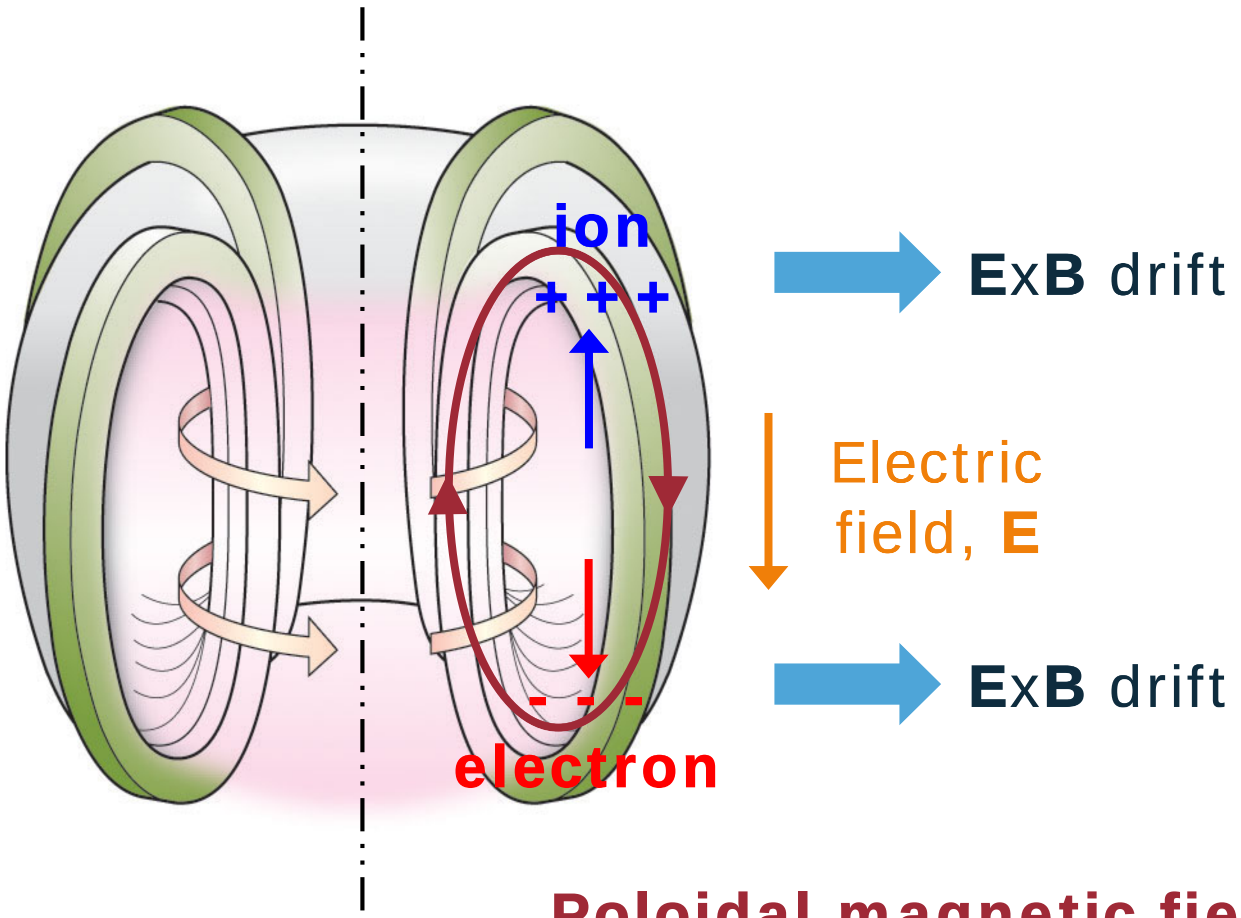
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

What is a stellarator?

