THE STELLARATOR:
NUCLEAR FUSION ENERGY

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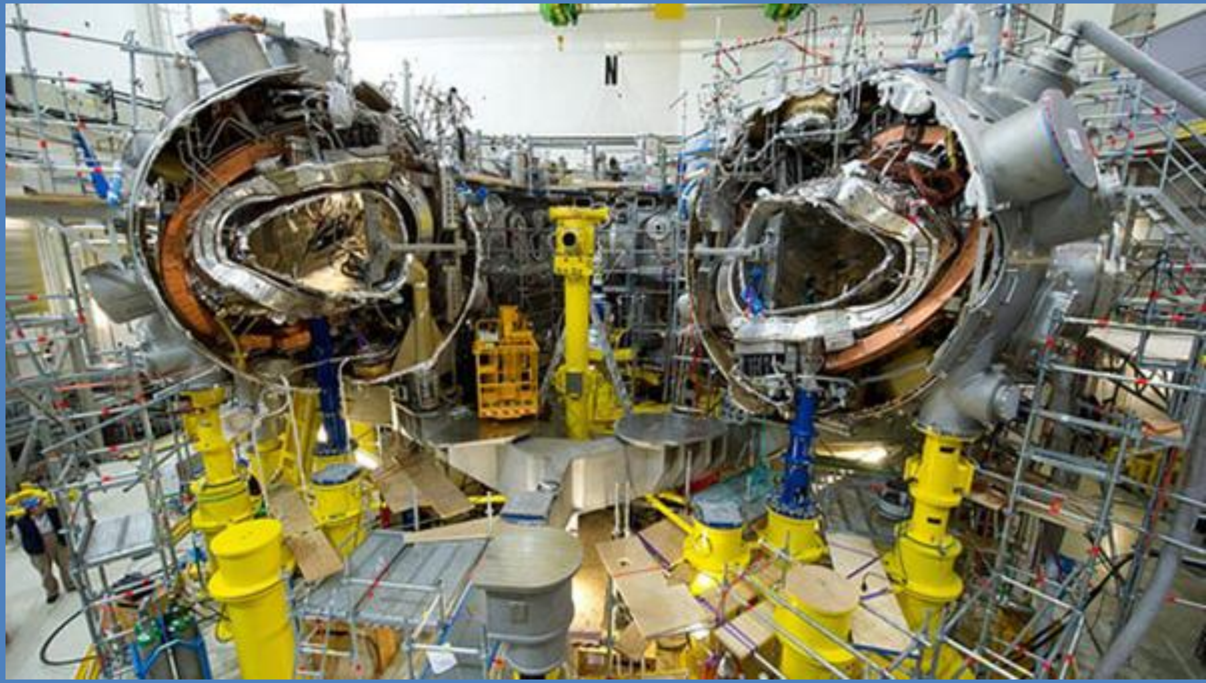
Proseminar Plasma Physics



Wendelstein 7-X Stellarator [www.engineering.com]

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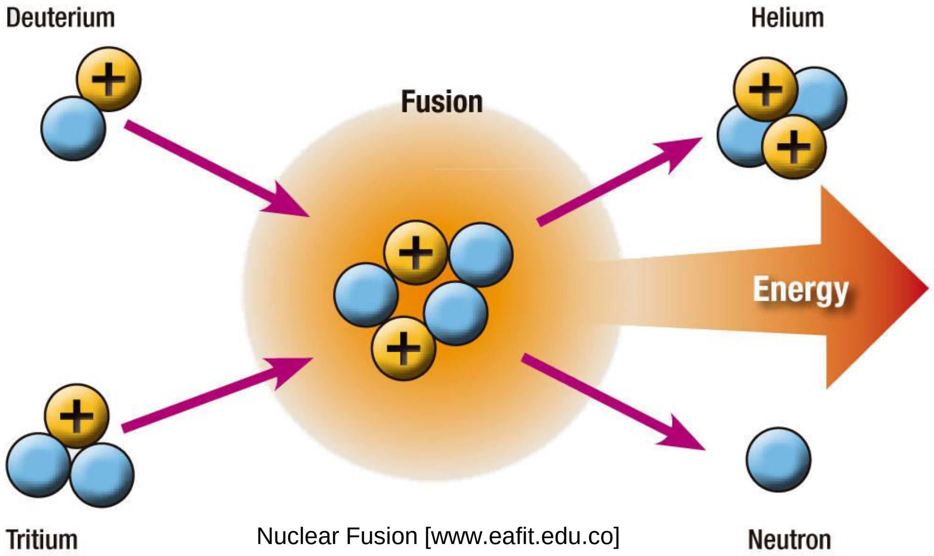
1. Introduction

Introduction (I)


Renewable Energies [www.datacenterdynamics.com]

Search for a clean, abundant and sustainable energy

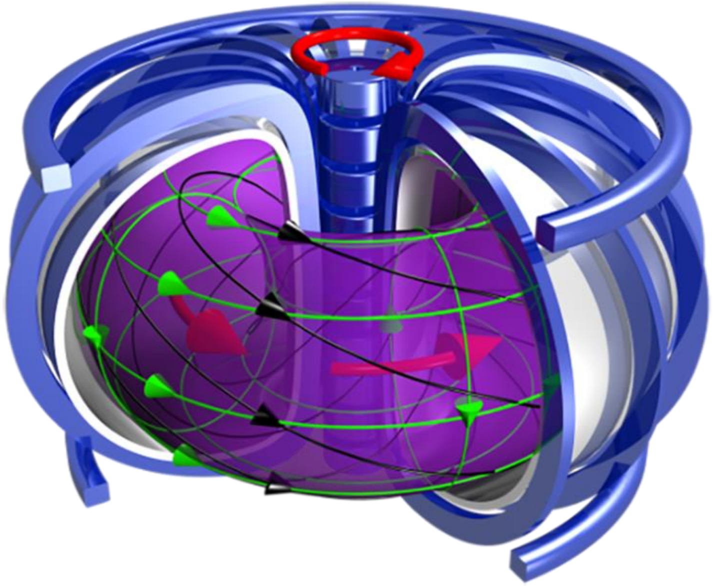
Promising Solution: Nuclear Energy

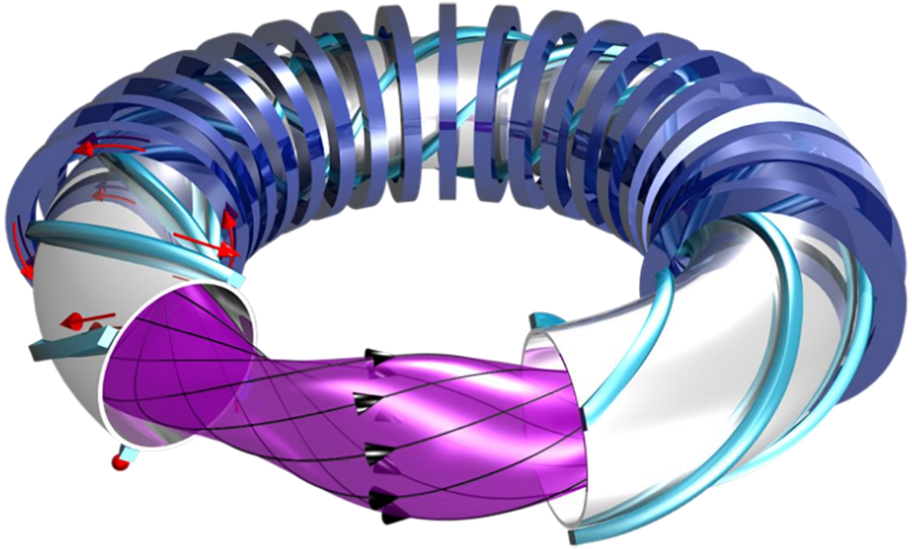


Nuclear Fusion [www.eafit.edu.co]

Introduction (II)

Recreating Fusion → Major Challenge → No known materials can withstand such high temperatures and pressures → Magnetic Fields





Stellarator:

