The long way to steady-state fusion plasma - the superconducting stellarator device Wendelstein 7-X

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Outline of the talk

An Institute of the
Max-Planck Society

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I. Fusion basics

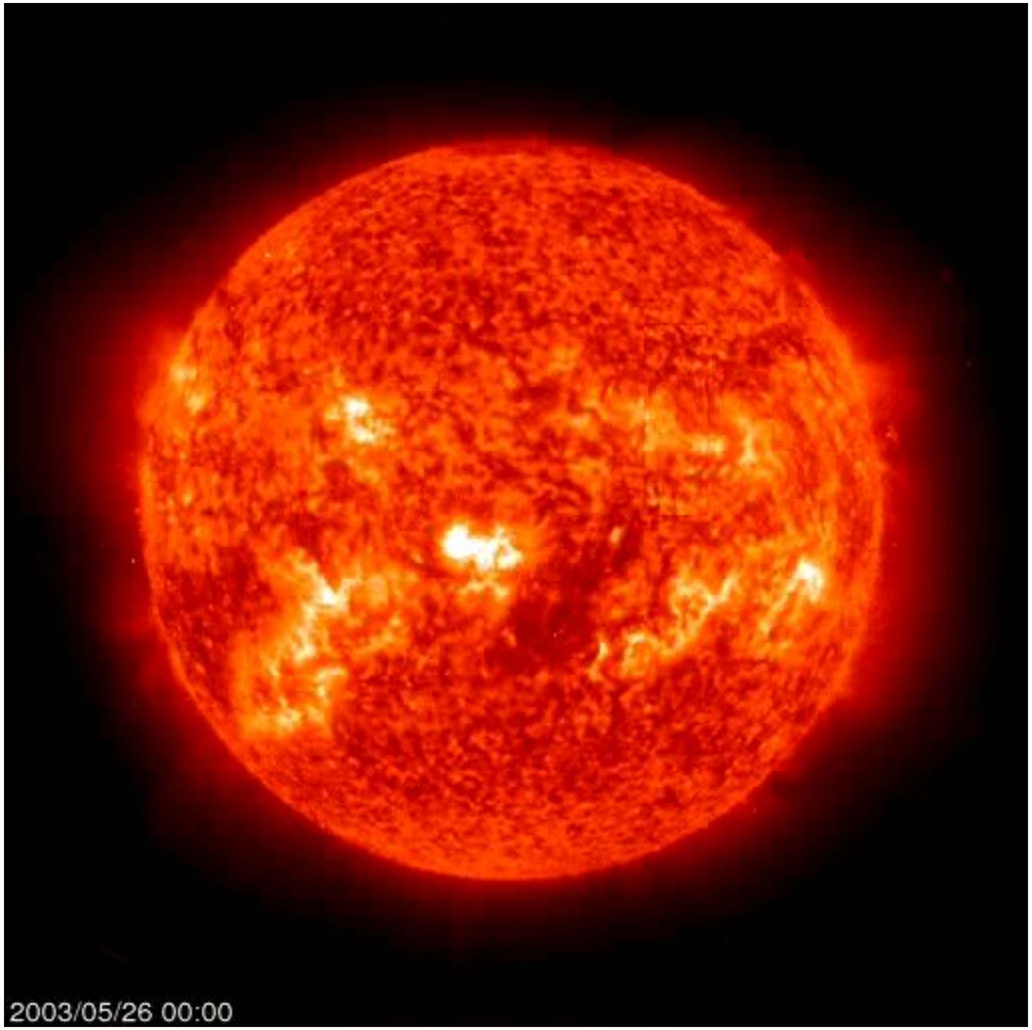
II. The device

III. Construction

IV. Research

The p-p-cycle in the sun

Credits to ESA, NASA, SOHO – EIT Consortium



power generation in the sun

fusion of light nuclei

p-p cycle $\rightarrow$ ^{4}He

$\downarrow$

difference in binding energy

$\downarrow$

energy surplus

- **plasma state (**H, He, Fe**)**
- **core temperature** ~ 1.3 keV
- **extremely small reaction rates**
- **gravitational confinement** $m_{\odot}$

The p-p reactions in the sun

weak interaction → $p + p \rightarrow d + e^+ + \nu_e$ ← small reaction rates

$p + d \rightarrow {}^3He + \gamma$

$^3He + {}^3He \rightarrow {}^4He + 2p$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$

$p + {}^7Li \rightarrow {}^4He + {}^4He$

$p + {}^7Be \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

branch I (85 %)

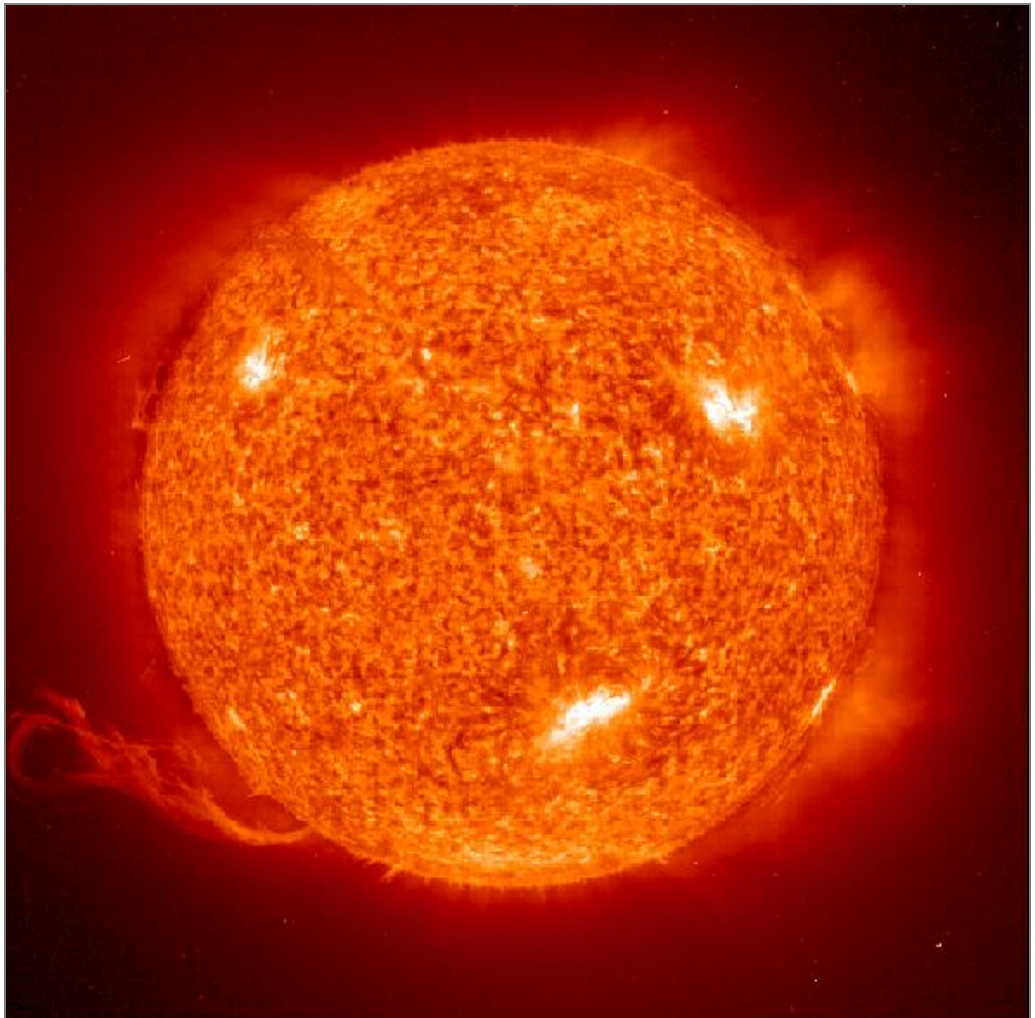
branch II (15 %)

branch III (0.02 %)

- neutrinos observed on earth

p-p fusion on earth?

Credits to ESA, NASA, SOHO – EIT Consortium



conditions in the sun core

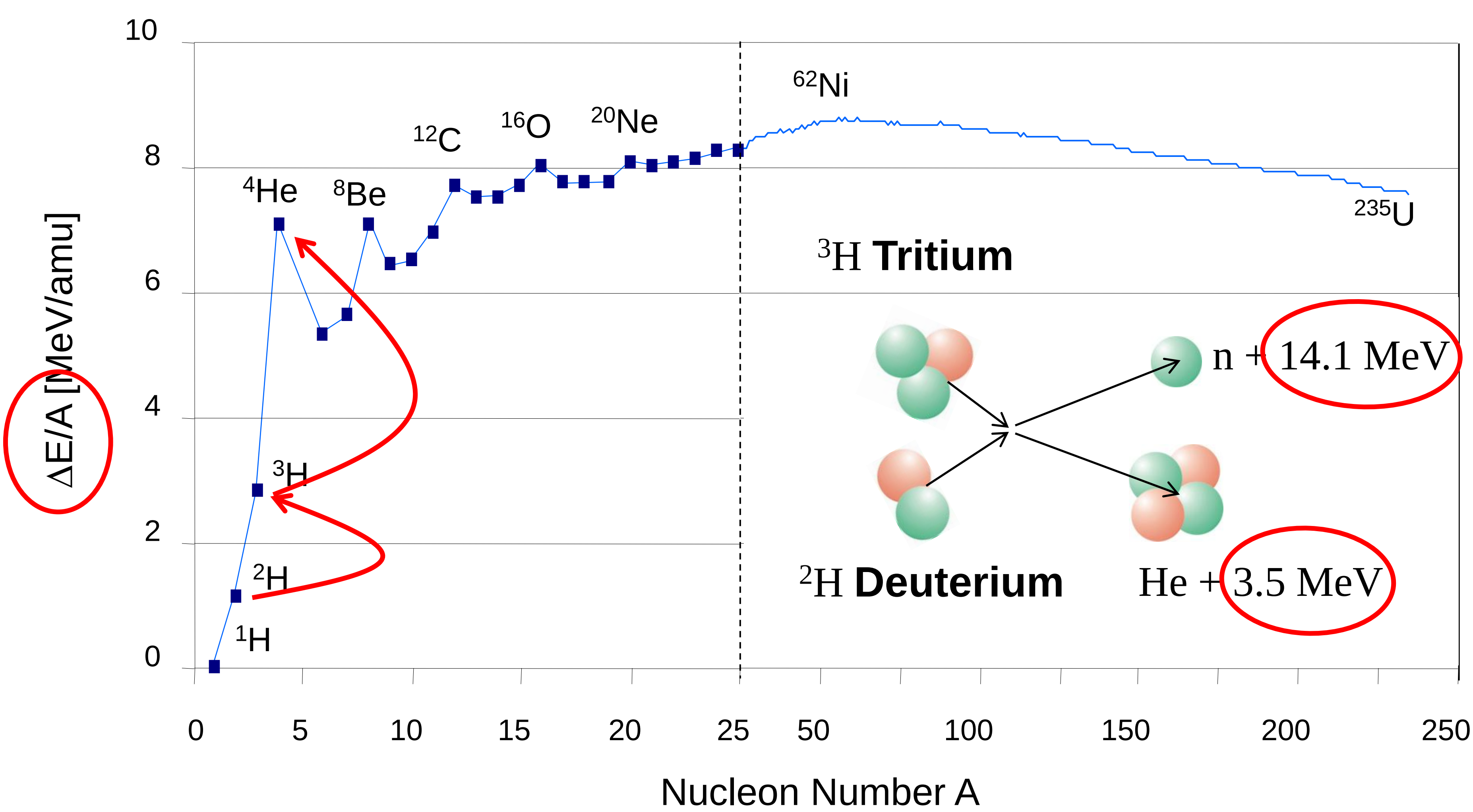
- core plasma density ~ 10^{31} m^{-3}
- core ion temperature ~ 1.5 keV
- plasma pressure ~ 2×10^{16} Pa
- total mass $m_{\odot} = 3.3 \times 10^5\ m_{\oplus}$
- reaction rate $\langle \sigma v \rangle = 10^{-43}$ cm^3/s

⇩

no!

