Der Stellarator

Ein alternatives Einschlusskonzept für ein Fusionskraftwerk

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Contents

- Magnetic confinement
- The stellarator concept (advantages and disadvantages)
- Current state of research
- Wendelstein 7-X
- Fusion power plant on the basis of a stellarator
- Summary

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- **Magnetic confinement**
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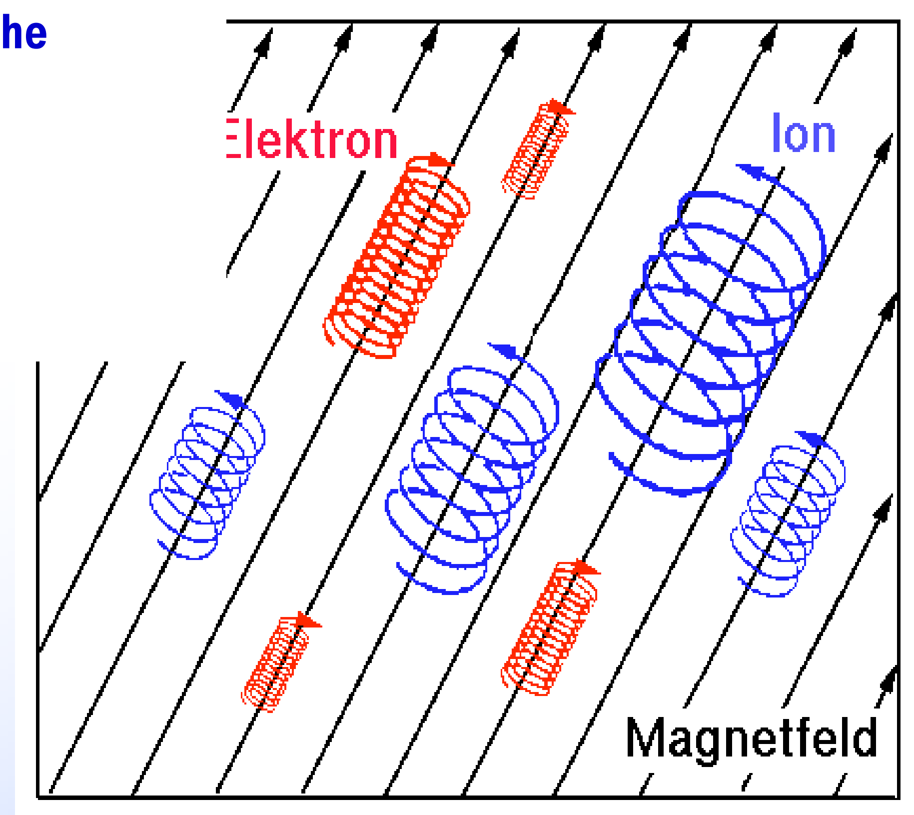
Magnetic field as heat insulation

Ignition

<u>Heating from fusion reactions</u> has to compensate losses (perpendicular to the magnetic field):

- **Radiations losses (impurities, bremsstrahlung, …)**
- **Heat conduction and convection**

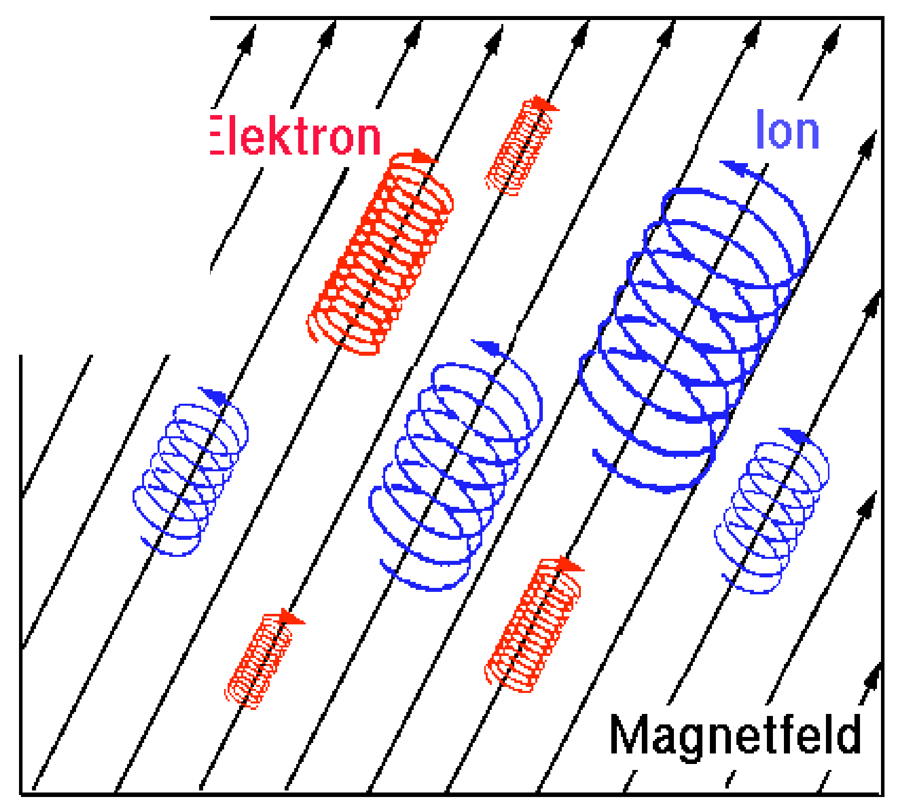


Magnetic field as heat insulation

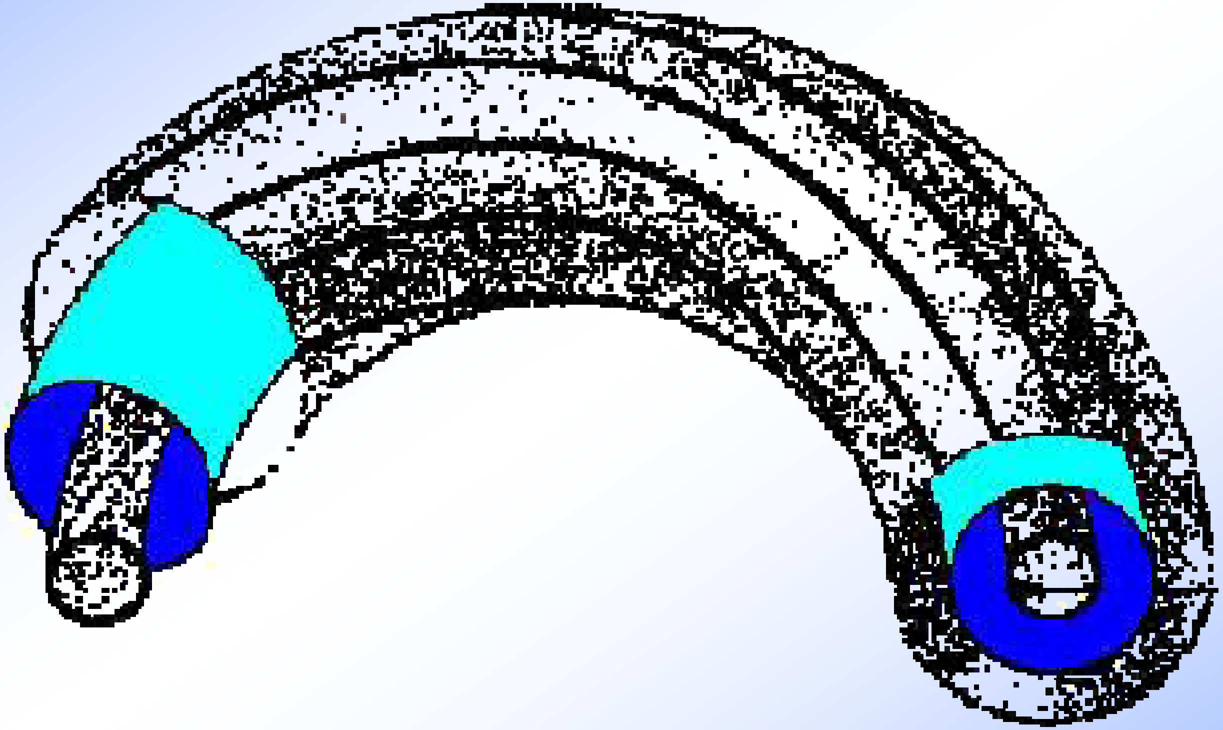
$Q = P_{fusion} / P_{heating} >> 1$

Heating from fusion reactions & external heating has to compensate losses (perpendicular to the magnetic field):

- Radiations losses (impurities, bremsstrahlung, …)
- Heat conduction and convection



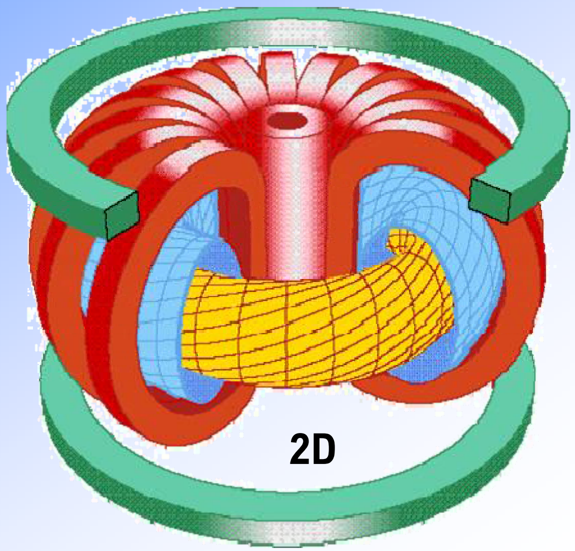
Toroidal configuration to avoid end losses



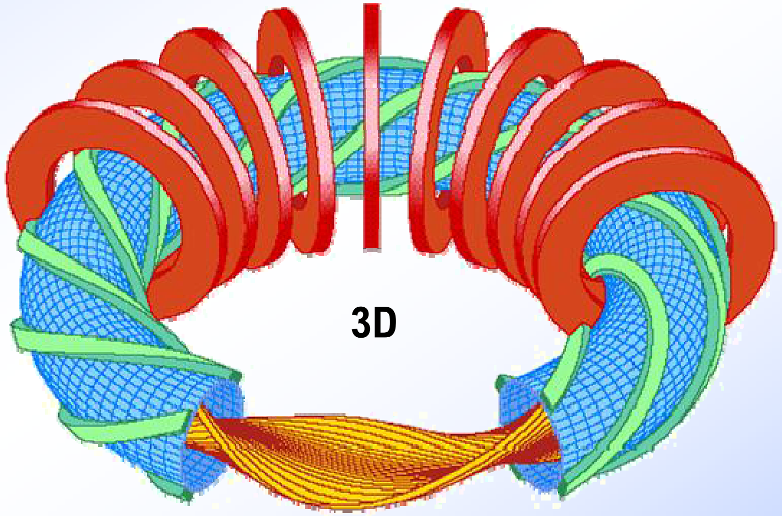
Important: Helically twisted magnetic field – rotational transform!