- Magnetic Confinement Device

- Extremely complex and precise magnetic fields

- Allow isotopes to fuse in a controlled manner

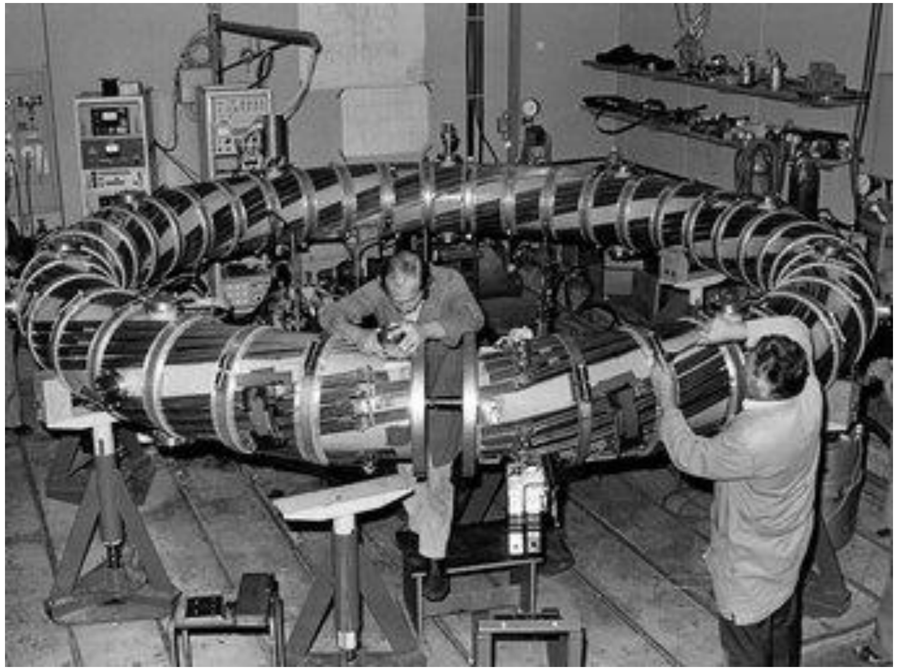
Tokamak & Stellarator [www.iaea.org]

2. History of the Stellarator

Major historical events since early nuclear fusion research

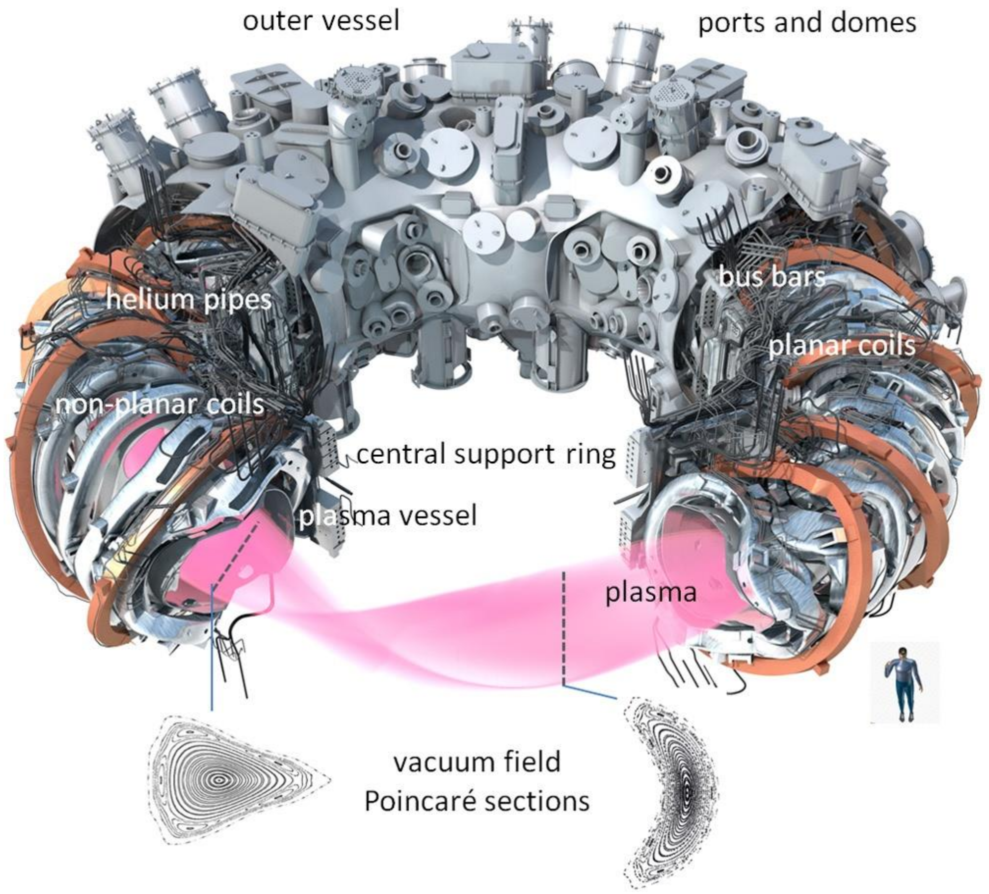
History of the Stellarator (I)

- Early 20th century: Scientist began to explore the possibility of replicating nuclear fusion.
- 1950s: Lyman Spitzer proposed the stellarator concept.
  - 1951: Stellarator-1 (Princeton Laboratory, USA)
  - 1958: Modular Coils (Advanced Stellarators)
- 1960s: Wolfgang Paul, Wendelstein 1 (Max Planck Institute for Plasma Physics, Germany)
- 1970s: Keith Symon contributed to the understanding of the relative merits of tokamaks and stellarators.
- 1980s: Wendelstein 7-A



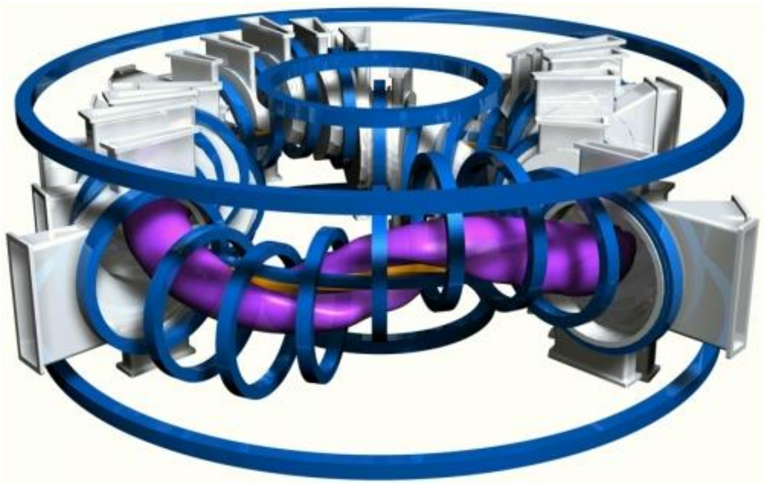
Wendelstein 7-A [www.ipp.mpg.de]

History of the Stellarator (II)



Wendelstein 7-X [www.ipp.mpg.de]

- 1990s: Wendelstein 7-X Project & TJ-II (CIEMAT, Spain)
- 2000s: LHD (Toki, Japan)
- 2010s: Wendelstein 7-X achieved the first successful operation
- 2020s: Research on stellarators continues



TJ-II [www.fusionwiki.ciemat.es]

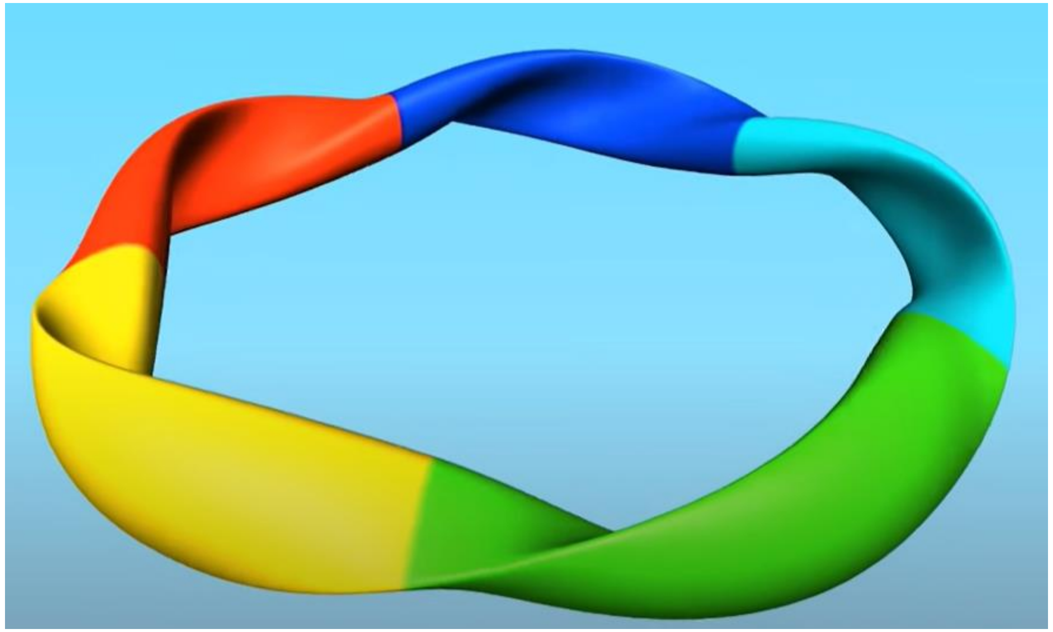
3. Principles of Operation

Main principles that explain the functioning of stellarators

Principles of Operation (I)