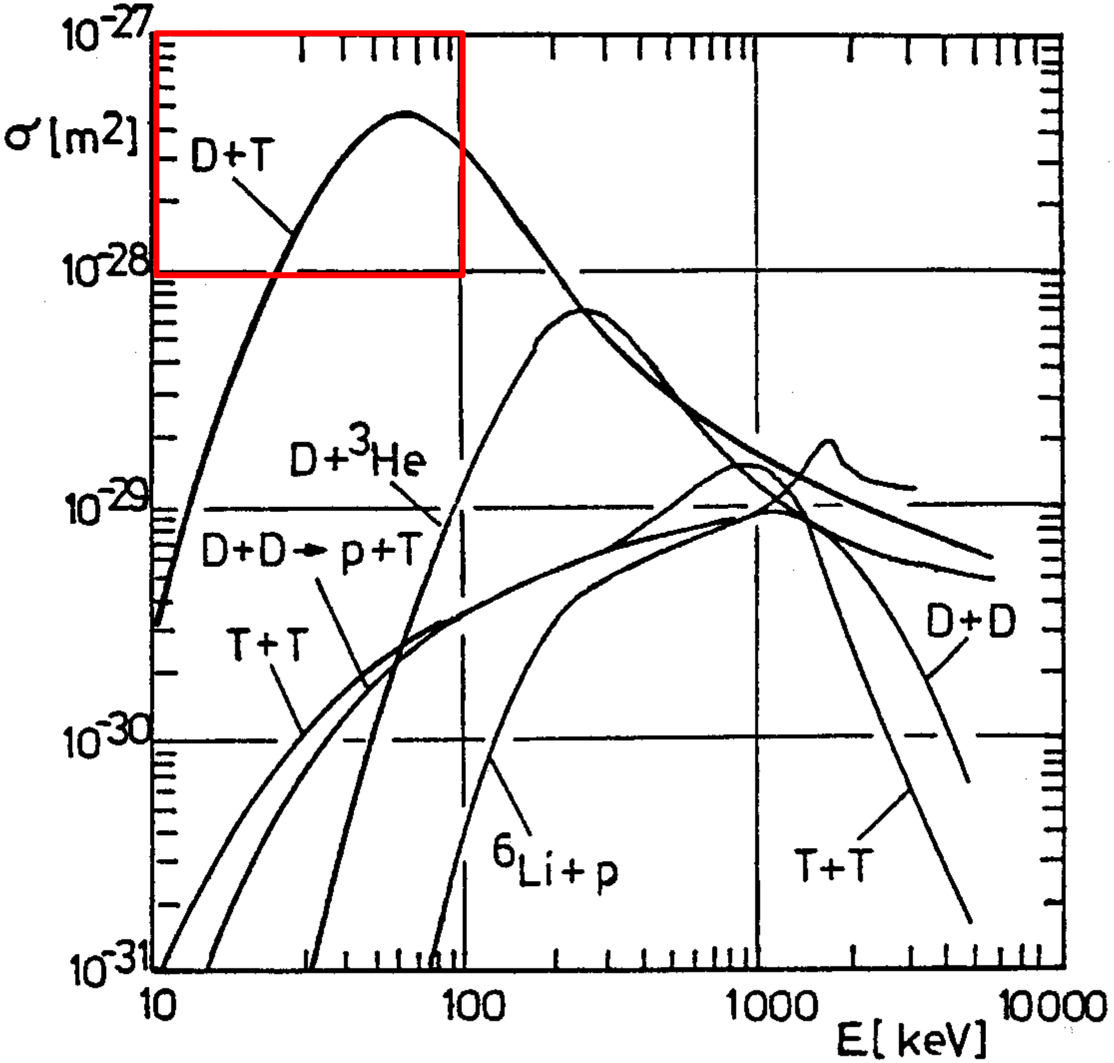
but

D-T nuclear fusion – binding energy



$$_1D^2 + {}_1T^3 \rightarrow {}_2He^4\ (3.5\ MeV) + {}_0n^1\ (14.1\ MeV)$$

Fusion collision cross sections

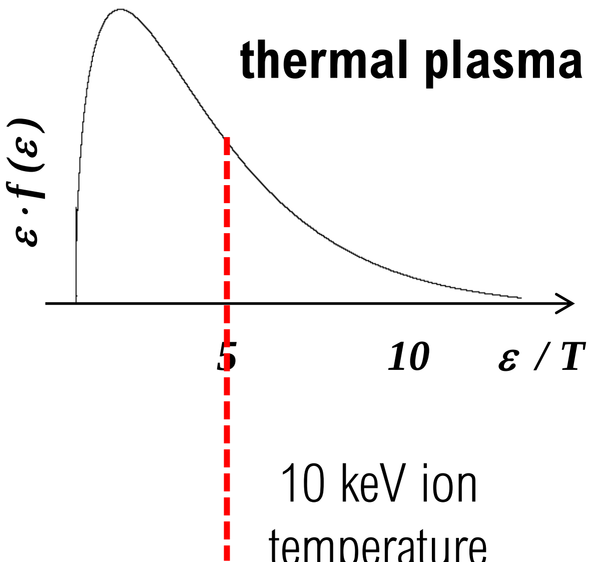


$D + D \rightarrow {}^{3}He + n + 3.27\ MeV$

$D + D \rightarrow T + p + 4.03\ MeV$

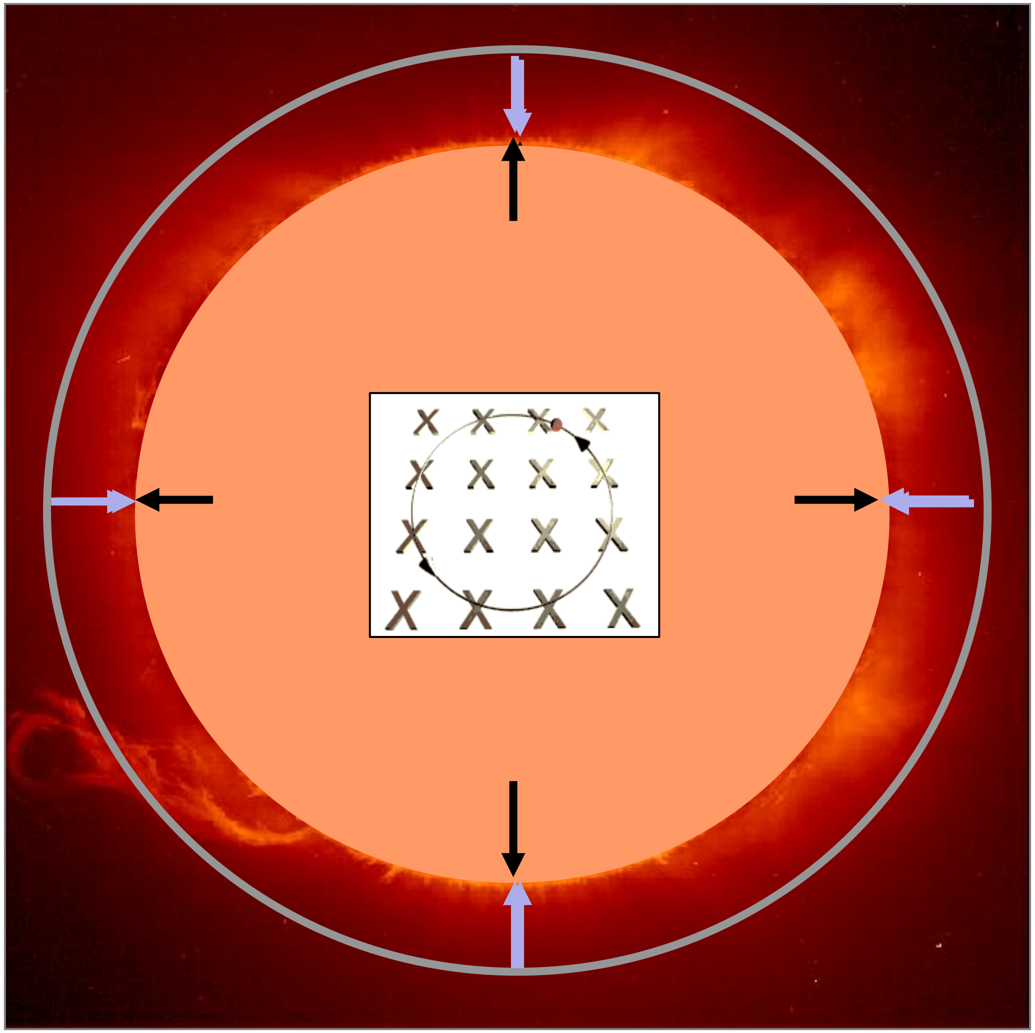
$D + T \rightarrow {}^{4}He + n + 17.59\ MeV$

$D + {}^{3}He \rightarrow {}^{4}He + p + 18.35\ MeV$



σ for p + p fusion 20 orders of magnitude below

Plasma confinement



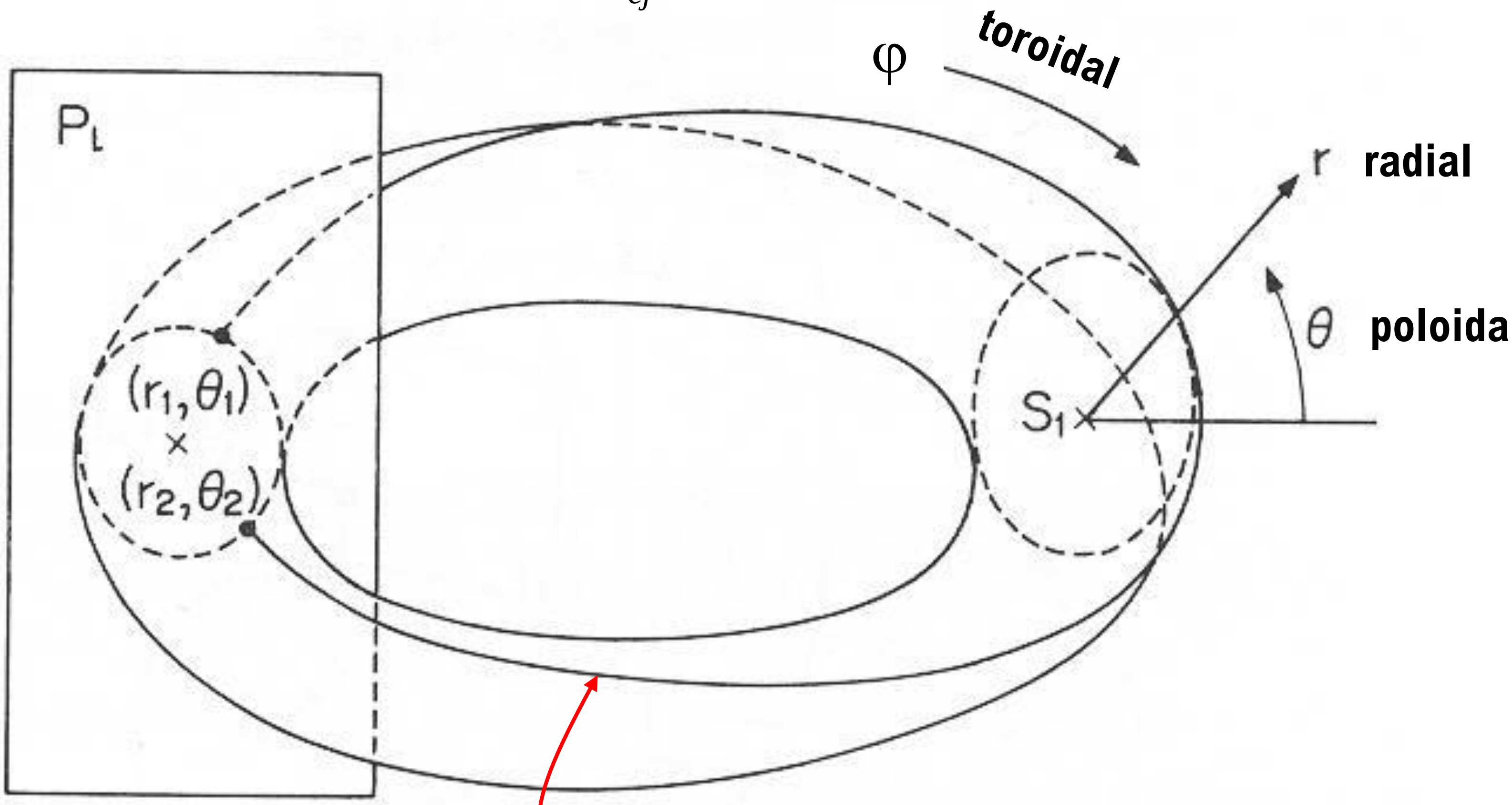
- **high density solar plasma**
- **high plasma pressure**
- **sun's gravitation field**
- **gravitational confinement**

$$\beta = \frac{p_{kin}}{p_{mag}} = \frac{n k_B T}{B^2 / (2\mu_0)}$$

- **evacuated plasma vessel**
- **low density fusion plasma**
- **plasma pressure** O(1 bar)
- **magnetic field** $\rightarrow$ **Lorenz force**
- **magnetic confinement**

Toroidal magnetic fields

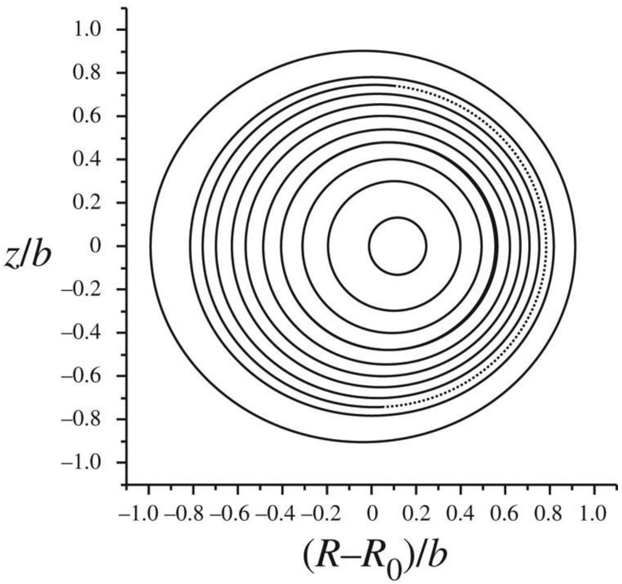
radial drift $v_R + v_{\nabla B} = \dfrac{v_\parallel^2 + v_\perp^2/2}{\omega_{cj}} \dfrac{\vec{B} \times \nabla \vec{B}}{B^2}$ **→ charge separation**

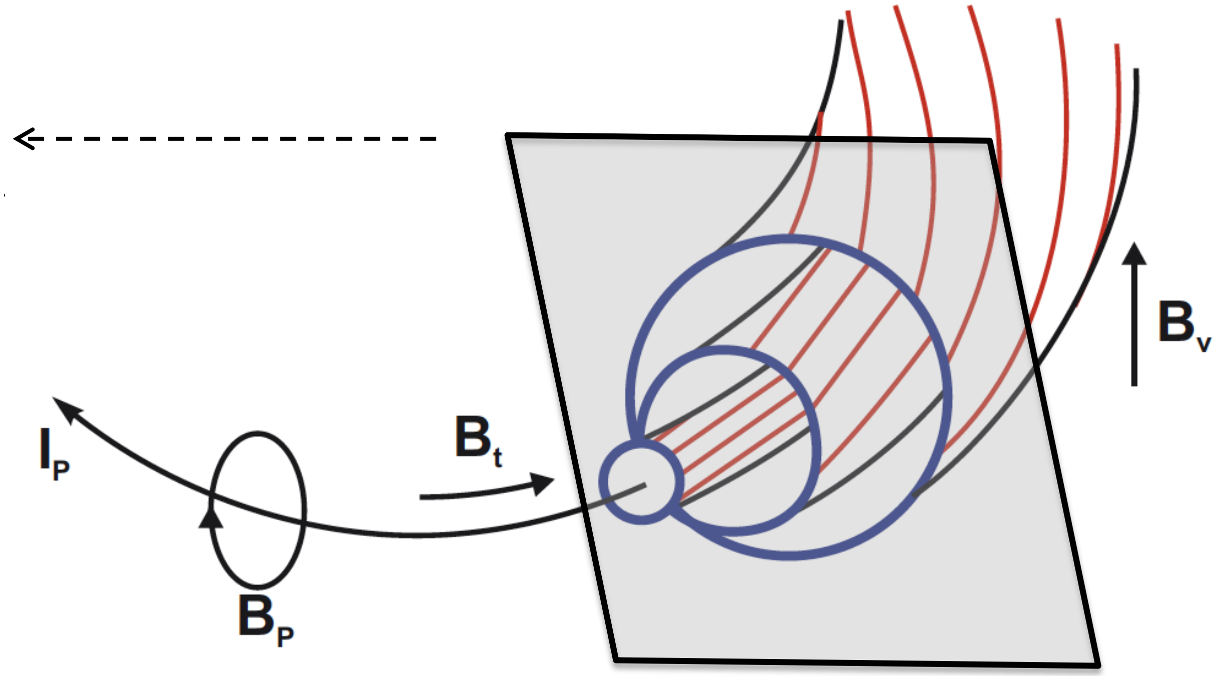


Poincaré section

toroidally twisted magnetic field line:
rotational transform $\iota / 2\pi = \langle \Delta(\theta_1, \theta_2) \rangle$

