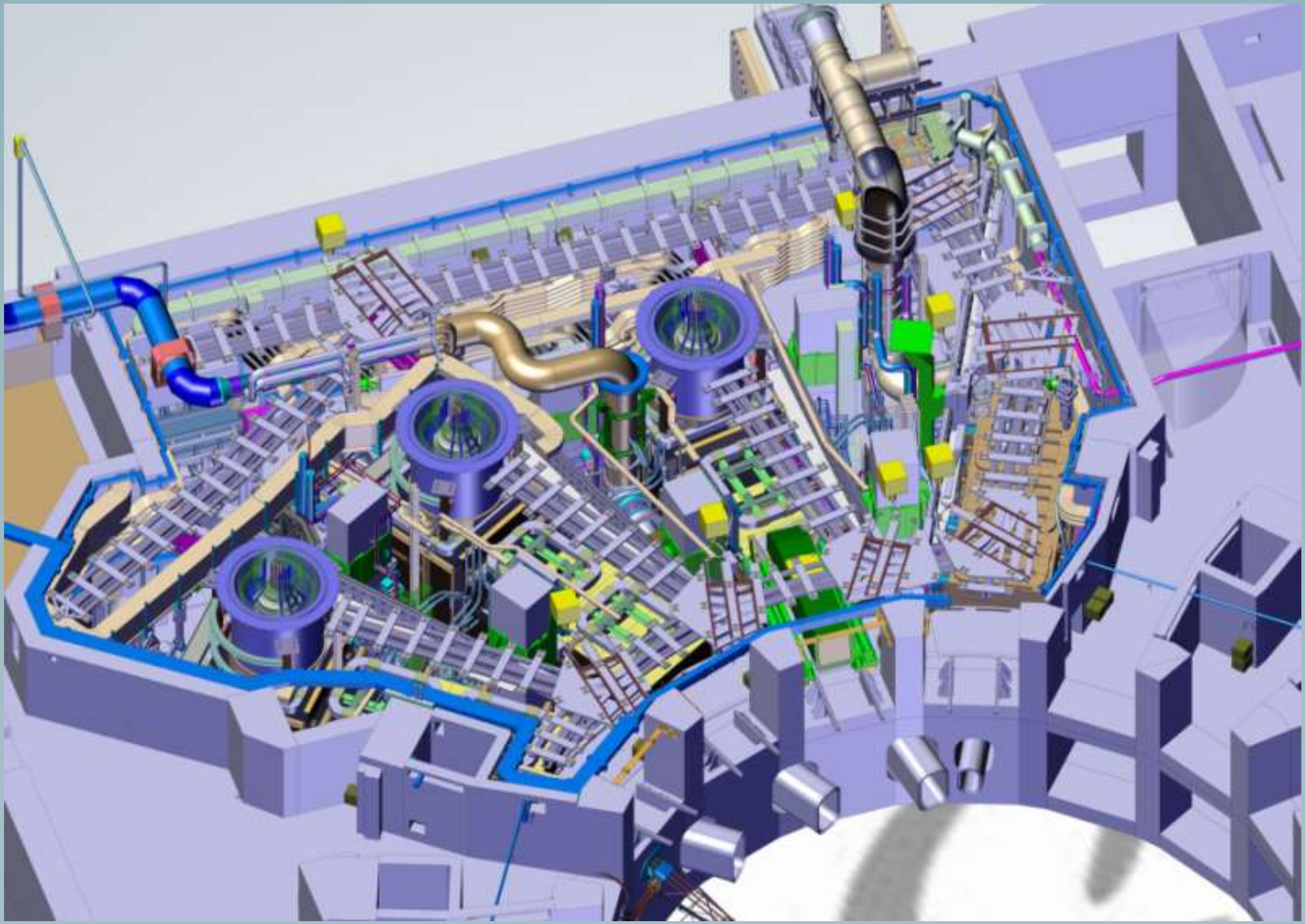
ITER Headquarters opened 15 October 2012



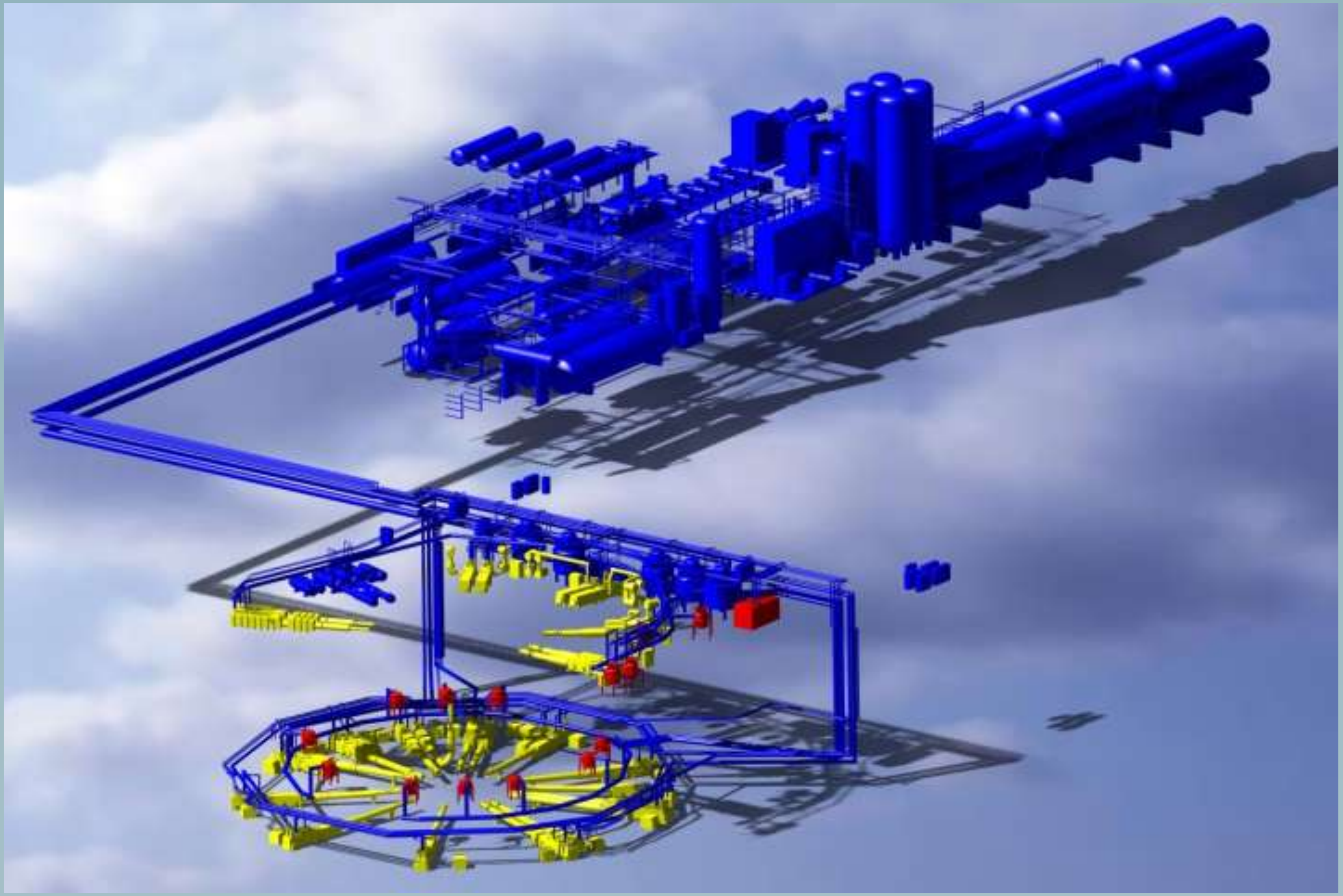
ITER vacuum vessel – more heavy than the Eiffel tower



