PRINCETON PLASMA PHYSICS LABORATORY

Stellarators

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Princeton Plasma Physics Laboratory

Introduction to Plasma Physics and Fusion Energy Course, Princeton Plasma Physics Laboratory, 2022

About me

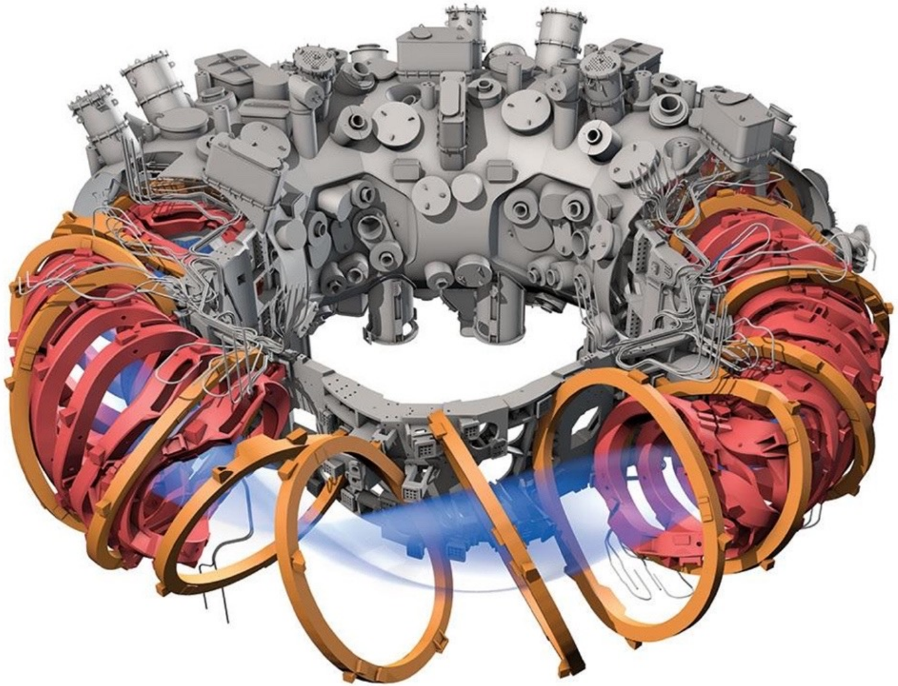
- 1990: born, Saratoga Springs, NY
- Activities: track, cross-country, trombone
- Wanted (and still want) to do something about climate change and decarbonization
- 2008-2012: majored in physics at Harvard
    - 2011: SULI internship @ PPPL!
- 2012-2017: PhD in applied physics at Columbia University
- 2017-2019: postdoc at the Max Planck Inst. for Plasma Physics, Greifswald, Germany
- 2019-present: staff research physicist, PPPL
    - 2021: mentored first SULI student
    - 2022: presented first SULI talk





Introduction

What is a stellarator?

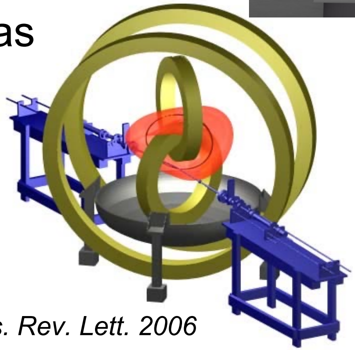


The Wendelstein 7-X Stellarator
Max Planck Institute for Plasma Physics, Greifswald, Germany
Image: T. Klinger et al., Nucl. Fusion 2019

- Toroidal magnetic plasma confinement device
- Magnetic field forms nested, closed flux surfaces
- Magnetic field is generated primarily by magnets external to the plasma
  - Plasma current not required

Why build a stellarator?

- Generate electricity
  - Inherently steady-state operation
  - Low/no plasma current required
    - Lower vulnerability to disruptions
    - Lower recirculating power required
- Perform basic plasma research
  - Single-species plasmas
  - Pair (positron/electron) plasmas

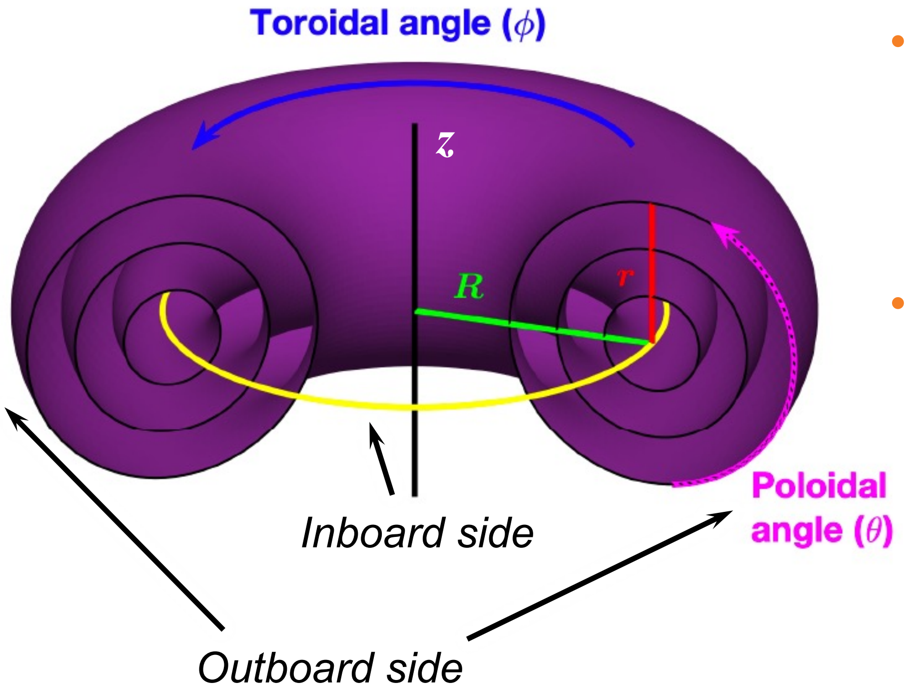


J. P. Kremer et al., Phys. Rev. Lett. 2006

S. Woodruff, Woodruff Scientific

Toroidal geometry and magnetic fields

Basics of toroidal geometry

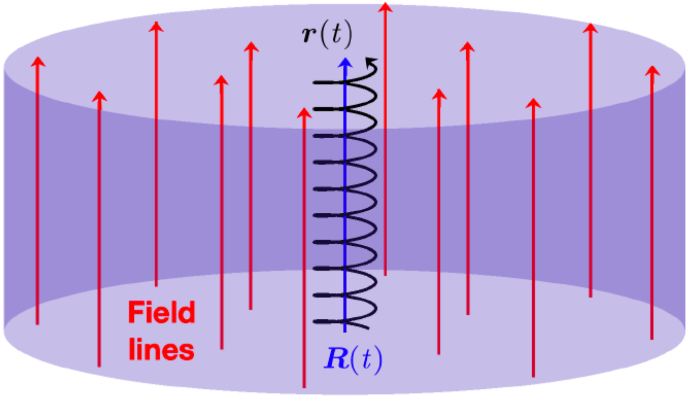


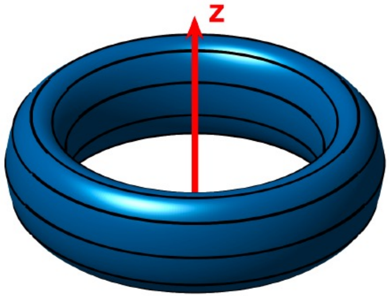
- Torus: a doughnut shape
- Cylindrical representation
  - *R*: radial dimension; distance from *z axis*
  - *z:* vertical dimension
  - $\boldsymbol{\phi}$: azimuthal/toroidal dimension
- Toroidal coordinates
  - *r:* minor radius; distance from yellow curve
  - $\boldsymbol{\theta}$: poloidal angle; short way around the torus
  - $\boldsymbol{\phi}$: toroidal angle; long way around the torus

L.-M. Imbert-Gérard et al., Introduction to Stellarators, 2020

Toroidal magnetic confinement: motivation

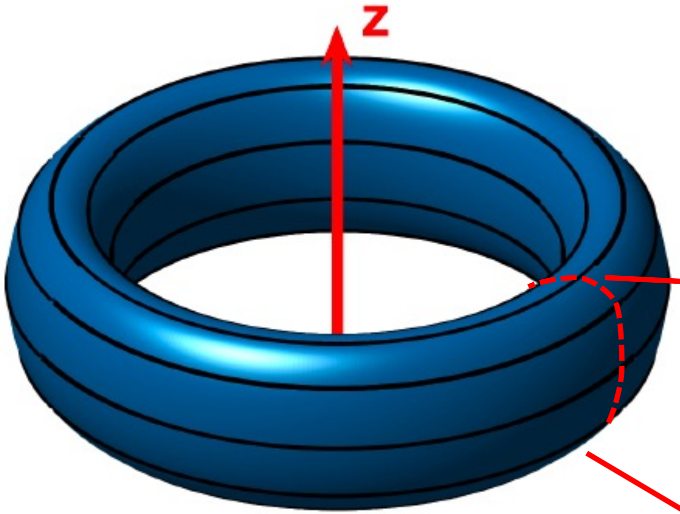
- Charged particles tend to gyrate around magnetic field lines
  ⟶ confined in the direction perpendicular the magnetic field **B**
- Particles can stream freely along magnetic field lines
  ⟶ not intrinsically confined parallel to **B**
- If the field lines wrap around form a torus
  - Particles stream quickly around the torus
  - Particles are slower to exit the torus
  - Enclosing wall is protected from the plasma (and vice versa)



