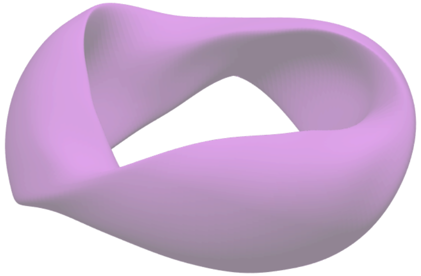
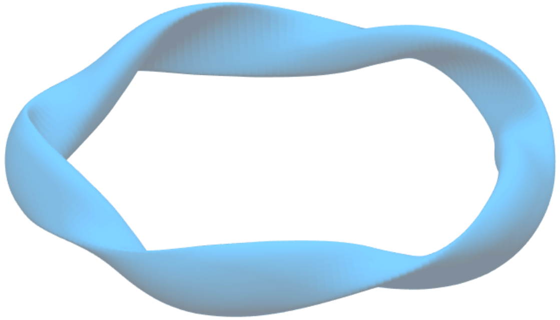
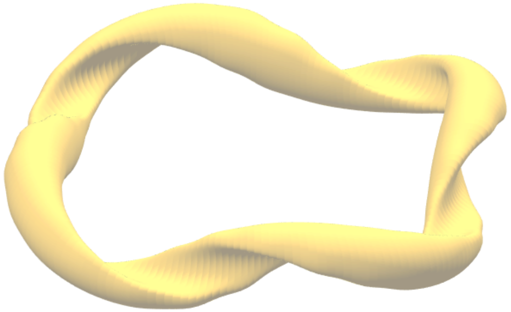
An introduction to stellarators







Elizabeth Paul

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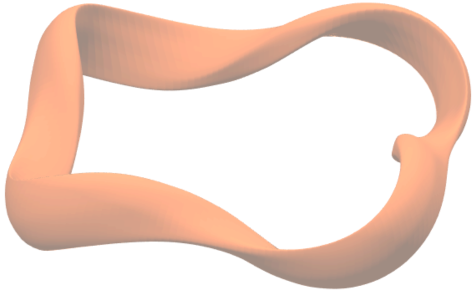
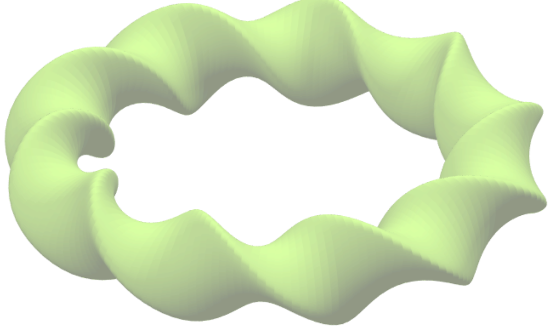
June 12, 2023





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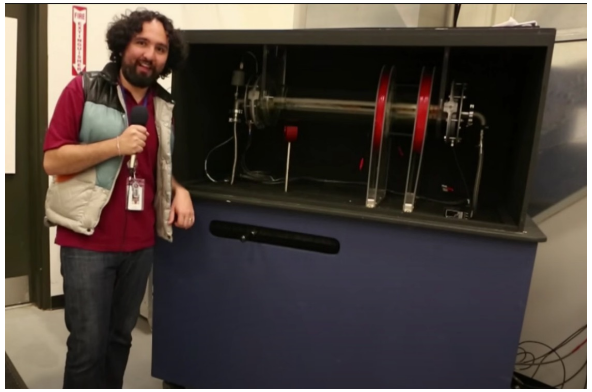
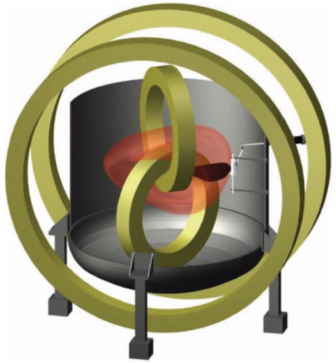
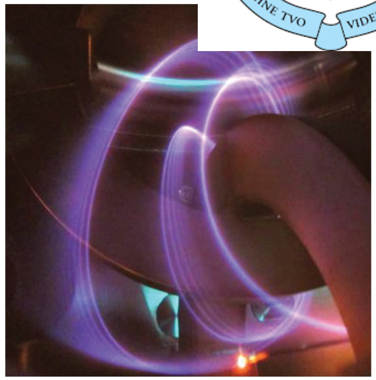
The Fu Foundation School of Engineering and Applied Science

Princeton Science Action (2013)

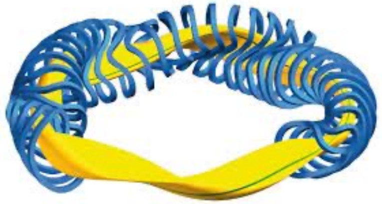


CU Assistant Prof. (2023-present)

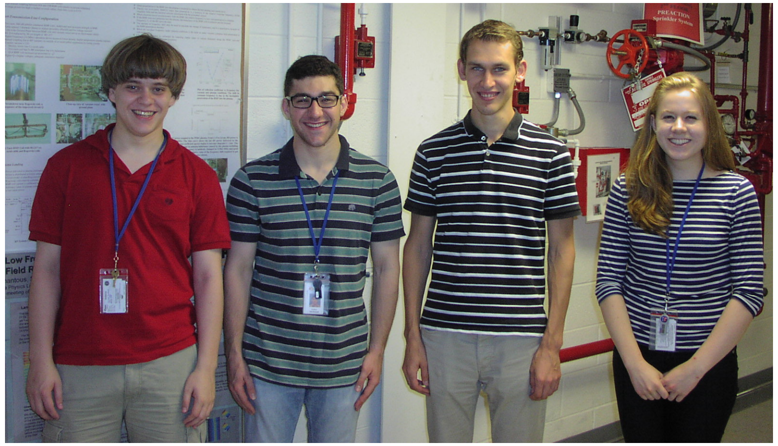


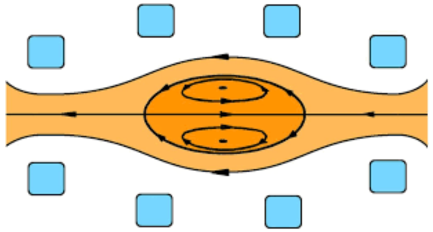


PU/PPPL Postdoc (2020-2022)

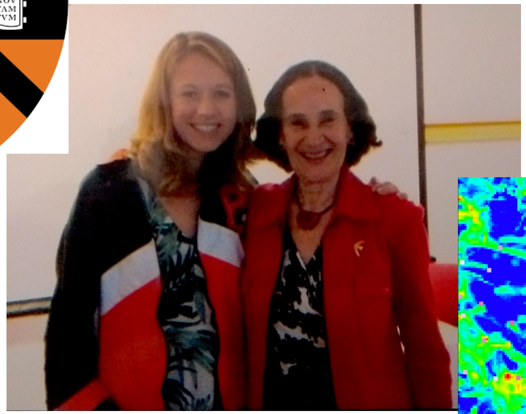


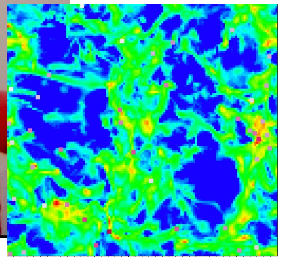
PPPL internship (2013)





Princeton A.B. Astrophysical Sciences (2011-2015)





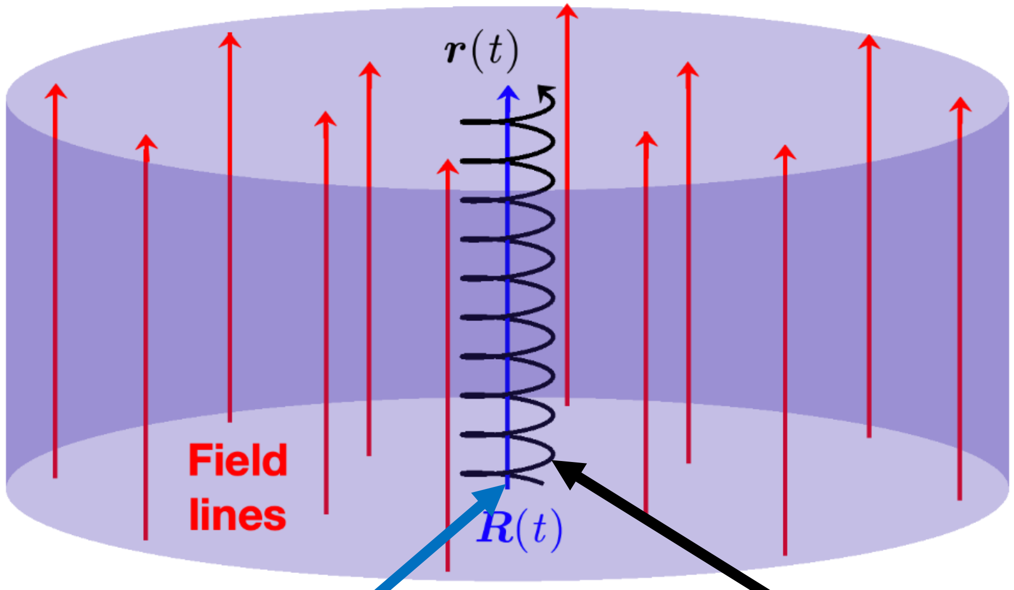
UMD Ph.D. Physics (2015-2020)

Outline

- **Magnetic confinement without symmetry**
- Ingredients of stellarator confinement
- How do we “cook” a stellarator?
- Stellarators in context

Toroidal magnetic confinement of charged particles

Straight, uniform magnetic field provides perpendicular confinement

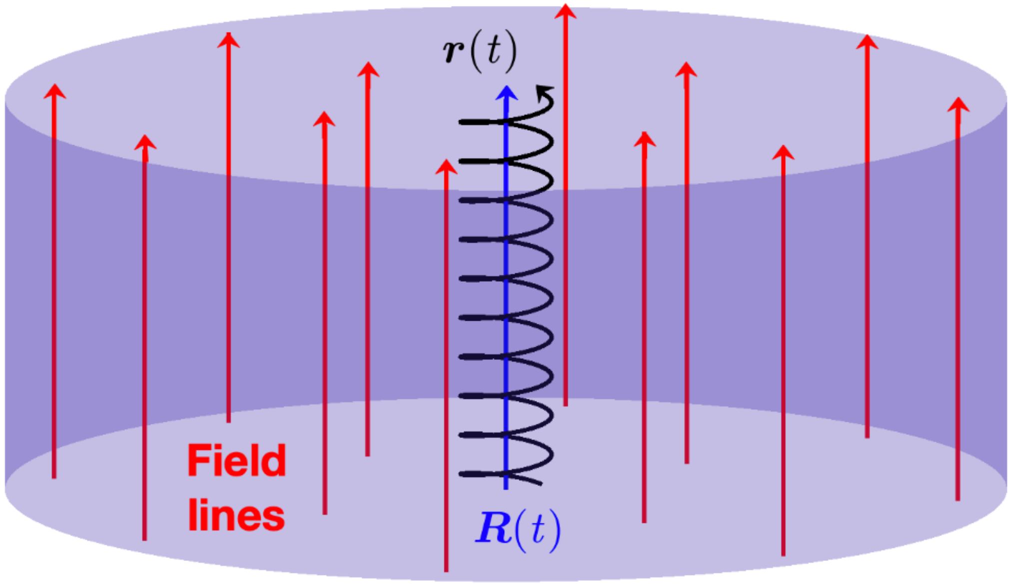


Charged particle

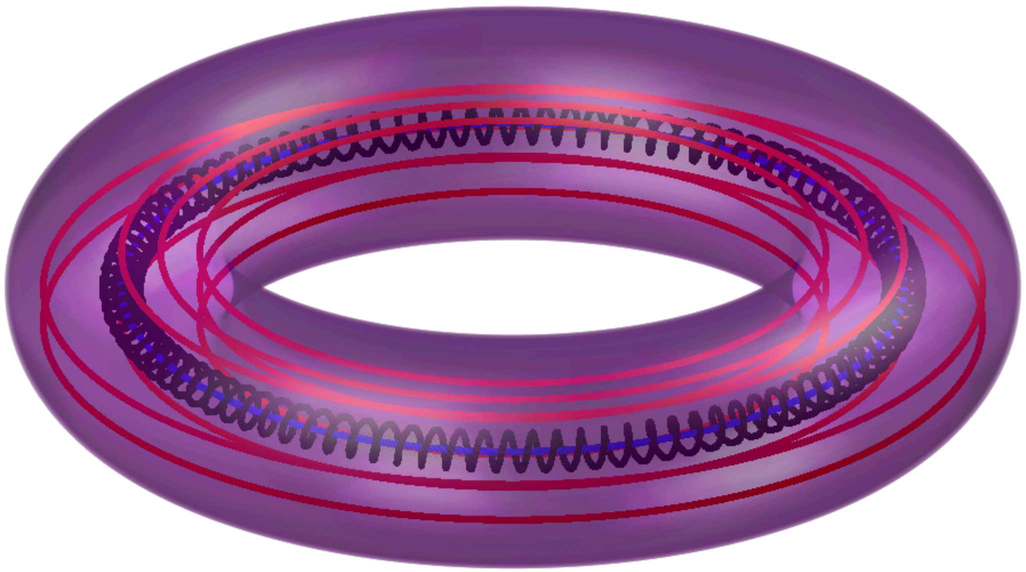
“Guiding center”