Closed magnetic flux surfaces





Poincaré section

Hamiltonian form

$$\frac{d\psi}{d\varphi} = -\frac{\partial H}{\partial \zeta}$$

$$\frac{d\zeta}{d\varphi} = \frac{\partial H}{\partial \psi}$$

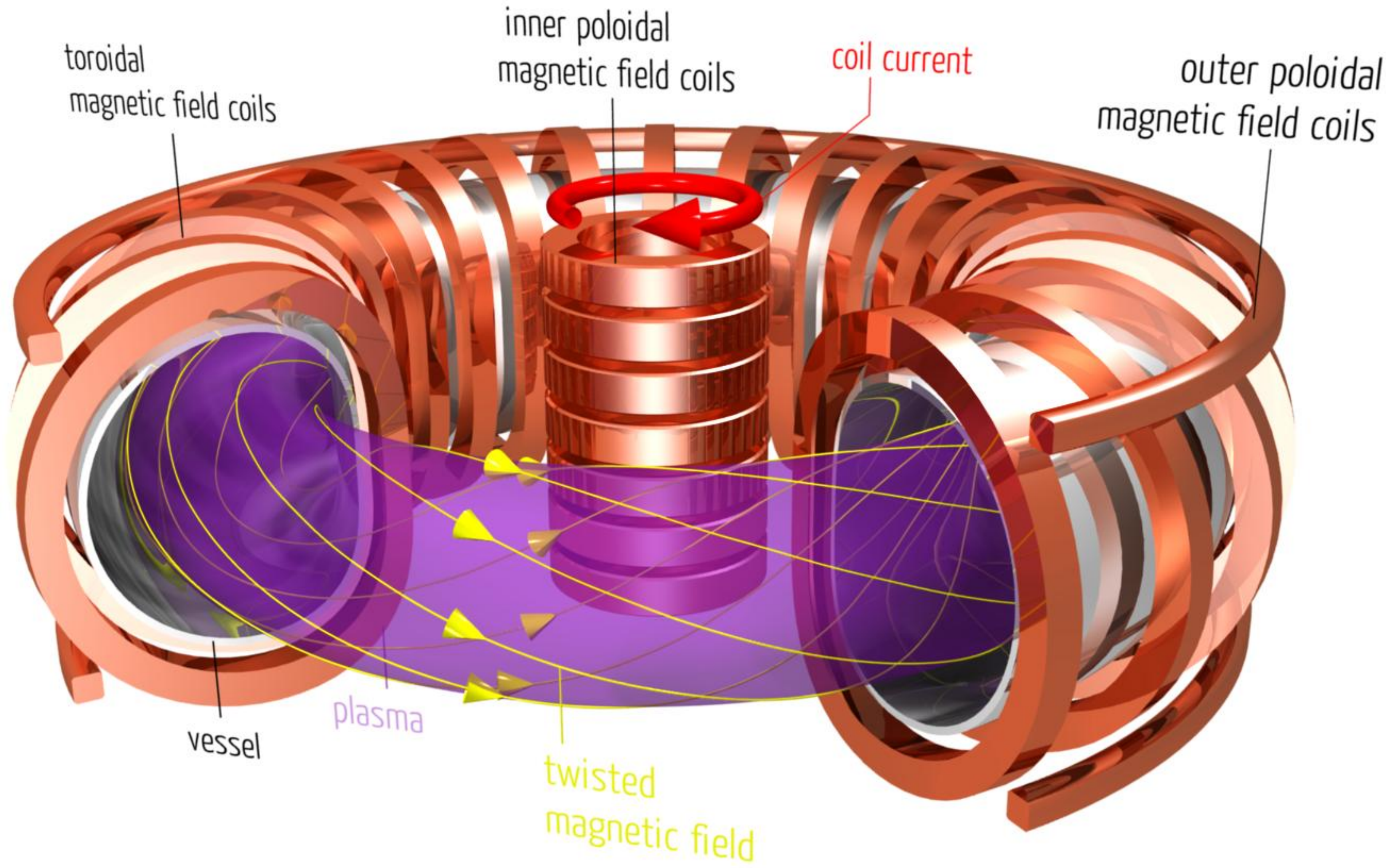
ψ toroidal flux

ζ canonical angle

The tokamak device

Tokamak (1951 Sacharov und Tamm)

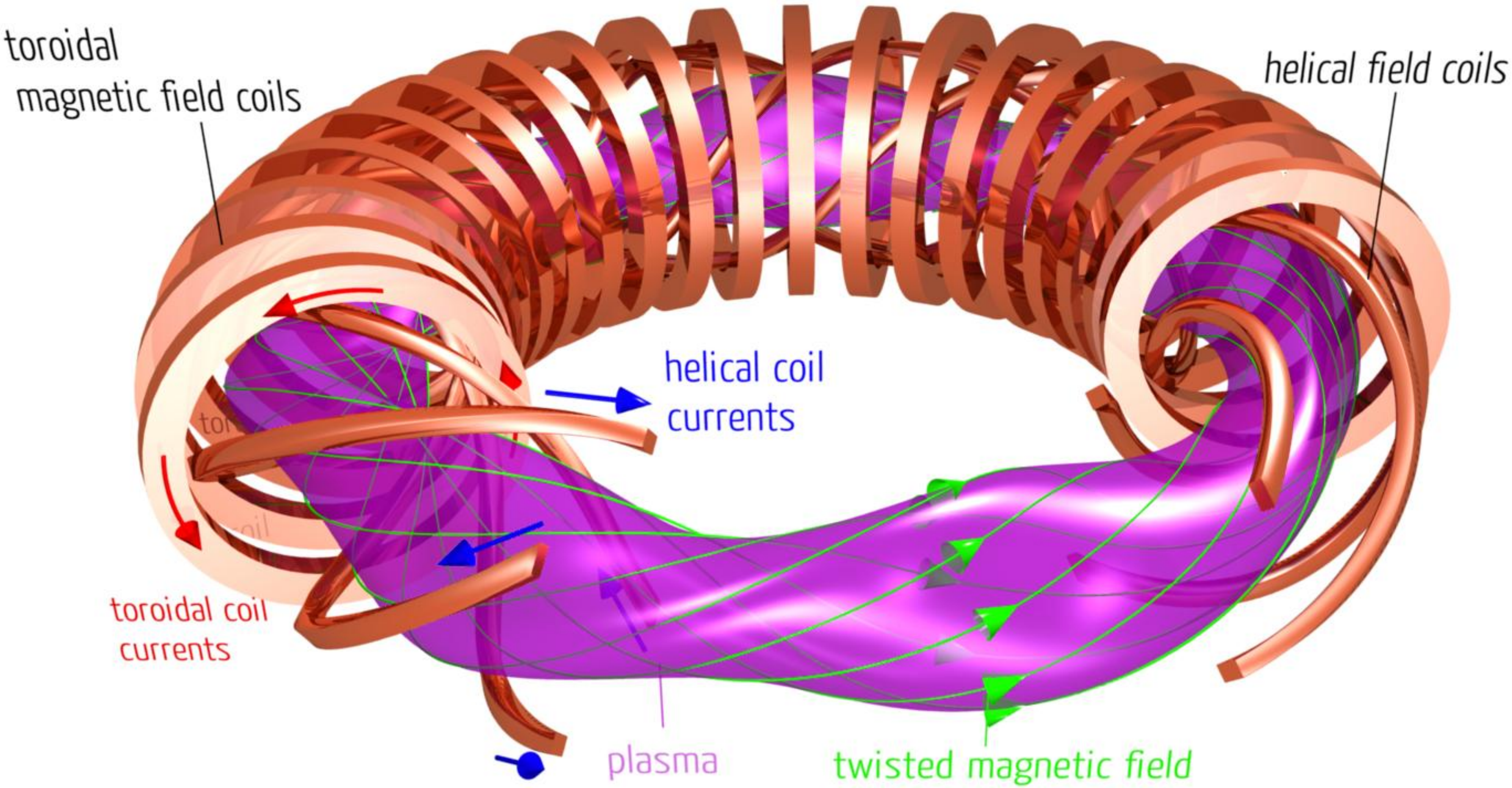
тороидальная камера в магнитных катушках
„toroidal chamber in magnets“



The stellarator device

Stellarator (1951 Spitzer)

Stella = star
„bringing the star“

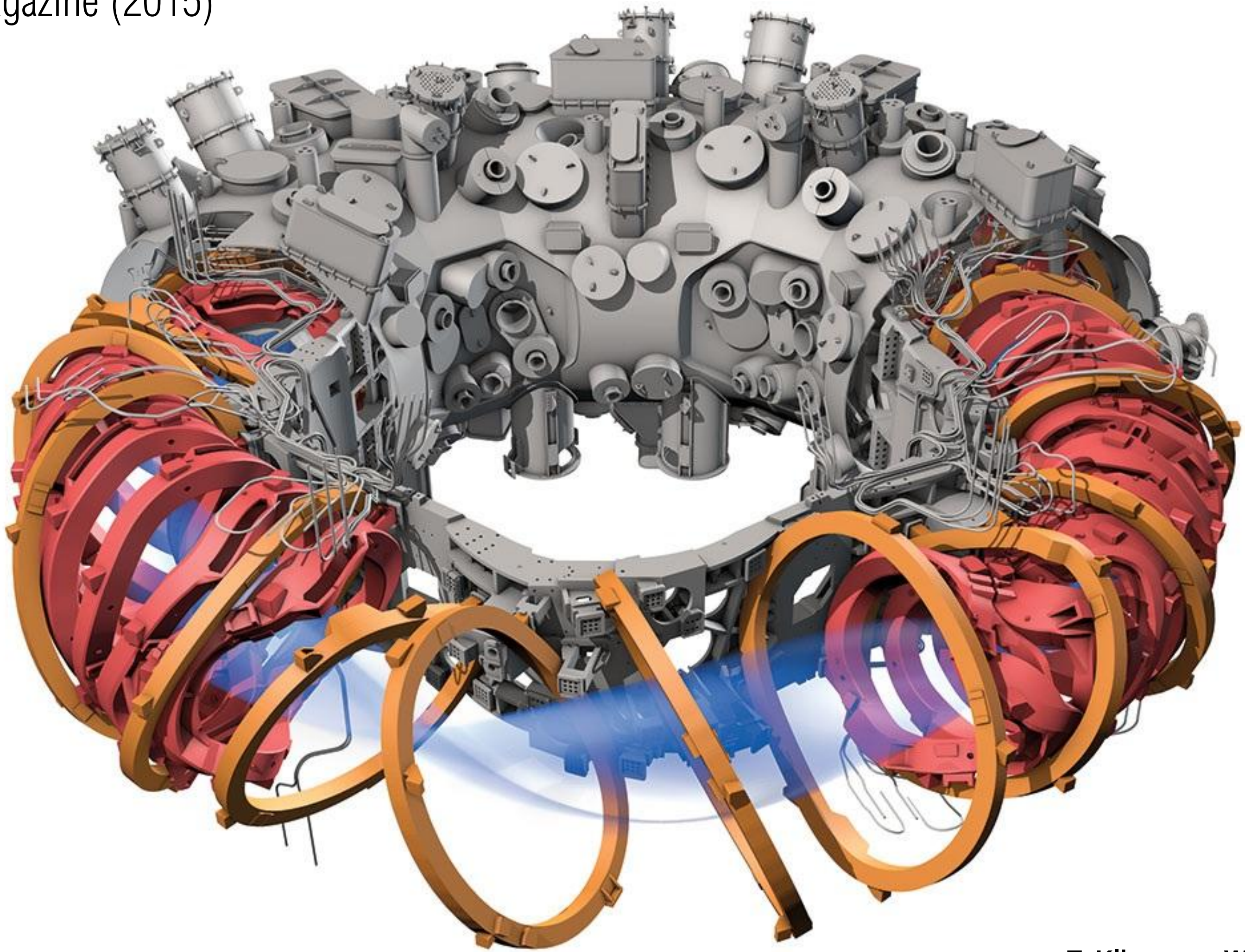


Stellarator now – how and why?

optimized stellarator (2015)

„Wendelstein 7-X“

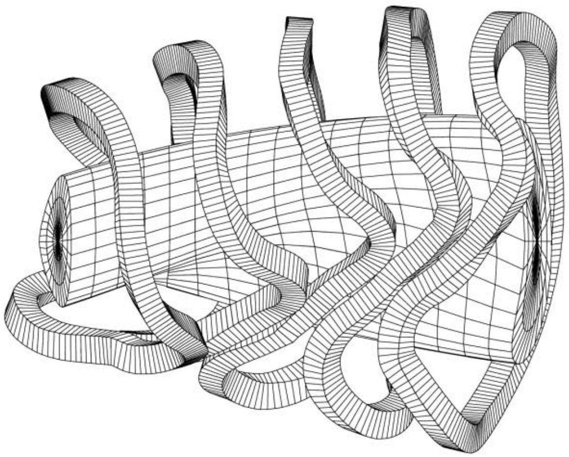
cf. Science Magazine (2015)

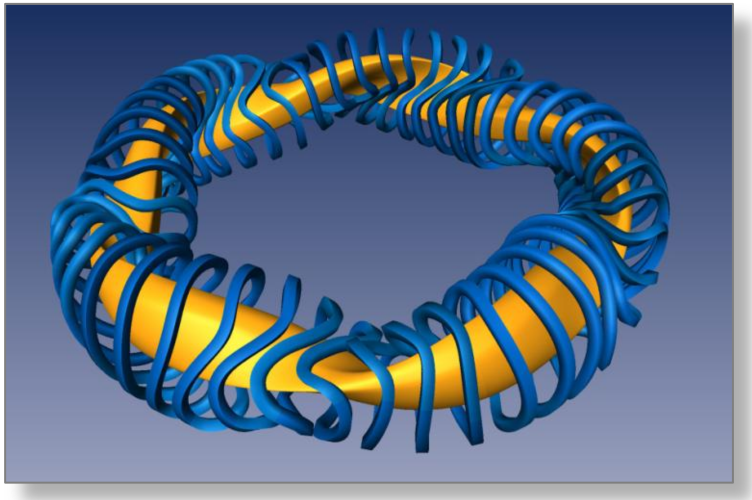


Physics optimisation

seven optimisation criteria

1. high quality of vacuum magnetic surfaces
2. good finite equilibrium properties @ $<\beta> = 5\%$
3. good MHD stability properties @ $<\beta> = 5\%$
4. reduced diffusive (neoclassical) transport
5. small equilibrium (bootstrap) current
6. good collisionless fast particle confinement
7. good modular coil feasibility



