

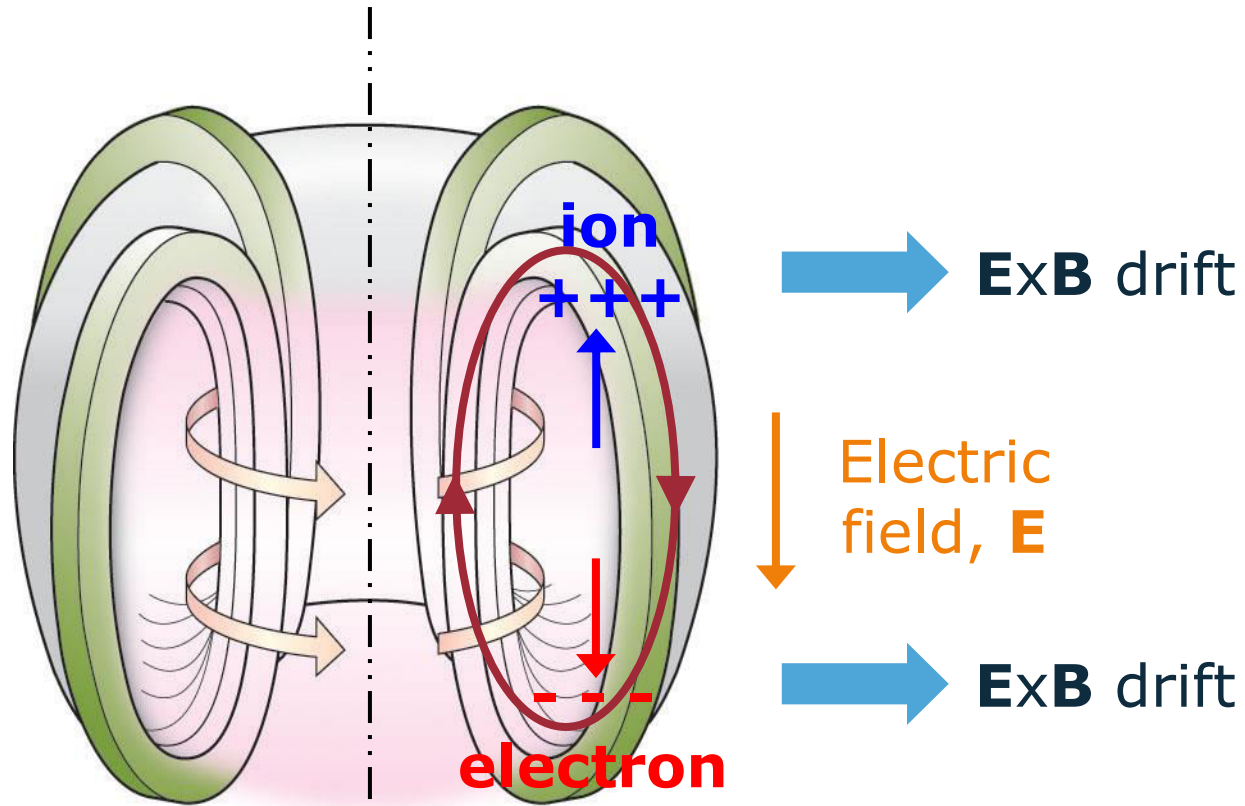
# Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

# What is a stellarator?

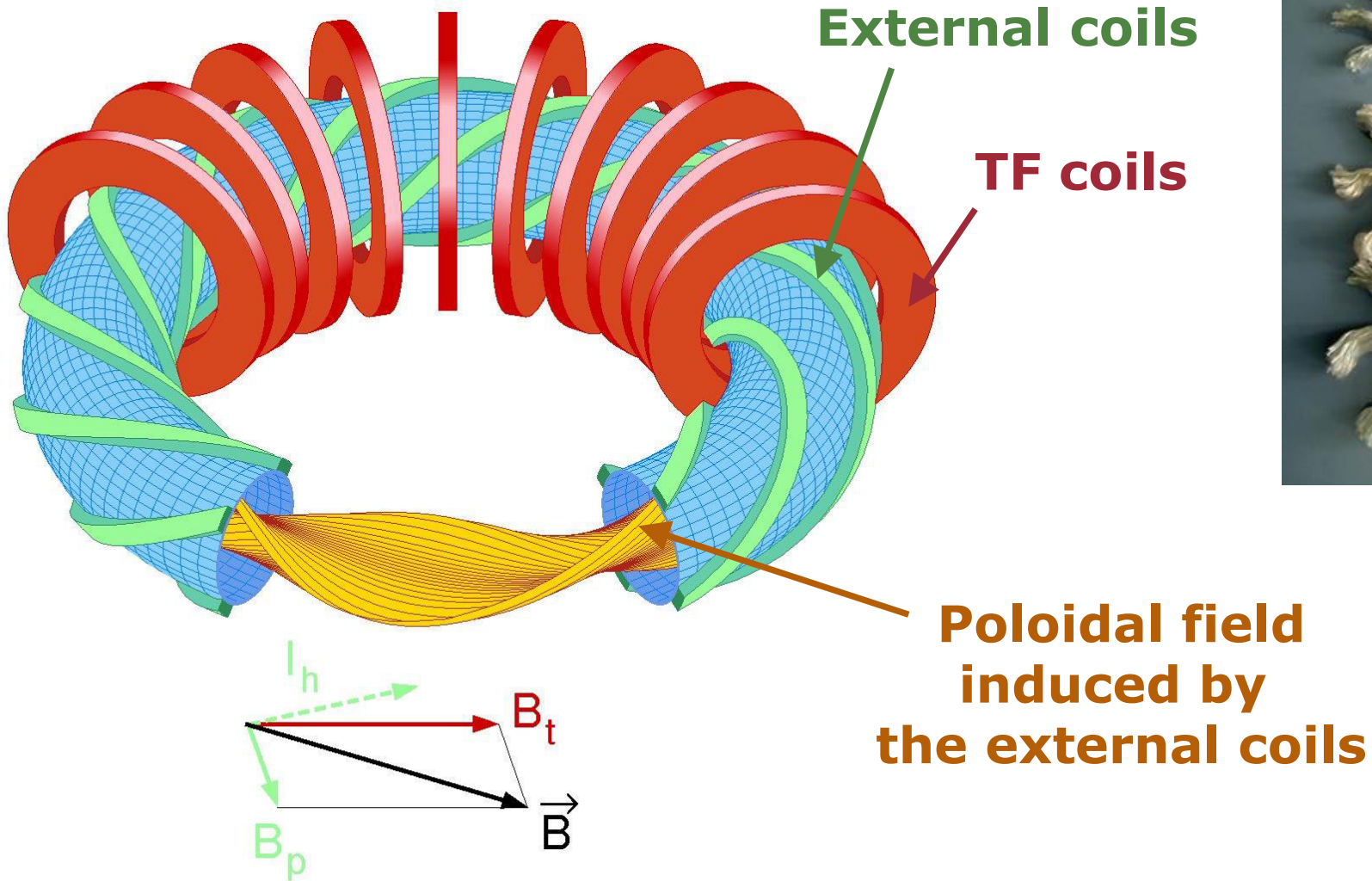
*M. Otthe, "Stellarator: Experiments", IPP Summer School (2008)*