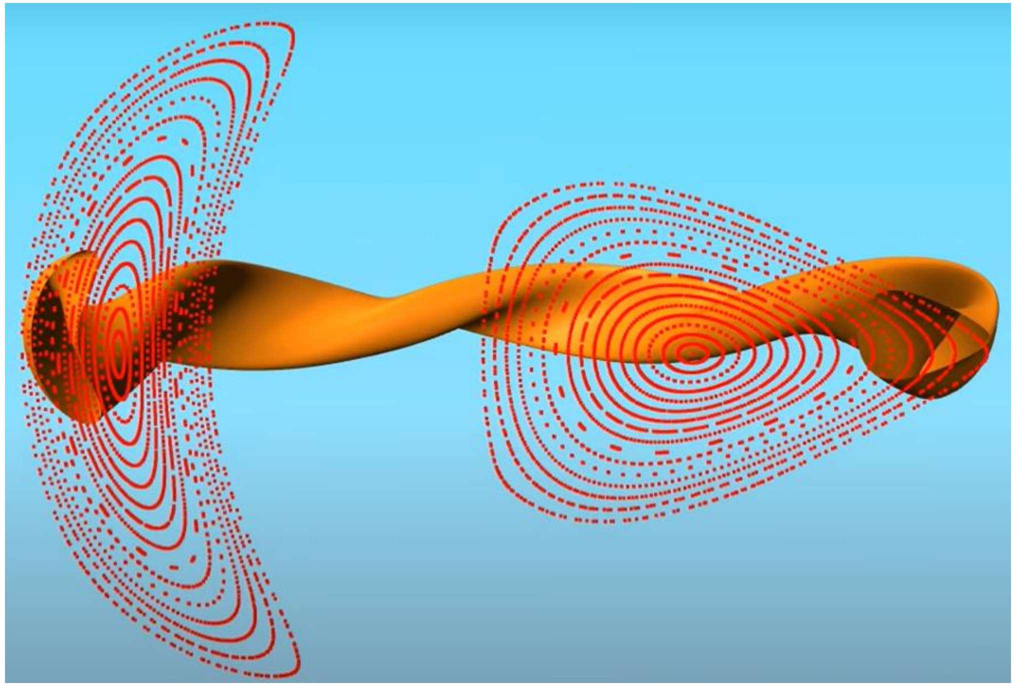
In 1980s thanks to Computer-Aided Optimization processes the ideal shape of the stellarator was determined:

- Fivefold Symmetry



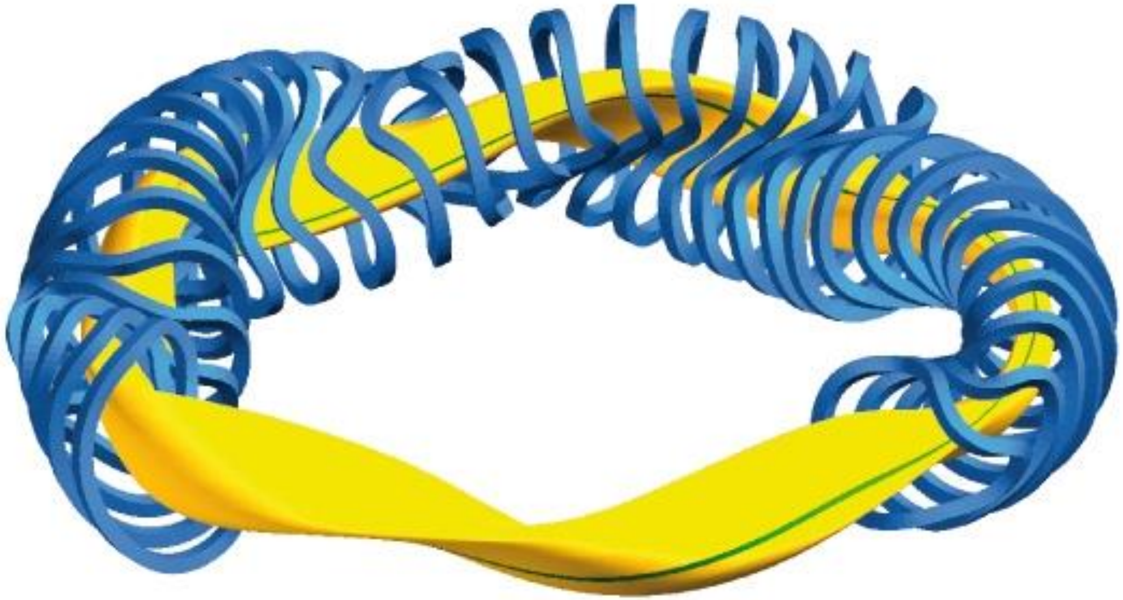
Fivefold Symmetry Wendelstein 7-X [www.engineering.com]

The magnetic cage should have a concentric structure to contain the enormous thermal energy of the plasma for a sufficient time.



Magnetic Field Lines [www.engineering.com]

Principles of Operation (II)



Magnetic Coils & Plasma Wendelstein 7-X [www.ipp.mpg.de]

1. Plasma Generation:

A stream of gas is injected into the vacuum chamber and is afterwards ionised by heating creating a plasma.

2. Magnetic Confinement and Plasma Stability:

Hot plasma is confined by magnetic fields generated by superconducting magnetic coils.

These magnetic fields hold the plasma in place keeping the plasma stable and preventing energy loss.

3. Rising Temperature:

Plasma must reach 100 million degrees.

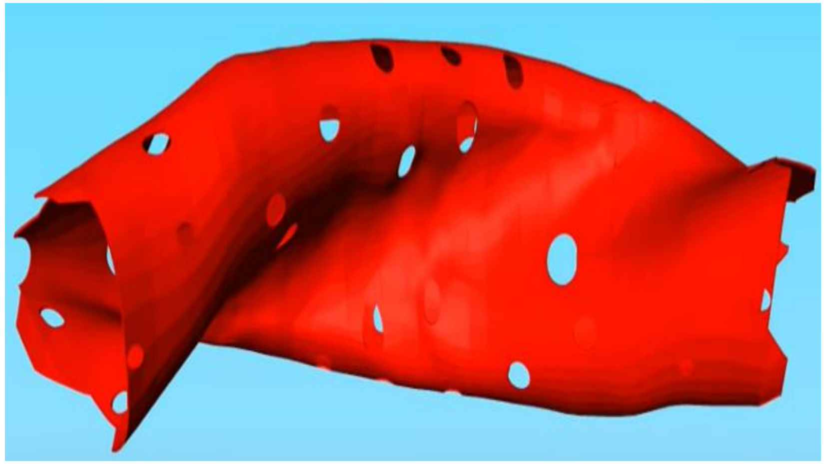
4. Plasma Control and Maintenance:

Control systems monitor plasma conditions and adjust parameters to keep the plasma stable.