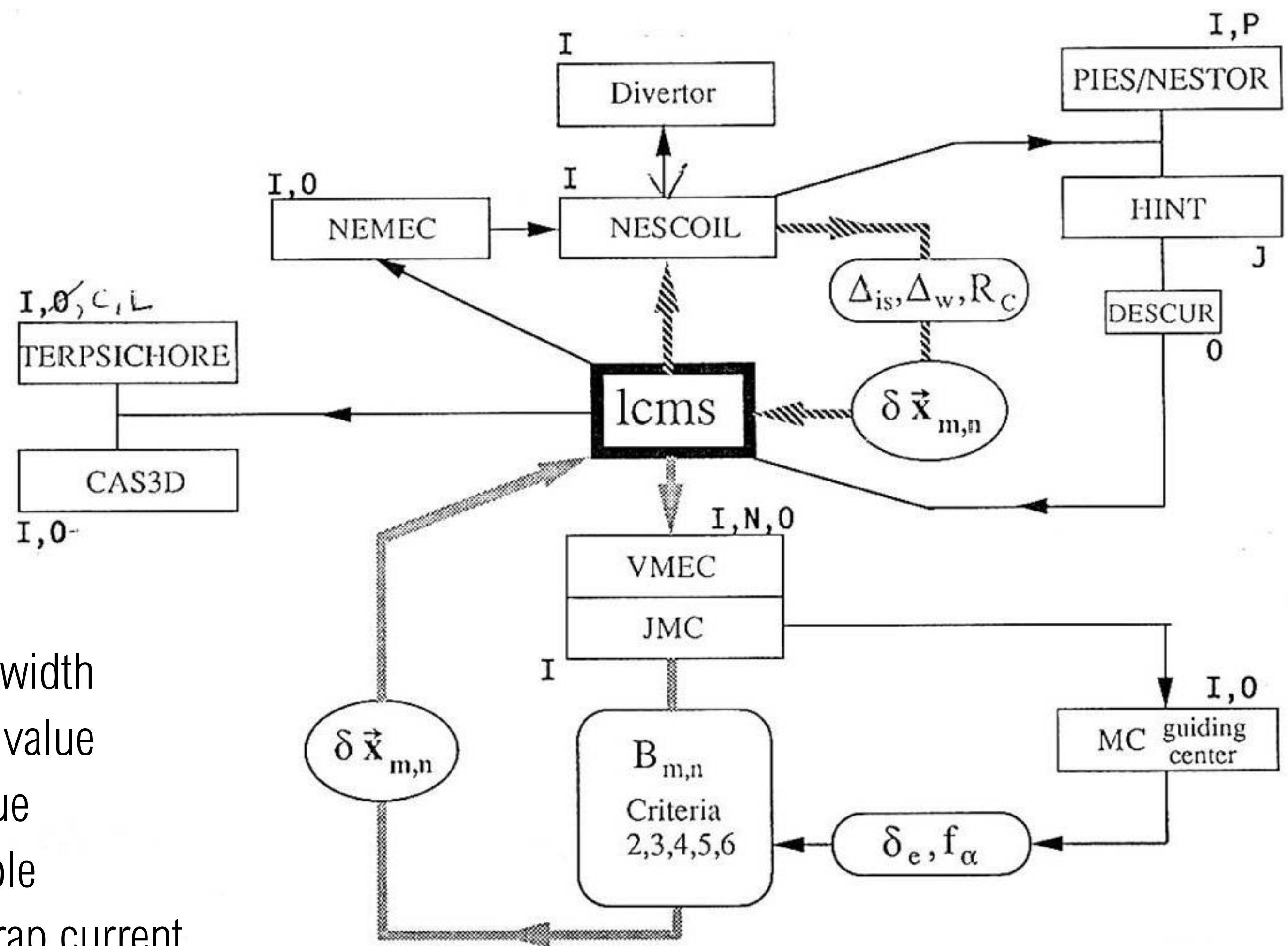


3d numerical codes

- vacuum field and coils
- MHD equilibrium
- MHD linear stability
- neoclassical transport
- Monte Carlo test particle
- edge and divertor

Example of a code map

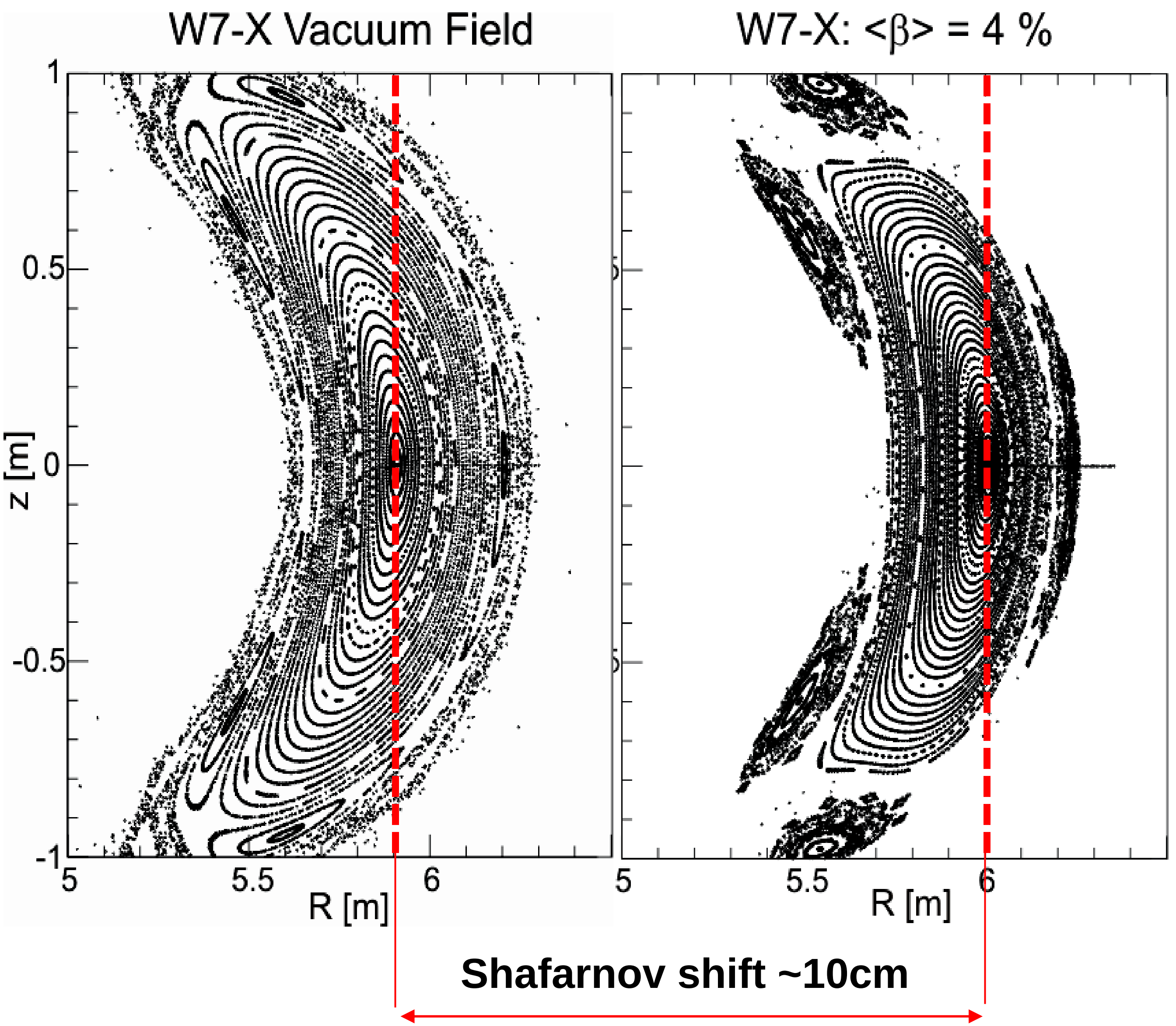
C	CRPP
I	IPP
L	LLL
J	NIFS
N	NYU
O	ORNL
P	PPPL



goodness parameters:

Δ_{is}	relative island width
β_{eq}	equilibrium-β value
β_{stab}	stability-β value
δ_e	equivalent ripple
i_{BS}	relative bootstrap current
f_α	fraction of lost α-particles
ΔW	distance plasma-first wall
R_c	minimum coil curvature

Robust equilibria



plasma equilibrium

$$\nabla p = \vec{j} \times \vec{B}$$

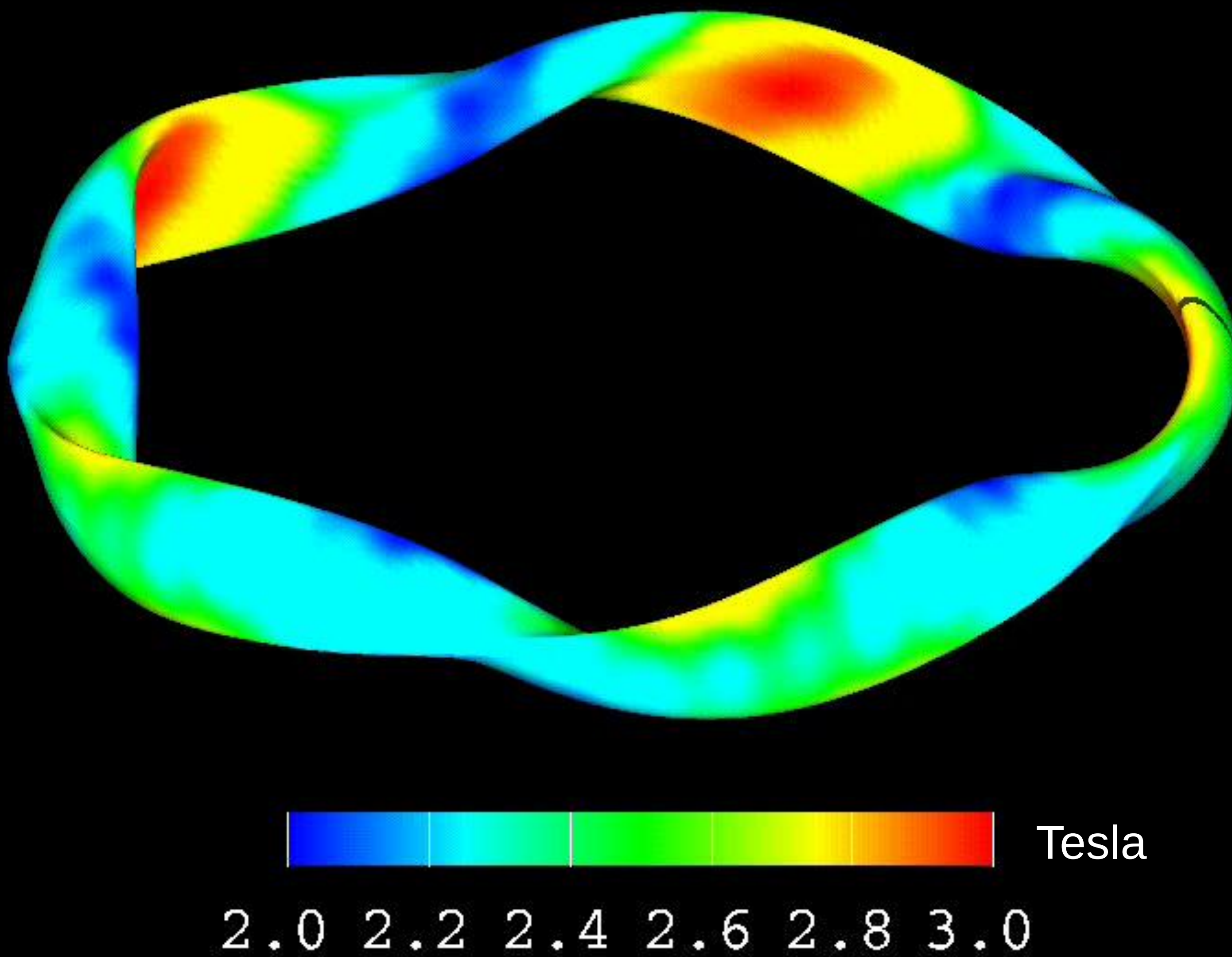
bean shaped cross section

high plasma pressure

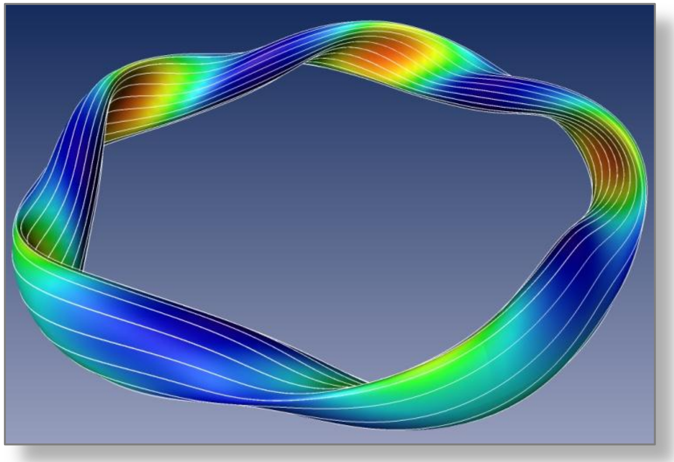
↓

- **equilibrium stiff**
- **island location**
- **confined volume**
- **plasma location**