# Closed Magnetic System

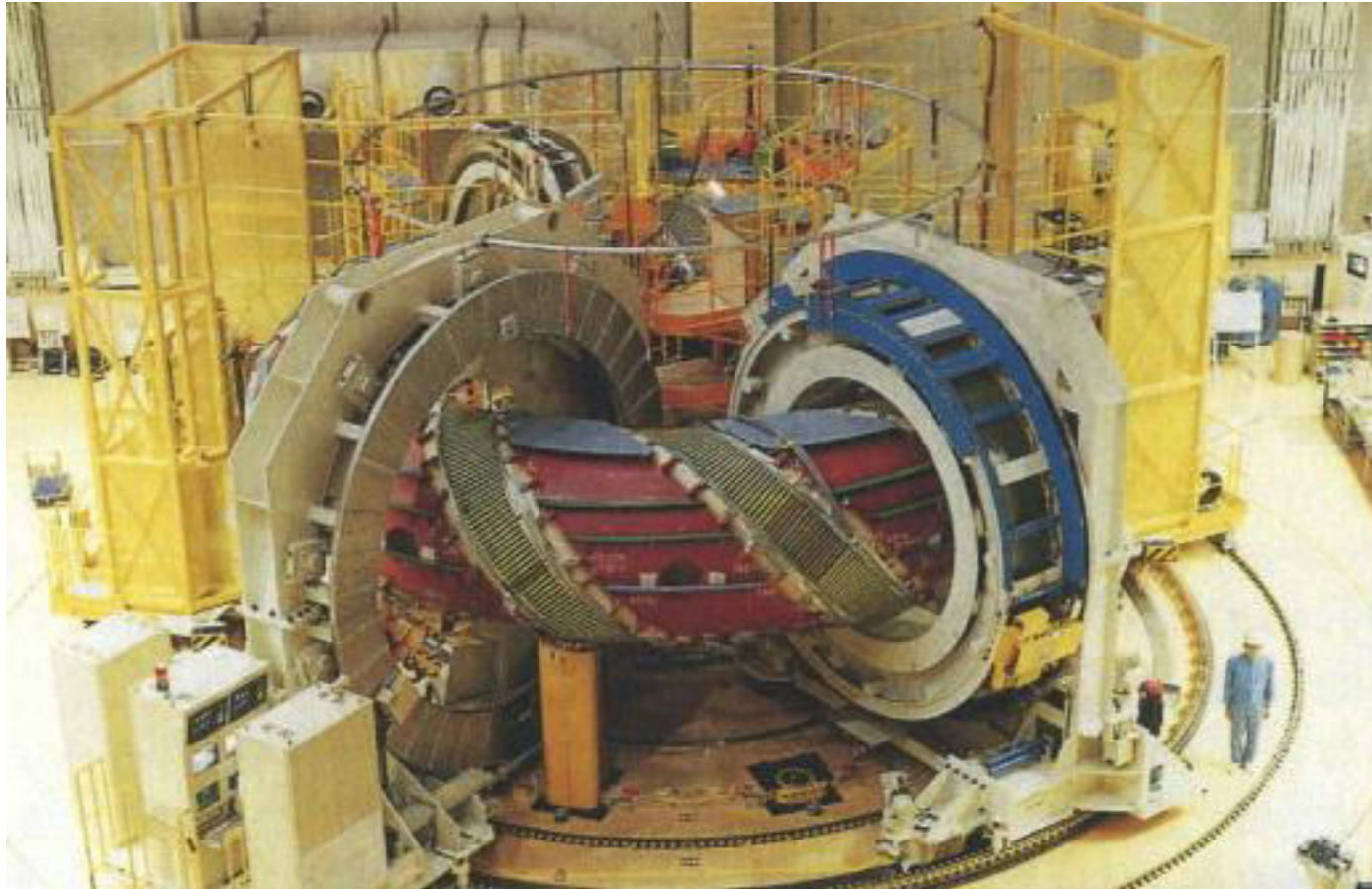


**Poloidal magnetic field required**  
**External coils → Stellarator**

# Stellarator



# Stellarator



LHD (Large Helical Device) under construction

# Stellarator

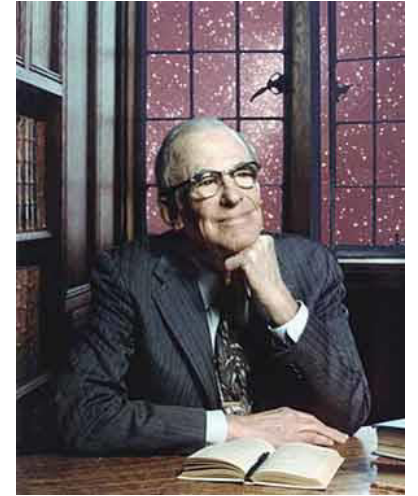
## THE PHYSICS OF FLUIDS

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VOLUME 1, NUMBER 4

JULY-AUGUST, 1958

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### The Stellarator Concept\*

LYMAN SPITZER, JR.

*Project Matterhorn, Princeton University, Princeton, New Jersey*

(Received May 27, 1958)

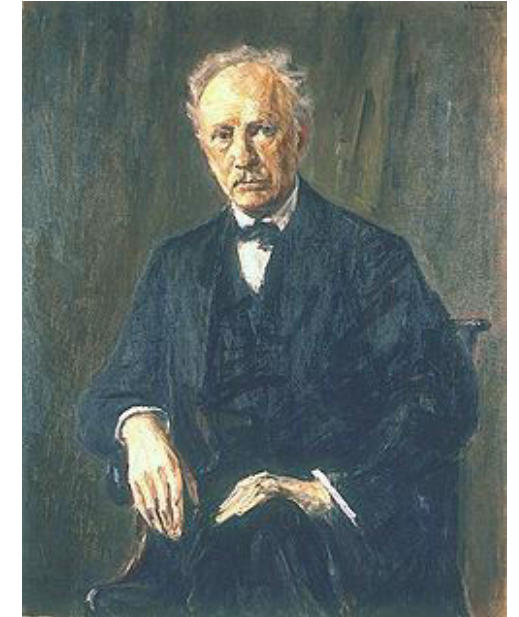
The basic concepts of the controlled thermonuclear program at Project Matterhorn, Princeton University are discussed. In particular, the theory of confinement of a fully ionized gas in the magnetic configuration of the stellarator is given, the theories of heating are outlined, and the bearing of observational results on these theories is described.

# Stellarator

Invented by Lyman Spitzer, Jr. in Princeton in 1951



Garmisch-Partenkirchen,  
Germany



Richard Georg Strauss  
(1864 – 1949)



# Stellarator

Invented by Lyman Spitzer, Jr. in Princeton in 1951

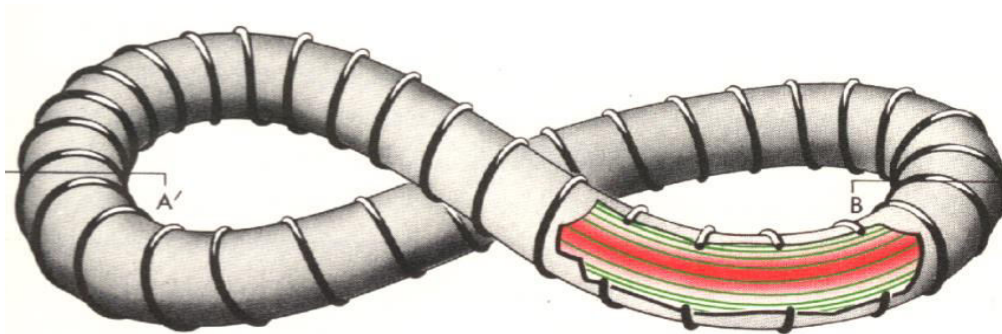
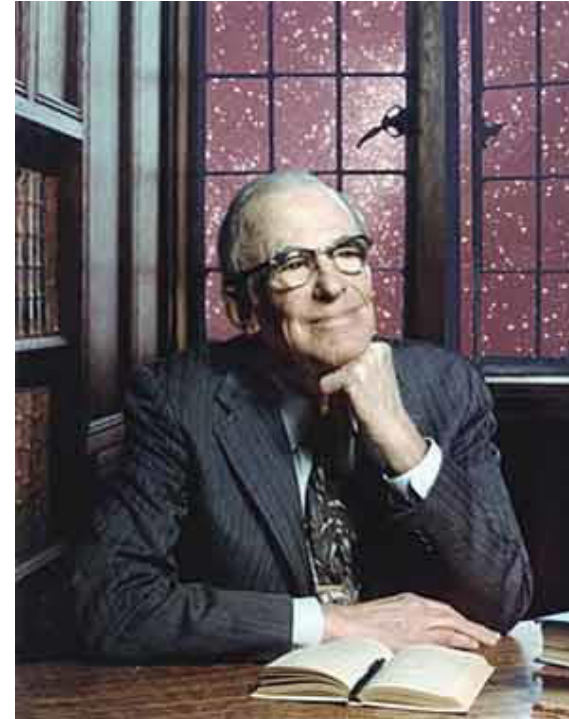
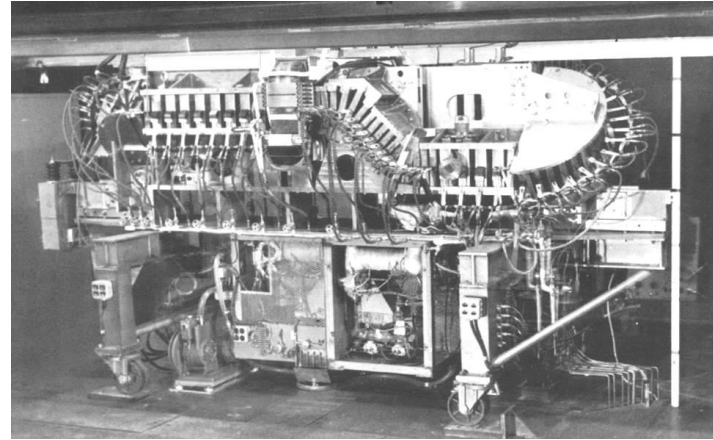
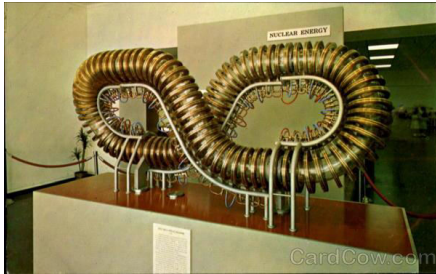


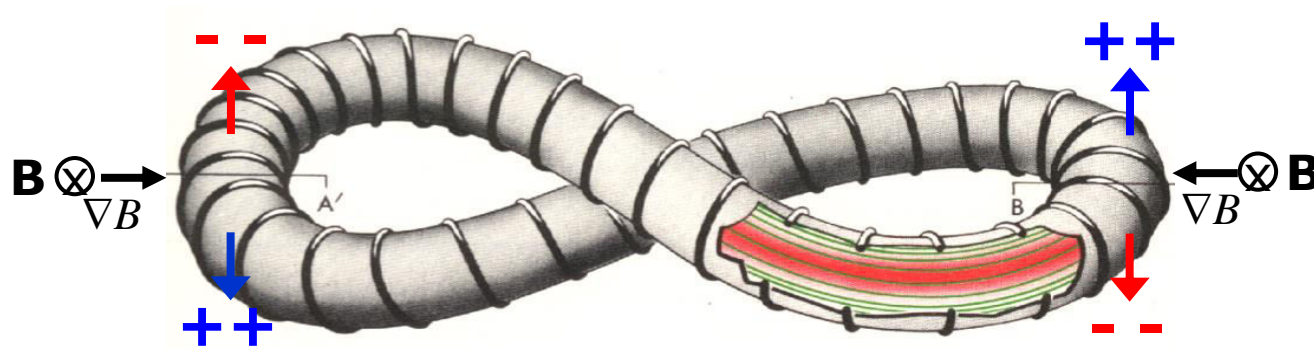
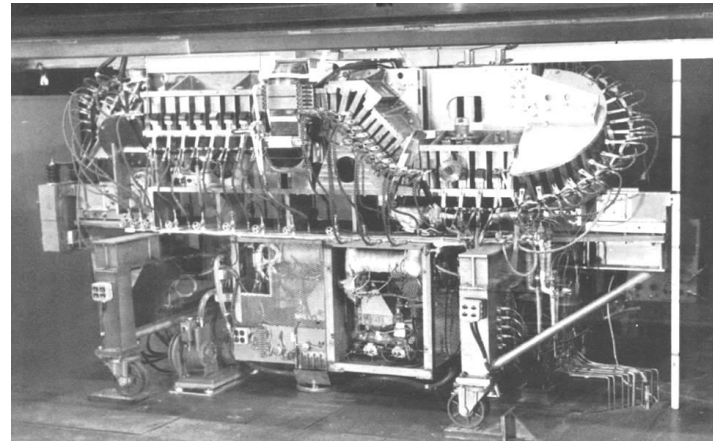
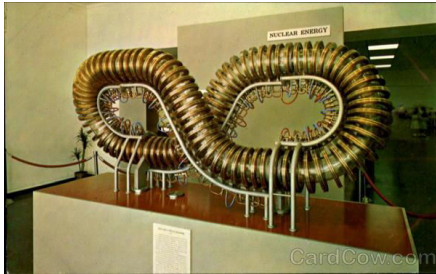
Figure-8 stellarator: Proof of principle experiment (helicity achieved by twisting the torus and hence the magnetic field)