Toroidal magnetic confinement of charged particles

Straight, uniform magnetic field provides perpendicular confinement

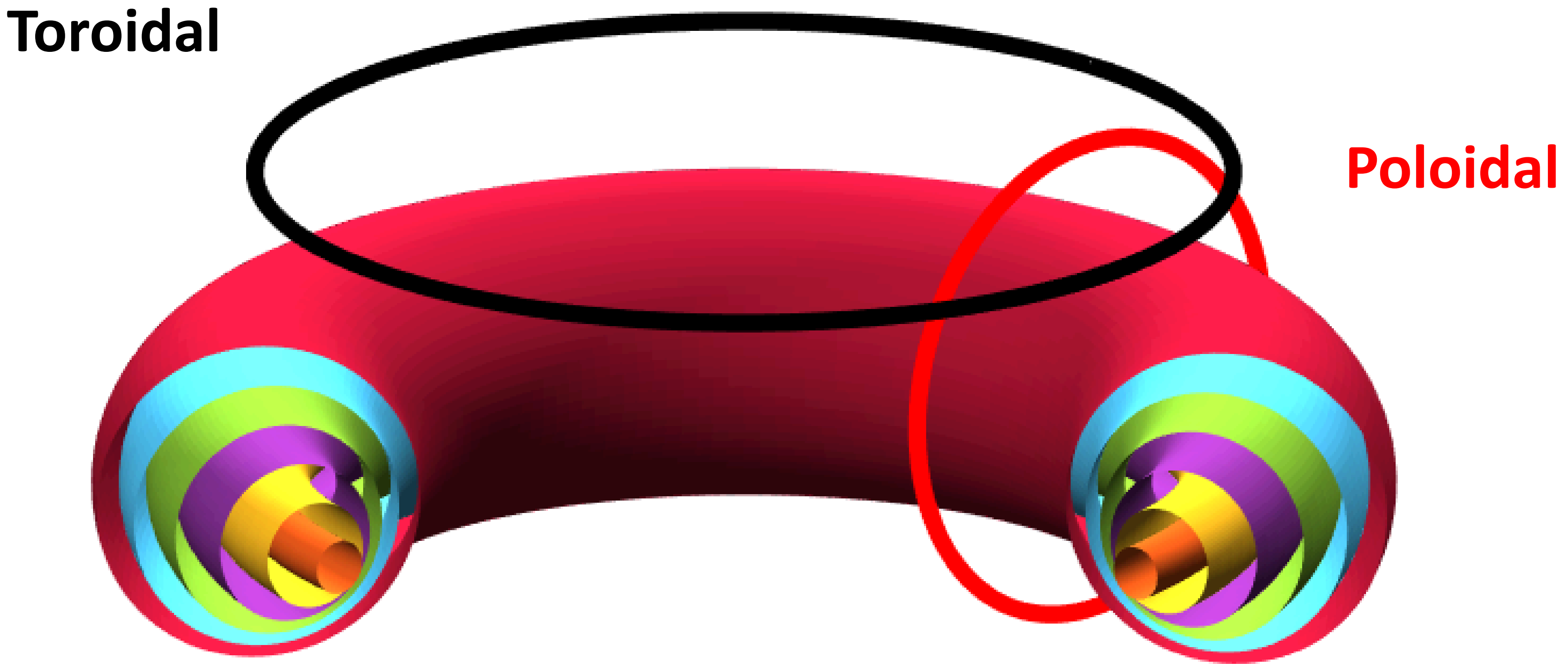


Avoid end losses!



Toroidal magnetic confinement of charged particles

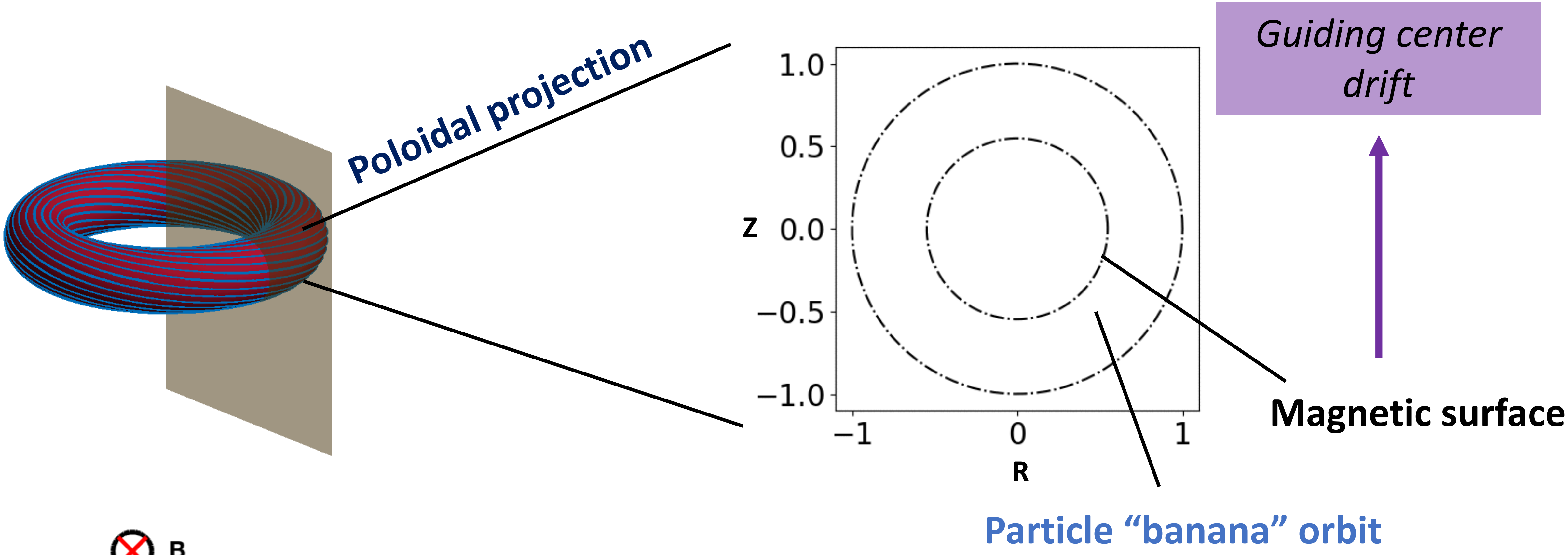
Step 1: Continuously nested toroidal surfaces

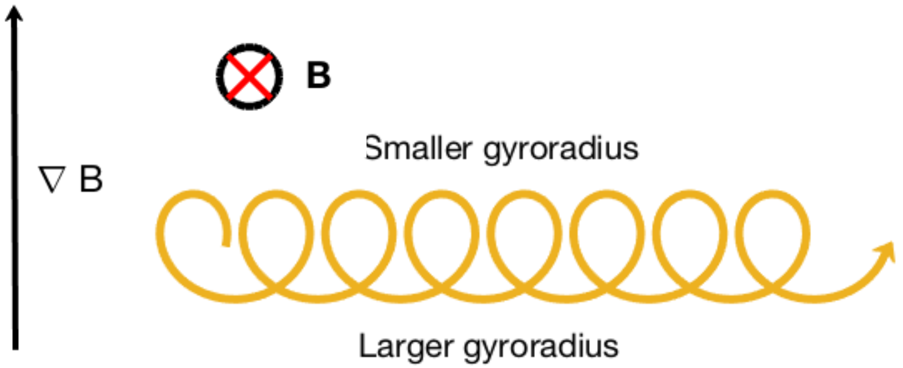


“Magnetic surfaces” (const ψ)

Toroidal magnetic confinement of charged particles

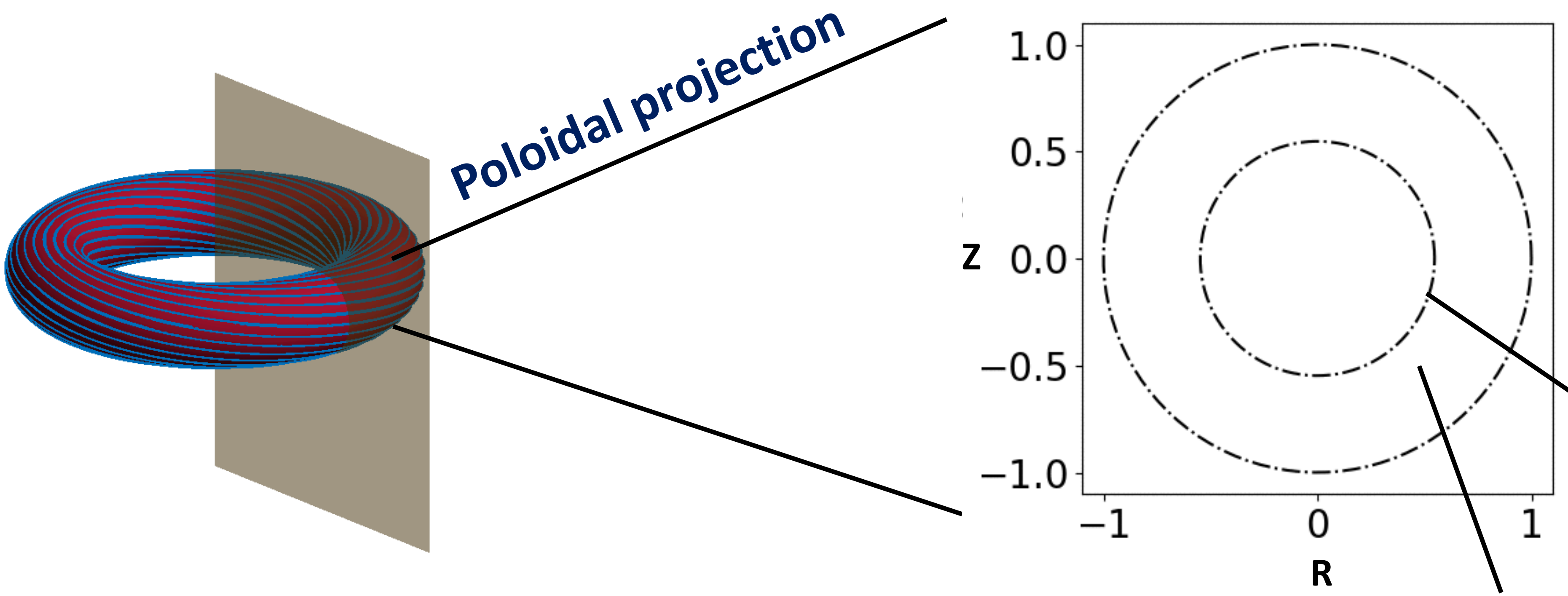
Step 2: Rotational transform





Toroidal magnetic confinement of charged particles

Step 2: Rotational transform



Guiding center drift

Magnetic surface

Particle "banana" orbit

Width $\sim 1/\iota$

$$\iota = \frac{\#\ \text{poloidal turns}}{\#\ \text{toroidal turns}}$$

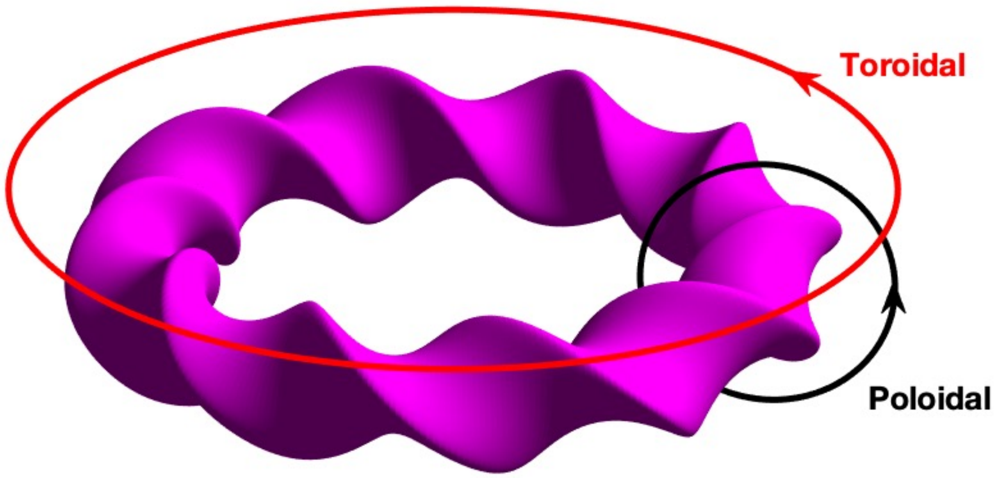
"rotational transform"

