Kernfusion durch magnetischen Einschluss - die letzten Hürden vor der Anwendung

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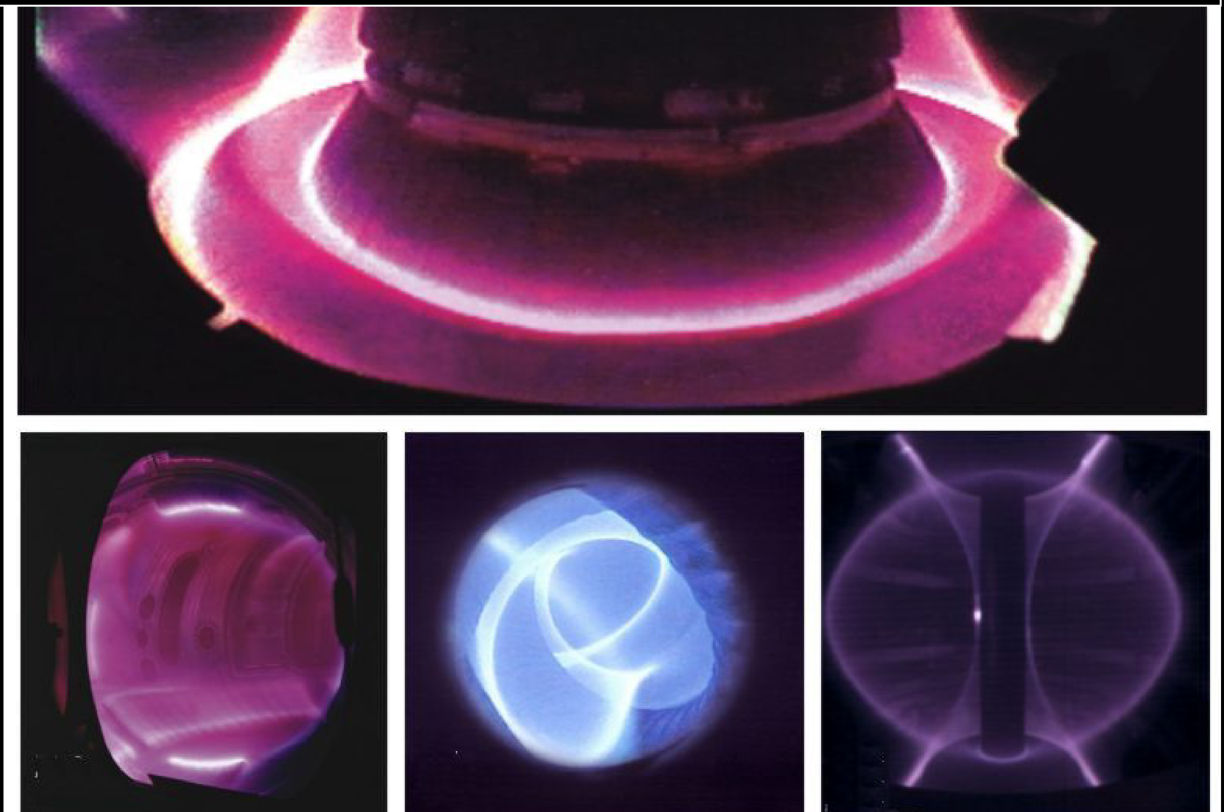
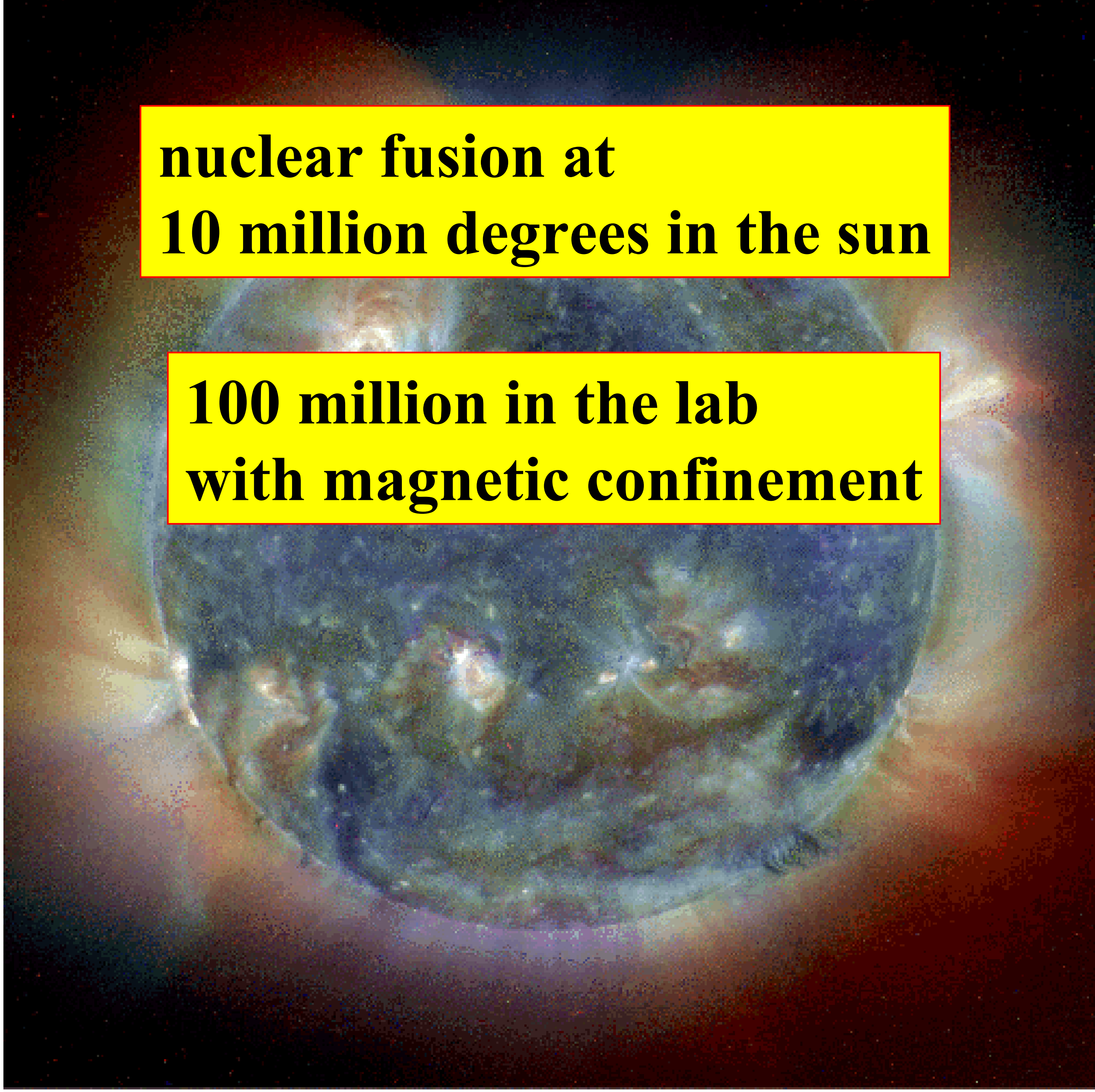


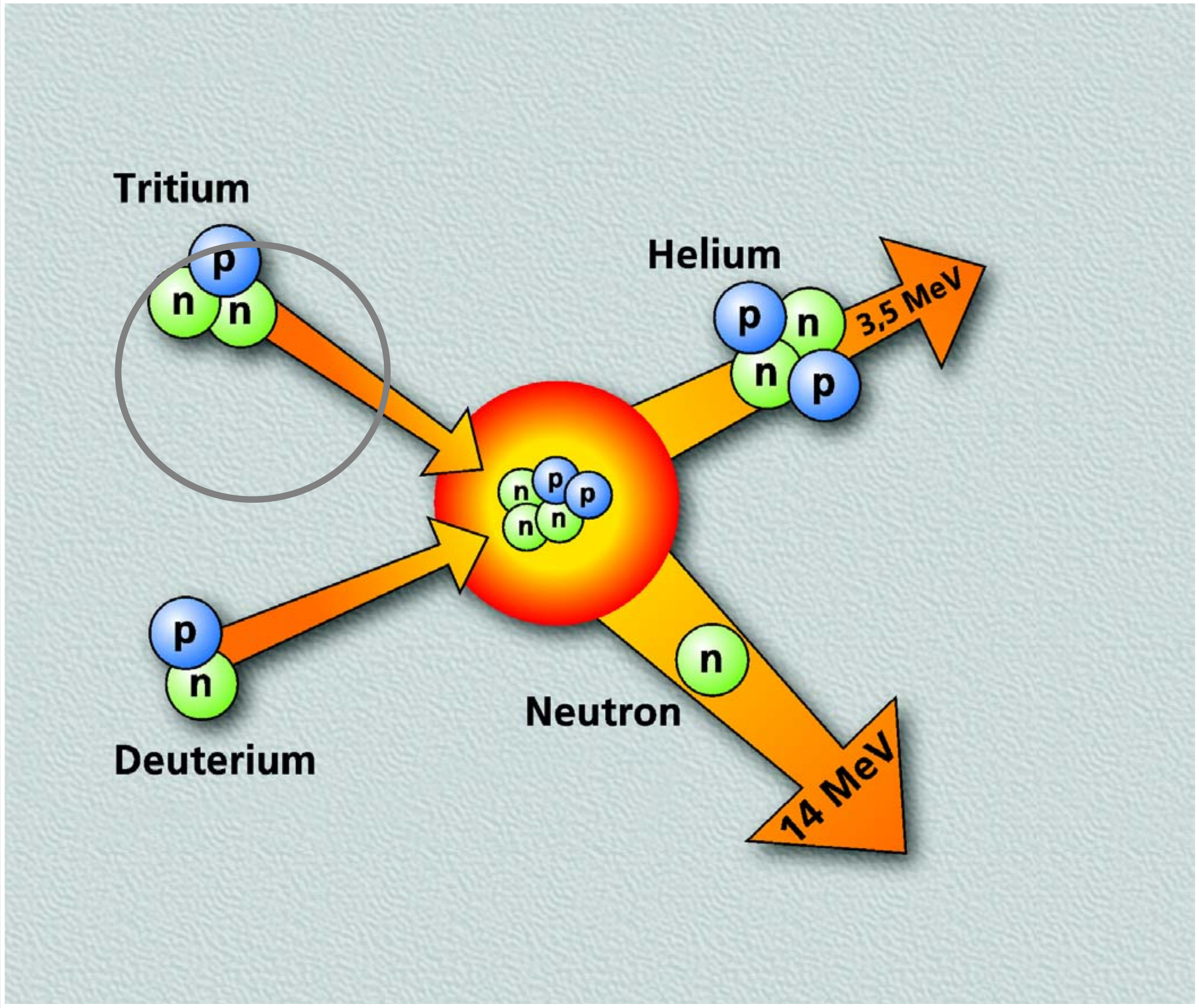
Seminar Energie-Forschung
Optionen in Entwicklung Aufwand an Forschung, Kosten, Zeit Potenziale im Verbund
26. – 28. Mai 2003
im Physikzentrum Bad Honnef