# Stellarator

Invented by Lyman Spitzer, Jr. in Princeton in 1951



$$\mathbf{v}_{D,R} = \frac{mv_{\parallel}^2}{qB_0^2} \frac{\mathbf{R}_0 \times \mathbf{B}_0}{R^2}$$

$$\begin{aligned} \mathbf{v}_{D,\nabla B} &= \pm \frac{1}{2} v_{\perp} r_L \frac{\mathbf{B} \times \nabla B}{B^2} \\ &= \frac{mv_{\perp}^2}{2qB} \frac{\mathbf{B} \times \nabla B}{B^2} \end{aligned}$$

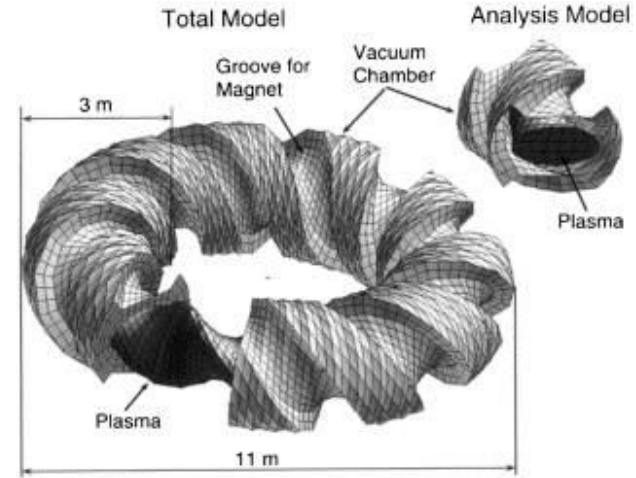
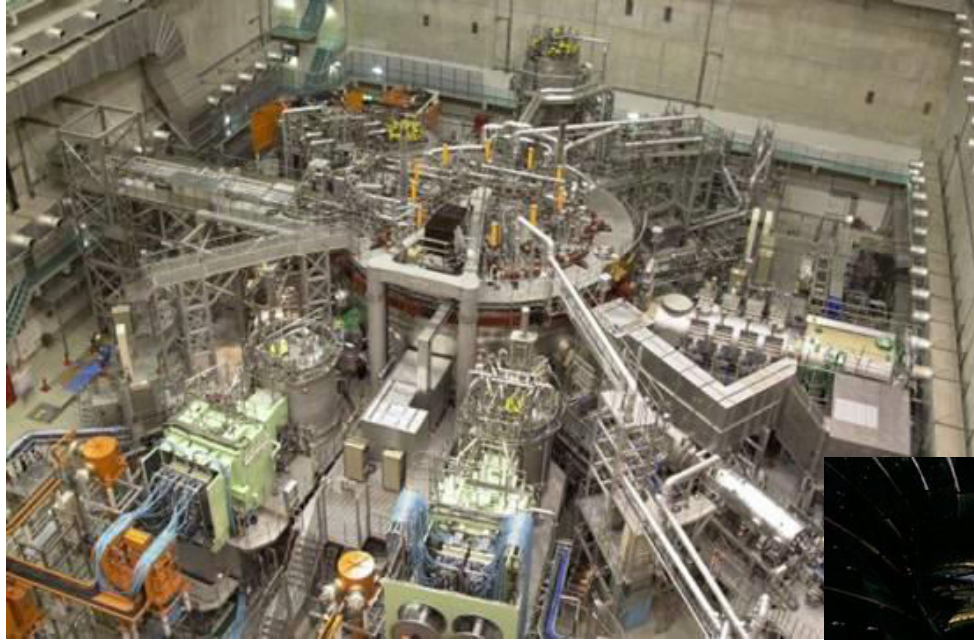
Figure-8 stellarator: Proof of principle experiment (helicity achieved by twisting the torus and hence the magnetic field)