Two possible magentic field configurations

Tokamak



Stellarator



Tokamak (from Russian „toroidalnaya kamera magnitnaya katishka“ / toroidale Kammer mit magnetischer Spule)

Dates back to I. Tamm und A. Sakharov

Major part of the magnetic field generated by plasma current (transformer principle)

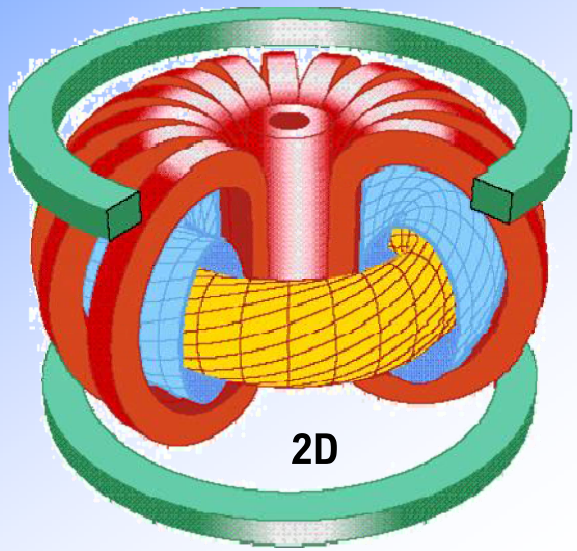
Stellarator (stands for the utilization of the energy source of the stars)

Dates back to L. Spitzer (Princeton Plasma Physics Laboratory)

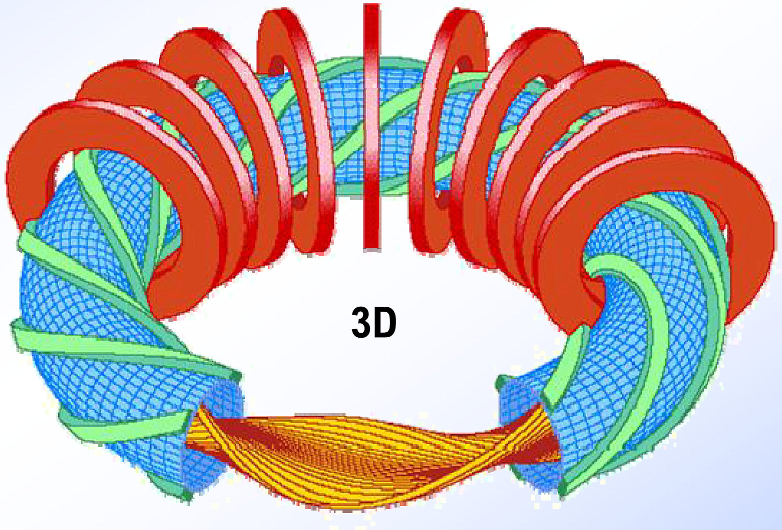
Magnetic field essentially generated by external coils

Two possible magentic field configurations

Tokamak



Stellarator



Further developed

- Good confinement properties
- Pulsed operation
- Current can cause plasma instabilities

Favourable properties for operating a power plant

- Intrinsically steady state
- Requires elaborate optimization (by means of high performance computers) in order to achieve necessary confinement
- Rotational transform from external coils results in loss of toroidal symmetry

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Advantages of the stellarator

- **Intrinsically steady state magnetic field**
  - current drive requirements limited to small adjustments of the rotational transform (one to two orders of magnitude smaller than in tokamaks)
  - intrinsically high Q (lower re-circulating power), could operate ignited (?)
  - quiescent steady state (at high $\beta = p_{plasma}/p_{magn.\ field}$)
- **No large (toroidal) plasma current**
  - no current driven instabilities
  - no requirements to (feedback) control such instabilities
  - no disruptions
    - eases design of plasma facing components (breeding blanket)
    - disruption avoidance or mitigation schemes not required
  - plasma density not limited by current profile instability (Greenwald density limit)
    - stay in optimum fusion reaction range at high β: $P_{fusion} = \int n^2 <\sigma v> E_f \, dV$
    - because of lower temperature easier plasma solutions for divertor
    - because of higher density reduced fast-ion instability drive

Disadvantages of the stellarator

- 3D magnetic field configuration
  - generally poor confinement of thermal plasma
  - generally poor fast particle confinement
  - tendency for impurity accumulation
  - more complex divertor (and other plasma facing components)
  - more complex coil configuration

Physics issues addressed by stellarator optimization

Physics issue addressed by finding a suitable confinement / operating regime

- Engineering issues addressed when designing and building new devices
- Development of feasible concepts will become important reactor design
- Here issues are maintenance and remote handling

In short,

Without a specially tailored magnetic field which avoids the disadvantages, stellarators do not fulfil the basic requirements of a power plant.

→ stellarator optimization

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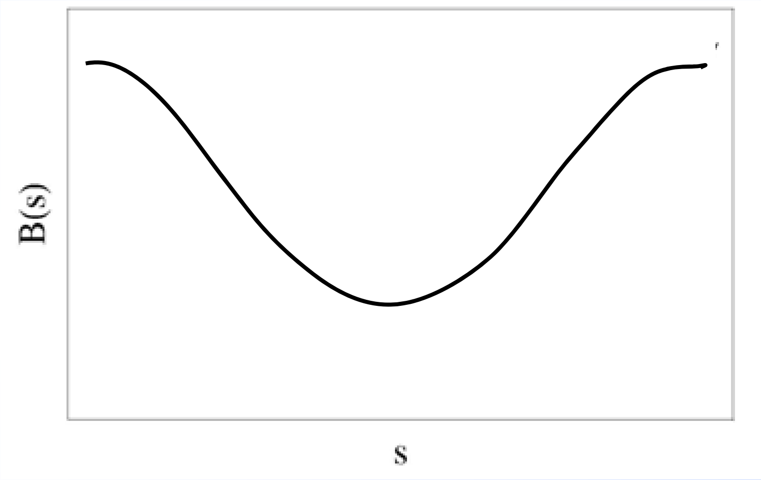
Confinement properties

In a torus: **Modulation of the magnetic field strength along the magnetic field lines**

magnetic field gradients; field line curvature

Diffusion of the thermal plasma: $D \sim \varepsilon_{eff} \cdot T^{7/2}$

Generally, because of large mean free path, radial drift of fast ions



Tokamak
→ toroidal trapping
(toroidal ripple not shown)

Coordinate along field line, one toroidal circumference

→ Quasi-symmetry acts on ε_{eff}

Confinement properties

In a torus: **Modulation of the magnetic field strength along the magnetic field lines**

magnetic field gradients; field line curvature

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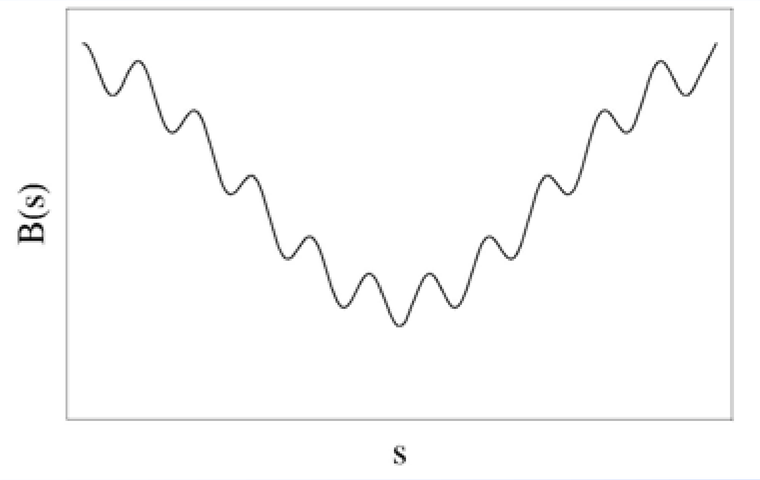


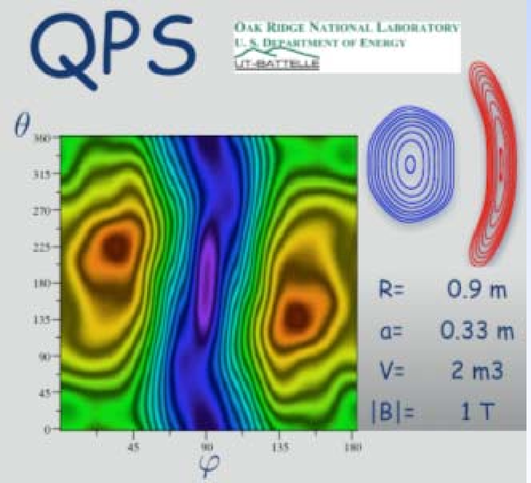
Stellarator
→ toroidal trapping →
helical trapping

Coordinate along field line, one toroidal circumference

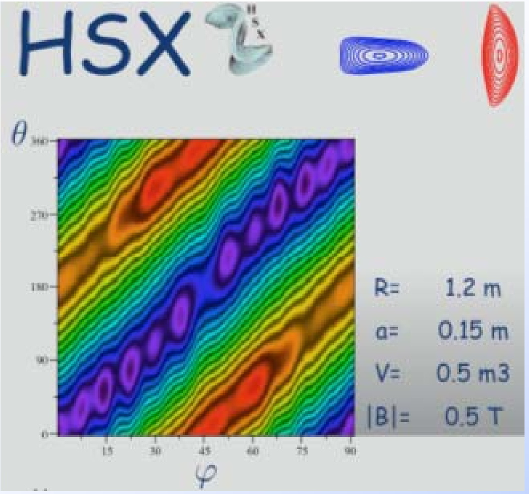
→ Quasi-symmetry acts on ε_{eff}

Quasi-symmetries

quasi-poloidal

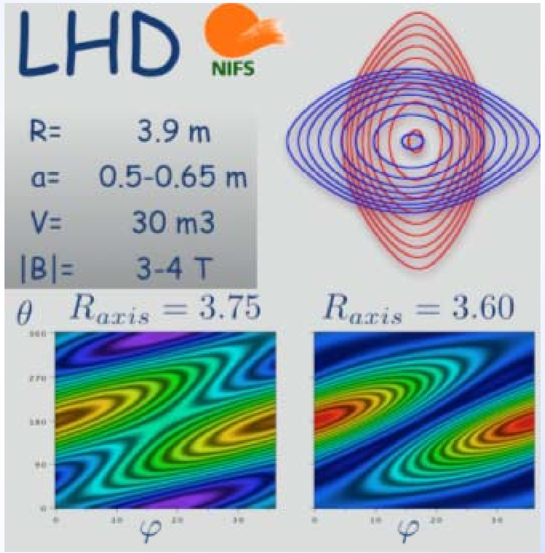


quasi-helical

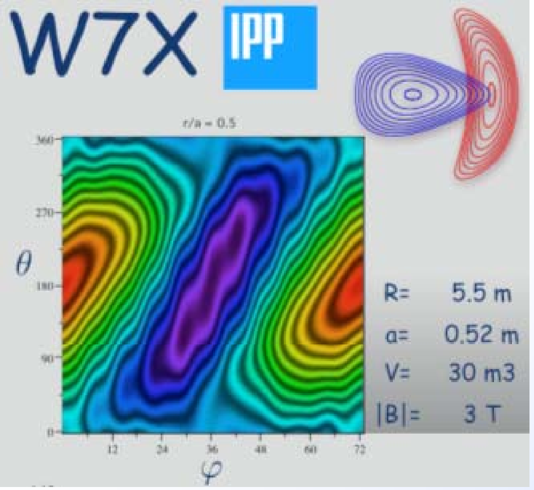


see Canik et al., PRL 98 (2007) 085002

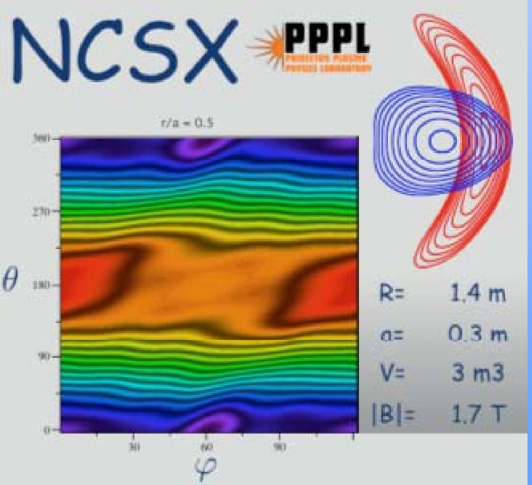
classical



quasi-isodynamic



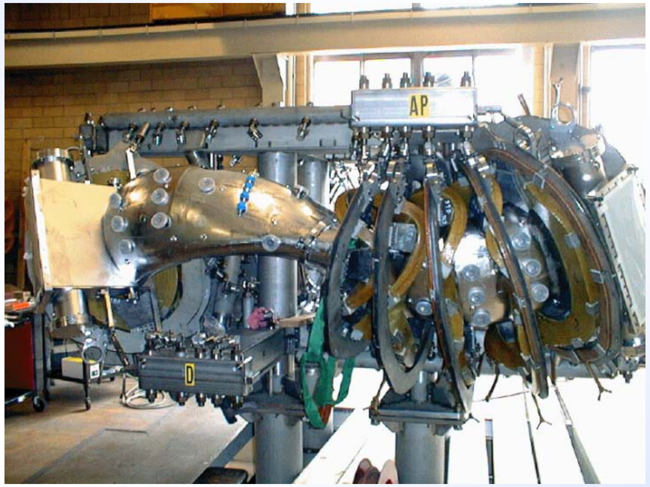
quasi-toroidal



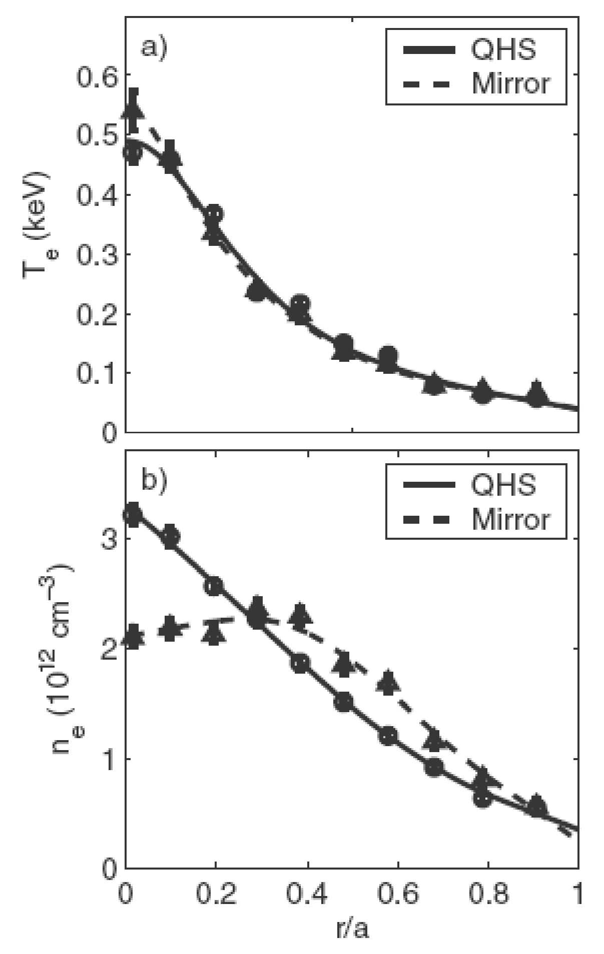
courtesy of J. Sanchez

Proof of principle

HSX (Madison, WI, USA)
26 kW – quasi-helical symmetry (QHS)
67 kW – mirror configuration