M. Otthe, “Stellarator: Experiments”, IPP Summer School (2008)

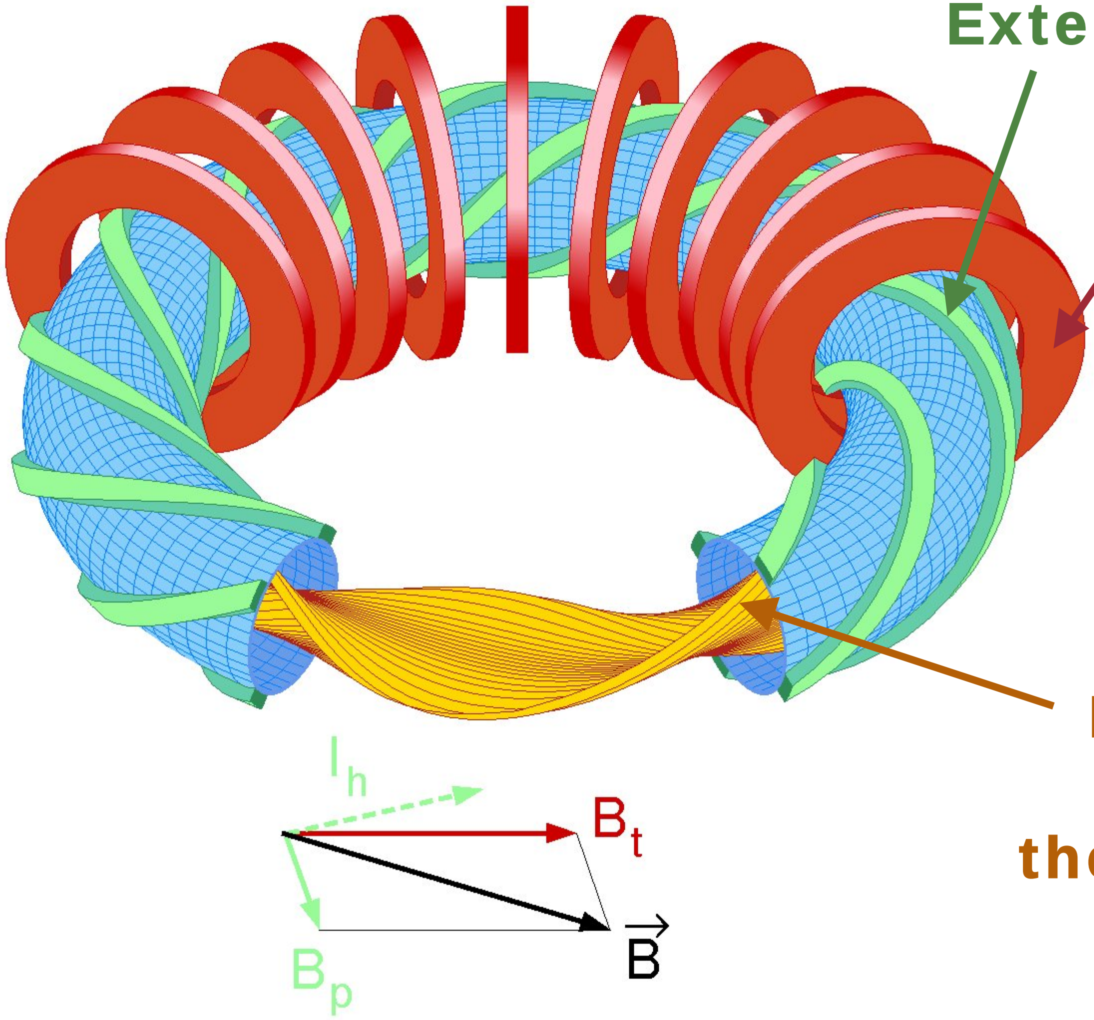
Closed Magnetic System



Poloidal magnetic field required

External coils → Stellarator

Stellarator



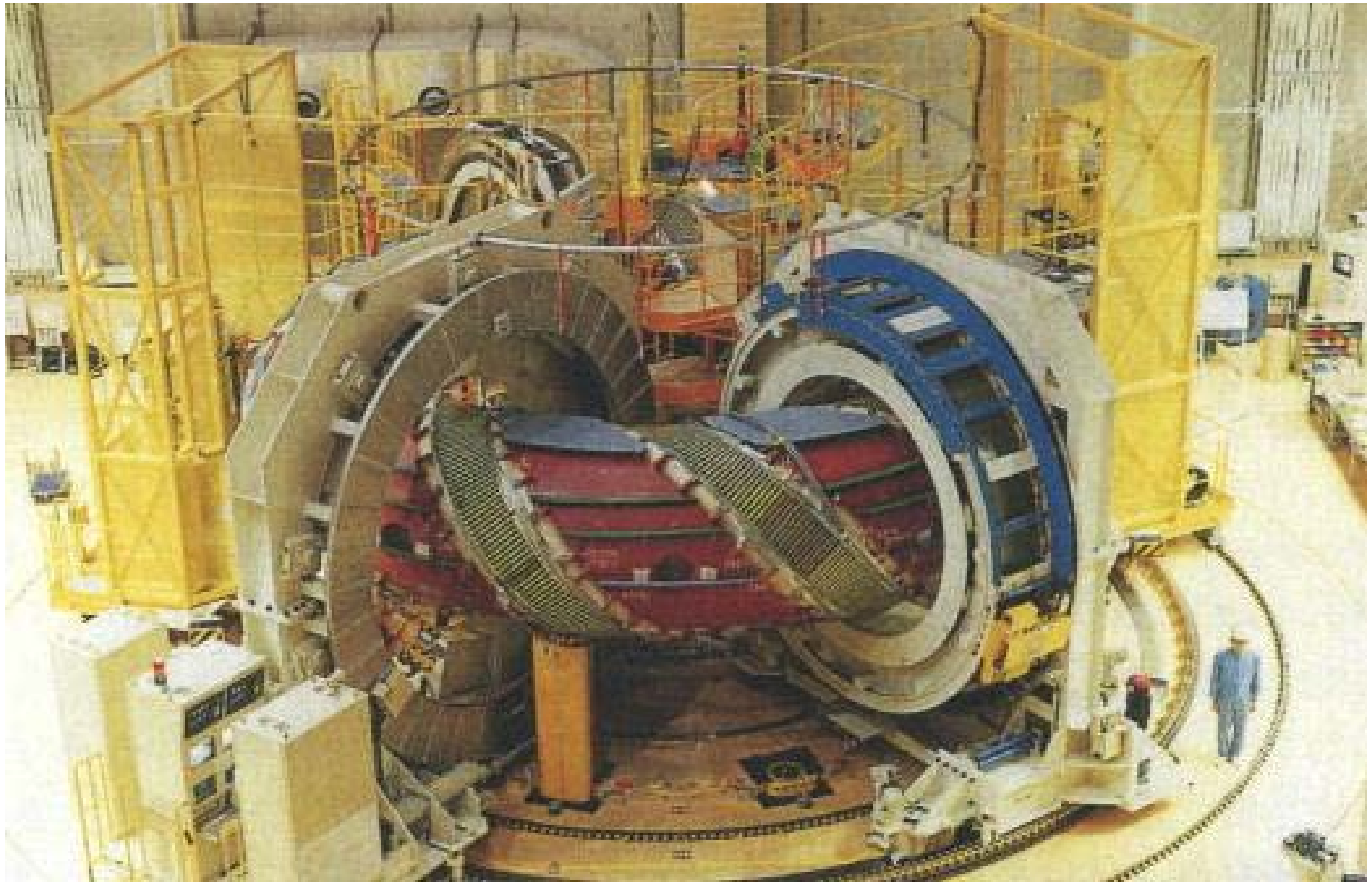
External coils

TF coils

Poloidal field induced by the external coils

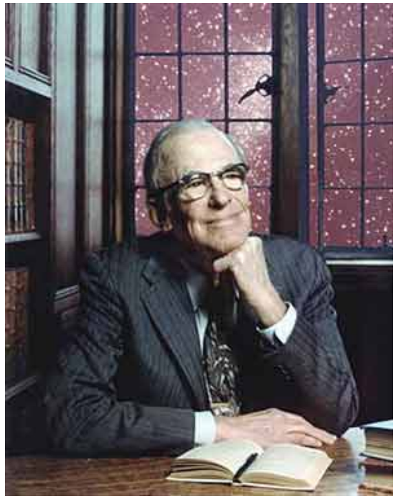
http://www.ua.all.biz/img/ua/catalog/1067534.jpeg

Stellarator



LHD (Large Helical Device) under construction

Stellarator



THE

PHYSICS OF FLUIDS

VOLUME 1, NUMBER 4 JULY-AUGUST, 1958

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

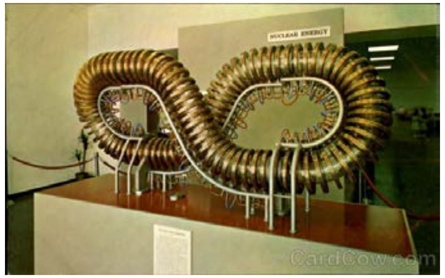
Richard Georg Strauss (1864 – 1949)

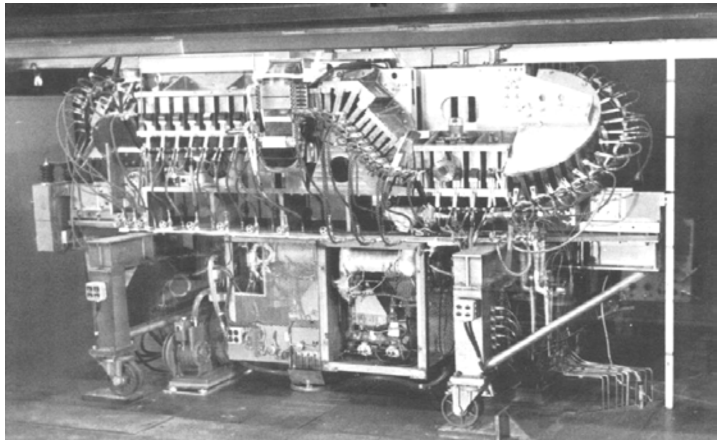
WIKIPEDIA

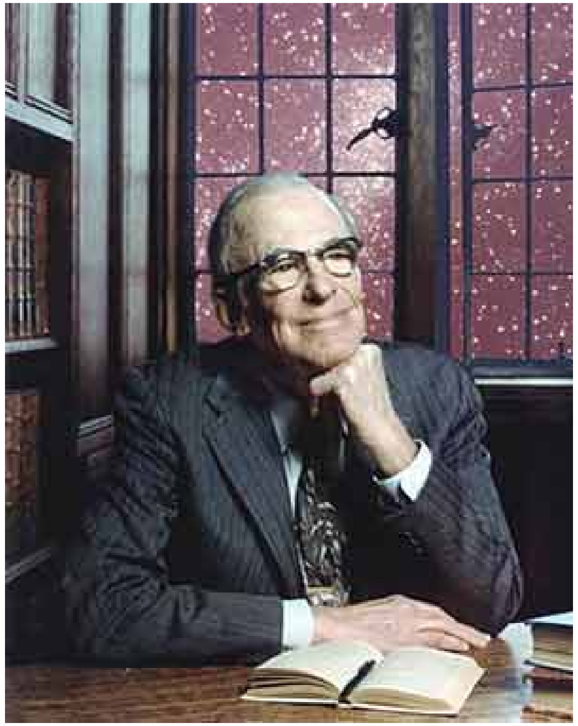
http://unterkunft-reise.com/garmisch-partenkirchen/

Stellarator

Invented by Lyman Spitzer, Jr. in Princeton in 1951







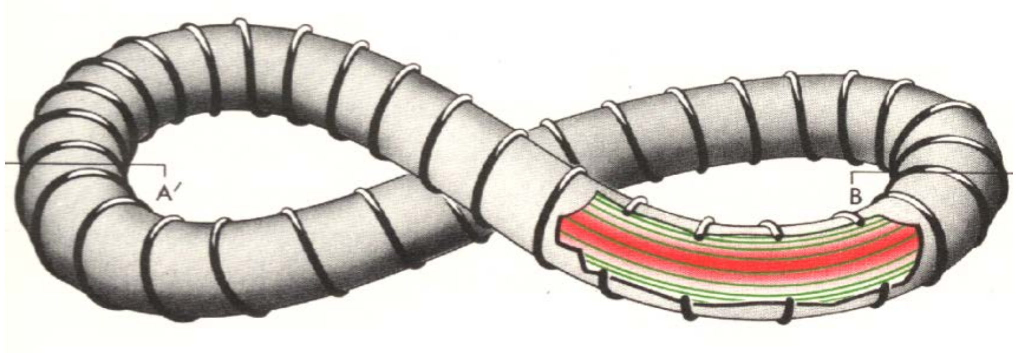
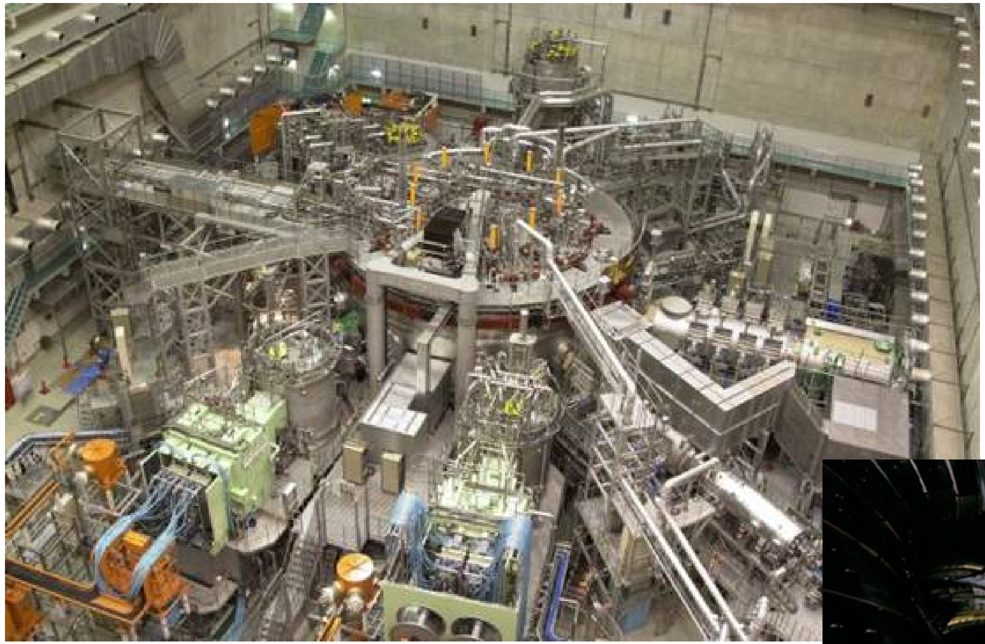
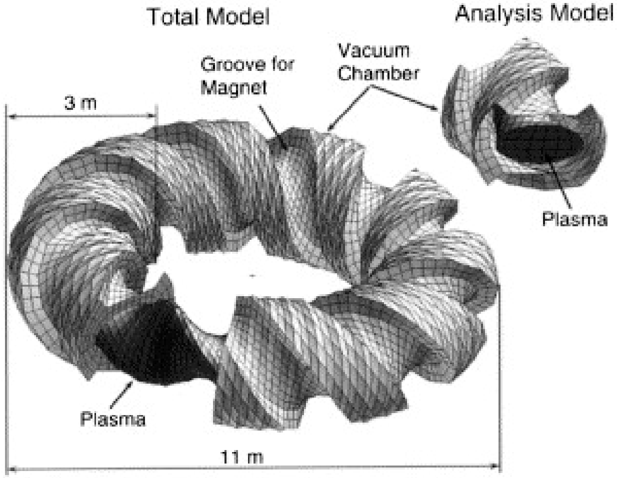