WIKIPEDIA

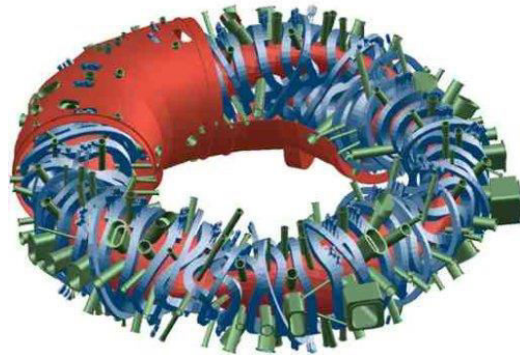
# Stellarator

## Large Helical Device (LHD), Japan

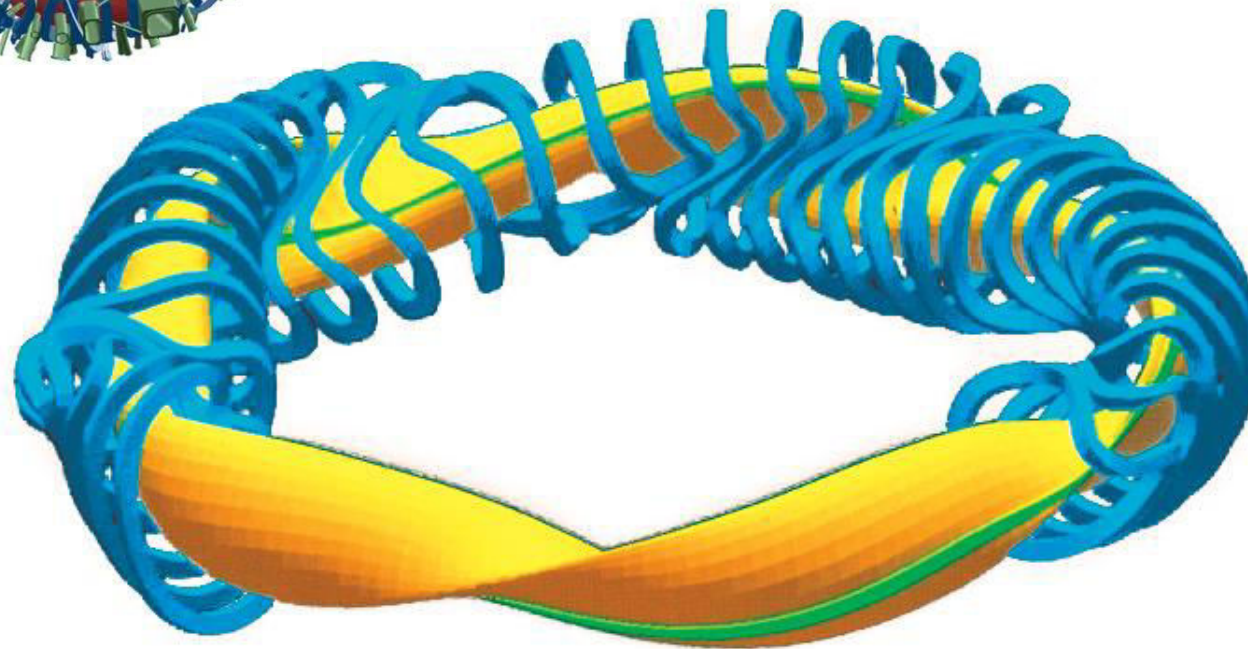


**3D configuration!**

# Stellarator



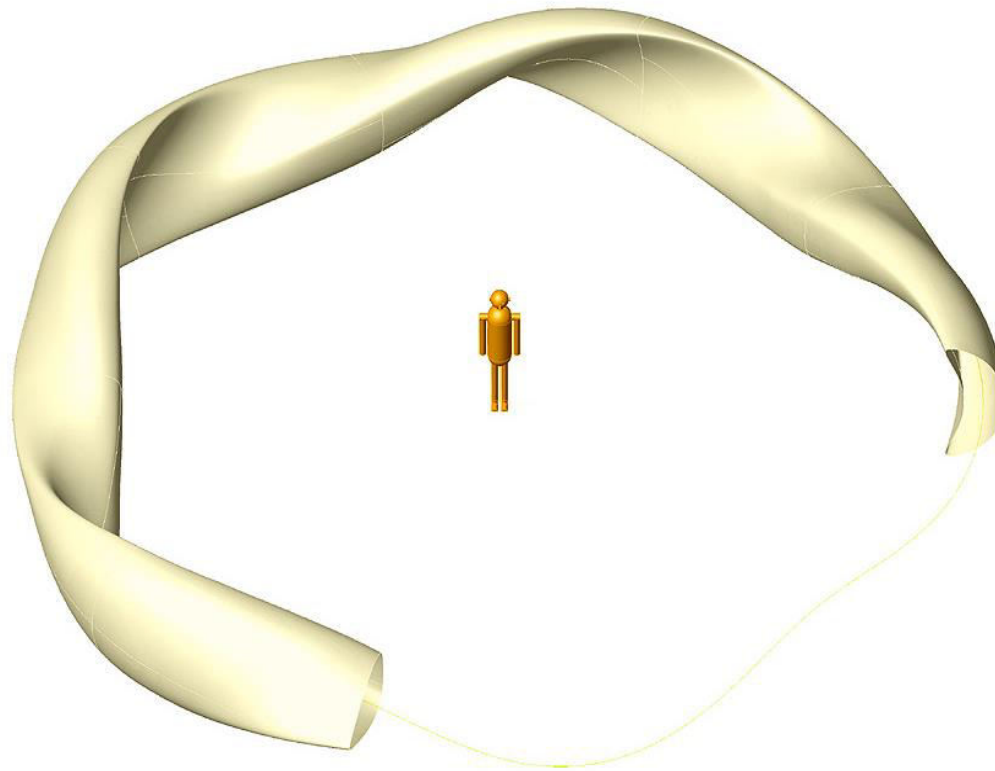
Wendelstein 7-X, Germany



**3D configuration!**

# Stellarator

## Plasma



### Plasma Parameter

$R$ : 5.5 m

$\langle a \rangle$ : 0.53 m

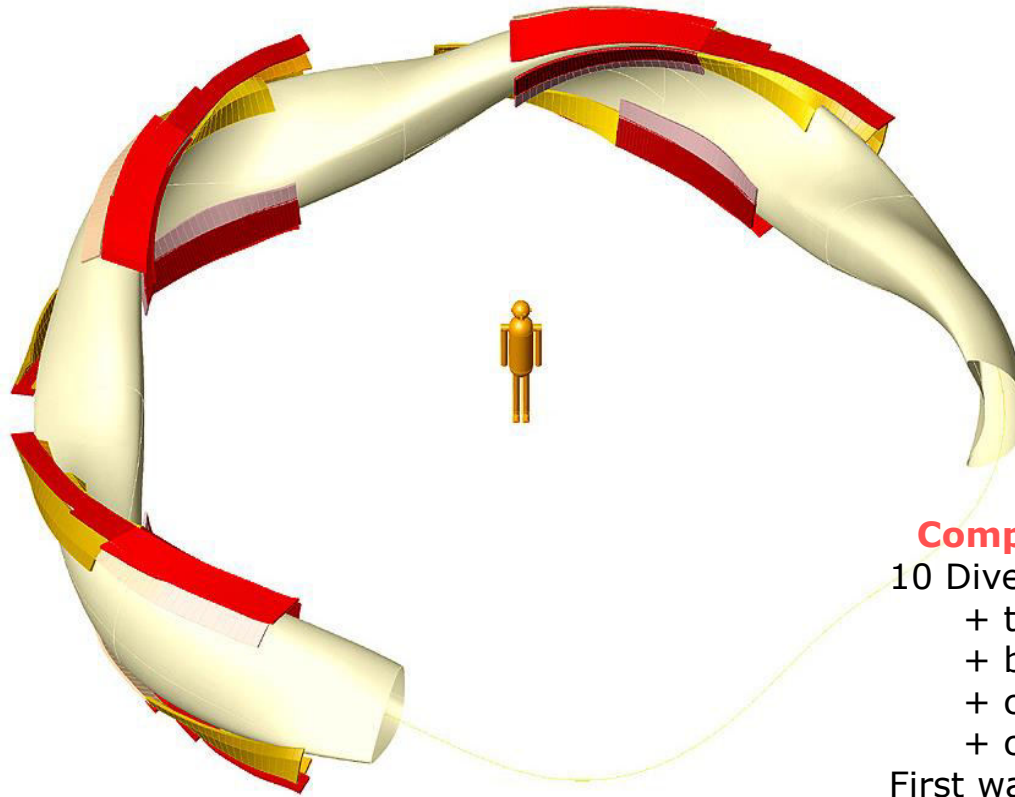
$n_e(0)_{\max}$ :  $3 \times 10^{20} \text{ m}^{-3}$

$T_e(0)_{\max}$ : 5 keV

$\langle \beta \rangle$ : < 5 %

# Stellarator

## Divertor



### Components inside plasma vessel

10 Divertor units

+ target elements (10 MW/m<sup>2</sup>)

+ baffle elements (0.5 MW/m<sup>2</sup>)

+ control coils

+ cryo pumps

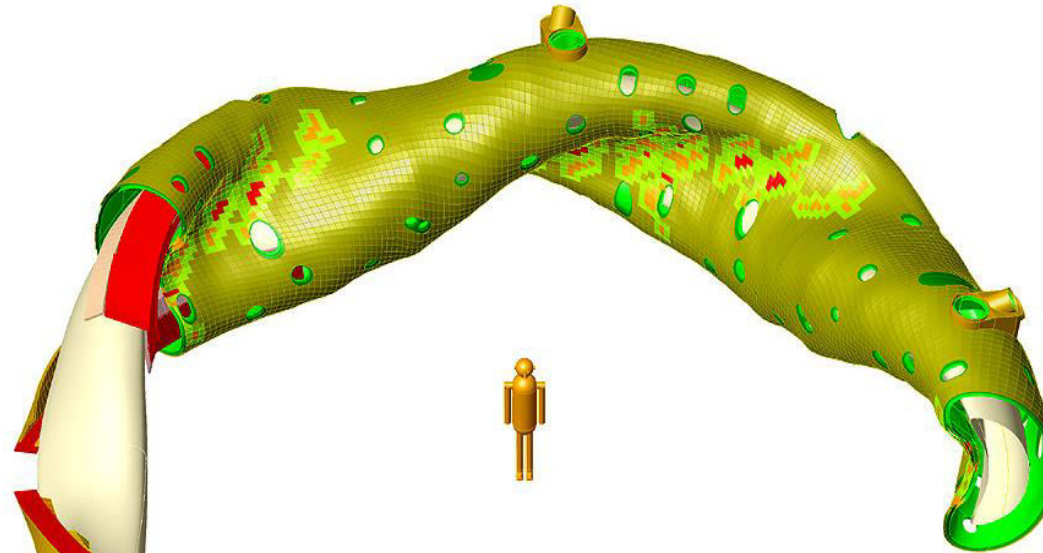
First wall with B<sub>4</sub>C coating (0.2 MW/m<sup>2</sup>)

Diagnostics

- Design for steady state operation -

# Stellarator

## Plasma Vessel

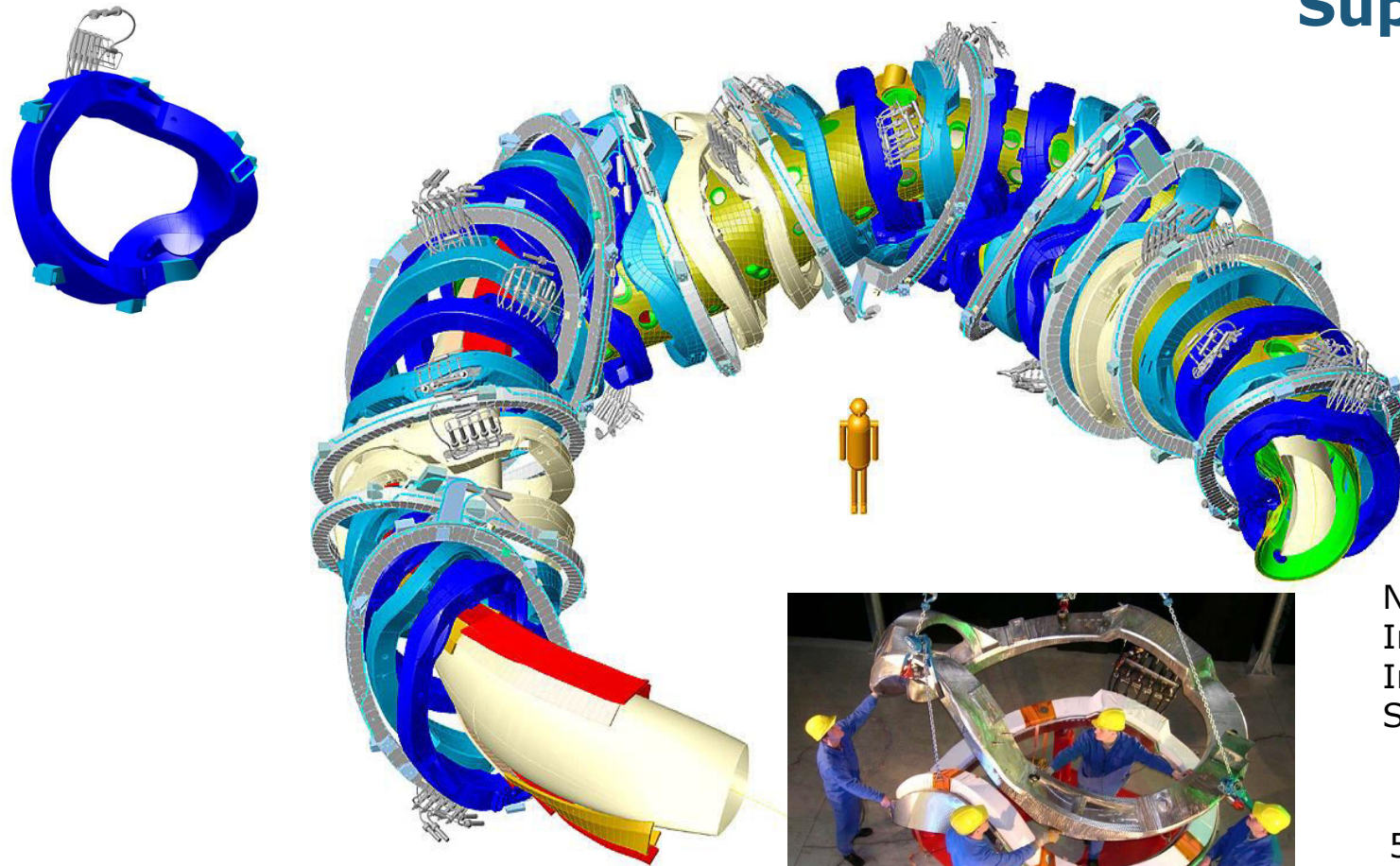


### Parameter

Volume: 110 m<sup>3</sup>  
Surface: 200 m<sup>2</sup>  
Vacuum: < 10<sup>-8</sup> mbar  
Mass: 35 t  
Tolerances < 2 mm