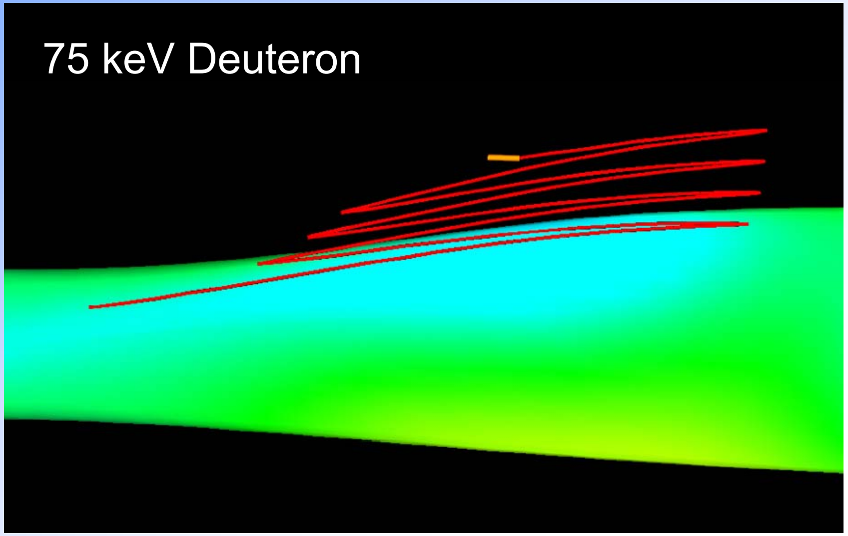


www.hsx.wisc.edu



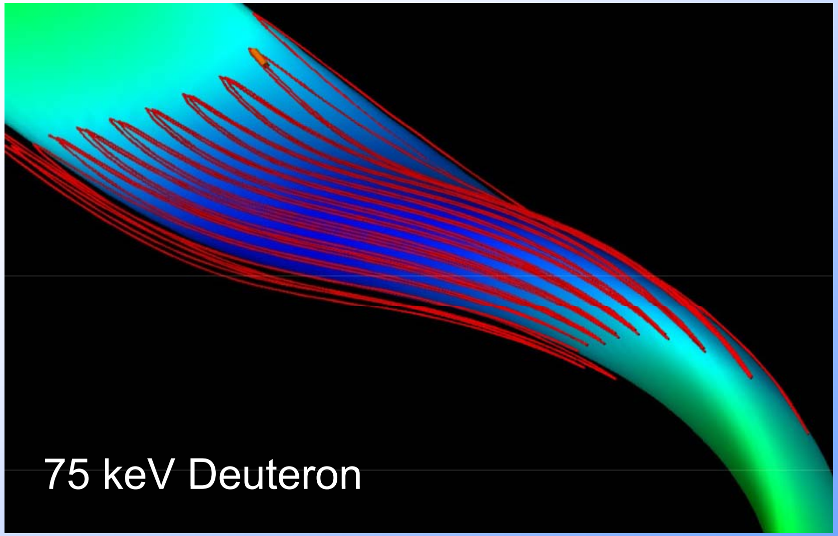
from Canik et al., PRL 98 (2007) 085002

Fast (He) ions have to be confined as well



In partially optimized W7-AS fast ions were not confined (at low collision frequency)

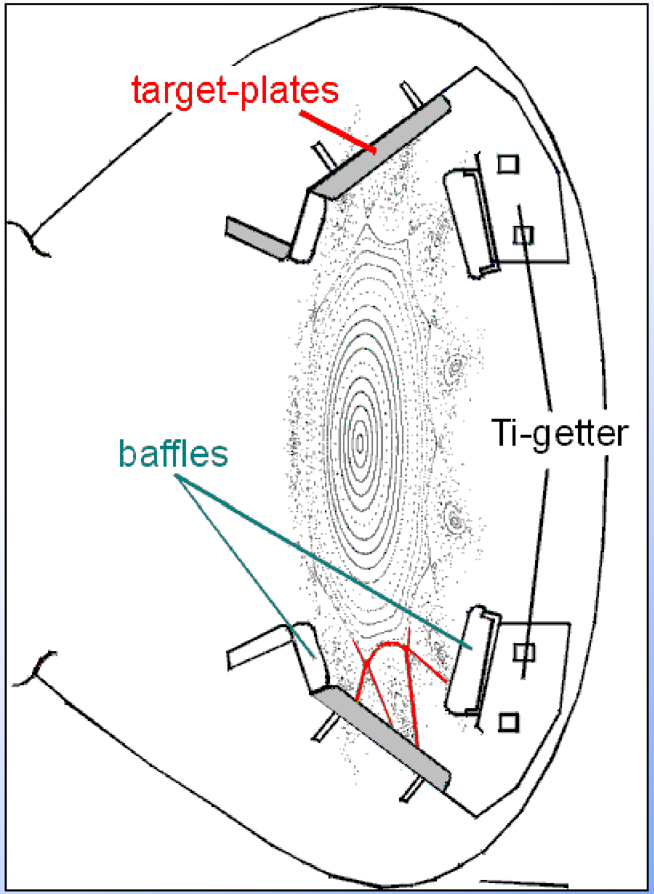
Drift optimization in W7-X (introducing quasi-symmetry / quasi-isodynamicity) serves the confinement of fast ions: Radial drift is transformed into a poloidal precession



Power and particle exhaust

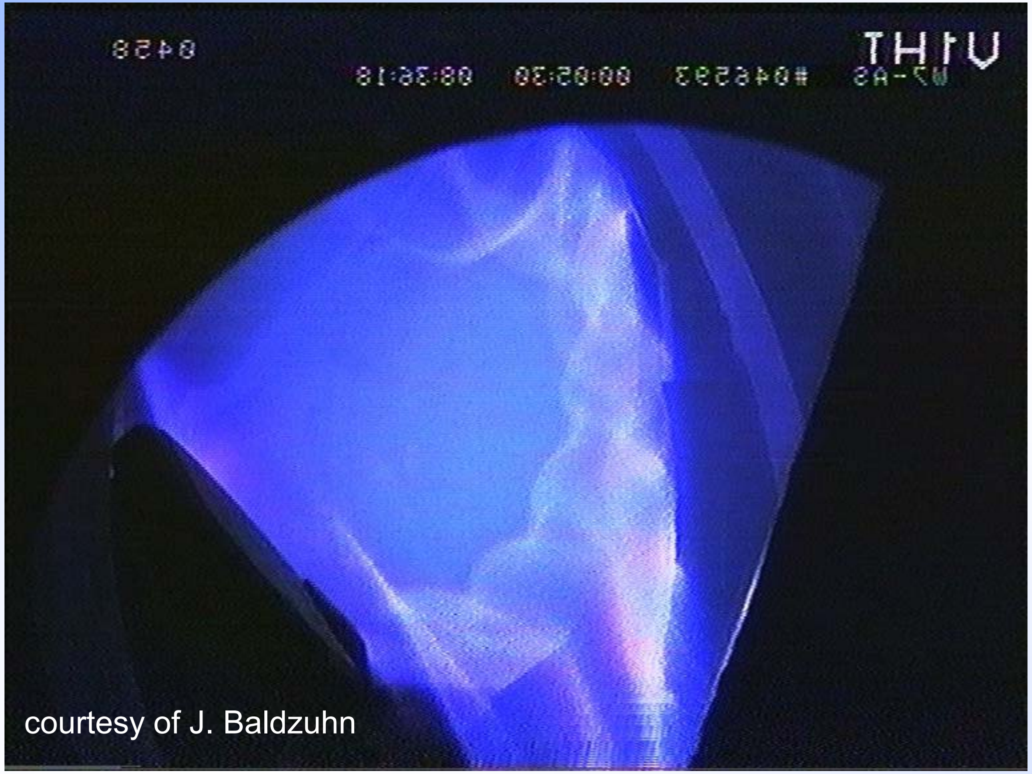
Magnetic island divertor in Wendelstein 7-AS