The Sun
our role model

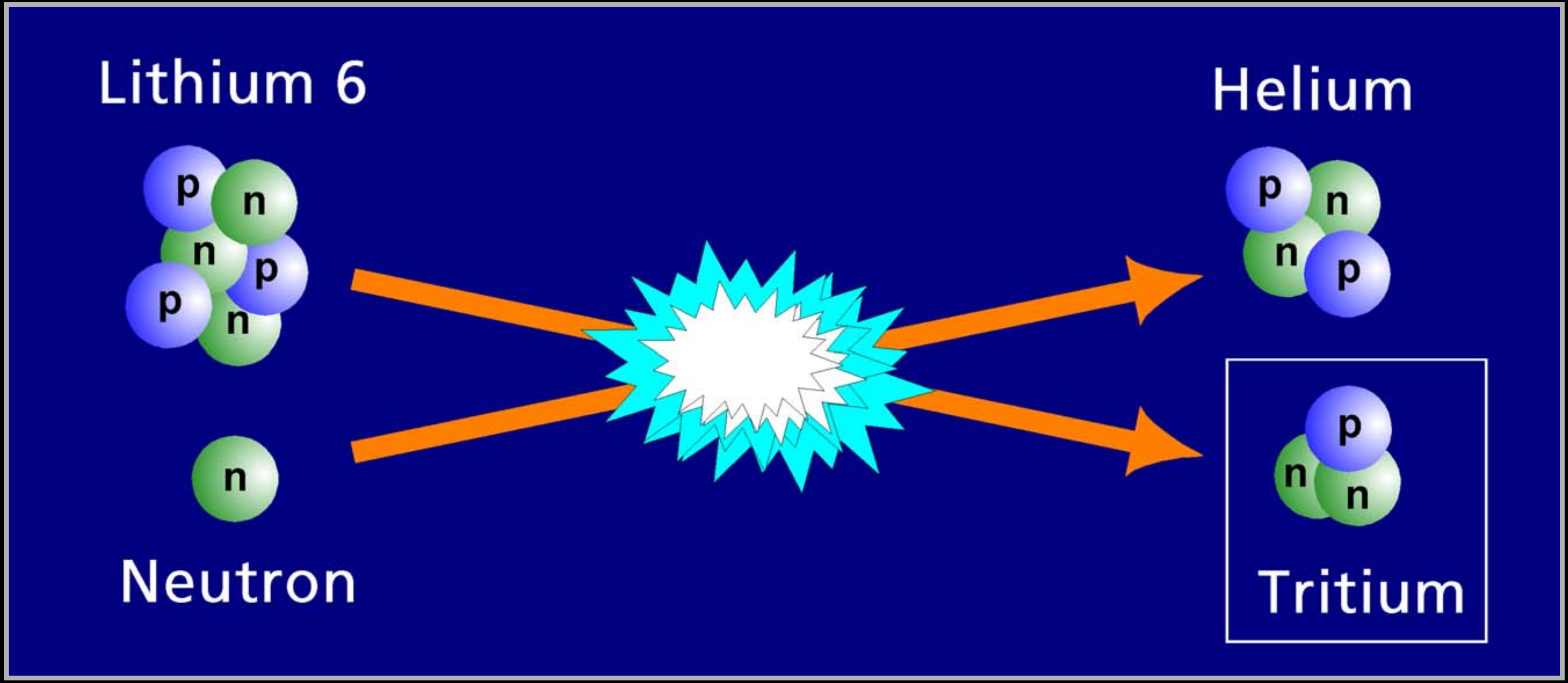
- high temperature
- plasma
- high pressure



The D-T-Reaction



Tritium breeding from Lithium



Tritium is radioactive. Half life time 12 years. Not enough found naturally.