# Stellarator



## Superconducting Coils

### Coils

NbTi superconductor ( $> 3.4$  K)  
Induction on axis: 2.5 T ( $< 3$ T)  
Induction at coil: 6.8 T at 17.8 kA  
Stored magnetic energy: 600 MJ

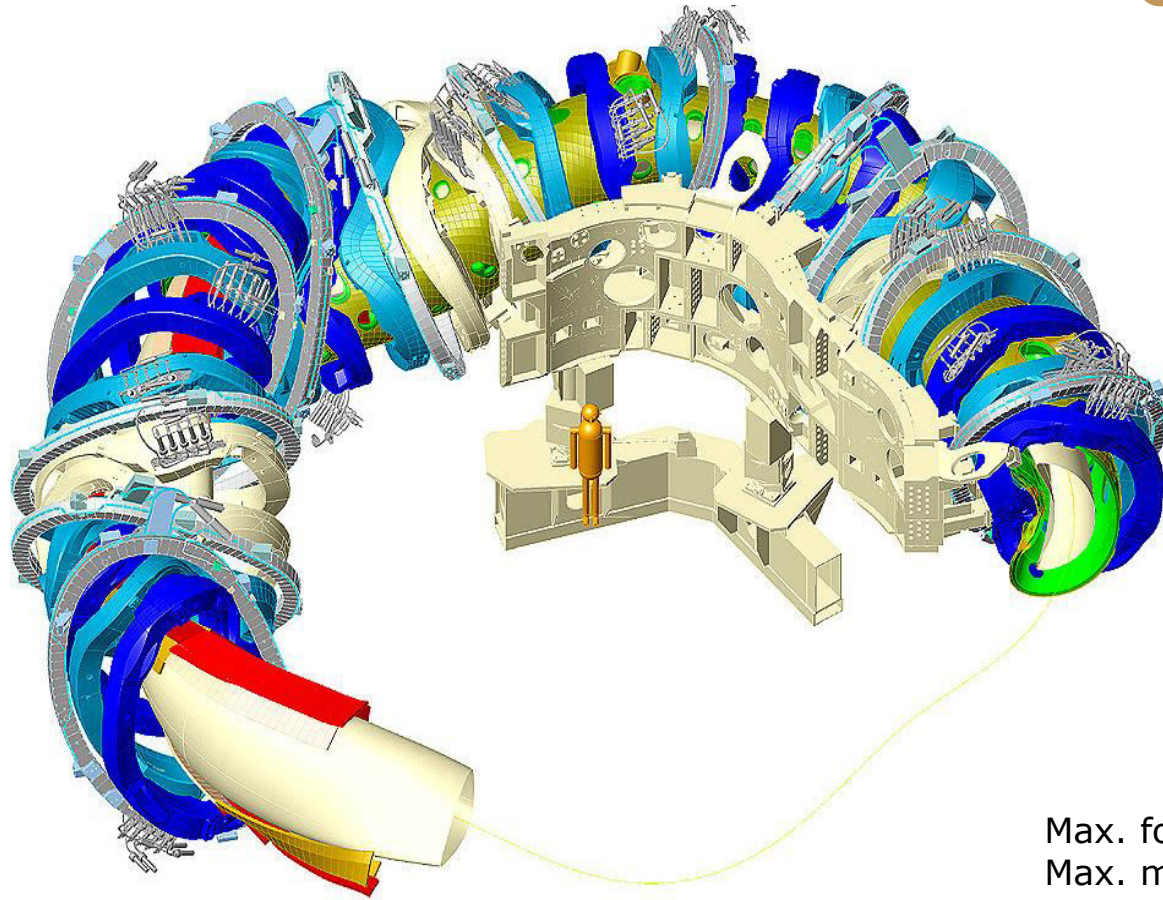
### Parameter

50 non-planar coils, 5 types  
20 planar coils, 2 types, variation  
5 modules, 2 sym. halfmodules