Drift optimization 50 keV ions

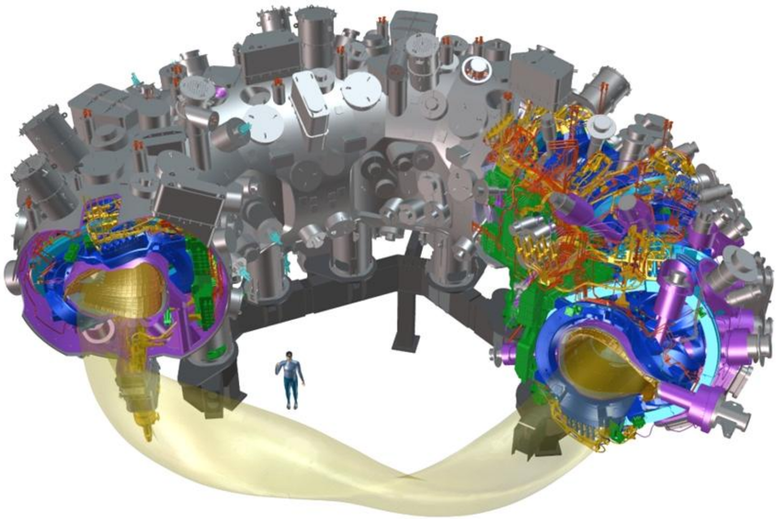


Facts and figures

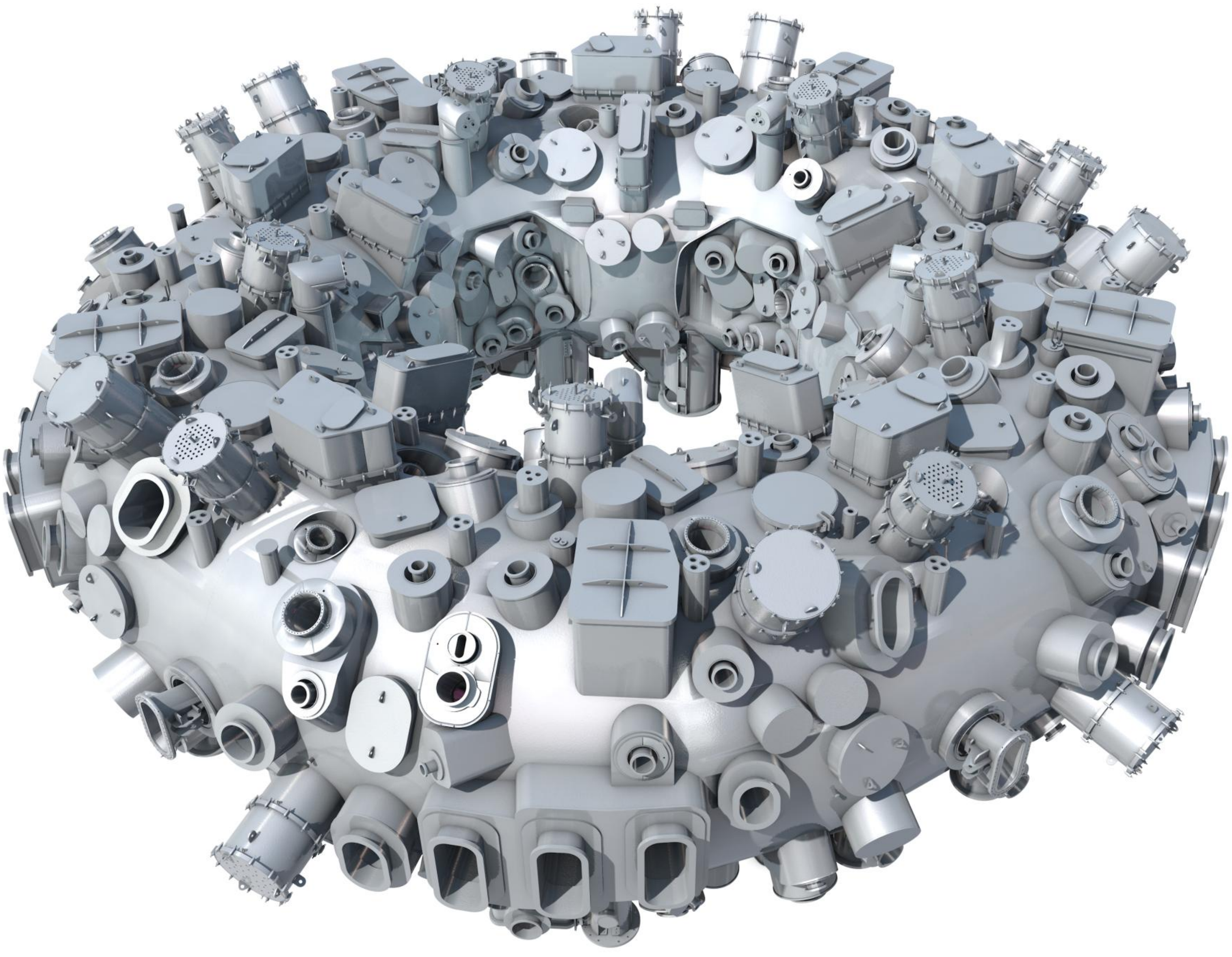


- five magnetic field periods
- modular non-planar coils
- optimized plasma equilibrium
- low equilibrium current $\rightarrow$ O(10 kA)
- high iota and low shear
- flexible magnetic field configurations

- 735 t mass with 435 t cold mass
- 70 superconducting NbTi coils
- 14 HTSC current leads
- 3 T magnetic induction on axis
- 254 ports of 120 different types
- 30 m^3 plasma volume
- 265 m^2 in-vessel components
- 4.5m height and 16 m diameter



Major elements of Wendelstein 7-X



Cryostat vessel and thermal insulation

Superconducting magnets

coil in the assembly handling unit

coil in the test bed @ CEA Saclay

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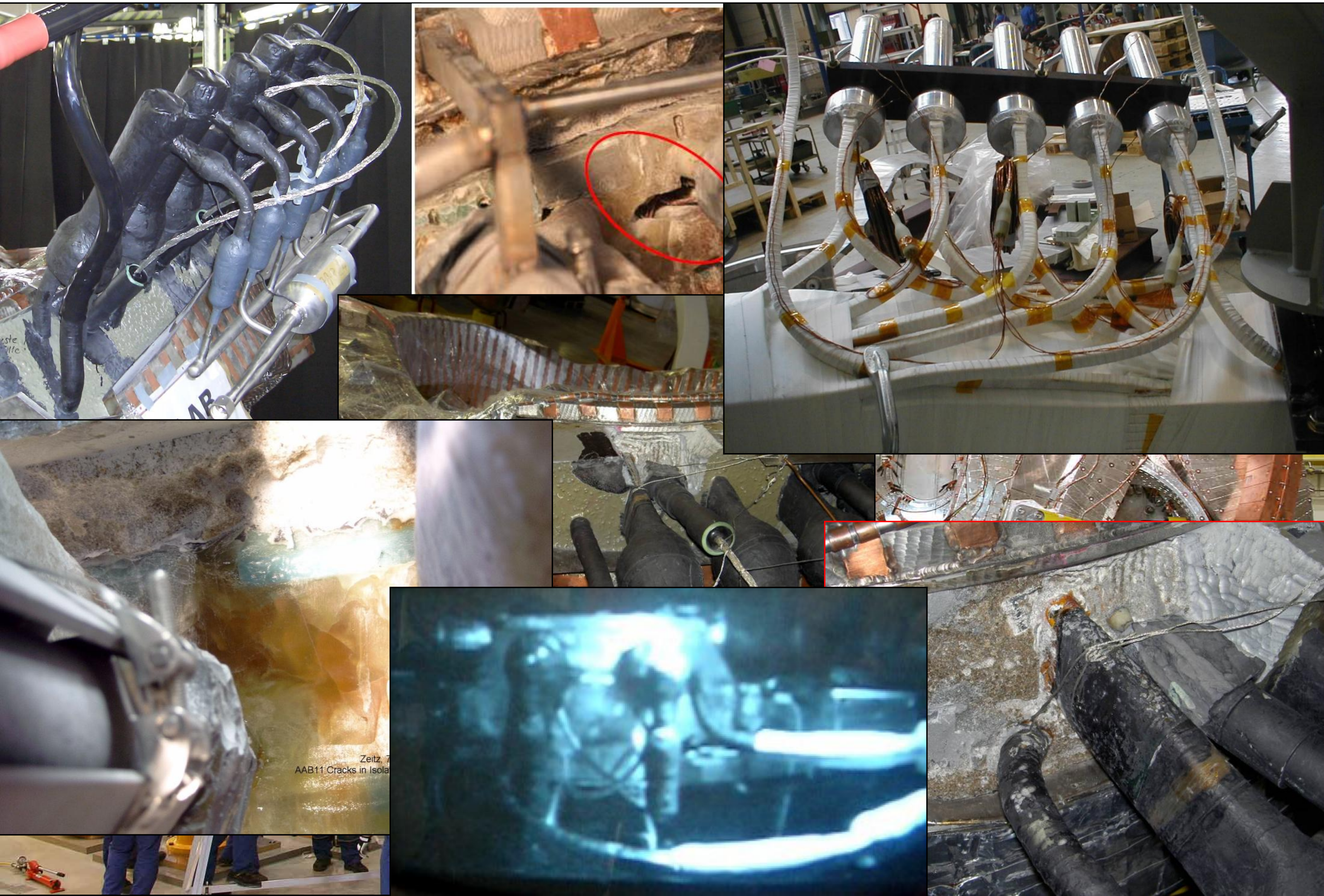
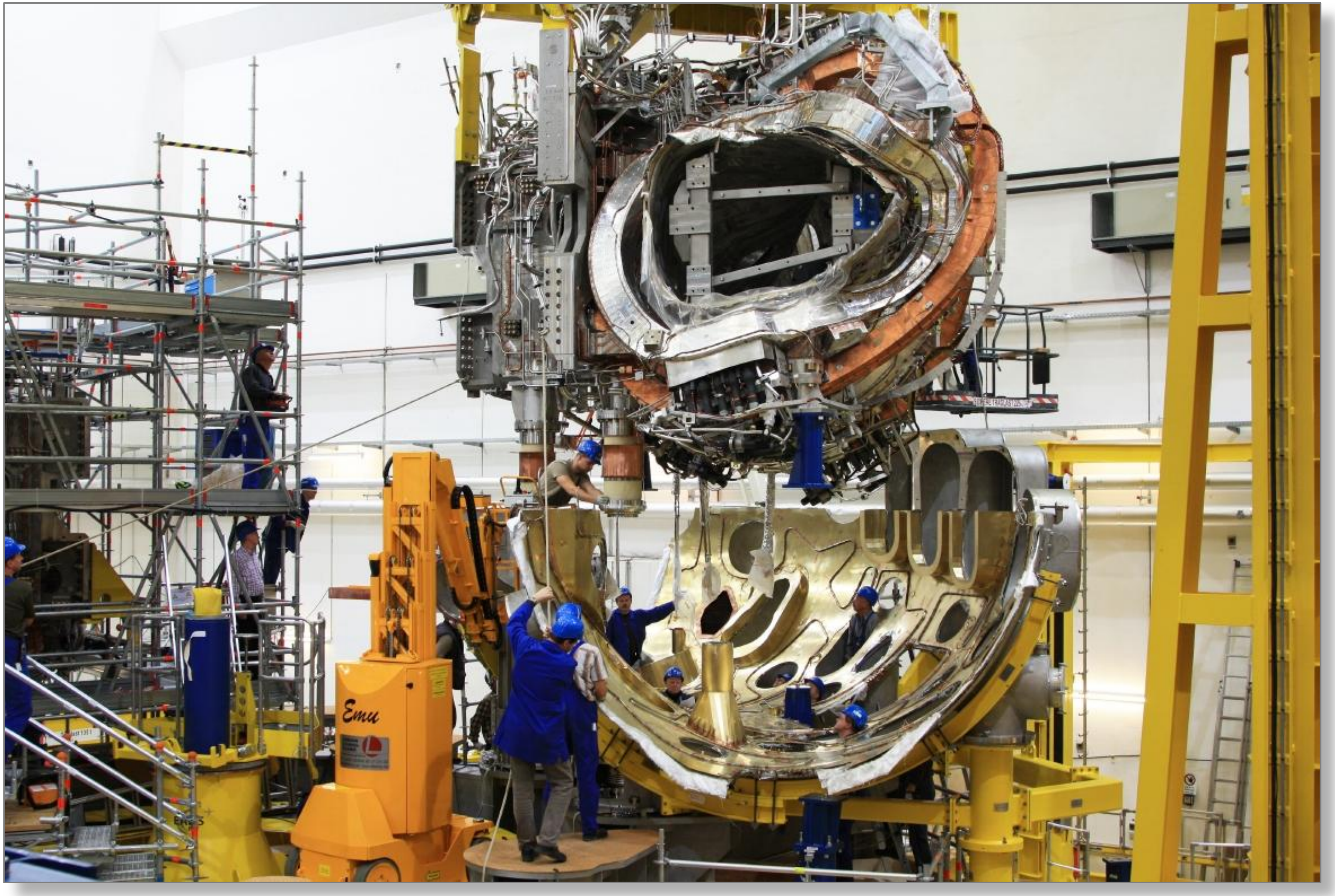
Magnet manufacturing was a pain