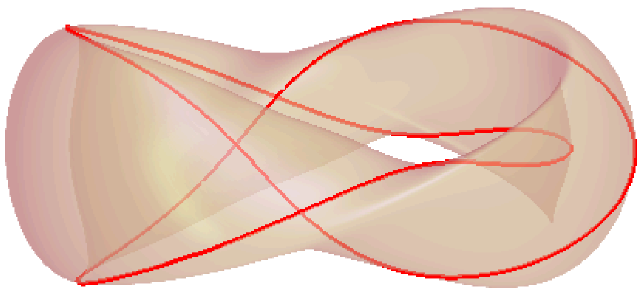
Magnetic confinement without symmetry

The solution: rotational transform

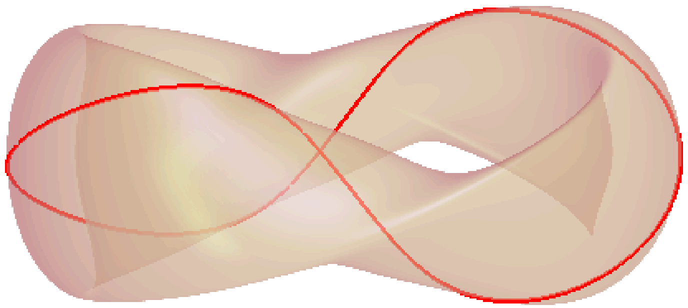
$$\iota = \frac{\#\text{ poloidal turns}}{\#\text{ toroidal turns}} = \frac{1}{q}$$

“rotational transform” **“safety factor”**





$\iota = 3/2$



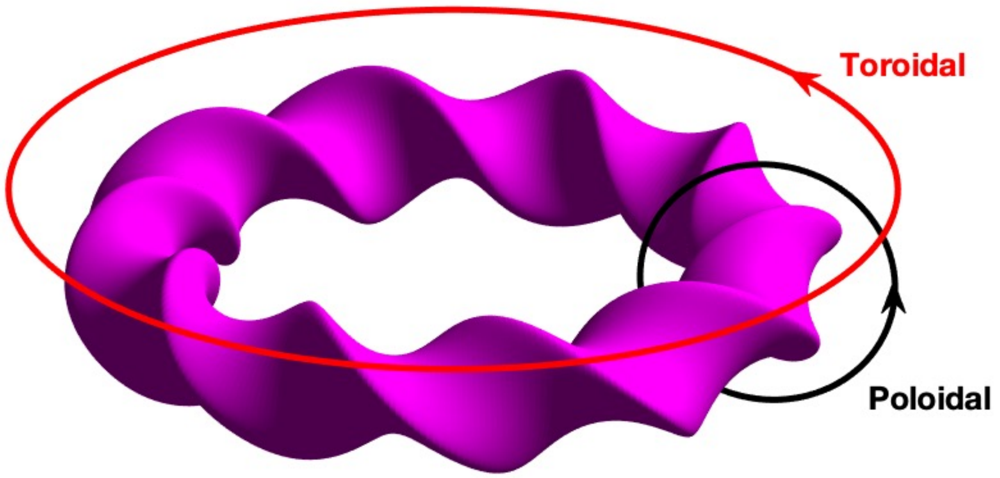
$\iota = 1$

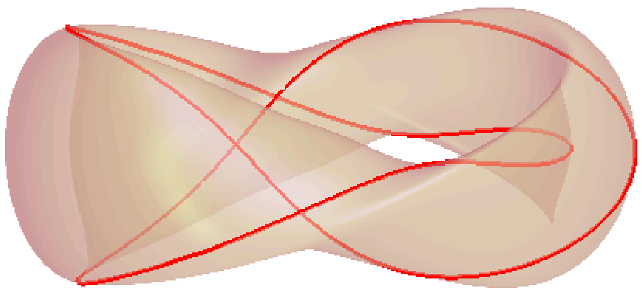
Magnetic confinement without symmetry

The solution: rotational transform

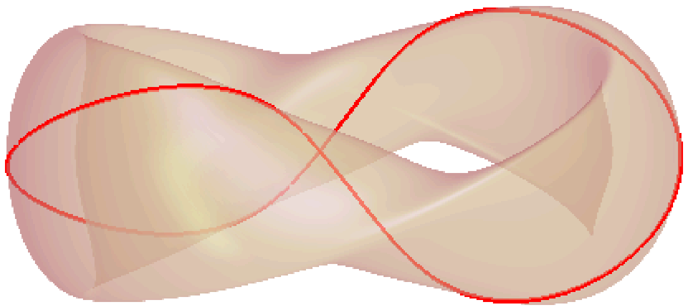
$$\iota = \frac{\#\ \text{poloidal turns}}{\#\ \text{toroidal turns}} = \frac{1}{q}$$

"rotational transform" **"safety factor"**



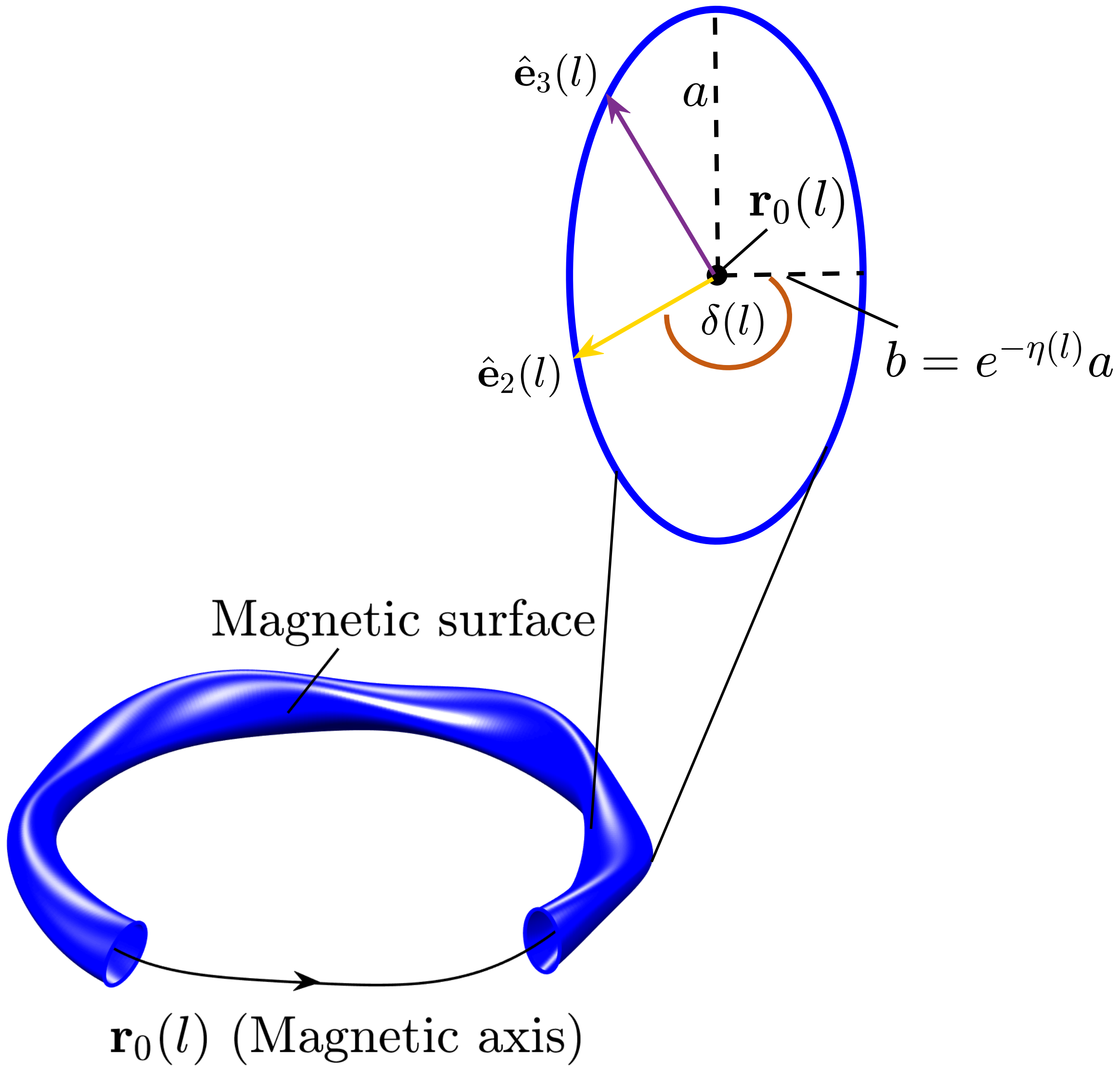


$\iota = 3/2$



$\iota = 1$

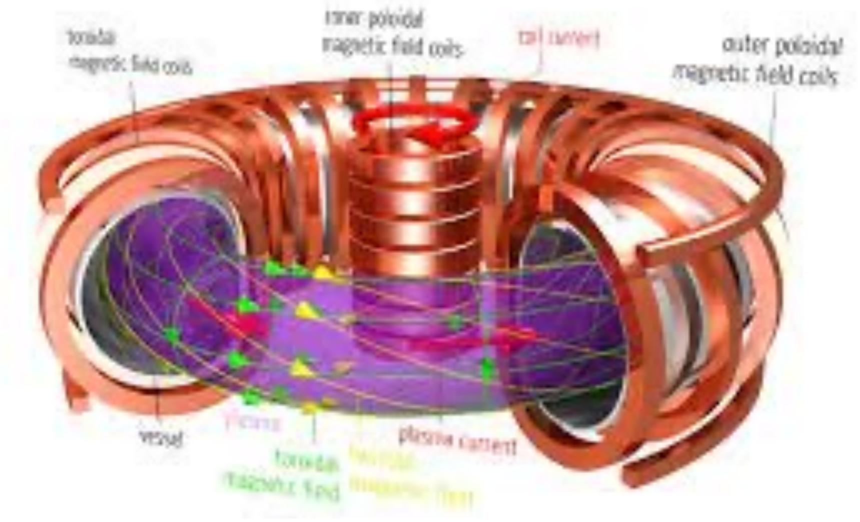
Rotational transform can be generated by symmetry-breaking