# Stellarator

## Coil Support Structure



### Parameter

Max. force/coil: 3.6 MN

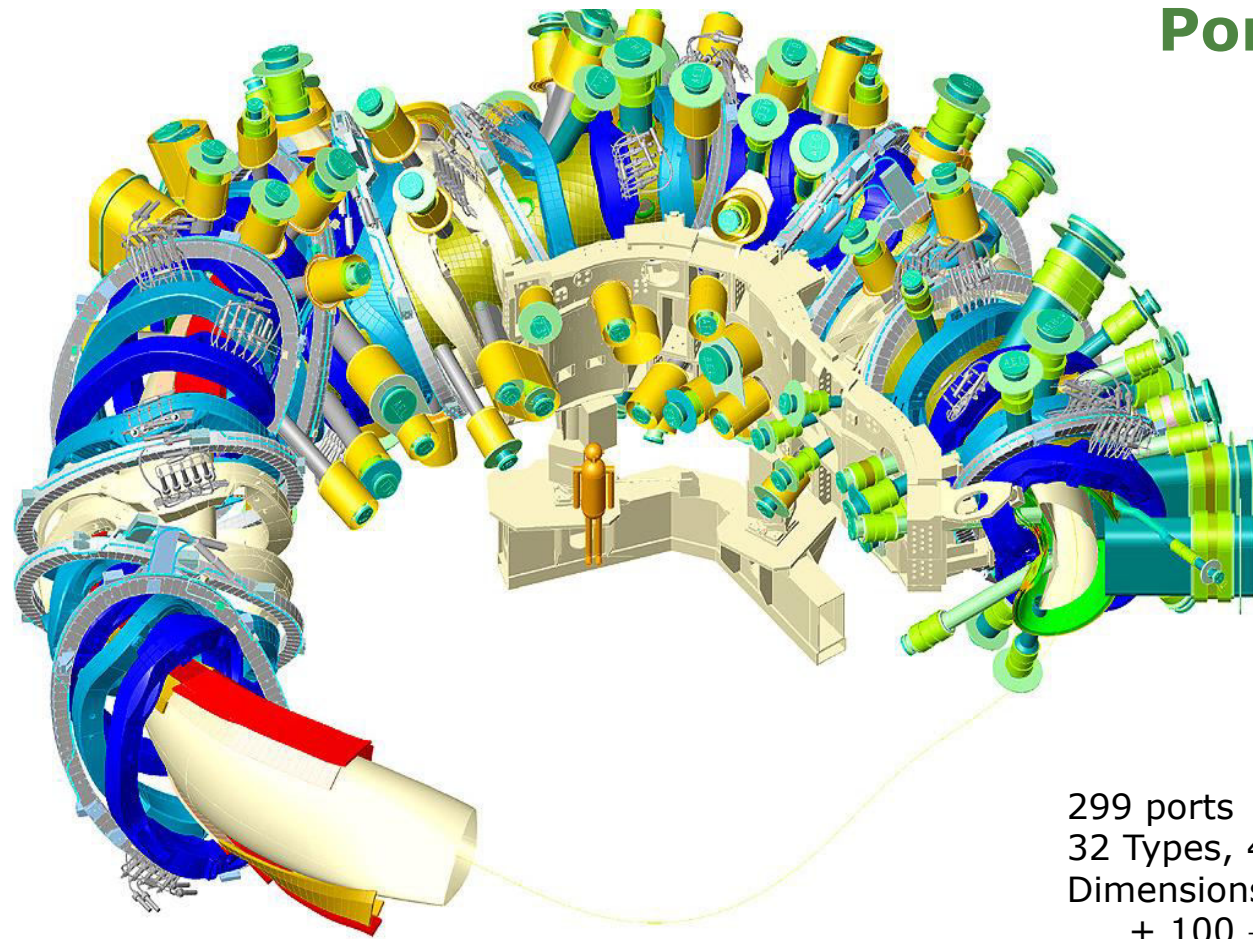
Max. moments: 0.8 MNm

2 supports/coil

Welded connections between coils



# Stellarator

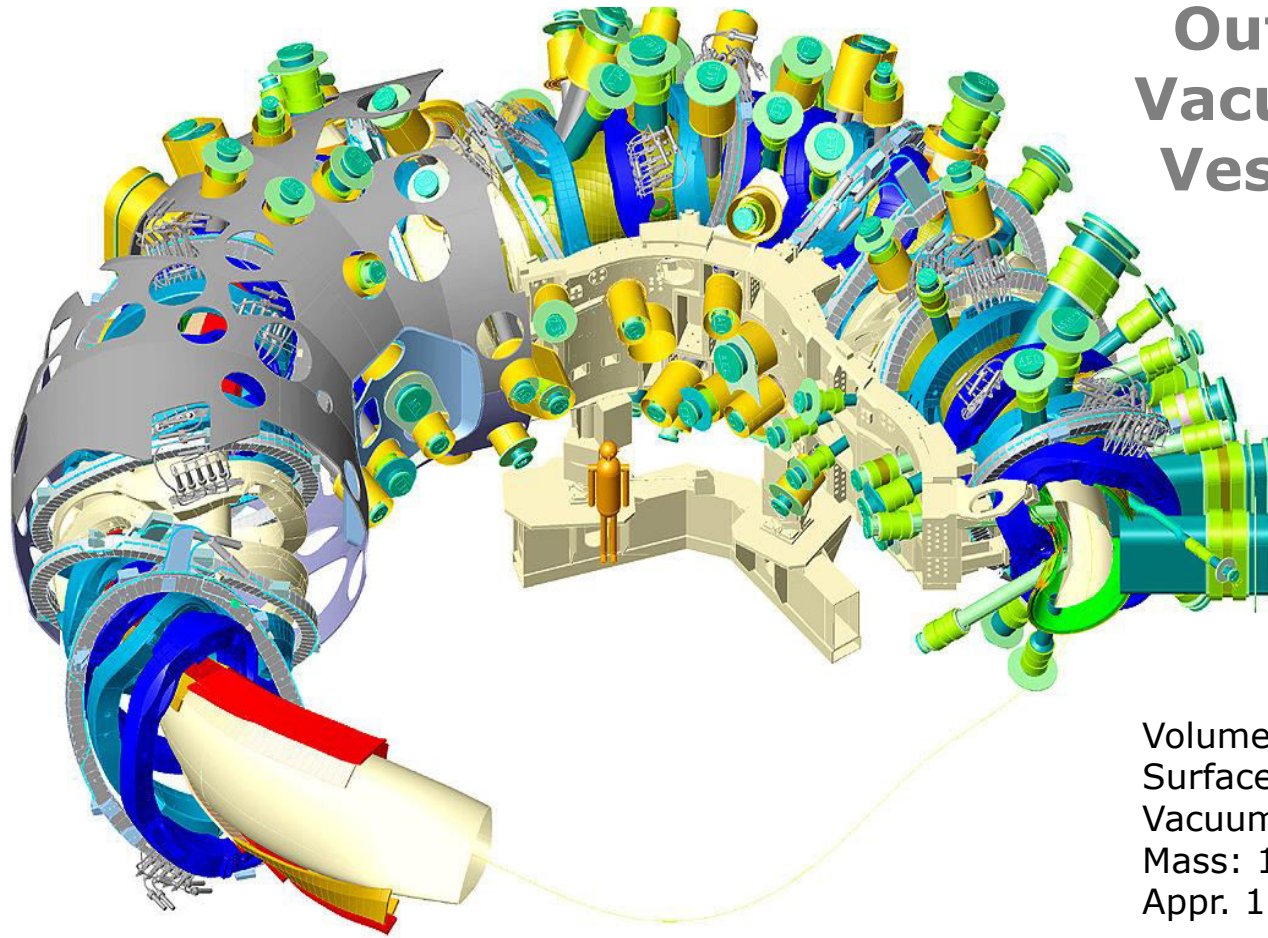


## Ports

### Parameter

299 ports  
32 Types, 47 shapes  
Dimensions  
+ 100 → 400 mm  
+ 150x400 → 400x1000 mm<sup>2</sup>

# Stellarator



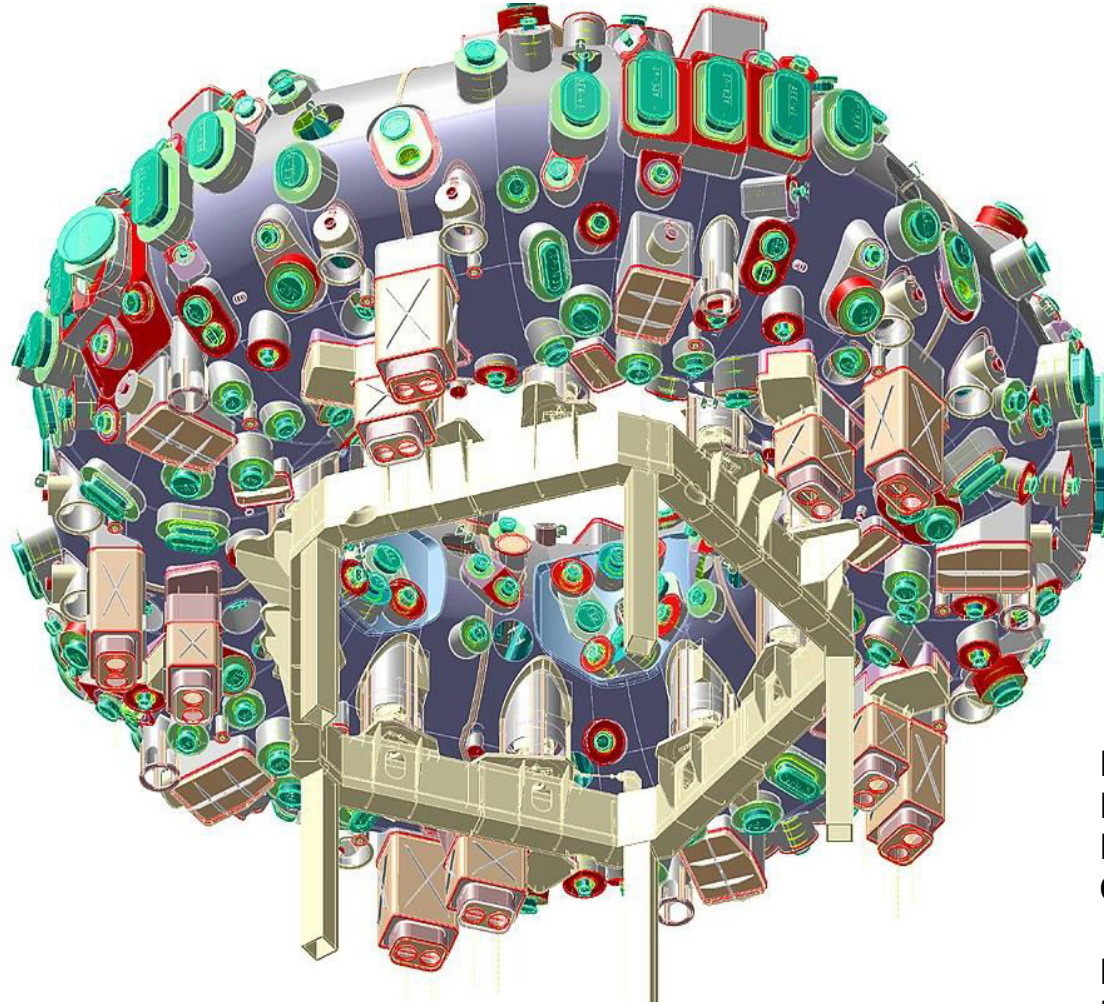
## Outer Vacuum Vessel

### Parameter

Volume: 525 m<sup>3</sup>  
Surface: 480 m<sup>2</sup>  
Vacuum: < 10<sup>-5</sup> mbar  
Mass: 150 t  
Appr. 1200 openings