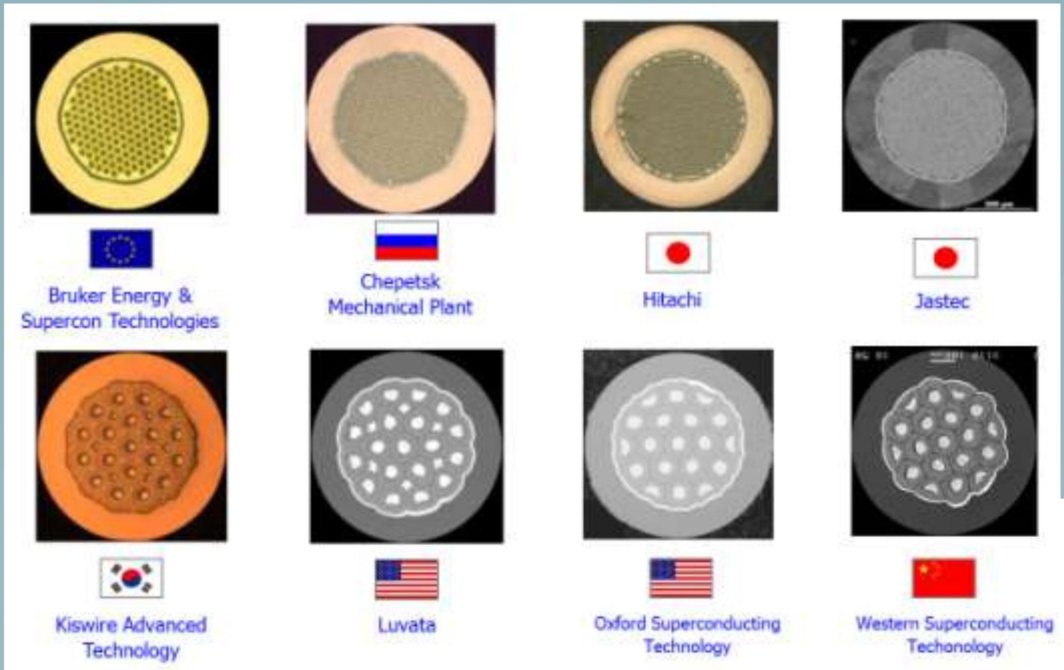
Neutral Beam heating



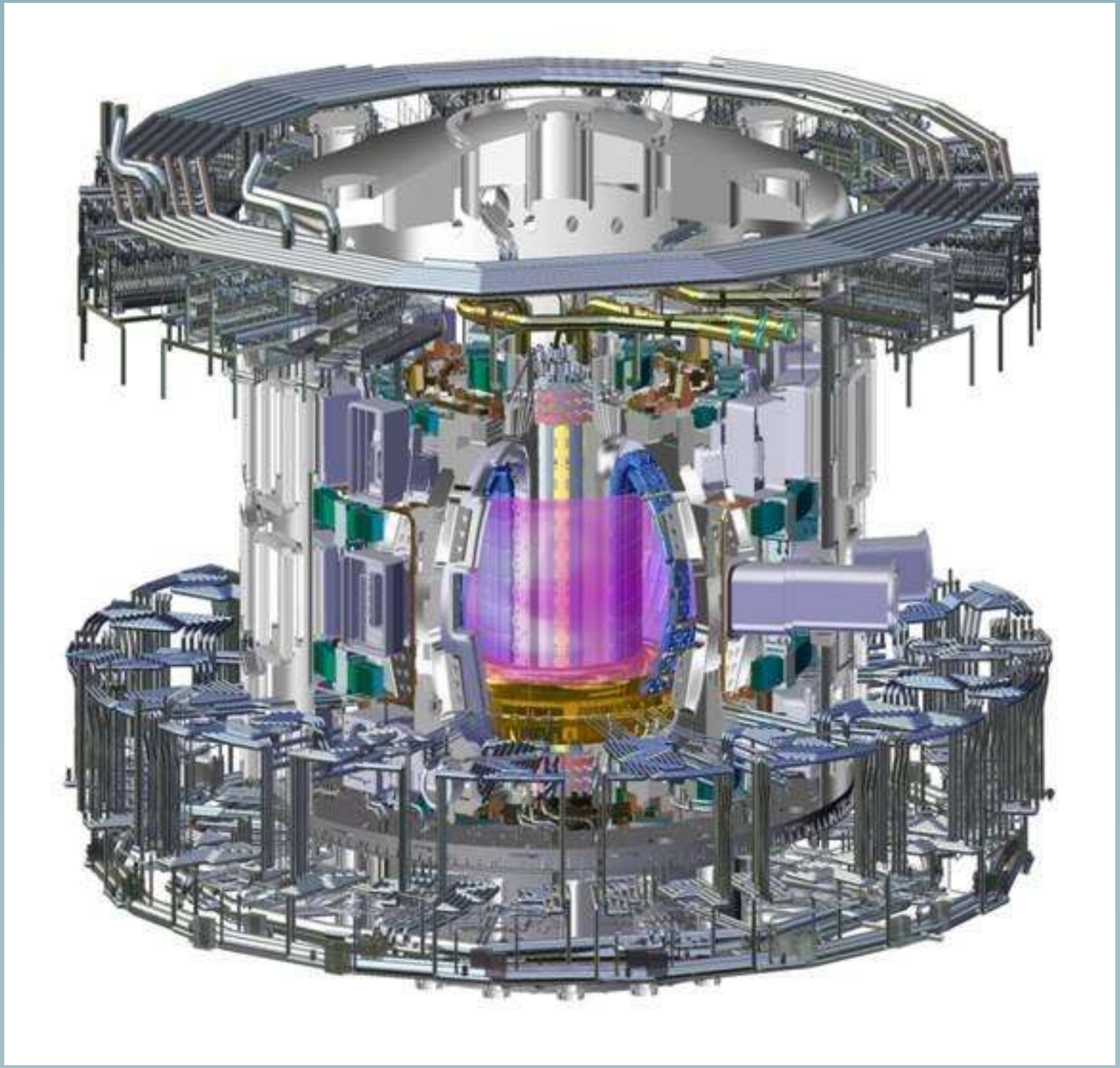
ITER cryogenic system

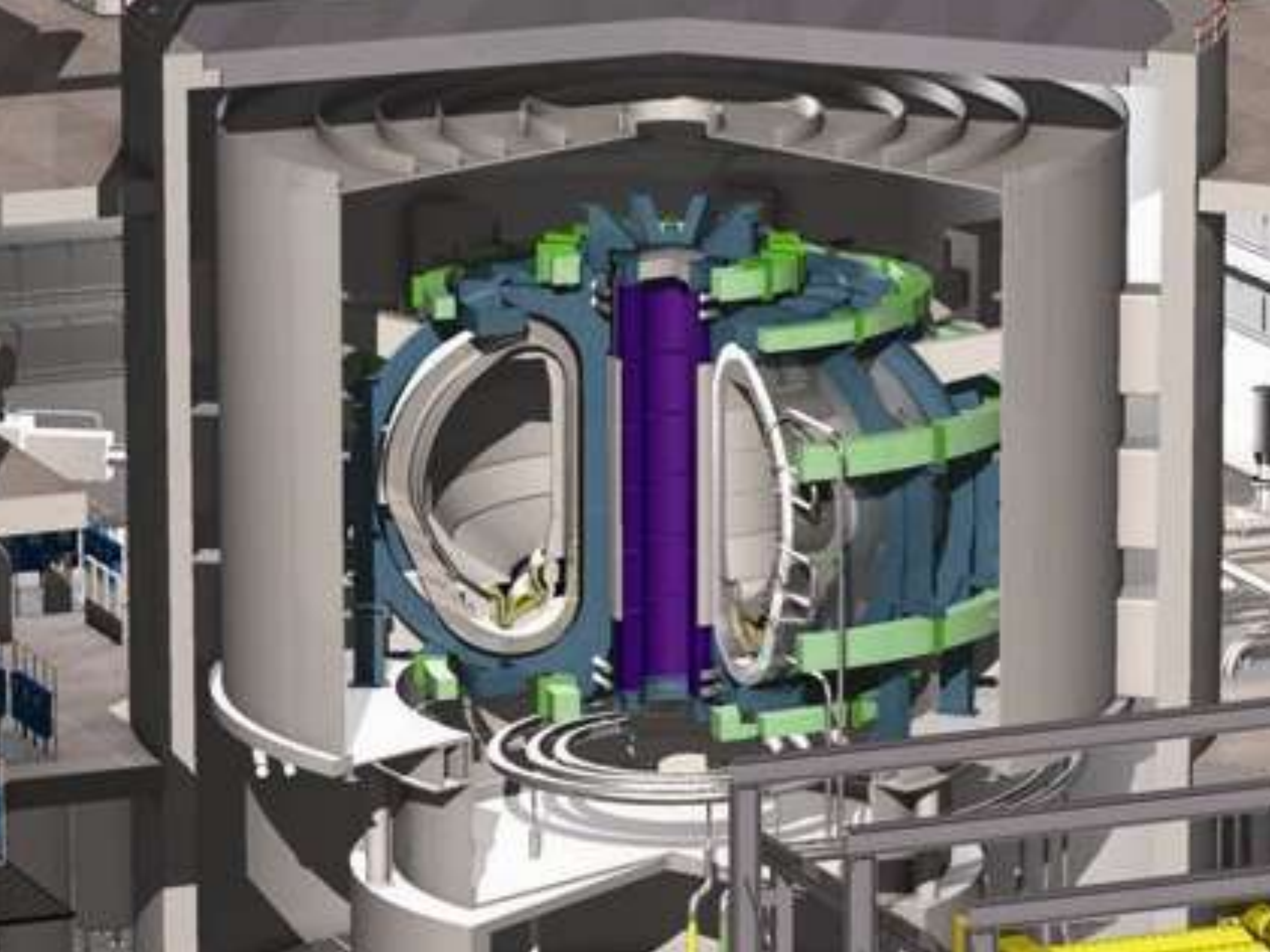


Superconducting cables

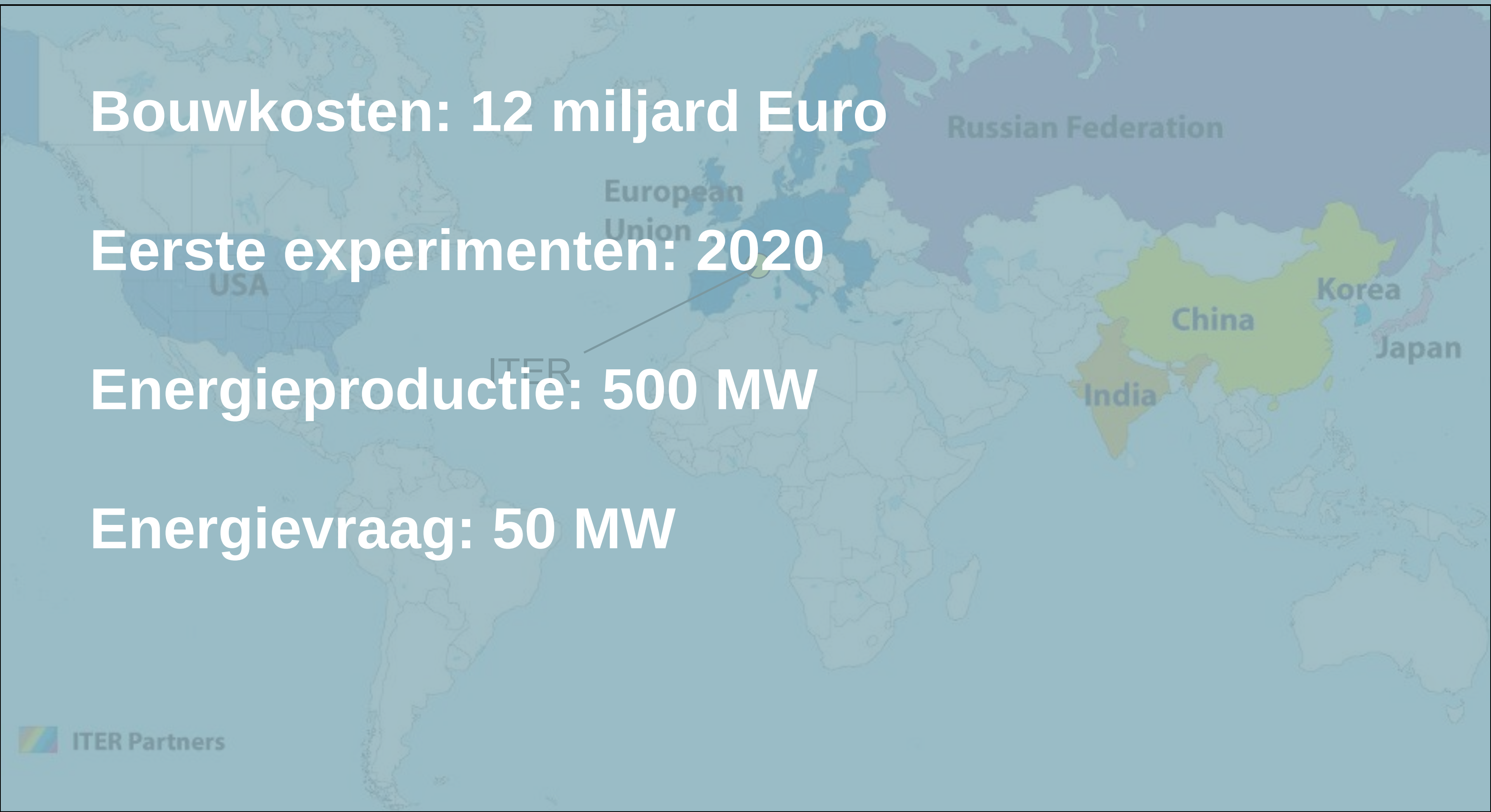


Cooling system





ITER is een wereldwijd project

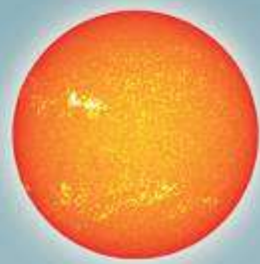


Bouwkosten: 12 miljard Euro

Eerste experimenten: 2020

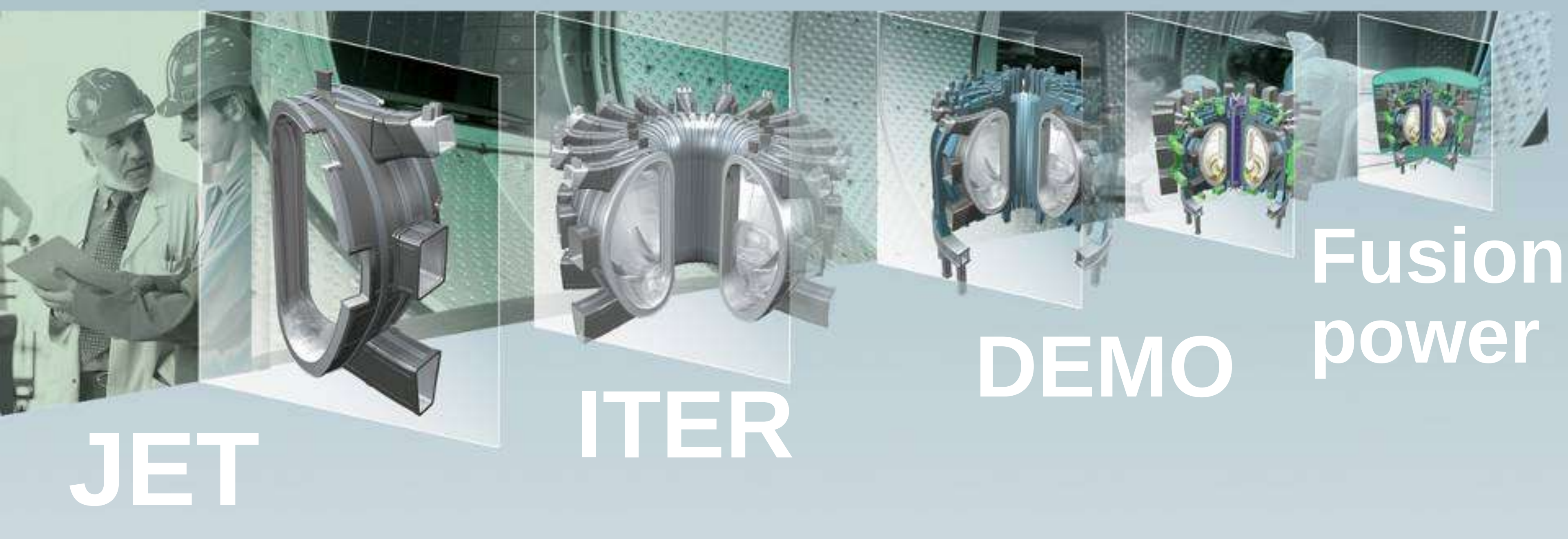
