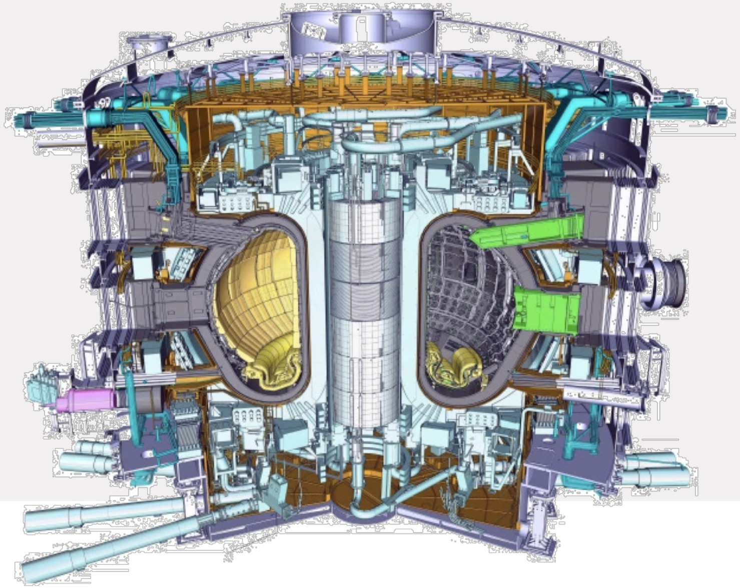
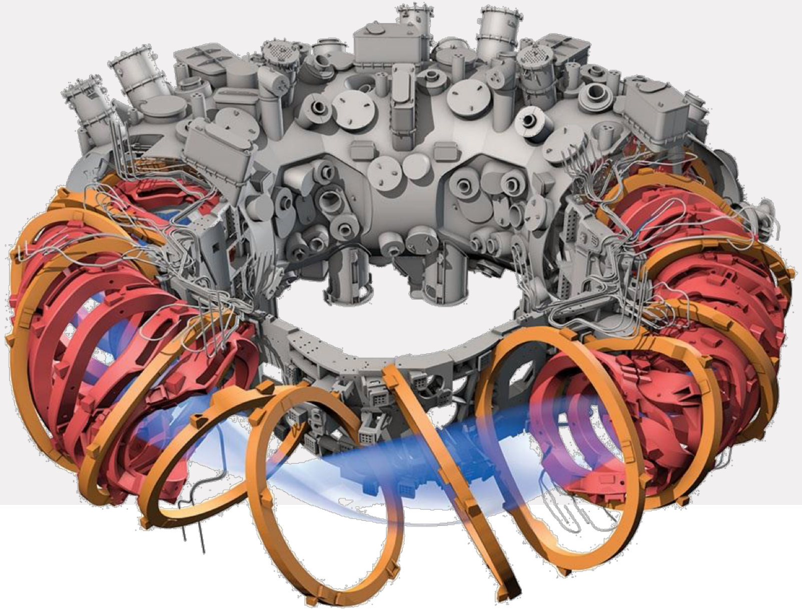
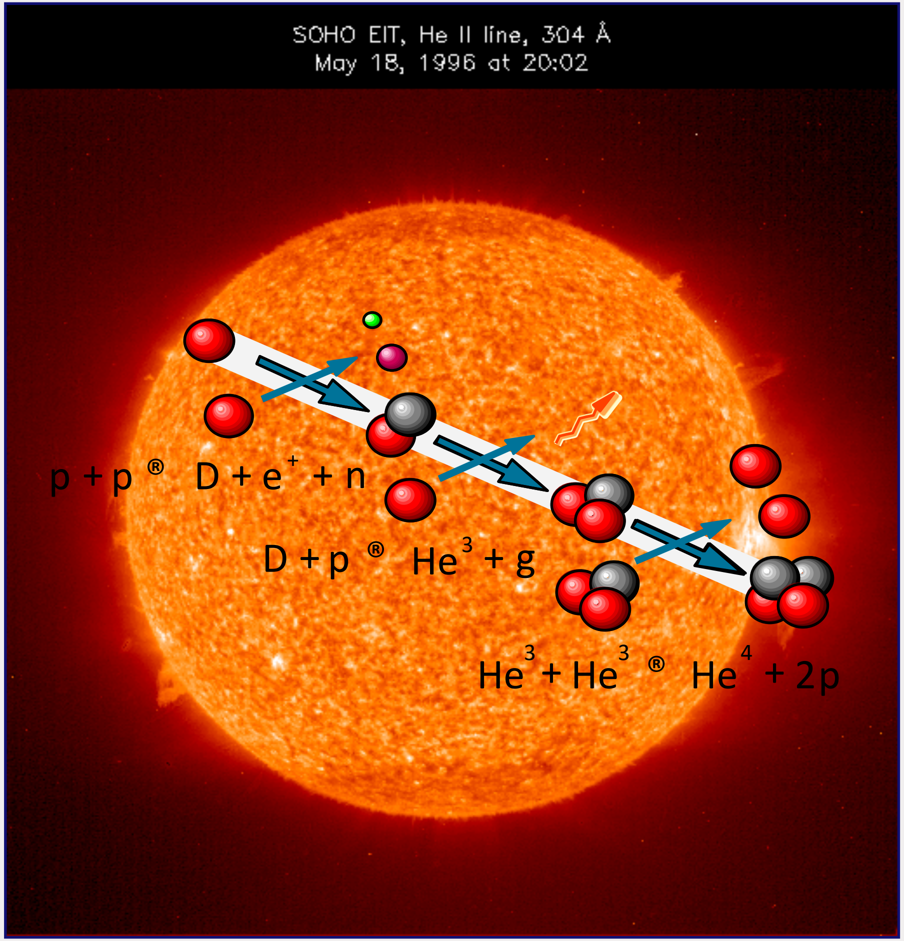
Of tokamaks and stellarators - why in nuclear fusion going simpler is not always better

Josefine H.E. Proll



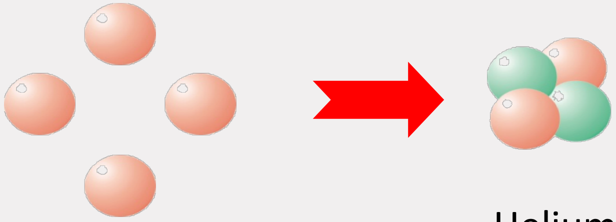




Prototype: nuclear fusion on the Sun

Energy production on Sun: fusion of light atoms

pp cycle



4 protons

Helium

+ energy

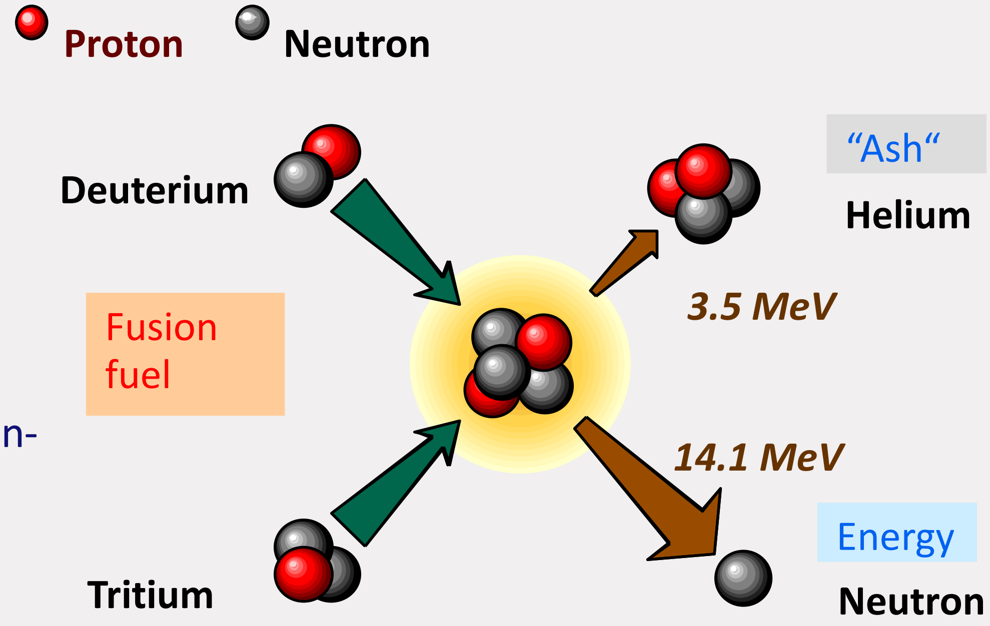
- plasma state
- high temperature: 15 MioK
- high pressure ~ 10^{11} bar
- confinement = gravity
- Low reaction rates, need factor 10^{27} higher in reactor

Fusion on Earth

Deuterium is contained in water (0.015%)

Tritium has to be produced in-situ:

$$^{7}\text{Li} + \text{n} \longrightarrow {}^{4}\text{He} + {}^{3}\text{T} + \text{n}$$



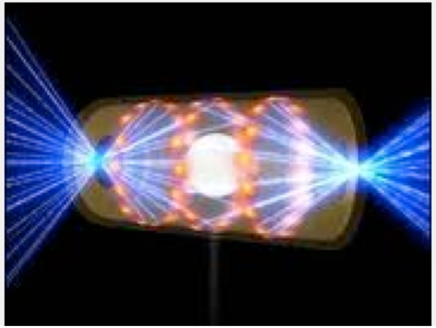
Need: **high temperature T** (overcome Coulomb repulsion)
high density n (higher probability of fusion)
high confinement time τ (energy passed on to heat plasma)

Two (realistic) ways to achieve fusion

Need: product $nT\tau$ time high enough

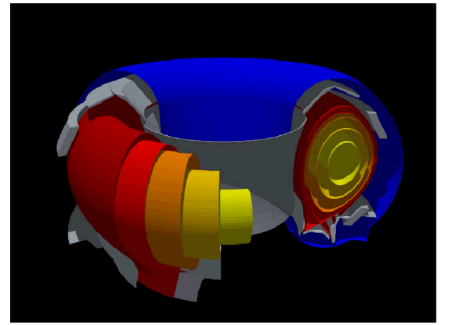
Intertial Confinement Fusion:

- Rapidly heat small pellets by lasers (mini-explosions)
- Pressure comparable to the core of the Sun
- Short confinement time

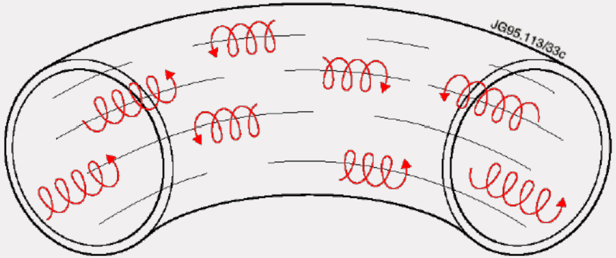


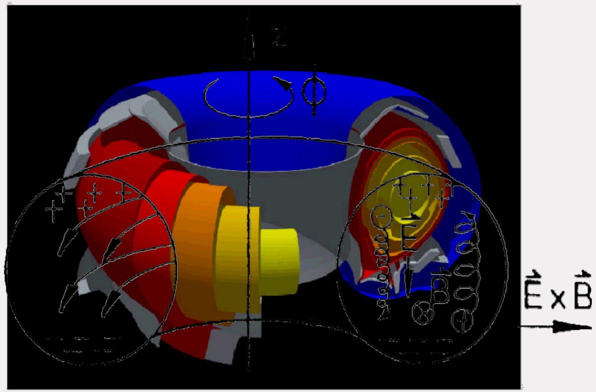
Magnetic Confinement Fusion:

- Confinement via magnetic fields
- very low pressure (< 10 atm)
- Long confinement time



Magnetic confinement Fusion





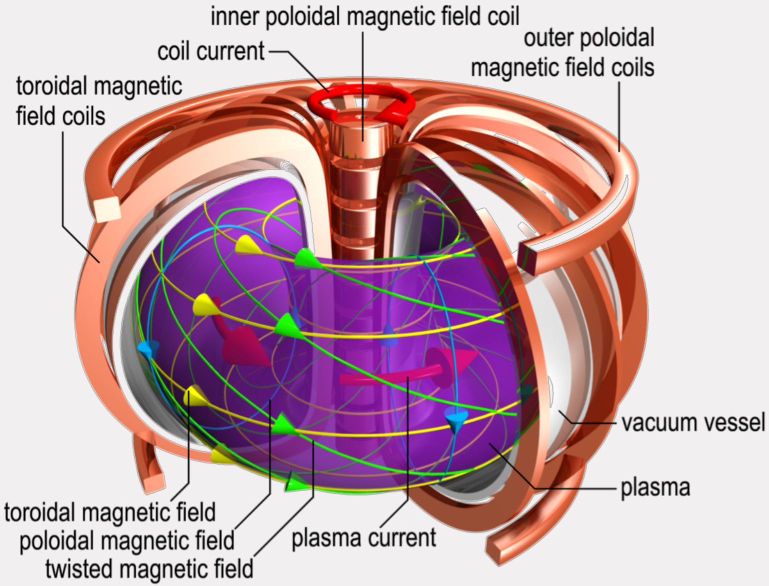
Magnetic field:

- Reduced particle motion perpendicular to the field (confinement of heat and particles)
- Balances plasma pressure

Toroidal field:

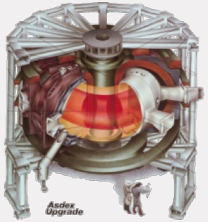
- No end losses
- Need twisted field to prevent perpendicular drifts

Tokamaks – the most investigated concept

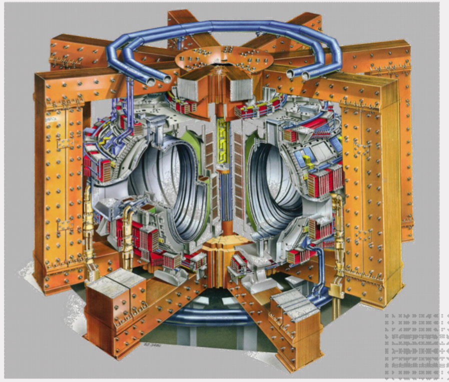


- Concept from 1958
- Magnetic field from coils and plasma current
- Current must be induced by transformer
  (once the plasma is in …)
- Axisymmetric → good confinement
- Some of the most successful experiments so far

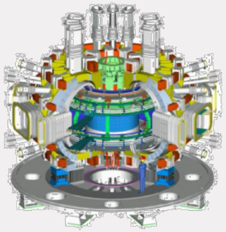
Tokamak experiments world-wide



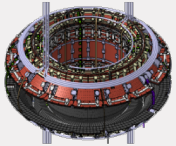
ASDEX Upgrade
Garching (D)



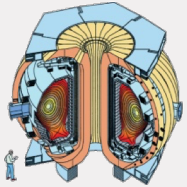
JET
Culham (GB)