Divertor module

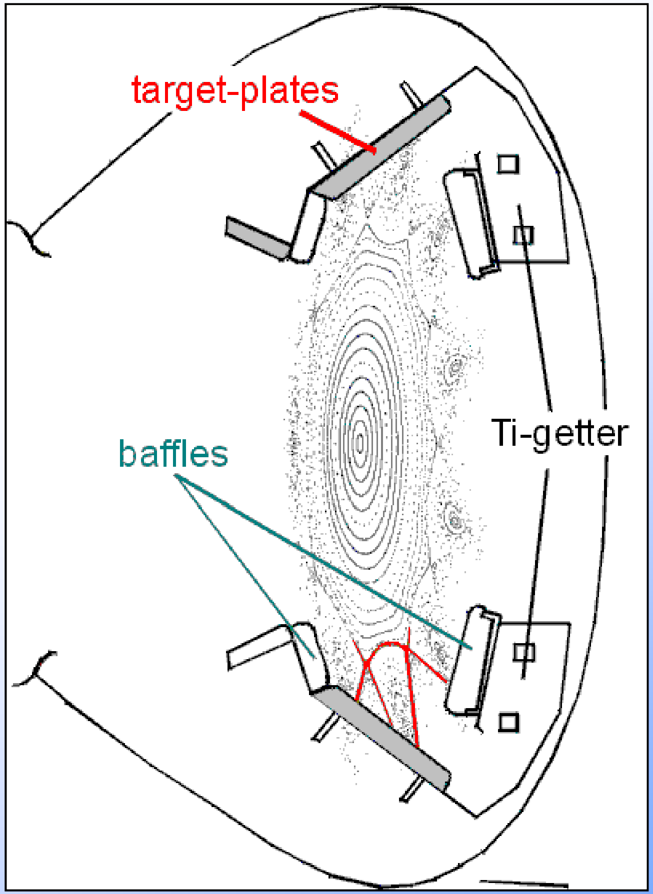


Power and particle exhaust

Magnetic island divertor in Wendelstein 7-AS



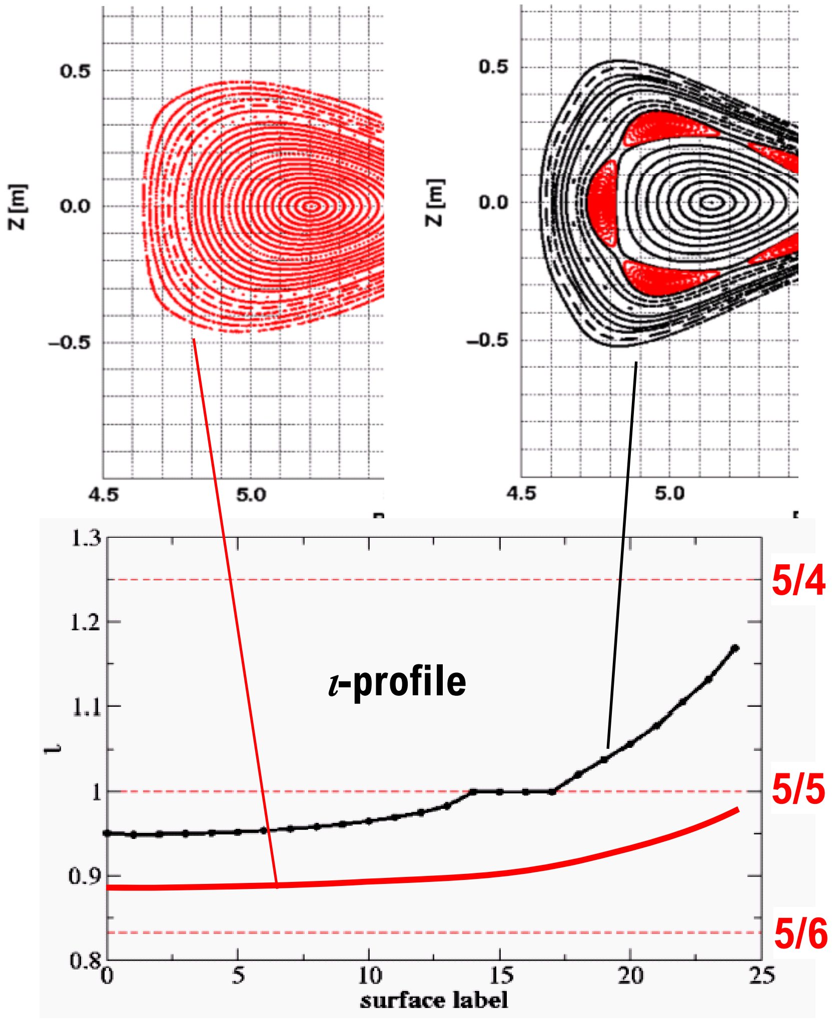
courtesy of J. Baldzuhn

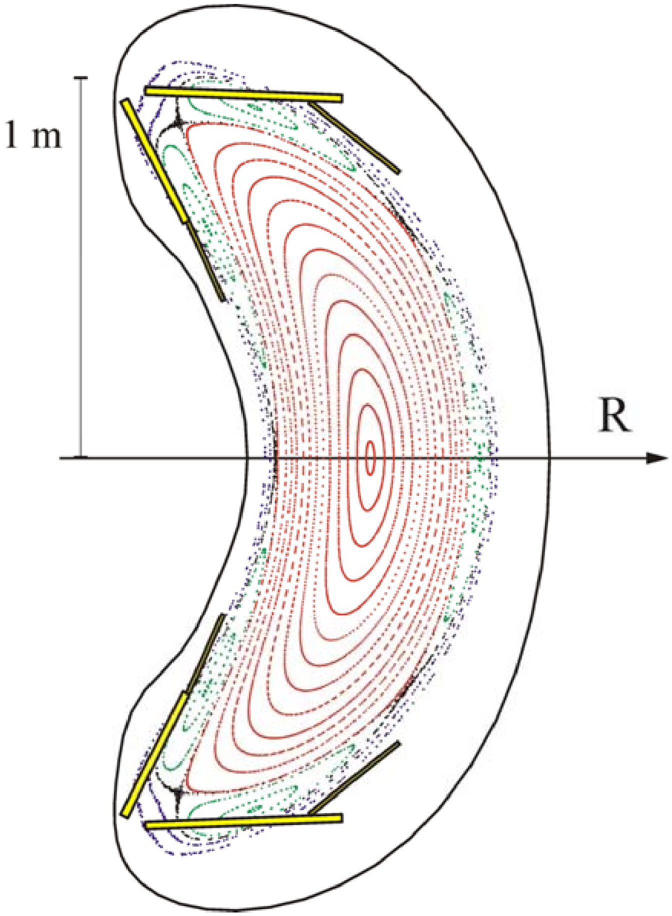


Island divertor requires low magnetic shear and resonance at the plasma boundary

W7-X standard case :
low m,n rationals
avoided

W7-X: high-iota case:
ι = 5/5 resonance
with islands





Low plasma currents are necessary to avoid influence of plasma ι-profile and hence divertor configuration

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The optimization criteria of Wendelstein 7-X

- **Generally small plasma currents guarantee equilibrium configuration which is as much as possible independent from plasma pressure**
- **High plasma stability up to $\langle\beta\rangle = 5\%$**
- **Small neoclassical transport $D \sim \varepsilon_{eff}^{3/2}\, T^{7/2}$**
- **Drift optimization (quasi-isodynamic configuration): Good fast particle confinement**

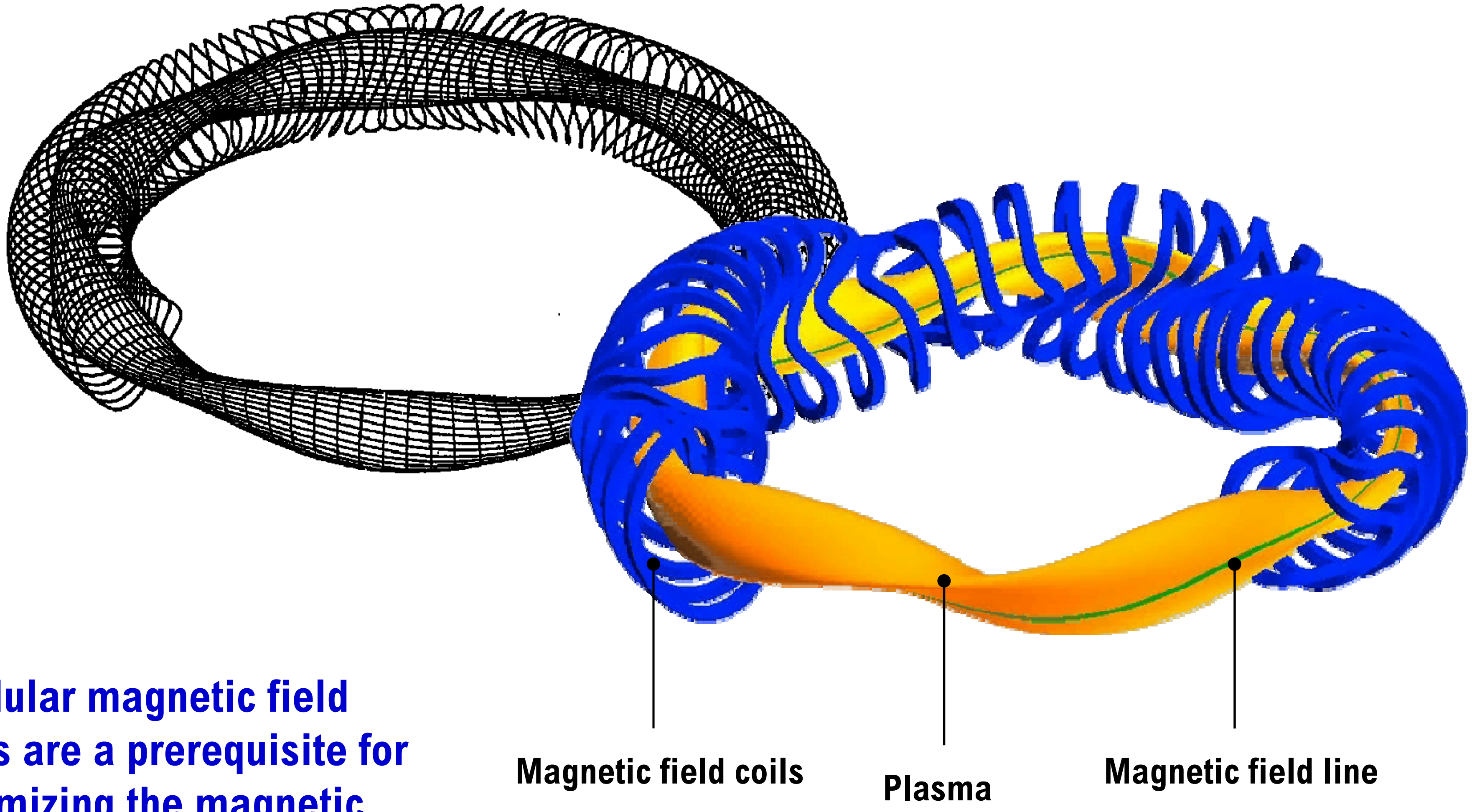
Additional objectives: Steady state operation including particle and energy exhaust with island divertor concept

- **Superconducting coils**
- **Actively cooled divertor and first wall components**
- **Low magnetic shear with large islands at the plasma boundary**
- **ι as much as possible independent of β**

→ In short: Plasma and magnetic field are as much as possible decoupled

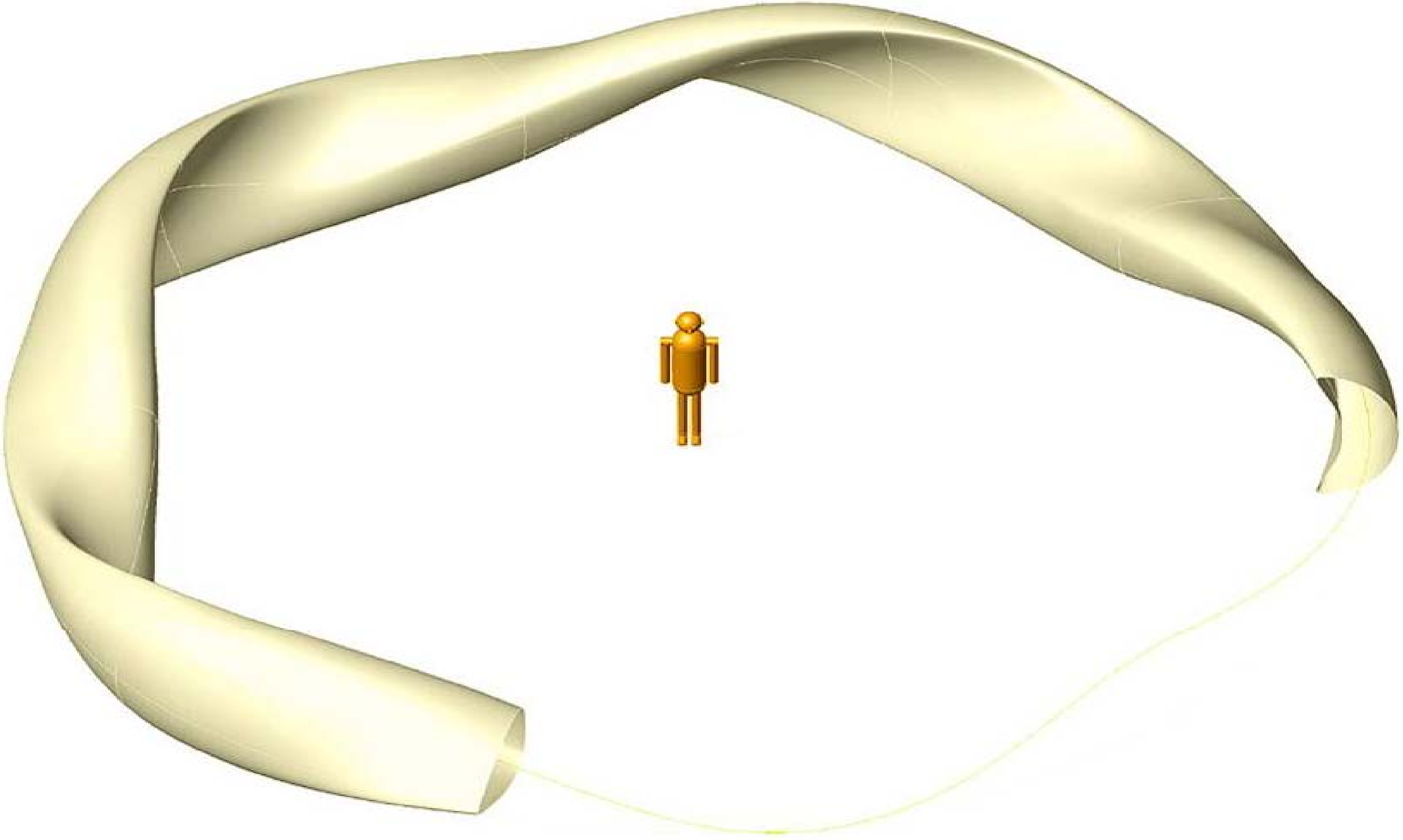
→ Other optimization criteria are thinkable