Energieproductie: 500 MW

Energievraag: 50 MW

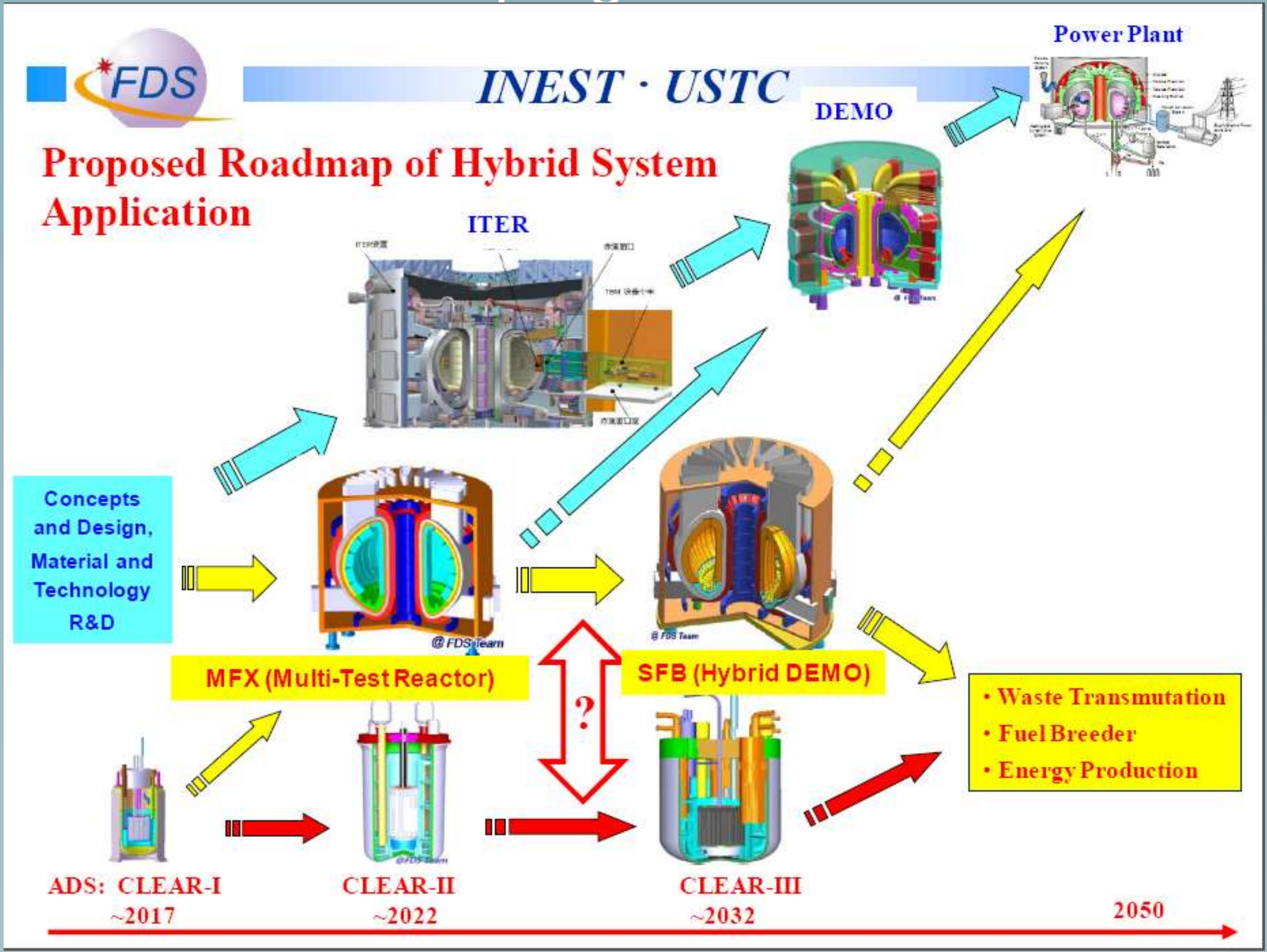


De toekomst?

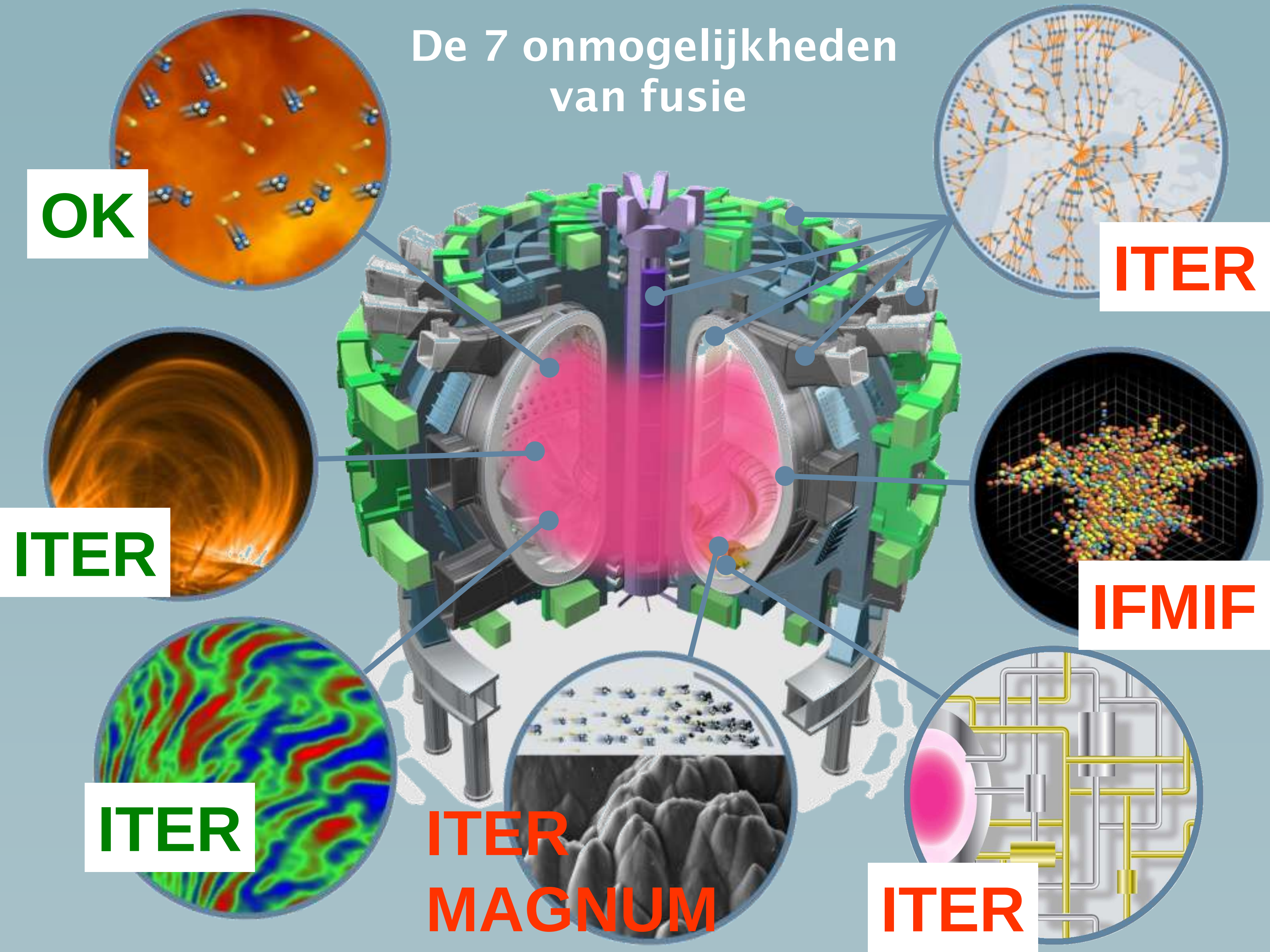
2000 2010 2020 2030 2040



Aziatische landen hebben zeer agressief programma



De 7 onmogelijkheden van fusie



www.fusie-energie.nl

Dank aan:
Niek Lopes Cardozo
Gieljan de Vries

Verdieping:

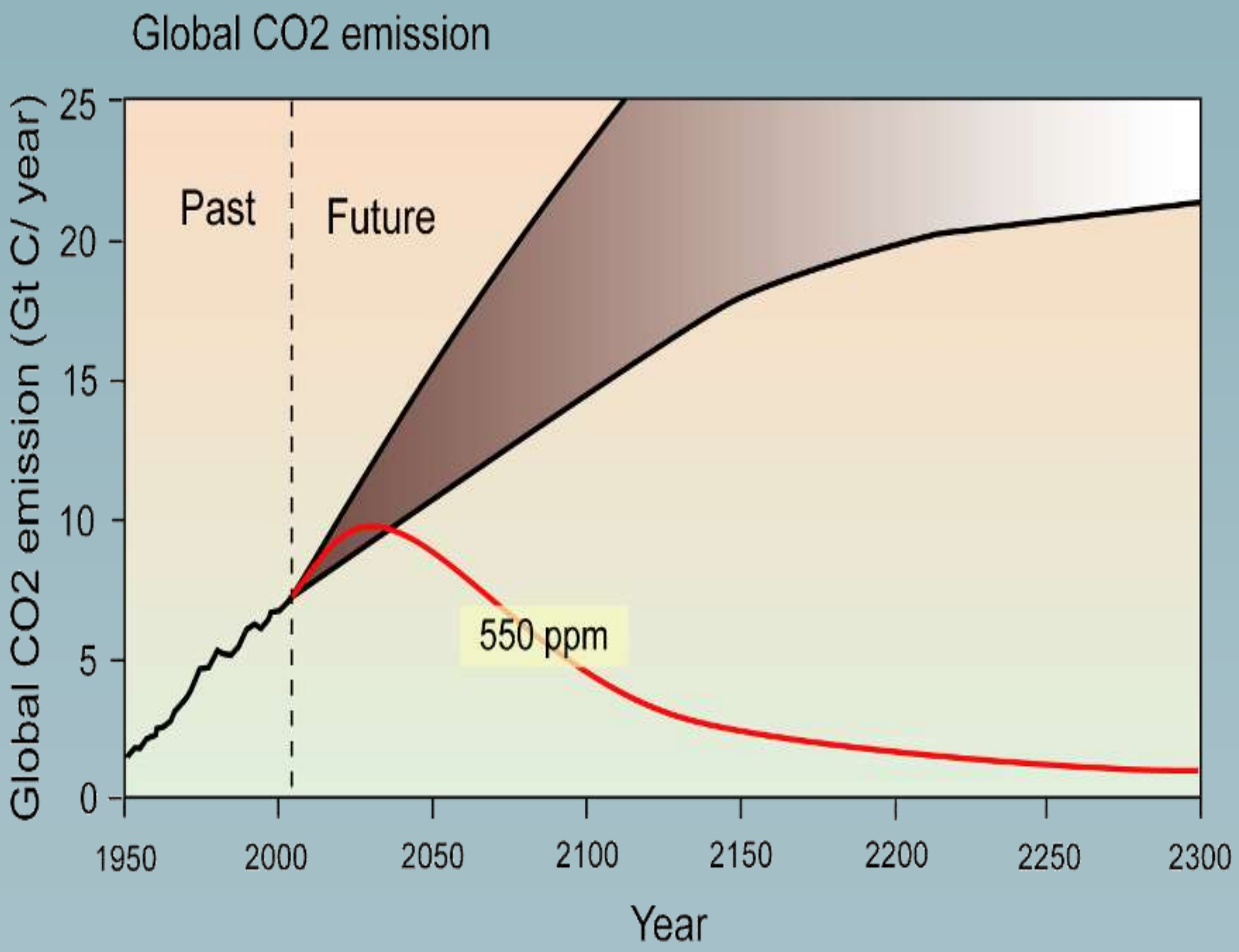
Veiligheid

Wanneer komt het, wat kost het?