4. Parts of the Stellarator

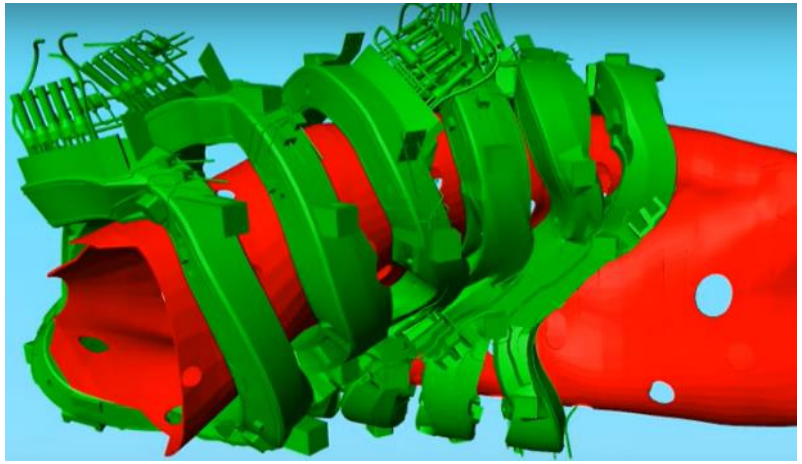
Enumeration and explanation of the most important parts of the stellarator structure

Parts of the Stellarator (I)



1. Steel Plasma Vessel:

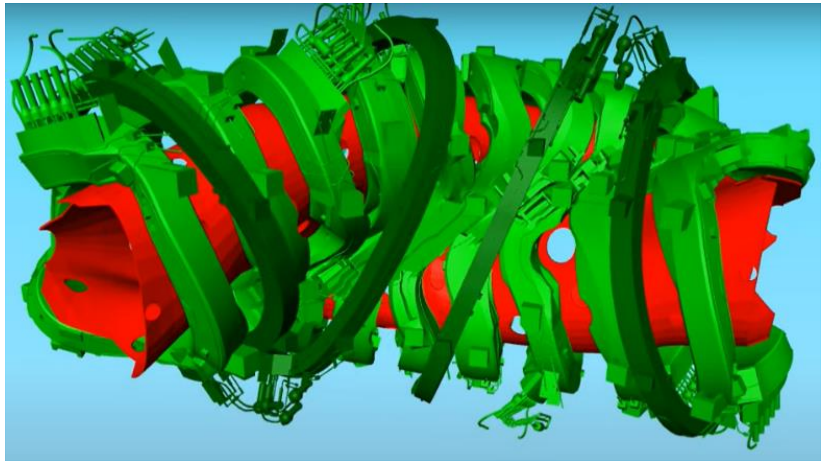
Fifth part of the torus which is repeated until it is complete.



2. Current carrying coils:

They produce the magnetic field necessary to confine the plasma.

The coils must remain around absolute 0.



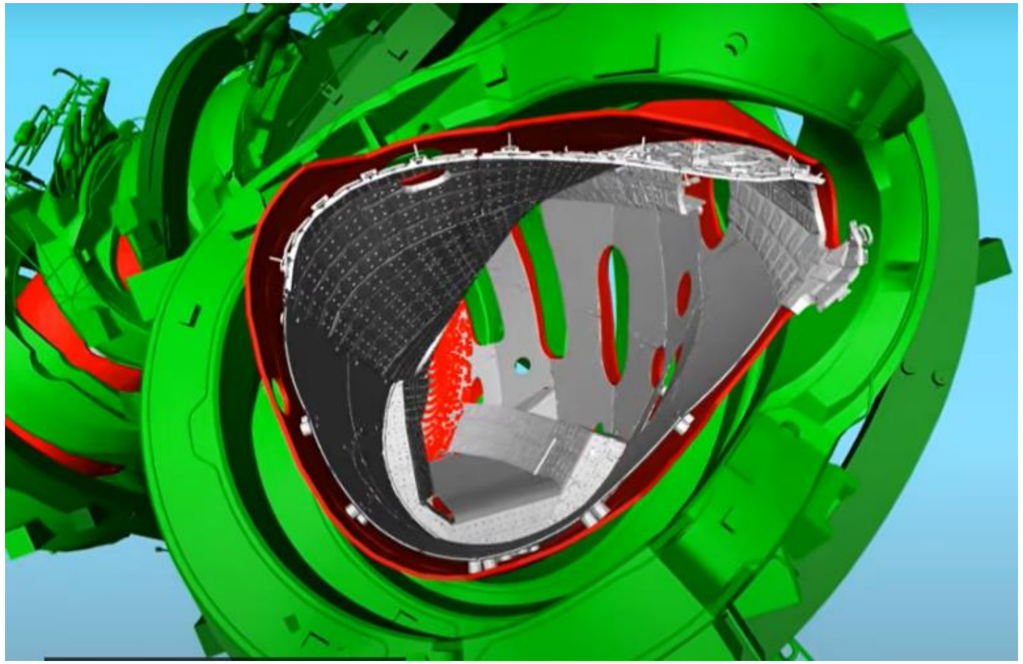
3. Planar coils:

Increase the experimental flexibility.

Parts of the Stellarator Wendelstein 7-X [www.engineering.com]

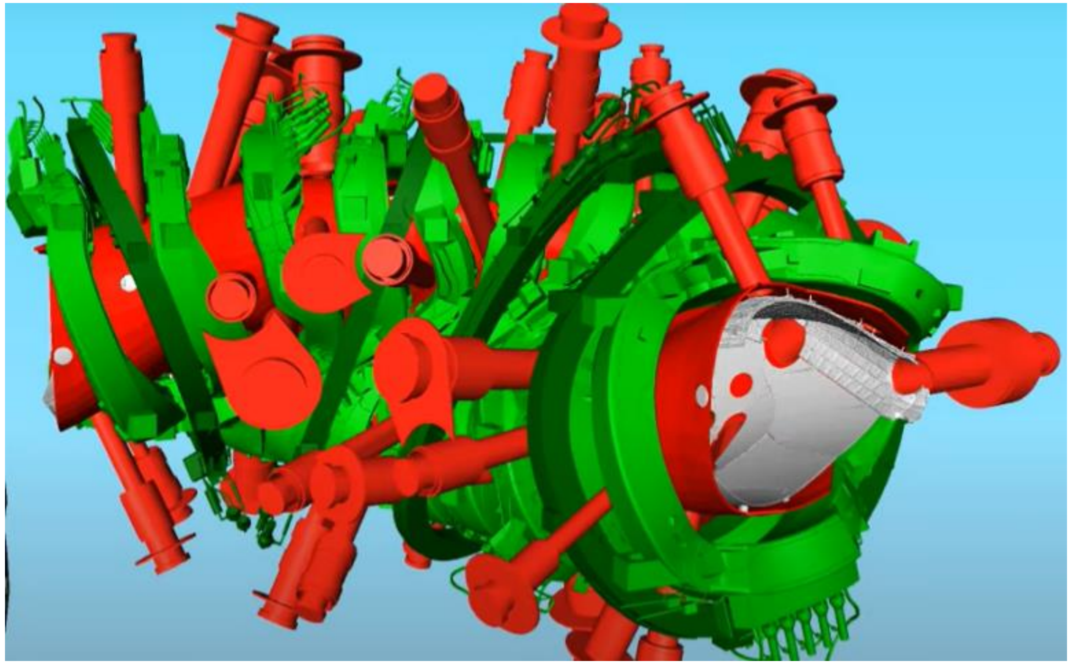
Technische Universität München

Parts of the Stellarator (II)



4. Divertor Plates and Wall Armour

High resistance and low activation

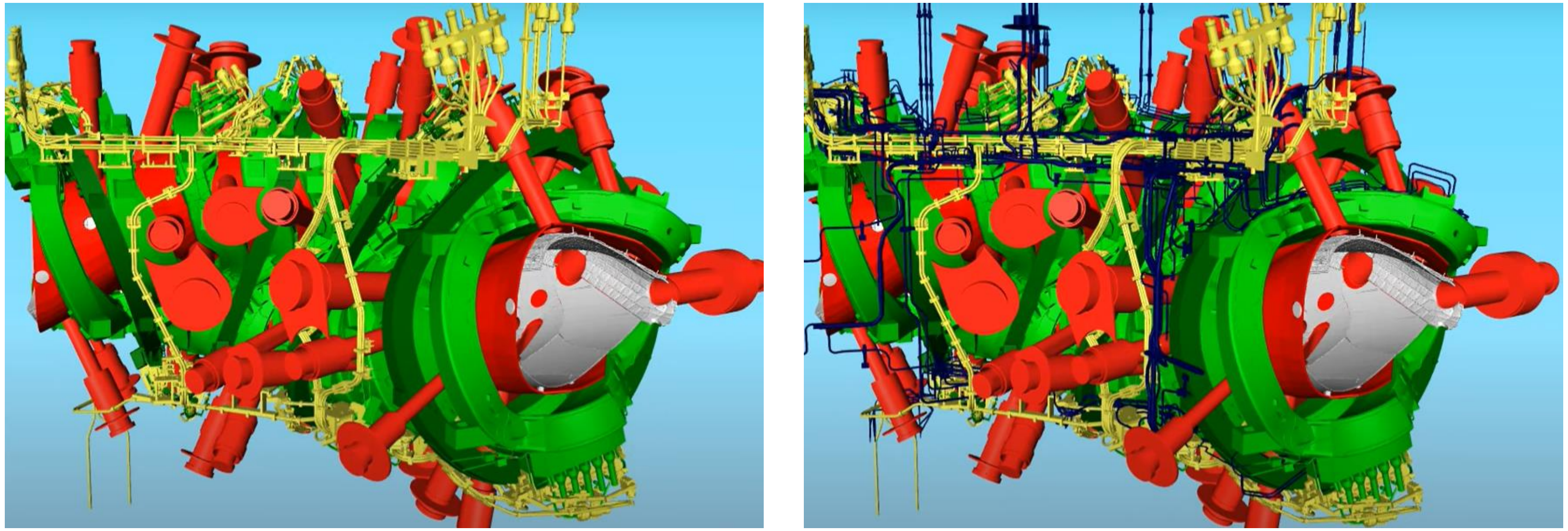


5. Ports with Thermal Insulation:

Mantain vacuum conditions and connect the outer wall of the chamber to the cryostat.