Thermal insulation on all warm surfaces of the cryostat

# Stellarator



## Schematic View

### Parameter

Machine height: 4.5 m

Machine diameter: 16 m

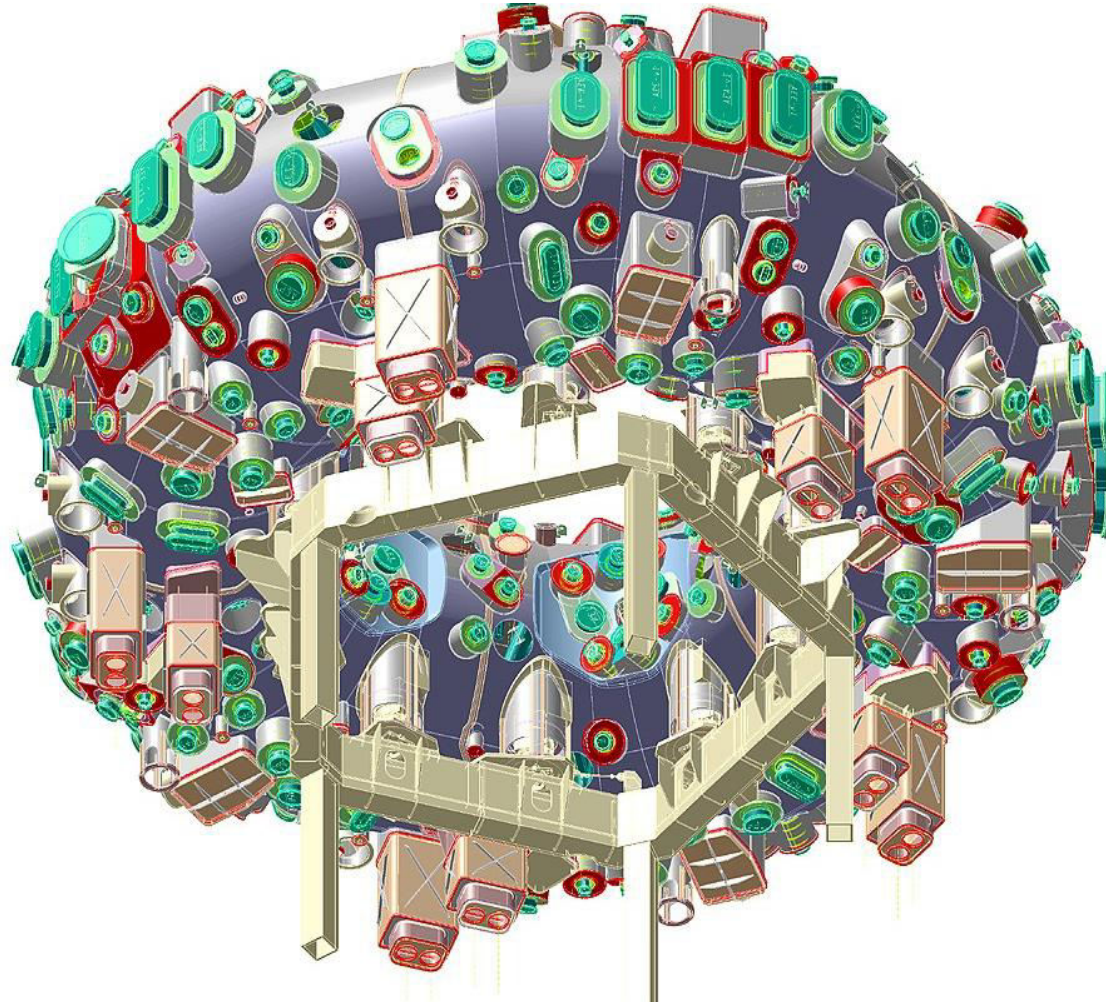
Machine mass: 725 t

Cold mass: 425 t

Heating power: 15 - 30 MW

Nominal pulse length: 30 min

# Stellarator



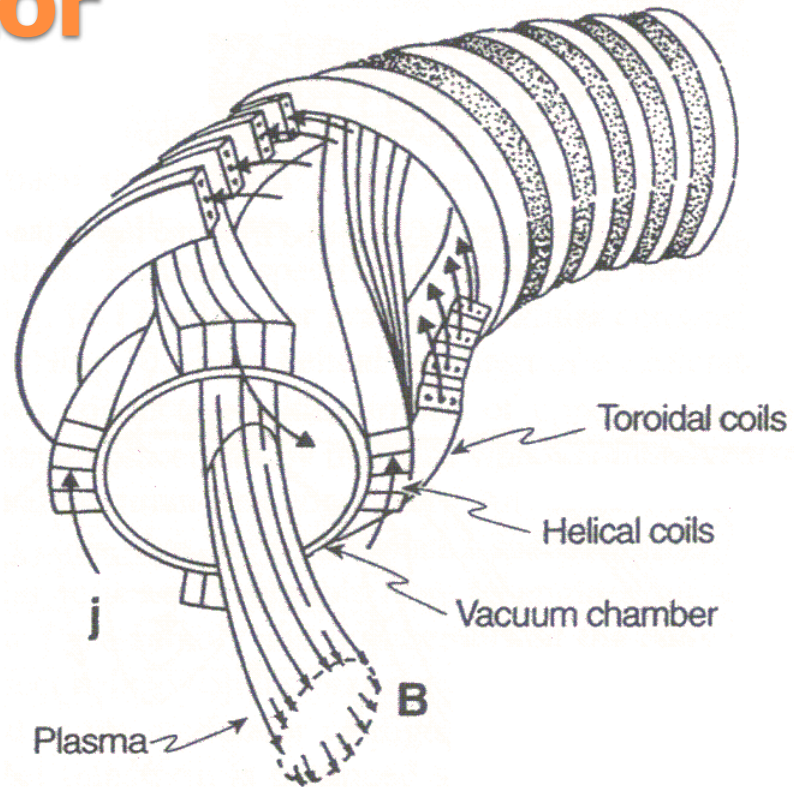
**What a complex system it is!**

# Stellarator



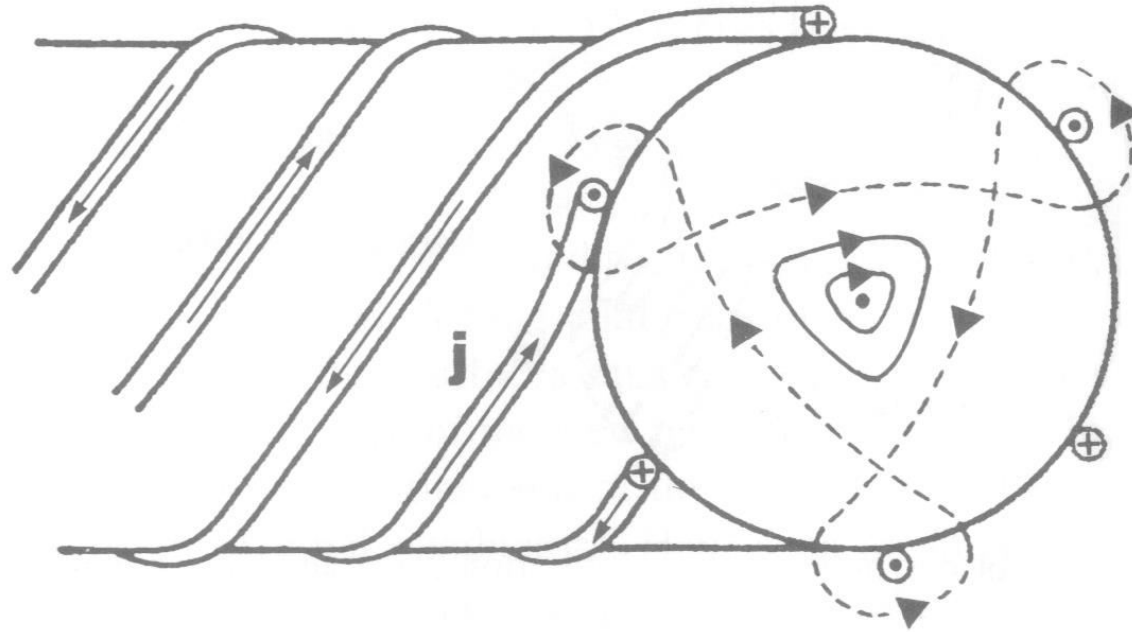
**What a complex system it is!**

# Stellarator



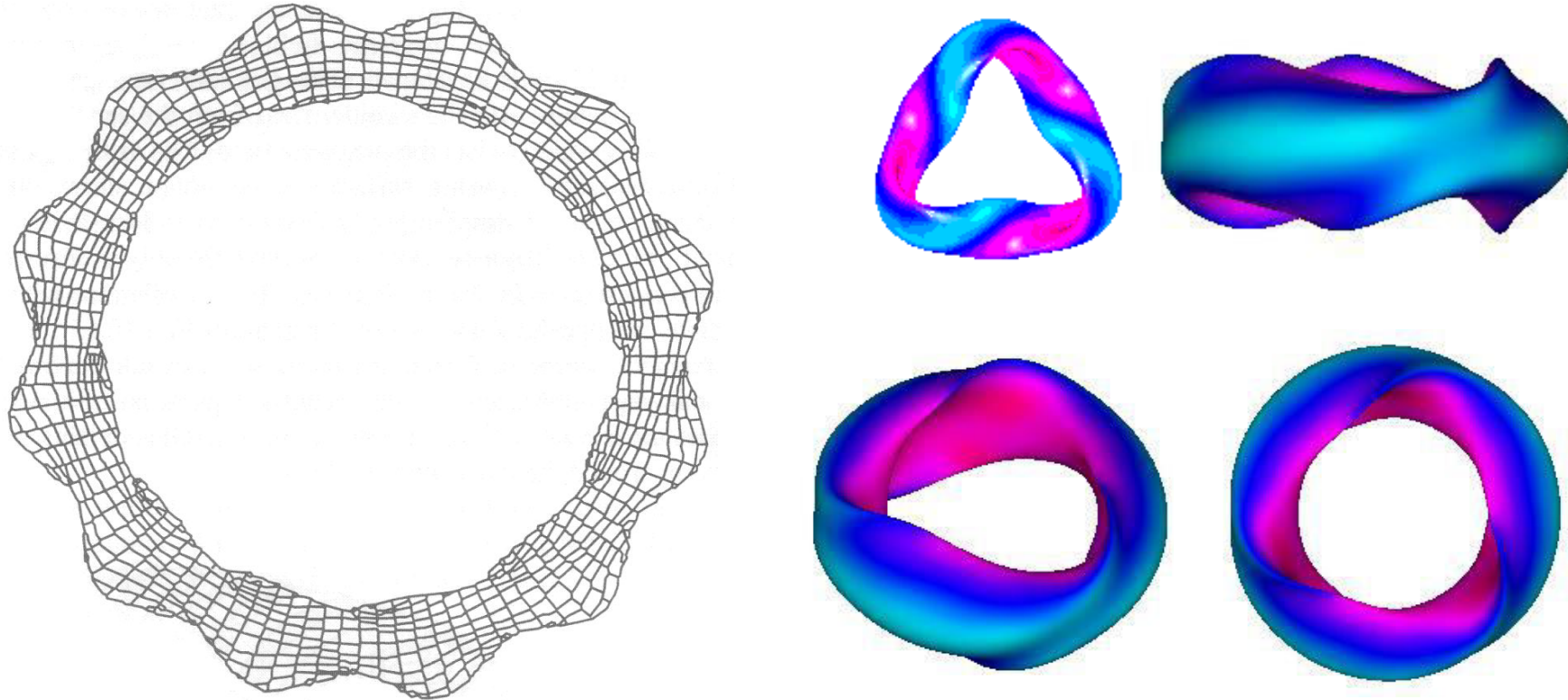
- The helical winding generates a toroidal field as well as a vertical field.
- To eliminate it, currents in adjacent helical windings of the same pitch flow in opposite directions canceling out one another's vertical fields and also their toroidal fields, on average. Thus, toroidal field coils are still required.

# Stellarator



The magnetic surface for a stellarator with  $l = 3$  pairs of helical coils of opposite currents

# Stellarator



Complete magnetic flux surfaces:  
The geometrical simplicity of axisymmetry lost

<http://www.ornl.gov/sci/fed/mhd/mhd.html>

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)



# Stellarator

- **Inhomogeneity of the magnetic field**

- Due to the absence of a current in a stellarator, Ampere's law yields,

$$\nabla \times \vec{B} = \mu_0 \mathbf{J} \rightarrow \oint_s \frac{\vec{B}}{\mu_0} \cdot d\vec{s} = 0$$