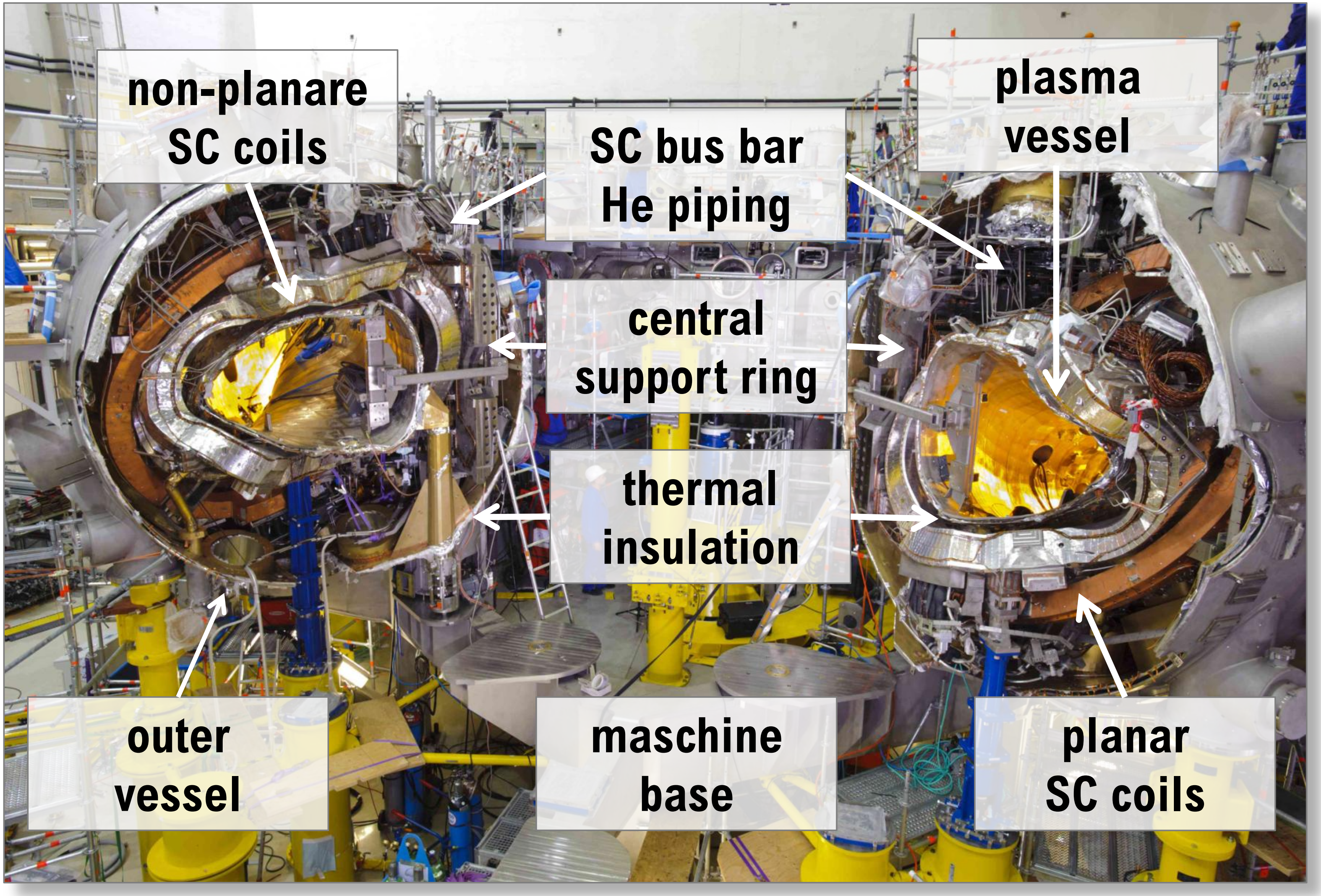
IPP



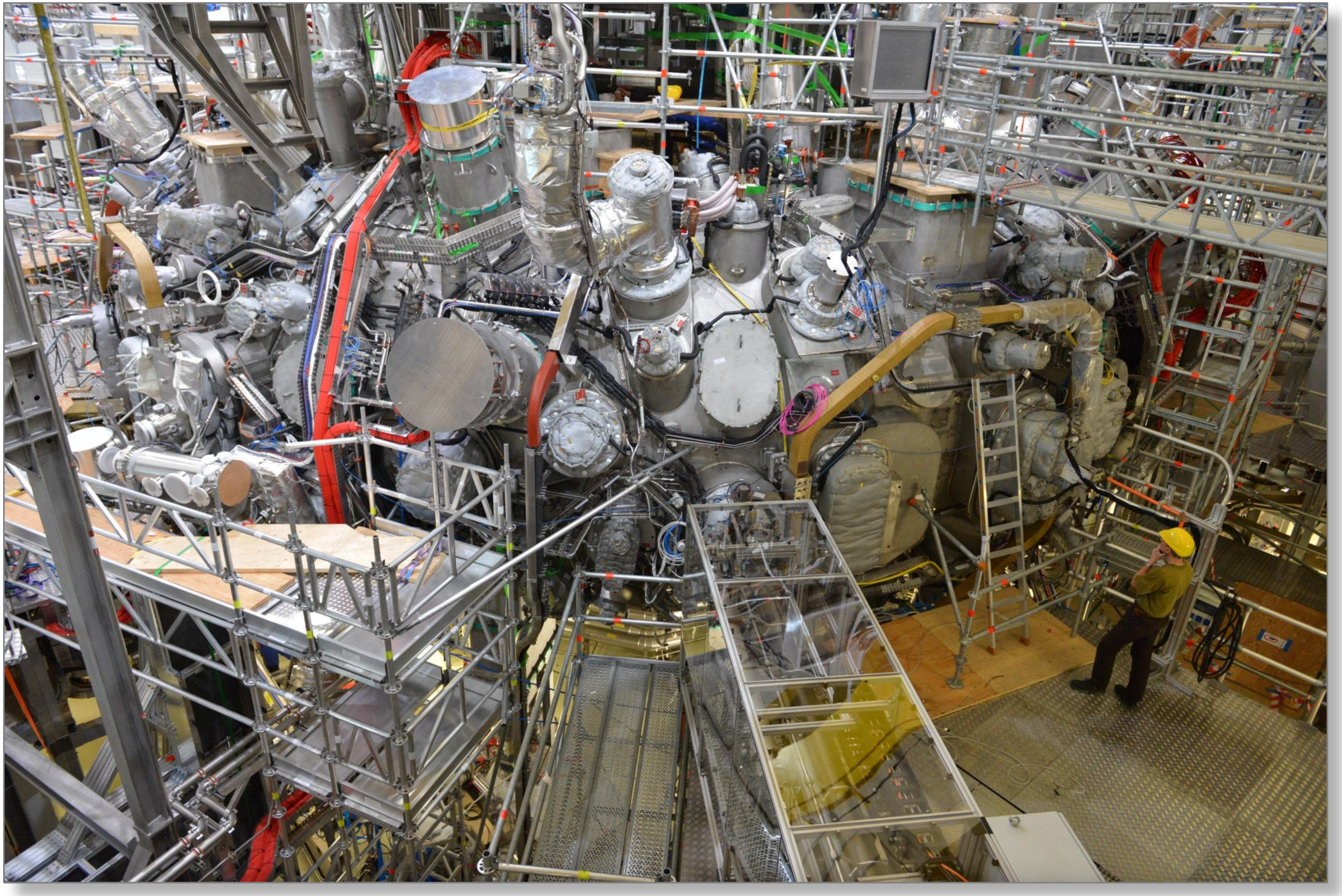
Integation of magnets and cryostat



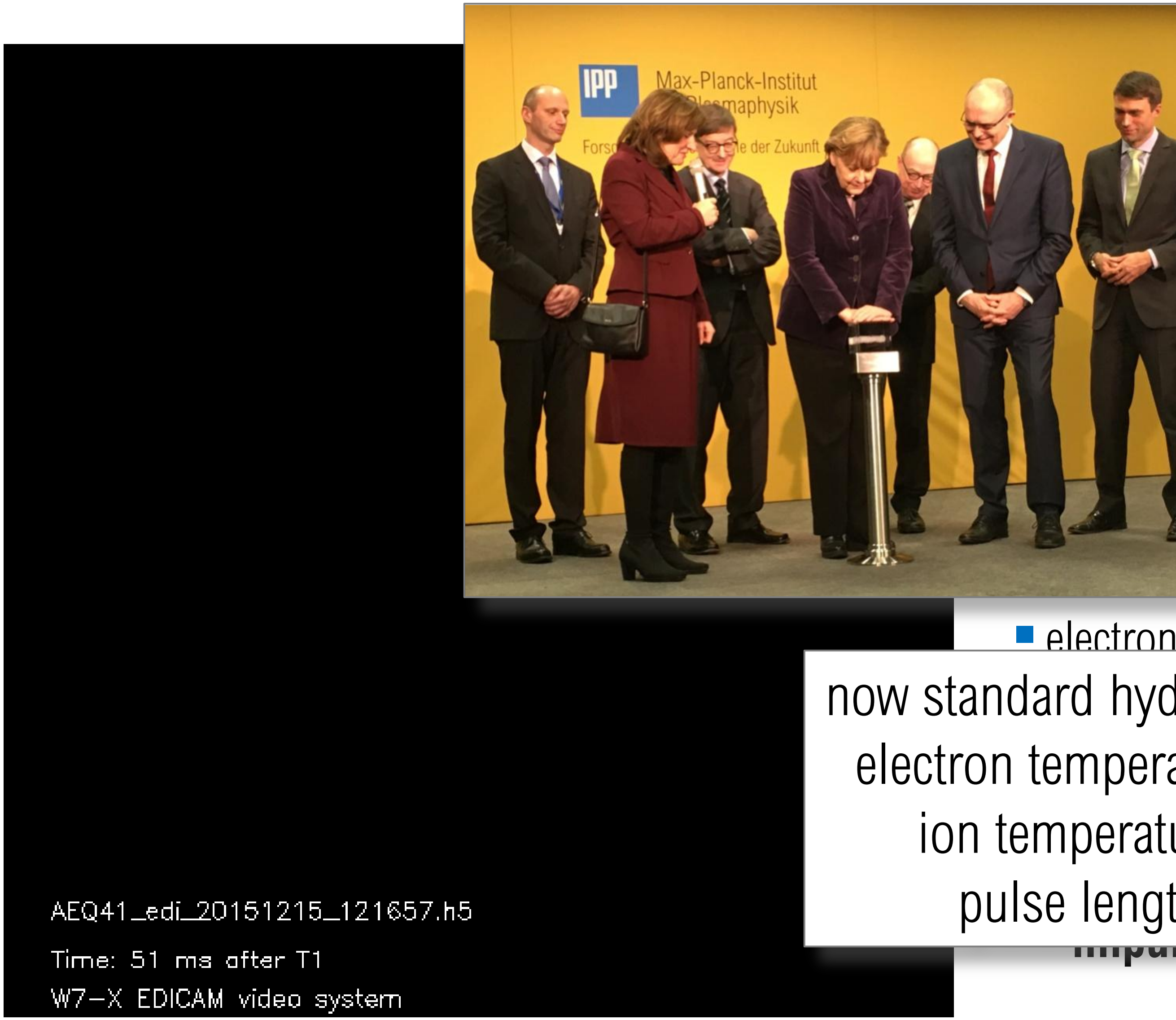
Four out of five modules



The device is complete



First He plasma fast video camera recording



…e parameters:

- …ve power 4 MW
- …ve frequency 140 GHz
- …c field on axis 2.5 T
- …pressure $5 \cdot 10^{-4}$ mbar

…arameters:

- …density $2 \cdot 10^{19}$ m^{-3}
- electron temperature 4 keV

now standard hydrogen plasmas
electron temperature 10 keV
ion temperature 2 keV
pulse length 1- 7 s

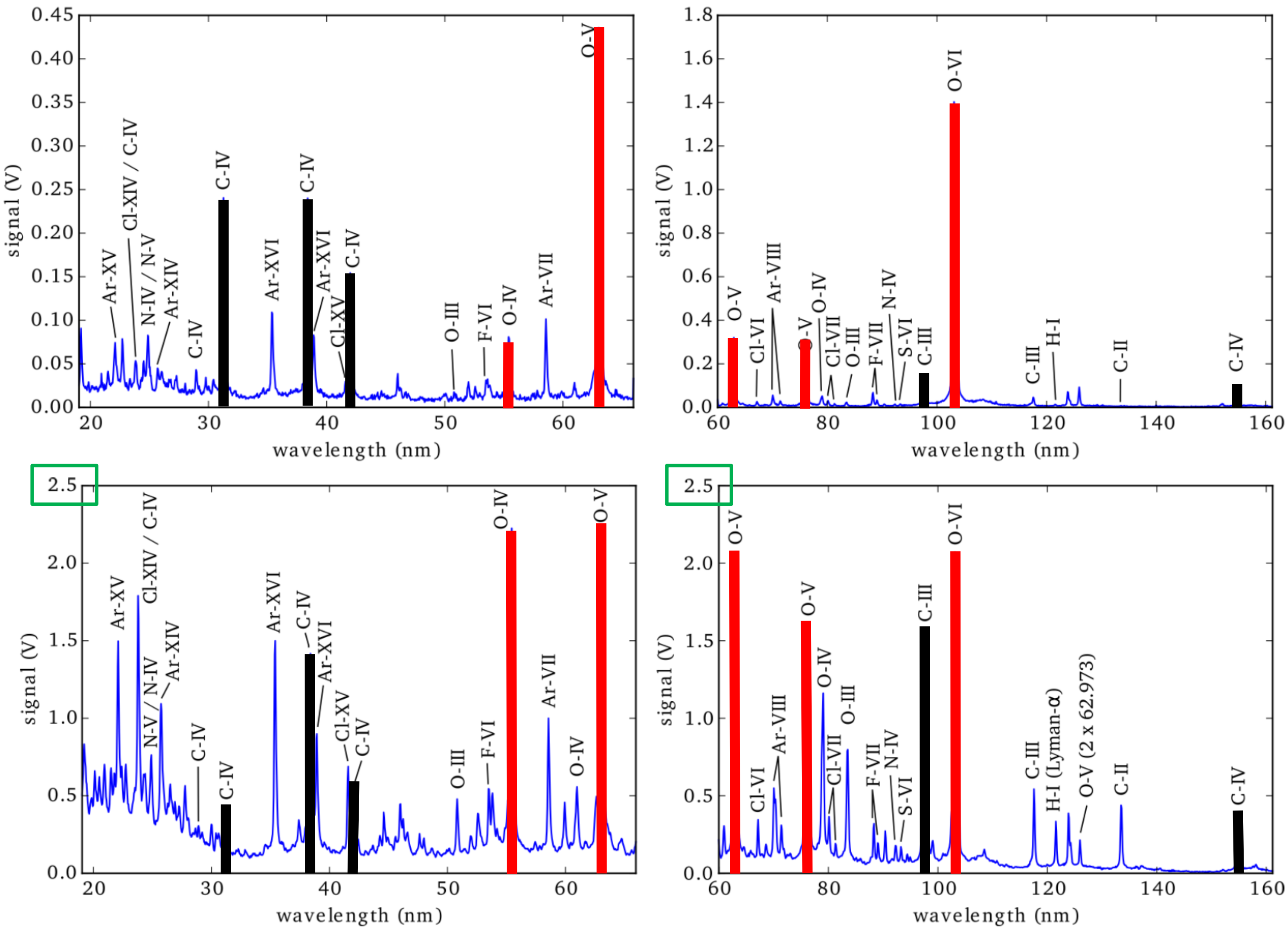
…wall!

Impurity spectroscopy

high resolution overview spectrometer wavelength range 20 – 160 nm

before radiation collapse

during radiation collapse



Overview of the first operation phase

The 10 weeks if the first operation phase has exceeded all our expectations.

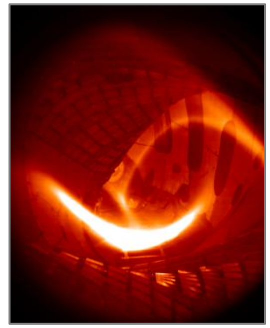
In the end 25 diagnostic systems were commissioned and delivered data.