⇒ **the primary fuel is <u>Deuterium</u> and <u>Lithium</u>**

the fuel for fusion

sufficient for the yearly electricity consumption of a family

75 mg Deuterium

225 mg Lithium

to be found i

2 liter water a

250 g earth/s

ene

48 0

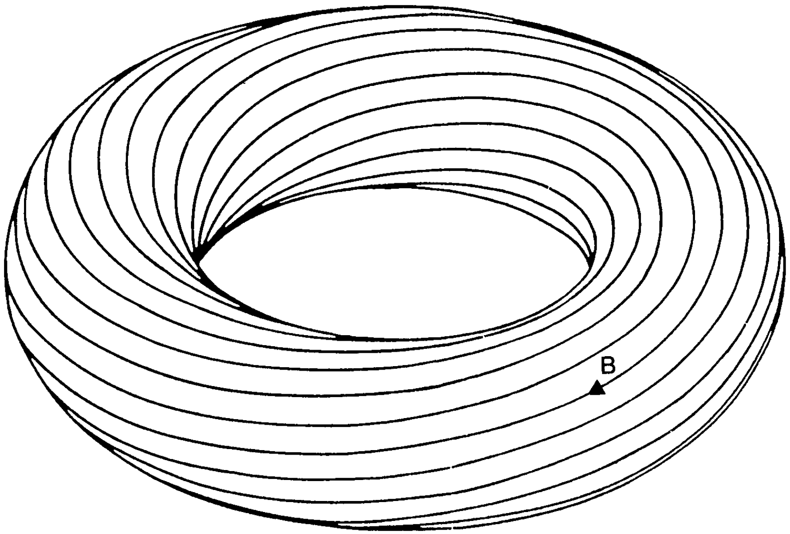
corresponding

1 000 liter oil

the fuel is cheap and accessible worldwide

... a new primary energy source

toroidal confinement with helical magnetic field

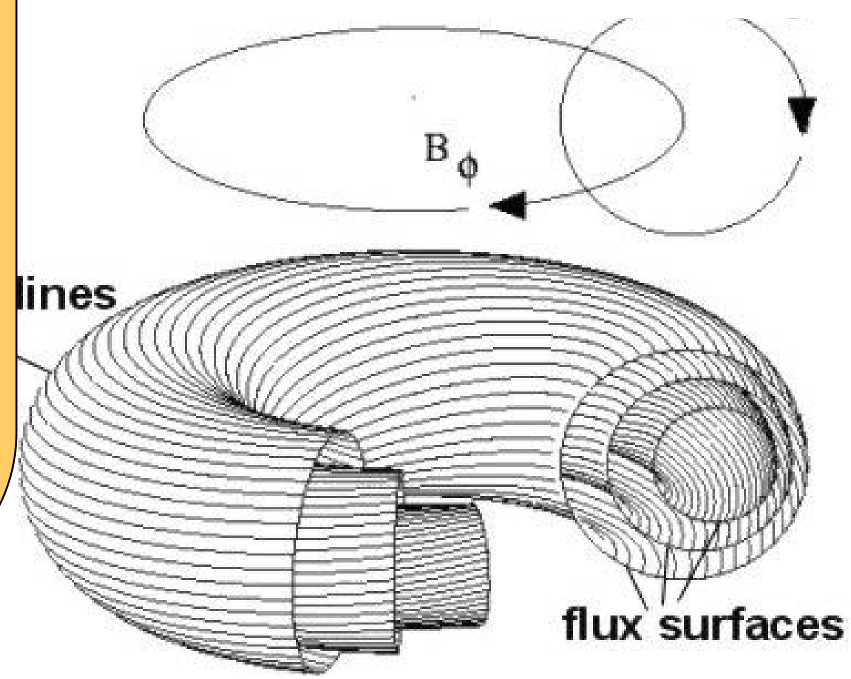


Tokamak

generation of the poloidal field with plasma current

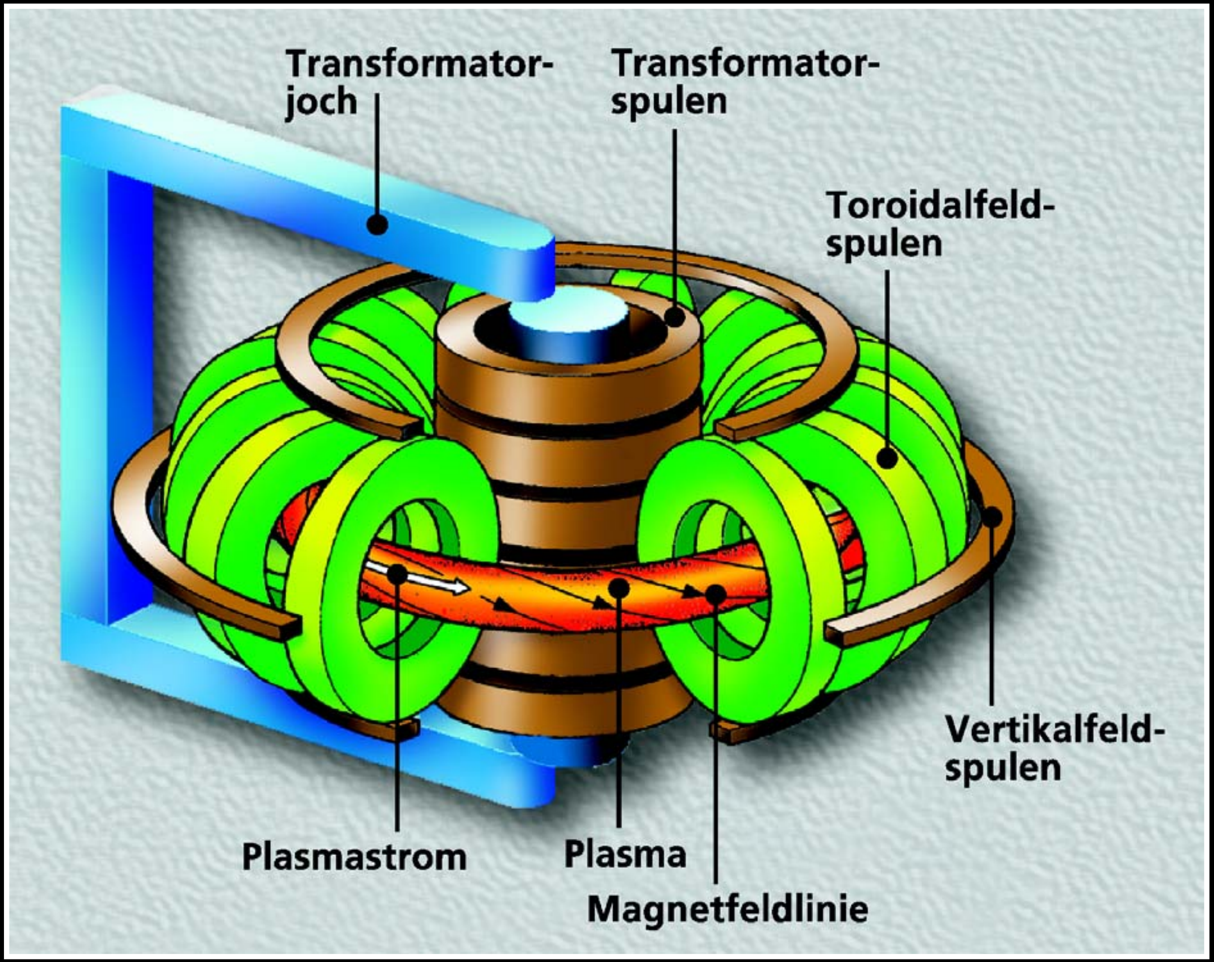
Stellarator

generation of poloidal field with helical coils



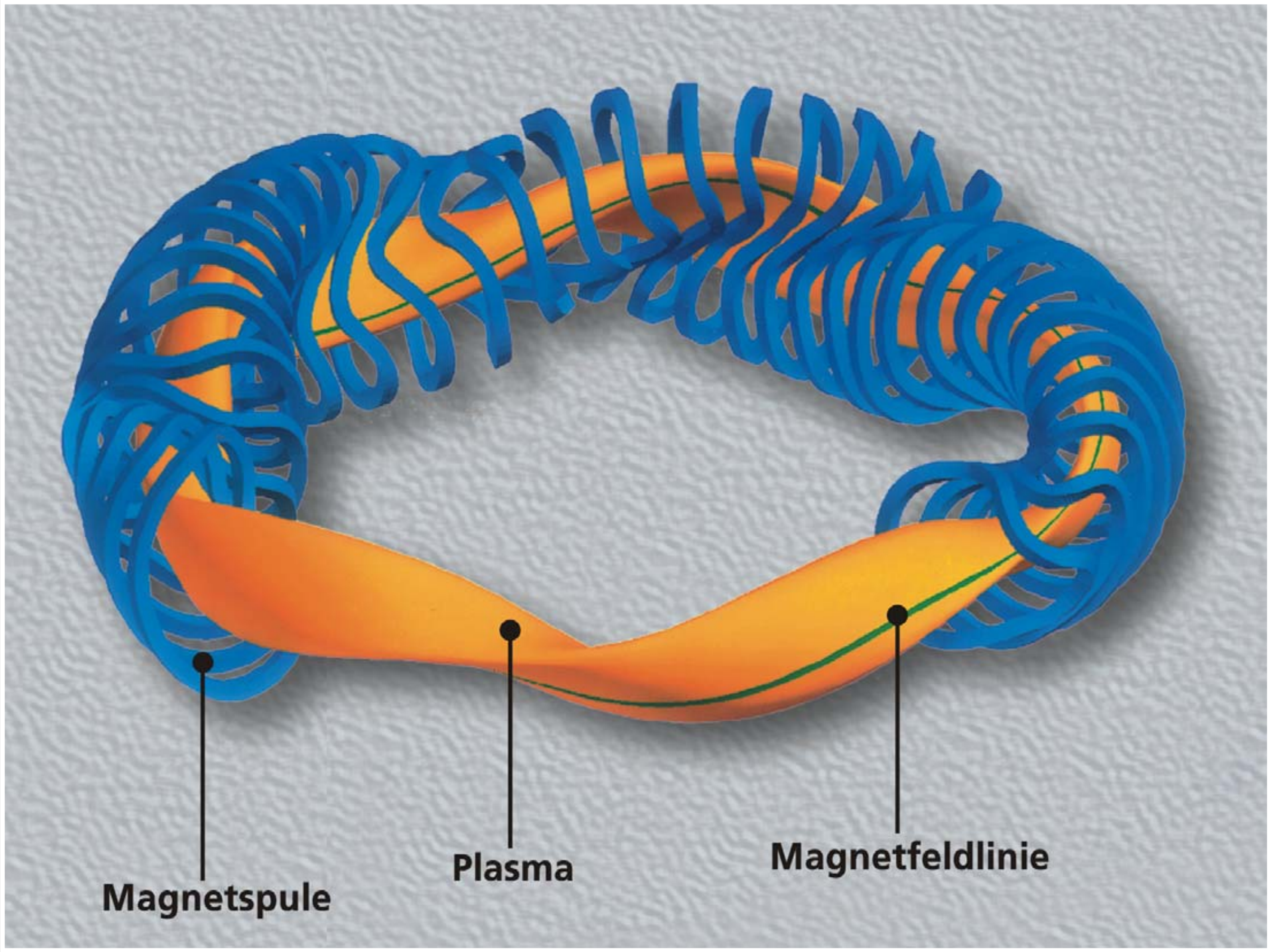
The Tokamak

plasma confinement in helical magnetic field

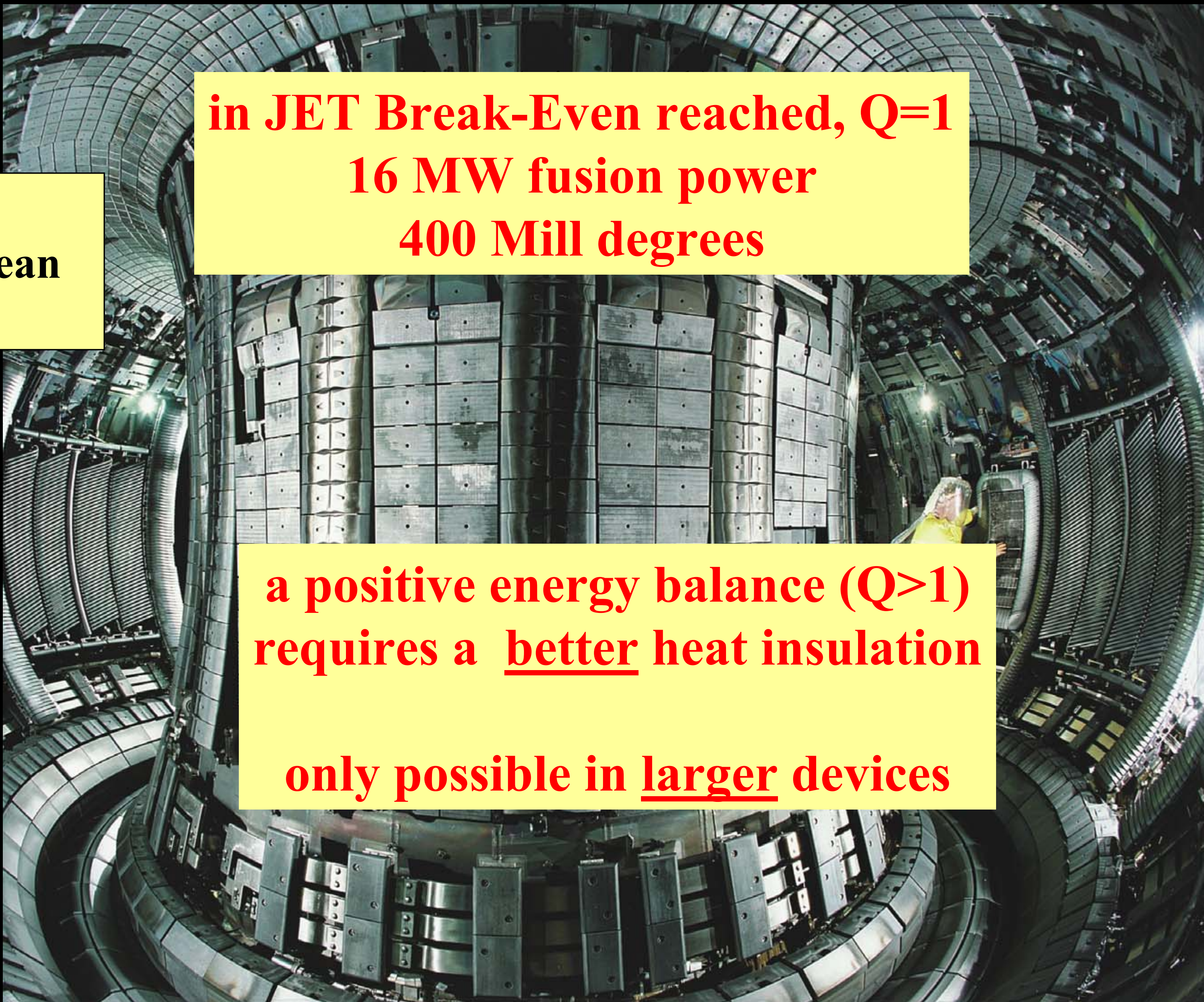


Stellarator: helical magnetic field without plasma current

e.g. Wendelstein 7-X in Greifswald



continuous confinement



Joint
European
Torus

in JET Break-Even reached, Q=1
16 MW fusion power
400 Mill degrees

a positive energy balance (Q>1)
requires a <u>better</u> heat insulation

only possible in <u>larger</u> devices

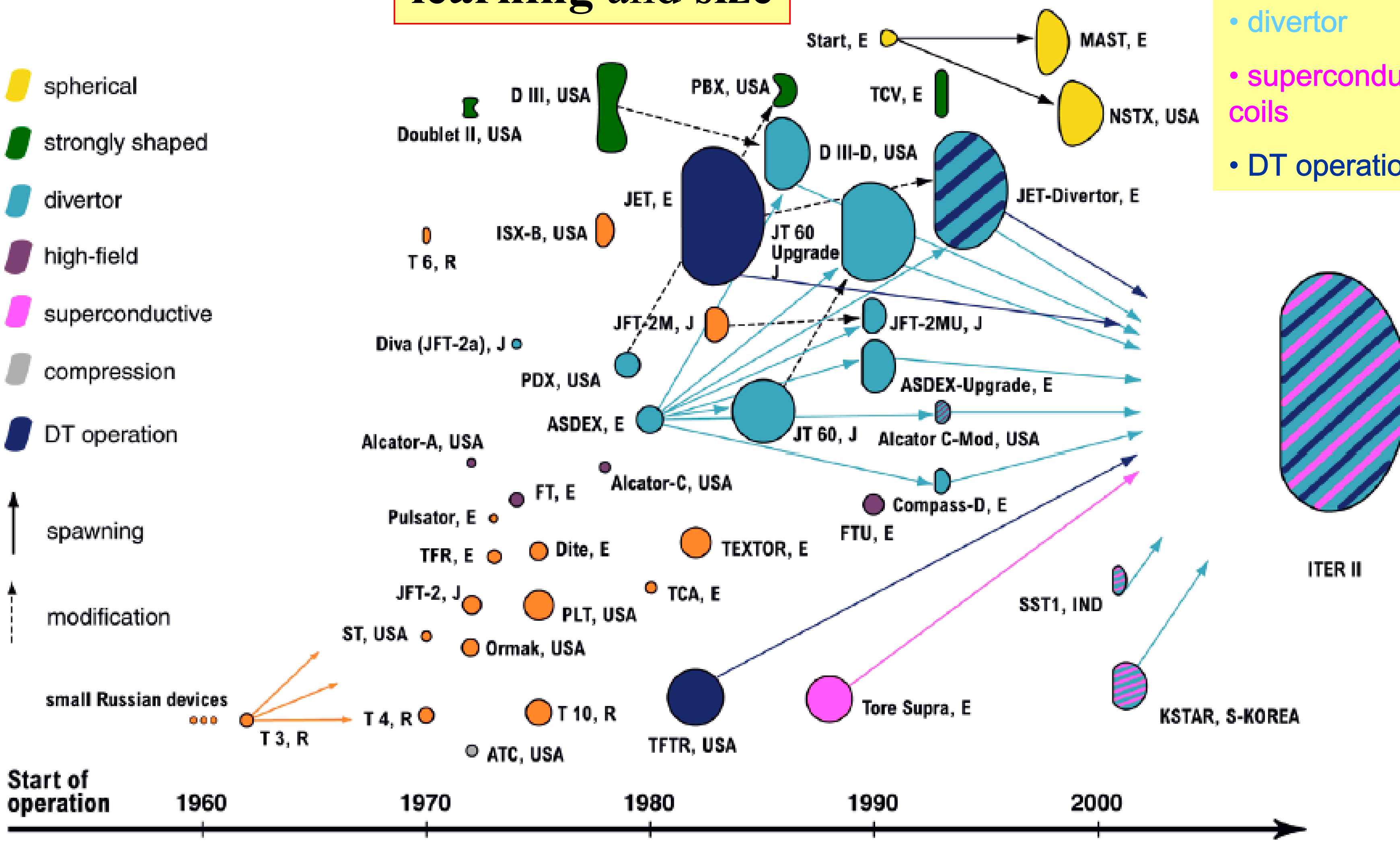
development of the tokamak concept

gaining by **learning** and **size**

ITER incorporates all successfull developments:

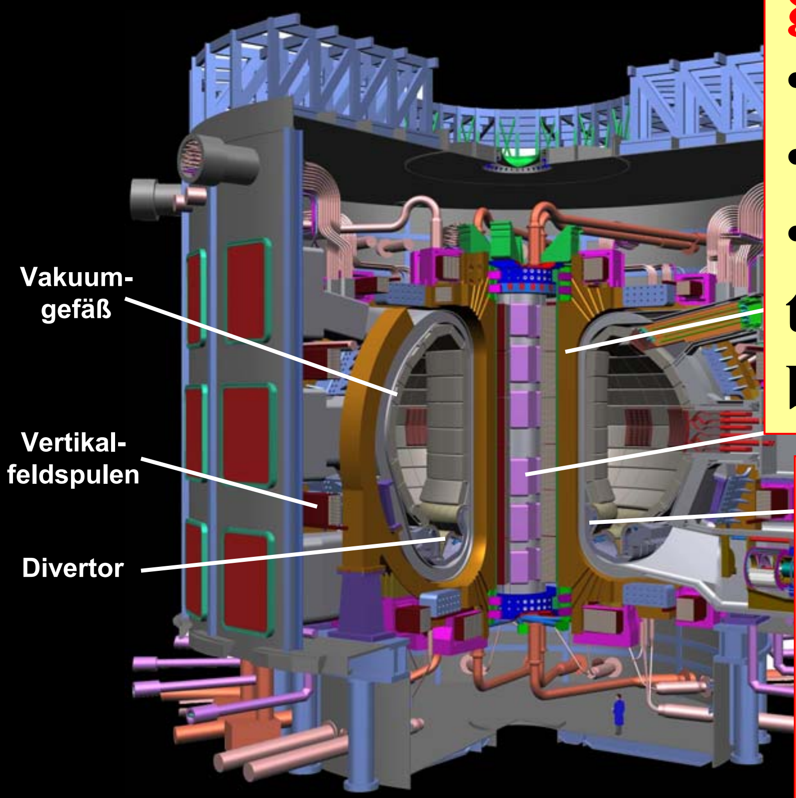
- elongated (D-shaped) cross-section
- divertor
- superconducting coils
- DT operation

Mayor Tokamak Facilities



ITER – a joint undertaking

Europe, Russia, Japan, Canada (USA, China)



goals

- **500 MW fusion power, Q=10**
- **burn time 8 min**
- **integration of physics and technology (Tritium, breeder blanket, super conductors, heating)**

open question

efficiency of <u>steady state operation</u> for power plant

plasma chamber:

Ø 15 m   6.8 m high   5.3 T   15 MA

open questions beyond ITER

continuous operation

efficiency of energy confinement (investment costs)

availability of the device (operation costs)

safety, environment (waste)