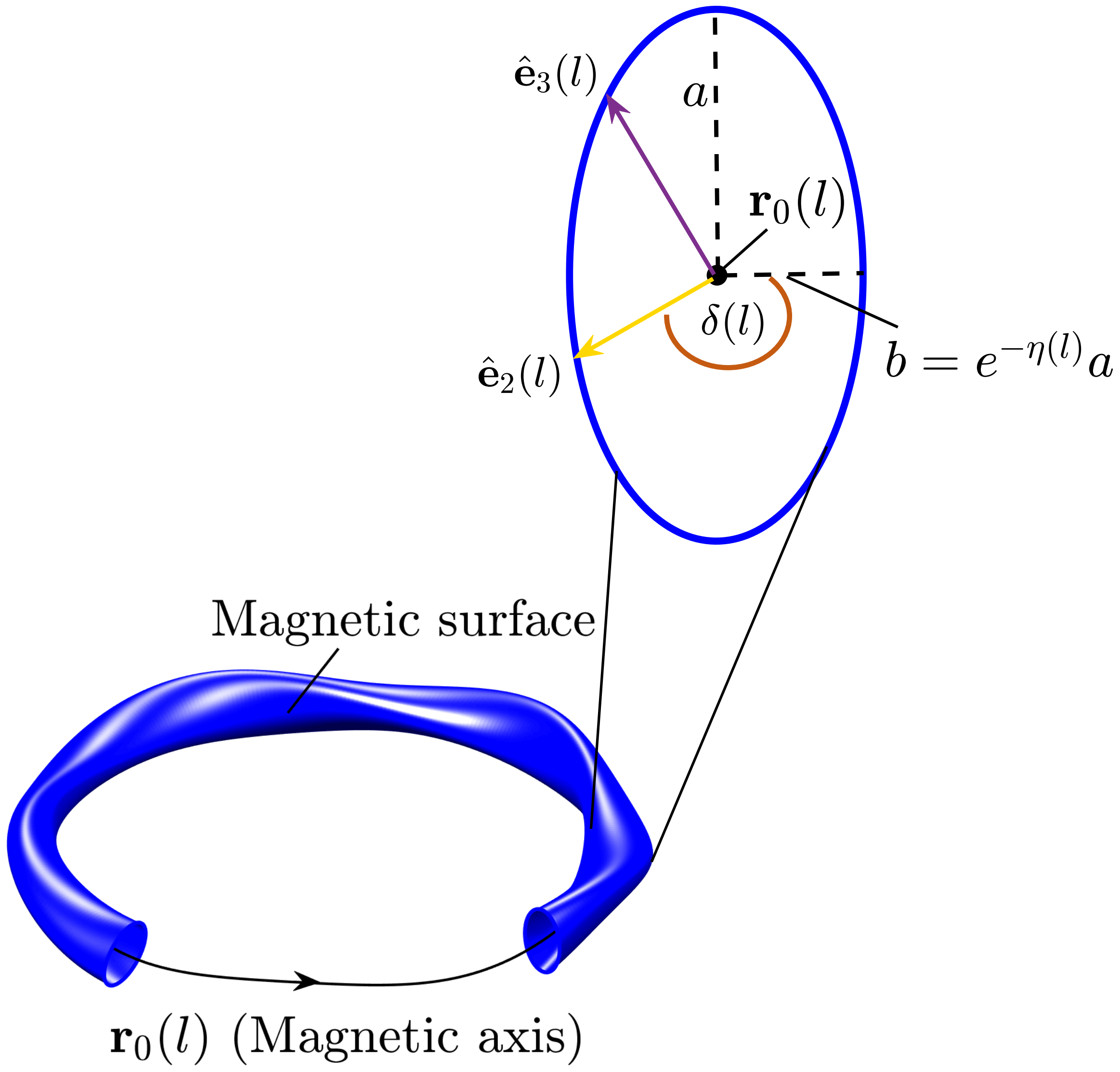


$\iota \approx$ current + rotating ellipticity + axis torsion

Rotational transform can be generated by symmetry-breaking

Tokamak

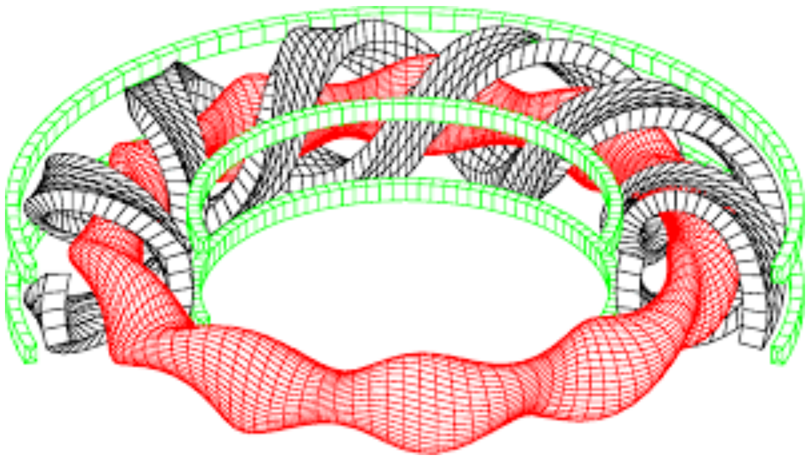




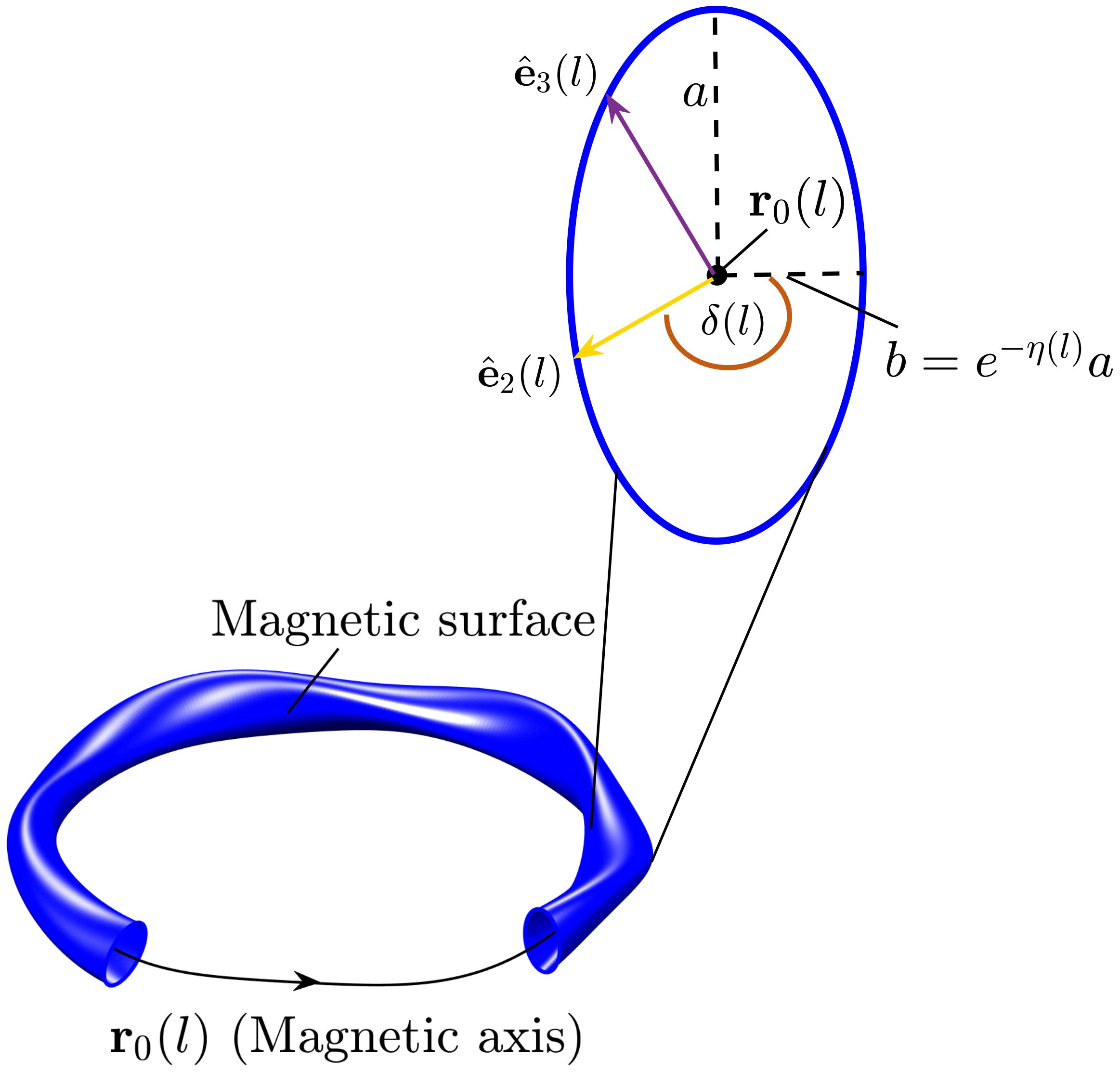
$\iota \approx$ current + rotating ellipticity + axis torsion

Rotational transform can be generated by symmetry-breaking

Large Helical Device



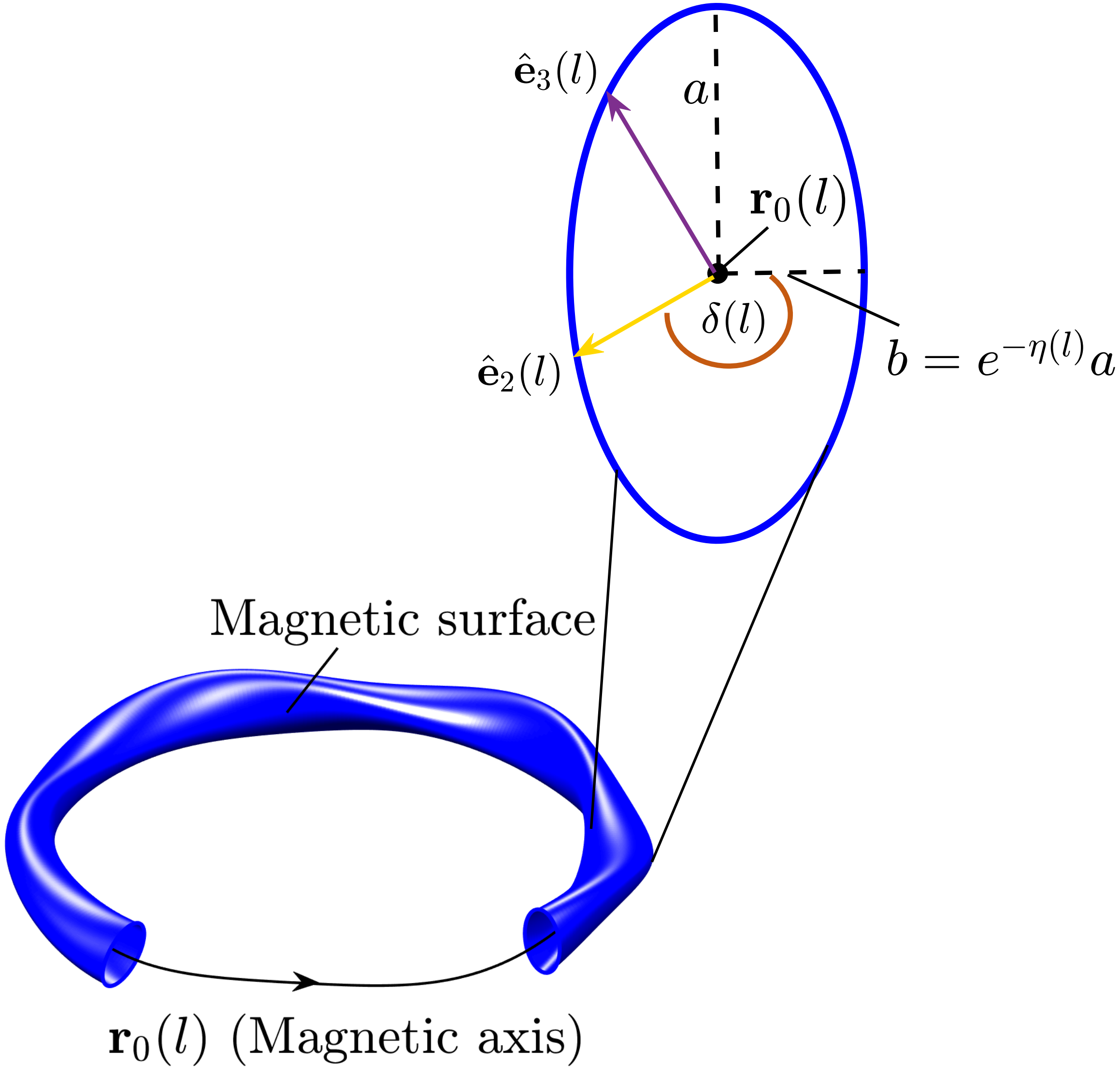
$\iota \approx$ current + rotating ellipticity + axis torsion