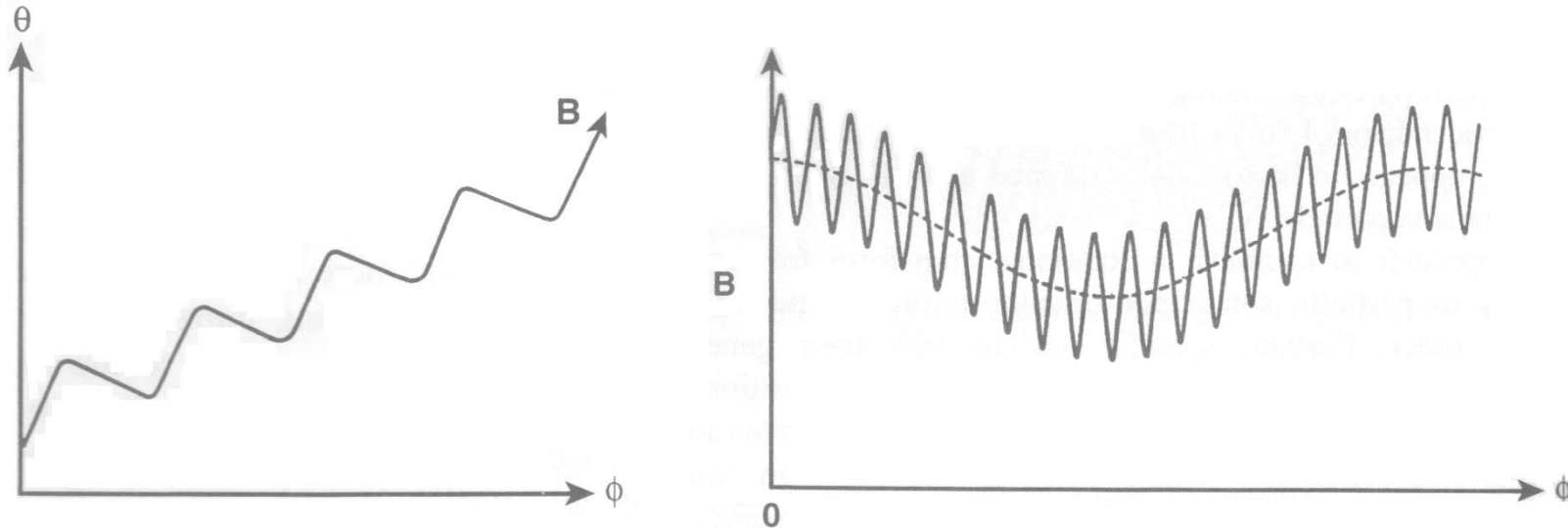
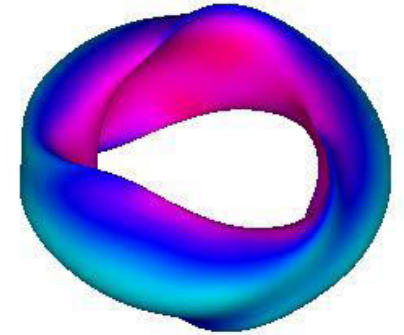
: The line integral of the poloidal component of the magnetic field vanishes along a contour  $s$  encircling the magnetic axis on each magnetic flux surface.

→ The poloidal field must change sign and magnitude along  $s$ . Each such so-called fundamental field period incrementally rotates the field lines in the poloidal direction.

- Curvature associated with torus geometry

# Stellarator

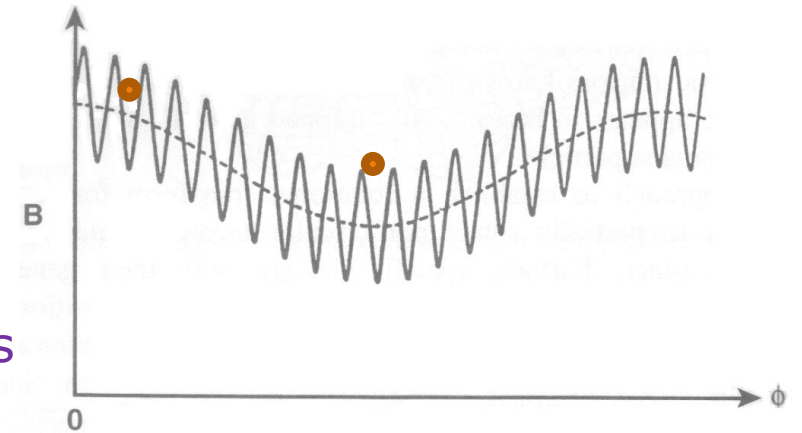
- Inhomogeneity of the magnetic field



- The deep and more frequent oscillations of  $\mathbf{B}$  are caused by the helical windings alternately carrying currents of different direction, and where the slow modulation of  $\mathbf{B}$  corresponds to the toroidal curvature.

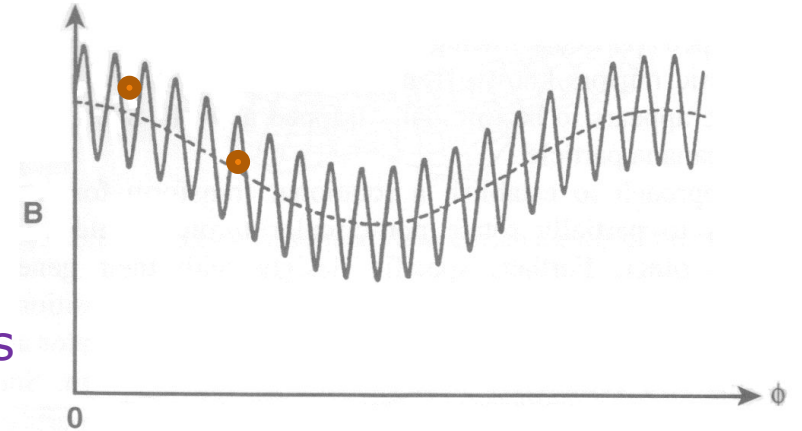
# Stellarator

- **Inhomogeneity of the magnetic field**
    - Particle motions in this magnetic field configurations
      - (1) Circulating particles passing entirely around the torus without encountering a reflection
      - (2) Helically trapped particles reflected in the local mirrors of the helical field
      - (3) Toroidally trapped particles tracing banana orbits reflected in the toroidal magnetic mirrors
- Cf. Superbanana particle: a helically and toroidally trapped particle



# Stellarator

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→ **Enhanced transport losses!**

# Stellarator

- LHD achievement up to 2016 before D operation

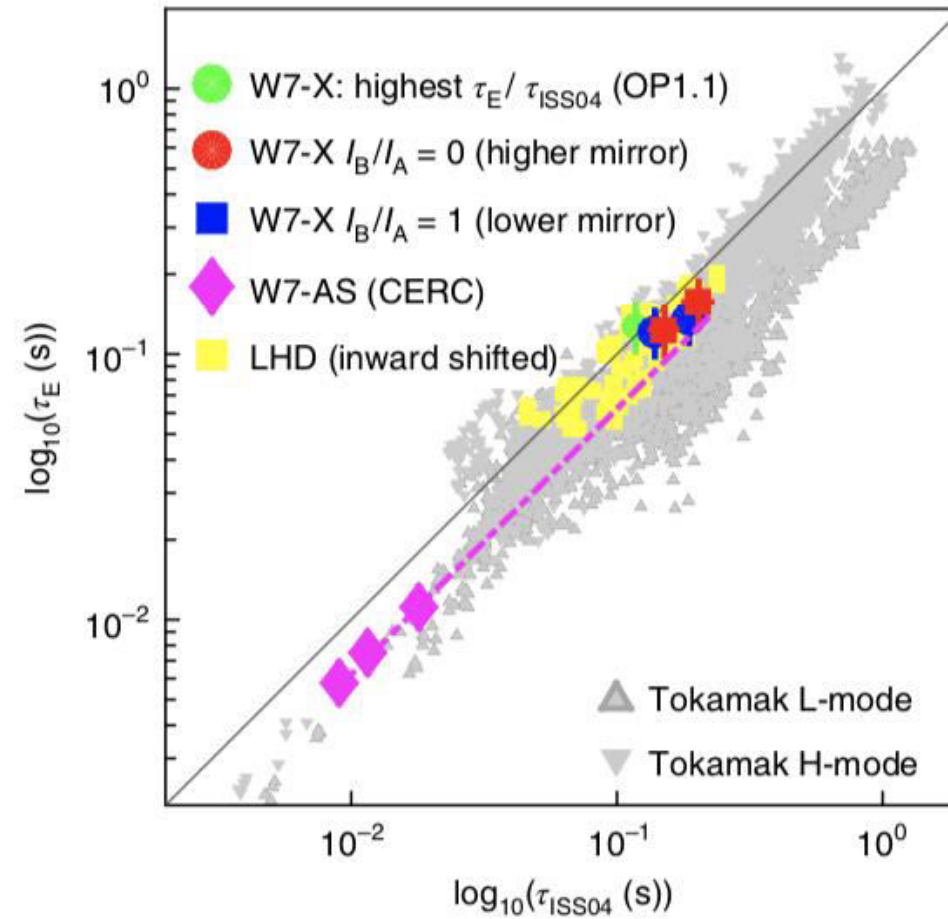
Plasma parameters	Achieved	Target	Fusion condition
Ion temperature	8.1 keV at $1 \times 10^{19} \text{m}^{-3}$	10 keV at $2 \times 10^{19} \text{m}^{-3}$	> 10 keV > $1 \times 10^{20} \text{m}^{-3}$
Electron temperature	20 keV at $2 \times 10^{18} \text{m}^{-3}$ 10 keV at $1.6 \times 10^{19} \text{m}^{-3}$	10 keV at $2 \times 10^{19} \text{m}^{-3}$	
Density	$1.2 \times 10^{21} \text{m}^{-3}$ with $T_e$ of 0.25 keV	$4 \times 10^{20} \text{m}^{-3}$ with $T_e$ of 1.3 keV	
Beta	5.1% at 0.425 T 4.1% at 1 T	5% at 1-2 T	> 5% at > 5 T
Steady-state operation	54min. 28sec (0.5 MW) (1keV, $4 \times 10^{18} \text{m}^{-3}$ ) 47min. 30sec. (1,2 MW) (2keV, $1 \times 10^{19} \text{m}^{-3}$ )	1 hour (3 MW)	Steady-state (1 year)



# Tokamak .VS. Stellarator

	Advantage	Disadvantage
<b>Tokamak</b>	<ul style="list-style-type: none"> <li>- Simple 2D structure, so relatively easy to analyze and fabricate the device</li> <li>- The most studied and successful up to now (mainstream in the roadmap to a feasible fusion reactor)</li> </ul>	<ul style="list-style-type: none"> <li>- Need an external current drive (inductive or non-inductive) for plasma current generation &amp; steady-state operation</li> <li>- Subject to plasma current-driven instabilities and disruptions</li> </ul>
<b>Stellarator</b>	<ul style="list-style-type: none"> <li>- No external current drive necessary, so inherently steady-state operation possible</li> <li>- Relatively free from plasma current-driven instabilities and disruptions</li> </ul>	<ul style="list-style-type: none"> <li>- Complicated 3D structure, so difficult to analyse and fabricate the device</li> <li>- Large system size required with a high aspect ratio</li> <li>- Subject to large neoclassical transport at low collisionality</li> <li>- existence of bootstrap current</li> </ul>

# Tokamak .VS. Stellarator



# Tokamak .VS. Stellarator