... determined by

energy confinement, turbulent transport

current drive efficiency (in tokamak)

alternative concepts: (e.g. stellarator)

plasma-wall-interaction

fusion materials under neutron irradiation

technology (super conduct. coils , heating, breeder blanket)

development of fusion materials (structural materials)

neutron irradiation damage **(life time relevant)**

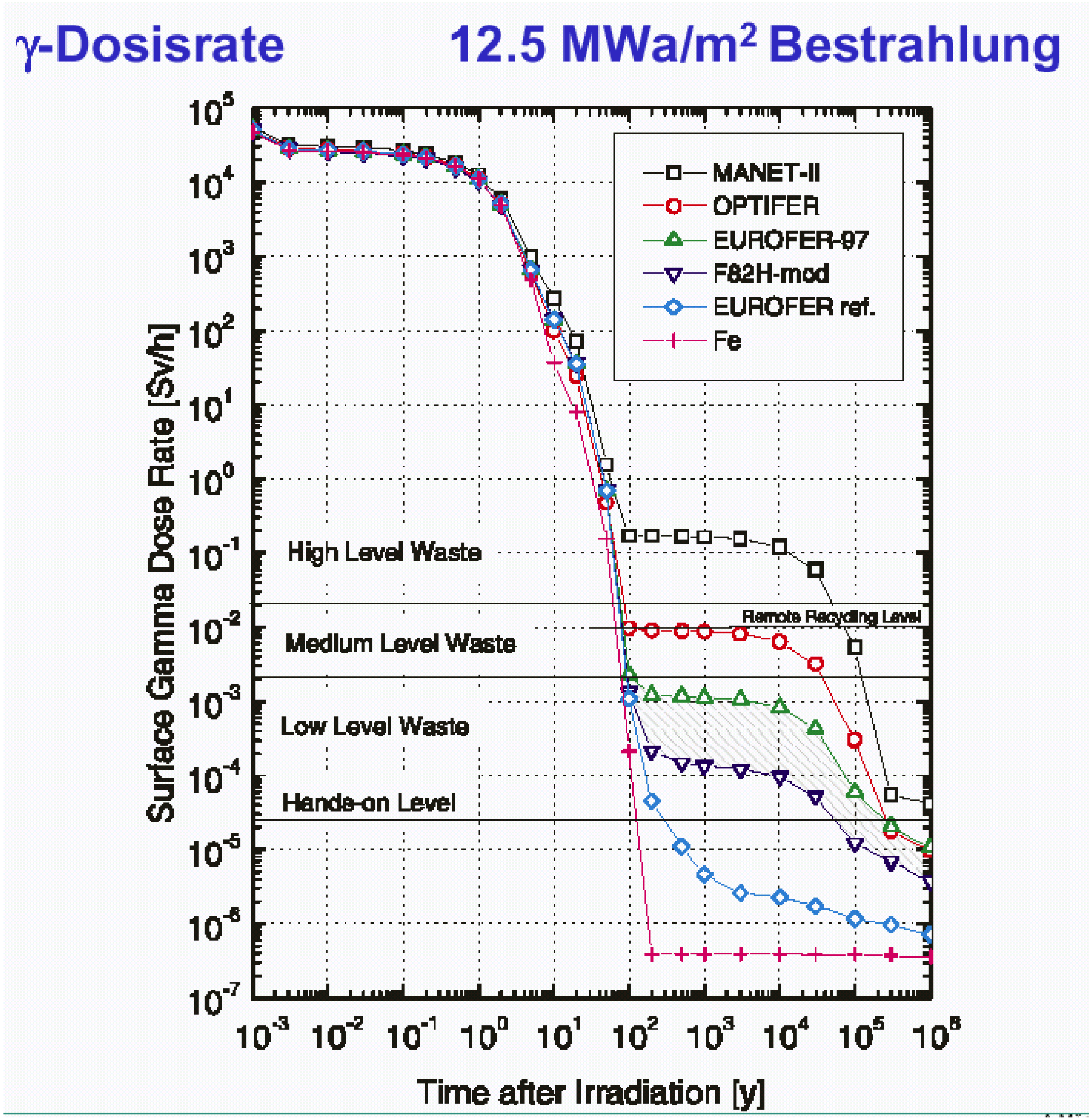
- transmutation: generation of H und He (n-p, n-alpha reactions)
- shrinking, swelling, embrittlement, lower heat conductivity
- irradiation measured in displacements per atom (dpa);
- self-healing at elevated temperatures: DBTT ductile to brittle transisition temperature; but remaining damage accumulates
- regular replacement of components foreseen
- ITER : **3 - 10 dpa** DEMO **80 - 150 dpa**

low activation **(waste relevant)**

- isotopes with long half life times to be avoided
- alloys with less molybdenum, nickel, niobium (ppm level)
- and more chromium, tungsten, titanium (7-10%)
- e.g. since 2000 the steel alloy **EUROFER** is available to be qualified with respect to engineering parameters and technical licensing
- an irradiation facility with 14 MeV neutrons is needed (IFMIF)

materials for DEMO & first generation plants :

ferritic steels



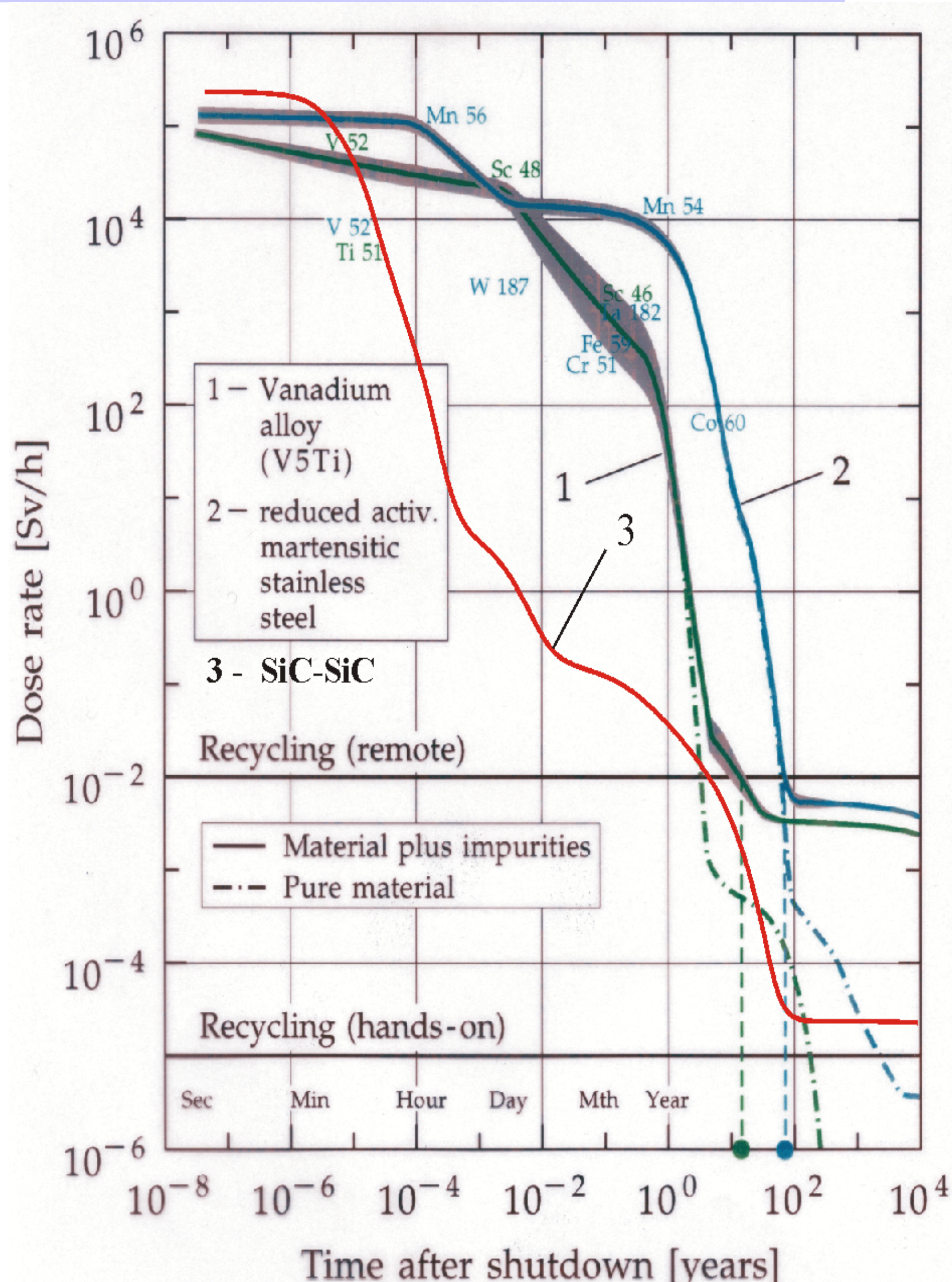
recycling by remote handling

recycling of a large fraction of all materials

further improvements with SiC-SiC materials

higher operation temperatures

easier recycling



cost of electricity:

$$\mathrm{COE} \quad \propto A^{-0.6} \eta_{th}^{-0.5} P_e^{-0.4} \beta_N^{-0.4} N^{-0.3}$$

availability (A)
thermodynamic efficiency (η_{th})
unit size (net electrical output, P_e)
normalised beta (β_n)
limiting density normalised to the Greenwald density (N)

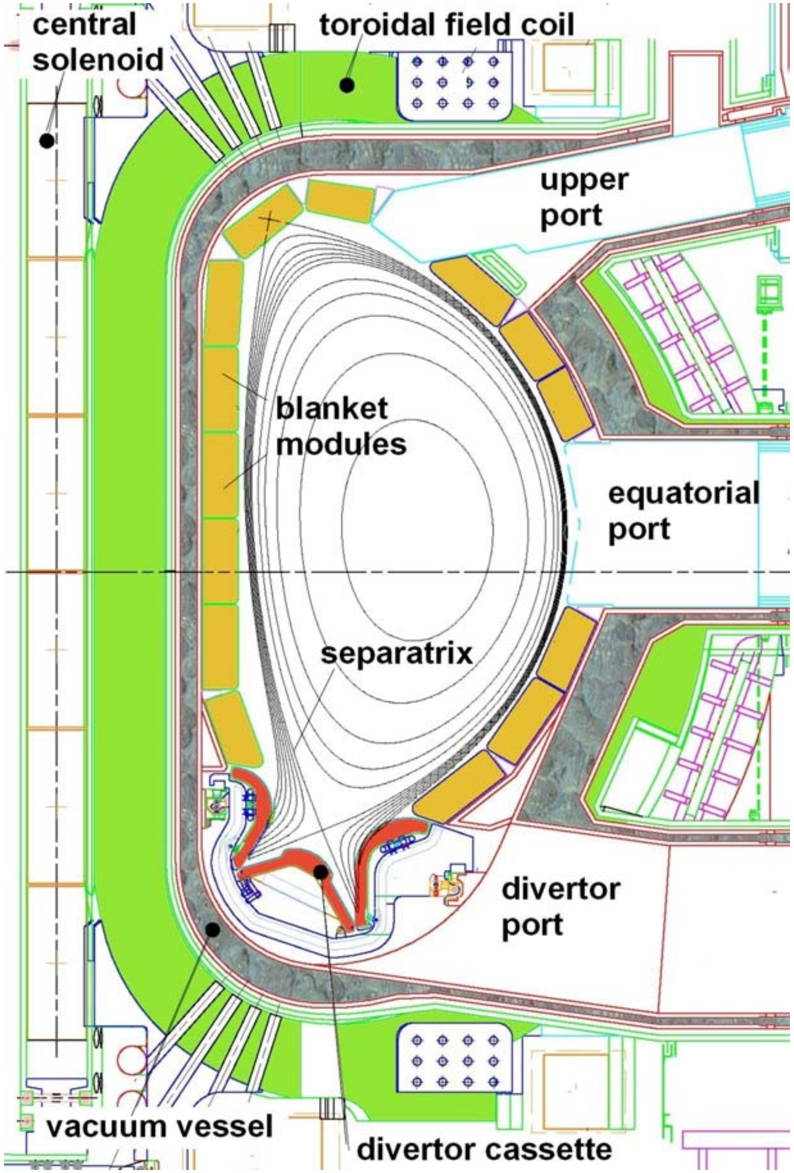
Power Plant Conceptual Study (PPCS) Stage II, D J Ward, I Cook, N P Taylor

the key issues determining the availability are:

- life time of wall components
- tritium retention

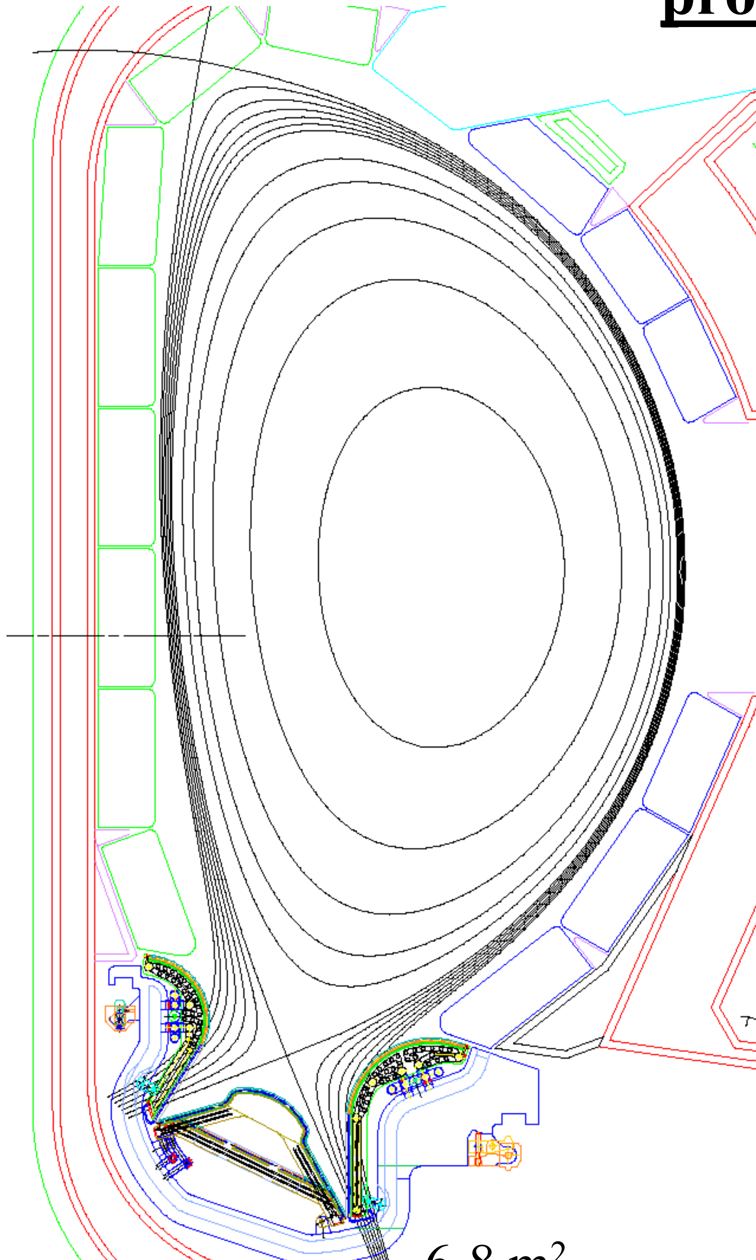
... determined by the processes of **plasma-wall-interaction**

ITER cross section



ITER

problems of plasma-wall-interaction



heat exhaust

150 MW plasma heating

on wall < 0.15 MW/m²

in divertor < 10 MW/m²

important role:

- intrinsic and seeded impurities
- PSI properties

erosion of wall materials

life time of wall components

plasma impurities

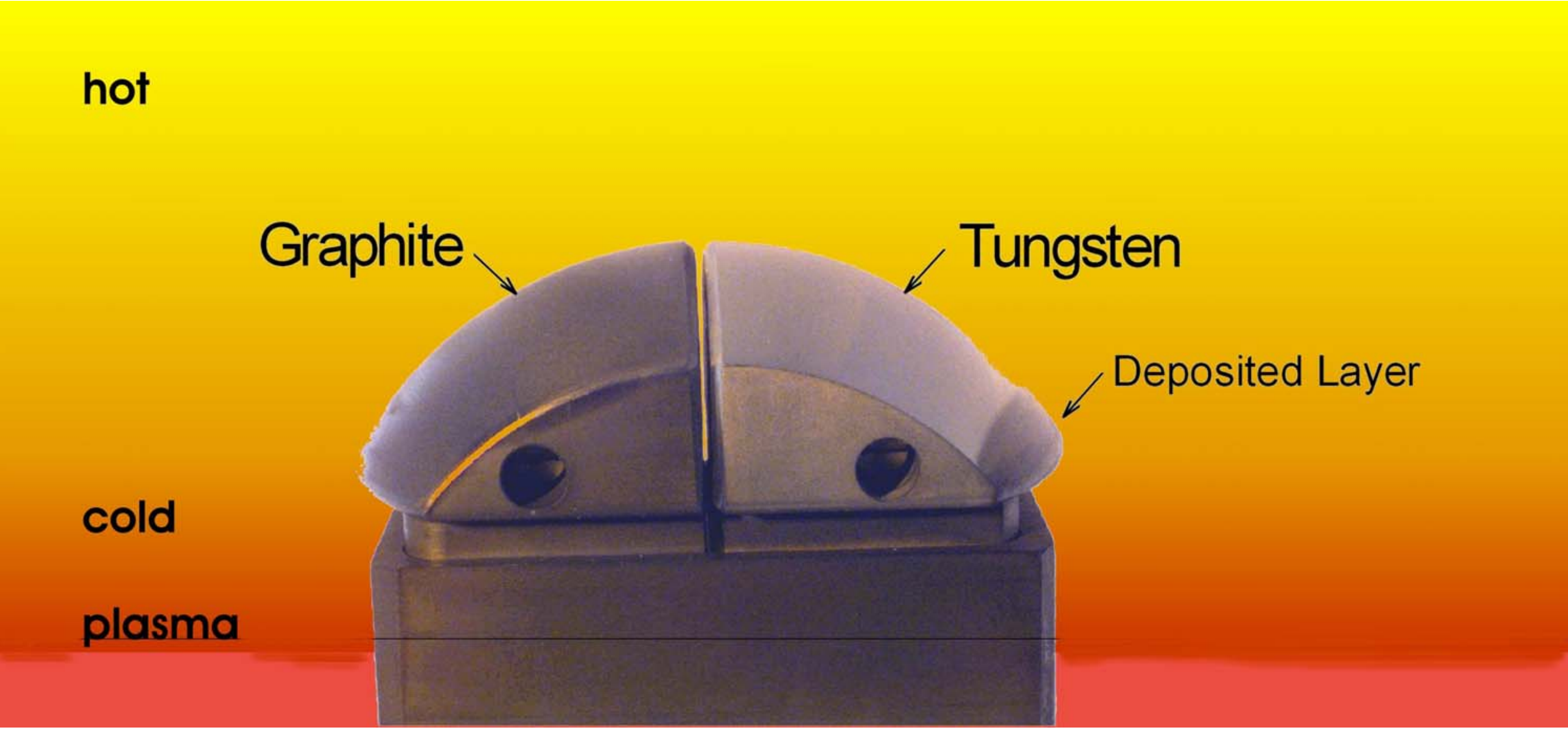
re-deposition, layer formation

tritium retention

limit on tritium inventory

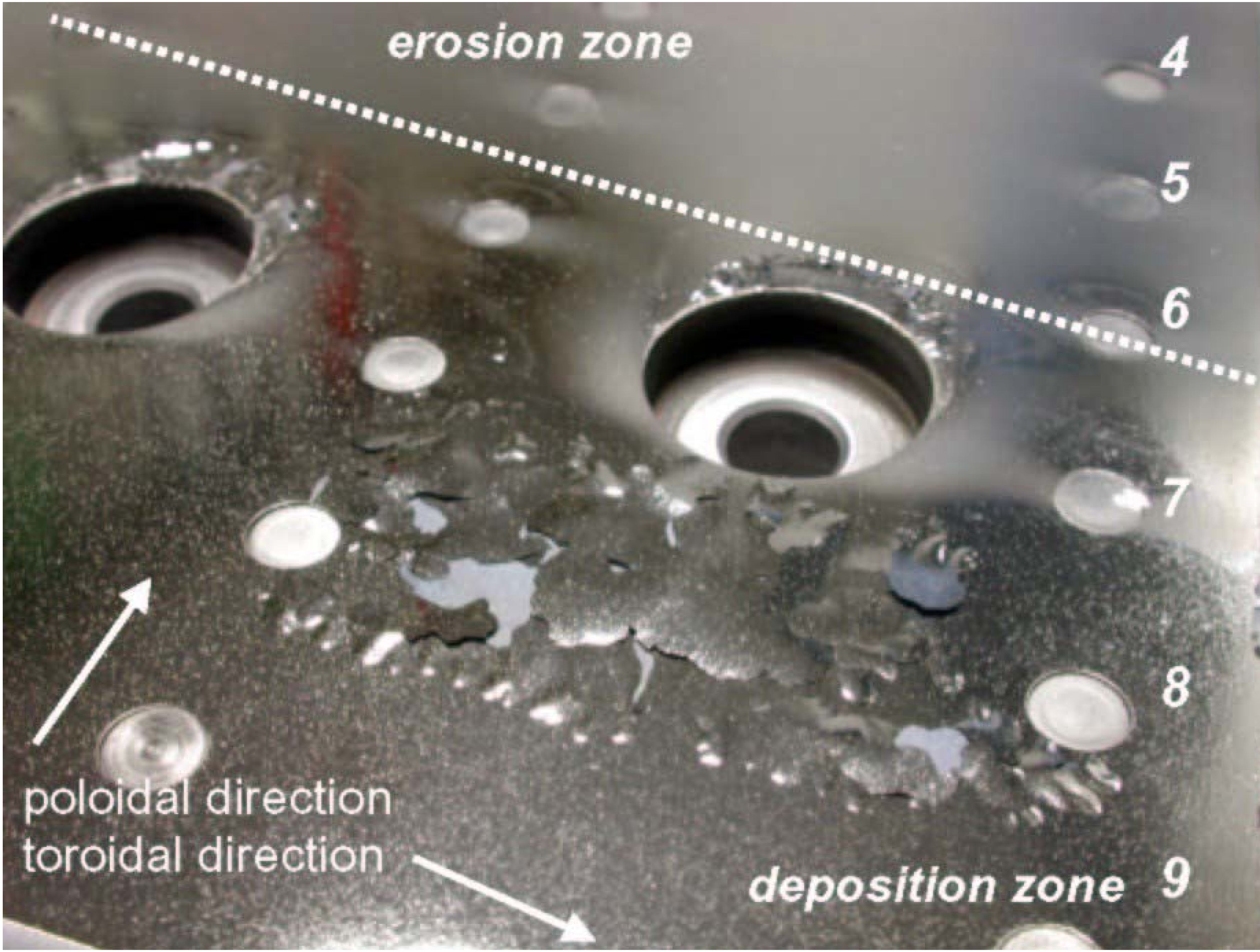
(350 g in ITER)