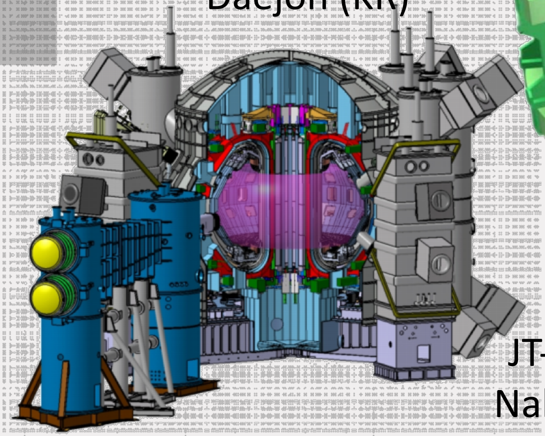
KSTAR
Daejon (KR)



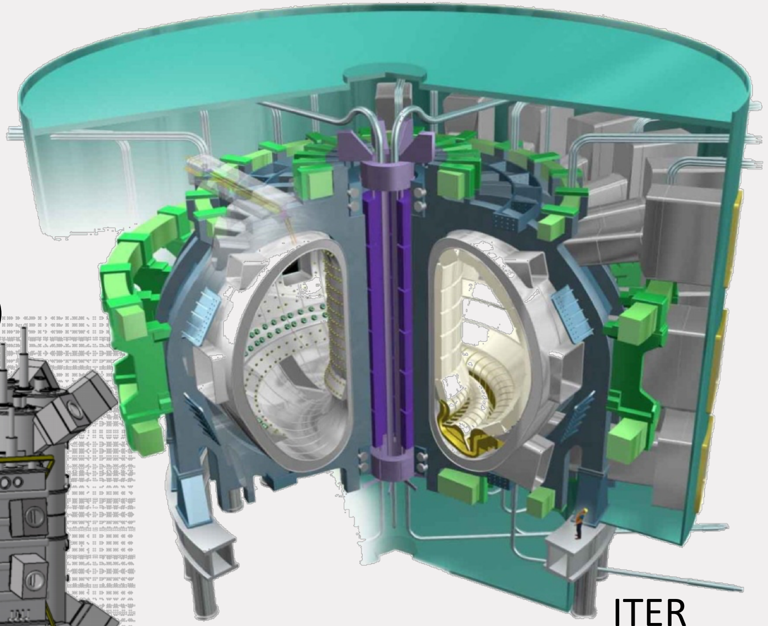
EAST
Chengdu (C)



DIIID
San Diego (USA)



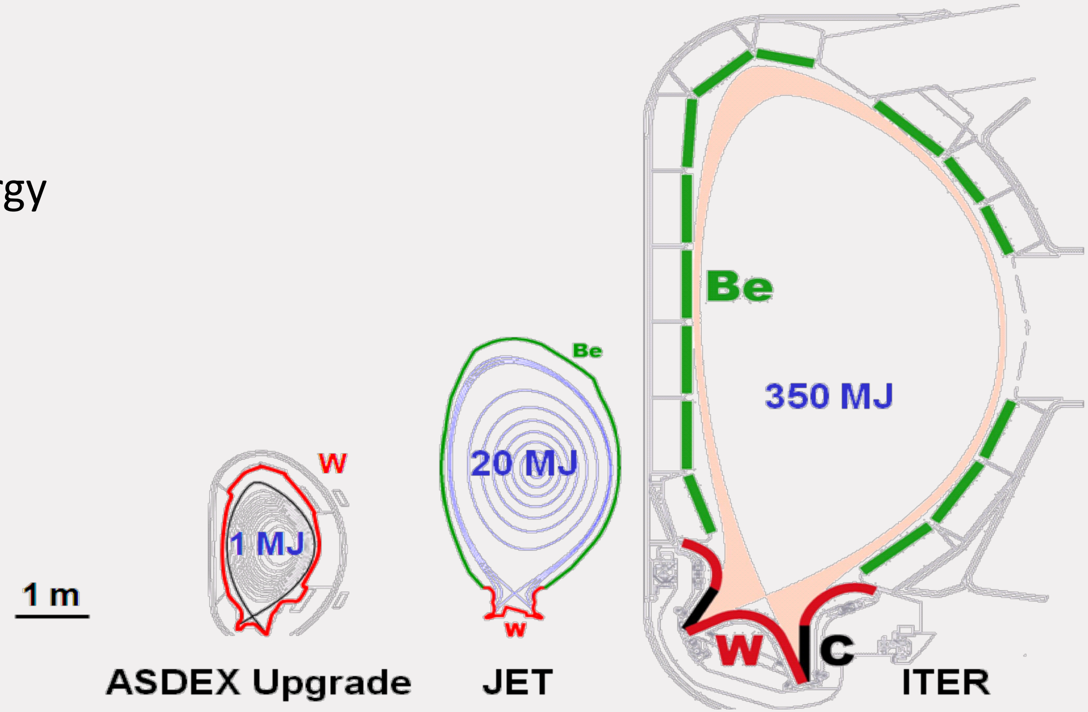
JT-60SA
Naka (JA)



ITER
Cadarache (F)

ITER: based on previous experiments

- ITER shape the same as previous experiments
- Larger size → better energy confinement



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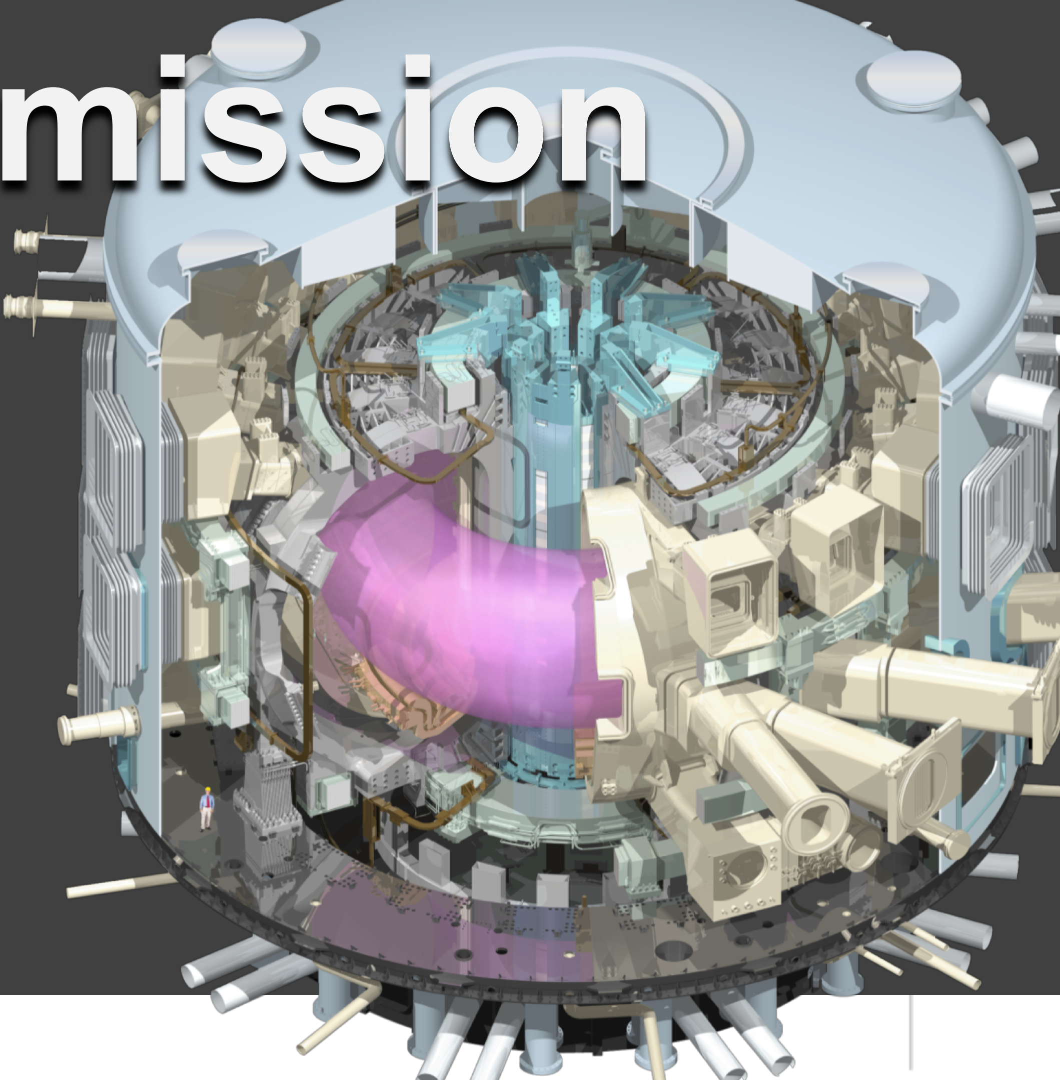
ITER mission

- demonstrate the scientific and technological feasibility of fusion power
- aimed to) produce a burning plasma (self-sustained, $nT\tau$ high enough)

Input (heating) 50 MW → Output 500 MW



ITER

A multinational scientific collaboration without equivalent in history

A large-scale experiment to demonstrate the feasibility of fusion energy

ITER: from paper project to steel-and-concrete reality

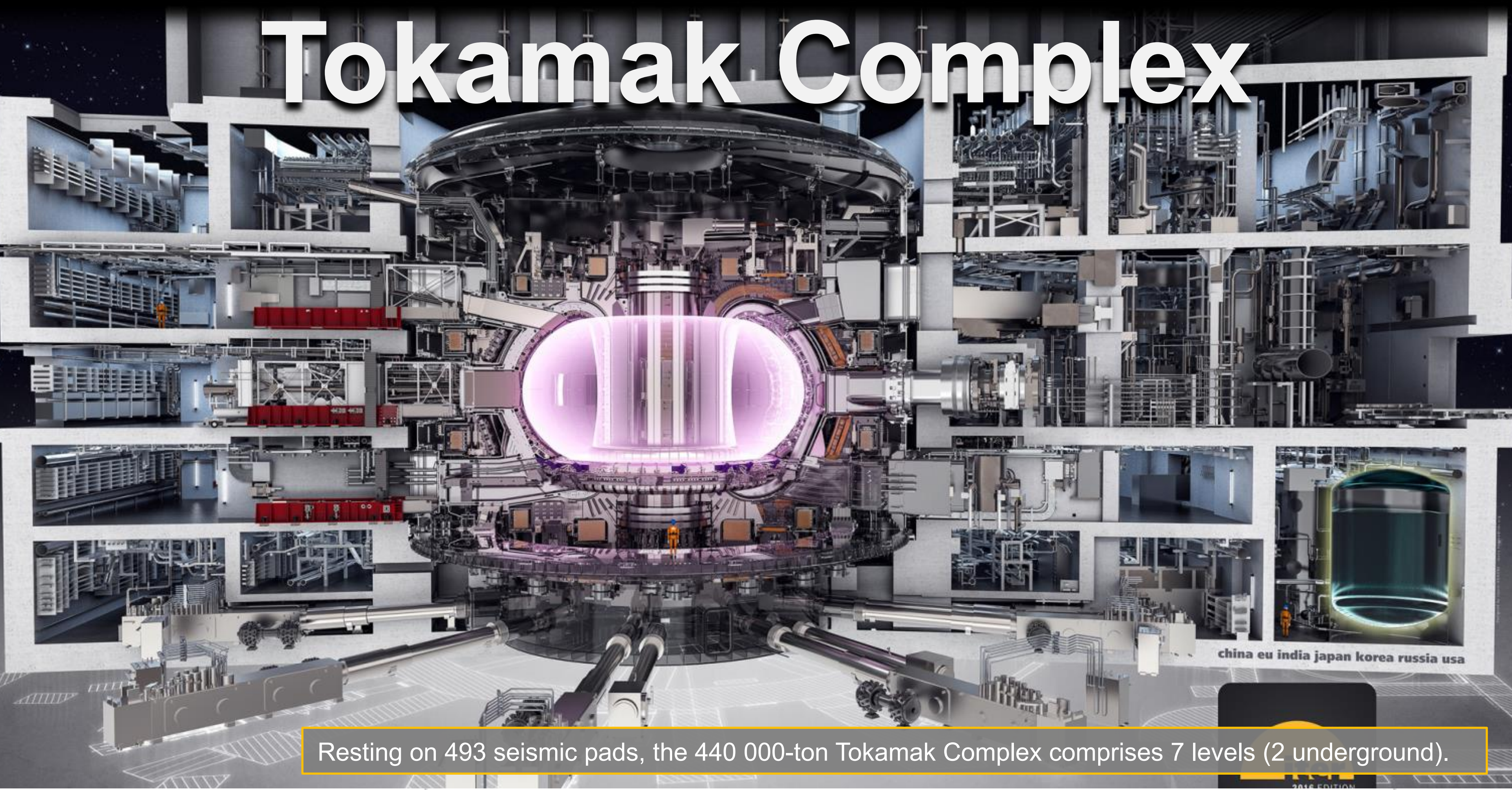
November 1985
At the Geneva Summit P^{dt} Reagan and Secretary G^{al} Gorbatchev give a decisive political push to an international collaboration on fusion *"for the benefit of all mankind"…*

January 2007
Preparation works by France (clearing, levelling, etc.) begins on the 42-hectare ITER Platform.

June 2005
The ITER Members unanimously agree to build ITER on the site proposed by Europe in southern France.

August 2010
Construction works begin in earnest.