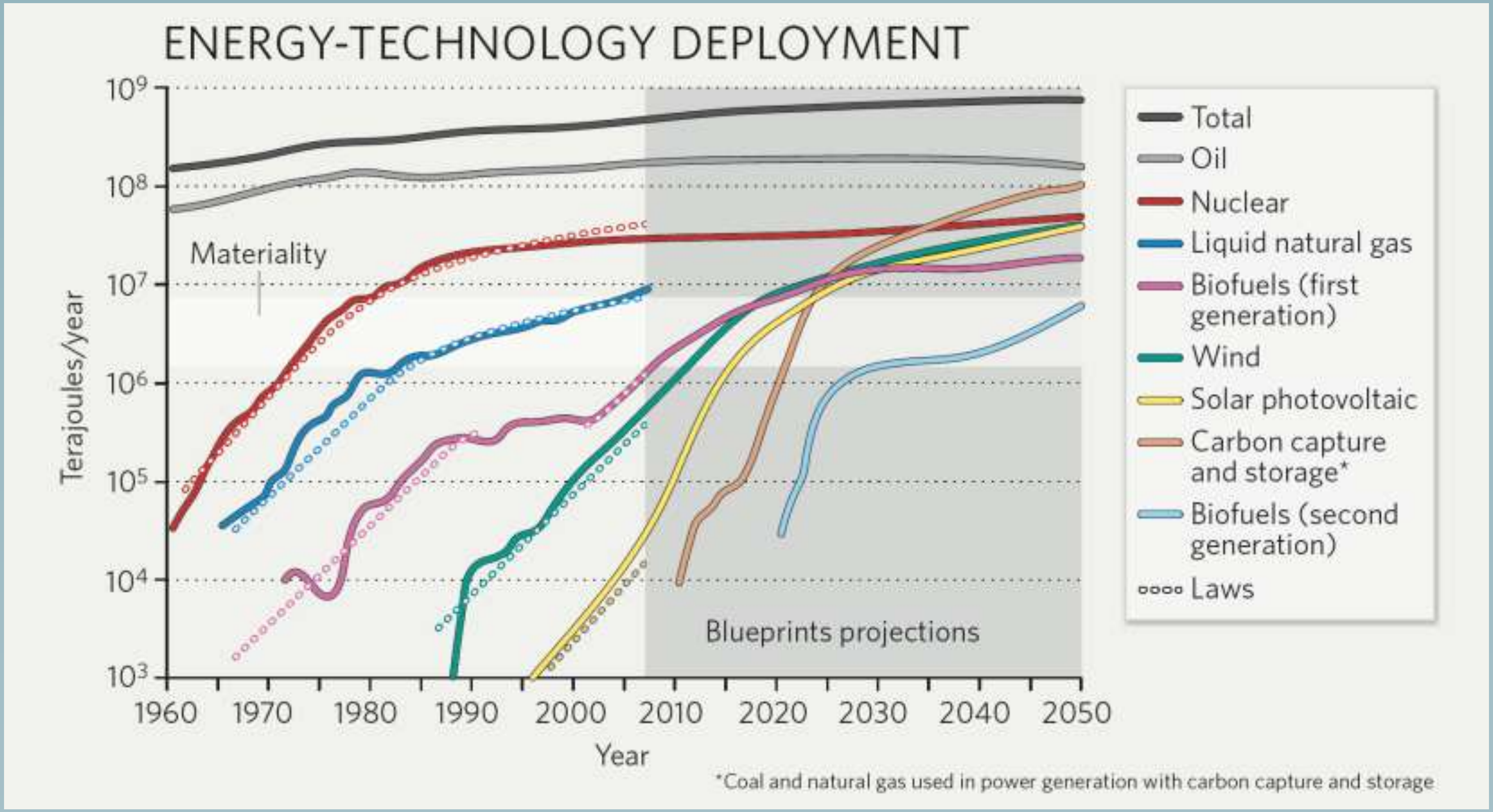
Andere vormen van fusie

Economie – wat bepaalt de kostprijs?

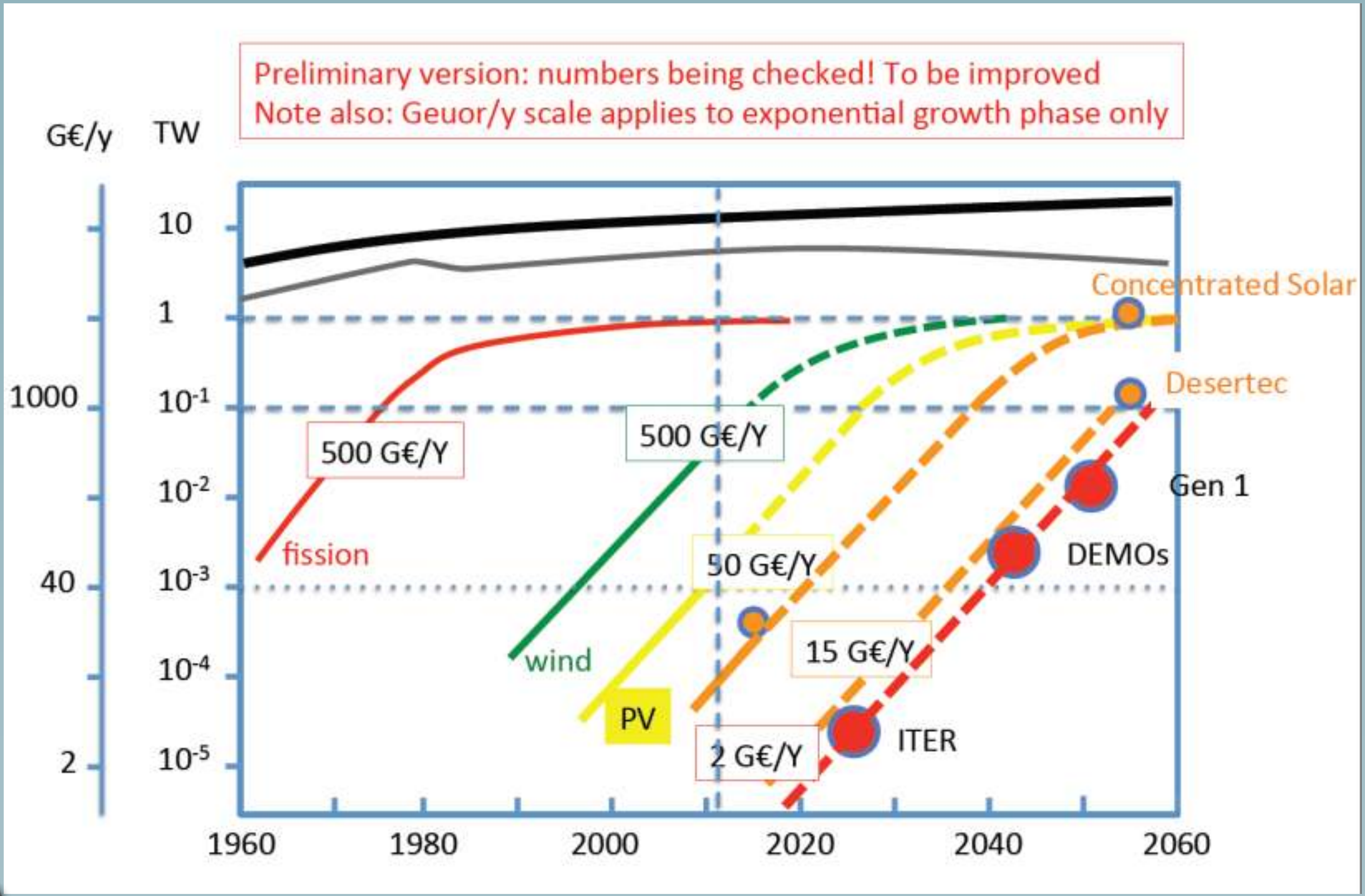
Komt fusie op tijd?



Groei van diverse energiebronnen (G.J. Kramer, Nature 2009)