Parts of the Stellarator Wendelstein 7-X [www.engineering.com]

Parts of the Stellarator (III)

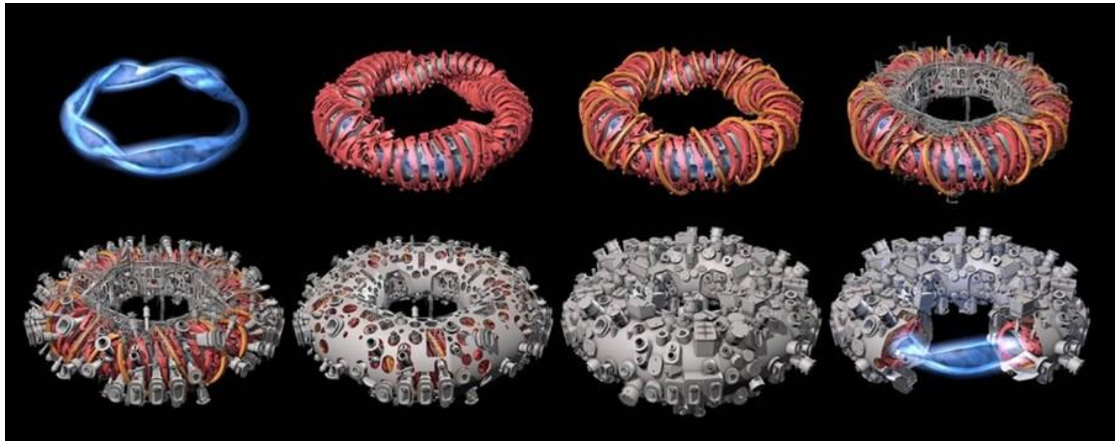


7. Cooling System

The superconducting coils are supplied with current by an electrical bus system which already has liquid helium as coolant by a cryogenic pipe work.

6. Electrical Bus System

8. Supporting Structure
9. Thermal Insulation Layers
10. Cryostat



Parts of the Stellarator Wendelstein 7-X [www.engineering.com]

Stellarator´s Structure [www.iter.org]

5. Advantages and Challenges

Advantages and Challenges

1. No Currents Required:

Reduces complexity of controlling the device

2. Plasma Stability:

Avoid plasma current driven instabilities

3. Less Impacts in the Walls:

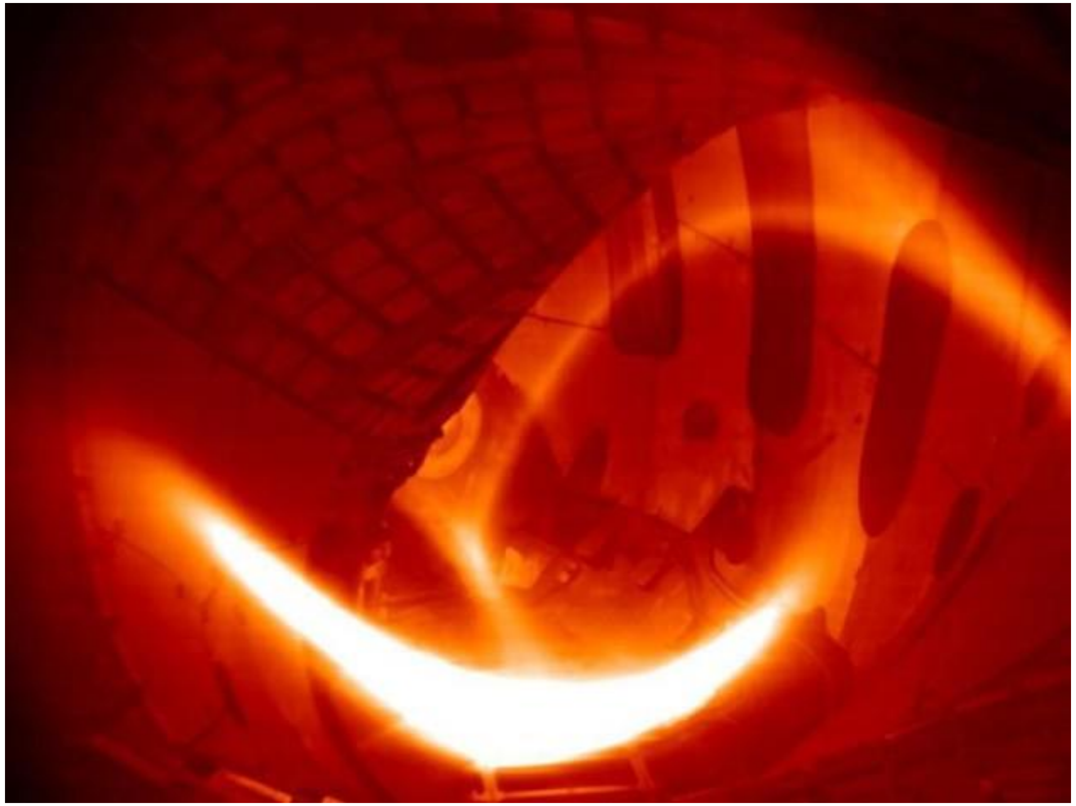
Increases lifetime and reduces maintenance costs.

4. Continuous Operating Conditions:

Advantageous in terms of efficiency and resource utilization.

5. Design Flexibility:

Allows the device to be adapted to specific challenges and optimize plasma stability.



First Hydrogen Plasma Wendelstein 7-X [www.geekwire.com]

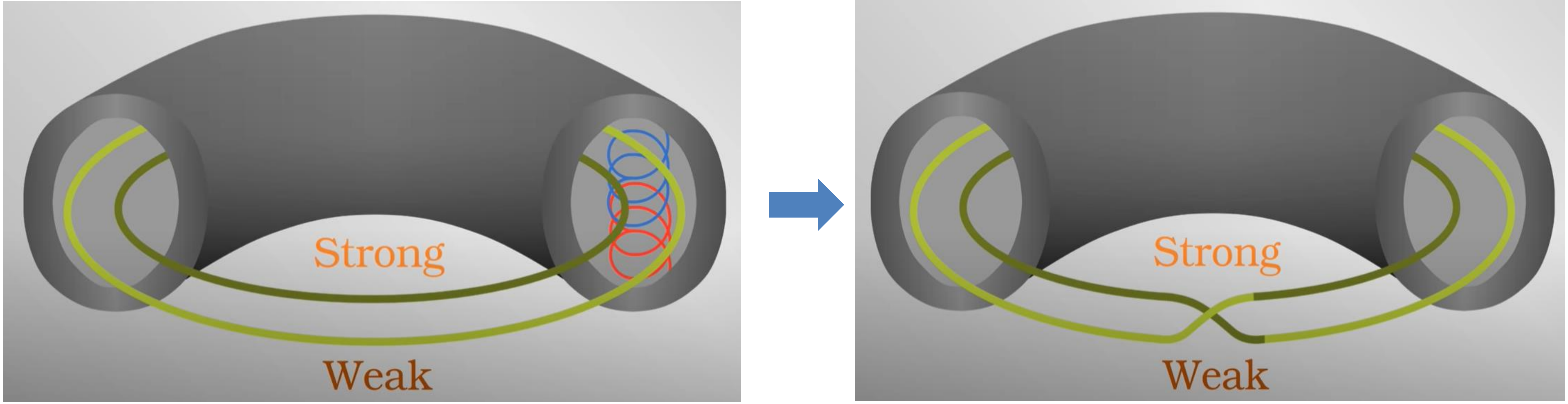
6. Comparison with Other Fusion Approaches

"In a stellarator, confining the plasma is like holding a broomstick firmly in your fist; in a tokamak, it's like trying to balance the same broomstick on your finger."

Thomas Klinger, scientific director of the Wendelstein 7-X project, 2011.