Tokamak Complex

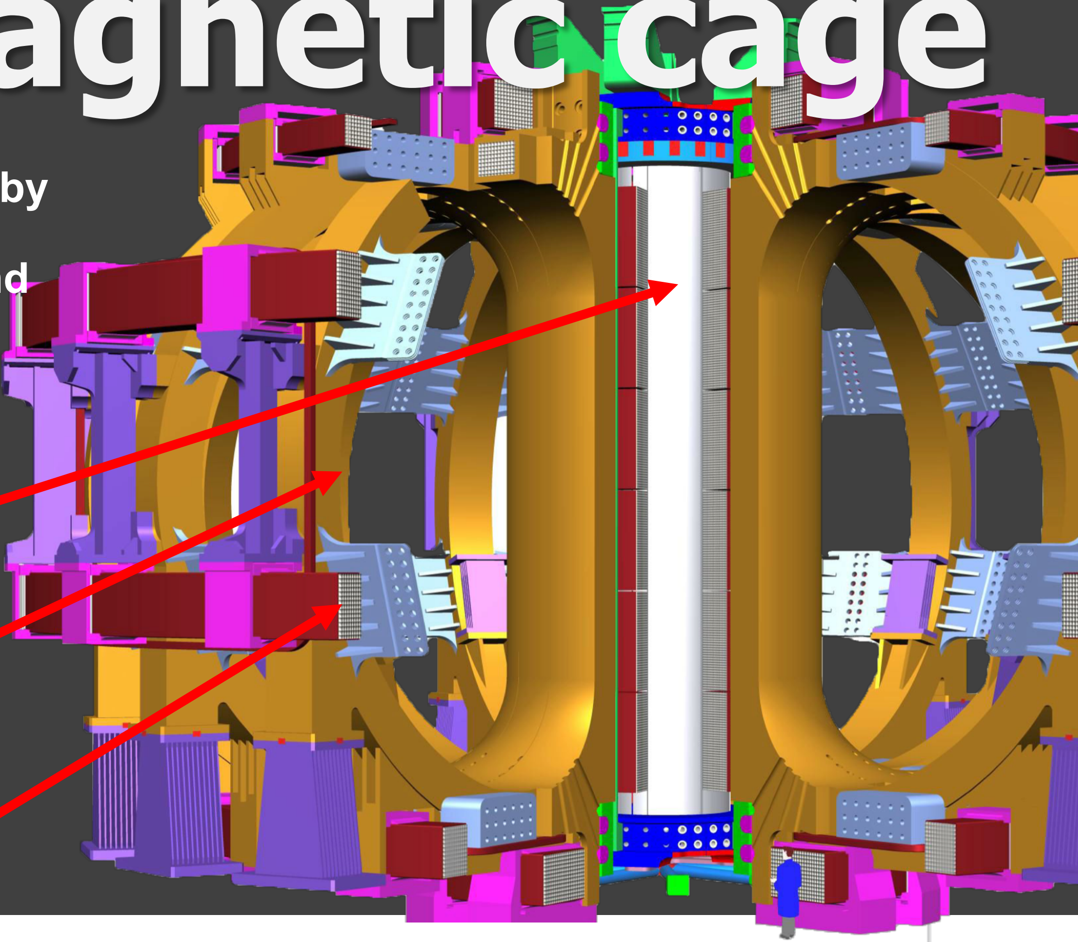


Resting on 493 seismic pads, the 440 000-ton Tokamak Complex comprises 7 levels (2 underground).

A large magnetic cage

An intense magnetic field, generated by powerful superconducting magnets shape and confine the hot plasma, and keep it away from the vacuum vessel wall.

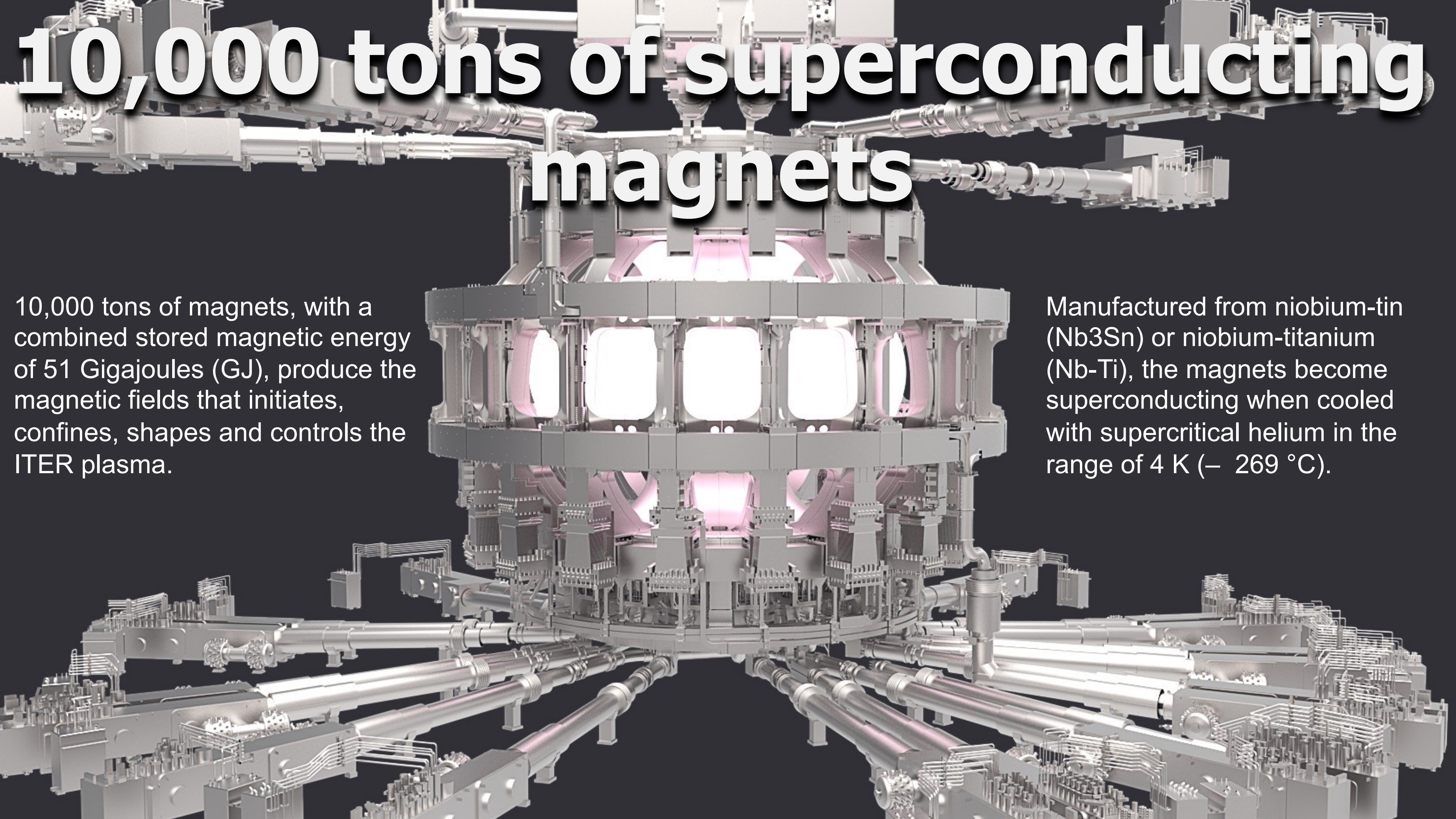
- **1 central solenoid, 13 m high, 1,000 tons, powerful enough to lift an aircraft-carrier out of the water**
- **18 Toroidal Field Coils, 17-metre high, 360 tons each.**
- **6 Poloidal Field Coils, 8 to 24 m. in diametre, 200 to 400 tons.**



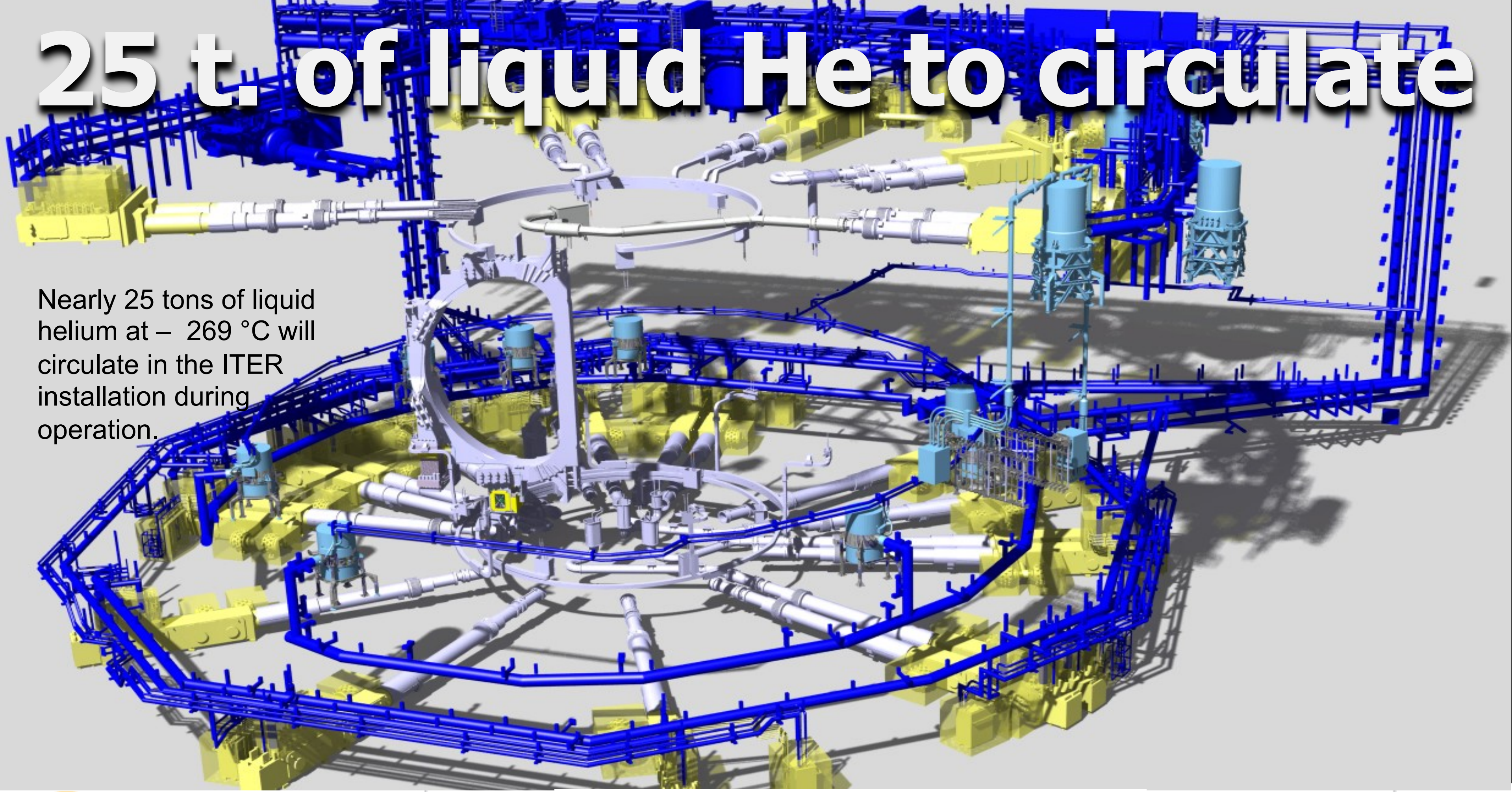
10,000 tons of superconducting magnets

10,000 tons of magnets, with a combined stored magnetic energy of 51 Gigajoules (GJ), produce the magnetic fields that initiates, confines, shapes and controls the ITER plasma.

Manufactured from niobium-tin (Nb3Sn) or niobium-titanium (Nb-Ti), the magnets become superconducting when cooled with supercritical helium in the range of 4 K (– 269 °C).