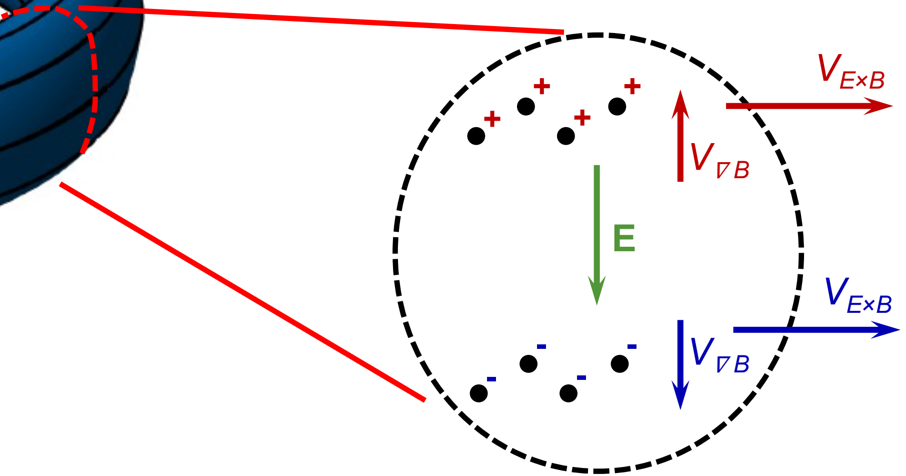


L.-M. Imbert-Gérard et al., Introduction to Stellarators, 2020

A purely toroidal field is not sufficient to confine a quasineutral plasma

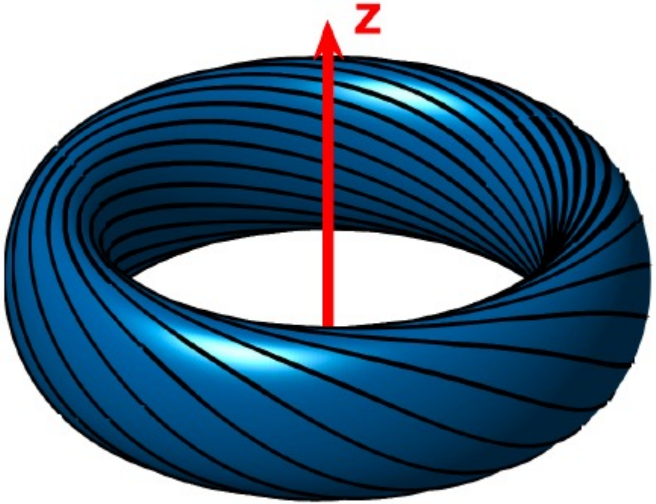


- Curvature and gradient in magnetic field cause electrons, ions to drift in opposite directions
- Charge separation creates a vertical electric field
- All particles drift outward in E×B direction



L.-M. Imbert-Gérard et al., Introduction to Stellarators, 2020

To confine a plasma in a toroidal field, the field lines must twist helically

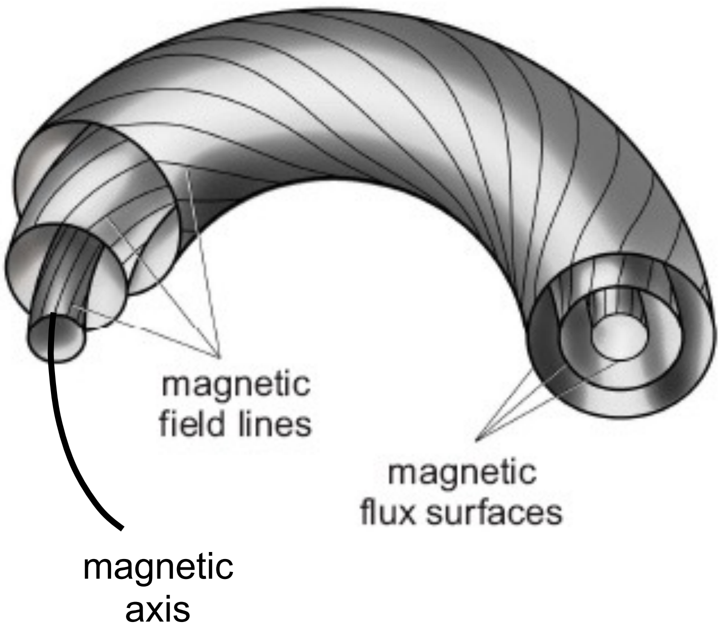


L.-M. Imbert-Gérard et al.

iStockPhoto

- Helical field lines sweep particles quickly from the top to the bottom of the torus and back
- Vertical drift motion persists, but alternates between inwards and outwards
- Sending the particles on helical paths is analogous to turning a honey dipper
  - Holding the dipper still: honey drips off
  - Rotating the dipper: honey remains confined

Flux surfaces and rotational transform



M. Bernert, PhD thesis, LMU Munich

- For good confinement, magnetic field lines should form nested *flux surfaces*
  - Surfaces surround a central curve: *magnetic axis*
- *Rotational transform,* ι is a measure of helical twistiness of the field on each flux surface
  - In tokamaks: the *safety factor* q is $1/\iota$
- Generating rotational transform
  - Tokamaks use a toroidal plasma current
  - Stellarators use external coils/magnets

How to generate a stellarator magnetic field

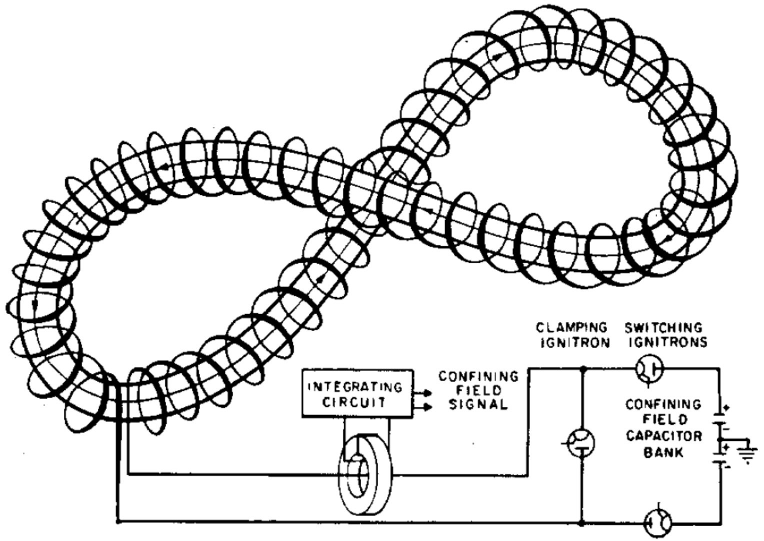
Origins of the stellarator

- Invented in the 1950s by Princeton astronomy professor Lyman Spitzer, Jr.
- Developed as part of Project Matterhorn, which eventually became the Princeton Plasma Physics Laboratory

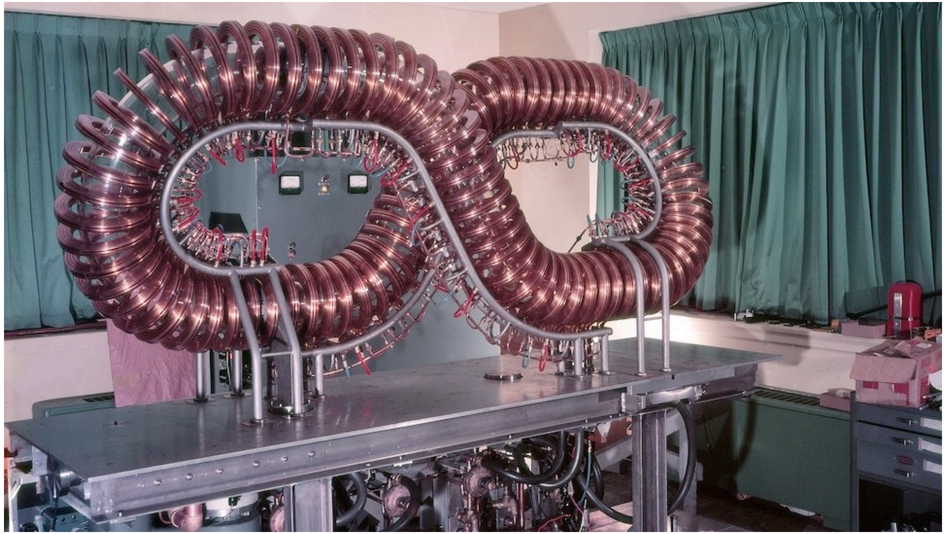
Lyman Spitzer with the Model A stellarator
Image: PPPL

How can external coils generate rotational transform?

- Spitzer's approach: solenoidal tube twisted into a figure-8
  - Crucial feature: *torsion*, or the departure of the tube's axis from a single plane

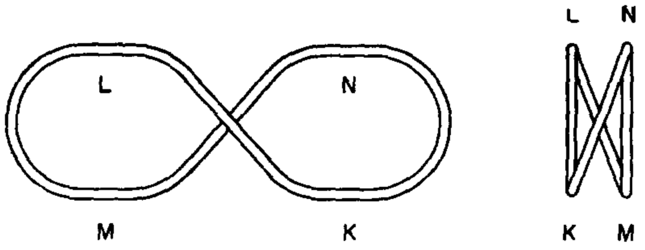


T. Coor et al., Phys. Fluids 1958



PPPL file photo

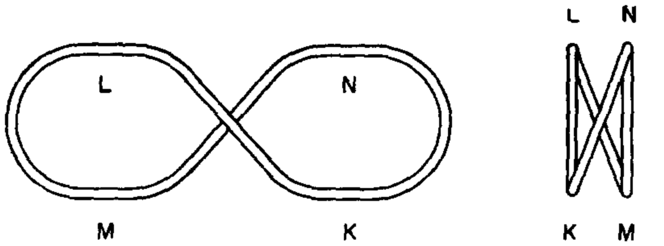
Rotational transform in a figure-8 solenoid

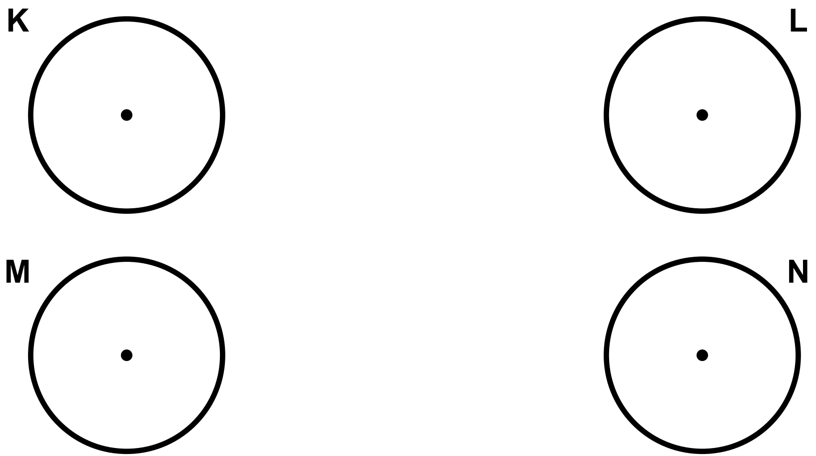


- Magnetic field in the figure-8 is approximately *solenoidal*, i.e. everywhere parallel to the central axis of the tube