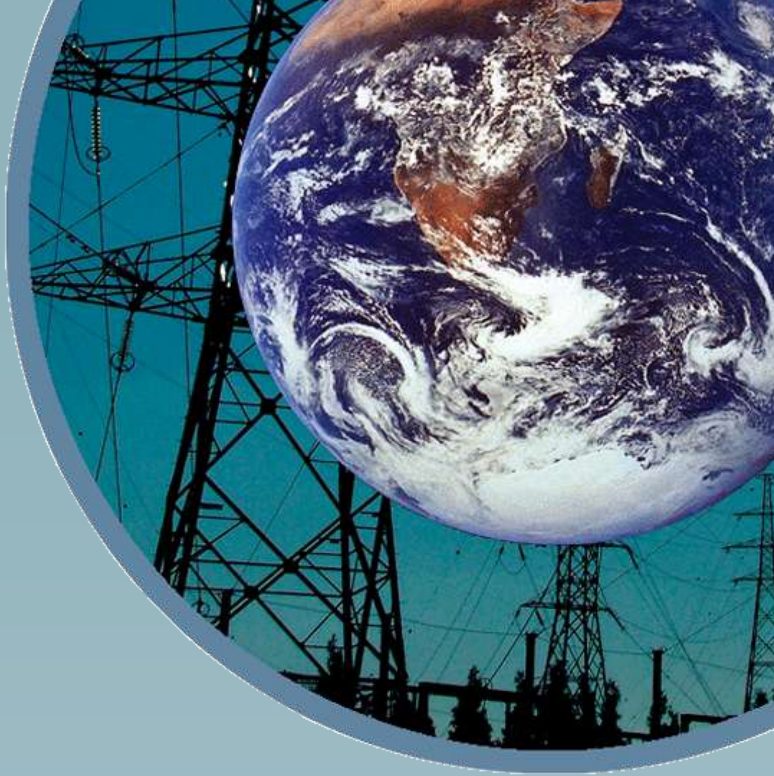


Fusie tov andere bronnen



Courtesy N.J. Lopes Cardozo

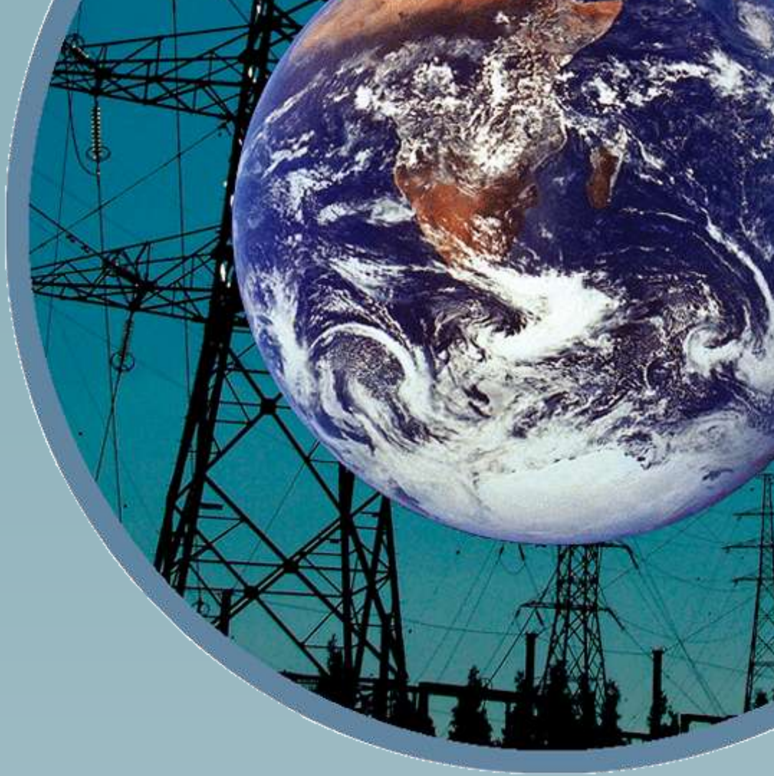
Veiligheid



Fusie is géén kettingreactie

Brandstof voor paar seconden

Veiligheid



Waterstof en helium
zijn ongevaarlijk

Géén vervoer radioactieve
stoffen tijdens bedrijf

Géén lang-levend kernafval

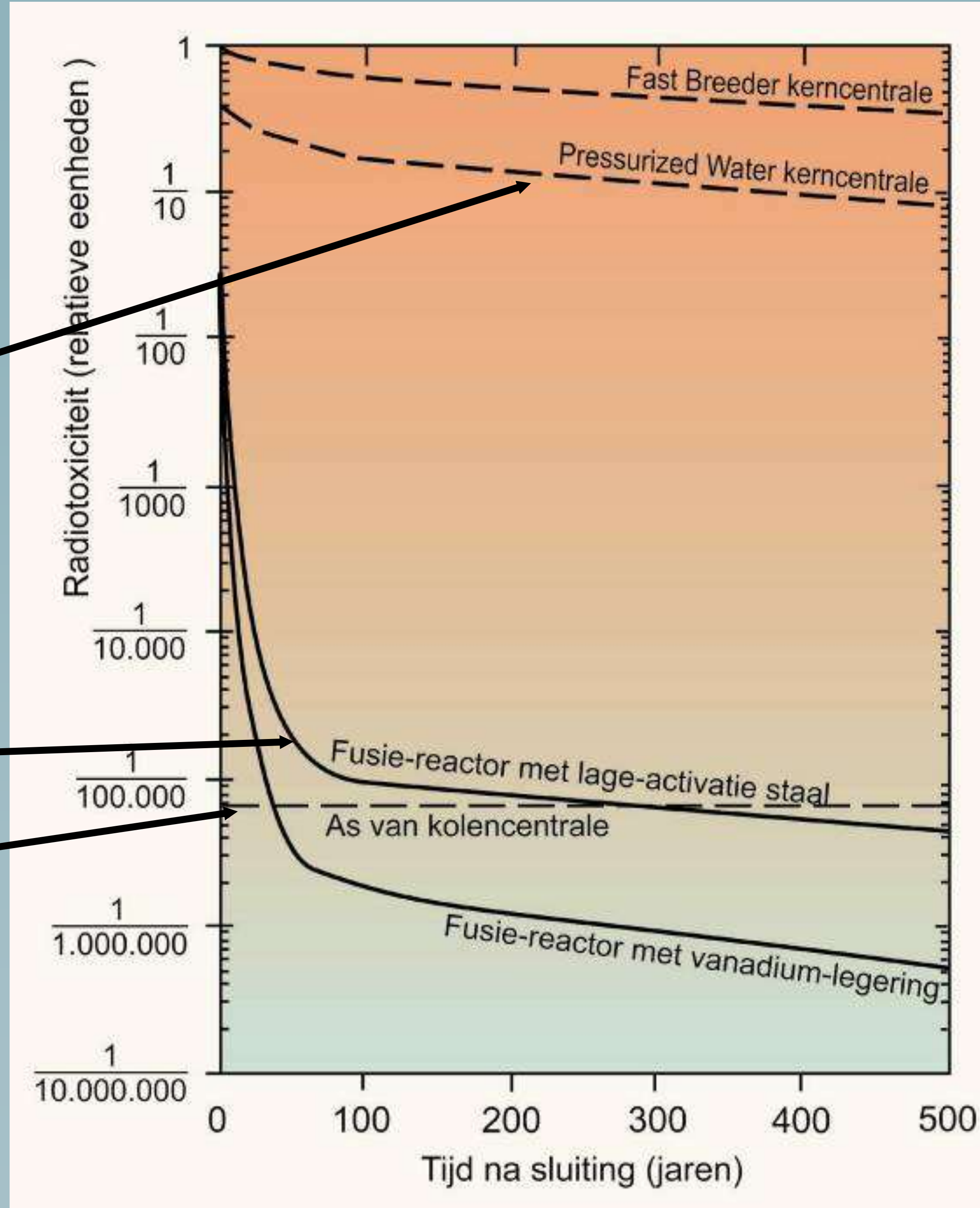
Géén uitstoot broeikasgas

Kernfval

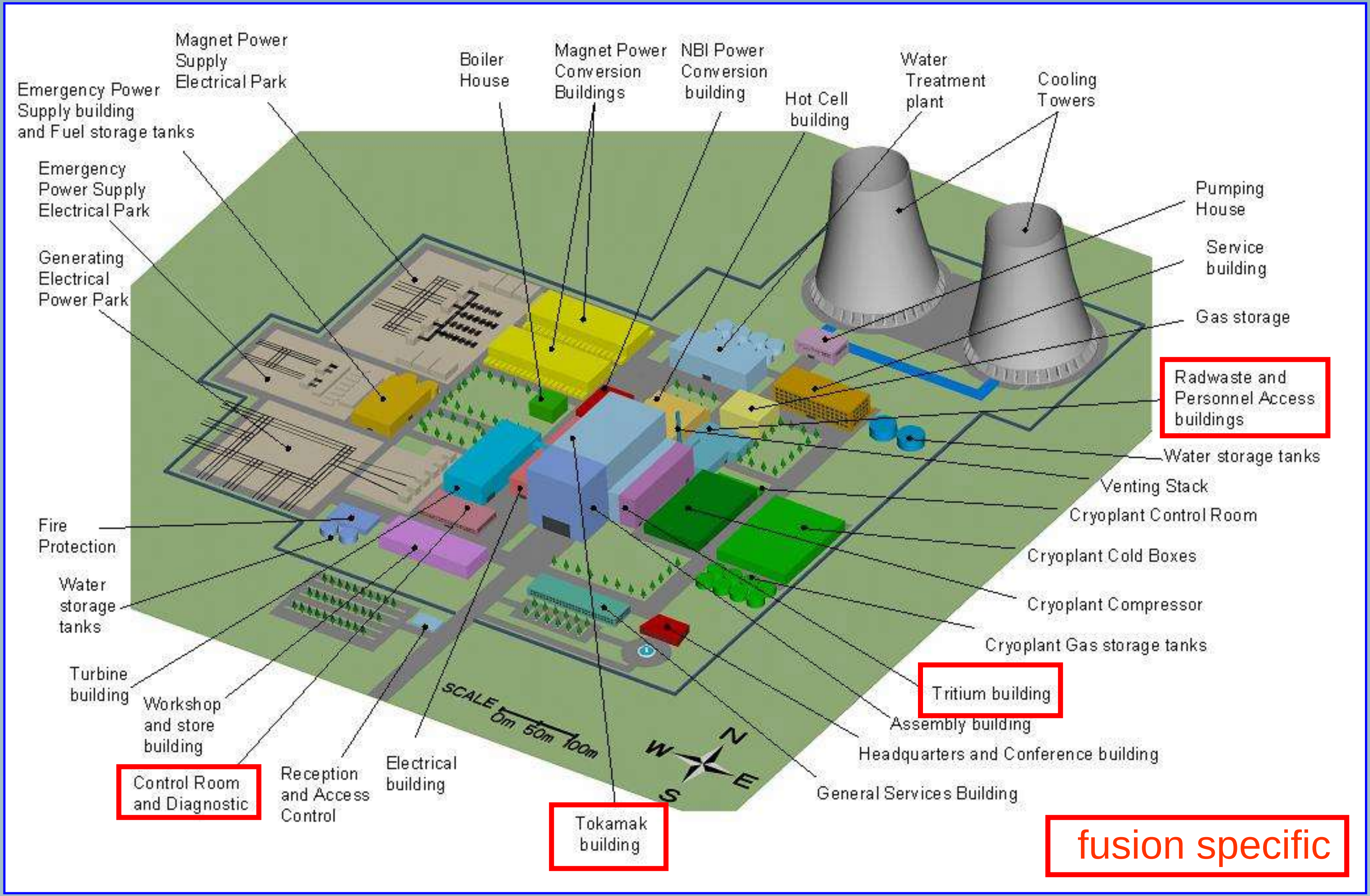
Kernsplijting

Kernfusie

Kolenas



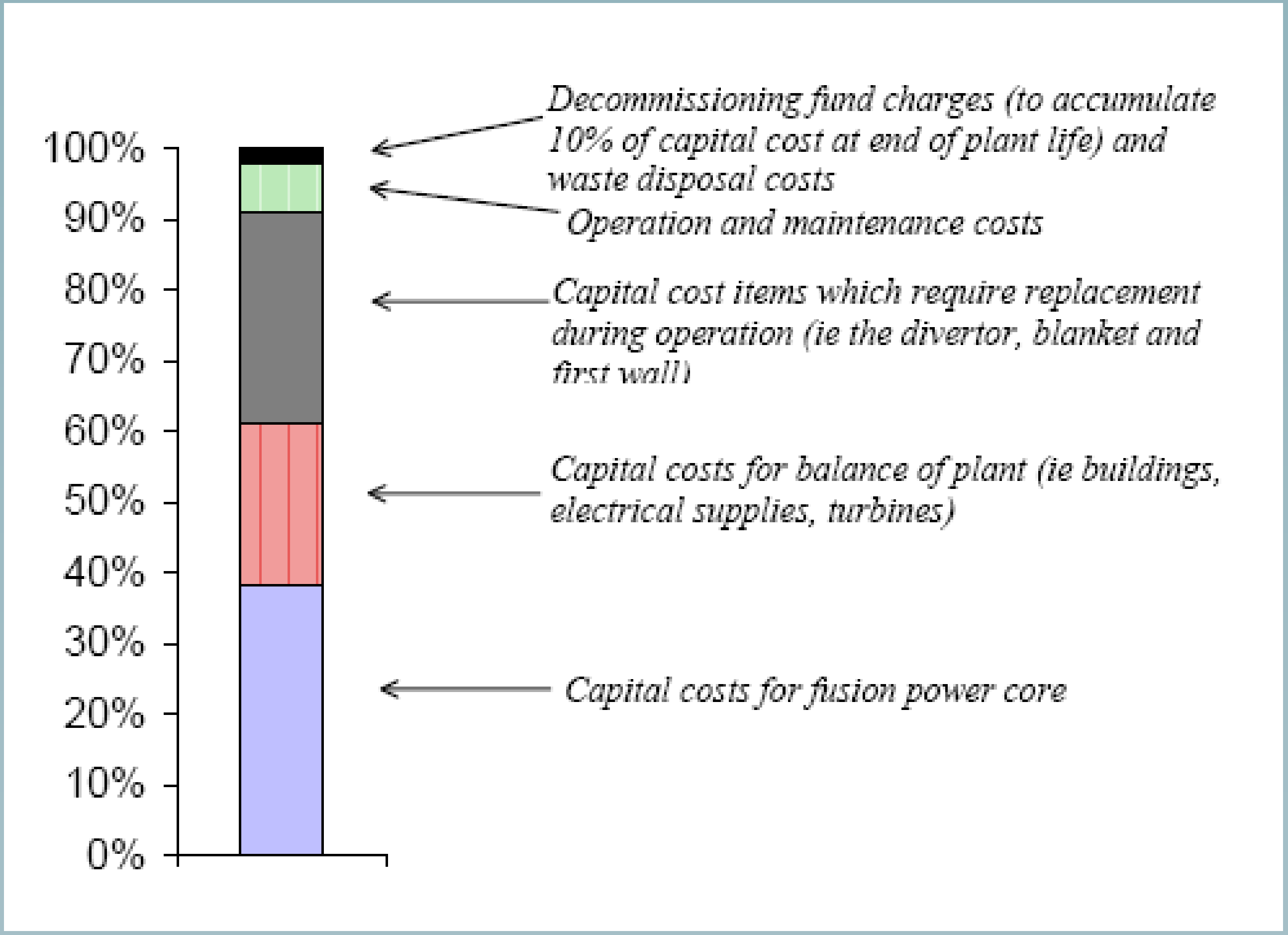
Economie: electriciteitskosten



Most of the plant is conventional, not fusion specific!