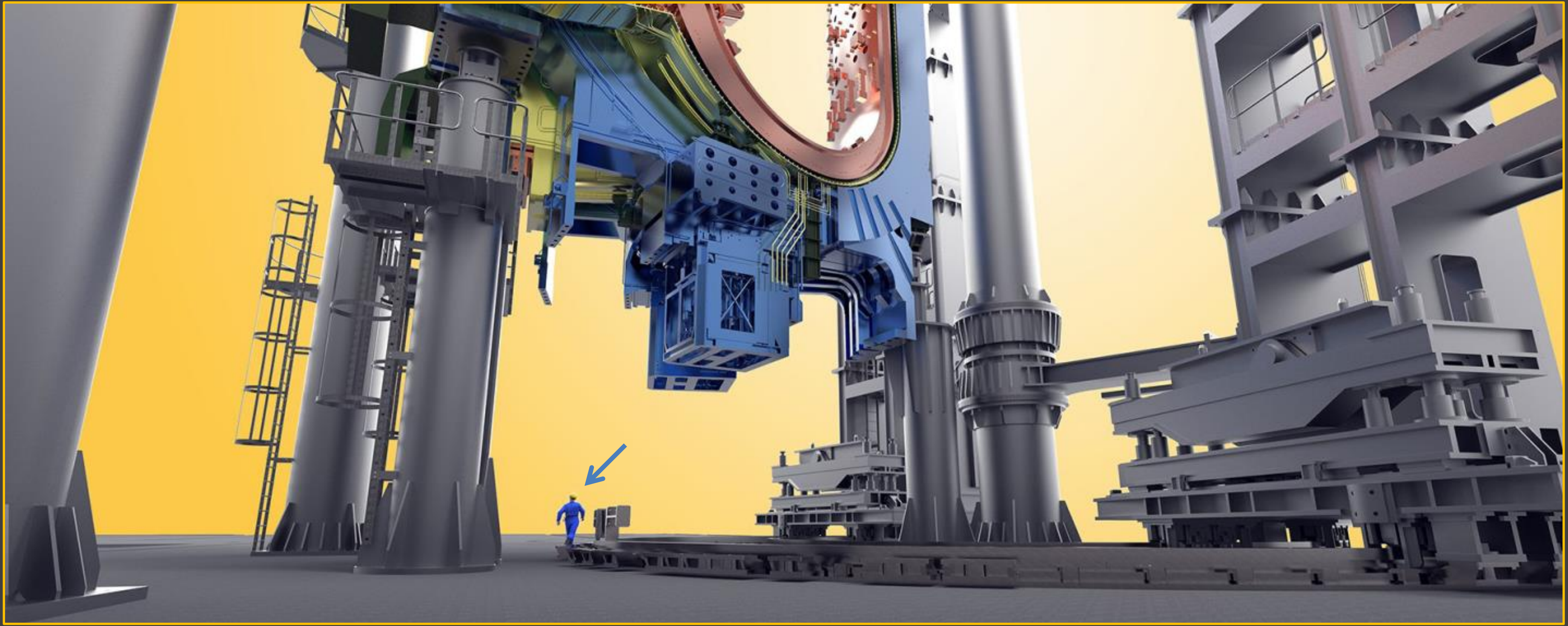


25 t. of liquid He to circulate



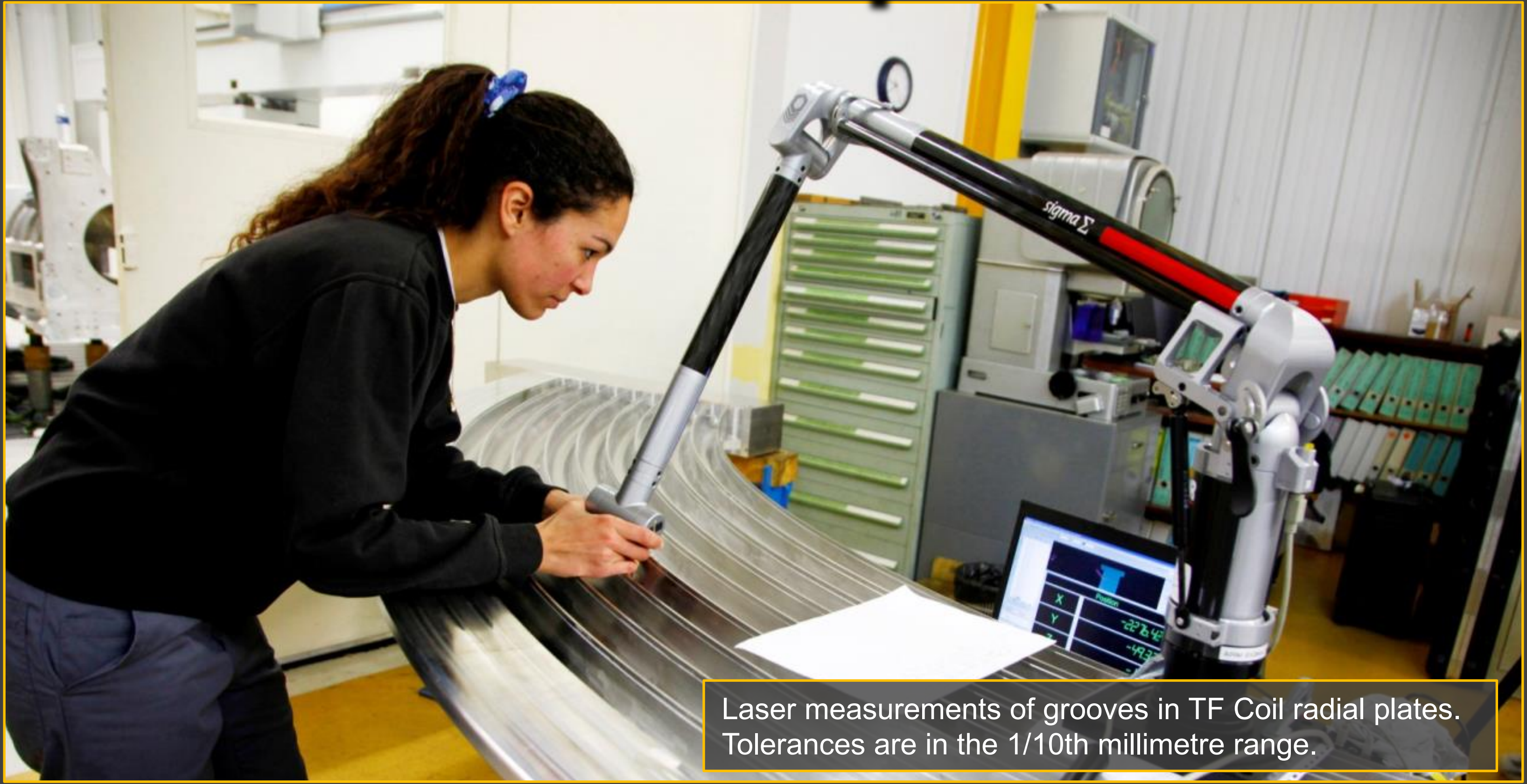
Nearly 25 tons of liquid helium at – 269 °C will circulate in the ITER installation during operation.

Naval construction-size components...



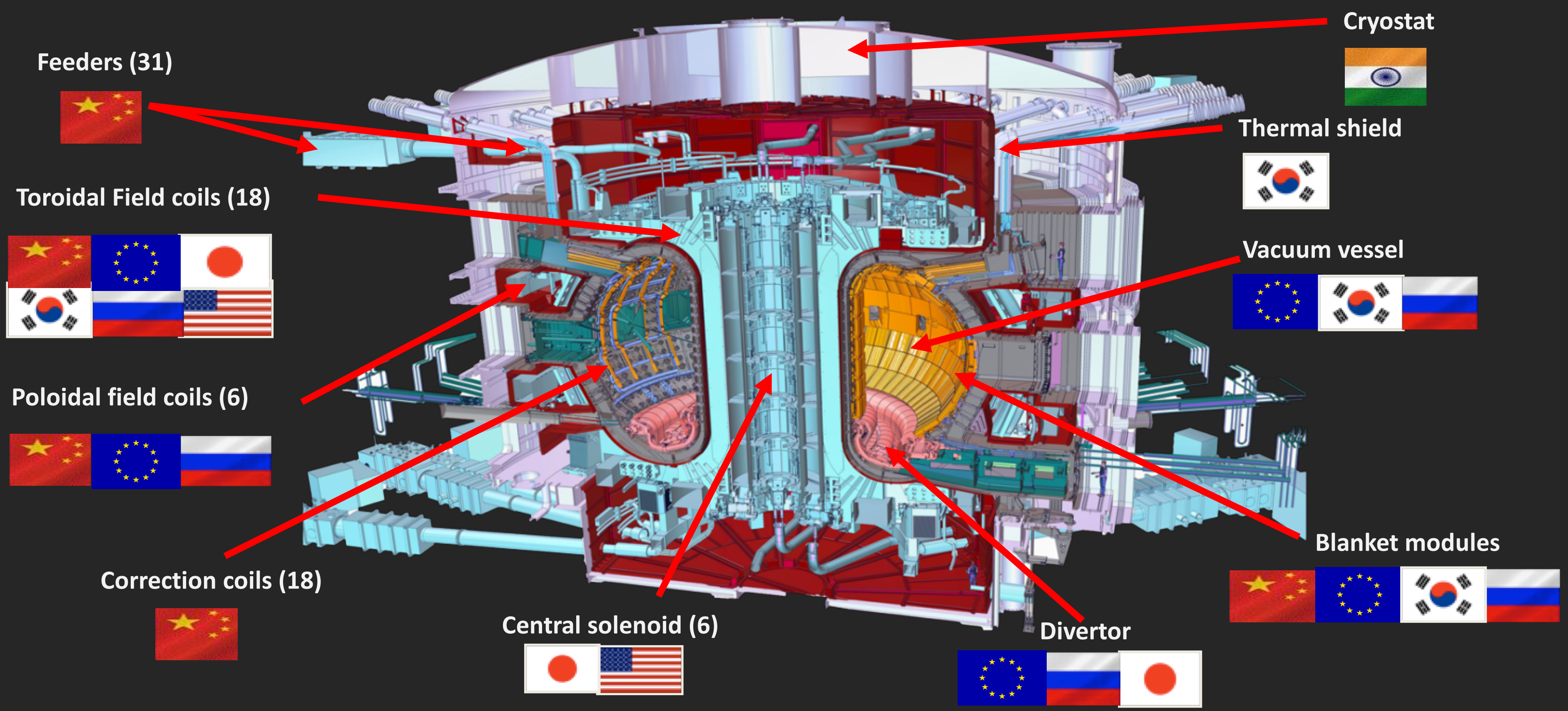
Inside the Assembly Hall, giant tools will handle loads up to 1,500 tons

...watch-like precision

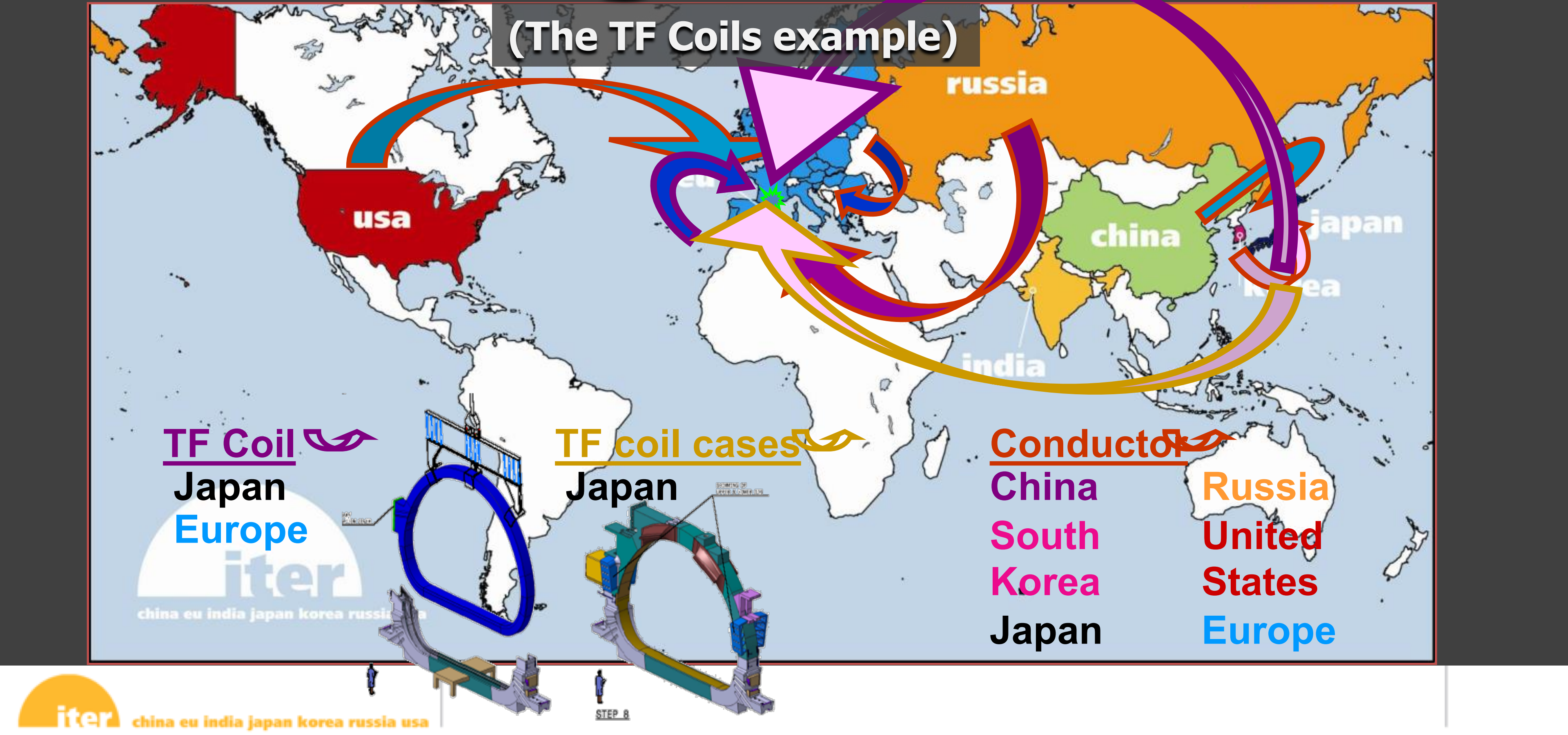


Laser measurements of grooves in TF Coil radial plates.
Tolerances are in the 1/10th millimetre range.

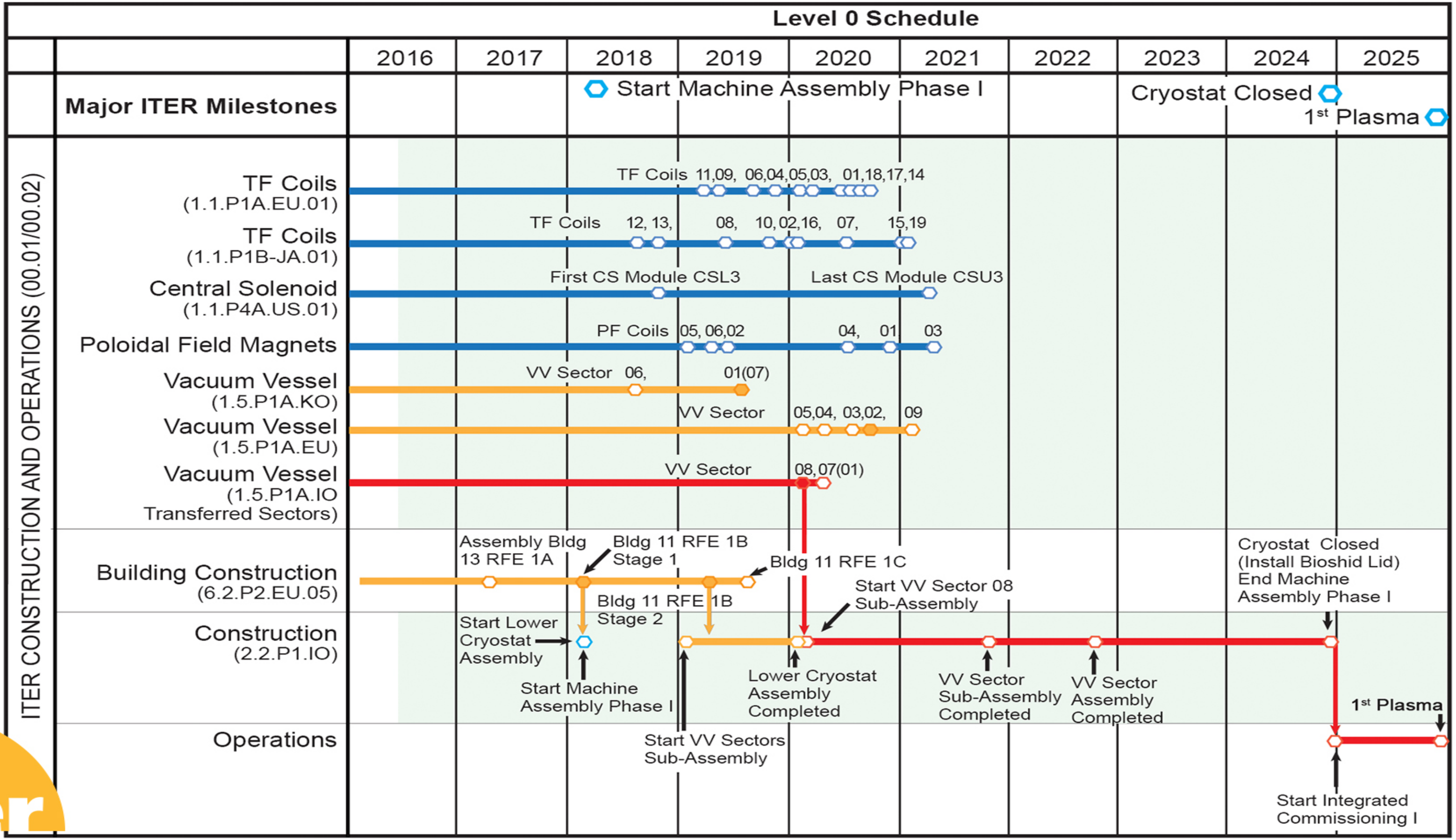
Who manufactures what?