L. Spitzer, Phys. Fluids 1958

Rotational transform in a figure-8 solenoid

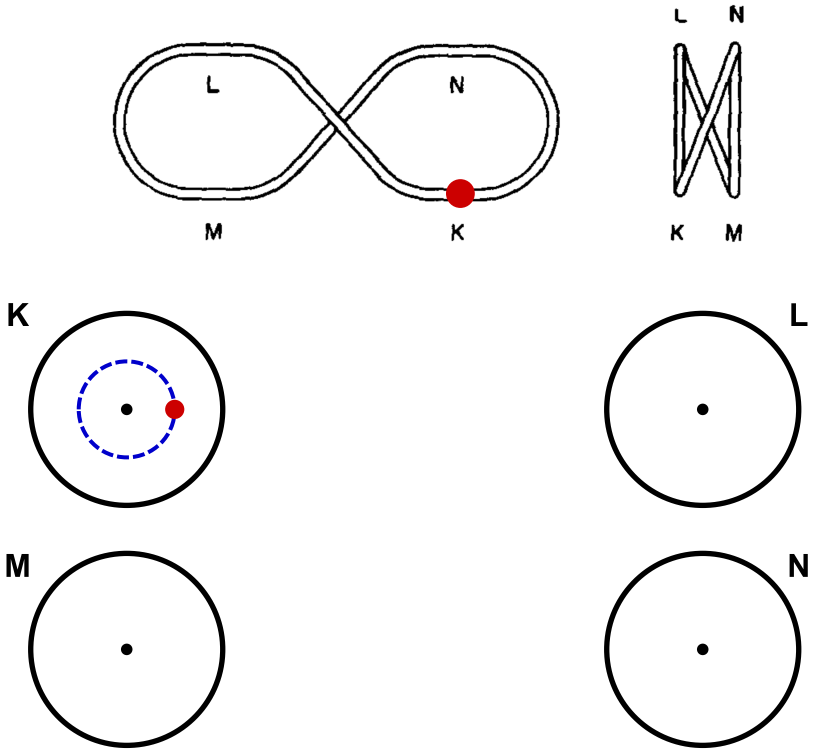




- Magnetic field in the figure-8 is approximately *solenoidal*, i.e. everywhere parallel to the central axis of the tube

L. Spitzer, Phys. Fluids 1958

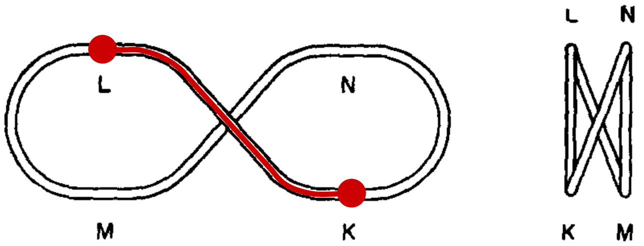
Tracing a field line around the track

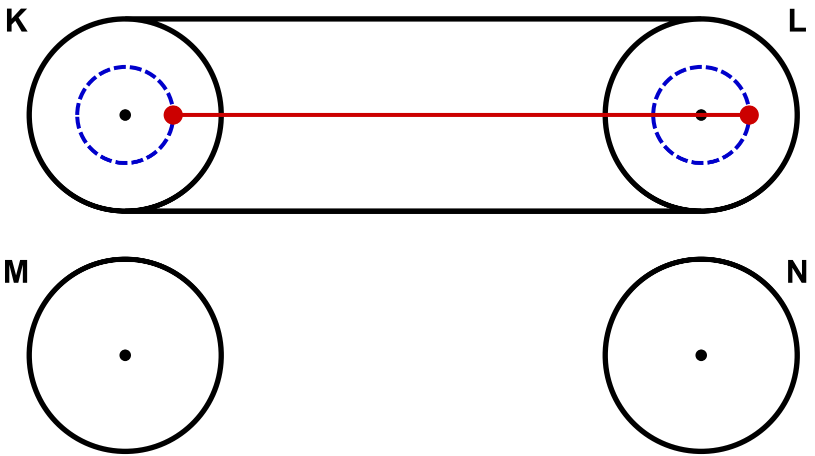


- Initialize a field line at at point in cross-section *K* a distance *r* from the central axis

L. Spitzer, Phys. Fluids 1958

Top stretch (*K*-*L*)

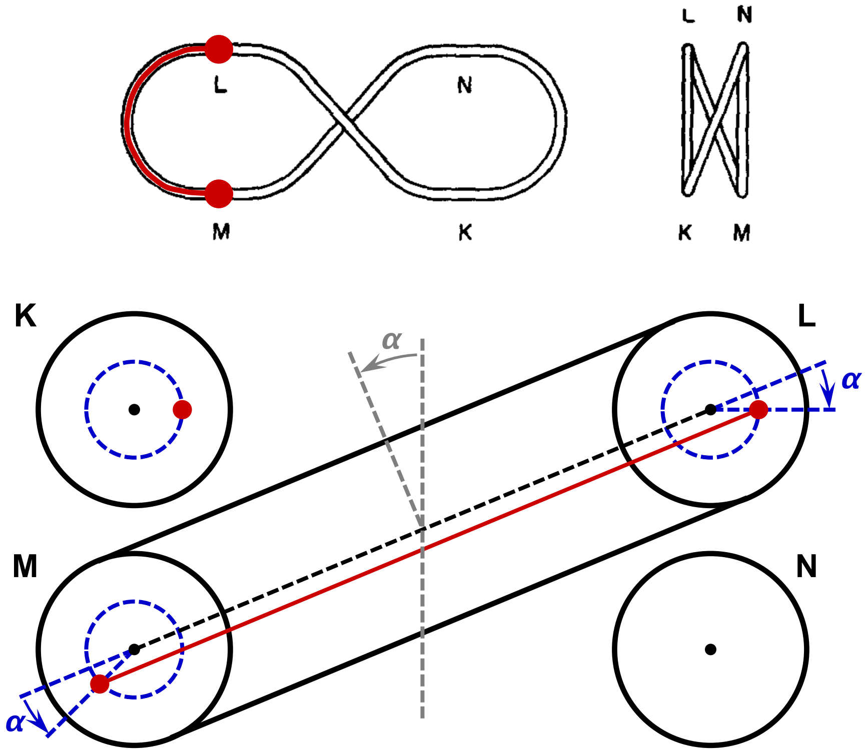




- Field line trajectory
  - Remains on horizontal plane
  - Heads into the slide in the cross-section view
  - Remains at “3:00” with respect to center axis

L. Spitzer, Phys. Fluids 1958

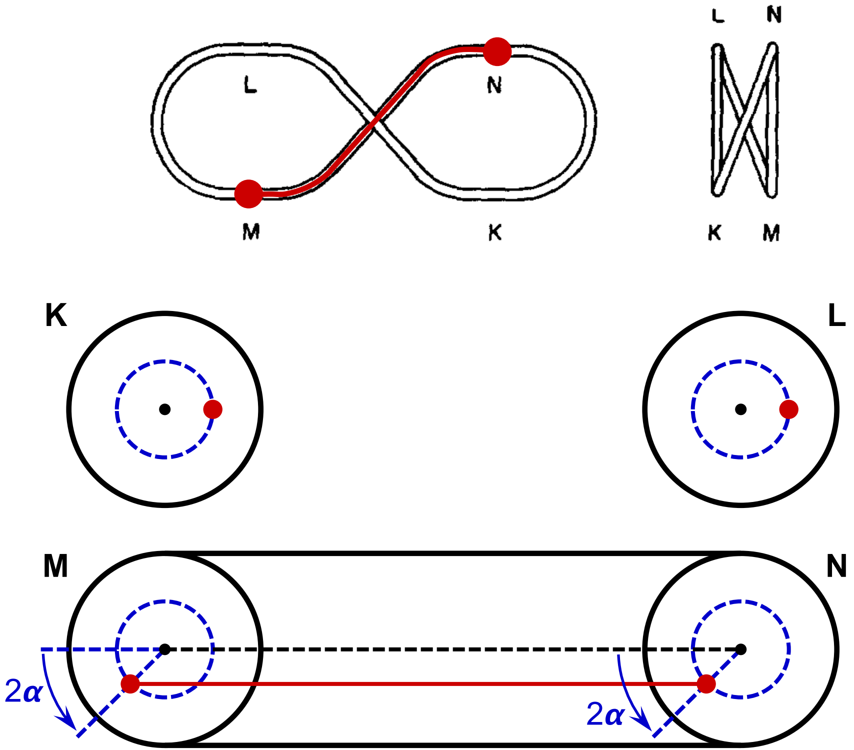
Back stretch (*L*-*M*)



- Field line trajectory
  - Remains on plane of curve (tilted an angle ***α*** to the horizontal)
  - Turns around in the cross-section view
  - "Puncture point" is reflected in the axis perpendicular to the plane of the curve

L. Spitzer, Phys. Fluids 1958

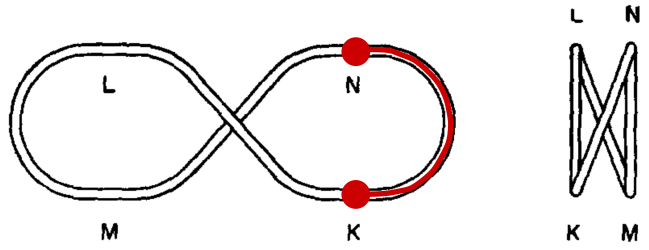
Bottom stretch (*M*-*N*)

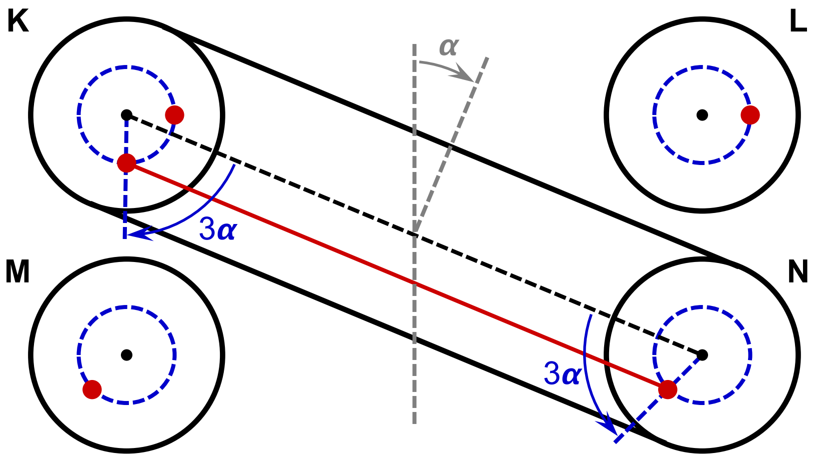


- Field line trajectory
  - Remains on horizontal plane
  - Heads out of the slide in the cross-section view
  - Remains at an angle 2α about the central axis with respect to the horizontal plane