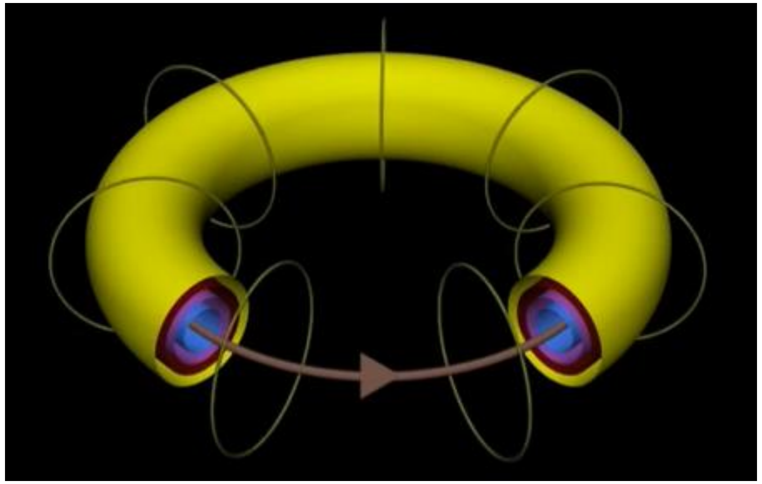
Comparison with Tokamaks (I)

Explanation of the magnetic field twist:

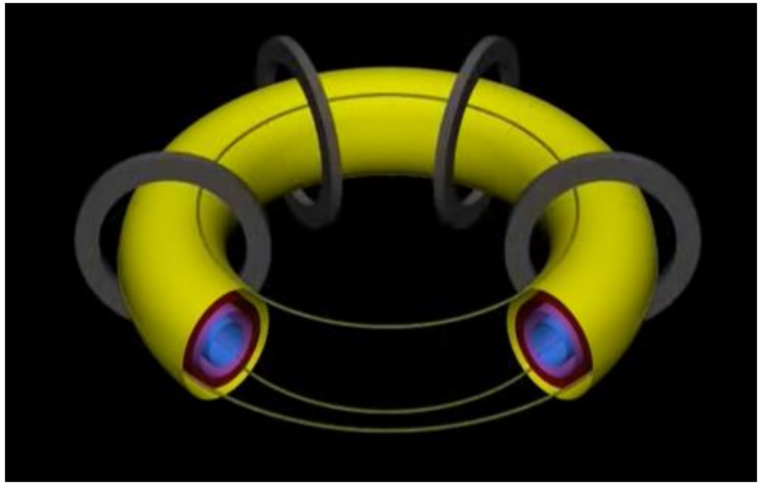


Magnetic Field Twist [www.youtube.com/watch?v=gwOrbr8KWDs]

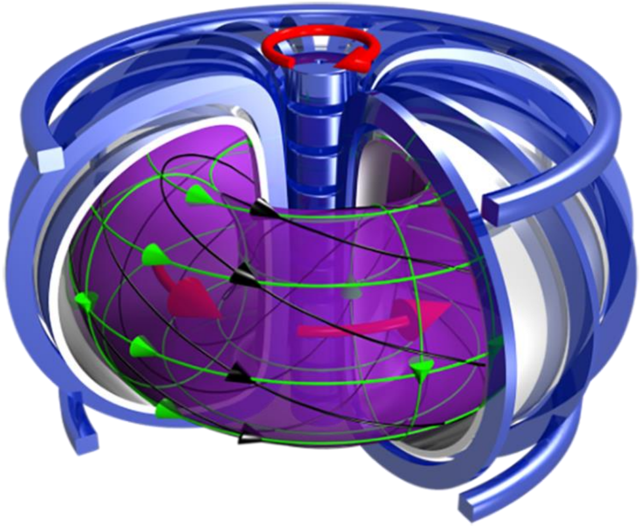
Comparison with Tokamaks (II)

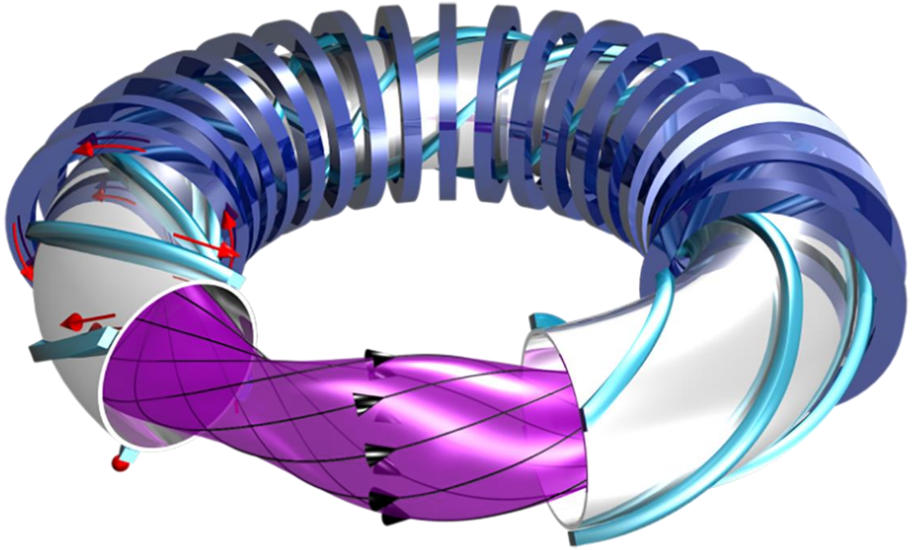


Poloidal Magnetic Field



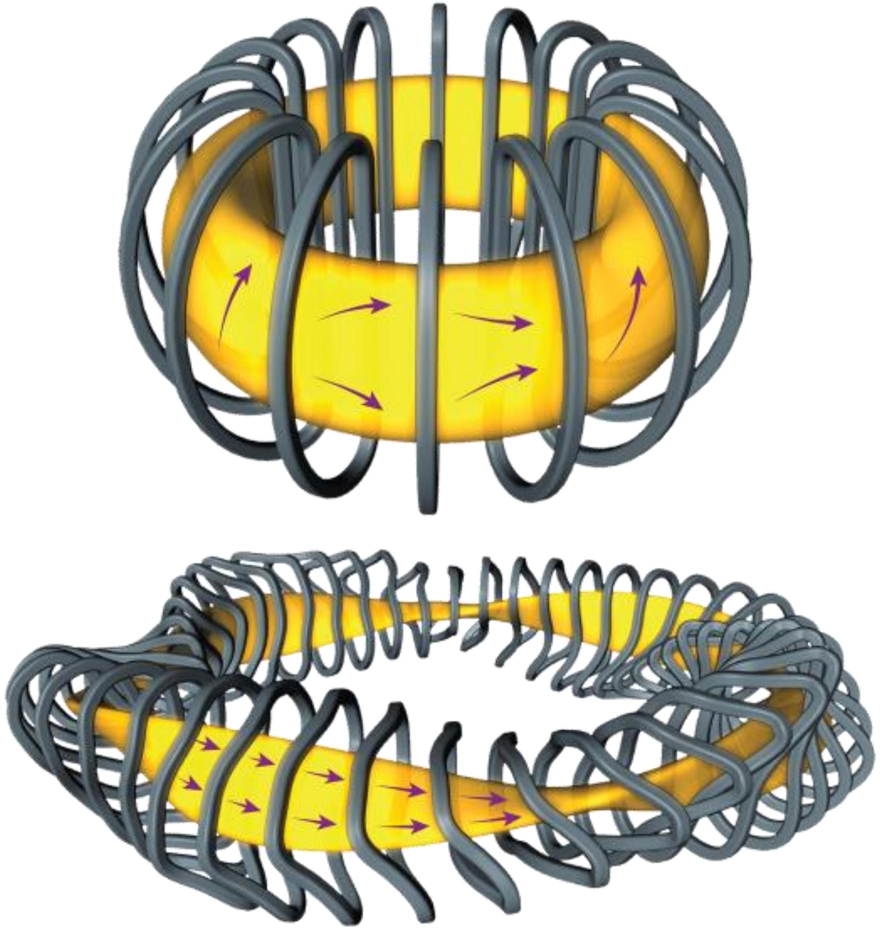
Toroidal Magnetic Field





Plasma of Tokamaks & Stellarators [www.iaea.org]

Comparison with Tokamaks (III)