Managing collaboration

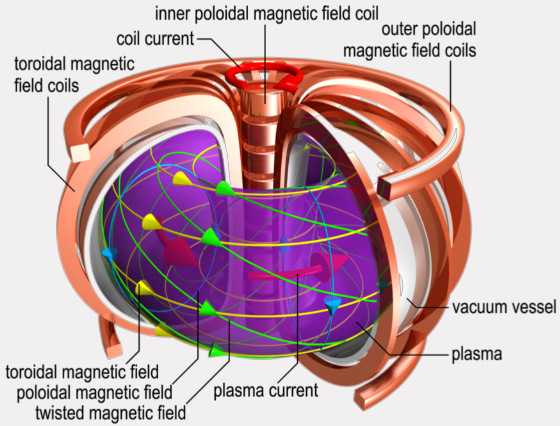


Major assembly milestones



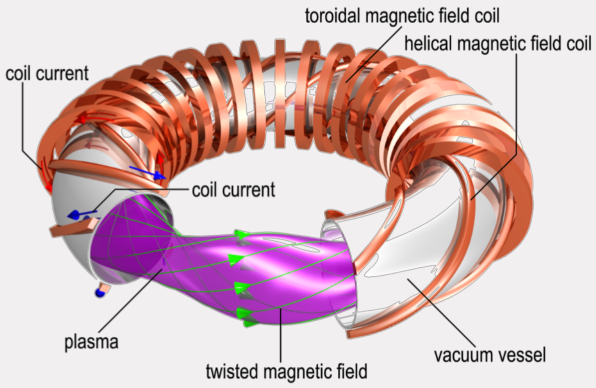

Worksite progress
Assembly Hall
Radiofrequency
Cryostat Workshop
PF Coil Winding Facility
Service Bdg.
Cooling System
400 kV Switchyard
~ Machine axis
Tritium Bdg.
Bioshield
Tokamak Bdg.
Diagnostics Bdg.
Magnet Power Conversions Bdgs.
11 October 2017

Tokamaks (2D, with plasma current)



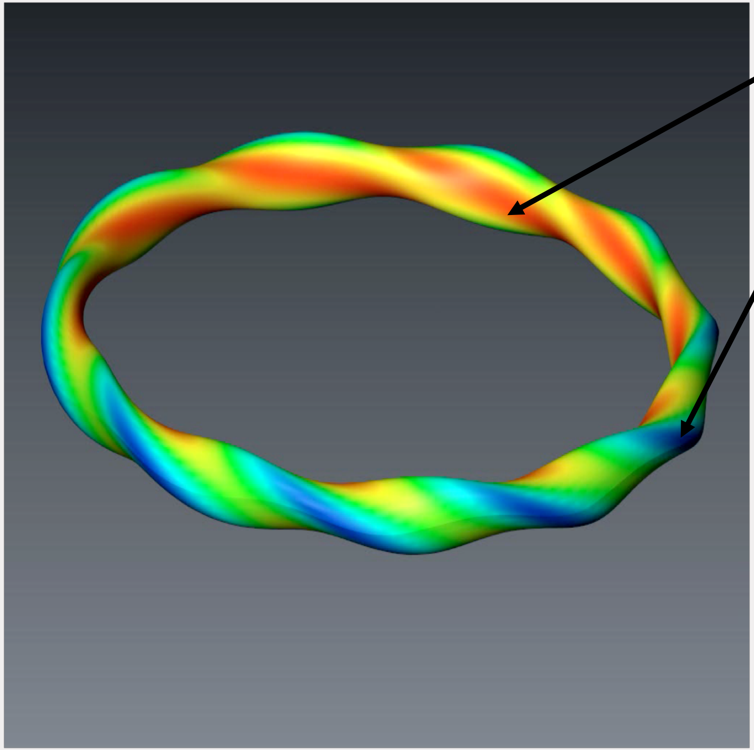
+ good insulation/confinement
+ toroidal symmetry
- Pulsed operation (transformer!)
- current-driven instabilities

Stellarators (3D, no plasma current)



- Bad insulation/confinement
- No exact symmetry, particles drift out
+ continuous operation
+ no current-driven instabilities

In un-optimised stellarators: reflected particles are lost!

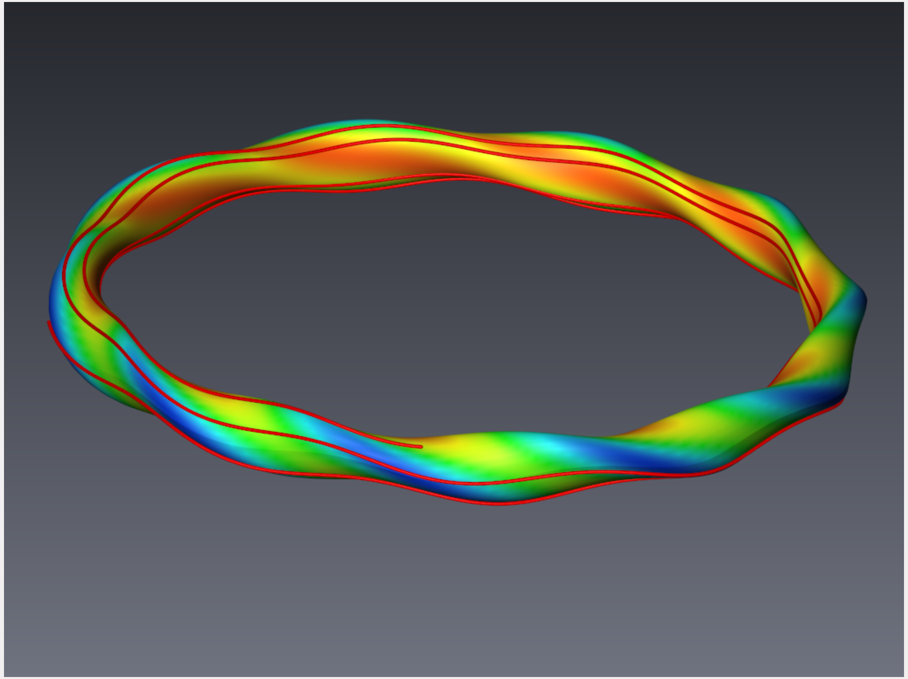


High magnetic field strength

Low magnetic field strength

Due to the structure of the magnetic field, with its minima and maxima, particles can either travel freely around the torus following along field lines (“passing particles”) or be trapped in regions of low magnetic field(“trapped particles”) due to the conservation of magnetic momentum.

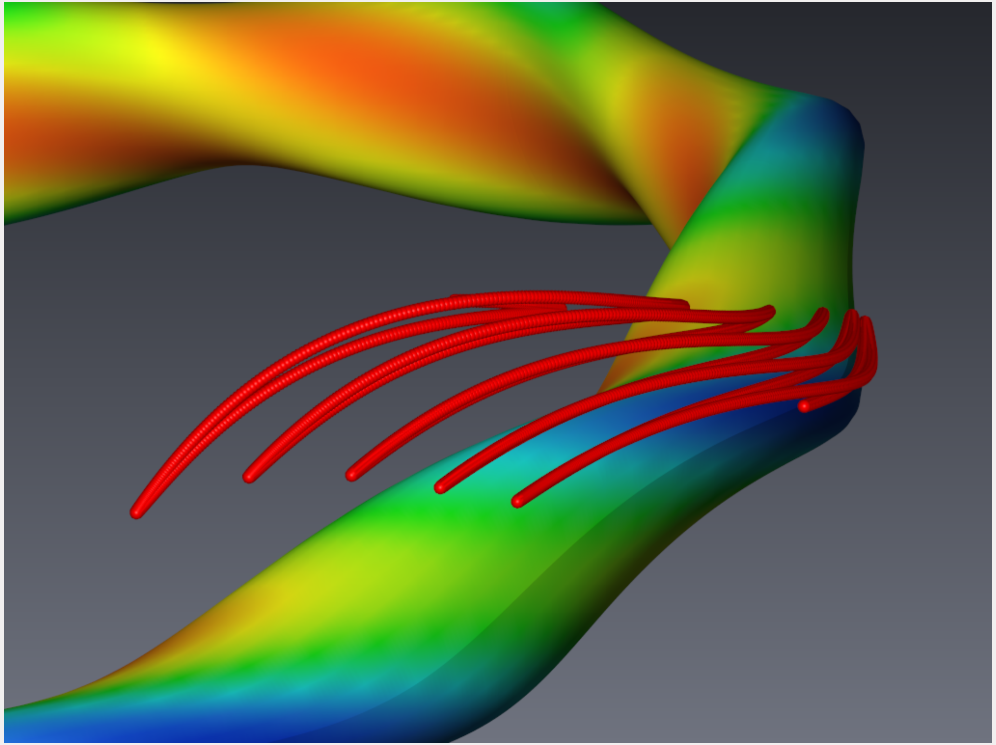
In un-optimised stellarators: reflected particles are lost!



Trajectory of a particle travelling around the torus completely while following a magnetic field line.

Any curvature the particle experiences will average out.

In un-optimised stellarators: reflected particles are lost!



Trajectory of a particle trapped in the region of low magnetic field.

Due to the curvature being similar in this region, the effective radial drift does NOT average out and the trapped particle drifts outside the plasma.

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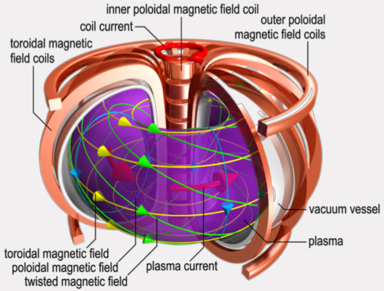
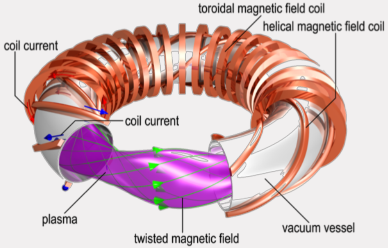
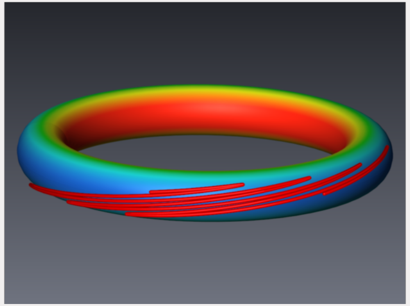
Tokamaks were favoured over stellarators because of better confinement

Tokamak



Stellarator

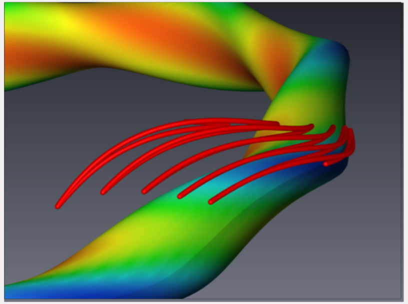




Particle confinement:

tokamak:
good (due to axisymmetry)

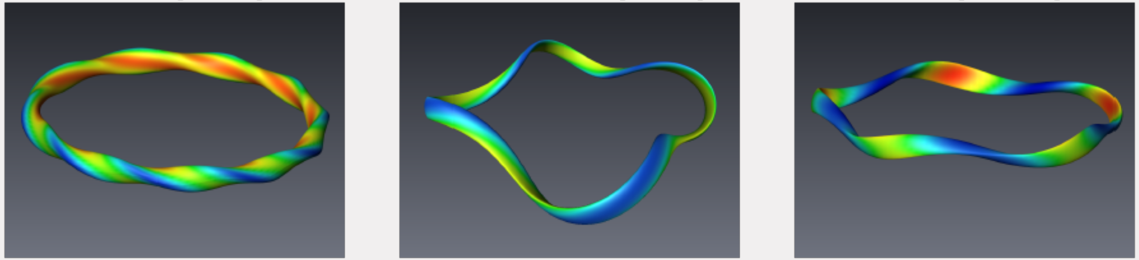
stellarator:
bad (no axisymmetry)



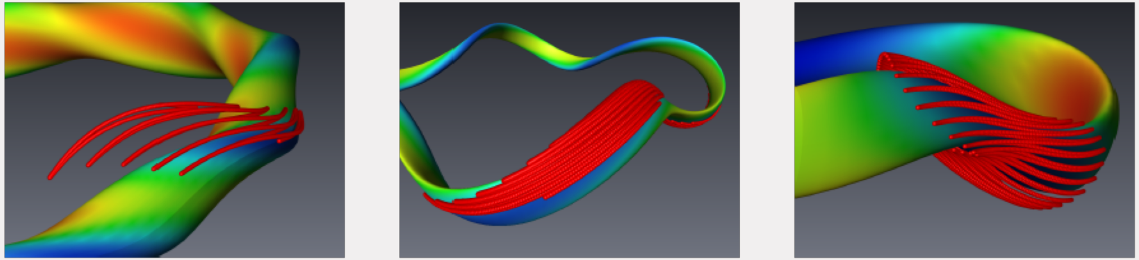
Josefine H.E. Proll

Optimised stellarators confine the particles well

Classical stellarator e.g. Large Helical Device (LHD)	Quasi-symmetry e.g. Helically Symmetric Experiment (HSX)	Quasi-isodynamicity e.g. Wendelstein 7-X (W7-X)

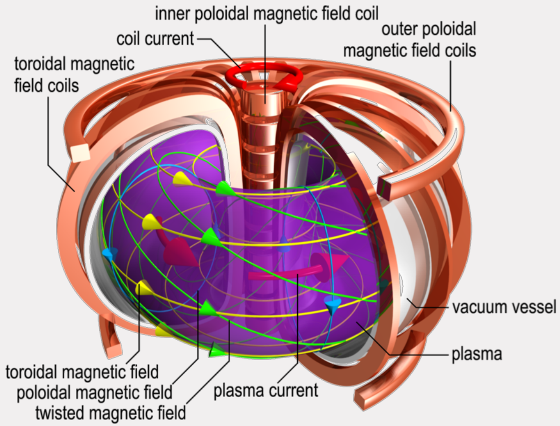


Magnetic field strength $|\mathbf{B}|$ on the flux surface of $r/a = 0.5$



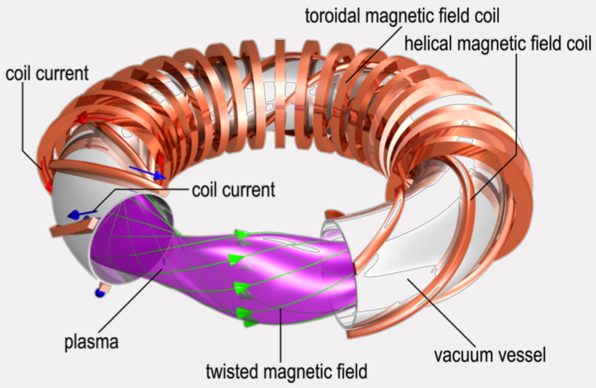
Trajectory of a trapped particle

Tokamaks (with plasma current)



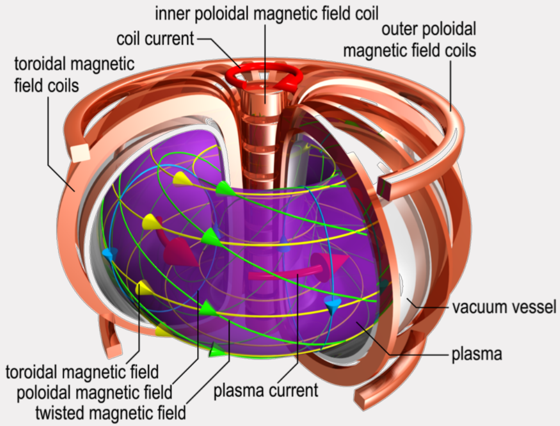
+ good insulation/confinement
+ toroidal symmetry
- Pulsed operation (transformer!)
- current-driven instabilities