L. Spitzer, Phys. Fluids 1958

Front stretch (*N*-*K*)

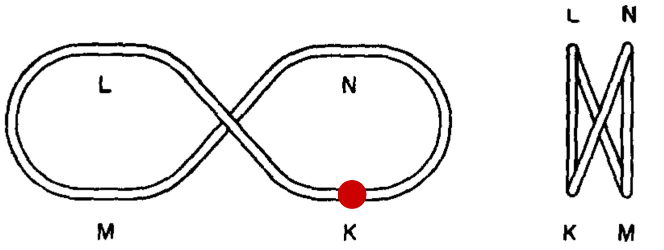


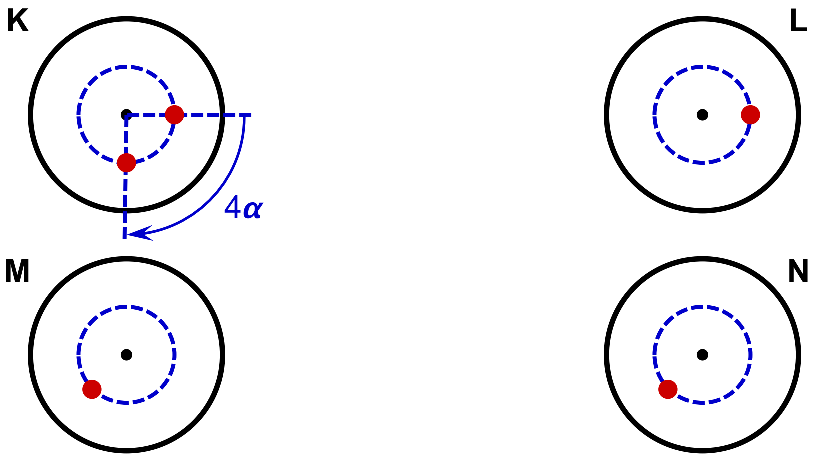


- Field line trajectory
  - Remains on plane of curve (tilted an angle α to the horizontal)
  - Turns around in the cross-section view
  - "Puncture point" is reflected in the axis perpendicular to the plane of the curve
  - Remains at an angle 3α about the central axis with respect to the plane of the curve

L. Spitzer, Phys. Fluids 1958

Field line has rotated poloidally upon its return to the starting plane!

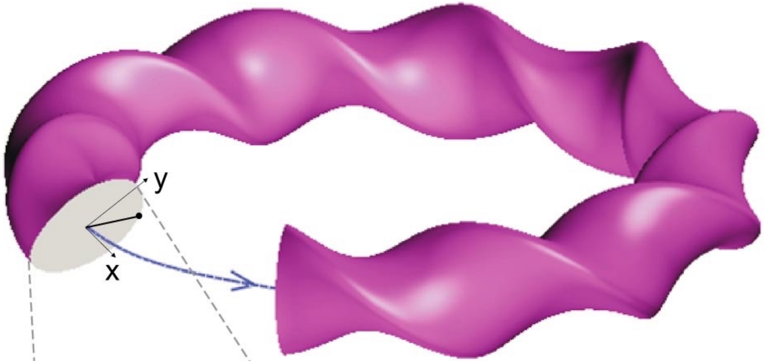




- "Puncture point" has rotated an angle of $4\boldsymbol{\alpha}$ from its starting location with respect to the central axis
- This corresponds to a rotational transform $\iota = 4\alpha/(2\pi)$
- Same argument applies for any radial distance from the central axis ⟶ every flux surface exhibits the same rotational transform

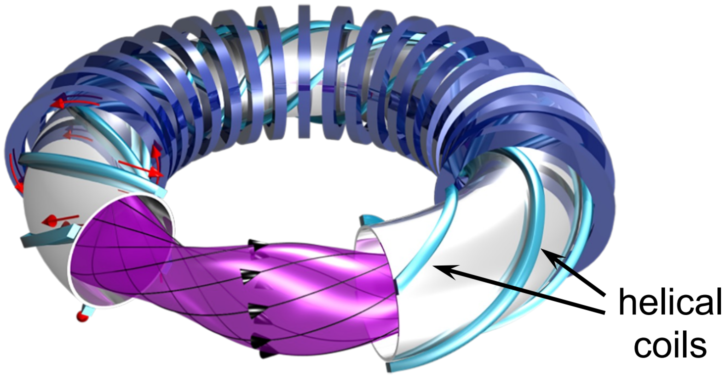
L. Spitzer, Phys. Fluids 1958

Rotational transform can also arise from a helically rotating poloidal cross-section



P. Helander, Rep. Prog. Mod. Phys., 2014

- This effect can be achieved with suitable coil shaping
  - Helical windings
  - Modular coils with non-planar shapes



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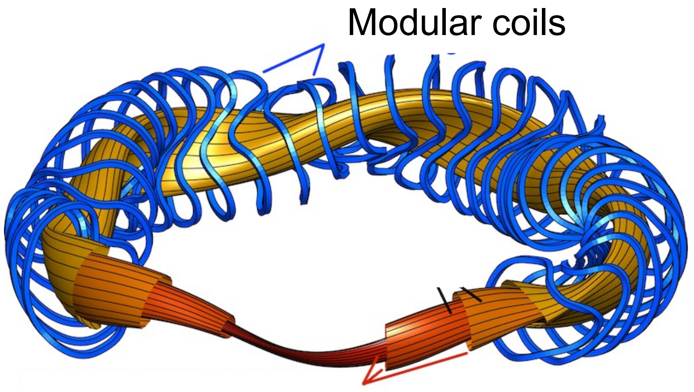
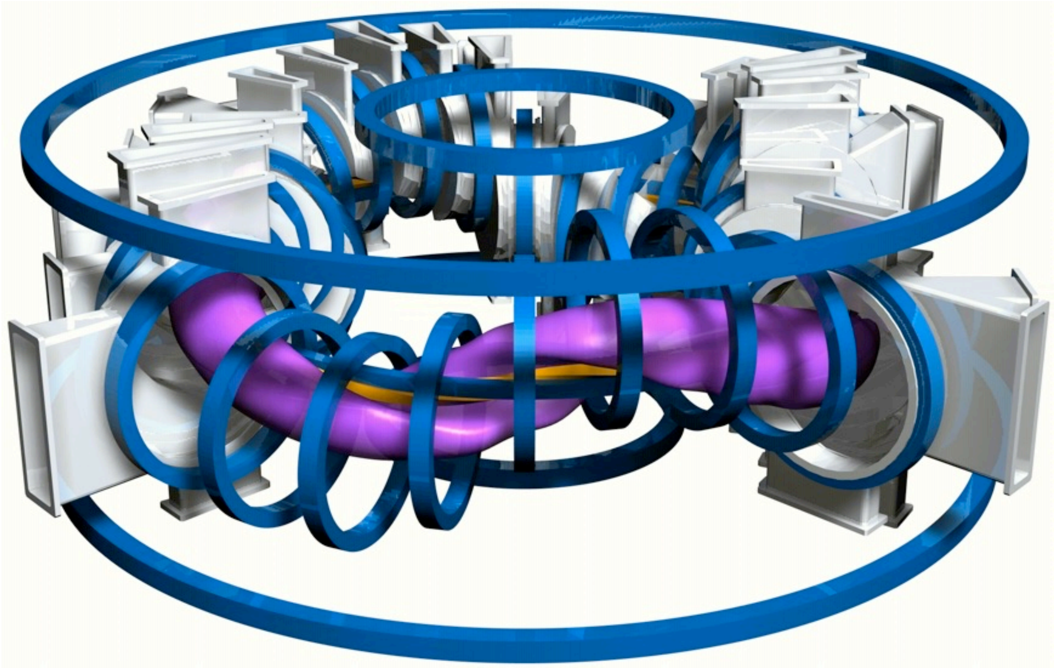


M. Landreman

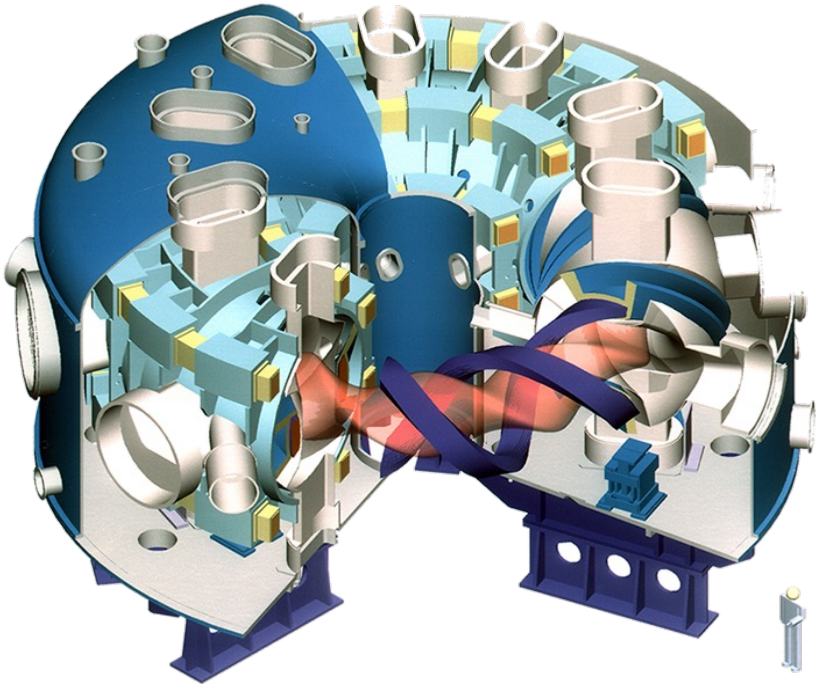
Stellarator coils can take many forms



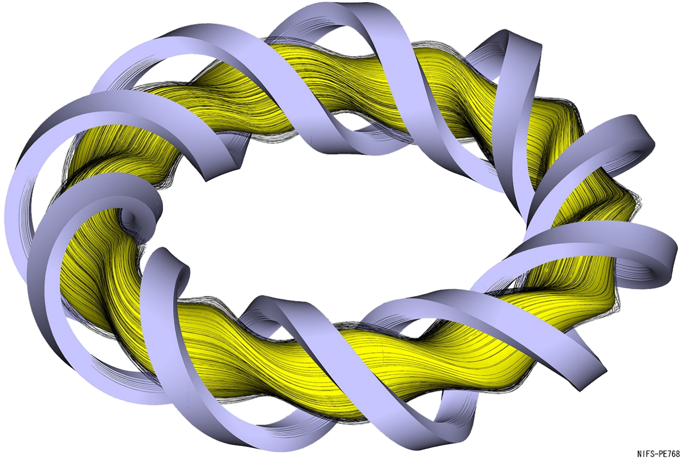
CIEMAT

- TJ-II, CIEMAT, Madrid, Spain
  - “Heliac” configuration
  - Most coils are circular and planar