Erosion and Deposition of Carbon and Tungsten



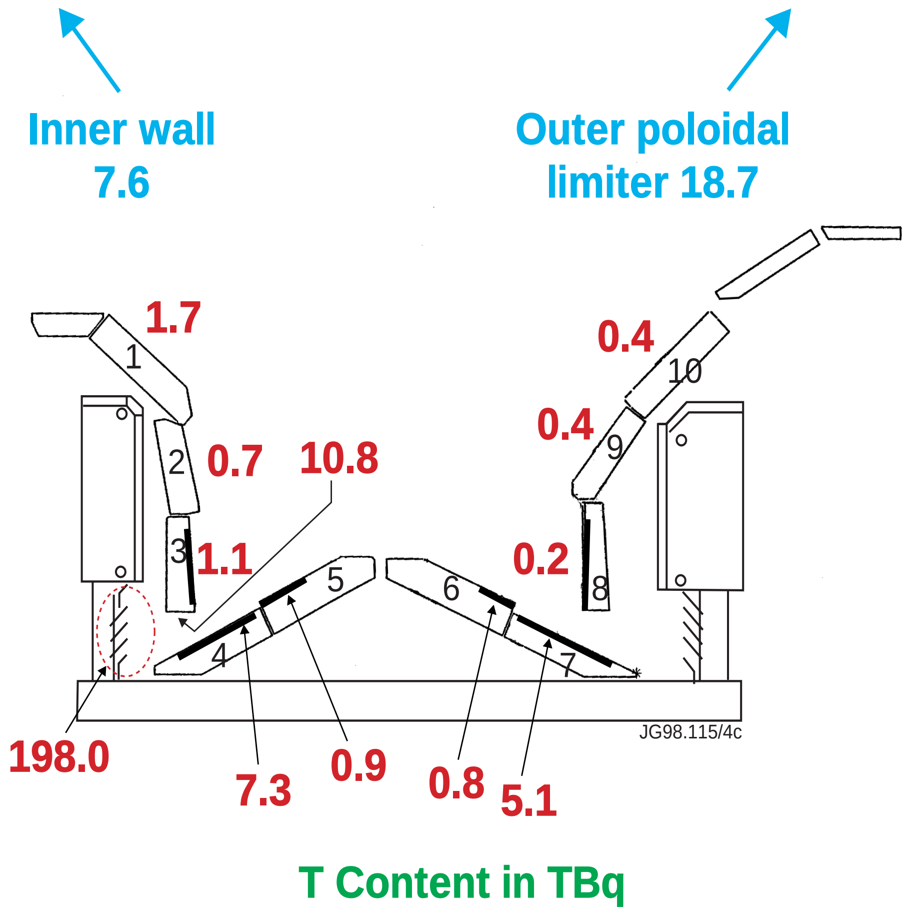
TEXTOR test limiter

co-existence of net-erosion and net-deposition areas



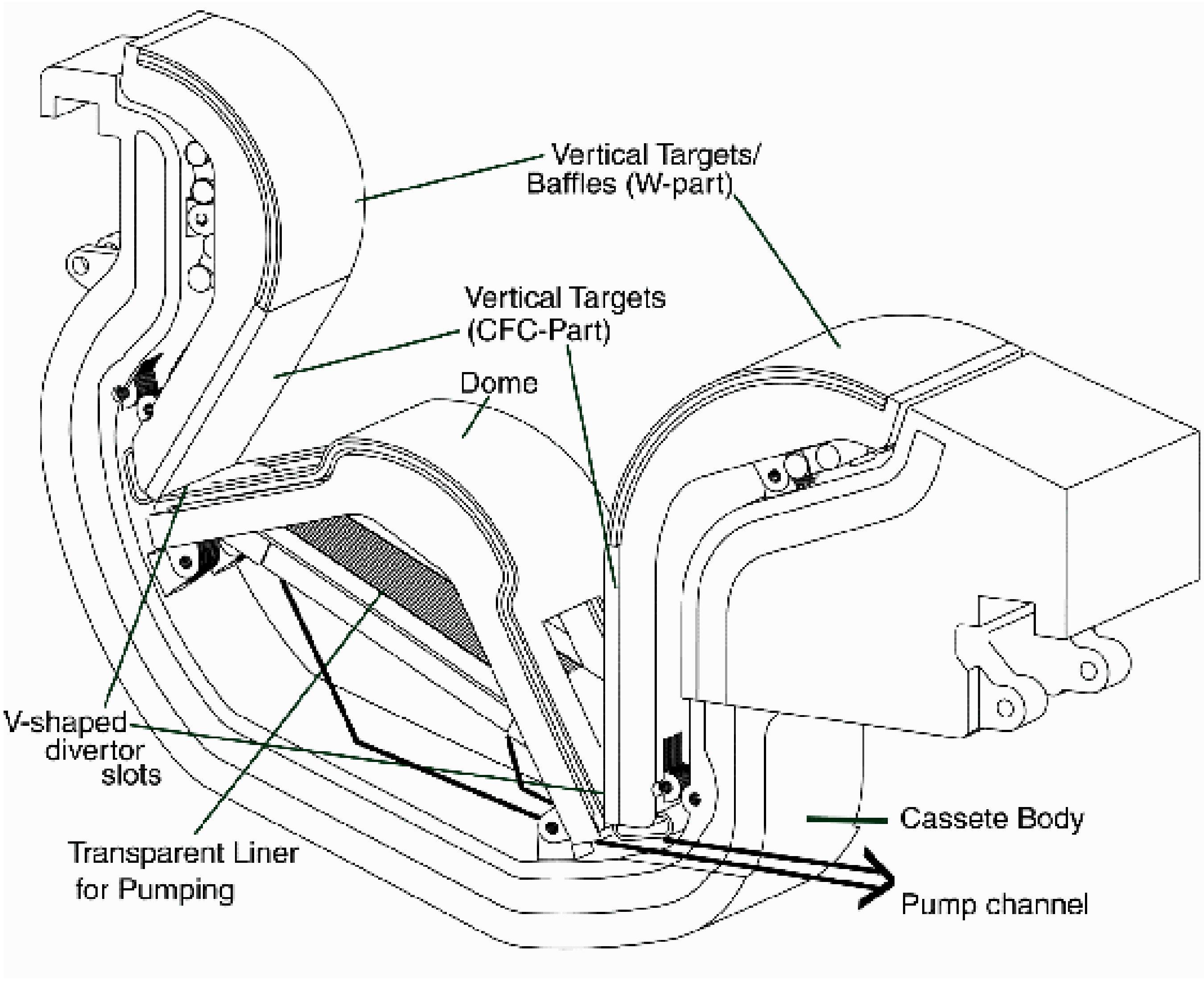
erosion zone
4
5
6
7
8
9
poloidal direction
toroidal direction
deposition zone

JET MKIIA Divertor: Tritium retention

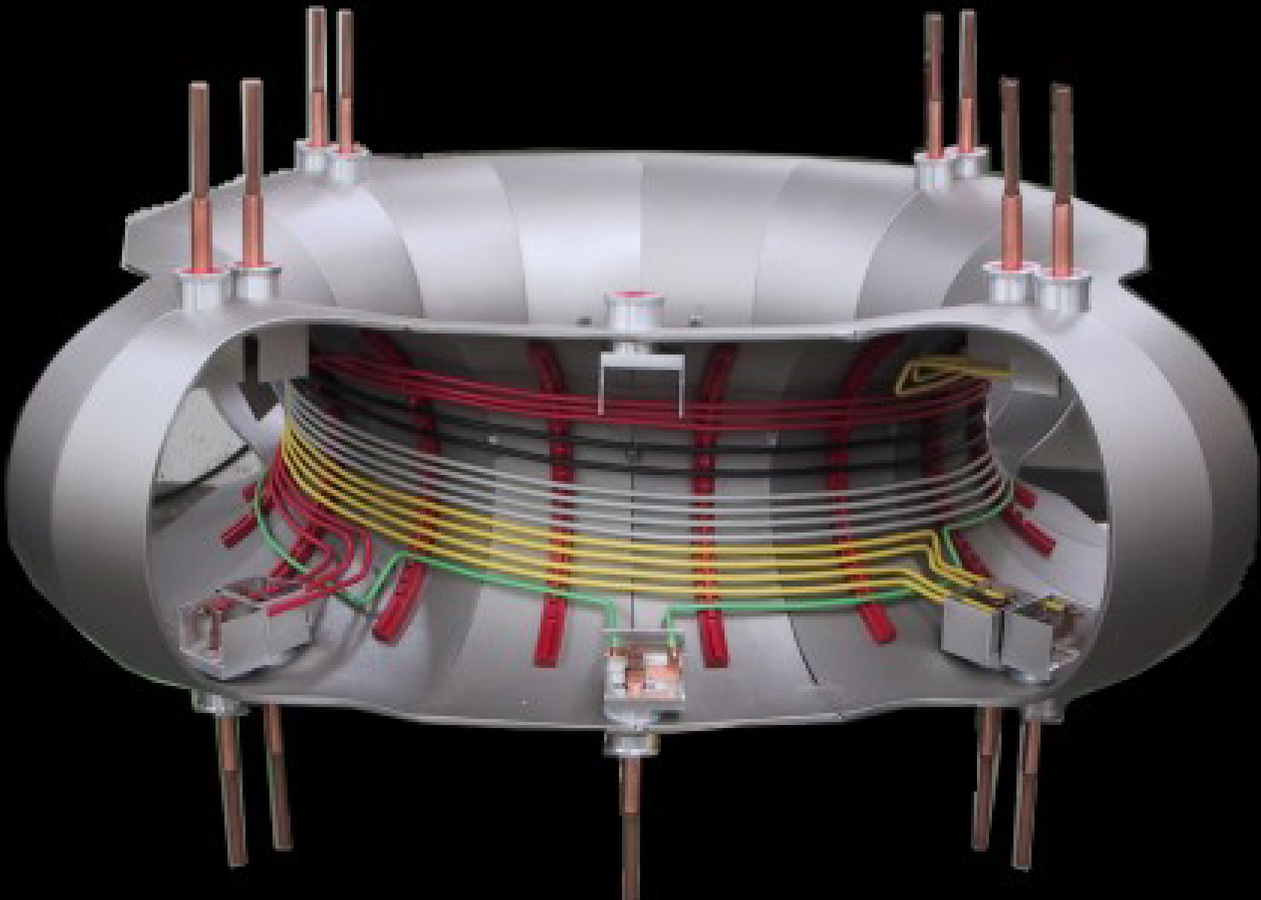


The majority of carbon deposition and tritium retention is on remote areas of louvres and shadowed parts of tiles

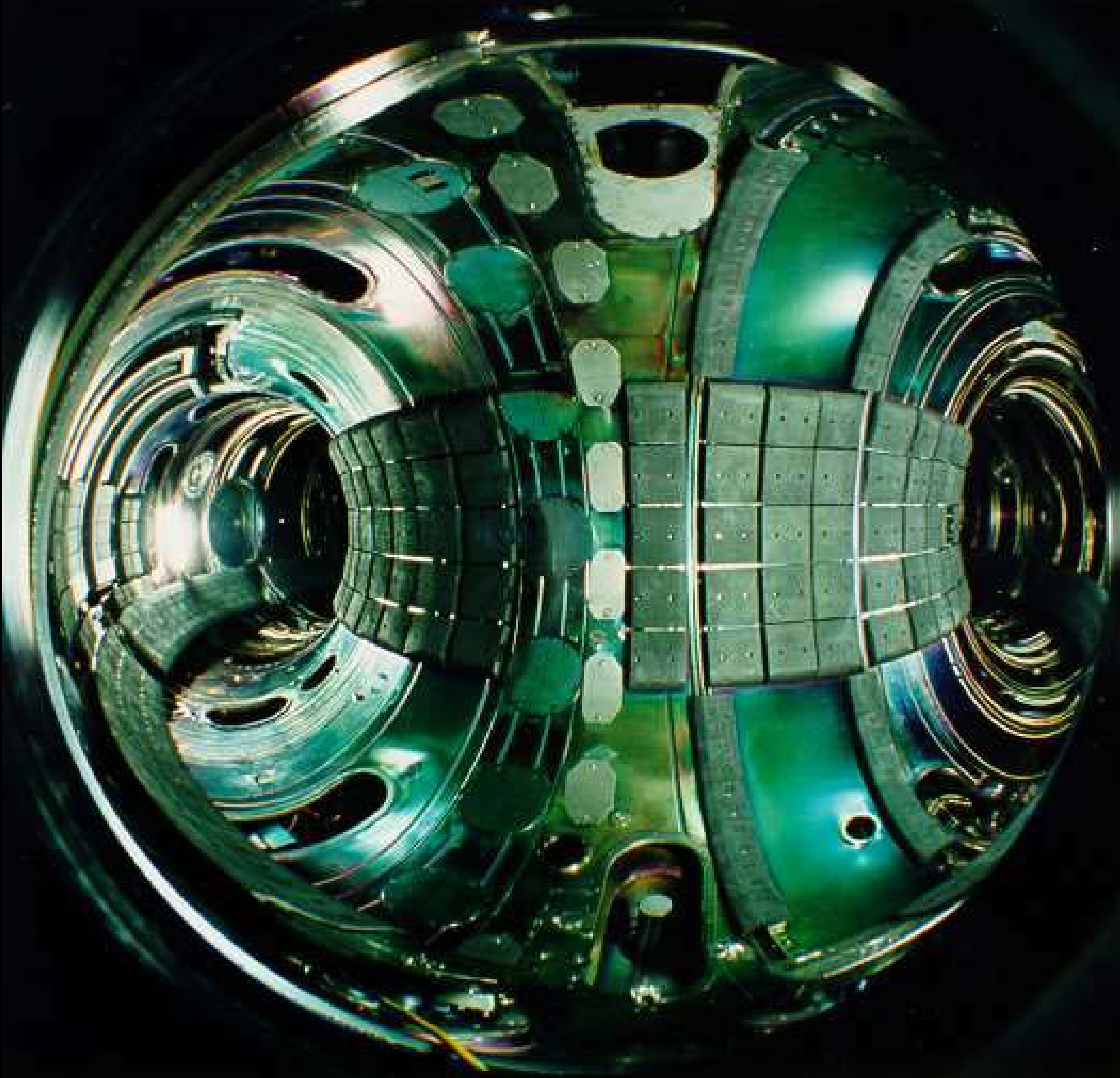
ITER divertor cassette – exchangable by remote handling