Stellarators (no plasma current)



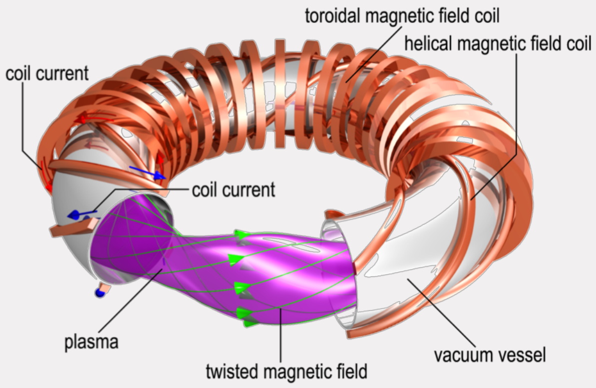
- Bad insulation/confinement
- No exact symmetry, particles drift out
+ continuous operation
+ no current-driven instabilities

Tokamaks (with plasma current)



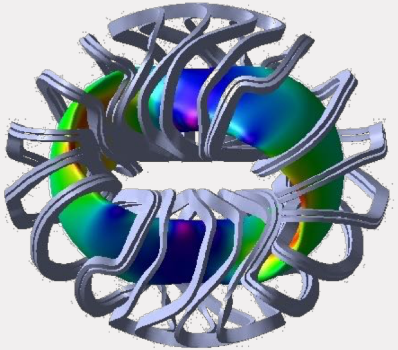
+ good insulation/confinement
+ toroidal symmetry
(+) continuous operation (current drive)
(+) active control of instabilities

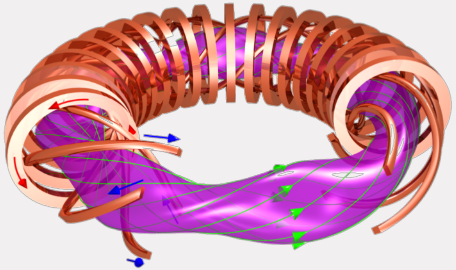
Stellarators (no plasma current)

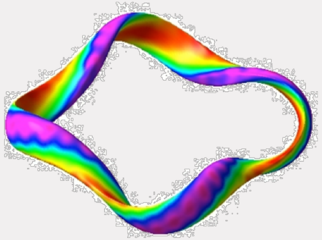


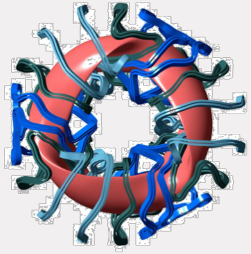
(+) good insulation/confinement
(+) quasi-symmetry
+ continuous operation
+ no current-driven instabilities

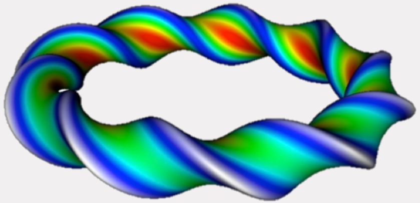
Many choices for the shape of stellarators …

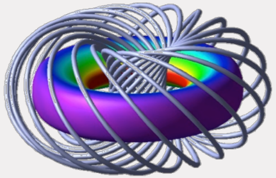


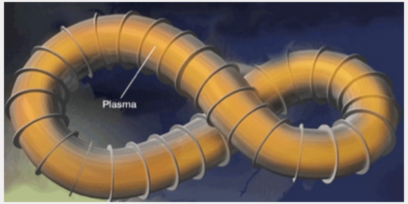


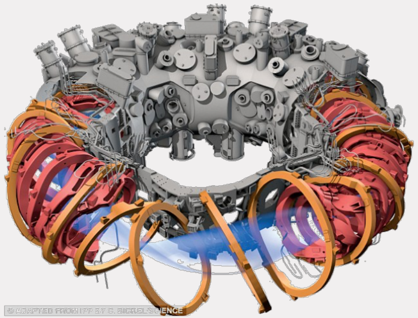








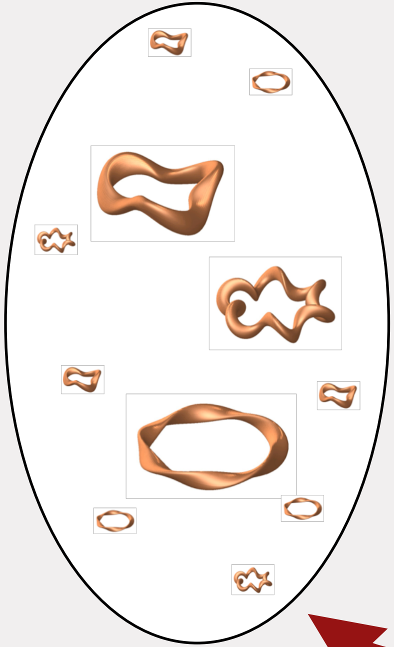




… but not all are equally good

[MPI Plasma Physics, PPPL, D. Spong]

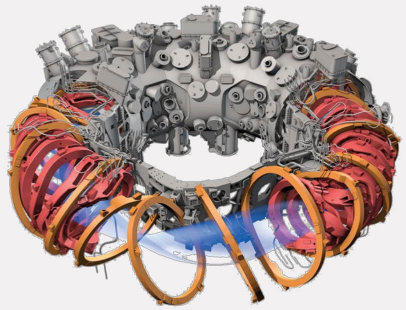
Optimisation routines are used to find the best shape



For each shape, calculate

- Particle drifts
- Fluid instabilities

Which shape performs best ?



Wendelstein 7-X

Major elements of Wendelstein 7-X

plasma 30 m^3

Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m³

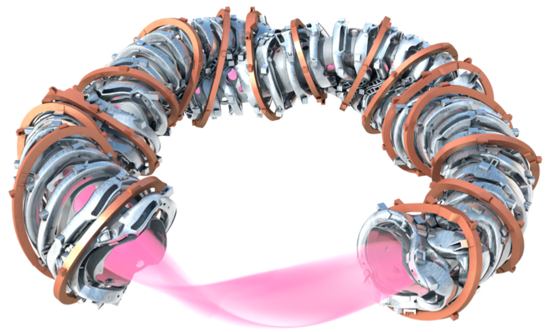
Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m³

20 planar NbTi coils
2 types DC <16 kA

plasma vessel 80 m³
265 m² in-vessel components

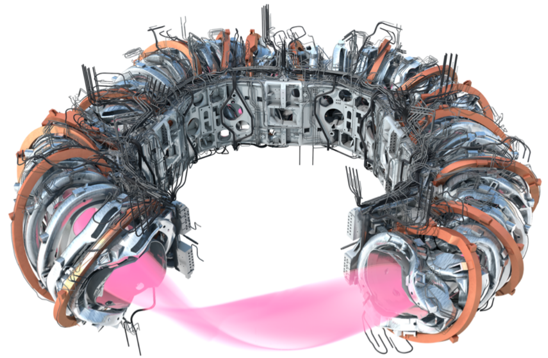


Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m³

20 planar NbTi coils
2 types DC <16 kA



plasma vessel 80 m³
265 m² in-vessel components

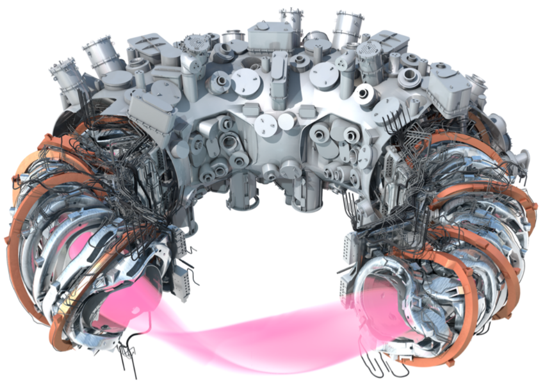
113 NbTi bus bars
14 HTSC current leads
about 1000 helium pipes
10 central support ring elements

Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m^3

20 planar NbTi coils
2 types DC <16 kA



plasma vessel 80 m^3
265 m^2 in-vessel components

113 NbTi bus bars
14 HTSC current leads
about 1000 helium pipes
10 central support ring elements

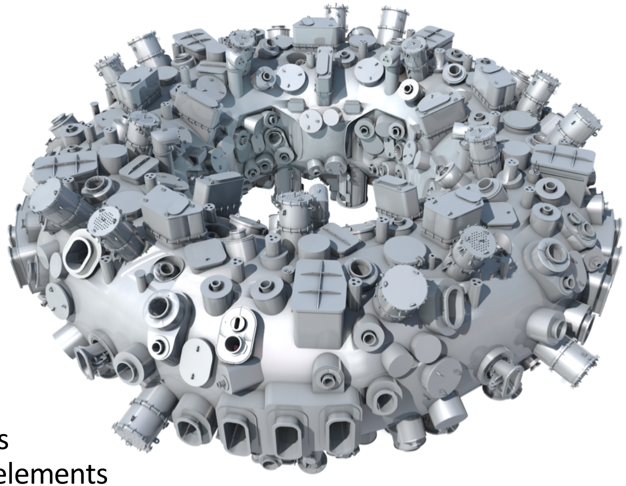
cryostat vessel 420 m^3
thermal insulation

Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m³

20 planar NbTi coils
2 types DC <16 kA



plasma vessel 80 m³
265 m² in-vessel components

254 ports 120 shapes

4.5 m machine height
16 m machine diameter
735 t device mass
435 t cold mass 3.4 K

113 NbTi bus bars
14 HTSC current leads
about 1000 helium pipes
10 central support ring elements

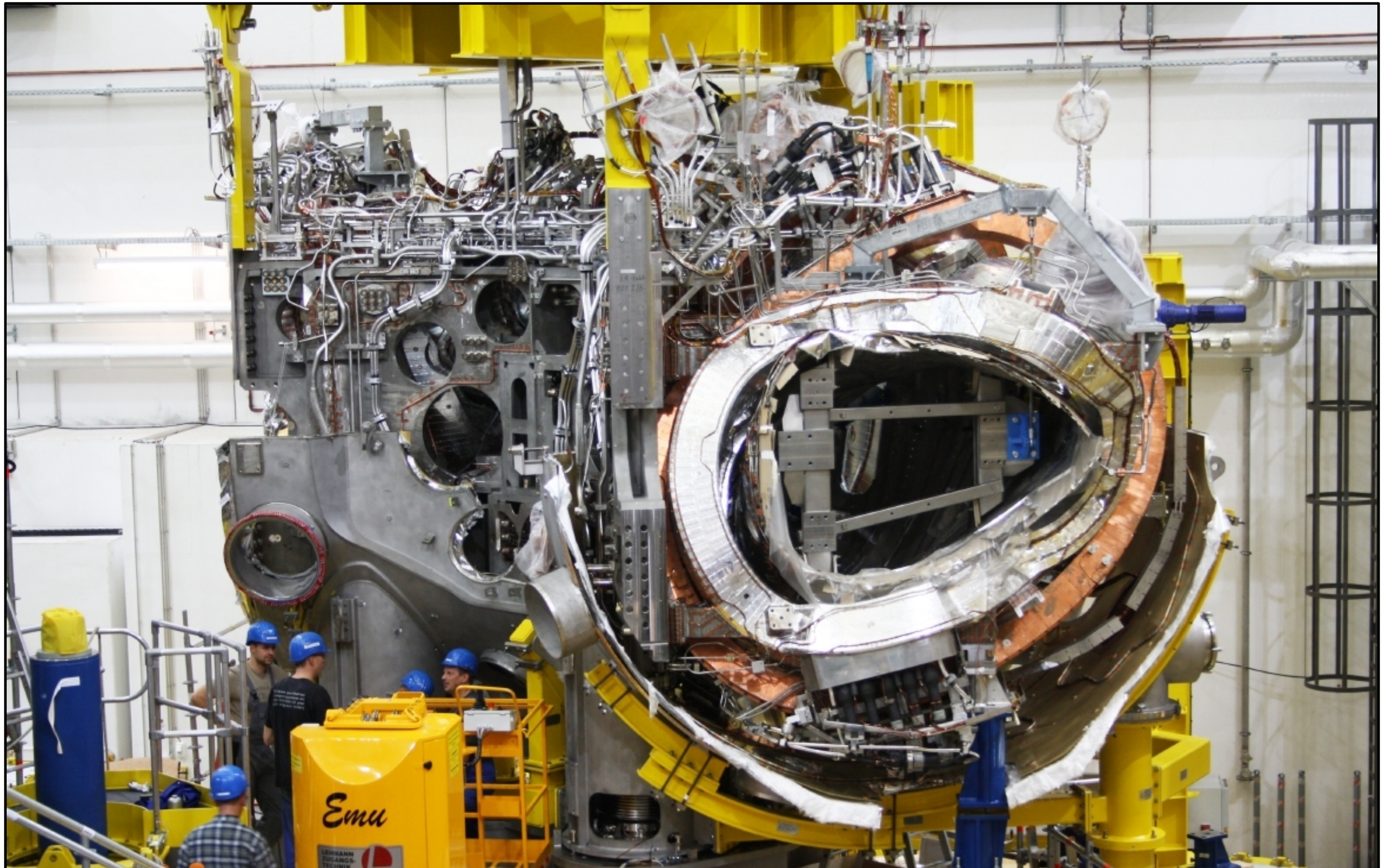
cryostat vessel 420 m³
thermal insulation