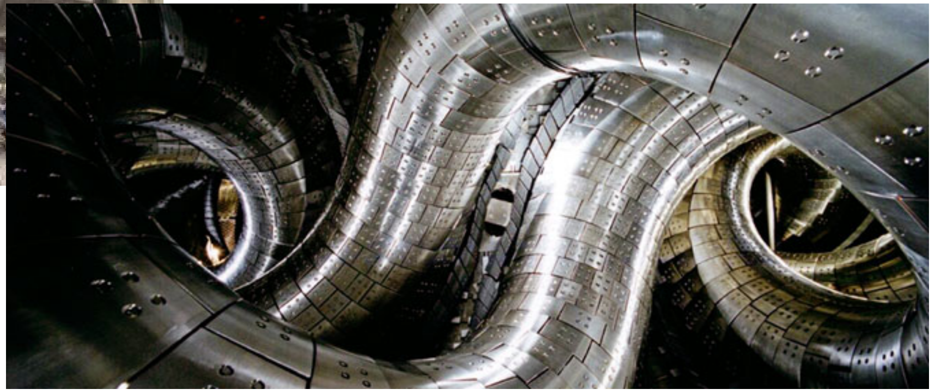
Figure-8 stellarator: Proof of principle experiment
(helicity achieved by twisting the torus and hence the magnetic field)

Stellarator

Large Helical Device (LHD), Japan



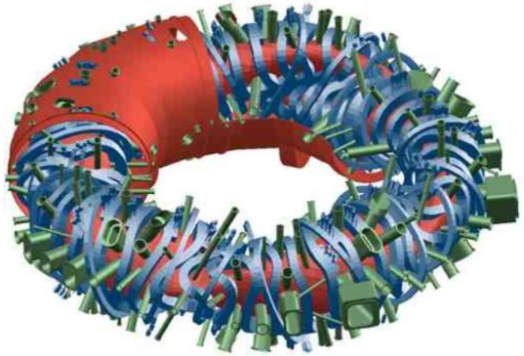




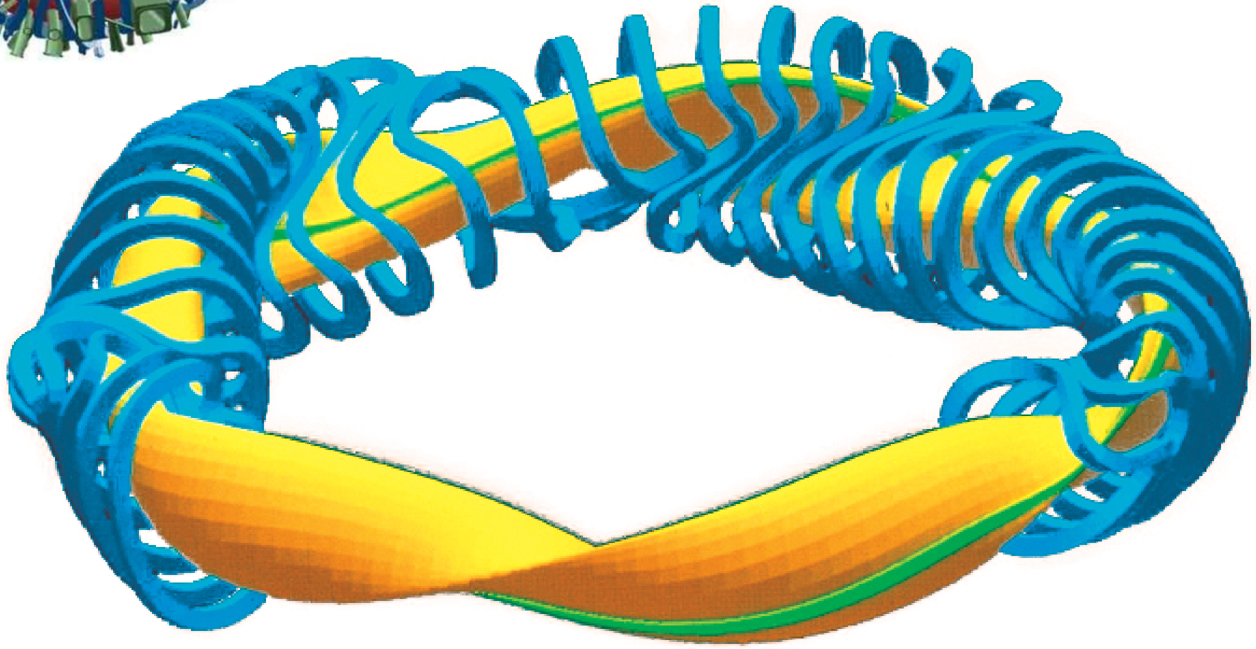
3D configuration!

http://fire.pppl.gov
http://ztopics.com/Large%20Helical%20Device/

Stellarator



Wendelstein 7-X, Germany

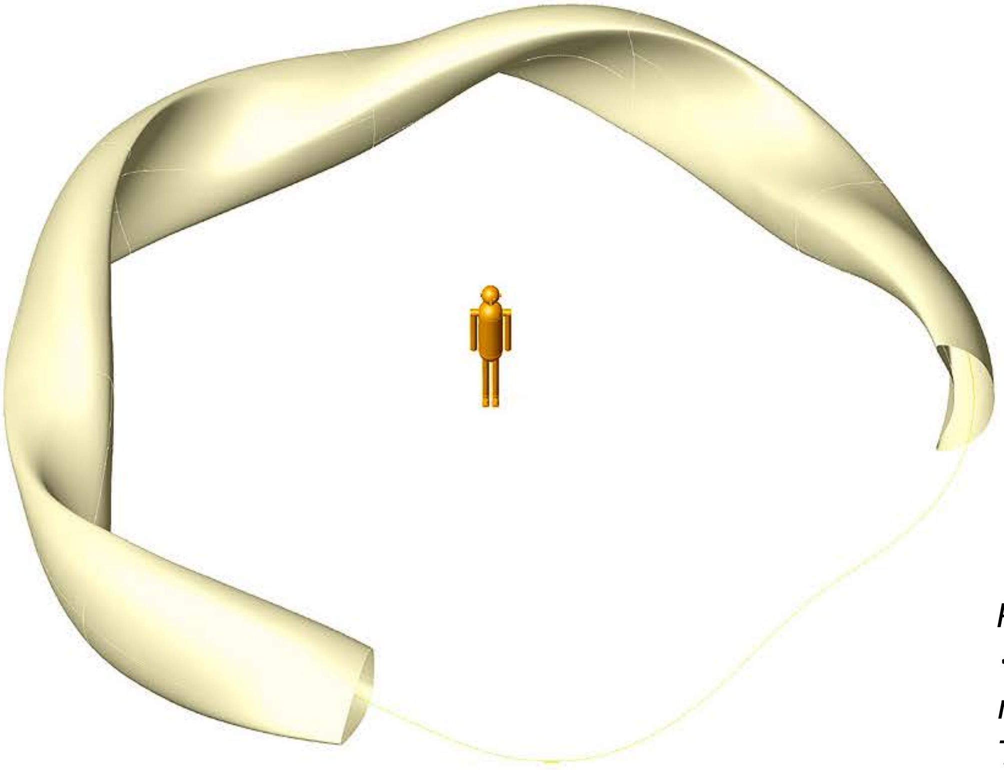


3D configuration!