Rotational transform can be generated by symmetry-breaking

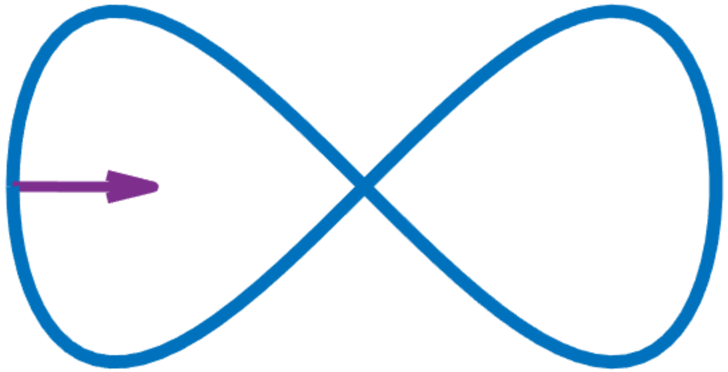
Spitzer's figure-eight

$\iota \approx$ current + rotating ellipticity + axis torsion

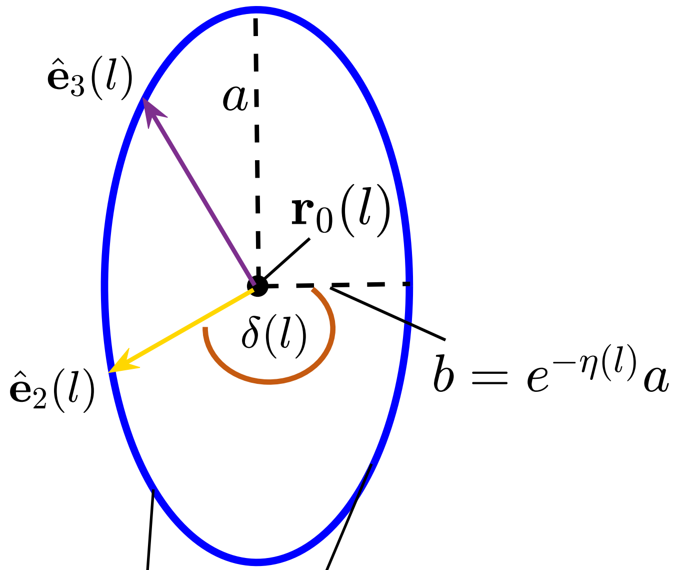


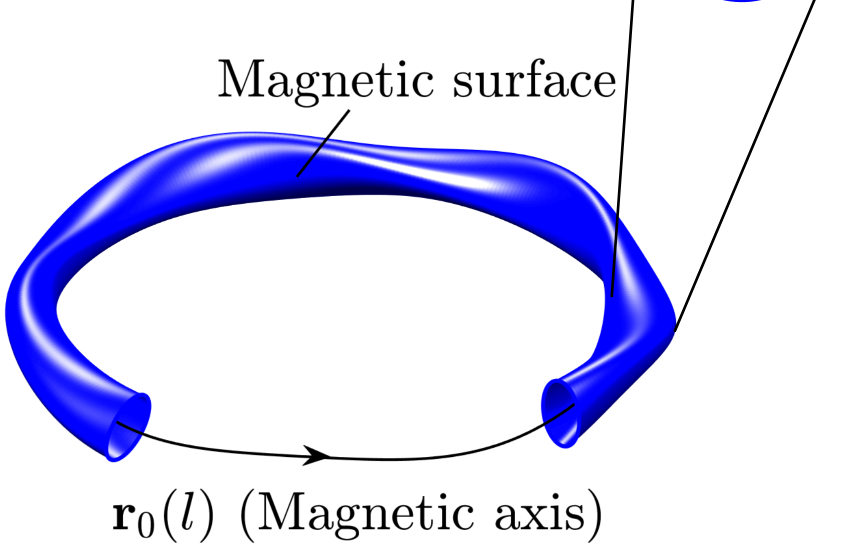
Rotational transform can be generated by symmetry-breaking

Top view



Side view

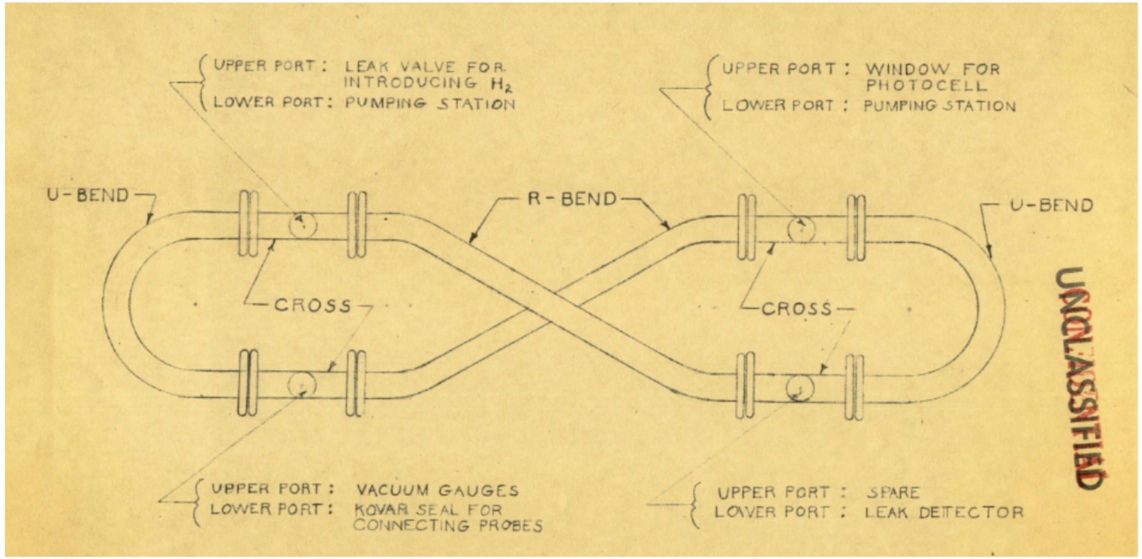




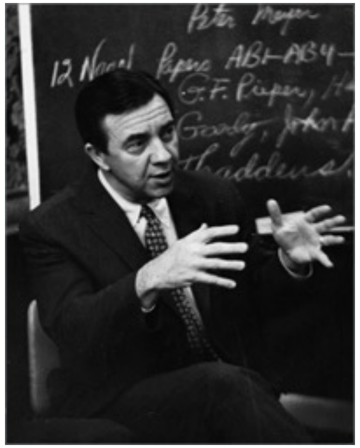
$\iota \approx$ current + rotating ellipticity + axis torsion

This formed the basis for early stellarator experiments

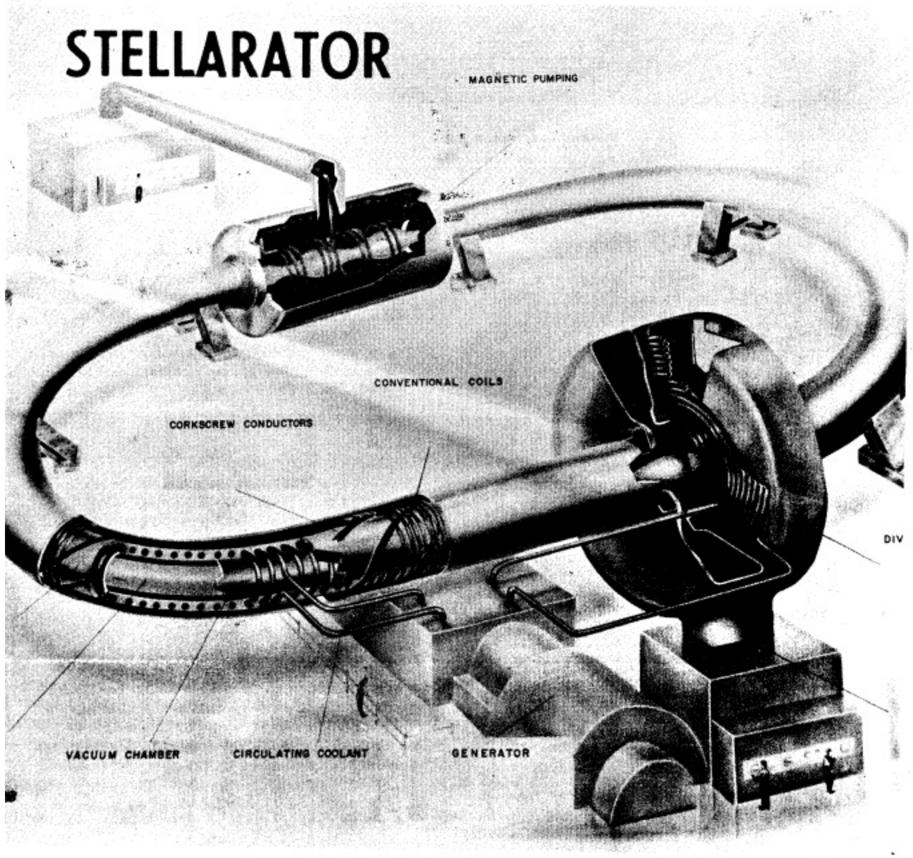
Figure-eight (Princeton Model A) – 1953-1958



C. H. Willis, *NJ Project Matterhorn* (1953).



Racetrack (Princeton Model C) – 1962-1969



The tokamak enters the scene

nature

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

by
N. J. PEACOCK
D. C. ROBINSON
M. J. FORREST
P. D. WILCOCK
UKAEA Research Group,
Culham Laboratory,
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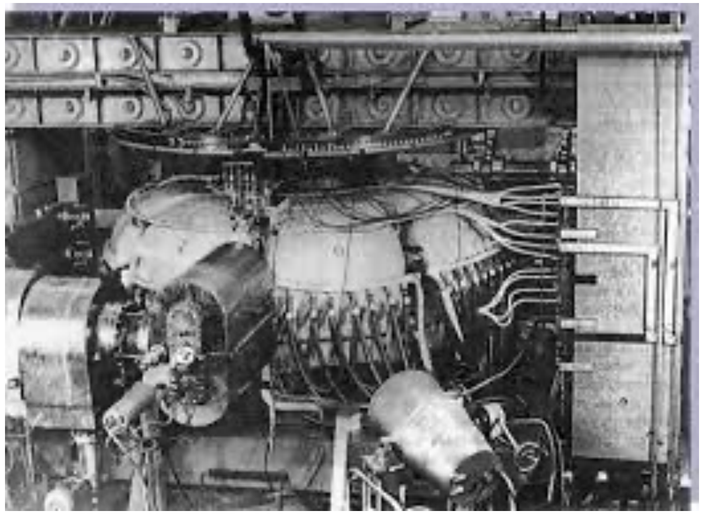
V. V. SANNIKOV
I. V. Kurchatov Institute,
Moscow

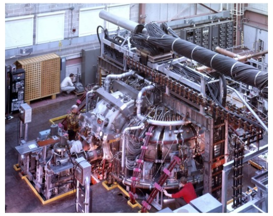
Electron temperatures of 100 eV up to 1 keV and densities in the range $1\text{–}3 \times 10^{13}$ cm^{-3} have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible.



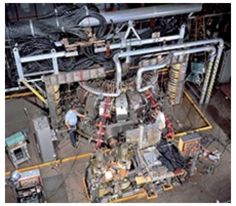
The tokamak enters the scene

Model A/B Stellarators

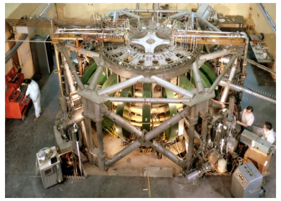
Model C Stellarator



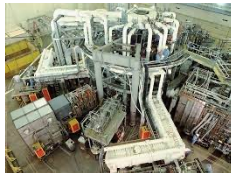
Symmetric Tokamak



Princeton Large Torus



Tokamak Fusion Test Reactor



National Spherical Torus Experiment

1950 1960 1970 1980 1990 2000 2010 2020

nature

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

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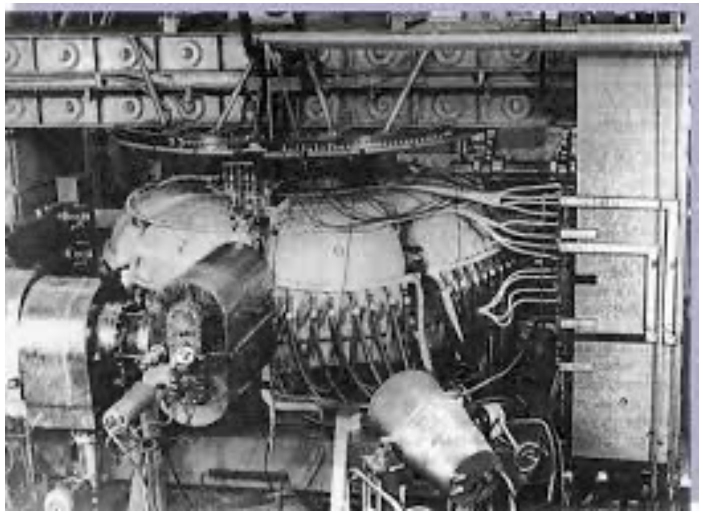
Electron temperatures of 100 eV up to 1 keV and densities in the range 1–3 $\times 10^{13}$ cm^{-3} have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible.