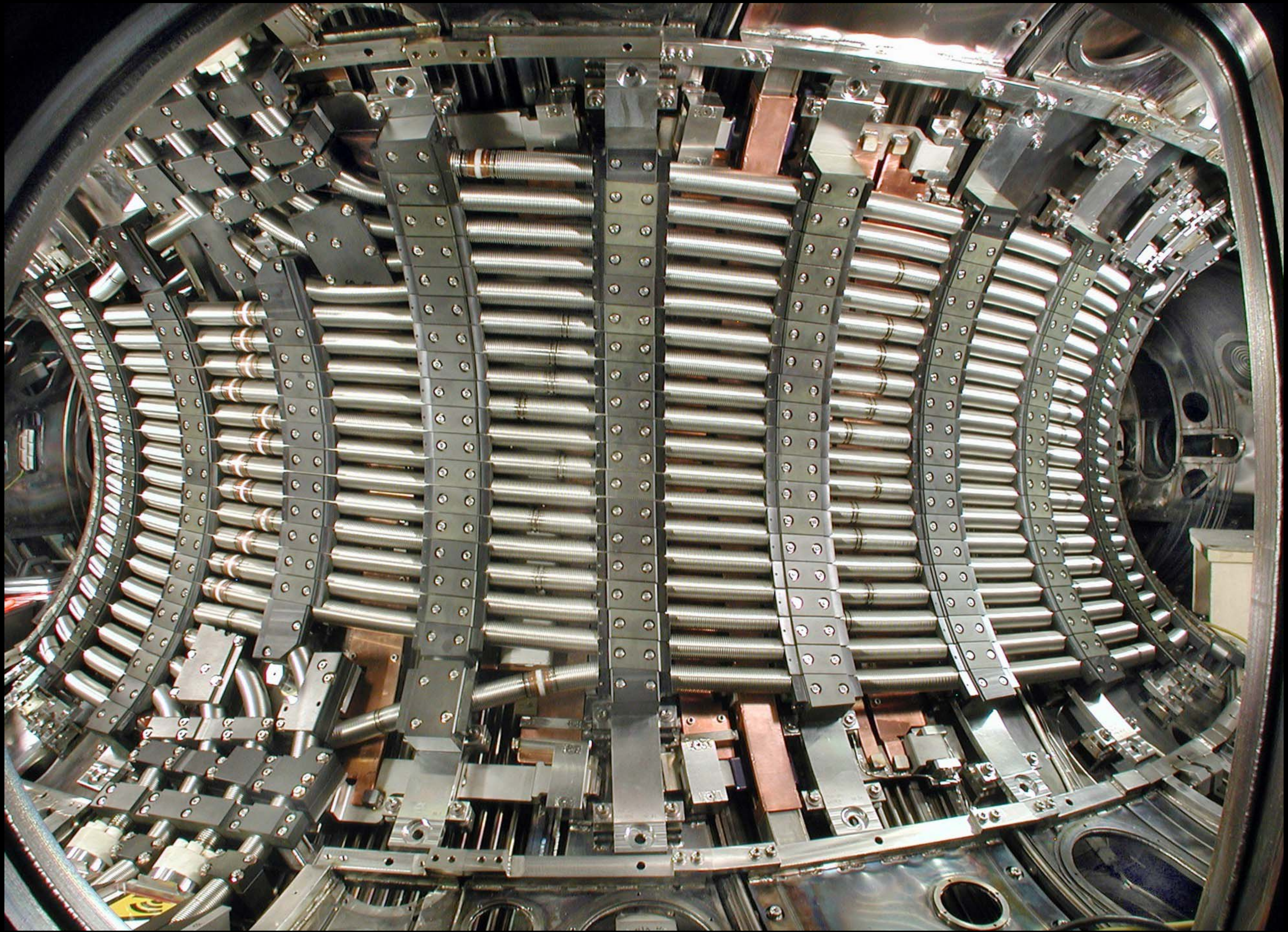


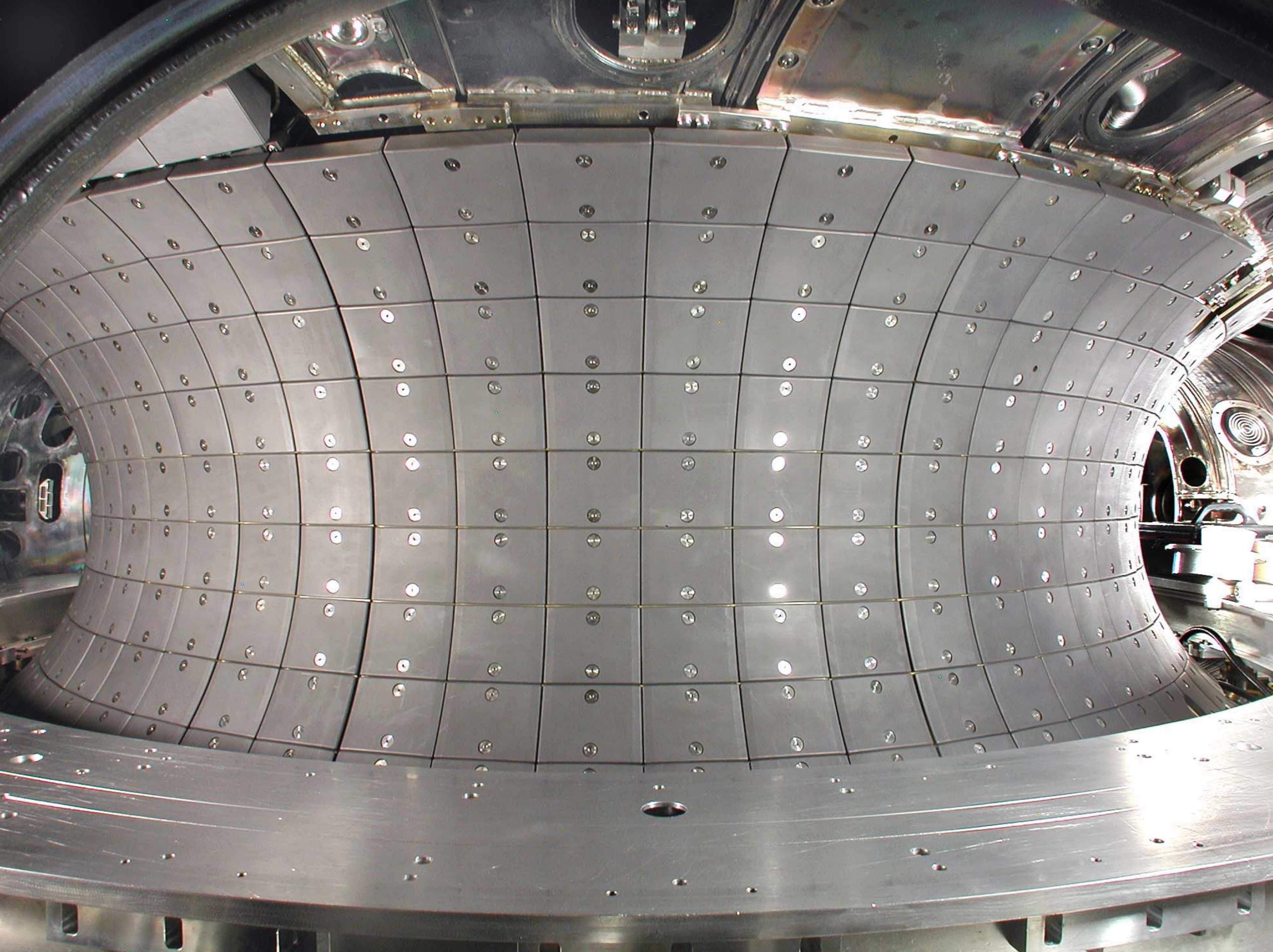
Dynamic Ergodic Divertor in TEXTOR



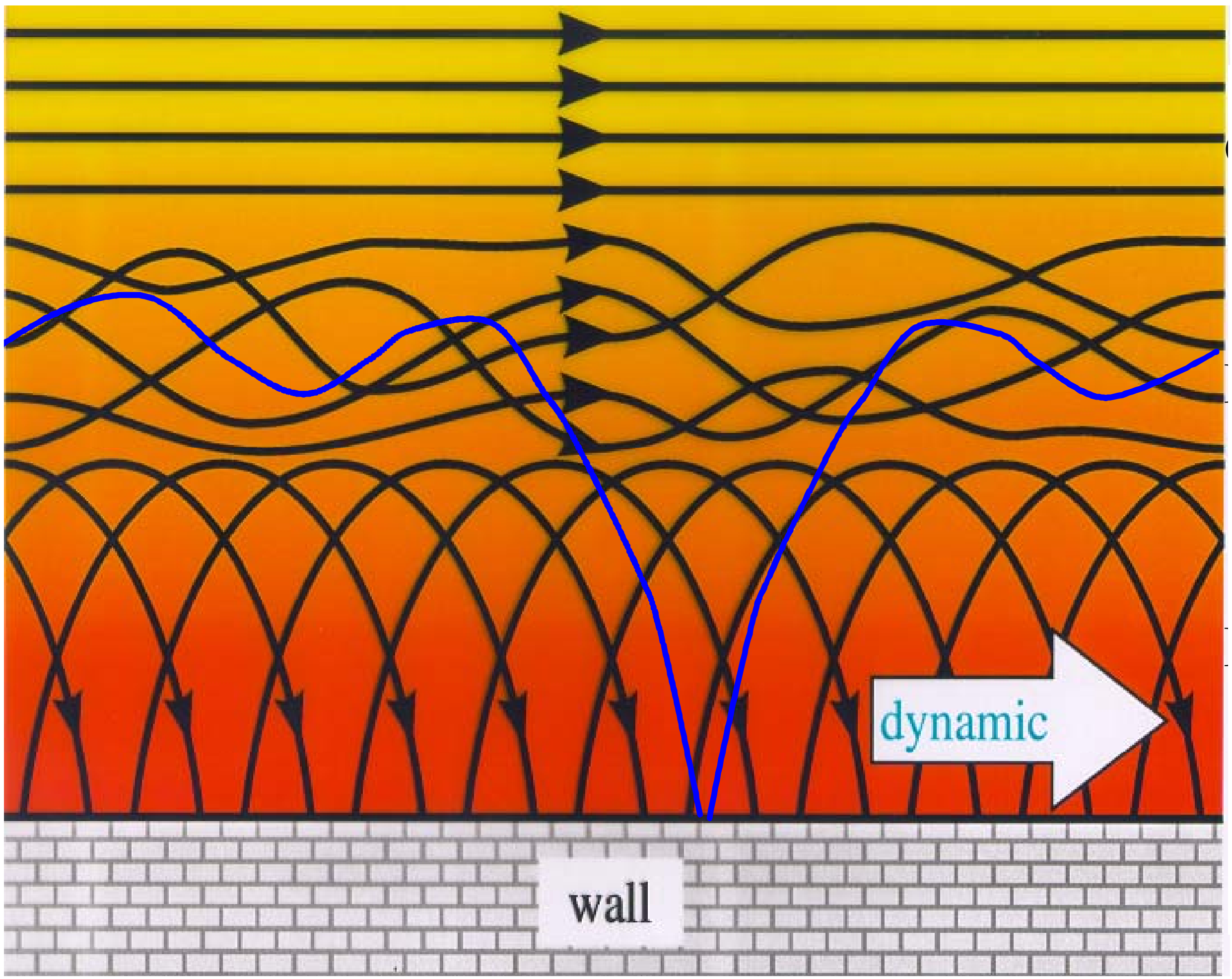
a novel concept to control the plasma boundary