Wendelstein 7-X

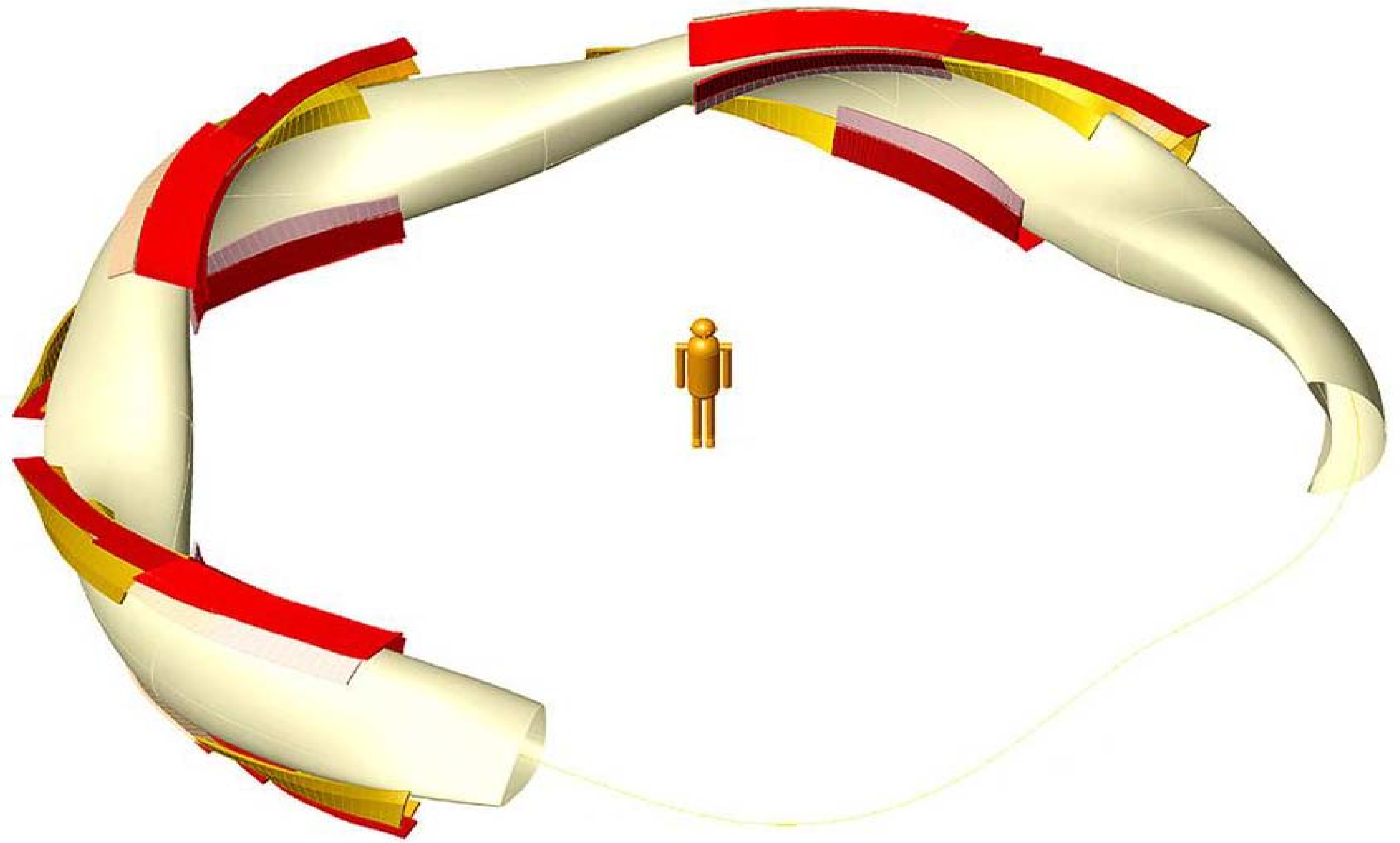


Modular magnetic field coils are a prerequisite for optimizing the magnetic field configuration