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator

Plasma



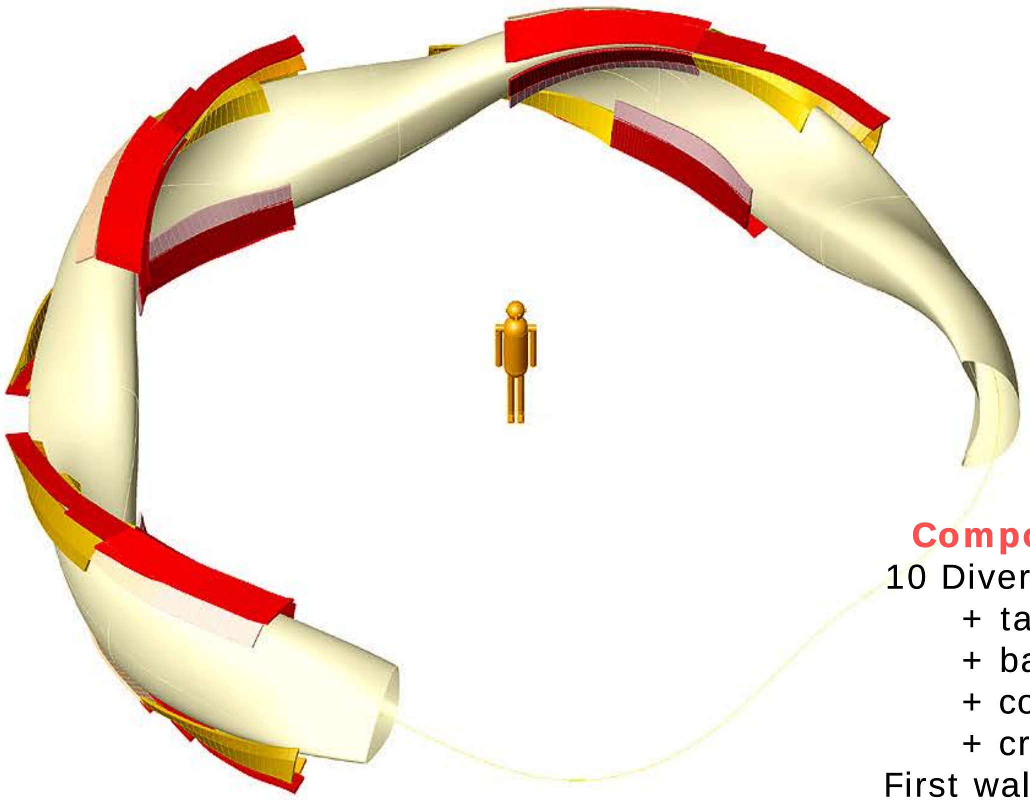
Plasma Parameter

R: 5.5 m
$<a>$: 0.53 m
$n_e(0)_{max}$: $3x10^{20}$ m^{-3}
$T_e(0)_{max}$: 5 keV
$<\beta>$: < 5 %

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator

Divertor



Components inside plasma vessel

10 Divertor units
- + target elements (10 MW/m^2)
- + baffle elements (0.5 MW/m^2)
- + control coils
- + cryo pumps

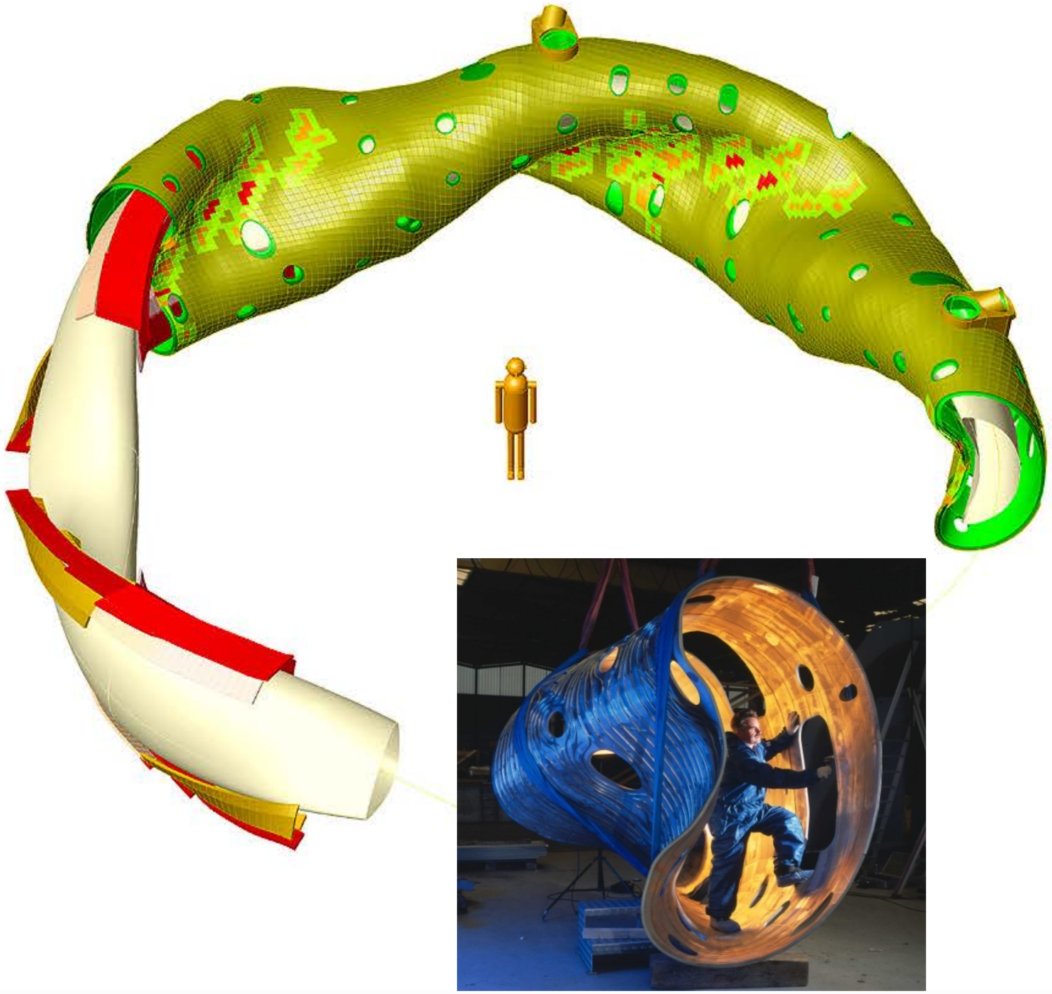
First wall with B_4C coating (0.2 MW/m^2)
Diagnostics

- Design for steady state operation -

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator

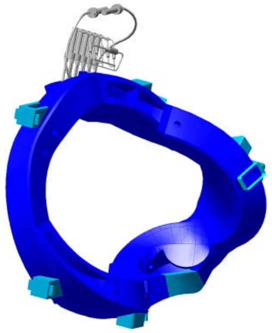
Plasma Vessel

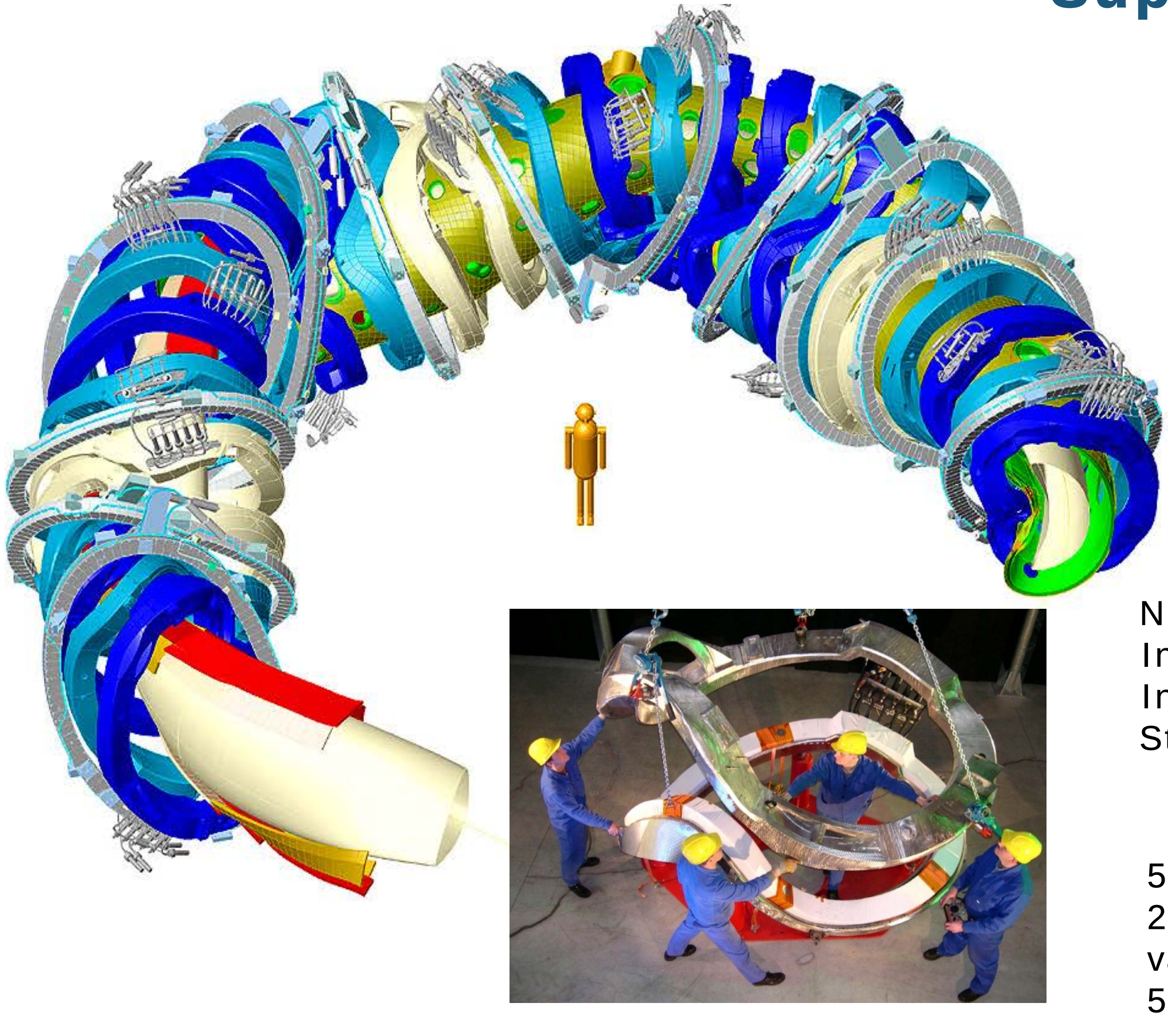


Parameter

Volume: 110 m^3
Surface: 200 m^2
Vacuum: < 10^{-8} mbar
Mass: 35 t
Tolerances < 2 mm