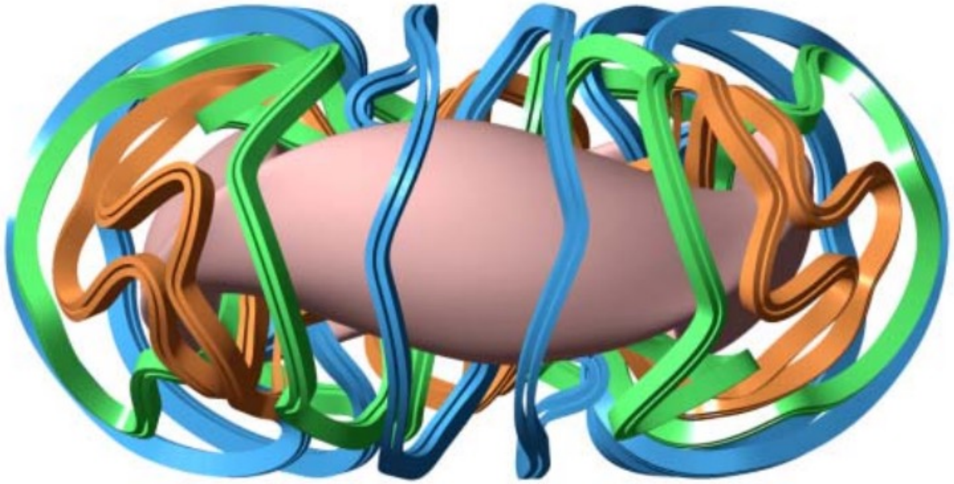
Outline

- Magnetic confinement without symmetry
- **Ingredients of stellarator confinement**
- How do we “cook” a stellarator?
- Stellarators in context

Ingredients of stellarator confinement

Magnetic field integrability

NCSX Modular Coils

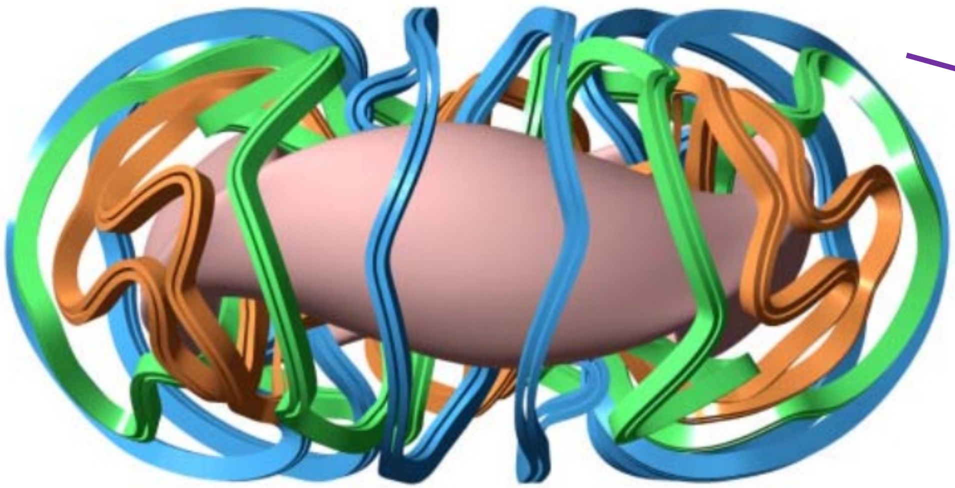


D. Strickler et al, *IAEA* (2004).

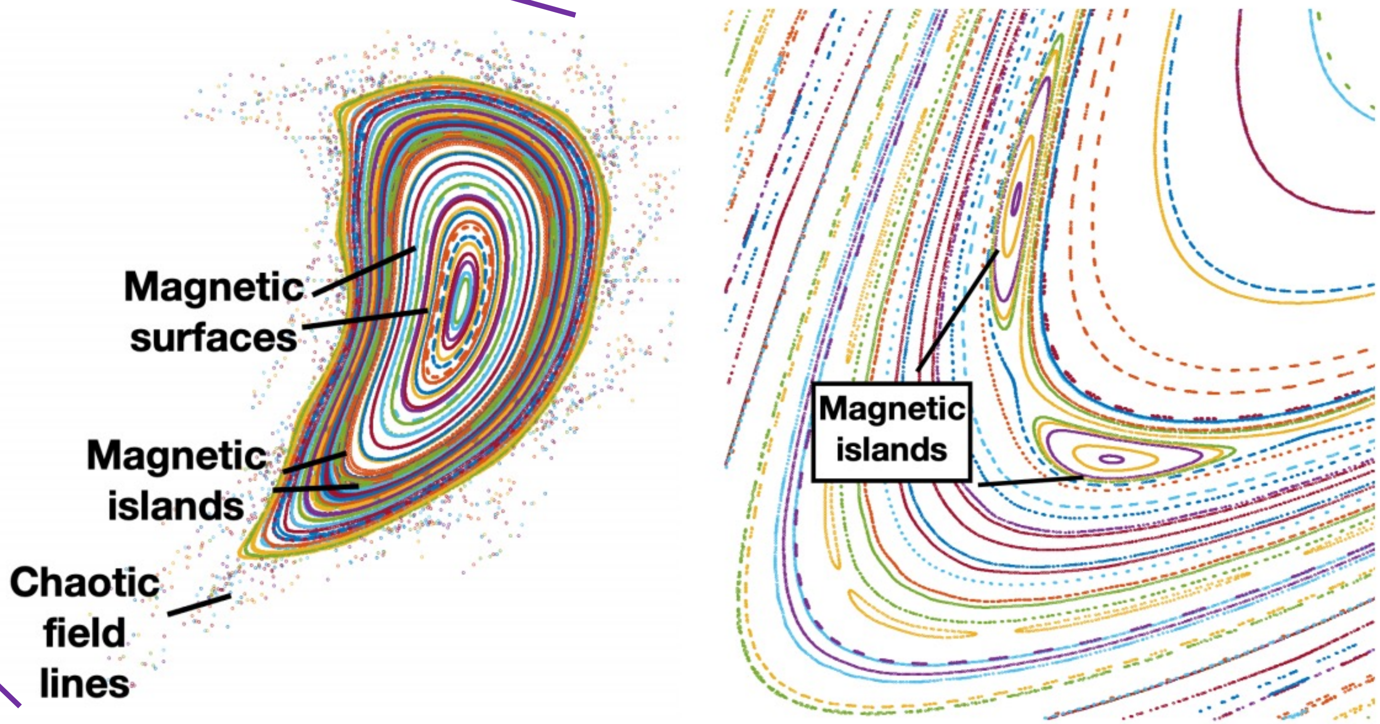
Ingredients of stellarator confinement

Magnetic field integrability

NCSX Modular Coils



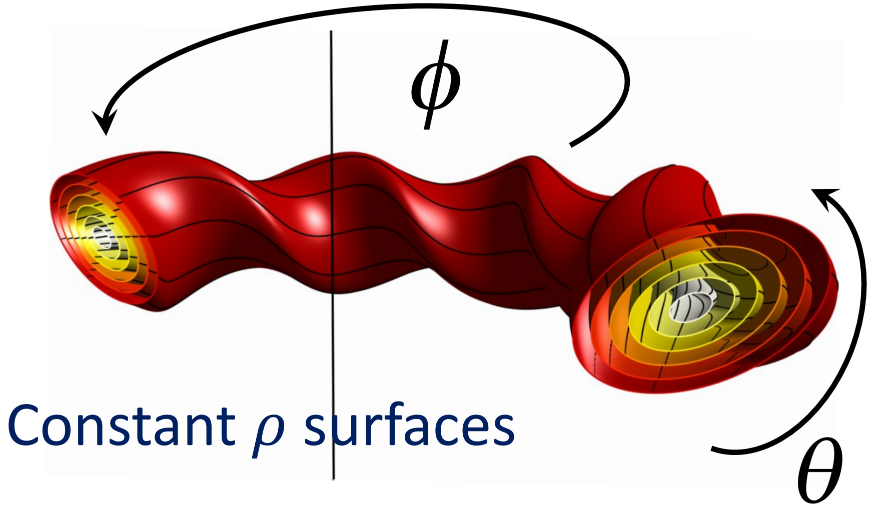
D. Strickler et al, *IAEA* (2004).



Ingredients of stellarator confinement

Magnetic field integrability – Hamiltonian nature of field line flow

$$\boldsymbol{A}(\rho,\theta,\phi) = \rho\nabla\theta - \chi(\rho,\theta,\phi)\nabla\phi$$
$$\boldsymbol{B}(\rho,\theta,\phi) = \nabla\rho\times\nabla\theta - \nabla\chi\times\nabla\phi$$

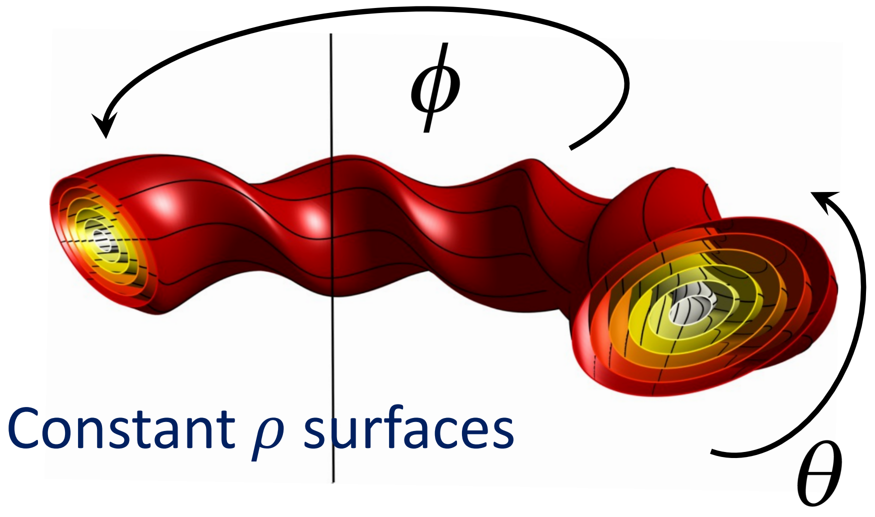


Ingredients of stellarator confinement

Magnetic field integrability – Hamiltonian nature of field line flow

$$\boldsymbol{A}(\rho,\theta,\phi) = \rho\nabla\theta - \chi(\rho,\theta,\phi)\nabla\phi$$
$$\boldsymbol{B}(\rho,\theta,\phi) = \nabla\rho\times\nabla\theta - \nabla\chi\times\nabla\phi$$

$$\frac{d\theta}{d\phi} = \frac{\boldsymbol{B}\cdot\nabla\theta}{\boldsymbol{B}\cdot\nabla\phi} = \frac{\partial\chi(\rho,\theta,\phi)}{\partial\rho}$$
$$\frac{d\rho}{d\phi} = \frac{\boldsymbol{B}\cdot\nabla\rho}{\boldsymbol{B}\cdot\nabla\phi} = -\frac{\partial\chi(\rho,\theta,\phi)}{\partial\theta}$$