Video: construction of W7-X

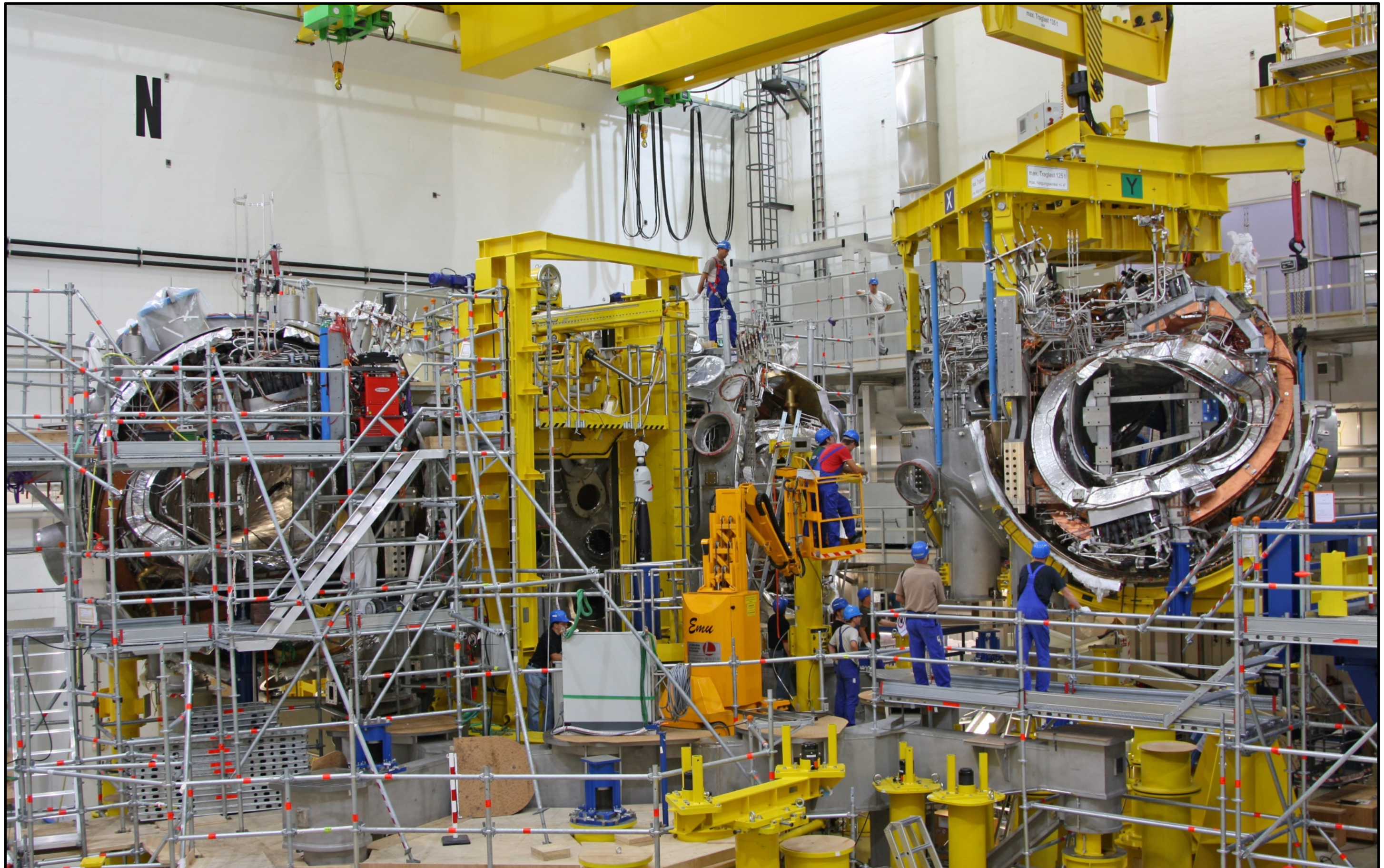
https://www.youtube.com/watch?v=MJpSrqitSMQ

Placing one module in the torus hall

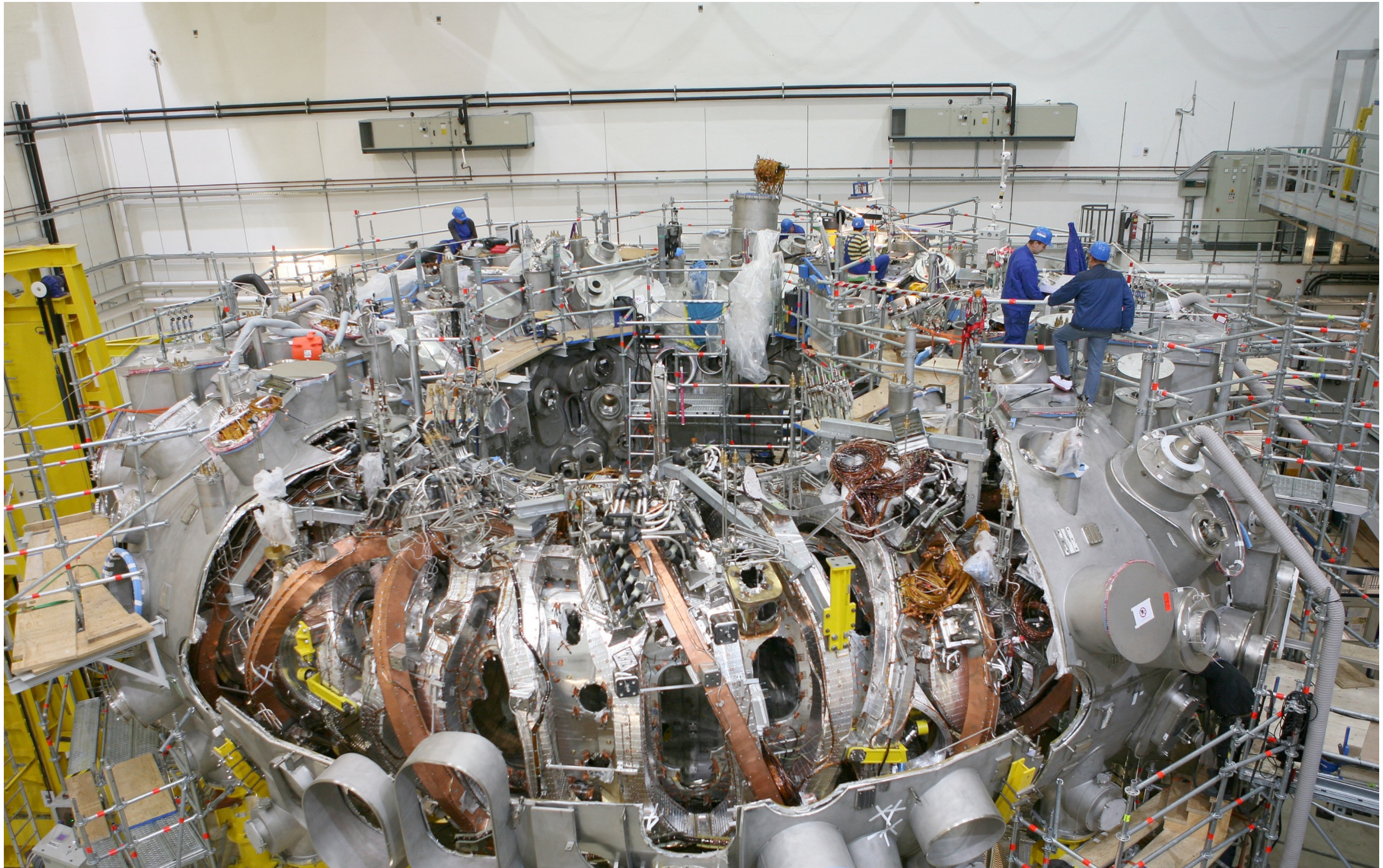
First module in the lower half of the outer vessel



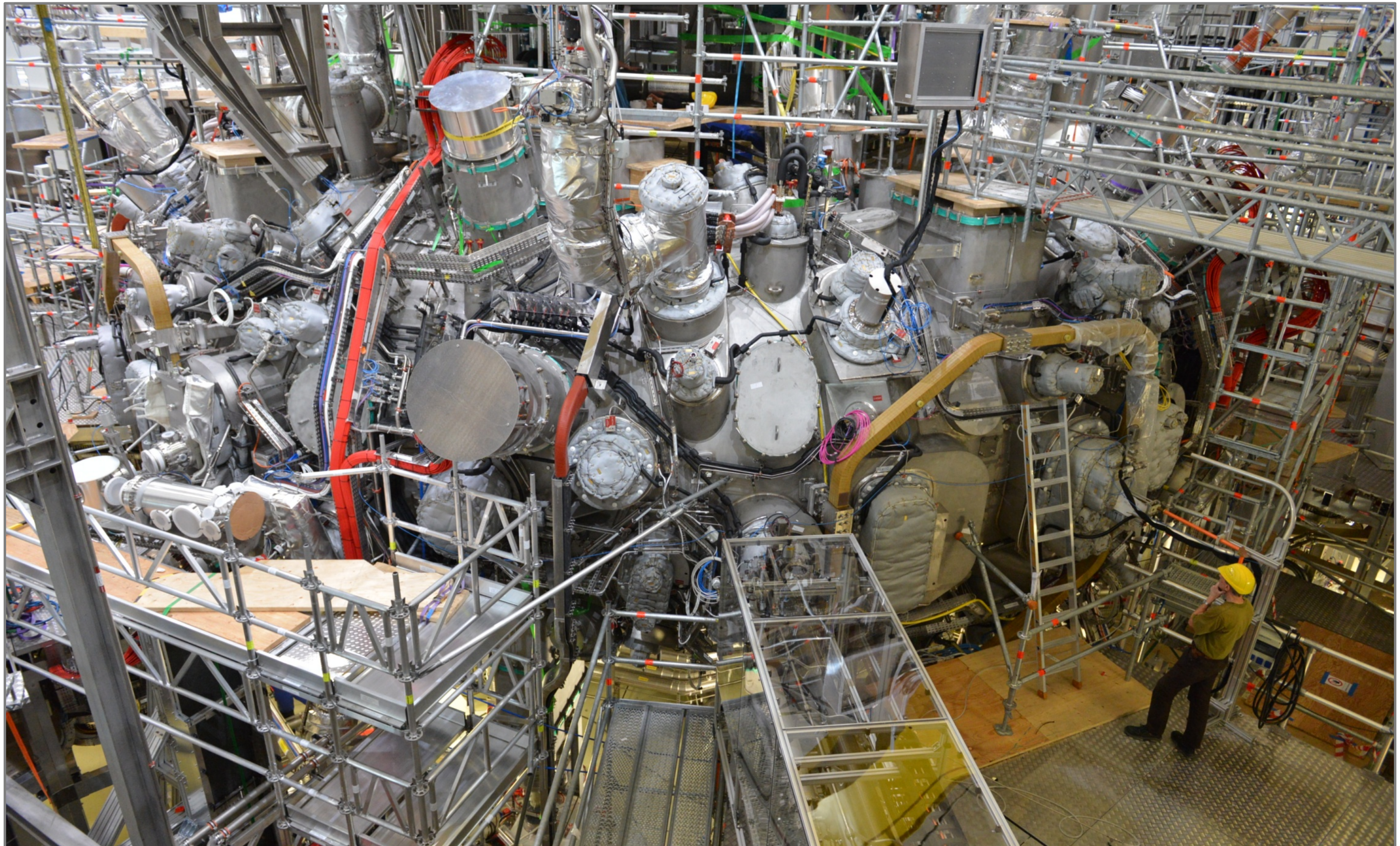
Torus hall with 2(3) of the modules out of 5



Last module put into place

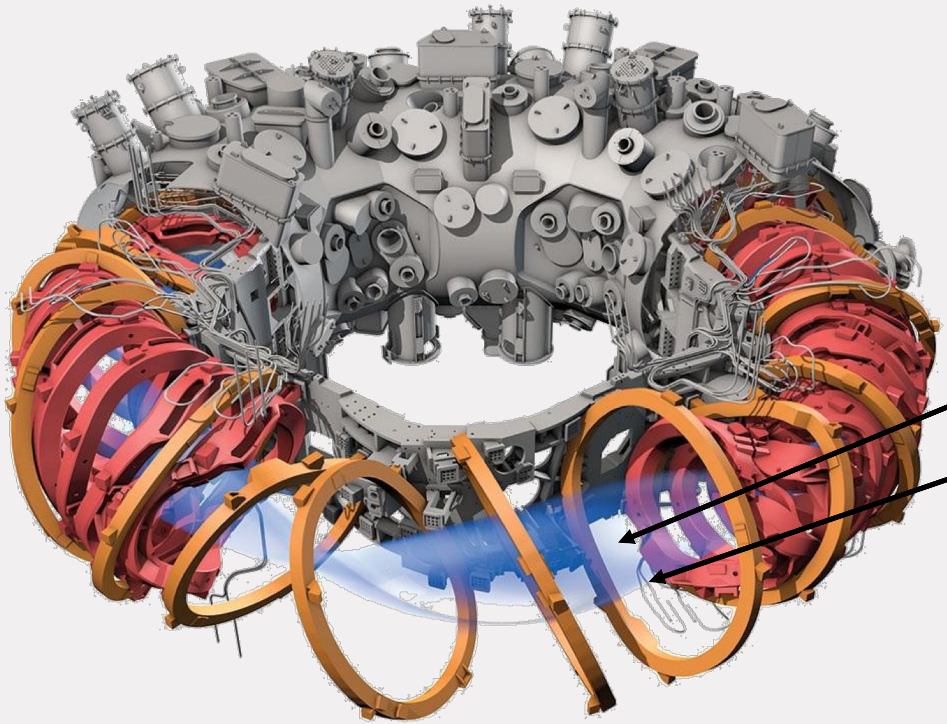


Completed machine



Wendelstein 7-X is operational since end of 2015

Now onto the next issue - turbulence



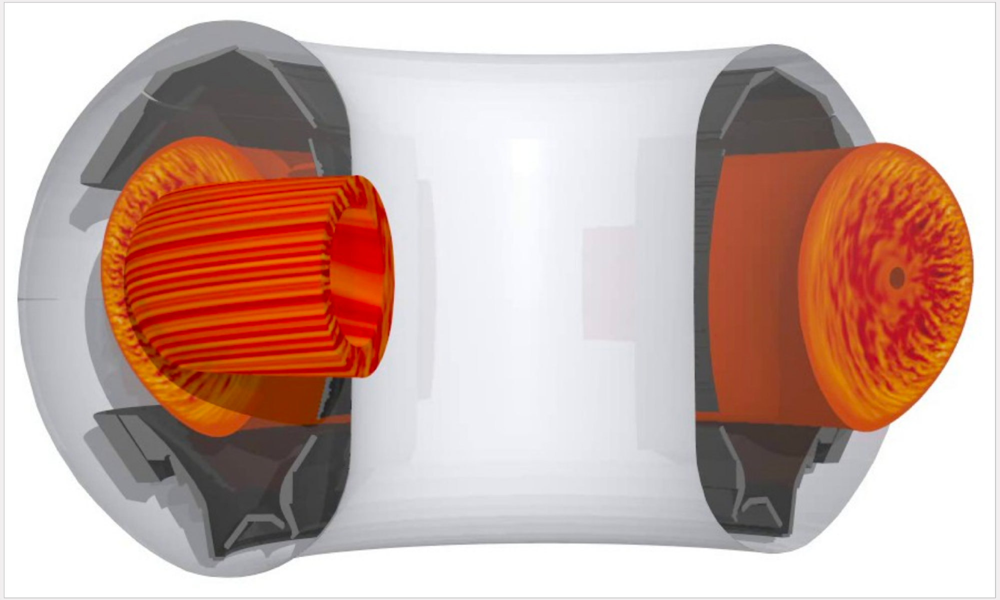
- Designed for good particle confinement
- Is performing well

Plasma centre: high density, temperature

Plasma edge: low density and temperature

➤ turbulence as major issue

Now turbulent transport also needs to be reduced!