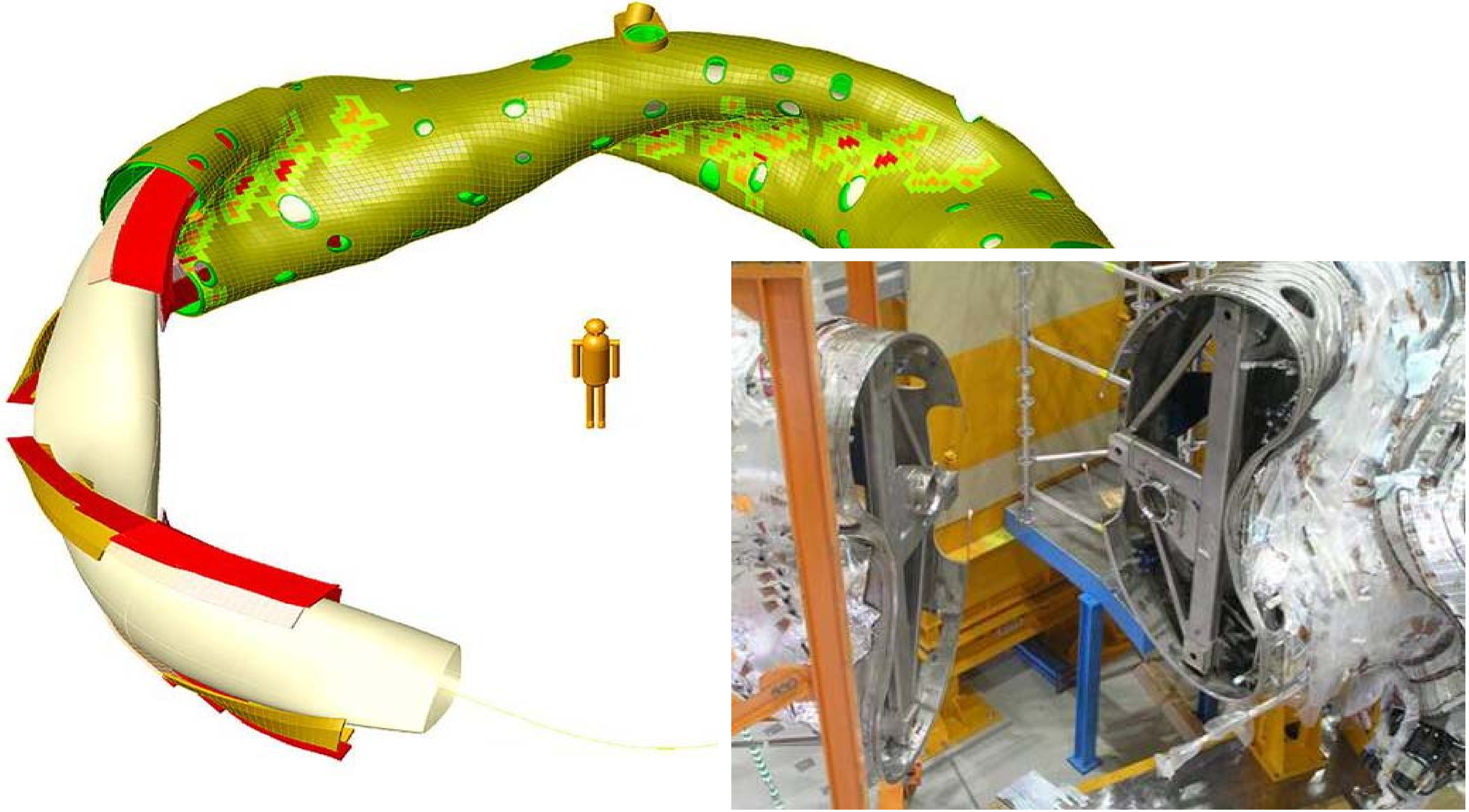
Wendelstein 7-X



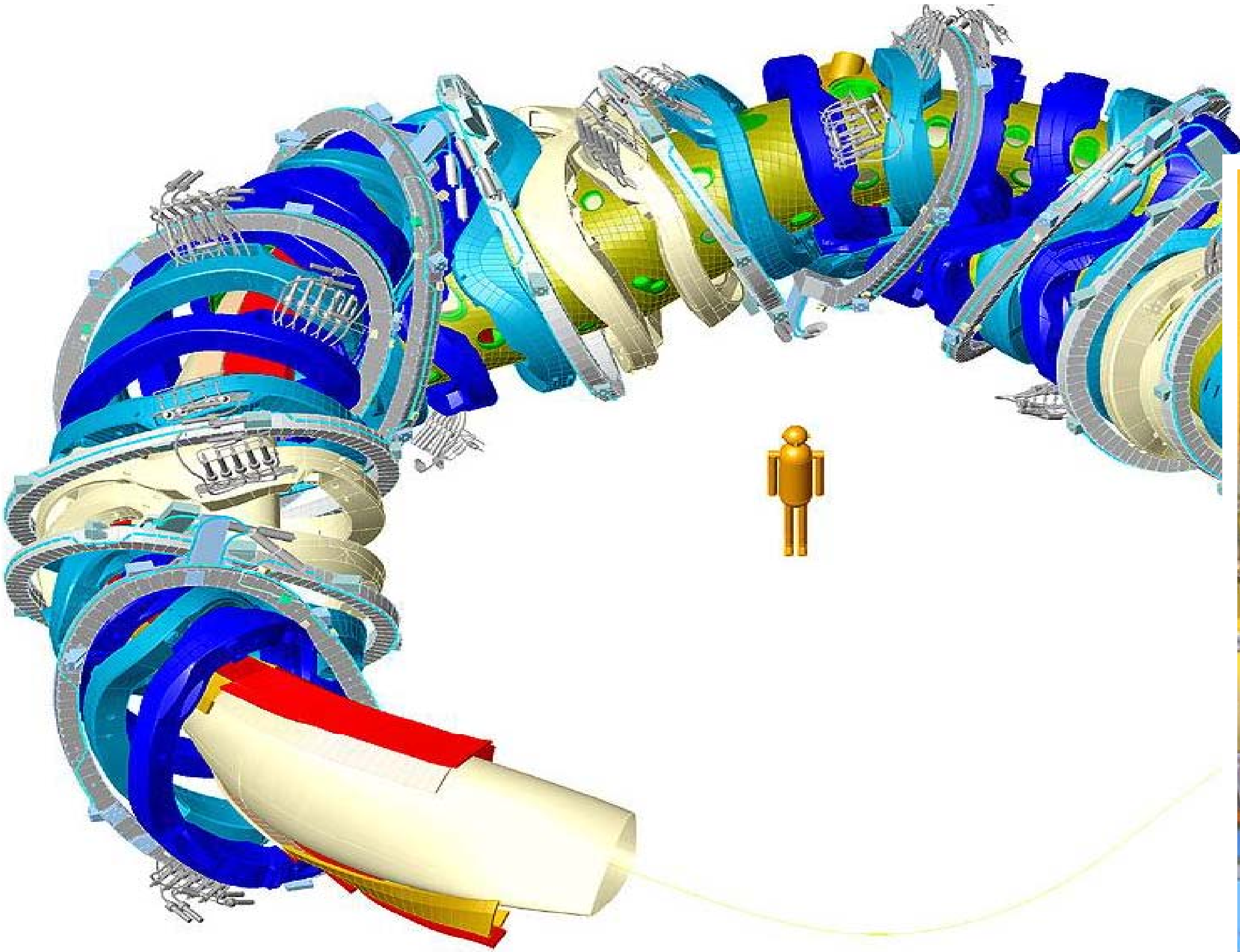
Wendelstein 7-X



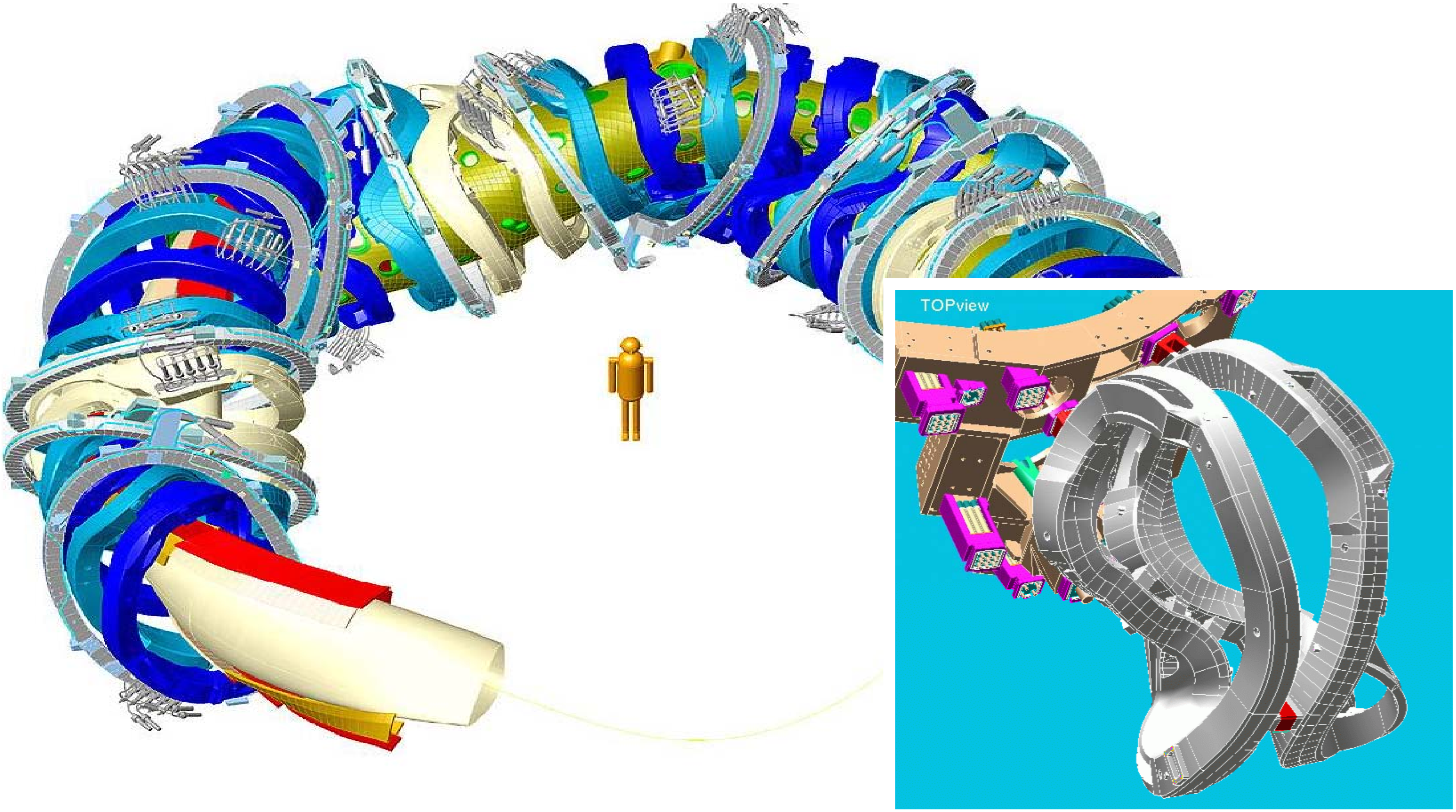
Wendelstein 7-X



Wendelstein 7-X



Wendelstein 7-X



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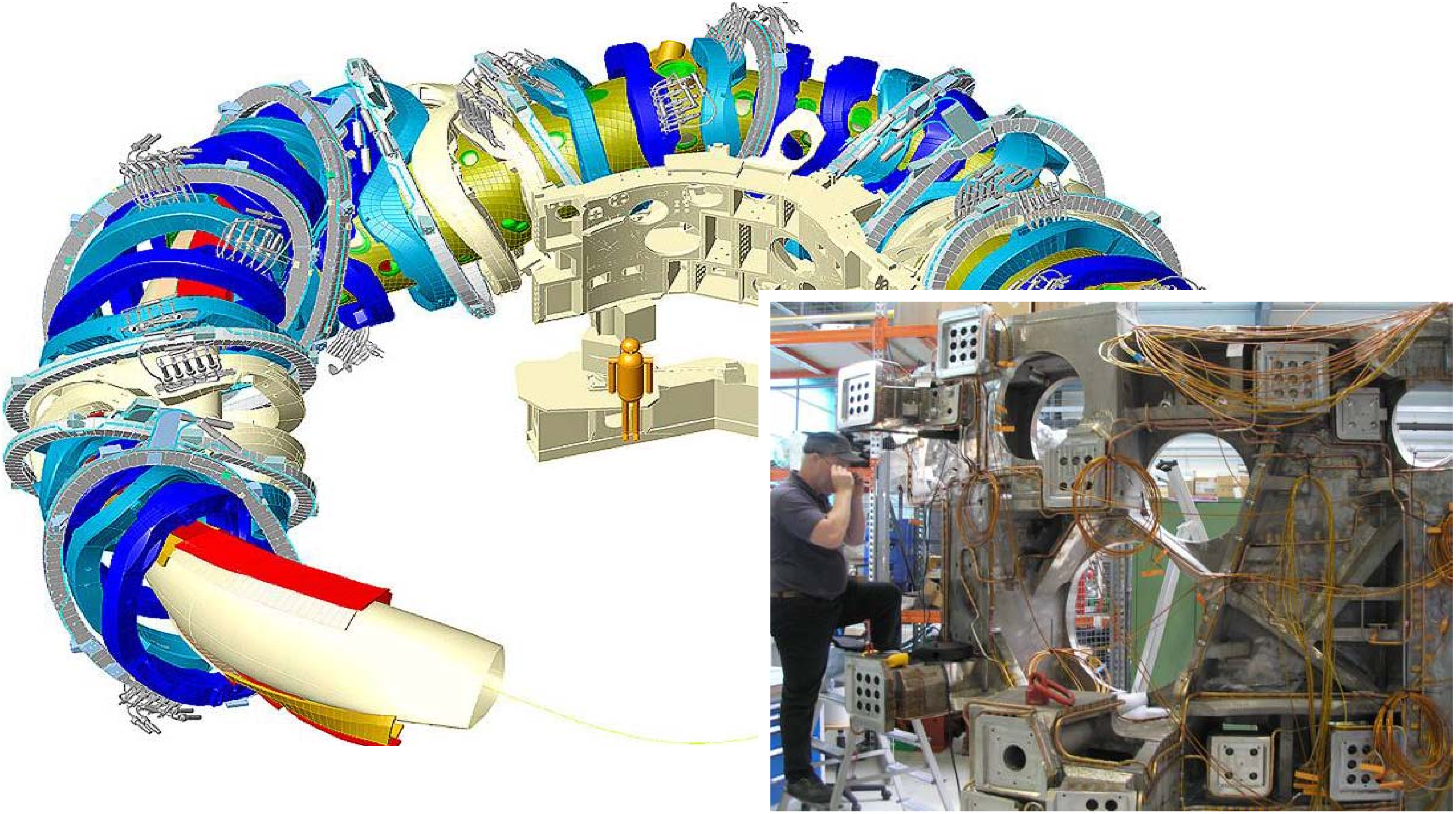

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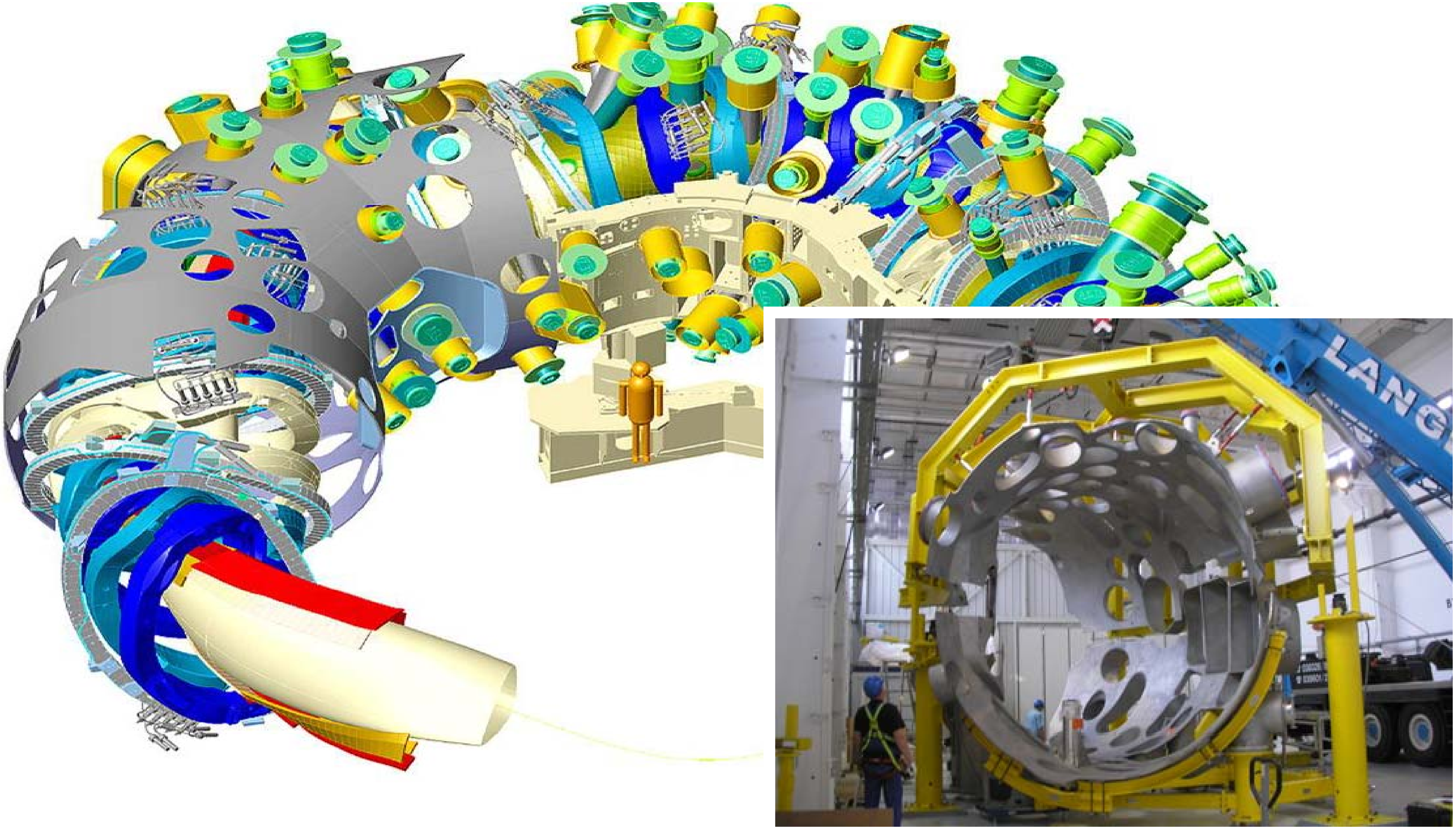