Economie: electriciteitskosten

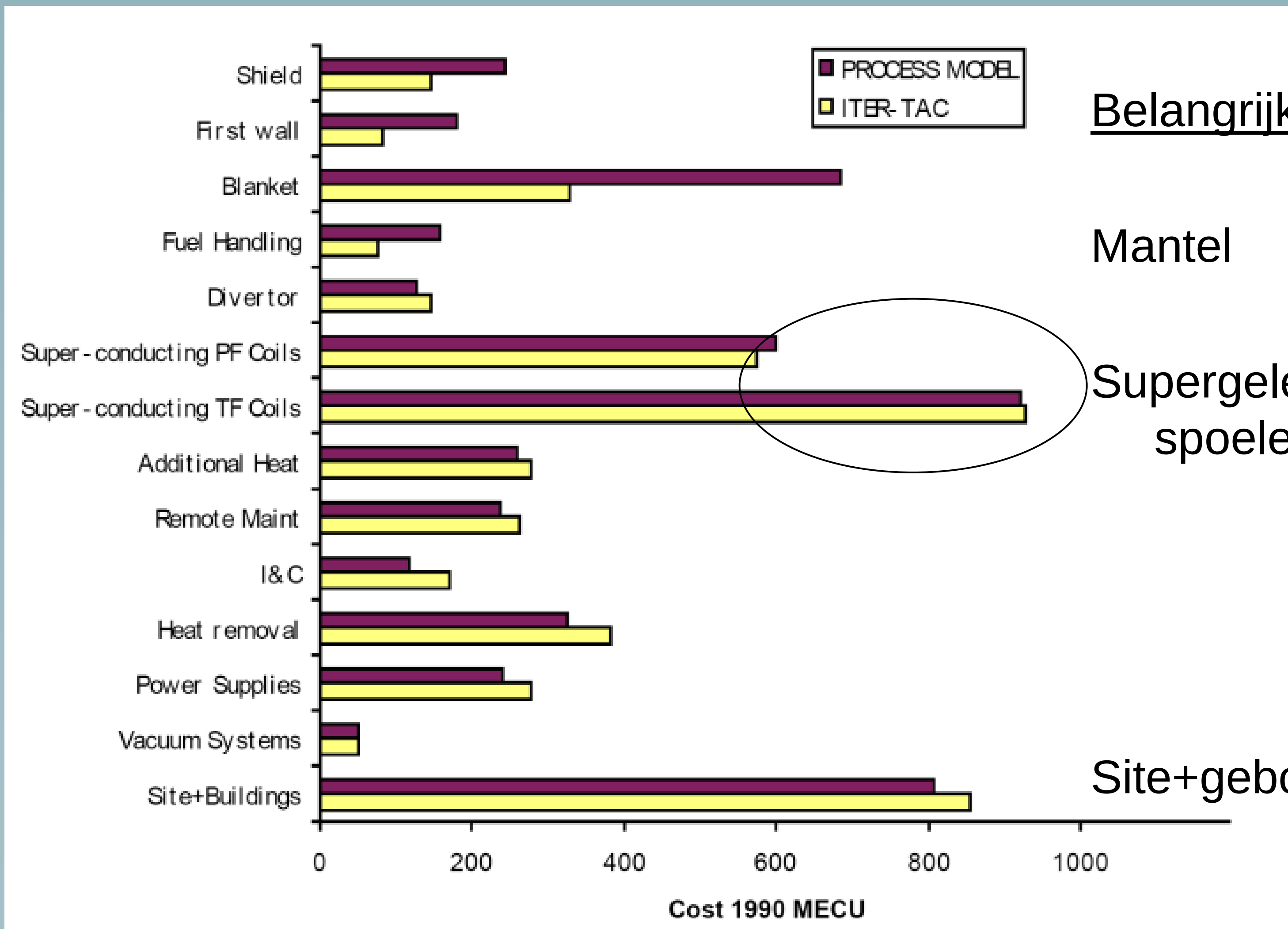
Samenstelling van directe kosten



Brandstofkosten bedragen slechts **0.5%** !

Economie: electriciteitskosten

Kosten voor diverse componenten



<u>Belangrijkste kosten:</u>

Mantel

Supergeleidende spoelen

Site+gebouwen

Economie: electriciteitskosten

The plant must be an affordable, reliable, maintainable energy source and all of these factors are contained in the cost of electricity:

$$coe = \frac{[C_{AC} + (C_{O\&M} + C_{SCR} + C_F) * (1 + y)^Y + C_{D\&D}}{(8760 * P_E * P_f)}, \text{ where}$$

C_{AC} is the annual capital cost charge (total capital cost x Fixed Charge Rate)
$C_{O\&M}$ is the annual operations and maintenance cost ← Minor Effect (salaries, equip)
C_{SCR} is the annual scheduled component replacement cost ← Minor Effect (cost, life)
C_F is the annual fuel costs
y is the annual escalation rate
Y is the construction and startup period in years
P_E is the net electrical power (MWe)
P_f is the plant capacity factor ← **Major Effect**
$C_{D\&D}$ is the annual decontamination and decommissioning converted to mills/kWhr

Economie: electriciteitskosten

Schaling van kosten met capaciteit

$$coe \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}}$$

A: Availability

η_{th}: thermodynamic efficiency

β_N: normalized plasma pressure

N: normalized plasma density

Economie: beschikbaarheid

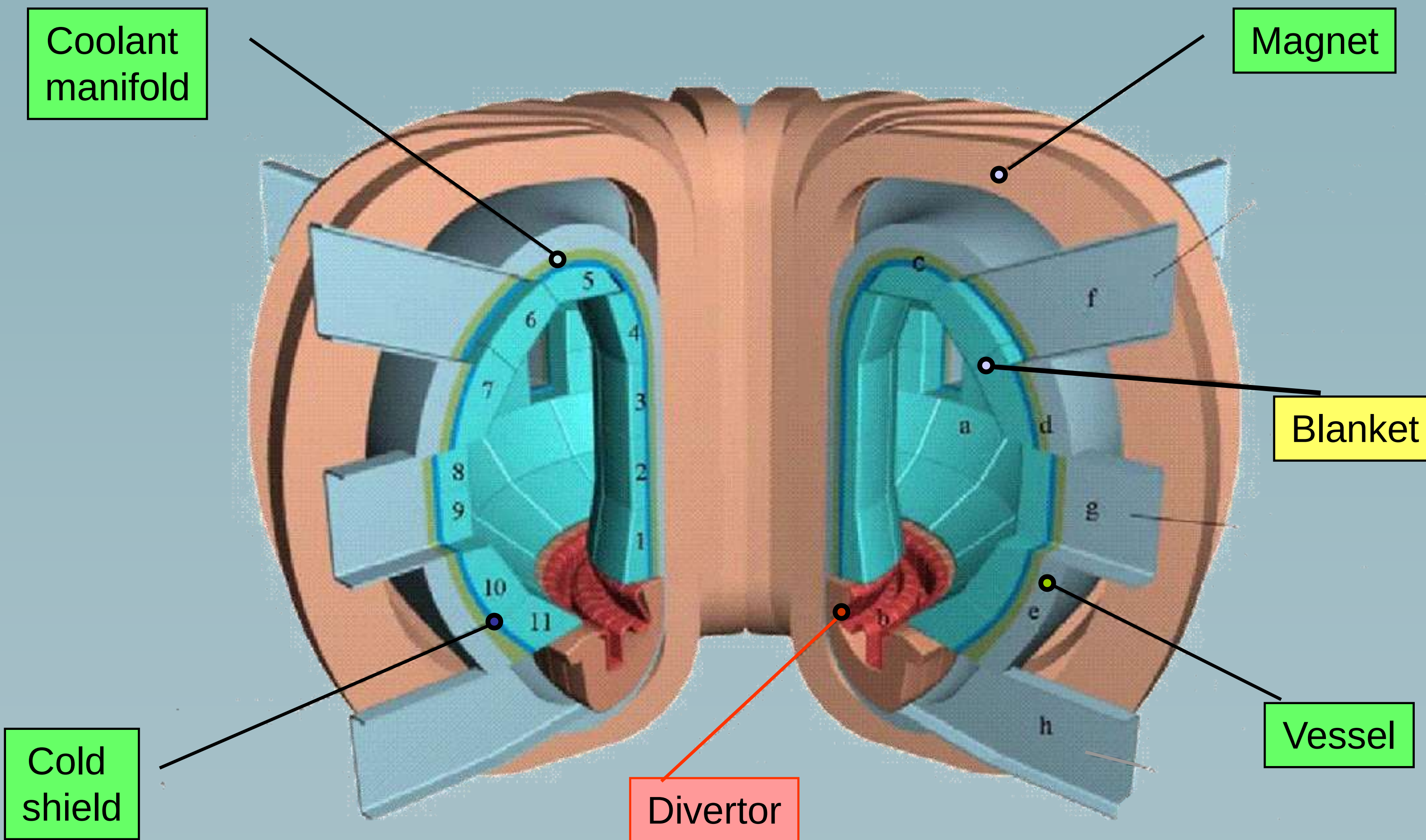
$$\textit{Availability} = \frac{\textit{Operational Time}}{\textit{Operational Time} + \textit{Scheduled Down Time} + \textit{Unscheduled Down Time}}$$

Operational Time is the power production time over a set period of time.

Scheduled Down Time is the sum of regularly scheduled maintenance periods for the power core, other reactor plant equipment, and balance of plant equipment

Unscheduled Down Time is the summation of maintenance times to repair unexpected operational failures that cause the plant to cease power production

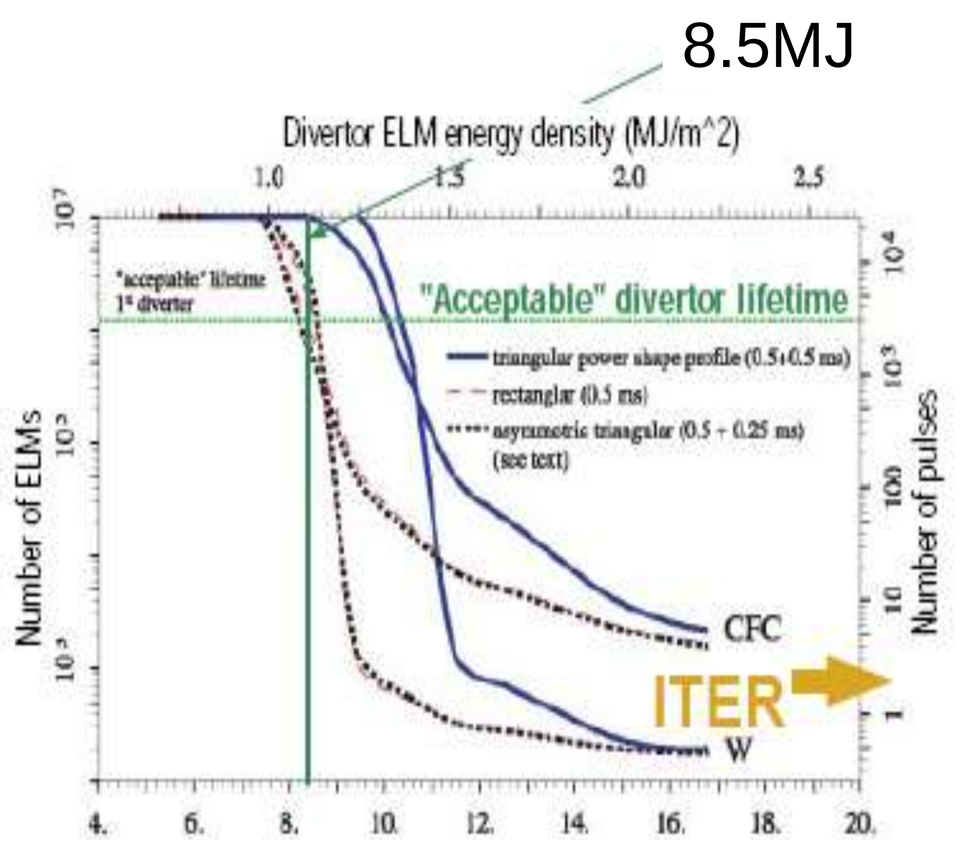
Permanent | 5-6 year | 2 year



(Power Plant Conceptual Study)