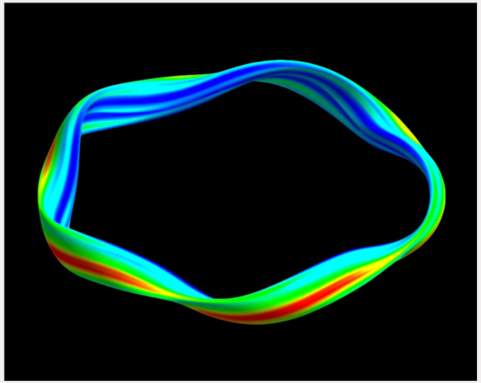
Density and temperature gradients:

Turbulence!

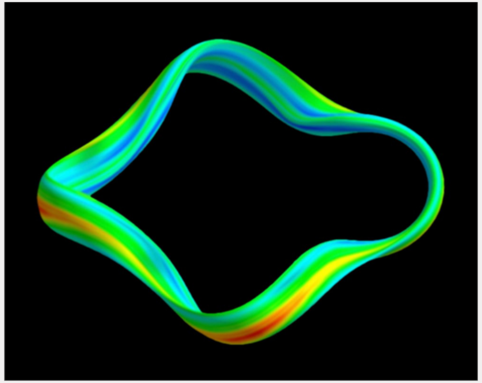
[Picture from genecode.org]

Turbulence depends strongly on the geometry

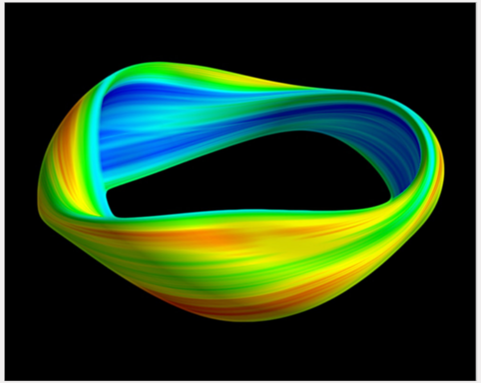
W7-X stellarator



HSX stellarator

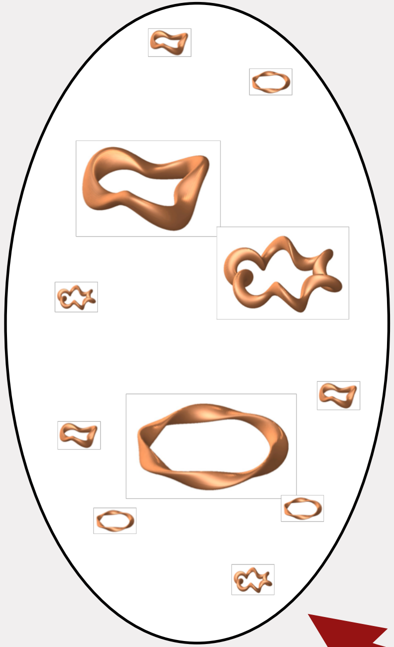


QPS stellarator



A great chance for stellarators!

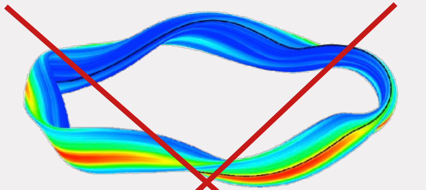
For optimisation: need full turbulence model



For each shape, calculate

- Particle drifts
- Fluid instabilities
- Turbulence - low heat flux

Which shape performs best ?

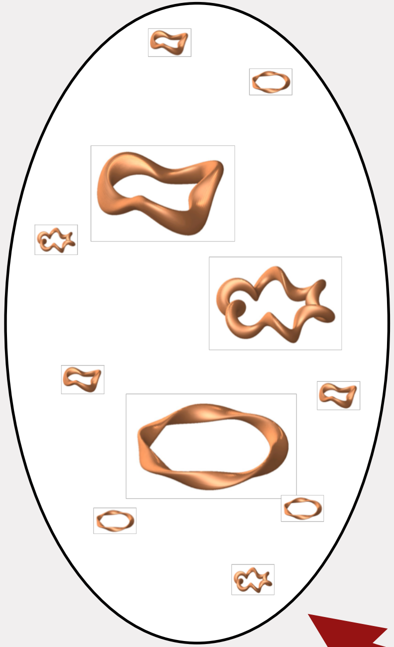


Nonlinear simulations:
1-5 Mio CPUh
with GENE code [Jenko 2001]

Better: simple model
fast + easy to compute

TU/e

We should optimise stellarators also for low turbulence!



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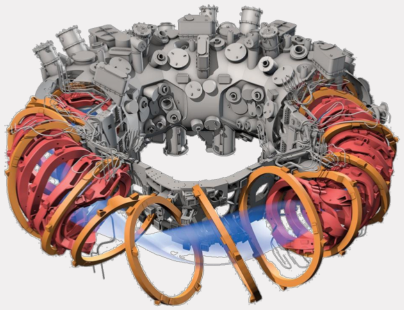

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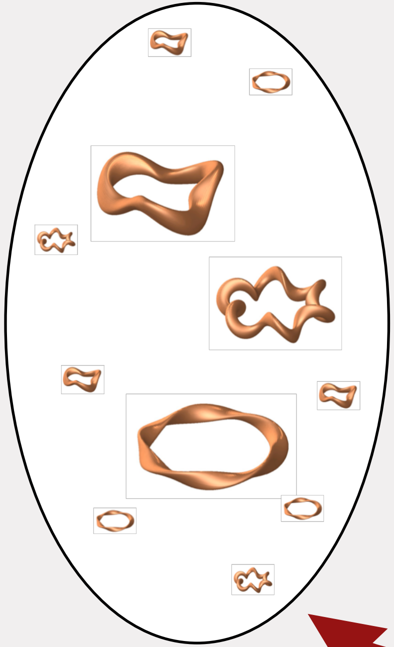

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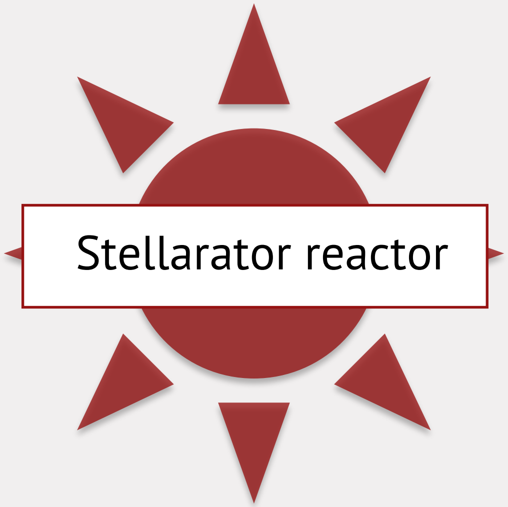
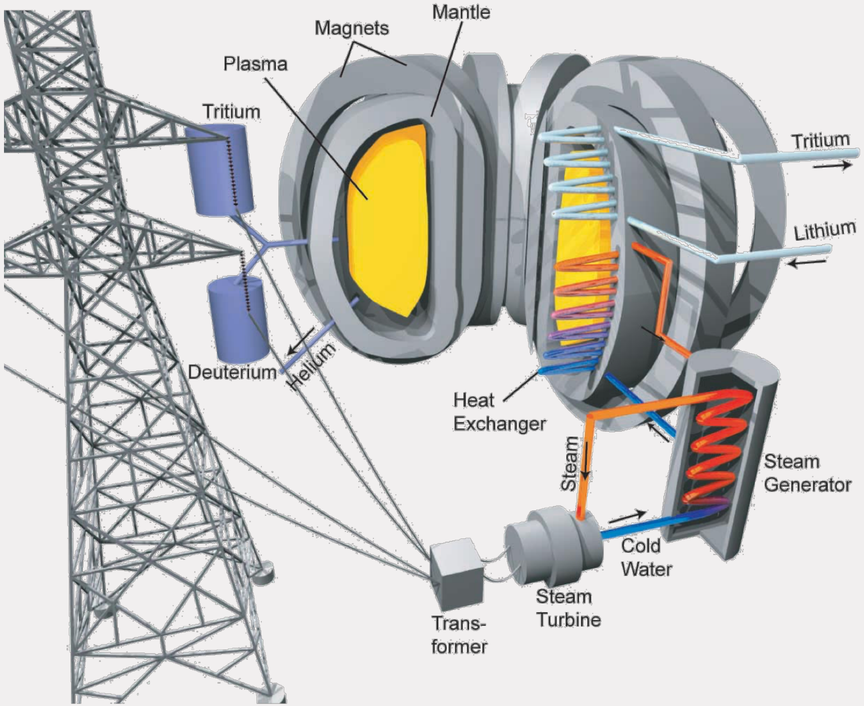
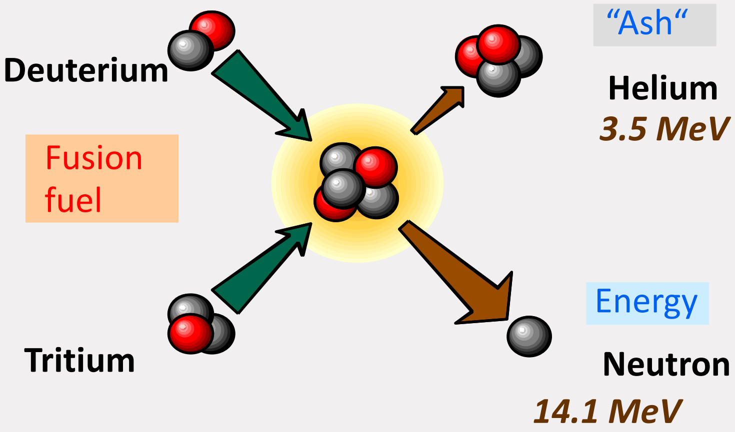


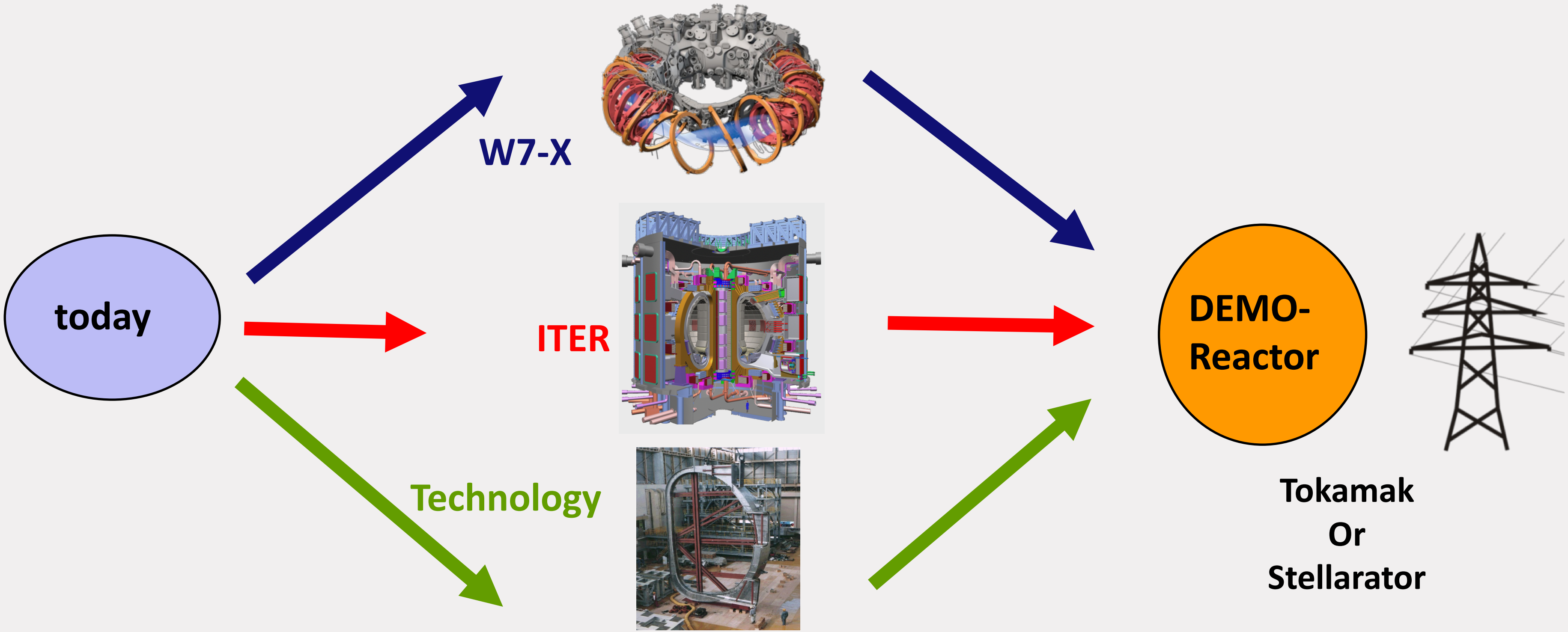
A future fusion power plant





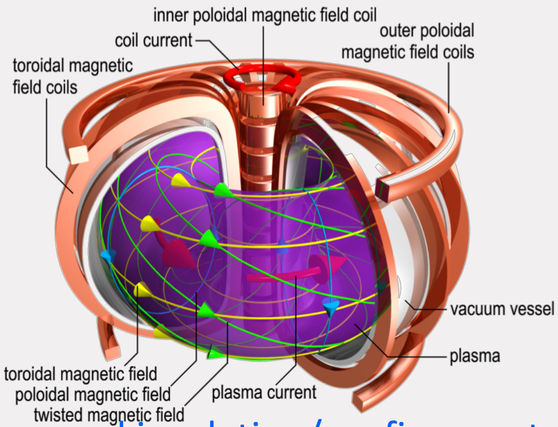
Neutrons from fusion heating up the wall → steam → generator

On route to a reactor



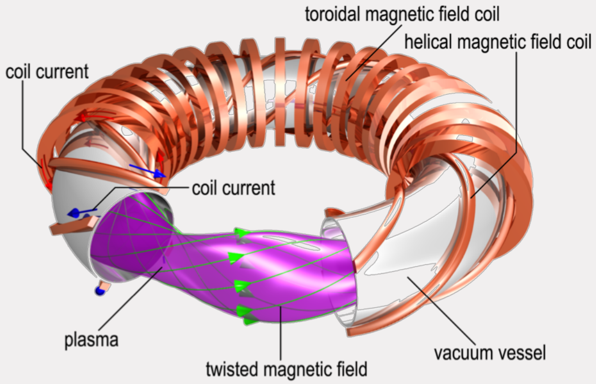
Both tokamaks and stellarators are promising candidates

Tokamaks (with plasma current)



+ good insulation/confinement
+ toroidal symmetry
(+) continuous operation (current drive)
(+) active control of instabilities

Stellarators (no plasma current)



(+) good insulation/confinement
(+) quasi-symmetry
+ continuous operation
+ no current-driven instabilities