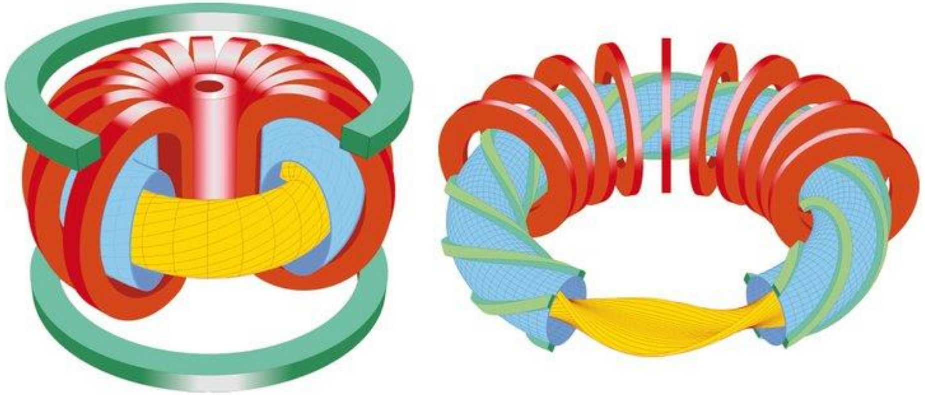


Tokamak & Stellarator [sciencesprings.wordpress.com]

	Stellarator	**Tokamak**
Plasma Stability	Highly stable	Current driven modes Disruptions
Complexity of Design	Complex	Simpler Transformer in central solenoid (Design Difficulty)
Conduction Current Effects	Minimised dependency	Dependency
Operation Mode	Continuous	Pulsed

Comparison with Tokamaks (IV)

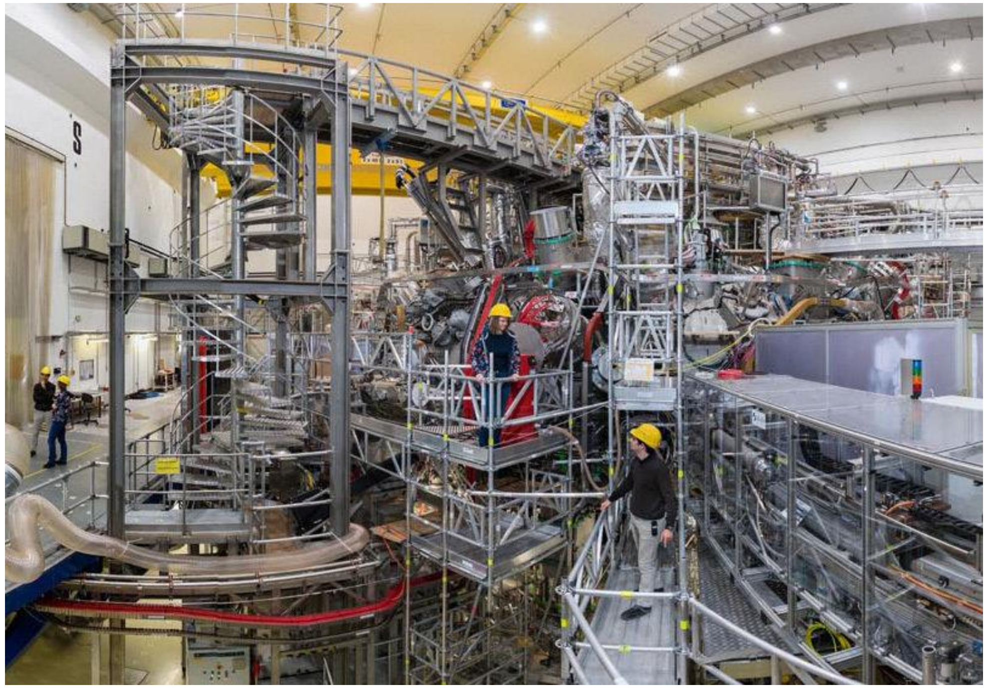
	Stellarator	**Tokamak**
Ease of Construction	✗	✓
Starting currents	✓	✗
Historical Progress	✗ *	✓



Tokamak & Stellarator [www.researchgate.net]

7. Examples of Stellarators

Examples of Stellarators (I)

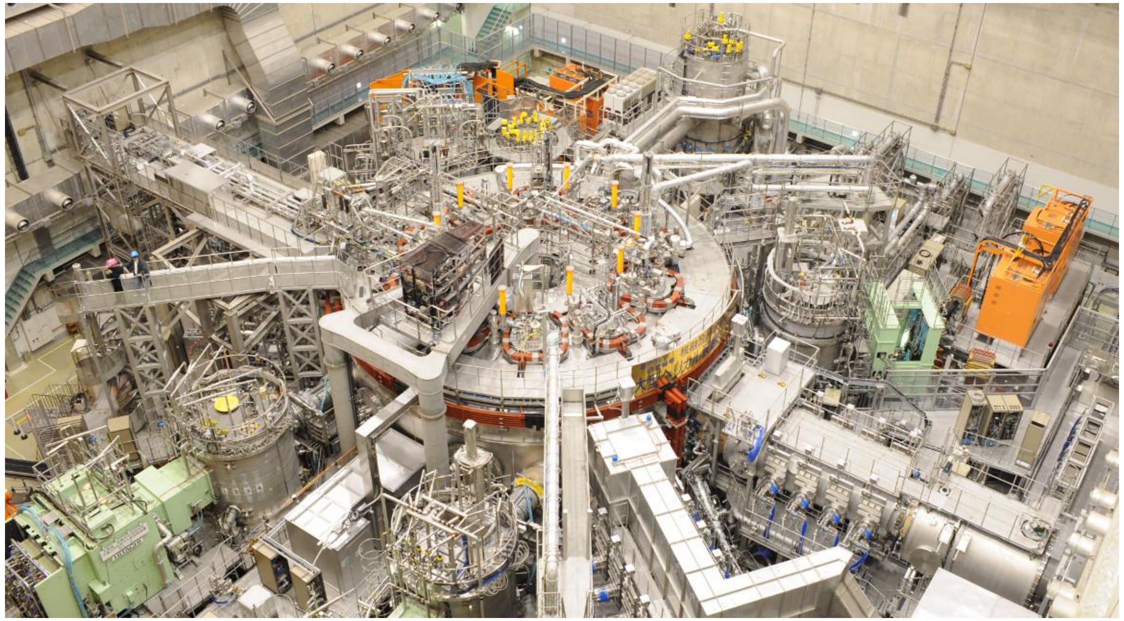


Wendelstein 7-X [www.ipp.mpg.de]

- Wendelstein 7-X:

Located in: Max Planck Institute for Plasma Physics, Greinfswald, Germany

Main objective: Demonstrate the feasibility of nuclear fusion as an energy source



Large Helical Device [www-lhd.nifs.ac.jp]

- LHD (Large Helical Device):

Located in: Japan's National Institute of Fusion, Toki, Japan

Main objective: Research on the confinement of high-temperature, high-density plasmas

Examples of Stellarators (II)

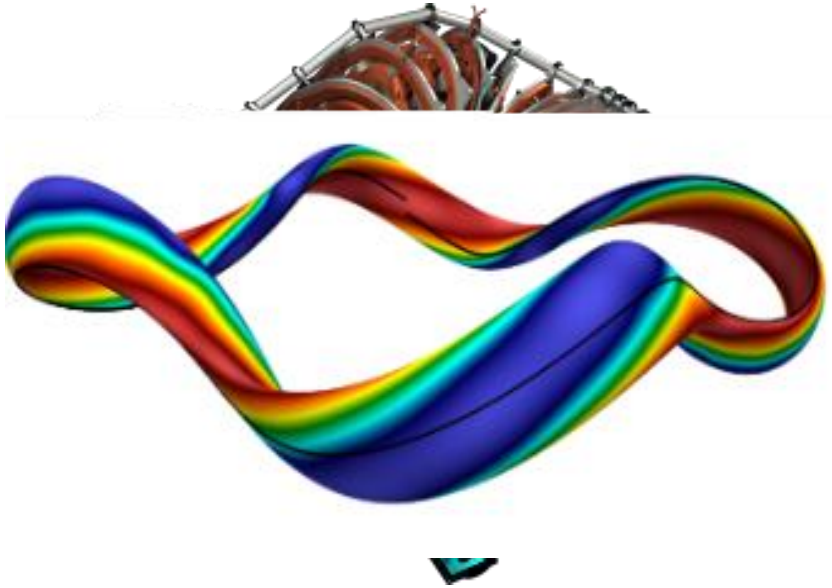
H-1NF [en.wikipedia.org]

○ H-1NF (H-1 Australian Plasma Fusion Research Facility):

Located in: ANU Research School of Physics, Canberra, Australia.

Main objective: Research on the basic physics of hot plasma which is magnetically confined.