Stellarator





Superconducting Coils

Coils

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

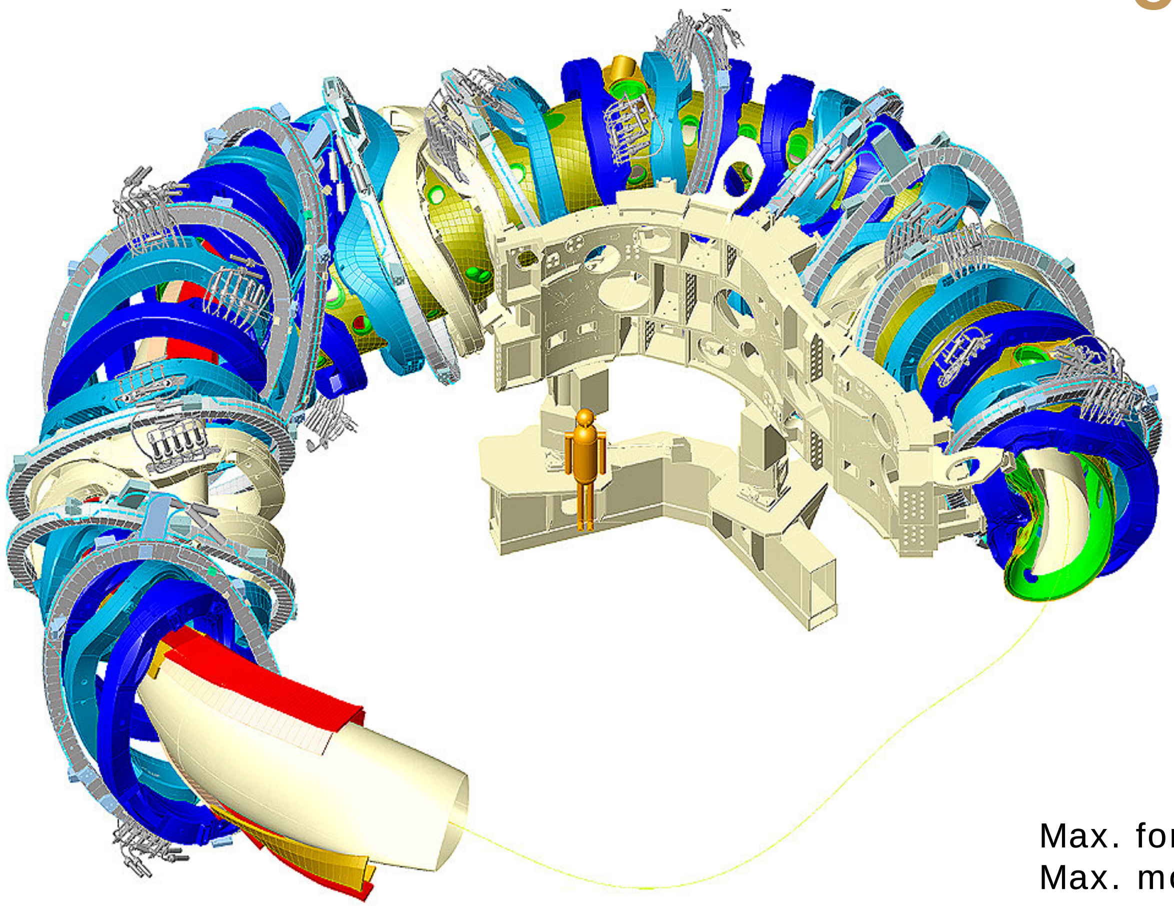
Parameter

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

WIKIPEDIA

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator



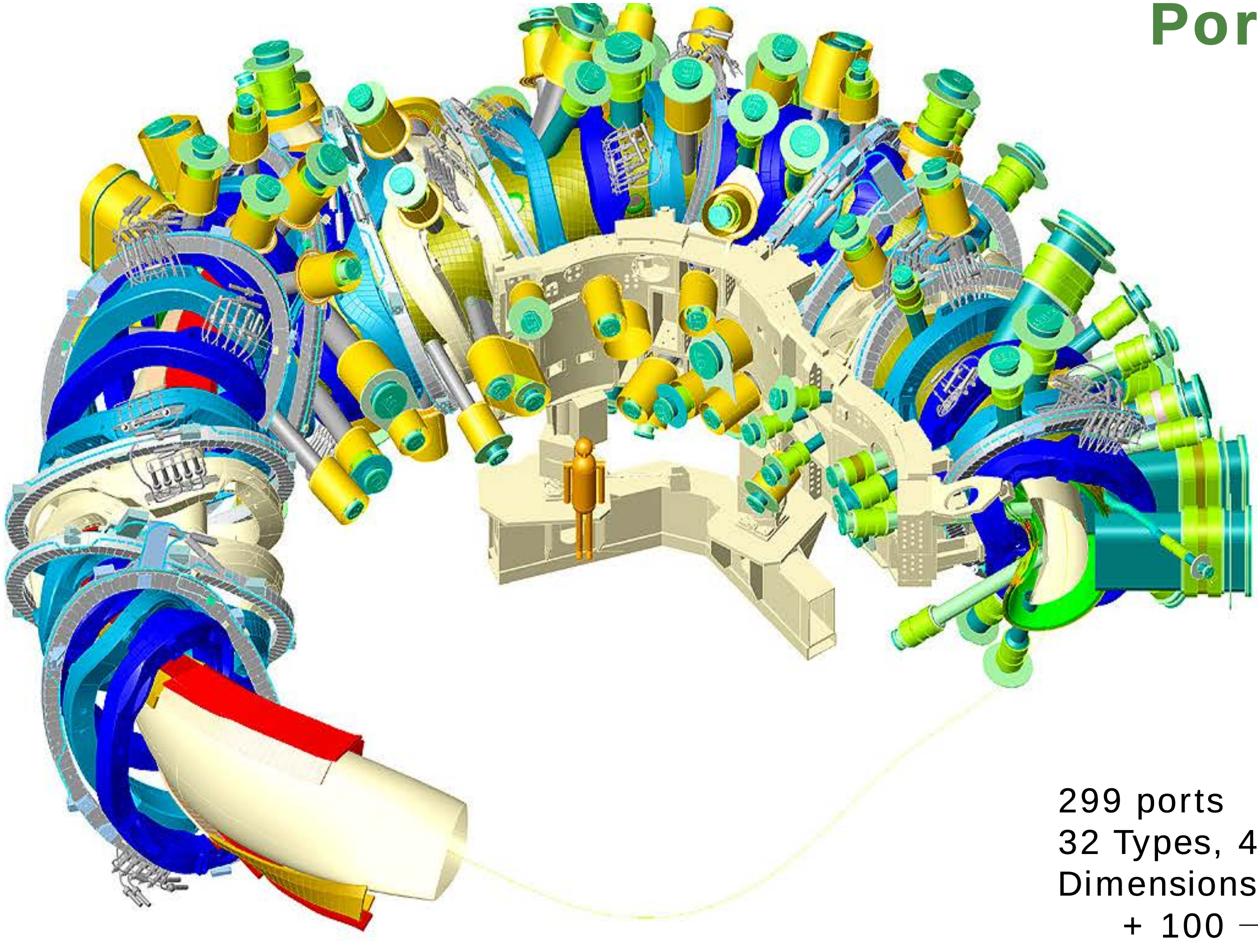
Coil Support Structure

Parameter

Max. force/coil: 3.6 MN
Max. moments: 0.8 MNm
2 supports/coil
Welded connections between coils