Stellarator coils can take many forms

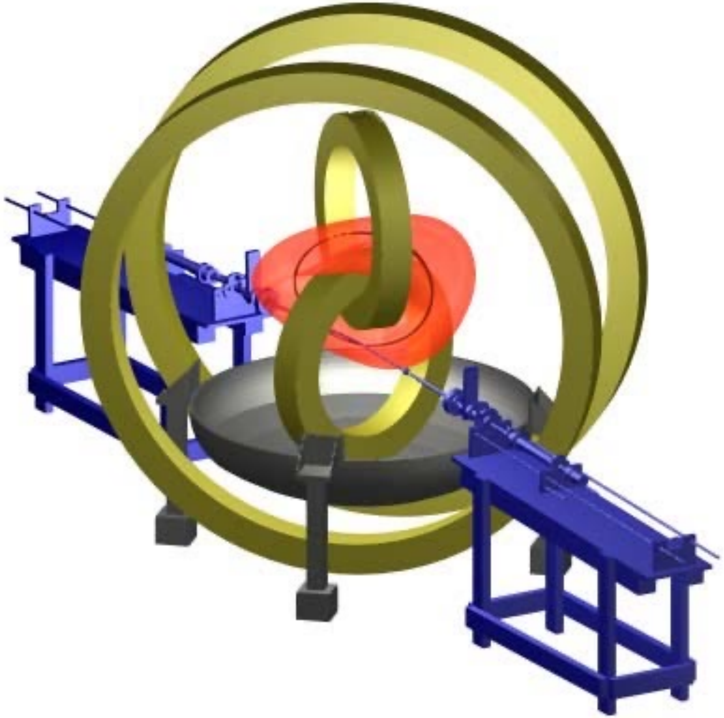


- Large Helical Device (LHD), National Institute for Fusion Science, Toki, Japan
  - Two superconducting helical coils provide most of the magnetic field



NIFS

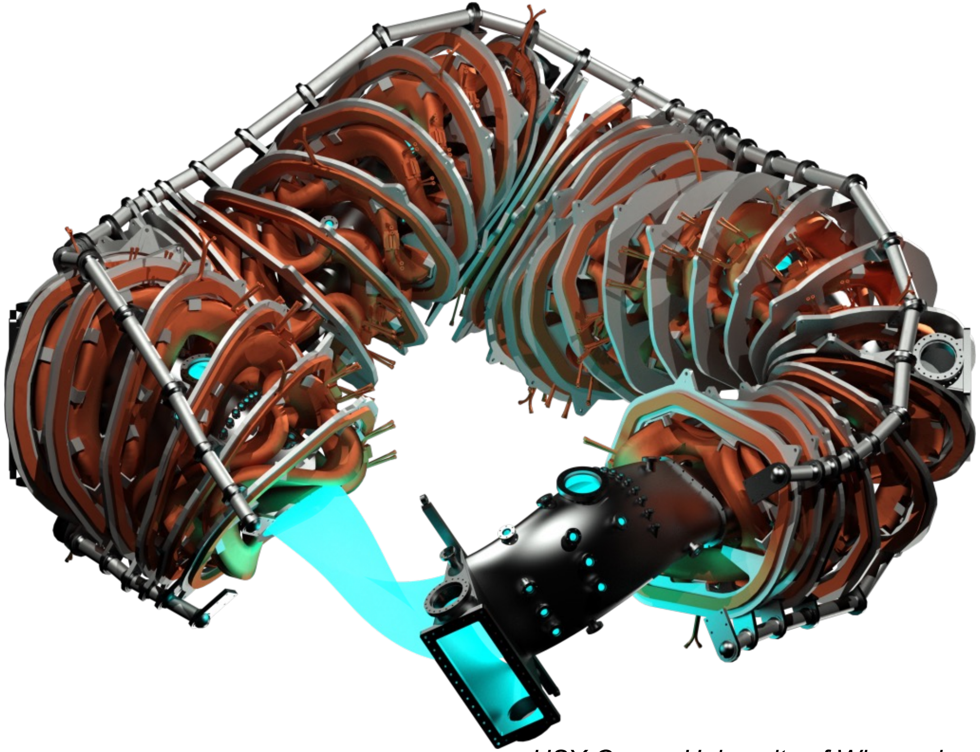
Stellarator coils can take many forms



J. P. Kremer et al., Phys. Rev. Lett. 2006

- CNT, Columbia University, New York, NY, USA
  - Arguably the simplest stellarator ever built
  - Four circular planar coils
  - Two coils are interlocked and tilted

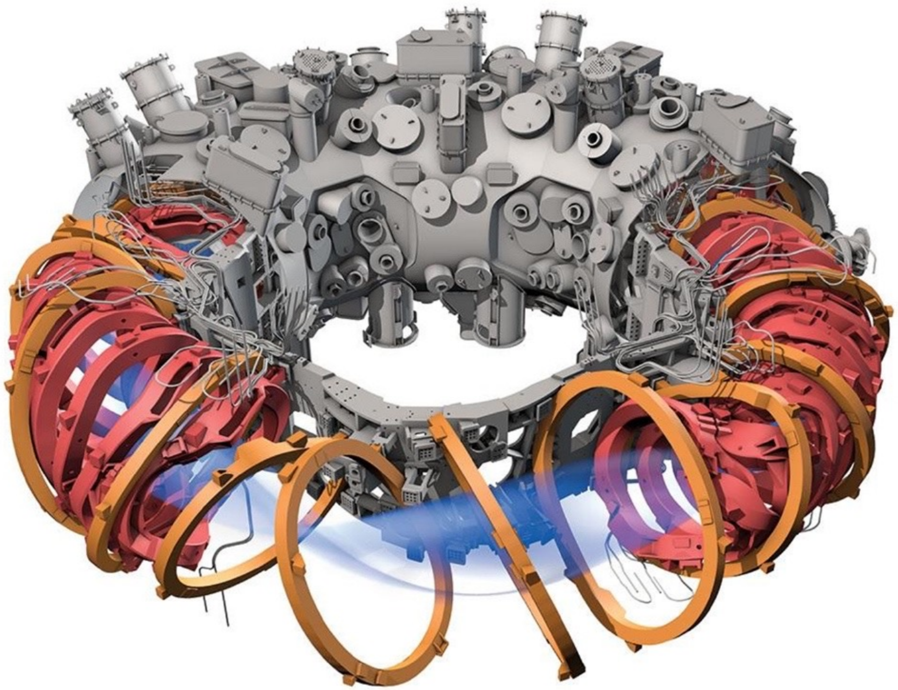
Stellarator coils can take many forms



HSX Group, University of Wisconsin

- Helically Symmetric Experiment (HSX), University of Wisconsin, Madison, WI, USA
  - Combination of Modular, “wiggly” coils and planar coils supply the main field
  - Modular coils optimized for good confinement

Stellarator coils can take many forms

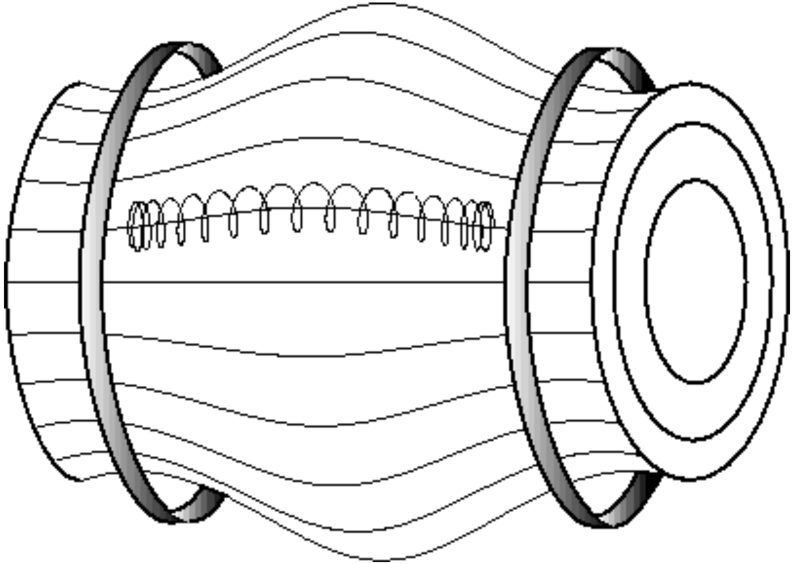


- Wendelstein 7-X (W7-X), Max Planck Institute for Plasma Physics, Greifswald, Germany
  - Most advanced stellarator built to date
  - Modular coils optimized for good confinement
  - Superconducting coils