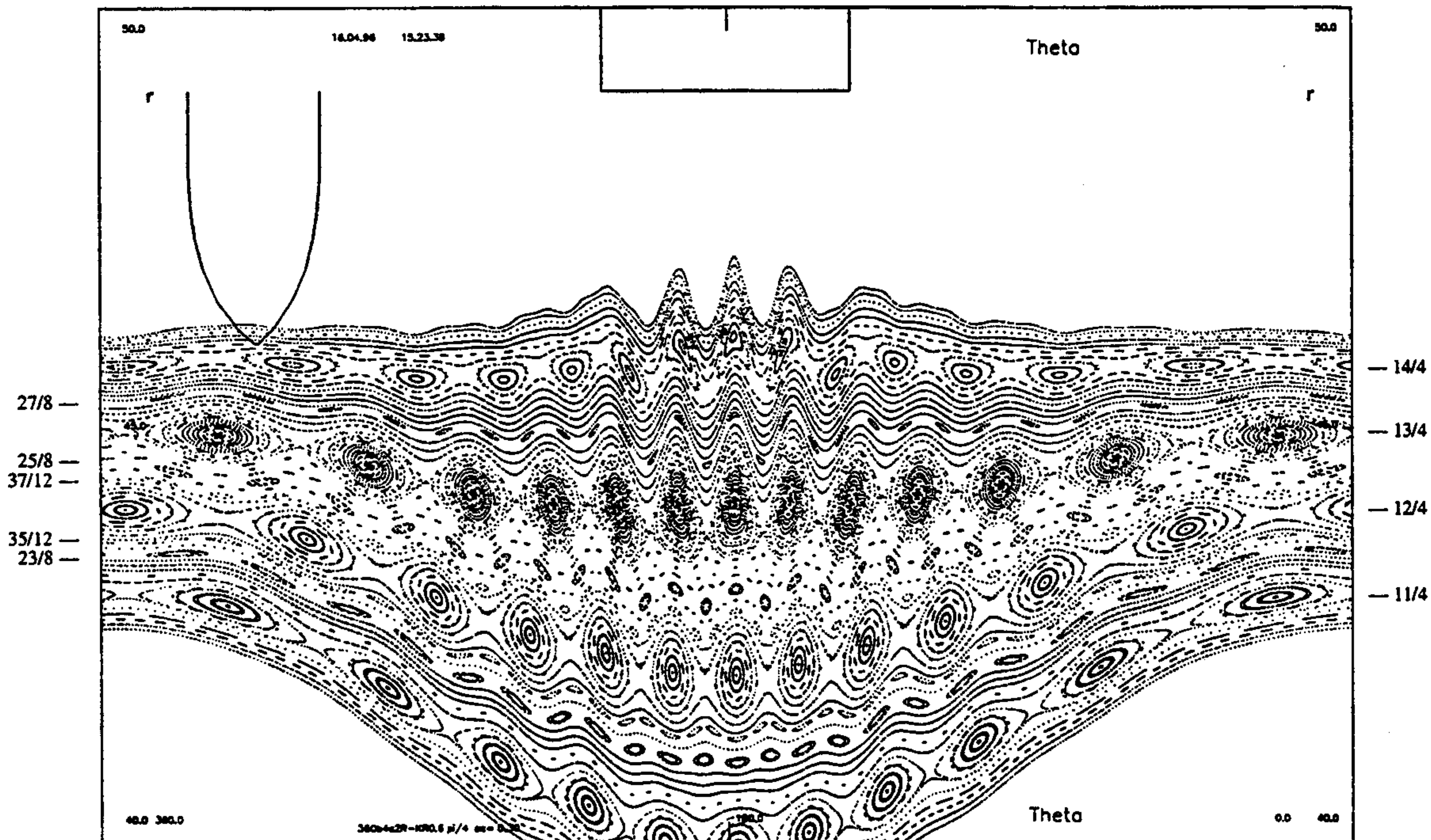
sketch of the magnetic field structure with DED



confinement zone

ergodic zone

laminar zone



Theta
r
r
27/8
25/8
37/12
35/12
23/8
14/4
13/4
12/4
11/4
Theta

Dynamic Ergodic Divertor

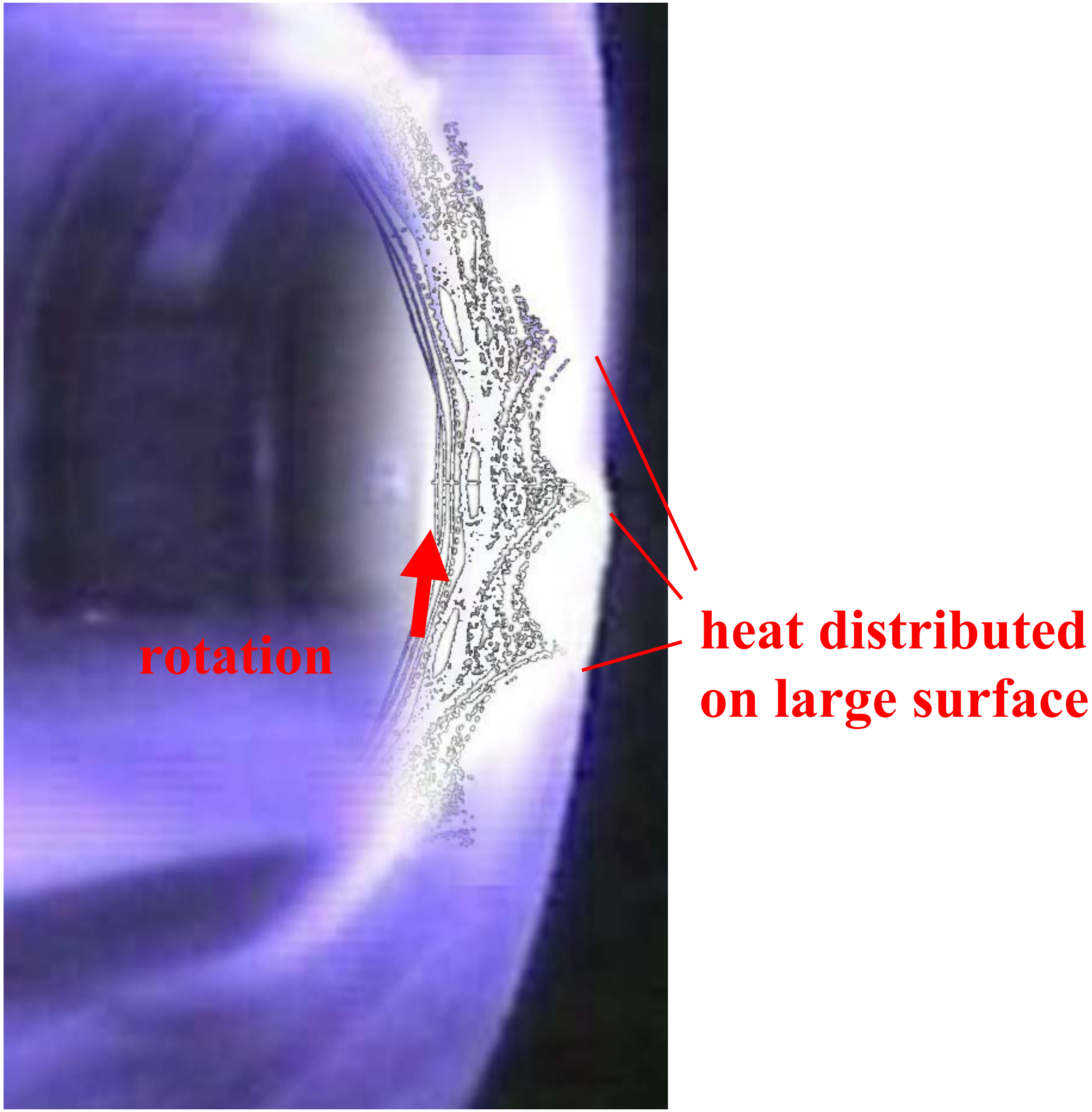
a pioneering experiment
to demonstrate:

improved heat exhaust

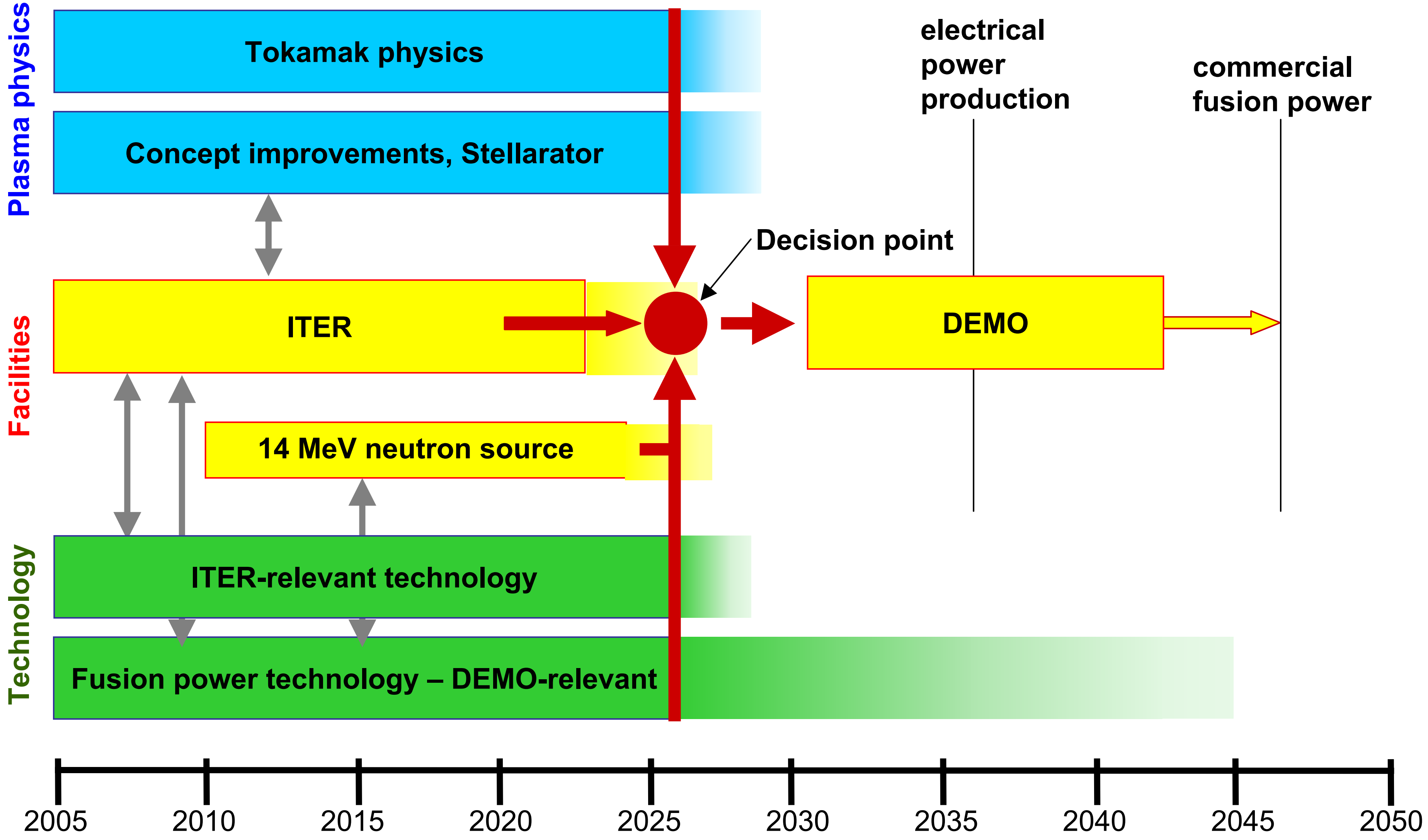
impurity screening

less erosion

improved confinement



Strategy for achieving fusion power



improvement of the fusion triple product compared to transistor integration and accelerator size

$$Q = \frac{\text{fusion power produced}}{\text{external heating power applied}} \sim n_{io} T_{io} \tau_E \quad (\text{for } Q << 5)$$