Develop advanced plasma measurement systems.



Helically Simmetric eXperiment [hsx.wisc.edu]

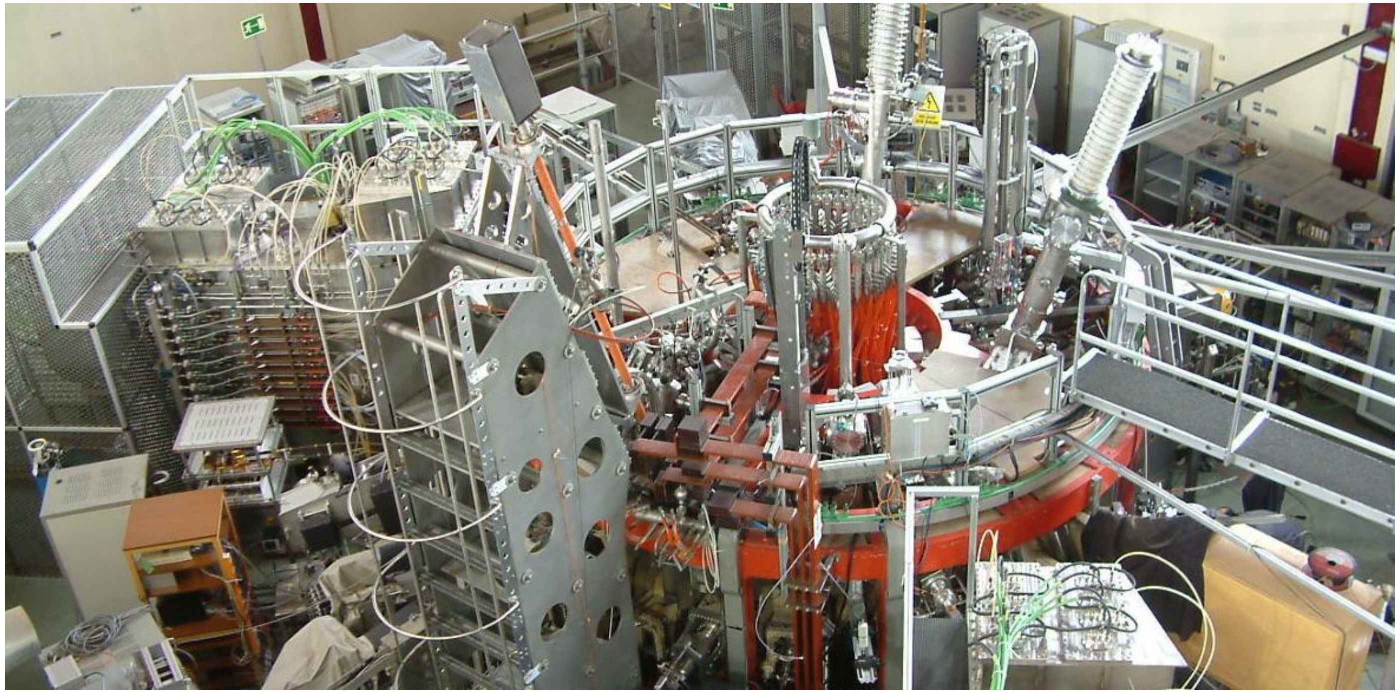
○ HSX (Helically Symmetric eXperiment):

Located in: University of Wisconsin, Madison, Wisconsin, USA.

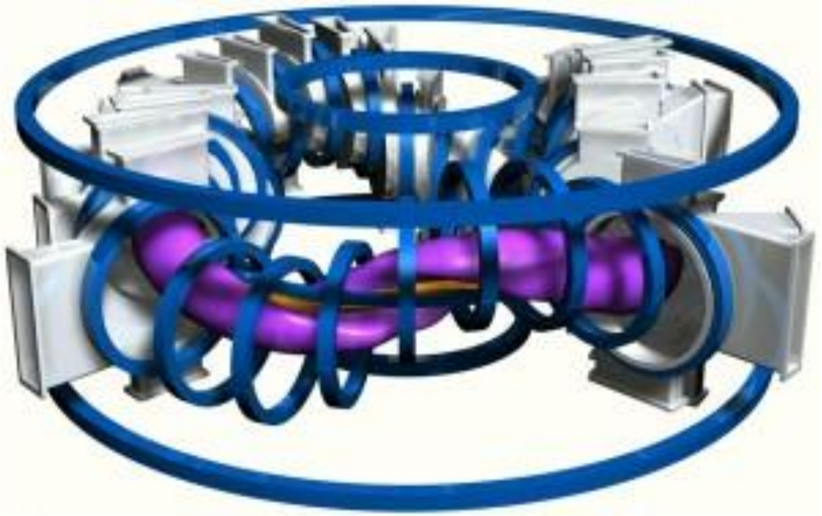
Main objective: Contribute to the physics basis.

Investigate new approaches to stellarator design

Examples of Stellarators (III)



TJ-II [www.fusion.ciemat.es]



TJ-II [www.fusion.ciemat.es]

- TJ-II:

Located in: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain.

Main objective: Study the physics of magnetically confined plasmas, with emphasis on the influence of the magnetic configuration on heat and particle transport.

8. Latest Developments

Latest Developments

On 6 March 2023, the latest publication by ITER on Wendelstein 7-X was made:

- The first target (an energy turnover of 1 gigajoule) was surpassed on 15 February 2023:

1.3 GJ

8 min

Lower Heating Power

100 sec

- Thomas Klinger, scientific director of the Wendelstein 7-X project:

"We are now exploring our way towards ever higher energy values, in doing so, we have to proceed step by step so as not to overload and damage the facility.“

- Final Goal:

18 GJ

30 min

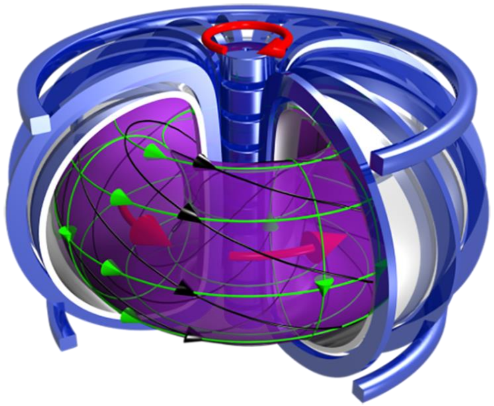
9. Key take away

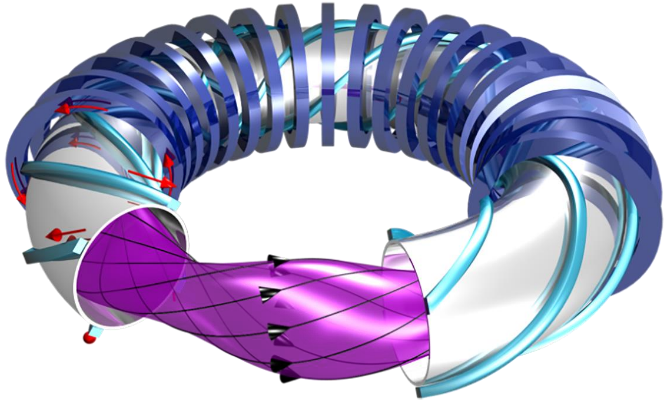
An overview of the most important ideas and principles of this type of this type of devices

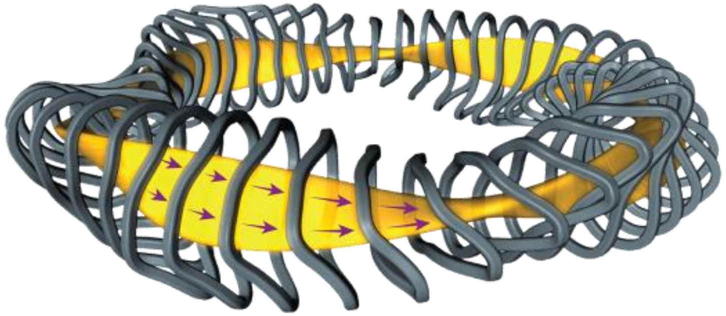
Key take away

- Stellarators and Tokamaks share the HELICITY of the magnetic field which is essential to:

  - Stabilize the plasma - Confine the plasma - Avoid the leakage







- The shape and stability of the plasma is achieved by the complex and precise magnetic field generated by the superconducting coils around the device.
- Stellarators have an enormous engineering complexity.
- Research on stellarators continues not only with the aim of improving the plasma stability and efficiency but also improving the materials used.