Improving confinement

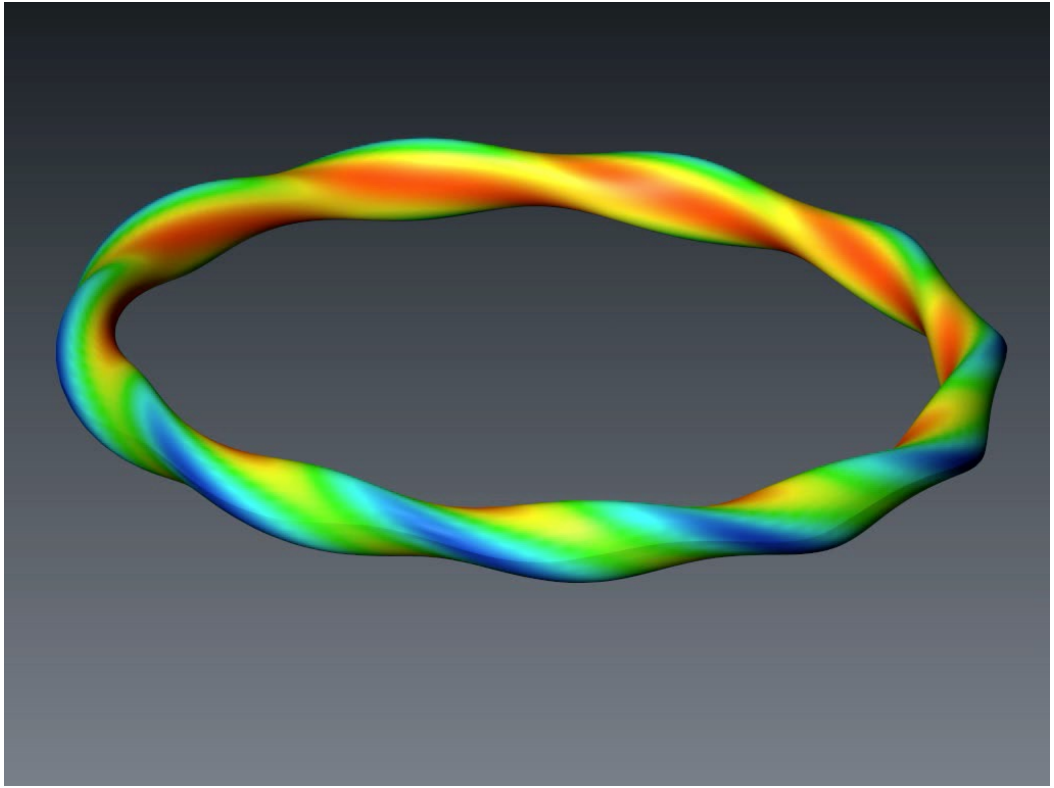
Helical, twisting field lines are necessary but not sufficient for good confinement

- Early stellarators exhibited poor energy and particle confinement despite producing flux surfaces with rotational transform
- Helical field lines generally confine *passing* particles well, but not necessarily *trapped* particles
  - *Trapped* particles bounce back and forth between points with high field strength due to magnetic mirror effect
  - *Passing* particles have a high enough $v_{\parallel}/v_{\perp}$ orbit toroidally without bouncing



R. Fitzpatrick

Orbits in a stellarator with poor trapped-particle confinement



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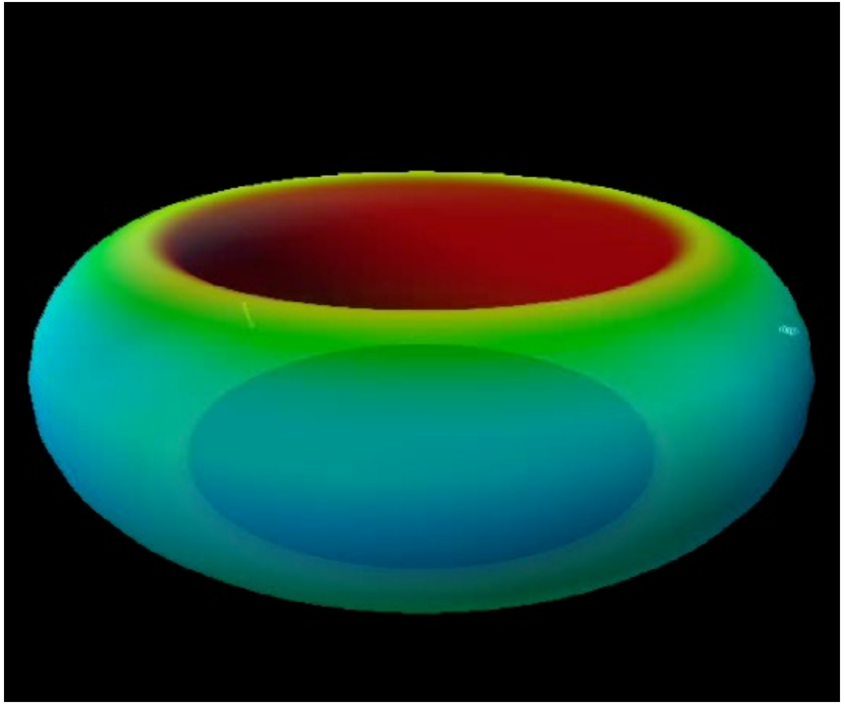
Trapped particle orbits can be confined if the plasma exhibits certain symmetries

- **Noether's Theorem:** if a physical system has a continuous symmetry, there is a corresponding quantity that remains constant (conserved) in time
- We seek symmetries that conserve the radial position (flux surface) of all particles, both trapped and passing

Simplest approach: axisymmetry

- Axisymmetry (cylindrical symmetry): plasma and magnetic field are invariant in the toroidal dimension
- Trapped particles remain confined
- *But:* axisymmetric plasmas…
  - Do not exhibit torsion of the magnetic axis or helical rotation
  - Require a large plasma current to generate the helical field line twist
  - Are not stellarators 😭
- For more on axisymmetric plasmas: see talk on *tokamaks* tomorrow by T. Wilks



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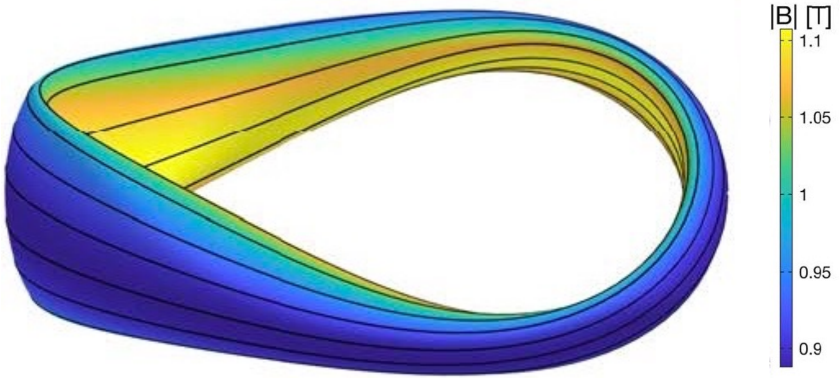
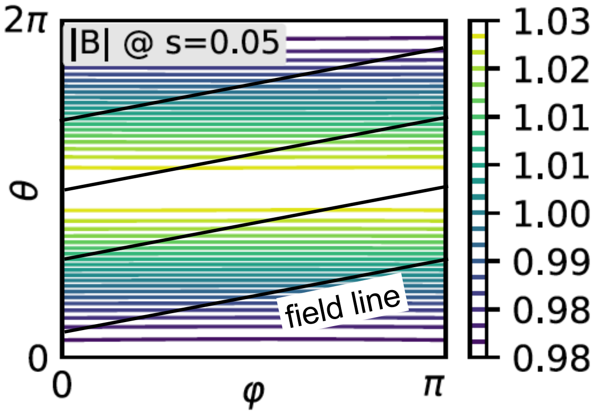
Alternate approach: quasisymmetry

- **Quasisymmetry:** invariance of the field strength |**B**| on a flux surface along a carefully chosen magnetic coordinate
- Coordinate system consists of [1]:
  - Flux surface label $\boldsymbol{\psi}$
  - Poloidal angle $\boldsymbol{\theta}_{\mathrm{B}}$
  - Toroidal angle $\boldsymbol{\phi}_{\mathrm{B}}$
- Field lines are straight lines in $\boldsymbol{\theta}_{\mathrm{B}}$, $\boldsymbol{\phi}_{\mathrm{B}}$
- In quasisymmetry, |B| contours are also straight lines

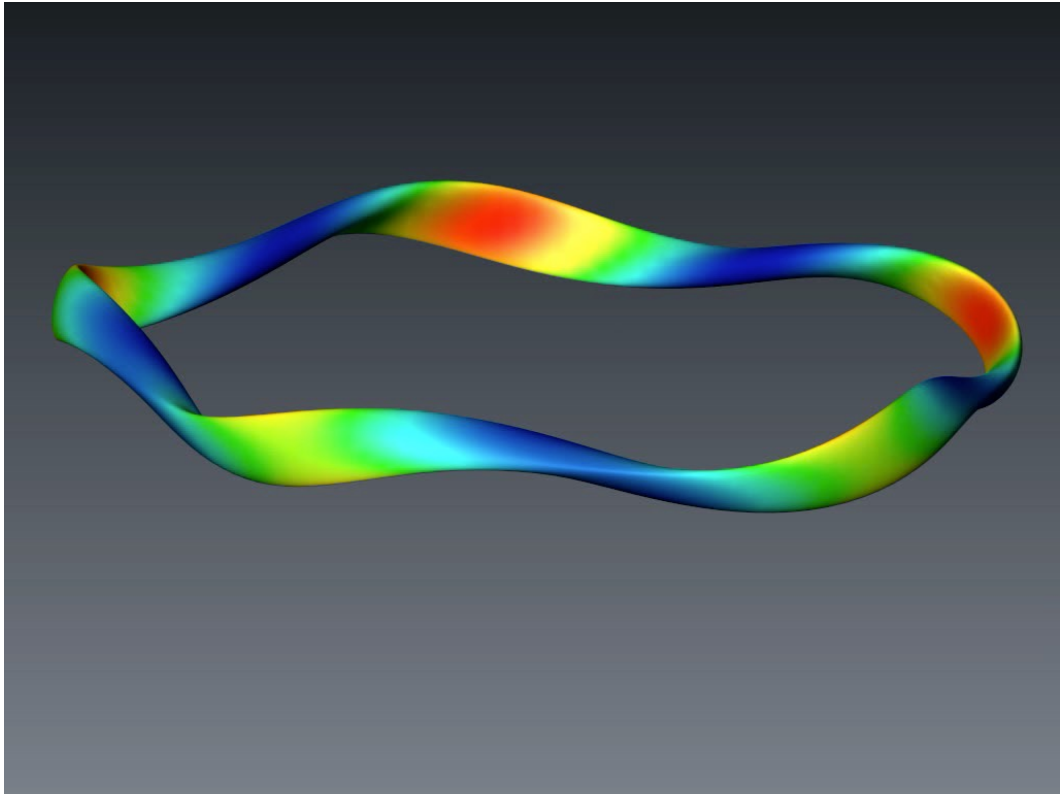




M. Landreman and E. Paul, Phys. Rev. Lett. 2022

[1] A. H. Boozer, Phys. Fluids, 1983

With the right symmetries, stellarators can confine trapped particles!