Hamiltonian $\rightarrow \chi(\rho,\theta,\phi)$

coordinate $\rightarrow \theta$

momentum $\rightarrow \rho$

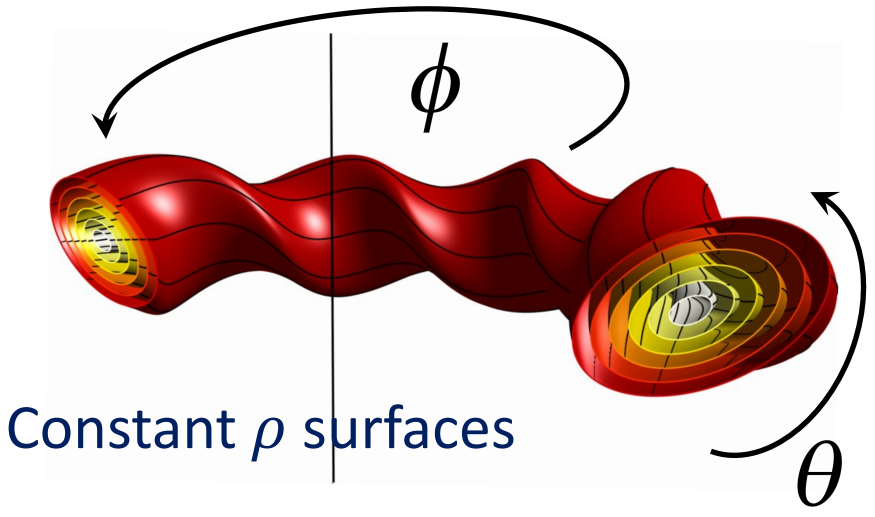
time $\rightarrow \phi$

Ingredients of stellarator confinement

Magnetic field integrability – Hamiltonian nature of field line flow

$$\boldsymbol{A}(\rho,\theta,\phi) = \rho\nabla\theta - \chi(\rho,\theta,\phi)\nabla\phi$$
$$\boldsymbol{B}(\rho,\theta,\phi) = \nabla\,\rho\times\nabla\theta - \nabla\chi\times\nabla\phi$$

$$\frac{d\theta}{d\phi} = \frac{\boldsymbol{B}\cdot\nabla\theta}{\boldsymbol{B}\cdot\nabla\phi} = \frac{\partial\chi(\rho,\theta,\phi)}{\partial\rho}$$
$$\frac{d\rho}{d\phi} = \frac{\boldsymbol{B}\cdot\nabla\rho}{\boldsymbol{B}\cdot\nabla\phi} = -\frac{\partial\chi(\rho,\theta,\phi)}{\partial\theta}$$



Hamiltonian $\rightarrow \chi(\rho,\theta,\phi)$
coordinate $\rightarrow \theta$
momentum $\rightarrow \rho$
time $\rightarrow \phi$

$\frac{\partial\chi(\rho,\theta,\phi)}{\partial\phi} = 0 \rightarrow$ integrability

$\boldsymbol{B}\cdot\nabla\chi = 0 \rightarrow \chi$ is a magnetic surface label

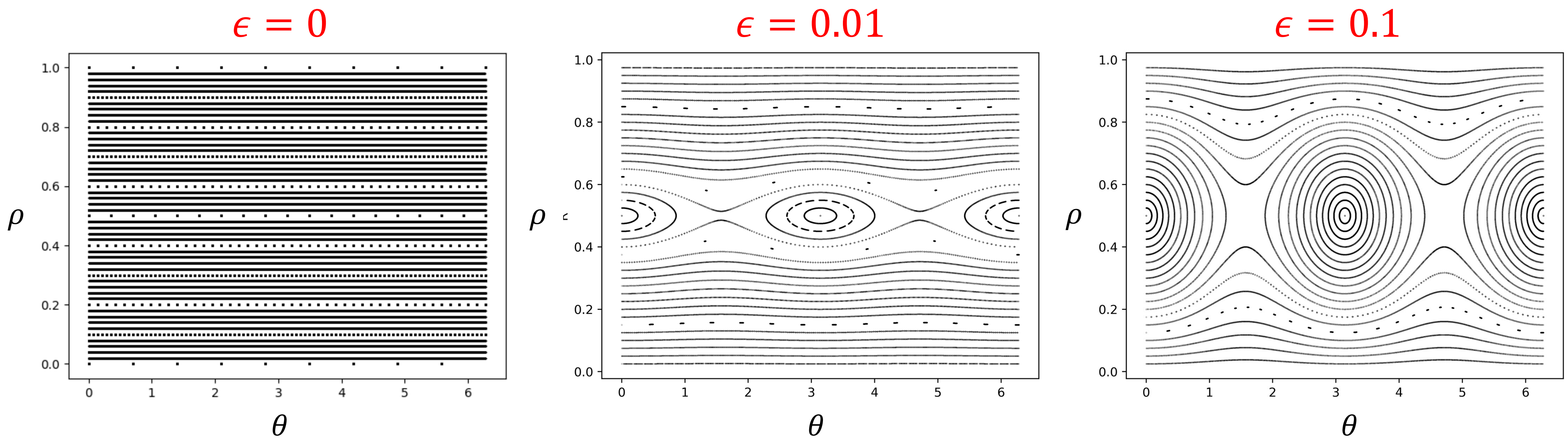
Ingredients of stellarator confinement

Magnetic field integrability – Hamiltonian nature of field line flow

$$\boldsymbol{B}(\rho,\theta,\phi) = \nabla\rho\times\nabla\theta - \nabla\chi(\rho,\theta,\phi)\times\nabla\phi$$

$$\chi(\rho,\theta,\phi) = \frac{1}{2}\rho^2 + \epsilon\cos(2\theta-\phi)$$

Integrable **Non-integrable**



Ingredients of stellarator confinement

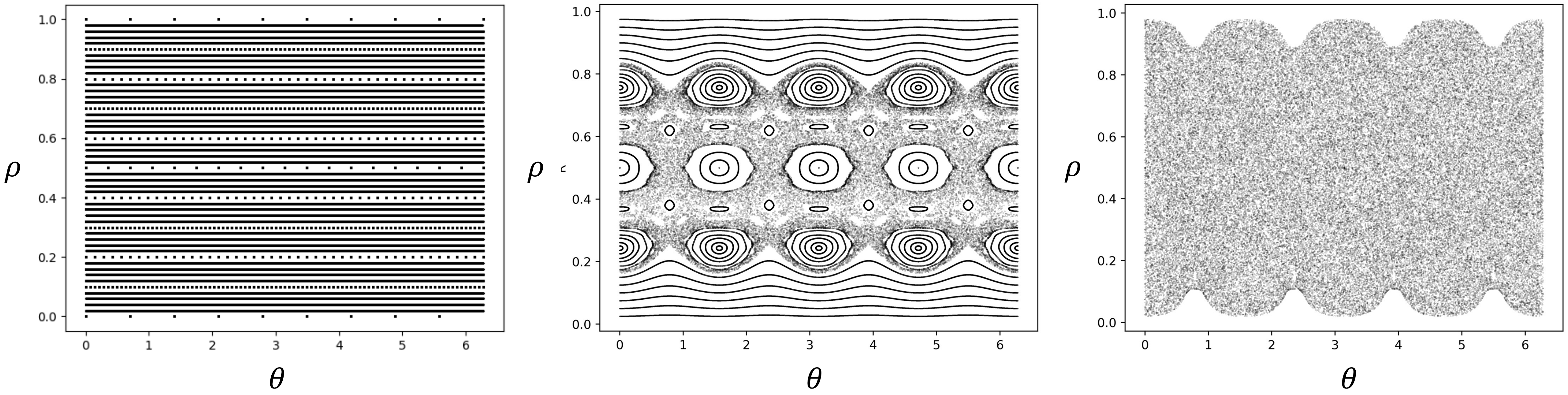
Magnetic field integrability – Hamiltonian nature of field line flow

$$\boldsymbol{B}(\rho,\theta,\phi) = \nabla\rho\times\nabla\theta - \nabla\chi(\rho,\theta,\phi)\times\nabla\phi$$

$$\chi(\rho,\theta,\phi) = \frac{1}{2}\rho^2 + \epsilon\left[\cos(4\theta-\phi) + \cos(4\theta-2\phi) + \cos(4\theta-3\phi)\right]$$

Integrable **Non-integrable**

$\epsilon = 0$ $\epsilon = 0.01$ $\epsilon = 0.1$

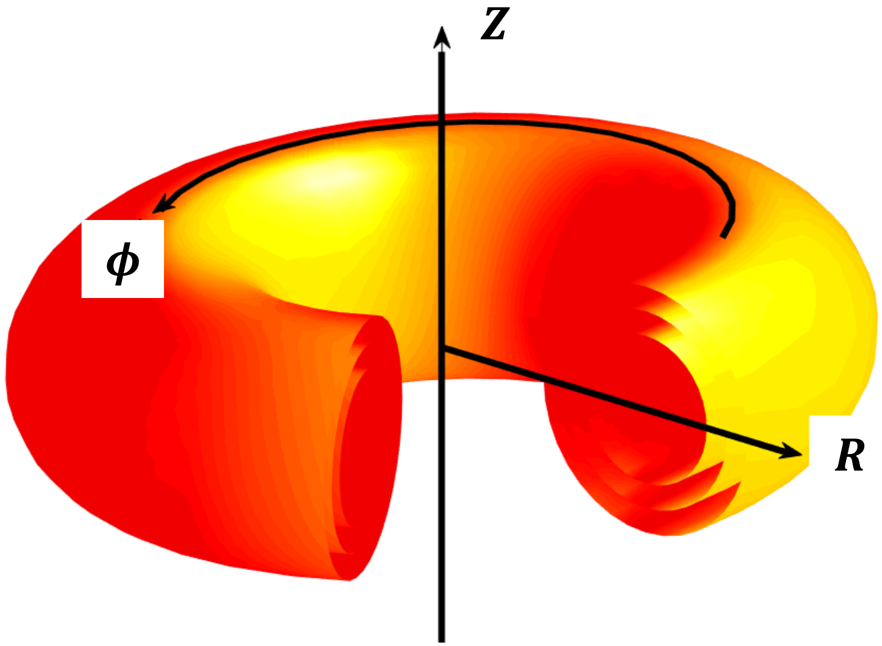


Continuous toroidal symmetry yields particle confinement

Single-particle Lagrangian

$$\mathcal{L}(\boldsymbol{x}, \dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + q\boldsymbol{A}(\boldsymbol{x}) \cdot \dot{\boldsymbol{x}}$$

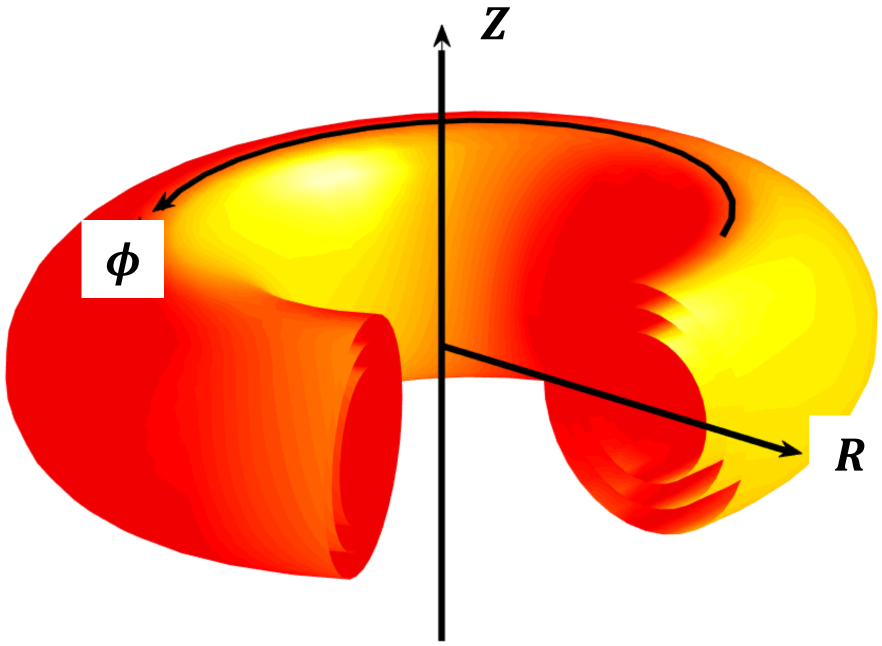
$$\frac{d}{dt}\left(\frac{\partial\mathcal{L}(R,\phi,Z,\dot{R},\dot{\phi},\dot{Z},t)}{\partial\dot{\phi}}\right) = \frac{\partial\mathcal{L}(R,\phi,Z,\dot{R},\dot{\phi},\dot{Z},t)}{\partial\phi}$$