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator



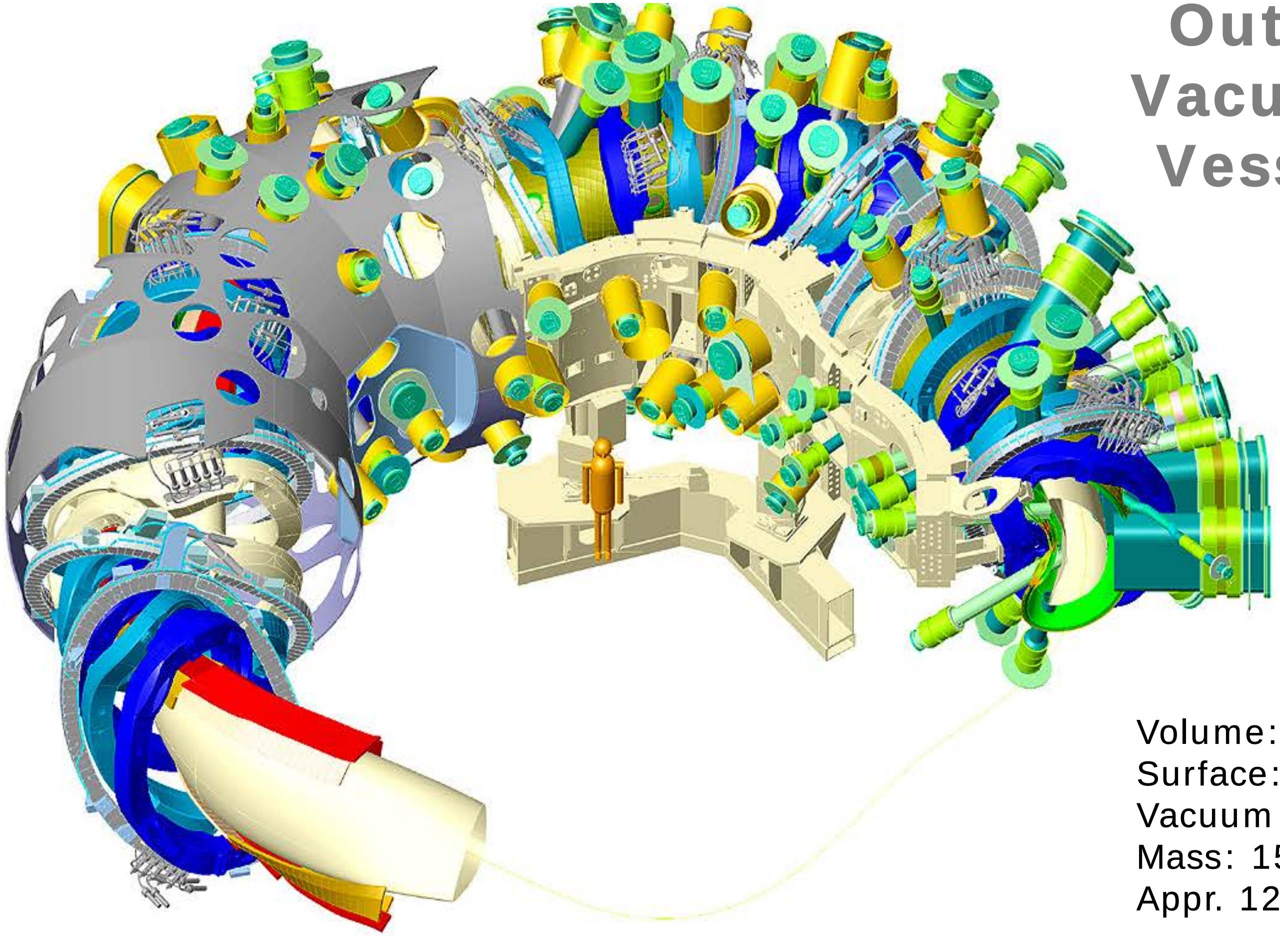
Ports

Parameter

299 ports
32 Types, 47 shapes
Dimensions
+ 100 → 400 mm
+ 150x400 → 400x1000 mm^2

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator



Outer Vacuum Vessel

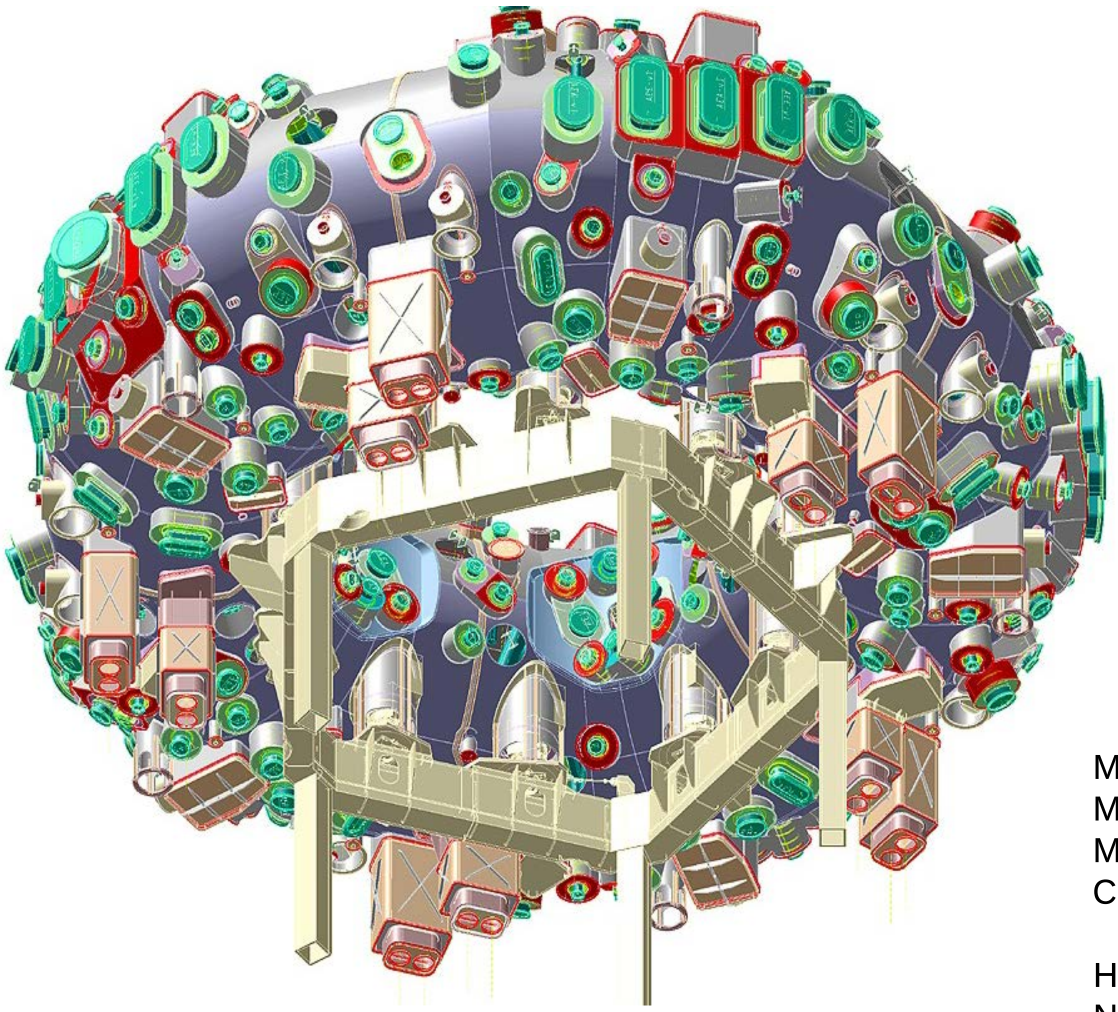
Parameter

Volume: 525 m^3
Surface: 480 m^2
Vacuum: < 10^{-5} mbar
Mass: 150 t
Appr. 1200 openings

Thermal insulation on all warm surfaces of the cryostat

http://scienceblogs.com.br/100nexos/2008/09/louvado-seja-o-grande-dispositivo-helicoidal/