$T_e = 1\,\text{keV}$

$T_i < 1\,\text{keV}$

$n_{e0} \sim 2 \cdot 10^{19}\text{m}^{-3}$

$t_d = 50\,\text{ms}$



$T_e = 7\,\text{keV}$

$T_i = 1.2\,\text{keV}$

$n_{e0} = 3 \cdot 10^{19}\text{m}^{-3}$

$t_d = 250\,\text{ms}$

$T_e = 8\,\text{keV}$

$T_i = 1\,\text{keV}$

$n_{e0} = 2 \cdot 10^{19}\text{m}^{-3}$

$t_d = 6\,\text{s}$

10.12.2015
1st He Plasma

2 MJ

3.2.2016
1st H Plasma

4 MJ

$T_e = 8\,\text{keV}$

$T_i = 2\,\text{keV}$

$n_{e0} = 3 \cdot 10^{19}\text{m}^{-3}$

$t_d = 500\,\text{ms}$

$T_e = 10\,\text{keV},\ 7\,\text{keV}$

$T_i = 1\,\text{keV},\ 2.1\,\text{keV}$

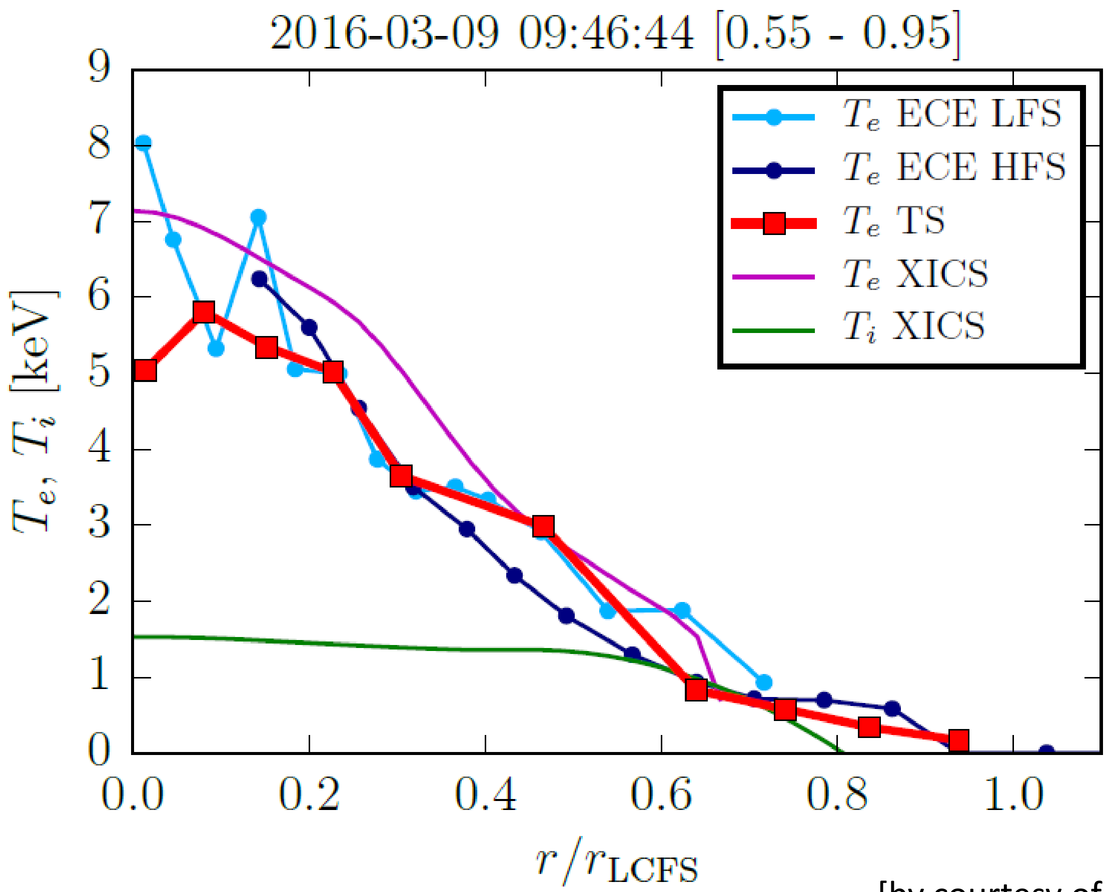
$n_{e0} = 5 \cdot 10^{19}\text{m}^{-3}$

$t_d = 1\,\text{s}$

~ 1000 experiments

On the 10th of March 2016 the operation was suspended as planned.

Typical radial temperature profiles



X-ray imaging crystal spectrometer

$500\,\mathrm{eV} < T_e < 10\,\mathrm{keV}$

$500\,\mathrm{eV} < T_i < 4\,\mathrm{keV}$

Ar impurity seeding

plasma densities

$n_e < 4\text{-}5 \cdot 10^{19}\,\mathrm{m}^{-3}$

[by courtesy of S. Bozhenkov]

Thomson scattering system

$20\,\mathrm{eV} < T_e < 10\,\mathrm{keV}$, $5 \cdot 10^{18}\,\mathrm{m}^{-3} < n_e < 5 \cdot 10^{20}\,\mathrm{m}^{-3}$, $\Delta r_{eff} \approx 2\text{-}3\,\mathrm{cm}$

two Nd-YAG lasers 2J/pulse @ f=20 Hz, laser beam ∅=5-7 mm

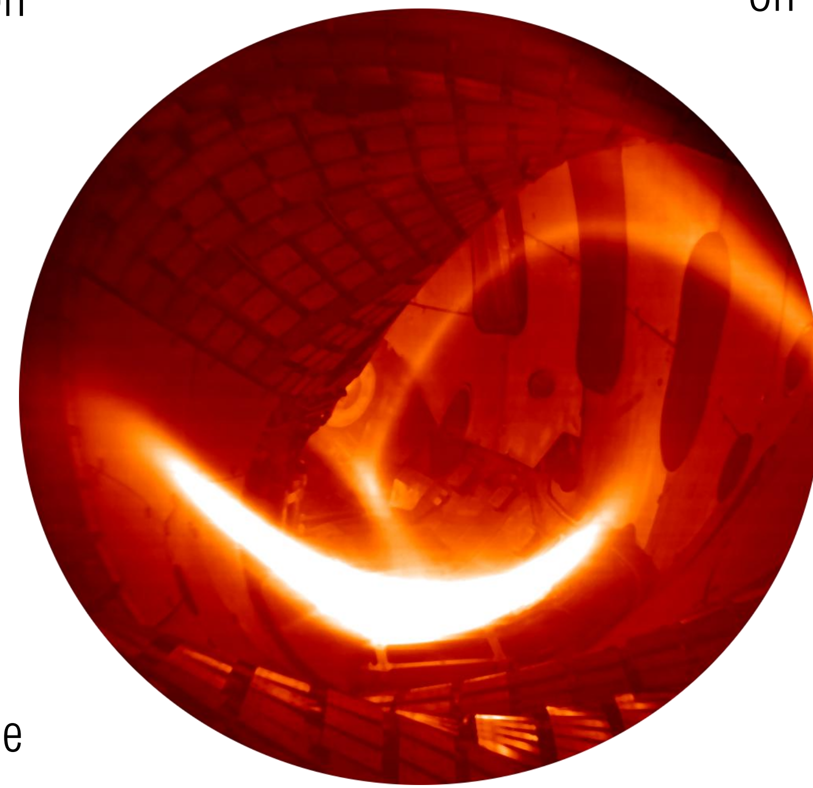
Numerous research topics addressed

radial electric field and
plasma rotation

magnetic configuration influence
on particle transport

heat wave experiments
for confinement studies

electron cyclotron
current drive



identification of
impurities and
radiation collaps

advanced
heating schemes

filamentation
in the plasma edge

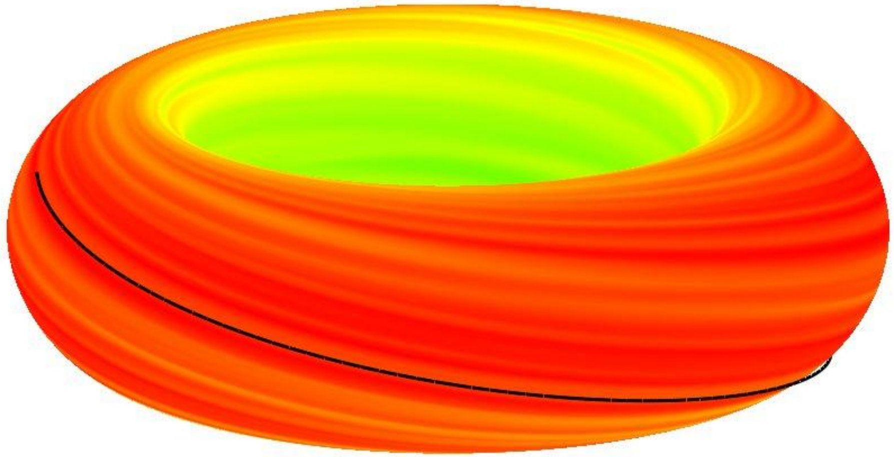
limiter heat loads
and influence of
trim coils

EUROfusion

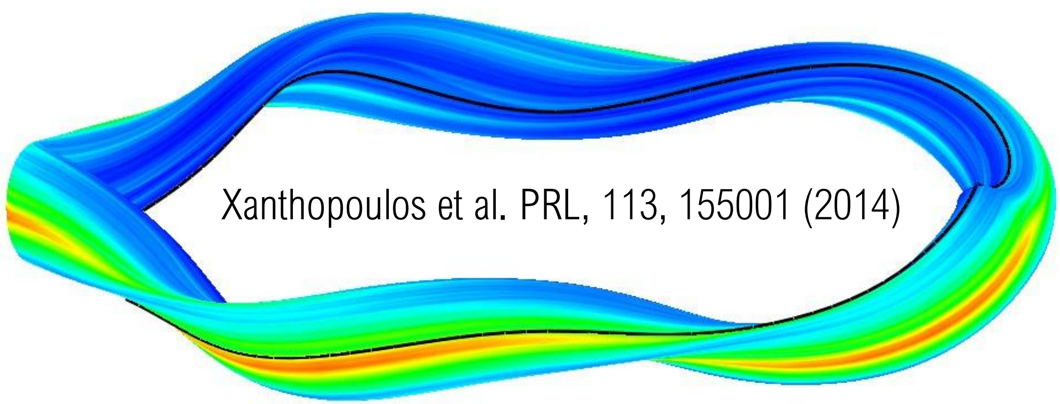
Unresolved: Turbulence in 3d magnetic field

turbulence amplitude

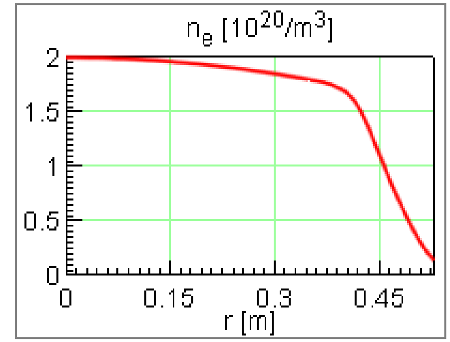
tokamak



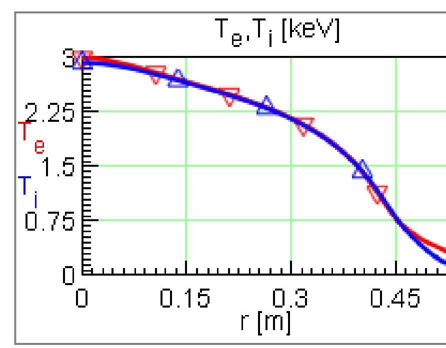
optimized stellarator



Xanthopoulos et al. PRL, 113, 155001 (2014)