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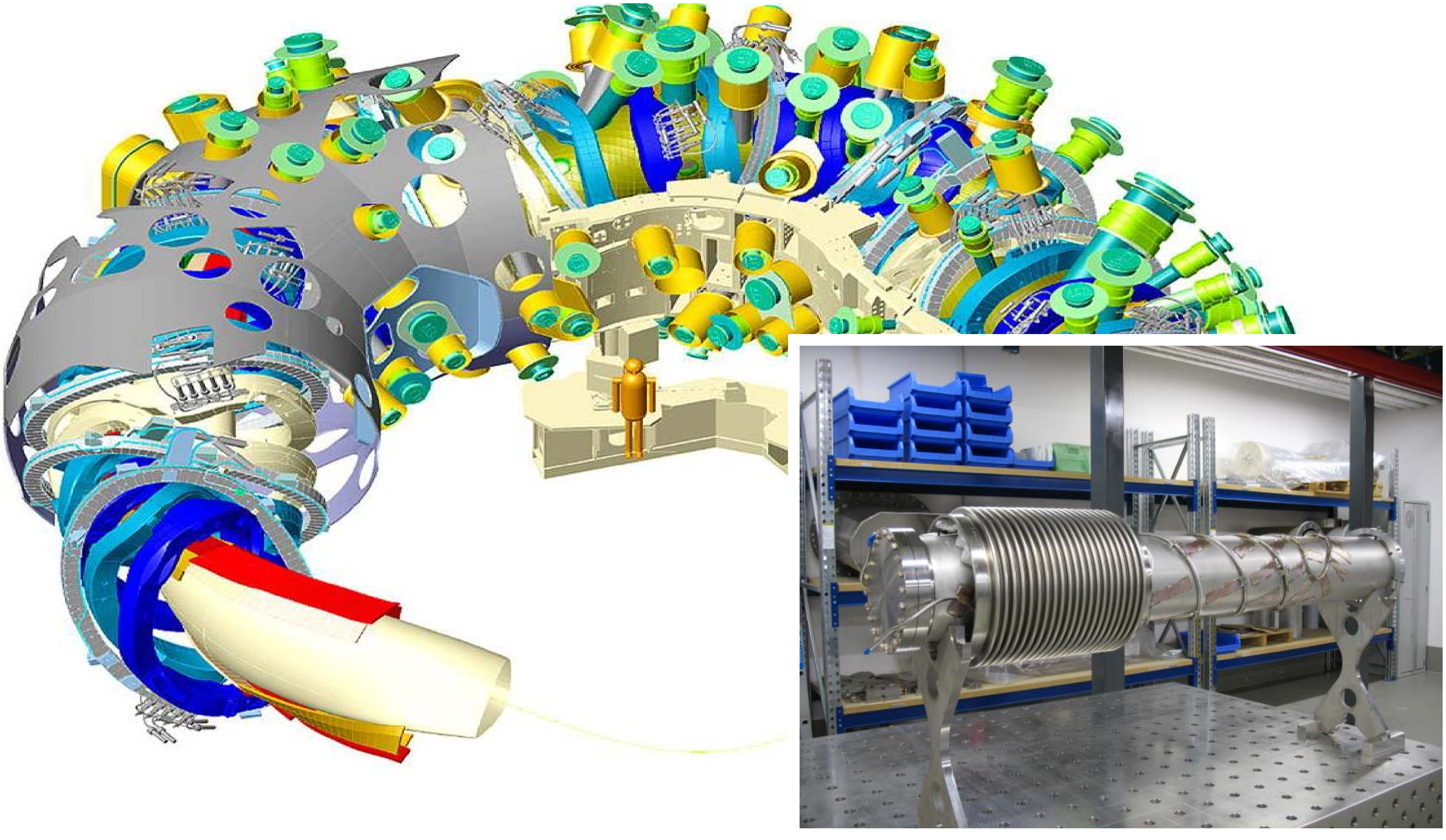
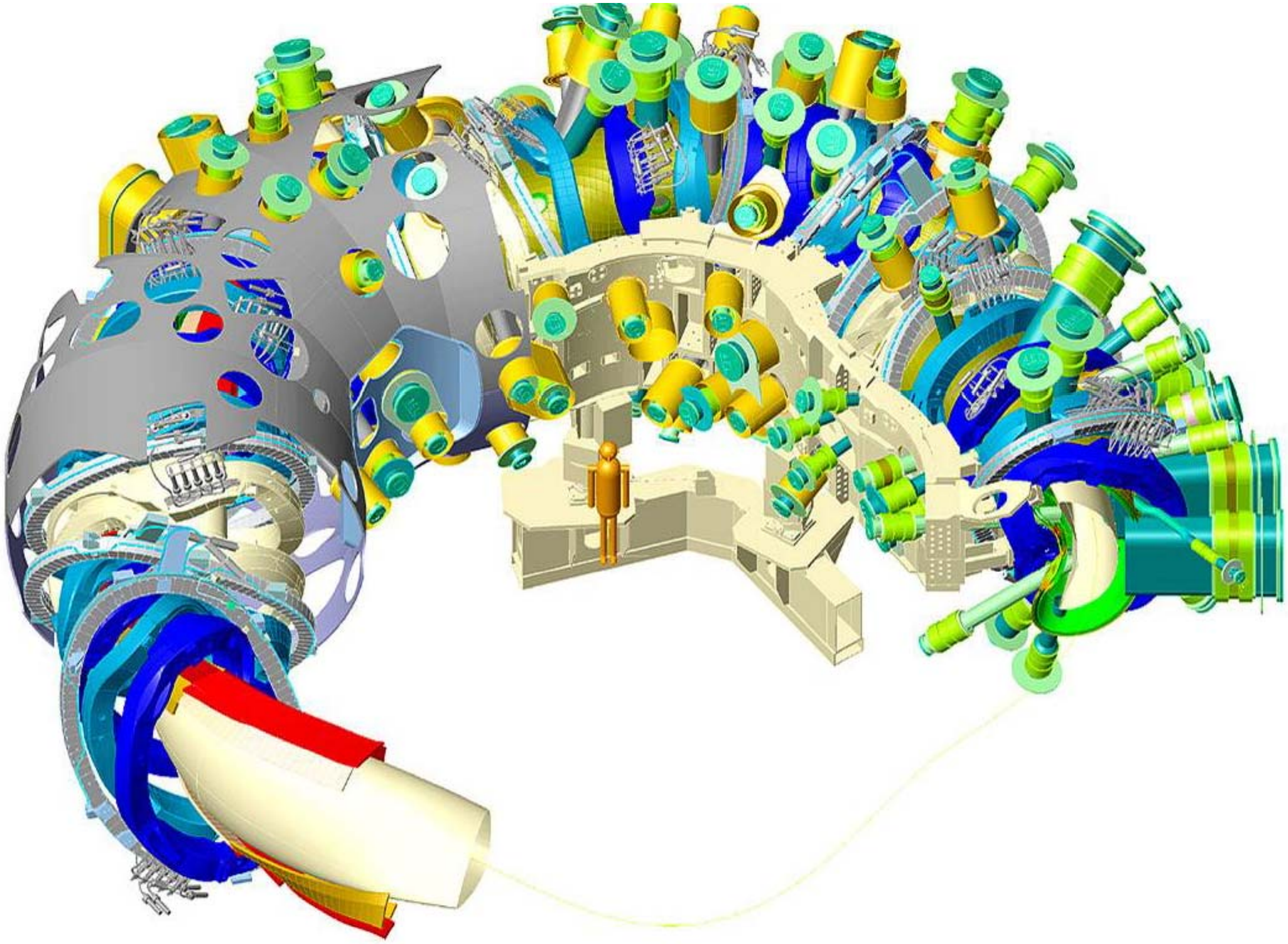


Wendelstein 7-X



Magnetic field
3 T

Superconducting coils
70

Magnetic field energy
600 MJ

Plasma volume
30 m^3

Discharge duration
30 minutes

Heating power
10 MW (30 MW)

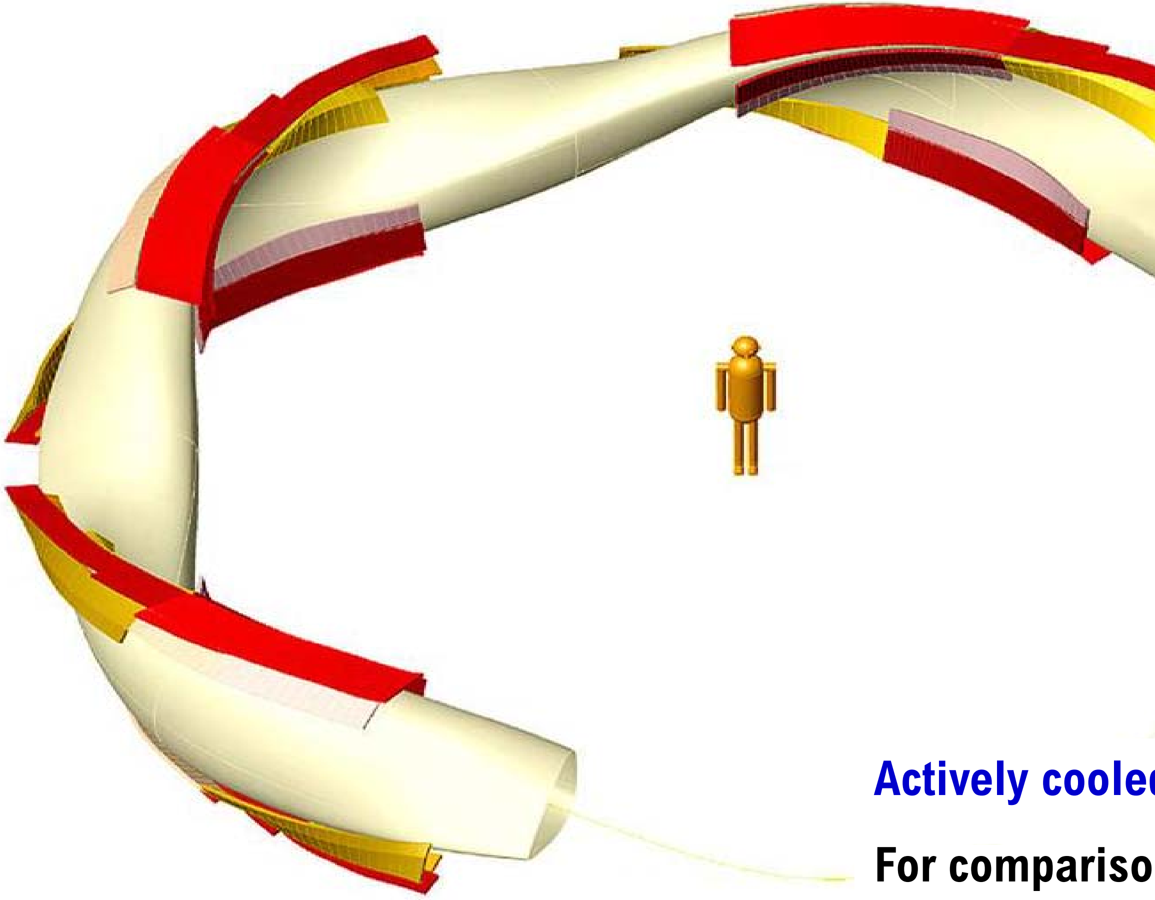
Maximum heat load
10 MW/m^2

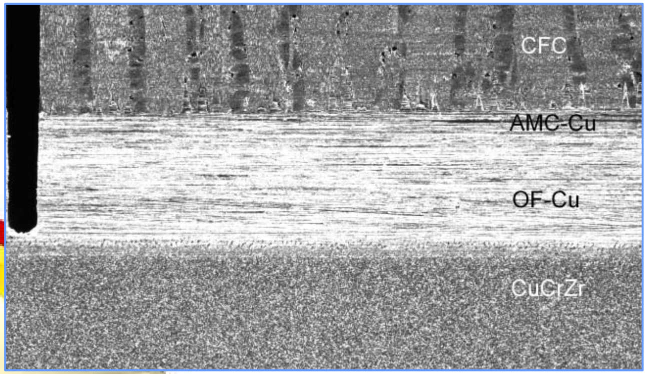
Wendelstein 7-X

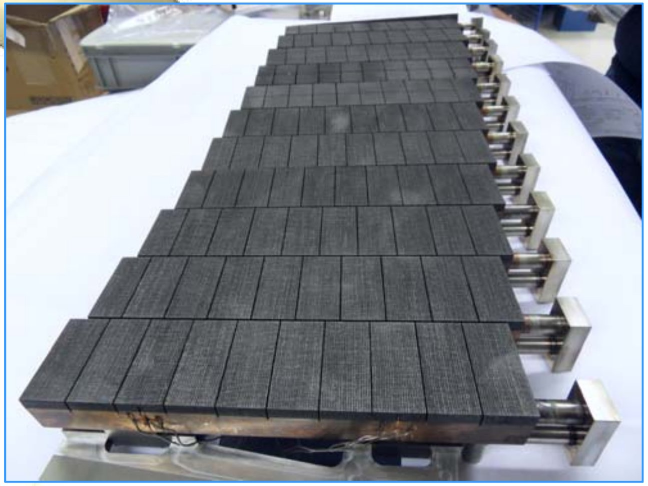
4 of 5 modules in their final position

Completion of assembly 2014

Examples of new technology developments





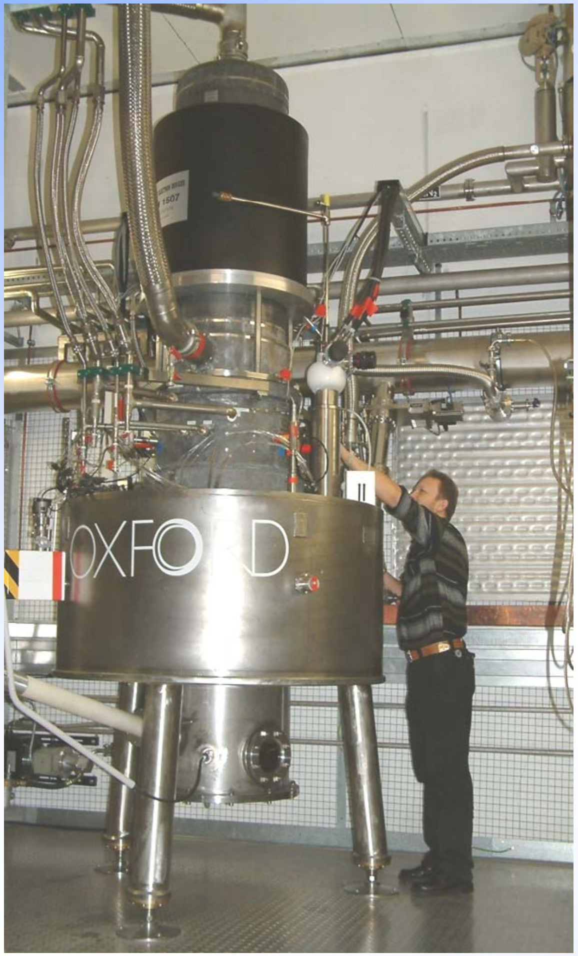


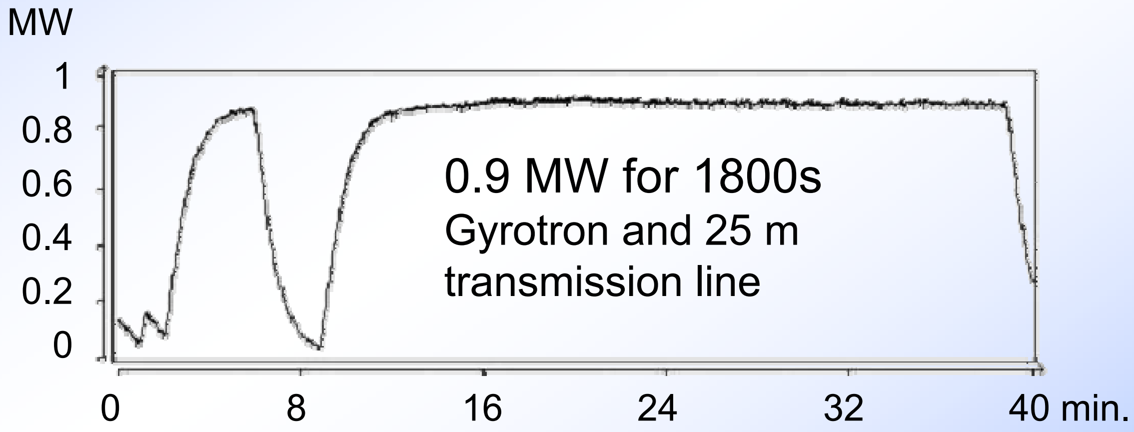
Actively cooled target elements: 10 MW/m²