Stellarator



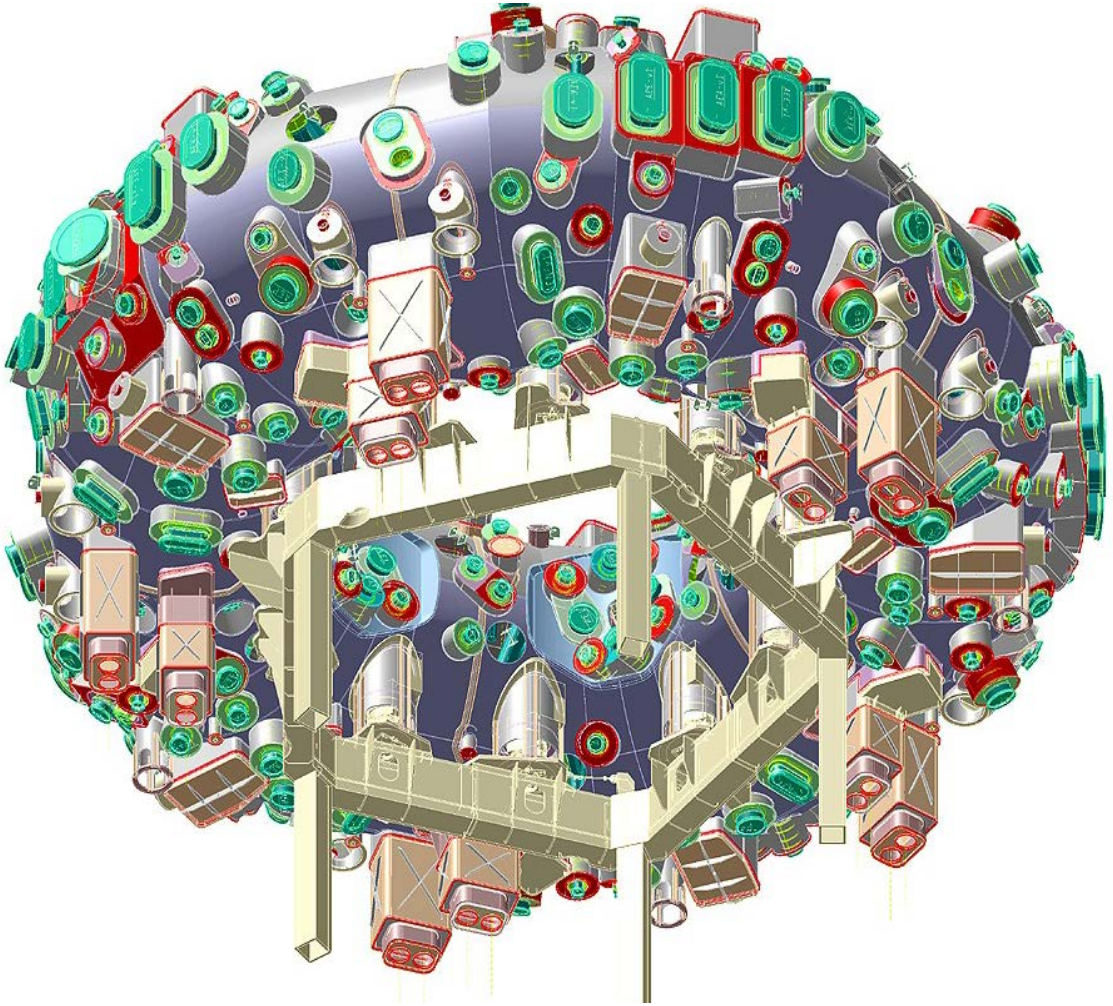
Schematic View

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

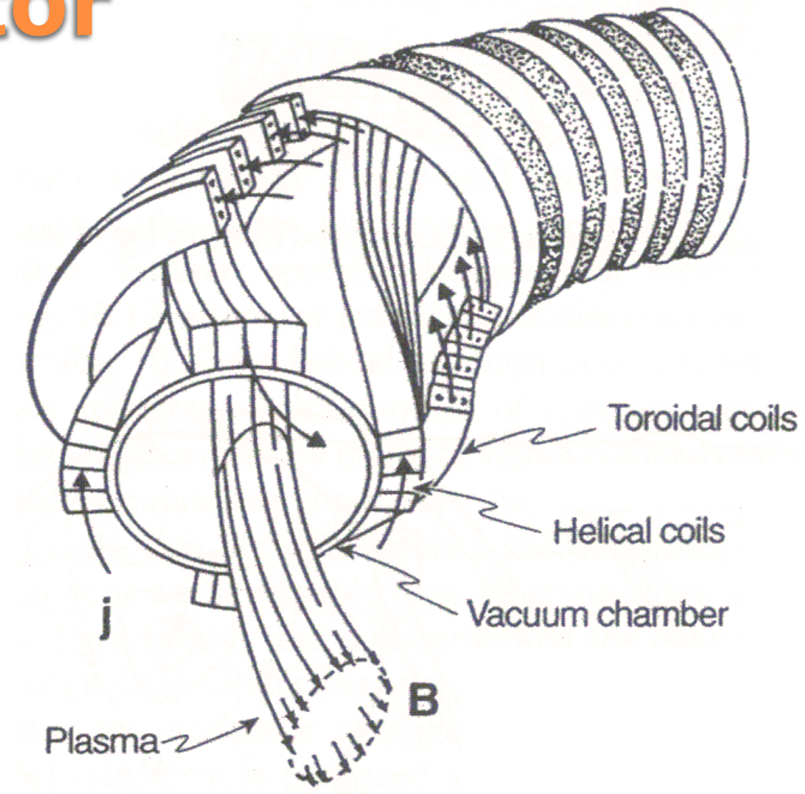


What a complex system it is!

Stellarator

What a complex system it is!

Stellarator

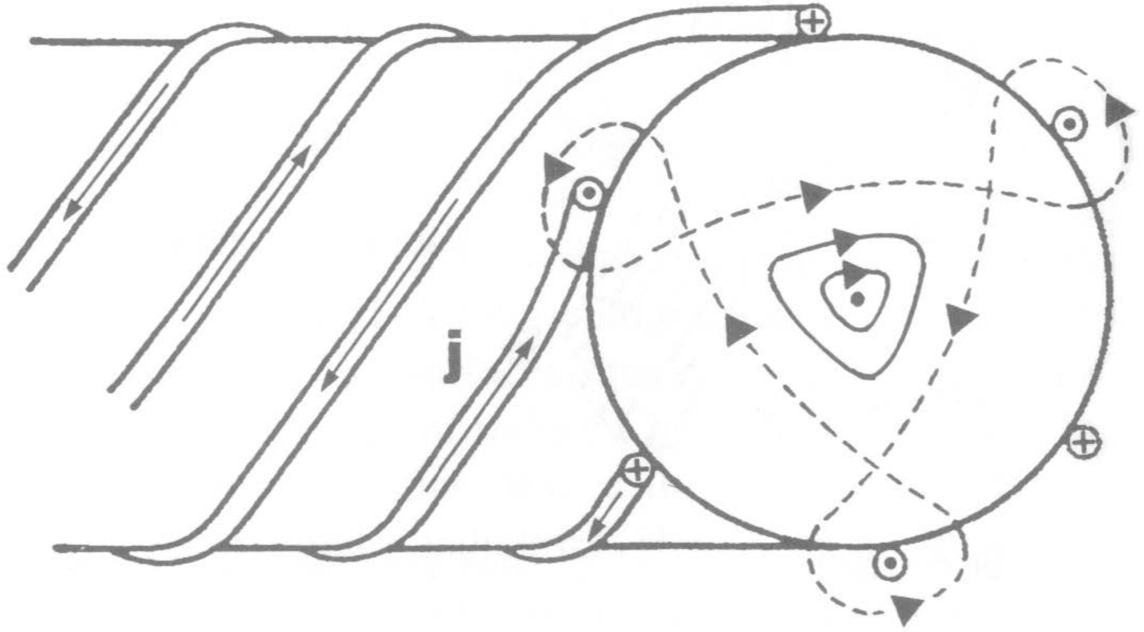


- The helical winding generates a toroidal field as well as a vertical field.

→ 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.

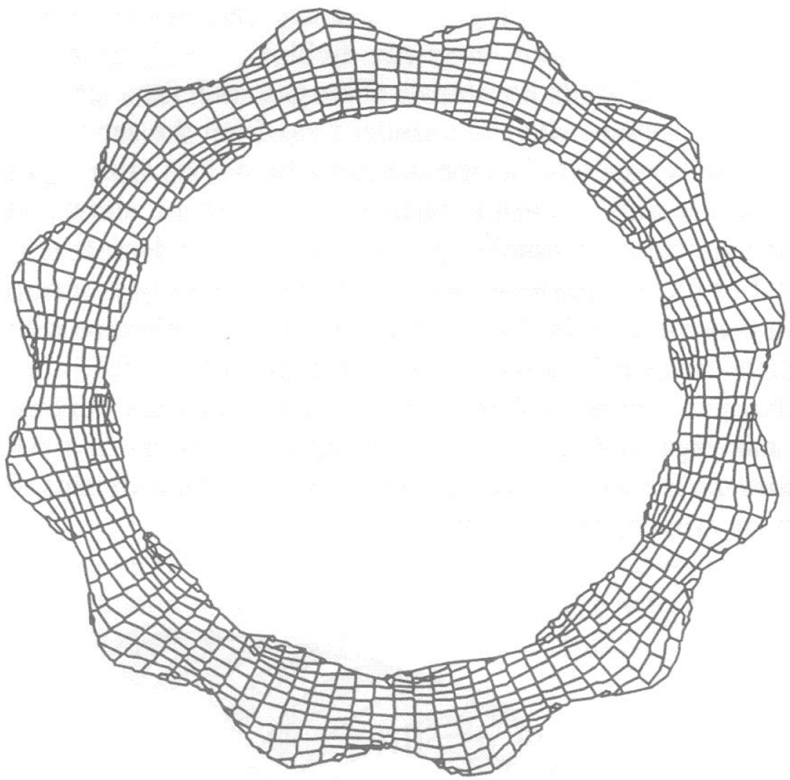
A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)
http://www.ua.all.biz/img/ua/catalog/1067534.jpeg