Economie: beschikbaarheid

Snelle warmteverliezen beperken de levensduur van ITER



Energy loss from plasma due to transients

F. Federici et al., PPCF 45 (2003) 1523

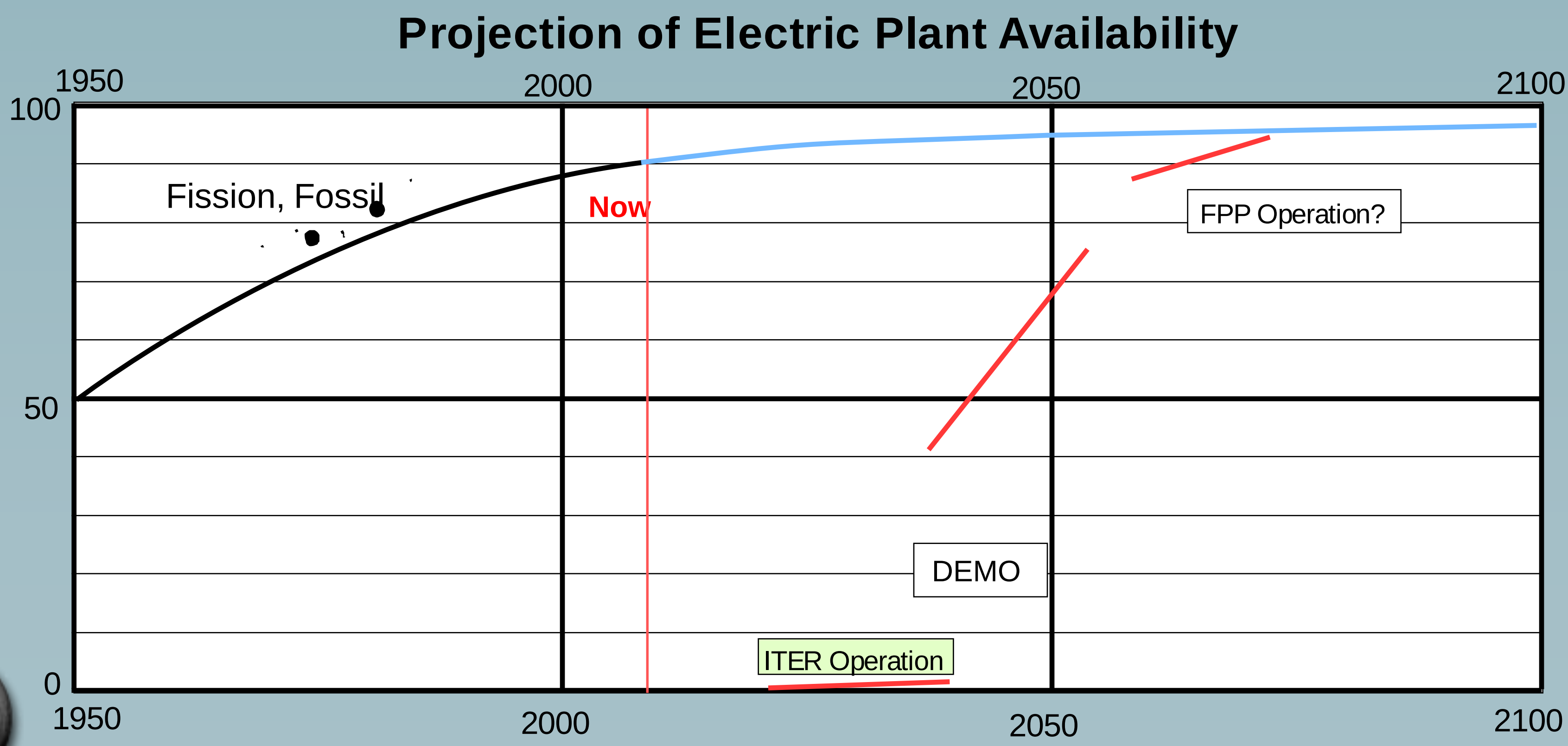
- **Transient heat losses of 1 ms duration are caused by edge instabilities (so called ELMs)**

➢ **Large ELMs are unacceptable**

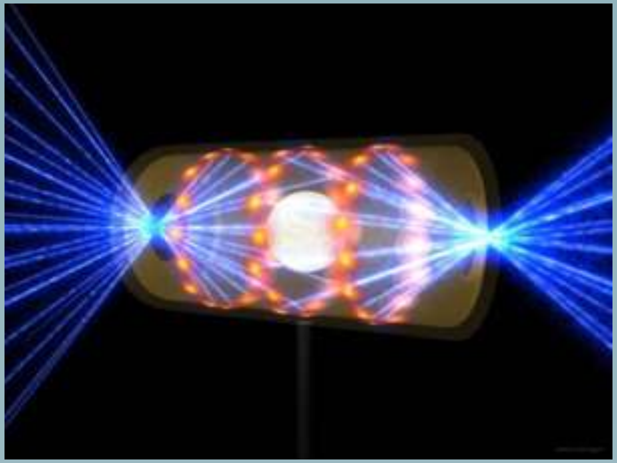
➢ **Mode of Operation should avoid ELMs**

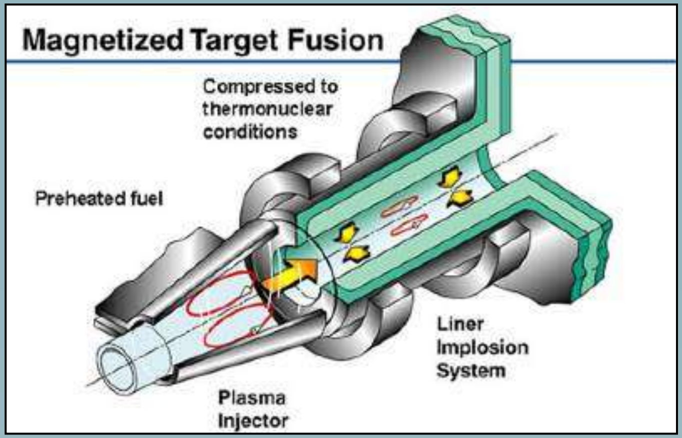
Economie: beschikbaarheid

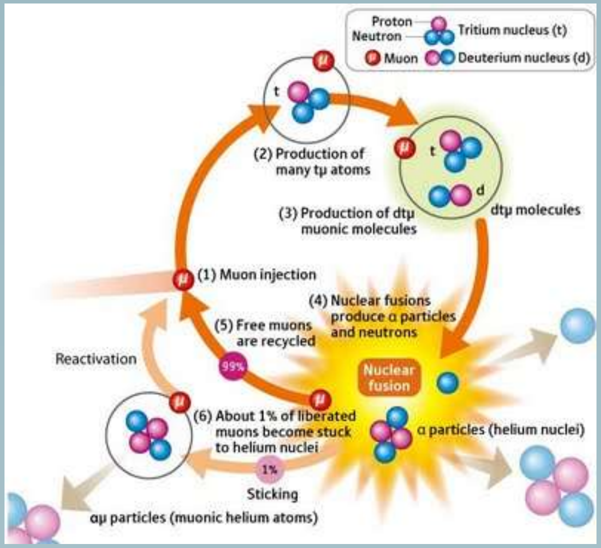
Beschikbaarheid moet groeien via ITER, DEMO tot een fusie-elektriciteitscentrale