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How to design a stellarator

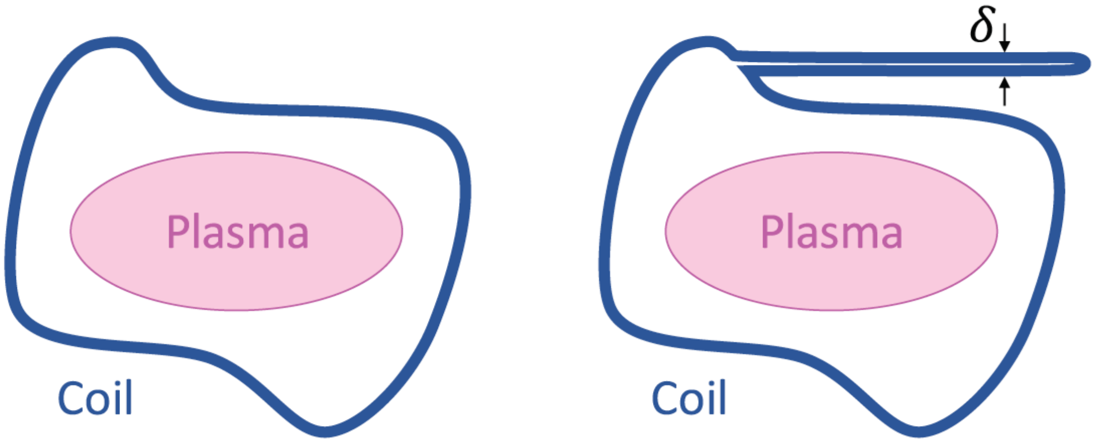
Numerical optimization is used to design stellarator plasmas with symmetry and other desirable properties

- Typical approach:
  - Define a weighted sum of objective functions for confinement and other properties:
    $\chi^2 = \lambda_1 \chi_{\text{symmetry}}^2 + \lambda_2 \chi_{\text{stability}}^2 + \lambda_3 \chi_{\text{turbulence}}^2 + \ldots$
  - Start with an initial guess of a plasma
  - Iteratively perturb the plasma to minimize the objective functions
- Frequently used optimization codes
  - STELLOPT [2]
  - ROSE (Rose Optimizes Stellarator Equilibria) [3]
  - SIMSOPT [4]

[2] https://github.com/PrincetonUniversity/STELLOPT
[3] M. Drevlak et al., Nucl. Fusion 2019
[4] https://github.com/hiddenSymmetries/simsopt

Modern stellarator coils are typically designed with an optimized plasma in mind

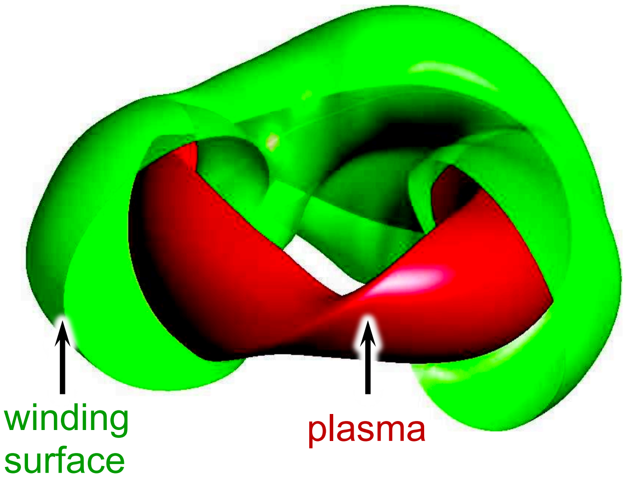
- Designing coils for a stellarator is an *ill-posed problem*: many nonunique solutions
- Designer must impose constraints

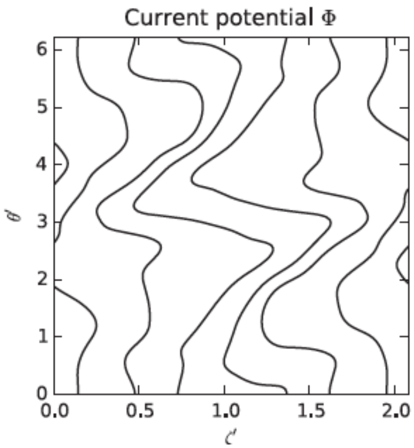


M. Landreman, Nucl. Fusion 2017

Merkel's method has been used to define coils on many current stellarators

1. Define a *winding surface* outside the plasma
2. Calculate surface current distribution necessary to confine plasma
3. Discretize the surface current into curves
4. Design coils from the shapes of the curves





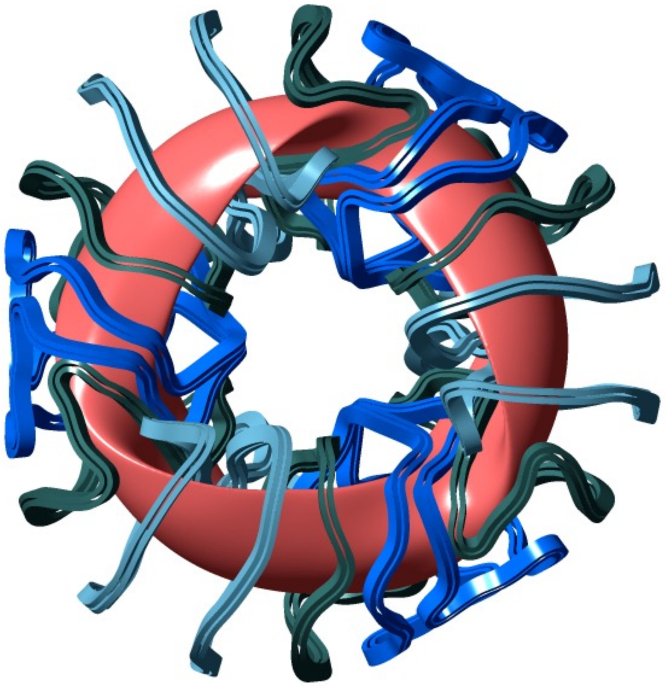
P. Merkel, Nucl. Fusion 1987
M. Landreman, Nucl. Fusion 2017

Current areas of research*

*not an exhaustive list!

Coil simplification: background

- Coils are one of the main cost drivers of current stellarators
  - Complex geometry
  - Tight tolerances
- Reducing complexity and/or increasing tolerances can reduce costs and make the stellarator more attractive as a reactor concept

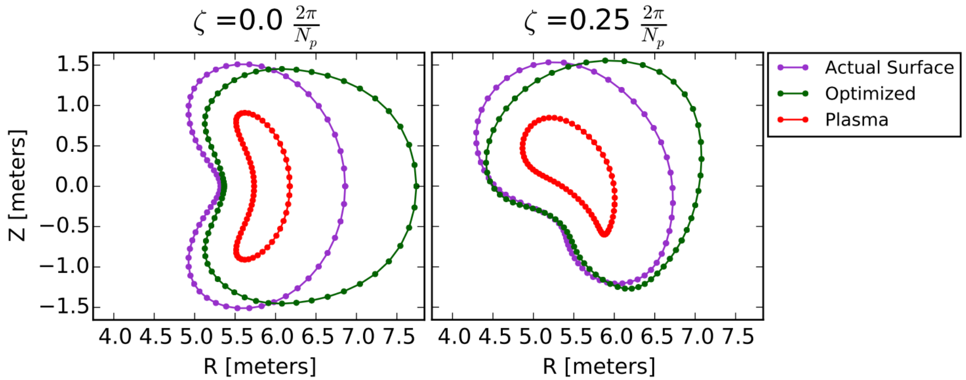


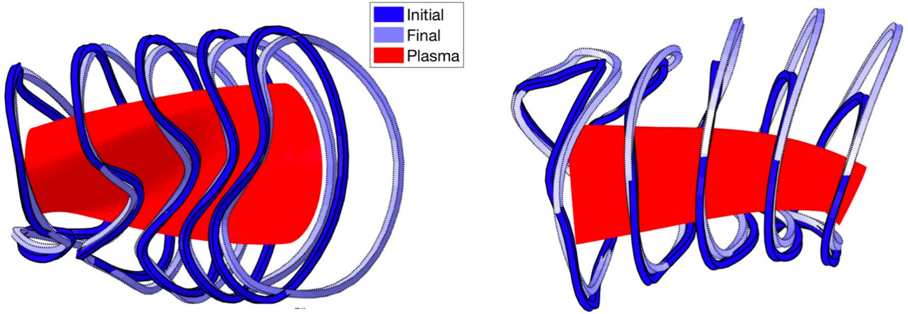
Coils and plasma for the NCSX stellarator, which was canceled due to delays and cost overruns

Coil simplification: optimization of the winding surface

- Initial choice of winding surface in Merkel's method may not be the best one (or even a good one)
- Winding surface geometry can be optimized to improve:
  - Field accuracy
  - Current density (coil-coil separation)
  - Enclosed volume (more room for components)

Optimization of the W7-X winding surface



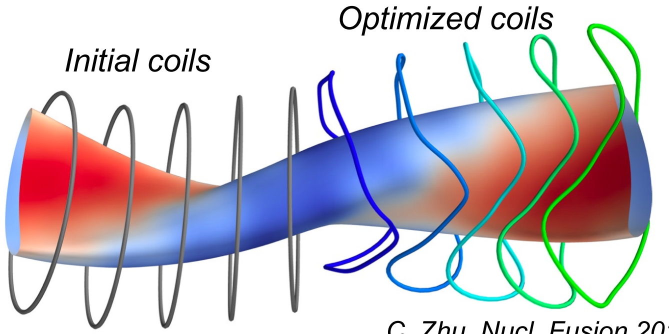


E. Paul, Nucl. Fusion 2018

Coil simplification: direct optimization of coil shapes

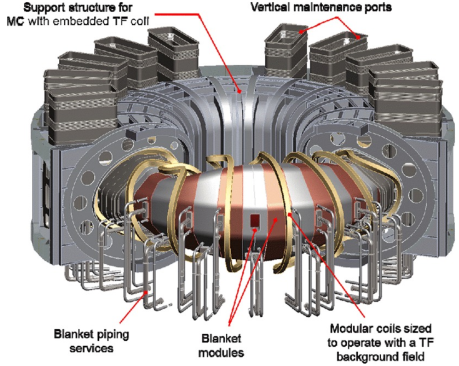
- Model each coil as a parametric curve
- Optimize the curve parameters for:
  - Field accuracy
  - Coil-coil separation
  - Curvature
  - etc.
- Constraints can be applied to curves, e.g. to enable simpler maintenance
- Codes: FOCUS, COILOPT++