For comparison heat exchanger of present day power plants: ~ 0,5 MW/m²

Examples of new technology developments

First demonstration of stationary high power microwave heating





0.9 MW for 1800s
Gyrotron and 25 m
transmission line

- **2nd harmonic electron cyclotron resonance heating**
- **140 GHz at 2.5 T**
- **10 × 1 MW for 30 minutes**

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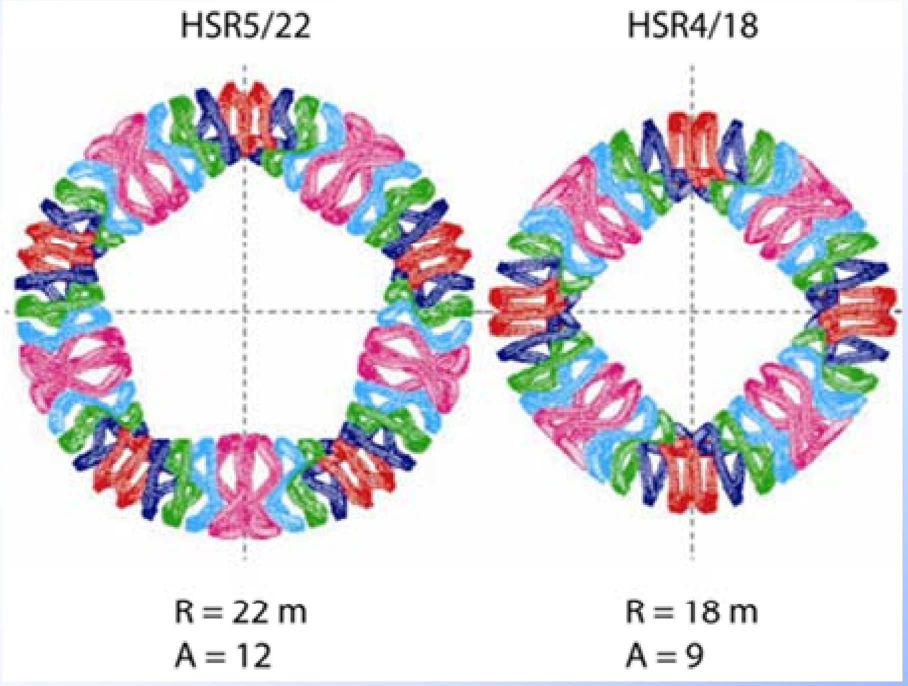
Extrapolation from Wendelstein 7-X

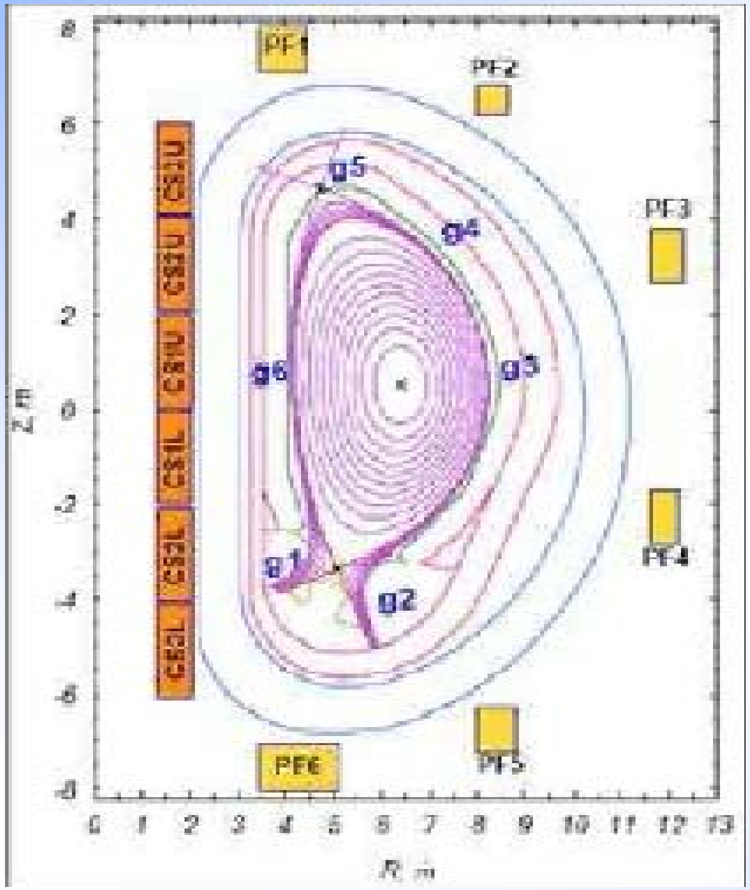
Requirements / parameters

- **Average magnetic field on axis 5T (max. field at coils 10 T)**
  → NbTi with super-fluid He at 1,8 K
  (or Nb_3Al at higher temperatures)
- **Sufficient space for blanket (~1.3 m)**
- **$\langle\beta\rangle = 4 – 5$ % (W7-X value!)**
- **Fusion power ~ 3GW**
- **Advantage of large aspect ratio**
  → reduced neutron flux to the wall (average 1 MW/m^2, peak 1.6 MW/m^2)

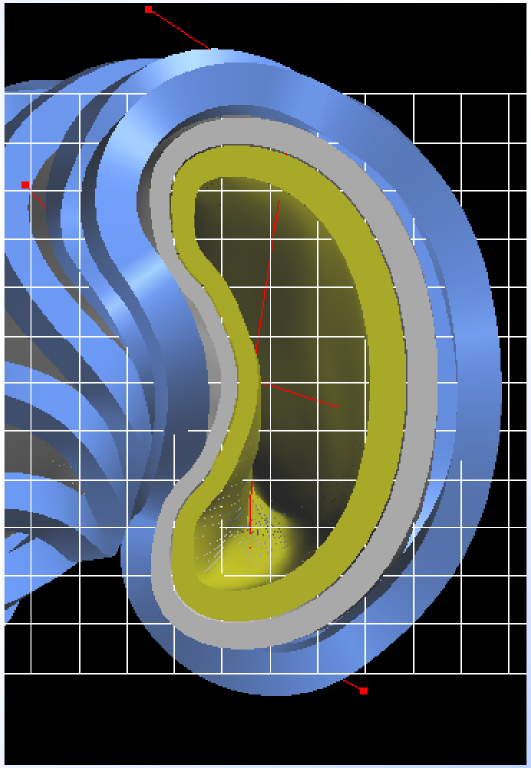


Extrapolation from Wendelstein 7-X

Comparison of ITER and HSR5 coils (same scale)



ITER toroidal field (TF) coil

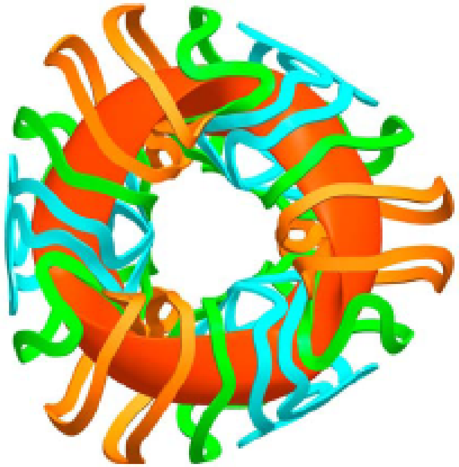


HSR50a coil #5

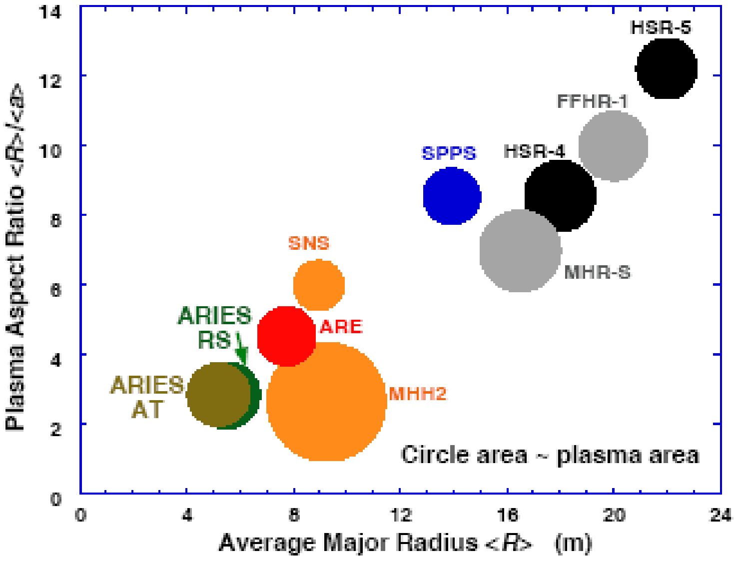
from F. Schauer et al., PFR 2010

Another type of stellarator

Compact stellarator with quasi-toroidal symmetry maximizing the toroidal bootstrap current generated by the plasma



Min. coil-plasma distance (m)	1.3
Major radius (m)	7.75
Minor radius (m)	1.7
Aspect ratio	4.5
β (%)	5.0
Number of coils	18
B_o (T)	5.7
B_{max} (T)	15.1
Fusion power (GW)	2.4
Avg./max. wall load (MW/m^2)	2.6/5.3
Avg./max. plasma q'' (MW/m^2)	0.58/0.76
Alpha loss (%)	~5



from Raffray et al., Fusion Science & Techn. 54 (2008) 725

	JET	ITER	Tokamak DEMO	W7-X	Stellarator DEMO
$nT\tau$ (10^{20}m^{-3} keV s)	1 – 10	60	100	1	100
Fast ion confinement	confirmed	essential	essential	to be confirmed	essential
Burning plasma Q	0,65	10	50	–	50
Fusion power / MW	16	500	2000 - 4000	–	1000 – 3000
Steady state operation	< 60s	400 s	> 8 hrs	30 minutes	steady state
Magnetic field Superconductor	3 T –	6 T yes	6 – 8 T yes	3 T yes	5 – 6 T yes
Neutron load	–	< 2 dpa	up to 150 dpa	–	up to 150 dpa
Blanket	–	test blanket ~ 0.025 g / d	breeding blanket ~ 550 g / d	–	breeding blanket ~ 550 g / d
Stationary cooling	–	10 MW/m^2	≥ 10 MW/m^2	10 MW/m^2	≥ 10 MW/m^2
Remote handling	tests	essential	essential	–	essential

Summary

- Stellarators are a promising alternative to the tokamak concept with beneficial properties
  - Intrinsically steady state (no current drive)
  - Promises to be more economical (reduced re-circulating power)
- The stellarator concept needs optimization to achieve basic confinement properties (thermal plasma and fast particles)
- The optimized stellarator Wendelstein 7-X
  - is designed to decouple plasma and magnetic field configuration as much as possible
  - aims at demonstrating fusion reactor capability of the concept
- Stellarator and tokamak share similar technology issues
- In addition, the stellarator is more complicated, concerning
  - plasma facing components (blanket, divertor, …)
  - maintenance (remote handling)