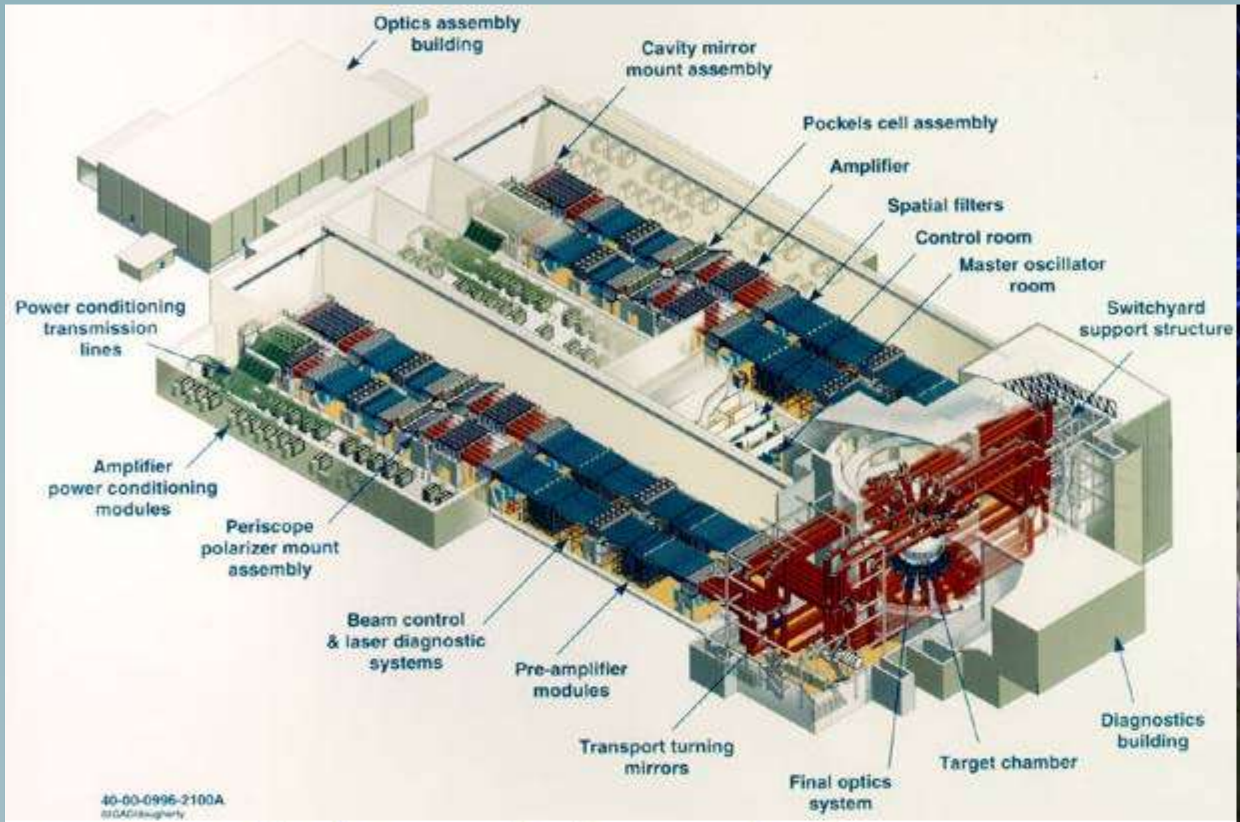
Andere vormen van fusie

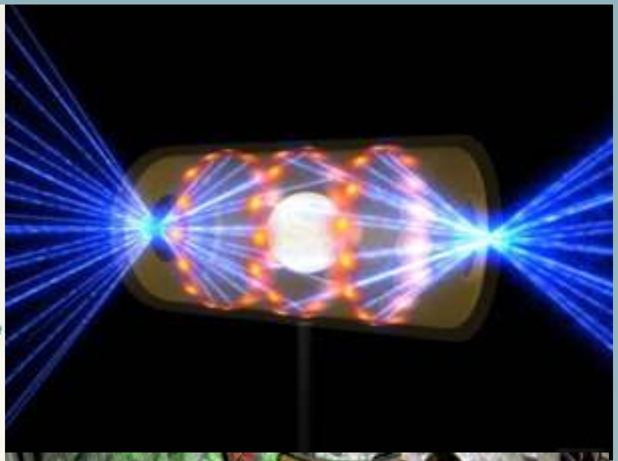


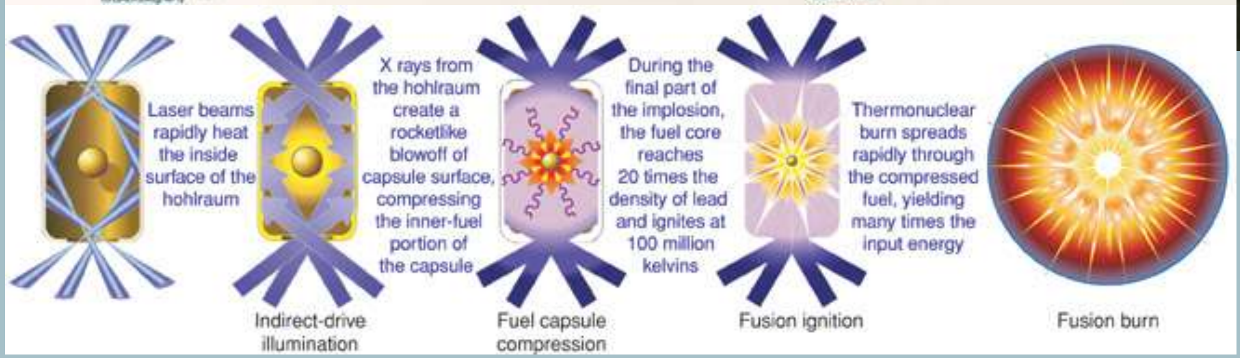




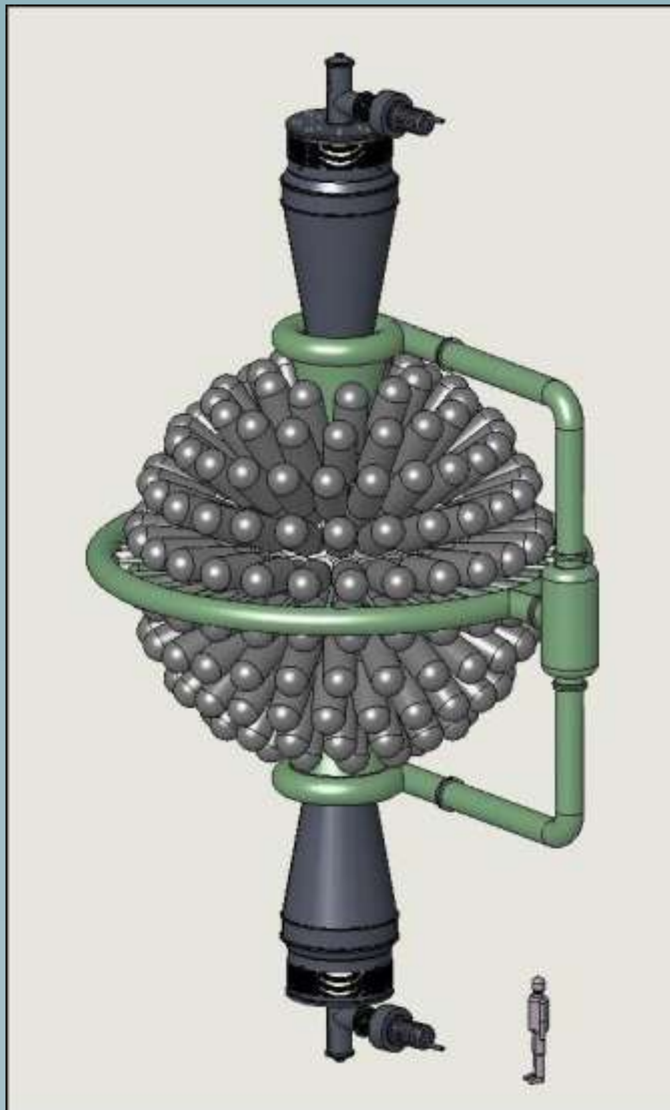
Traagheidsopsluiting (laserfusie)

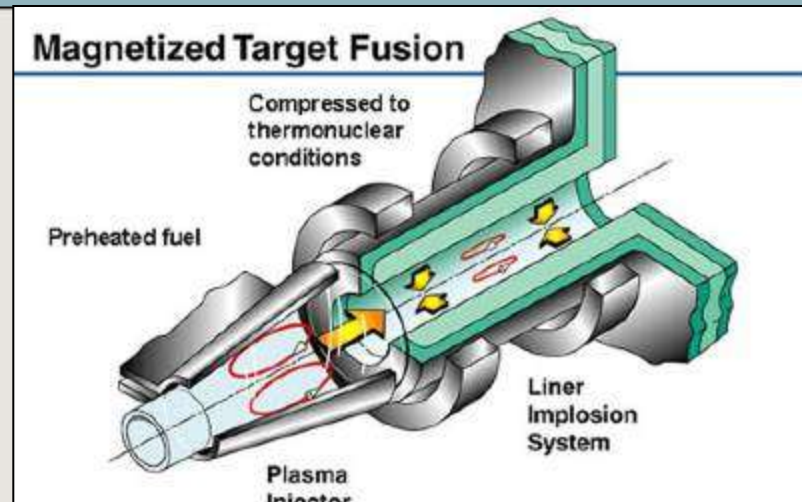


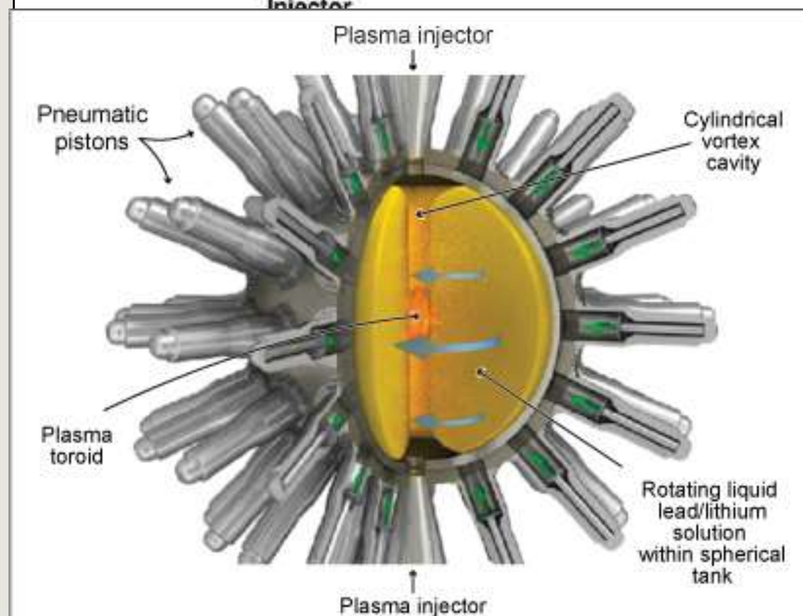




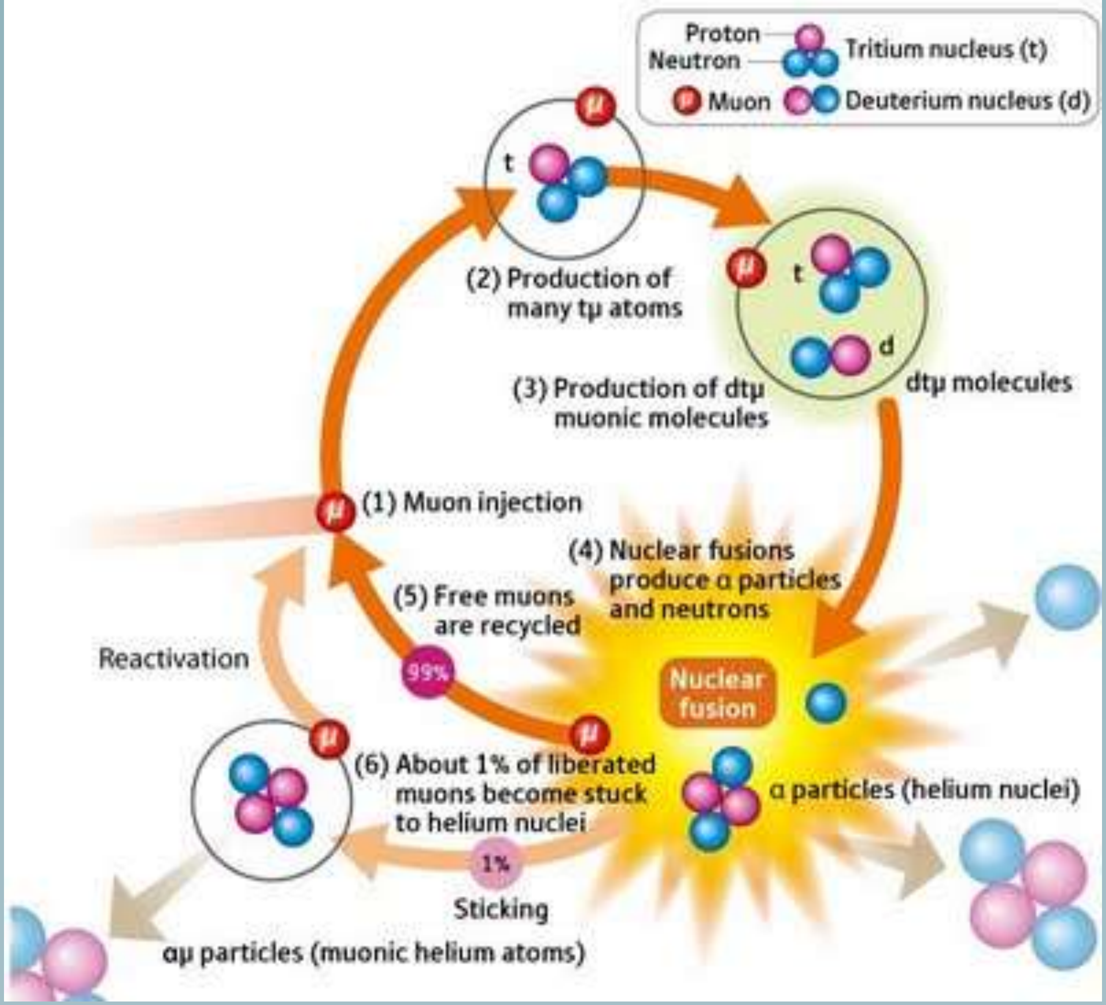
Magnetized Target Fusion



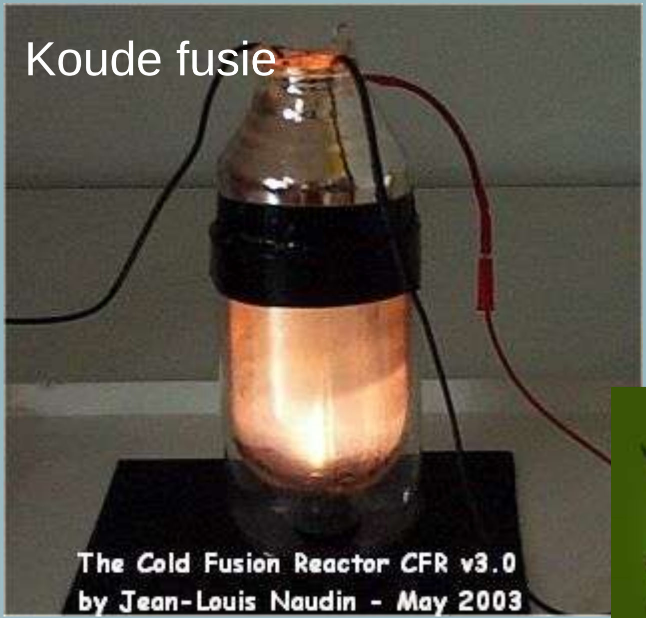




Muon-gekataliseerde fusie



Confusie



Bubble fusion