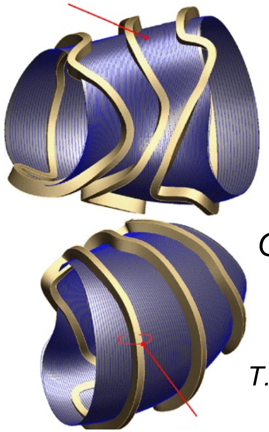
Optimizing coils with FOCUS



C. Zhu, Nucl. Fusion 2018

Reactor concept with straight-outer-leg coils





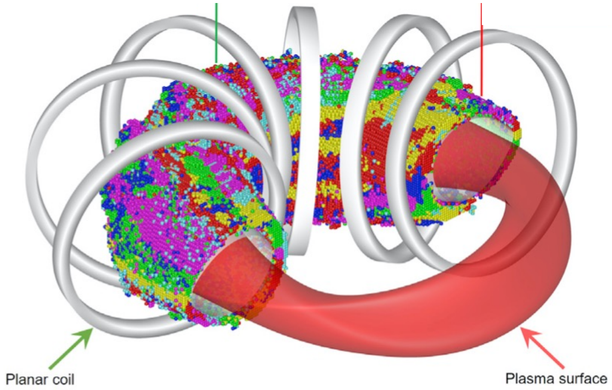
Inboard view

Outboard view

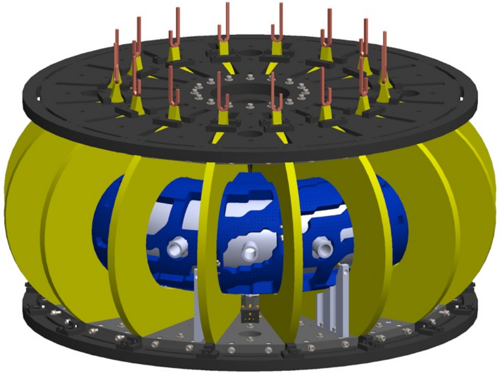
T. Brown et al., SOFE 2015

Coil simplification: use permanent magnets for shaping

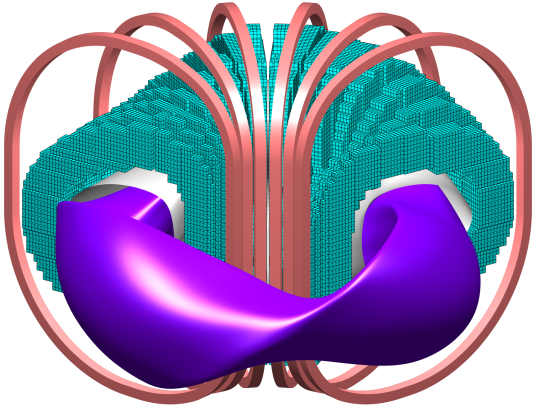
- External permanent magnets cannot create a toroidal magnetic field, but they can contribute to 3D shaping necessary for optimal plasma properties
- Recent designs combine planar coils with arrays of magnets



Z. Y. Lu et al., Cell Rep. Phys. Sci., 2022



MUSE: tabletop experiment at PPPL
T. Qian et al.

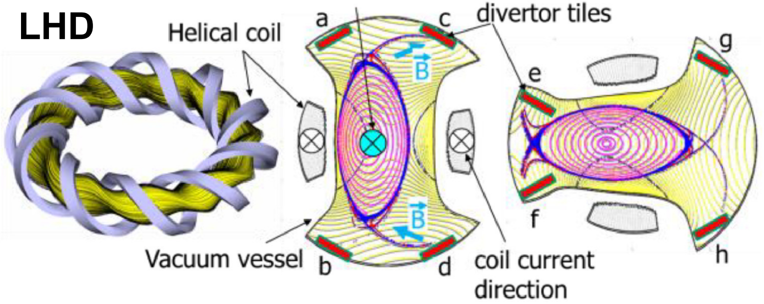


NCSX with scaled-down field
K. C. Hammond et al.

Divertor design: background

- Divertors
  - Collect plasma heat and particle fluxes that escape confinement region
  - Direct fuel exhaust (helium) out of reactor
- Design and placement of present-day stellarator divertors guided from magnetic topology
  - LHD: helical divertor
  - W7-X: island divertor

LHD



S. Masuzaki, Nucl. Mat. Energy 2019

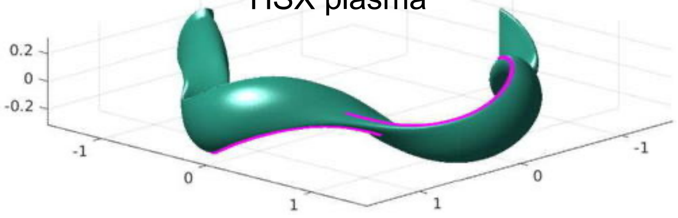
W7-X

R. C. Wolf et al., Phys. Plasmas 2019

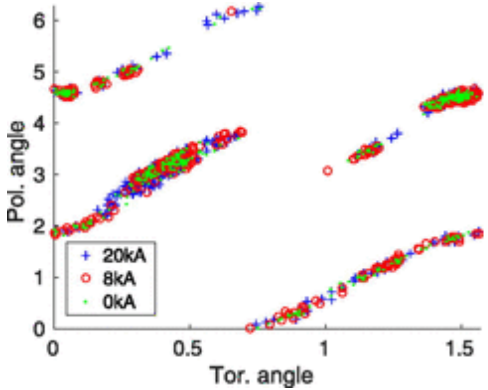
Divertor design: non-resonant divertors

- Sometimes, the topological guidelines aren't so obvious
- *Non-resonant divertors* must be used in the absence of clear island chains, helical x-points, etc.
    - Heat and particle flux still tend to exhibit well-defined patterns
    - Non-resonant divertors must be localized to these patterns

HSX plasma



Simulated particle fluxes through a surface enclosing the plasma



A. Bader et al.,, Phys. Plasmas 2016

Summary

- Stellarators are toroidal magnetic plasma confinement devices
  - Three-dimensional, non-axisymmetric geometry
  - Magnetic field generated by external coils
  - Little to no plasma current required
- Stellarator coils can take on many forms
- Confining magnetic field must exhibit rotational transform and sufficient symmetry to confine trapped particles
- Numerical optimization is crucial element of modern stellarator design
- There is much more to be learned!

Further reading

- Book recommendation:

An Introduction to Stellarators
From magnetic fields to symmetries and optimization

Lise-Marie Imbert-Gérard, Elizabeth J. Paul, Adelle M. Wright

https://arxiv.org/abs/1908.05360

Stellarators

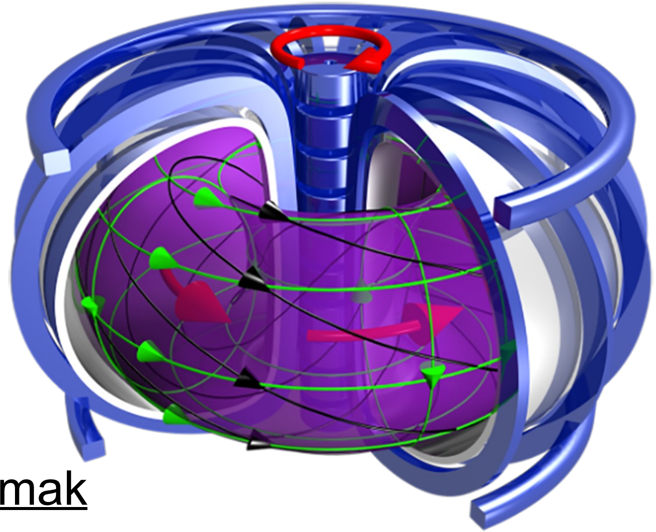
Kenneth C. Hammond

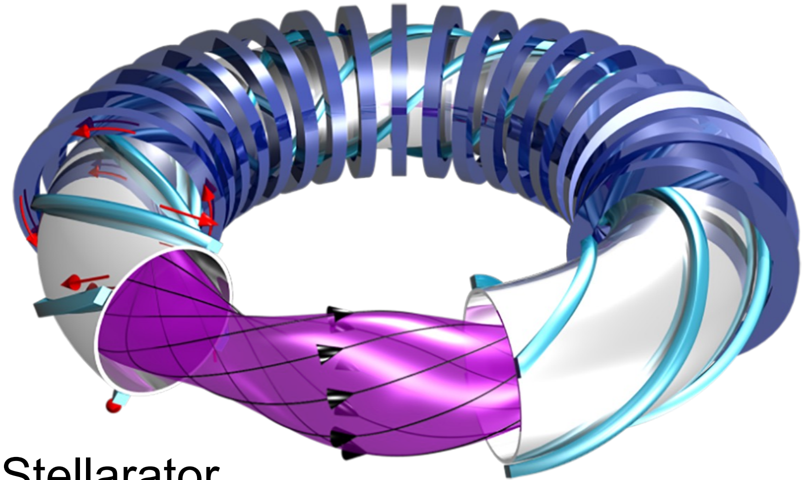
Staff Research Physicist

Princeton Plasma Physics Laboratory

Introduction to Plasma Physics and Fusion Energy Course, Princeton Plasma Physics Laboratory, 2022

Tokamaks and stellarators represent alternate approaches to toroidal magnetic confinement





<u>Tokamak</u>

- (nominally) axisymmetric / 2-dimensional
- Helical twist of the magnetic field is created by plasma current
  - Input power required to drive current

<u>Stellarator</u>

- Non-axisymmetric / 3-dimensional
- Helical twist of the magnetic field is created by external magnets/coils
  - Easier to operate in a steady state

Images: Max Planck Institute for Plasma Physics