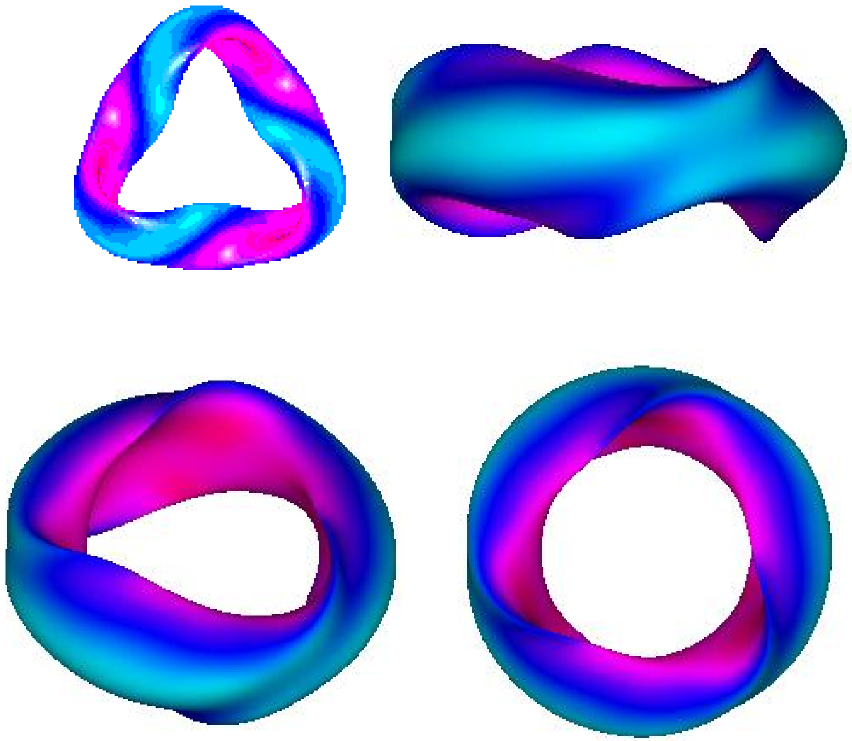
Stellarator



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,

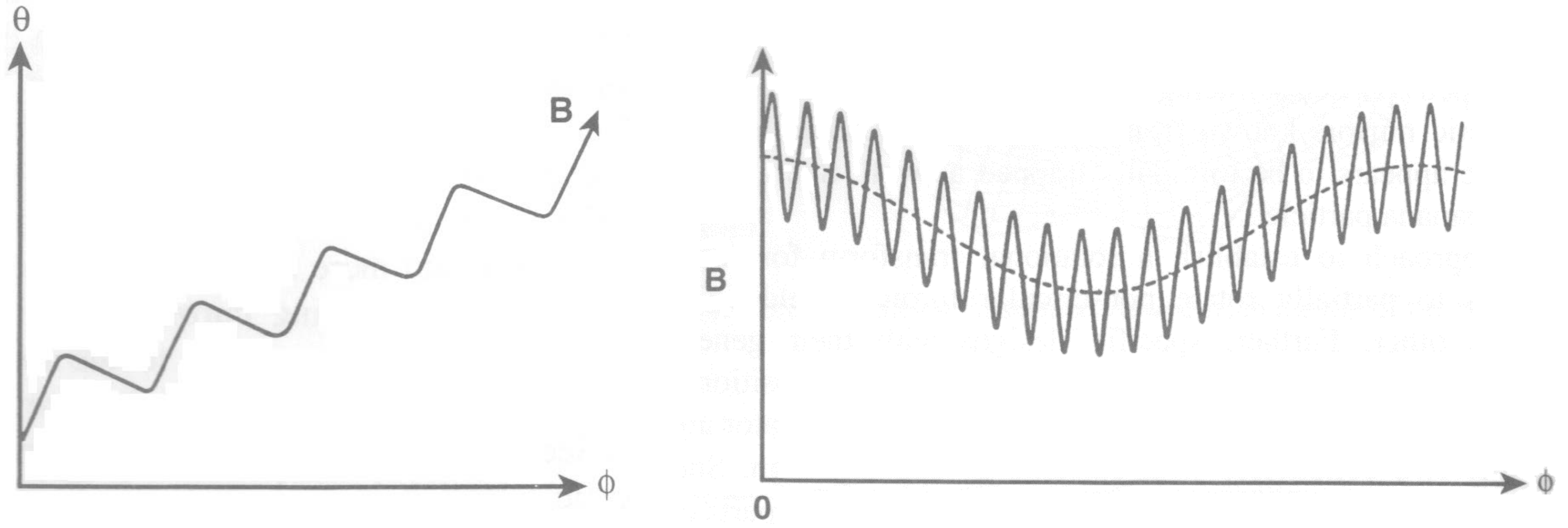
$$\oint_s \frac{\vec{B}}{\mu_0} \cdot d\vec{s} = 0$$

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

  - Curvature associated with torus geometry

Stellarator

- **Inhomogeneity of the magnetic field**

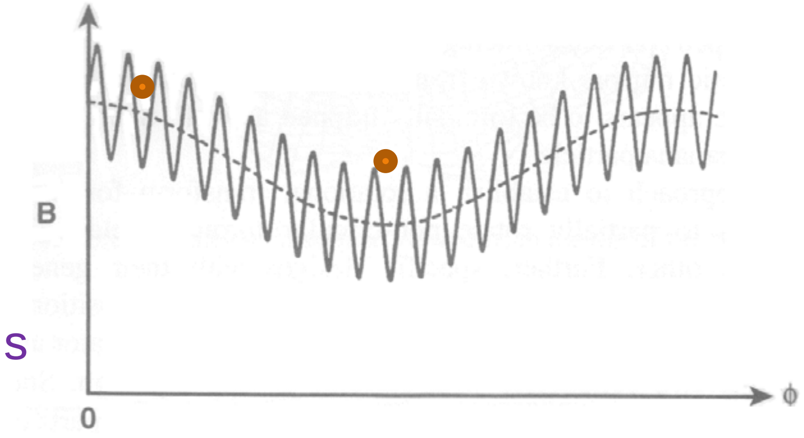


- The deep and more frequent oscillations of **B** are caused by the helical windings alternately carrying currents of different direction, and where the slow modulation of **B** corresponds to the toroidal curvature.

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

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

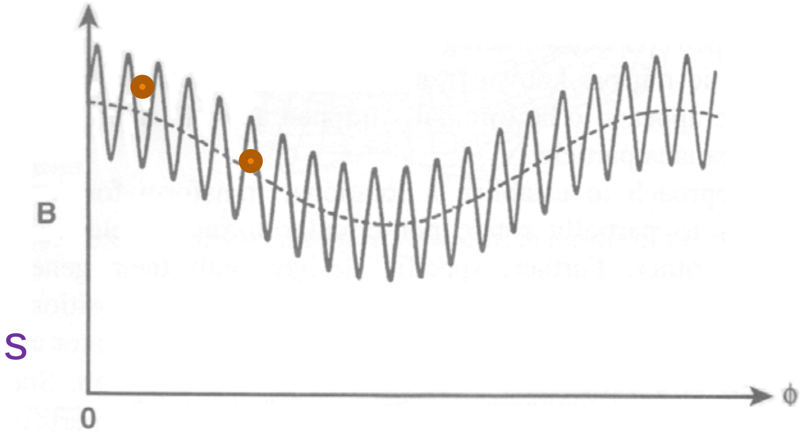
(2) Helically trapped particles reflected in the local mirrors of the helical field

(3) Toroidally trapped particles tracing banana orbits reflected in the toroidal magnetic mirrors

Cf. Superbanana particle: a helically and toroidally trapped particle

Stellarator

- **Inhomogeneity of the magnetic field**



- Particle motions in this magnetic field configurations
  (1) Circulating particles passing entirely around the torus
      without encountering a reflection
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      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

→ Enhanced transport losses!

Stellarator

- **LHD achievement up to 2016 before D operation**

Plasma parameters	Achieved	Target	Fusion condition
Ion temperature	8.1 keV at $1\times10^{19}m^{-3}$	10 keV at $2\times10^{19}m^{-3}$	> 10 keV > $1\times10^{20}m^{-3}$
Electron temperature	20 keV at $2\times10^{18}m^{-3}$ 10 keV at $1.6\times10^{19}m^{-3}$	10 keV at $2\times10^{19}m^{-3}$	
Density	$1.2\times10^{21}m^{-3}$ with T_e of 0.25 keV	$4\times10^{20}m^{-3}$ 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, $4\times10^{18}m^{-3}$) 47min. 30sec. (1,2 MW) (2keV、$1\times10^{19}m^{-3}$)	1 hour (3 MW)	Steady-state (1 year)

Tokamak .VS. Stellarator

	Advantage	Disadvantage
Tokamak	- Simple 2D structure, so relatively easy to analyze and fabricate the device - The most studied and successful up to now (mainstream in the roadmap to a feasible fusion reactor)	- Need an external current drive (inductive or non-inductive) for plasma current generation & steady-state operation - Subject to plasma current-driven instabilities and disruptions
Stellerator	- No external current drive necessary, so inherently steady-state operation possible - Relatively free from plasma current-driven instabilities and disruptions	- Complicated 3D structure, so difficult to analyse and fabricate the device - Large system size required with a high aspect ratio - Subject to large neoclassical transport at low collisionality - existence of boostrap current

Tokamak .VS. Stellarator