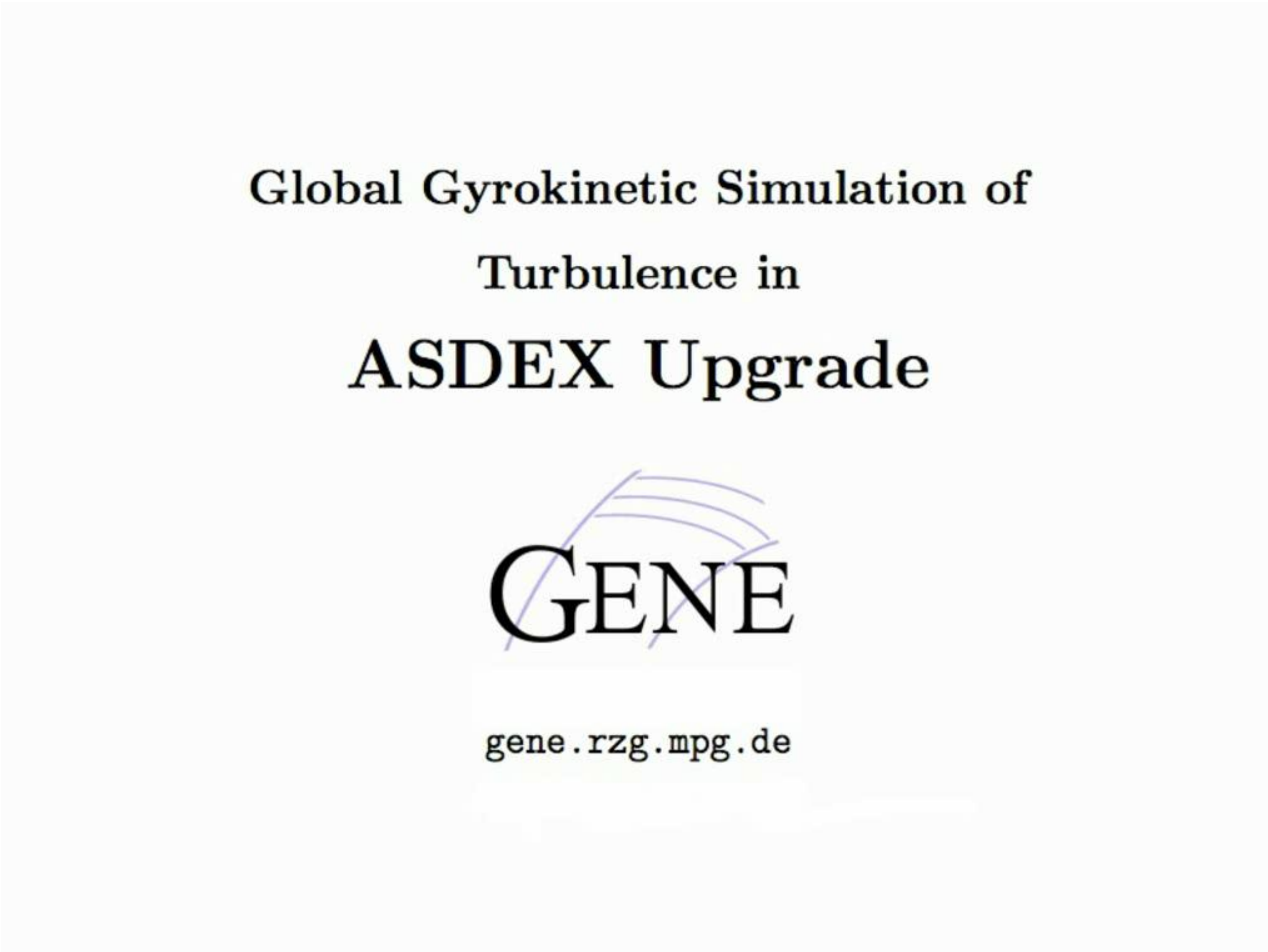


∇T_i driven turbulence



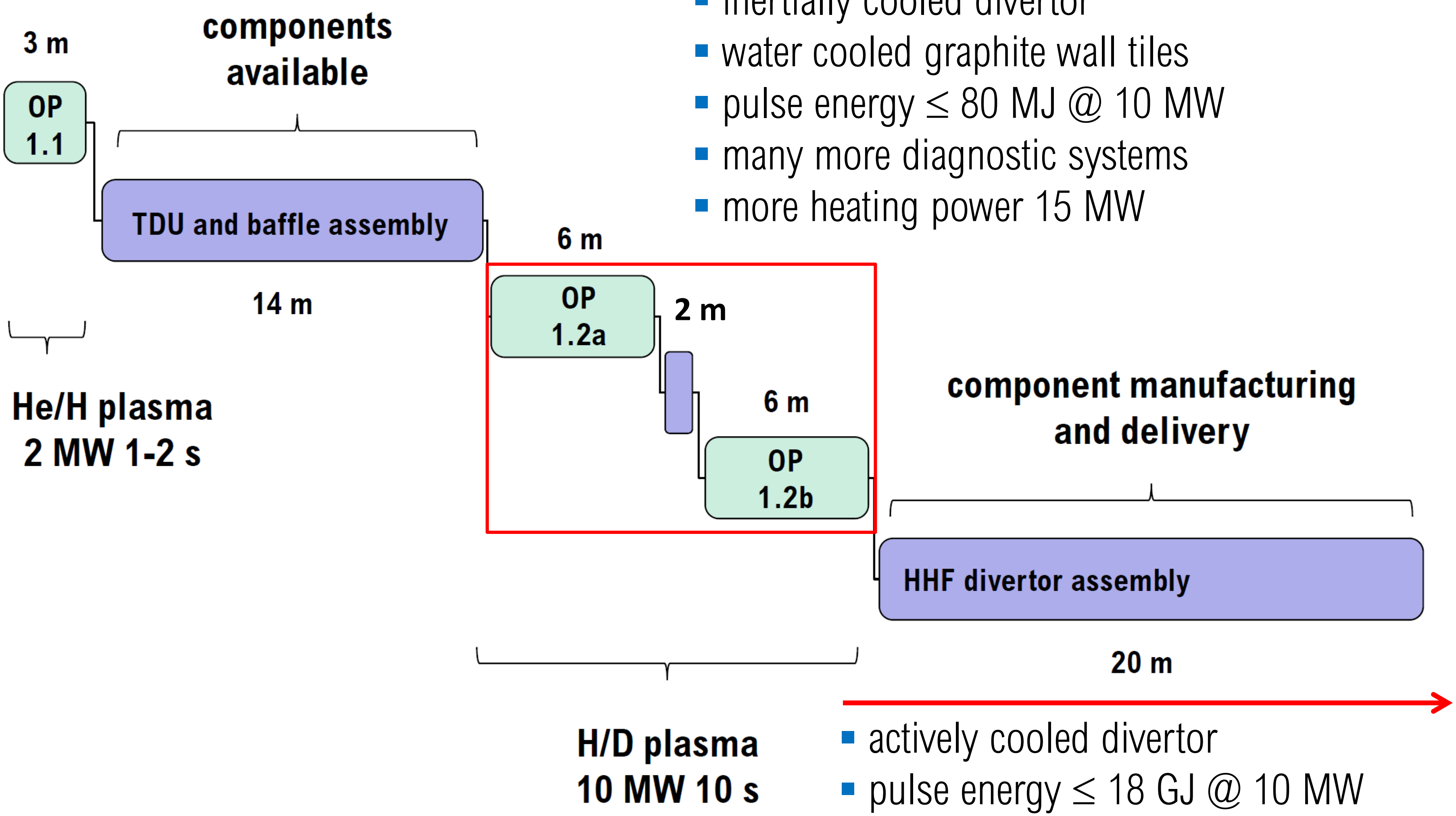
Wendelstein 7-X „by chance“ turbulence optimized?

Turbulence in a tokamak – gyrokinetic code

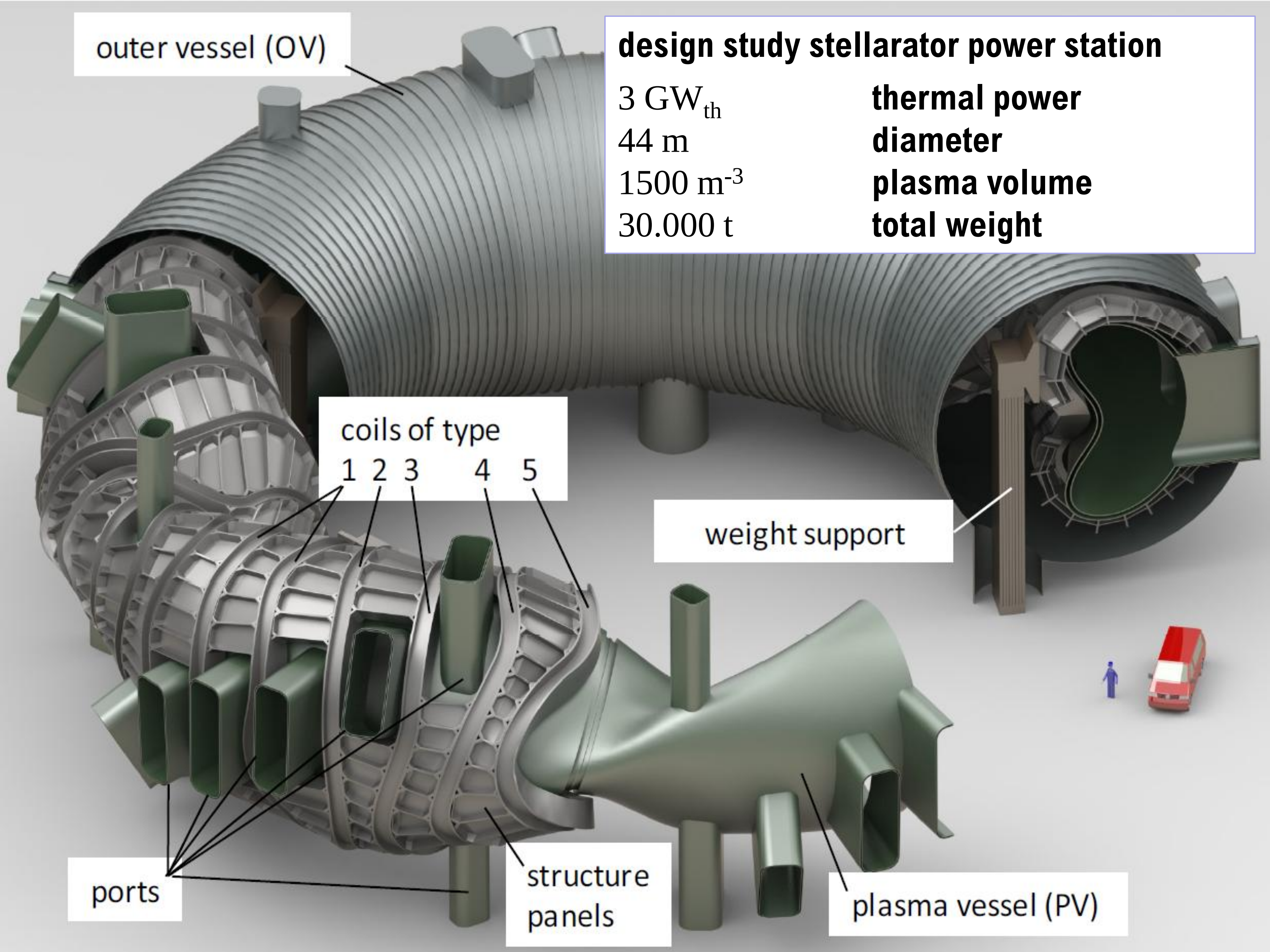


The mid term plan for Wendelstein 7-X

- inertially cooled divertor
- water cooled graphite wall tiles
- pulse energy ≤ 80 MJ @ 10 MW
- many more diagnostic systems
- more heating power 15 MW



- actively cooled divertor
- pulse energy ≤ 18 GJ @ 10 MW
- more heating power 20 MW


design study stellarator power station
3 GW_{th} thermal power
44 m diameter
1500 m^{-3} plasma volume
30.000 t total weight
outer vessel (OV)
coils of type
1 2 3 4 5
weight support
ports
structure panels
plasma vessel (PV)

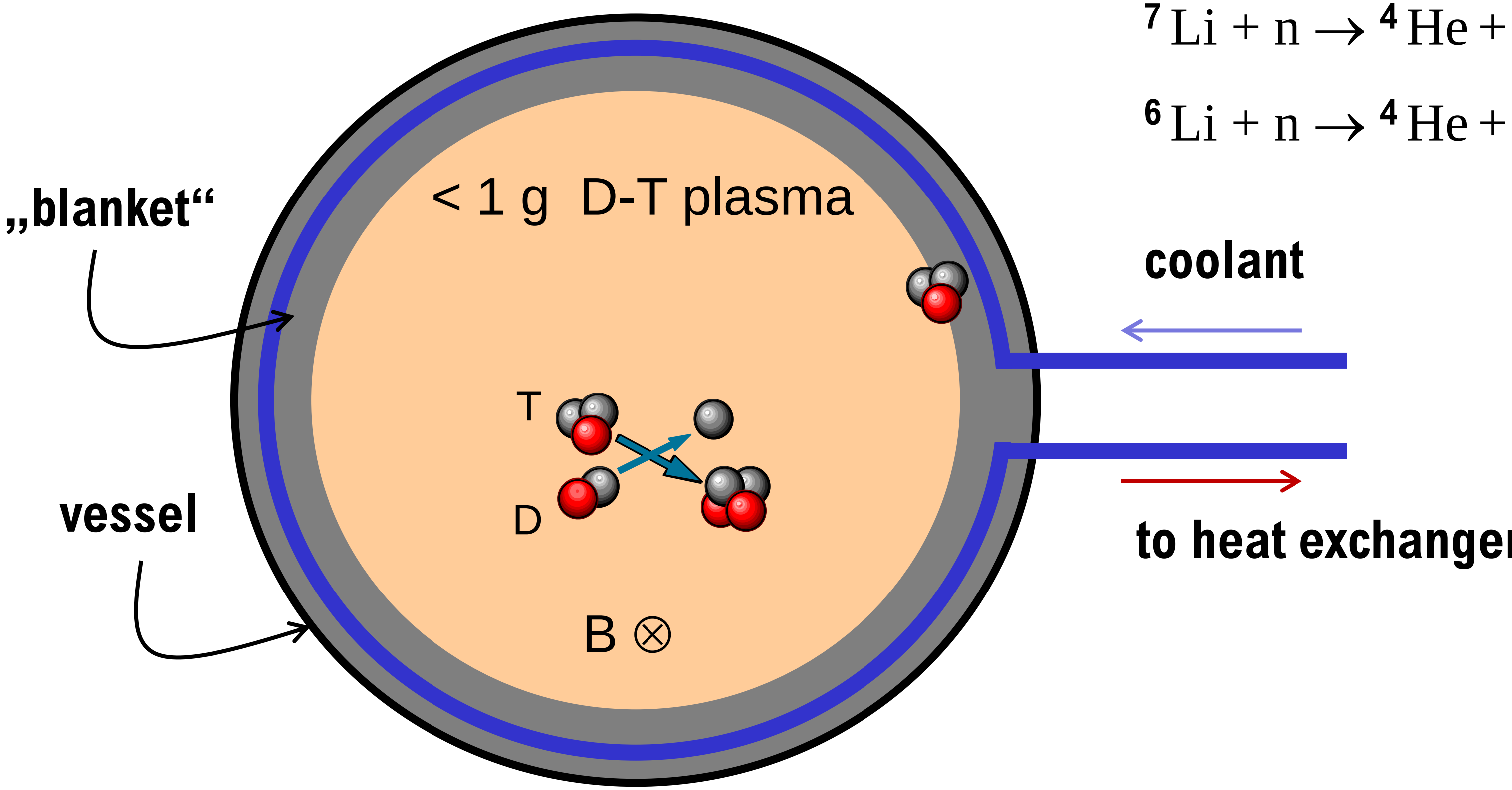
The reactor scheme

D concentration in water 0.015%

in situ T generation

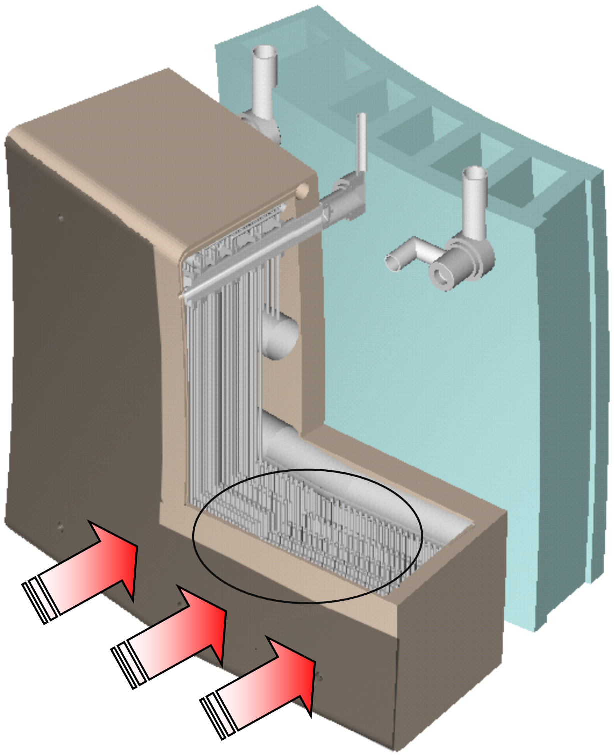
$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T} + \mathrm{n}$$

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T}$$

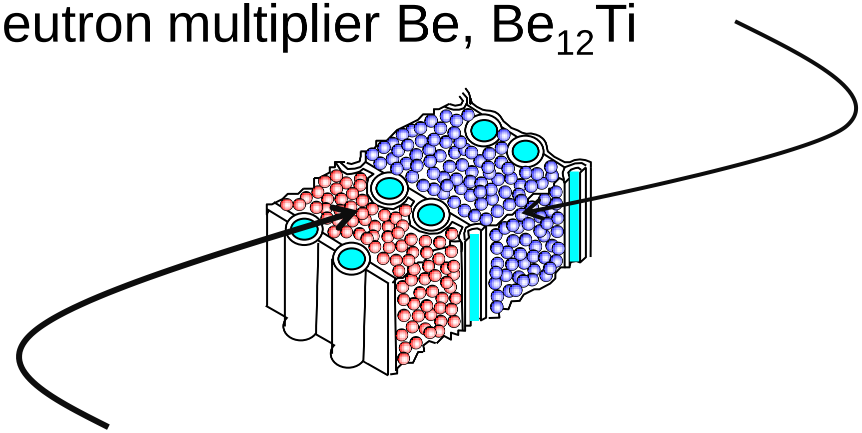


a fully ionized D-T-plasma at 10 keV ion temperature with an average particle density $n_d \sim n_T \sim 10^{20}\,\mathrm{m}^{-3}$ yields a fusion power density $P/V \sim 2\ \mathrm{MW/m}^3$

The blanket – a critical component



neutron multiplier Be, $Be_{12}Ti$



Tritium breeder
Li_2TiO_3, Li_2O

critical is the T self-sufficiency

a comprehensive reserach program is needed and must be intensified – first test blanket modules will be investigated in the ITER tokamak (under construction)

https://www.iter.org/mach/Blanket
https://www.fusion.kit.edu
http://www-fusion-magnetique.cea.fr

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Summary and Concluding remarks

IPP

- Wendelstein 7-X is an optimized SC stellarator
- completed after 15 years of construction
- the machine works perfectly fine
- the first plasma operation with He and H has started
- physics program based on a staged approach to steady-state

Why fusion at all and why stellarators?

- a new primary energy source – probably needed in future
- backbone power stations of the GW class
- basic research on magnetized high-temperature plasmas needed
- the stellarator promises stable steady-state operation
- Wendelstein 7-X is the key experiment for reactor extrapolation