Continuous toroidal symmetry yields particle confinement

Single-particle Lagrangian

$$\mathcal{L}(\boldsymbol{x}, \dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + qA(\boldsymbol{x}) \cdot \dot{\boldsymbol{x}}$$



$$\frac{d}{dt}\underbrace{\left(\frac{\partial \mathcal{L}(R, \phi, Z, \dot{R}, \dot{\phi}, \dot{Z}, t)}{\partial \dot{\phi}}\right)}_{p_\phi} = \cancel{\frac{\partial \mathcal{L}(R, \phi, Z, \dot{R}, \dot{\phi}, \dot{Z}, t)}{\partial \phi}}$$

Toroidal symmetry

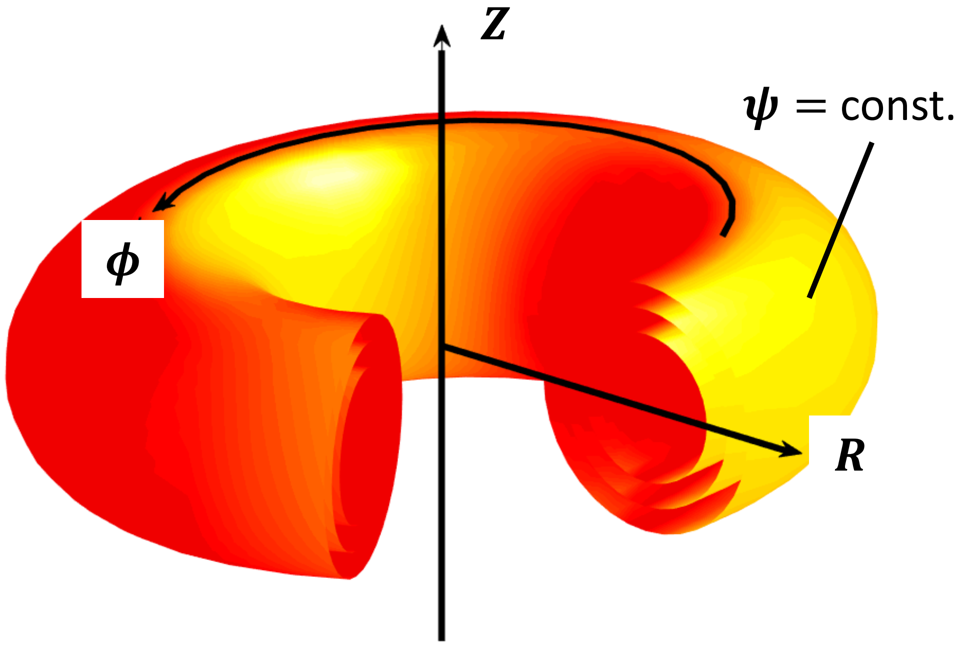
Continuous toroidal symmetry yields particle confinement

Single-particle Lagrangian

$$\mathcal{L}(\boldsymbol{x}, \dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + qA(\boldsymbol{x}) \cdot \dot{\boldsymbol{x}}$$

$$\frac{d}{dt}\underbrace{\left(\frac{\partial\mathcal{L}(R,\phi,Z,\dot{R},\dot{\phi},\dot{Z},t)}{\partial\dot{\phi}}\right)}_{p_\phi \approx \psi} = \cancel{\frac{\partial\mathcal{L}(R,\phi,Z,\dot{R},\dot{\phi},\dot{Z},t)}{\partial\phi}}$$

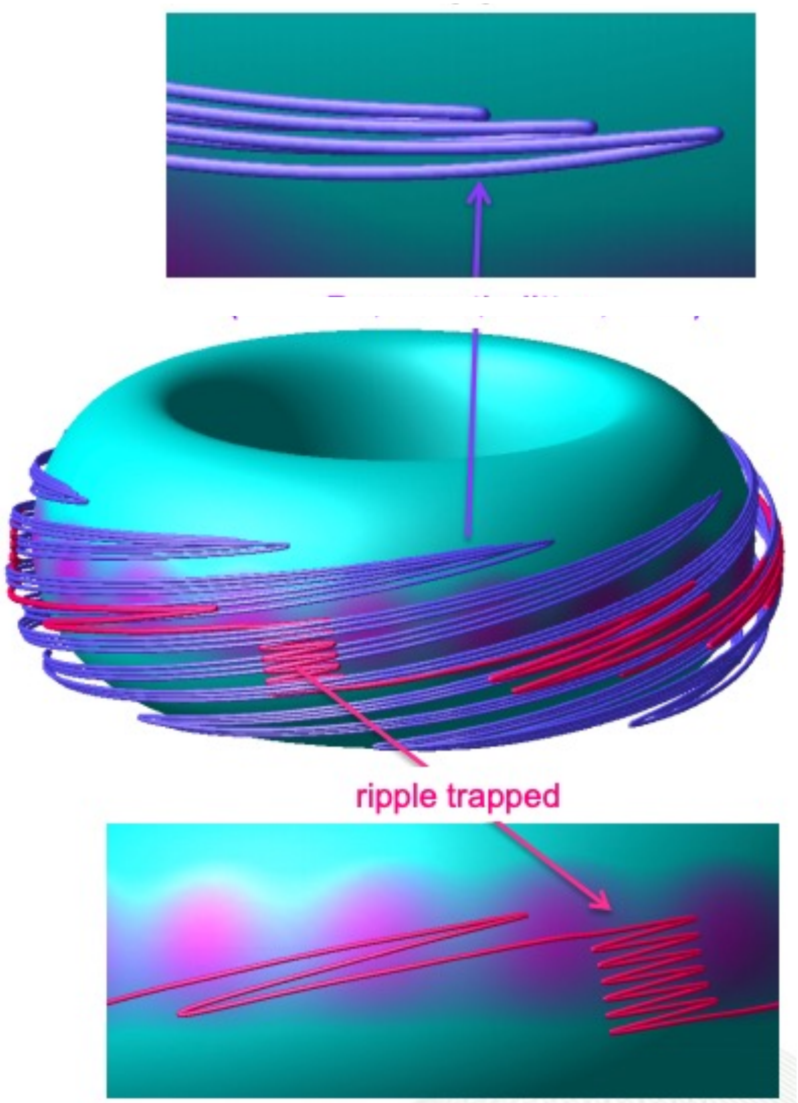
Toroidal symmetry



Confinement to ψ surfaces!

The zoology of particle orbits in 3D fields

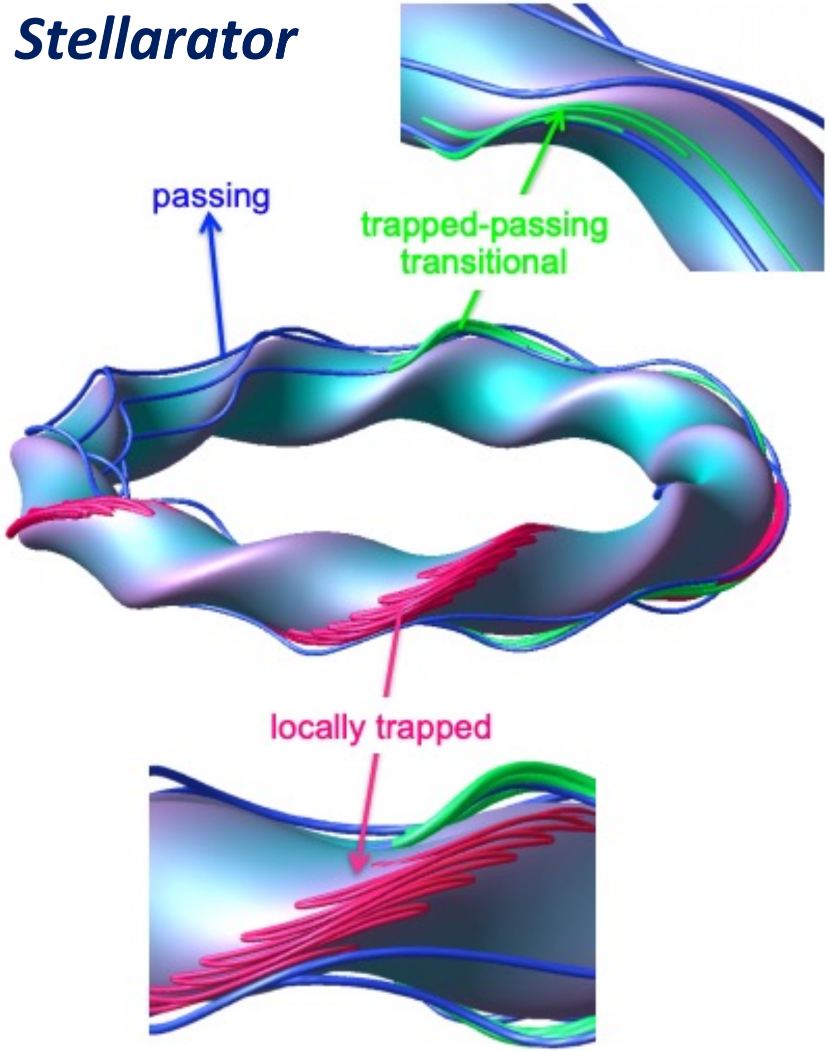
Perturbed tokamak



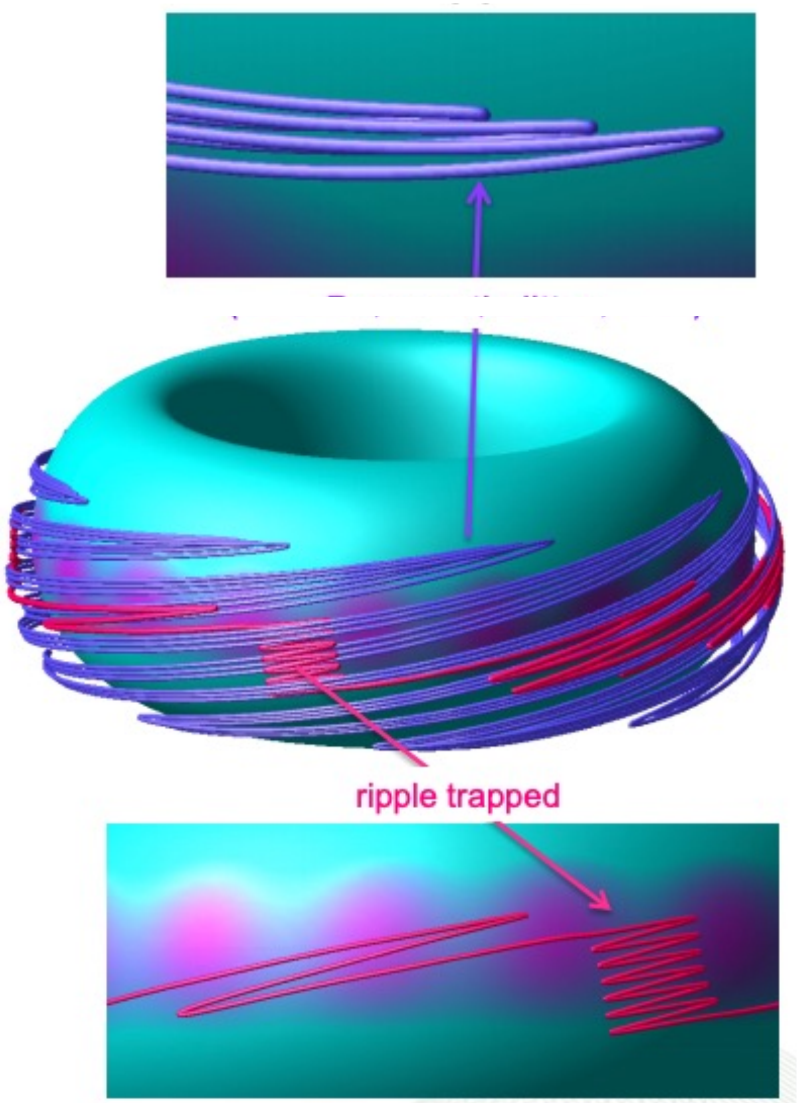
D.A. Spong et al, *APS DPP* (2014).

The zoology of particle orbits in 3D fields

Stellarator



Perturbed tokamak



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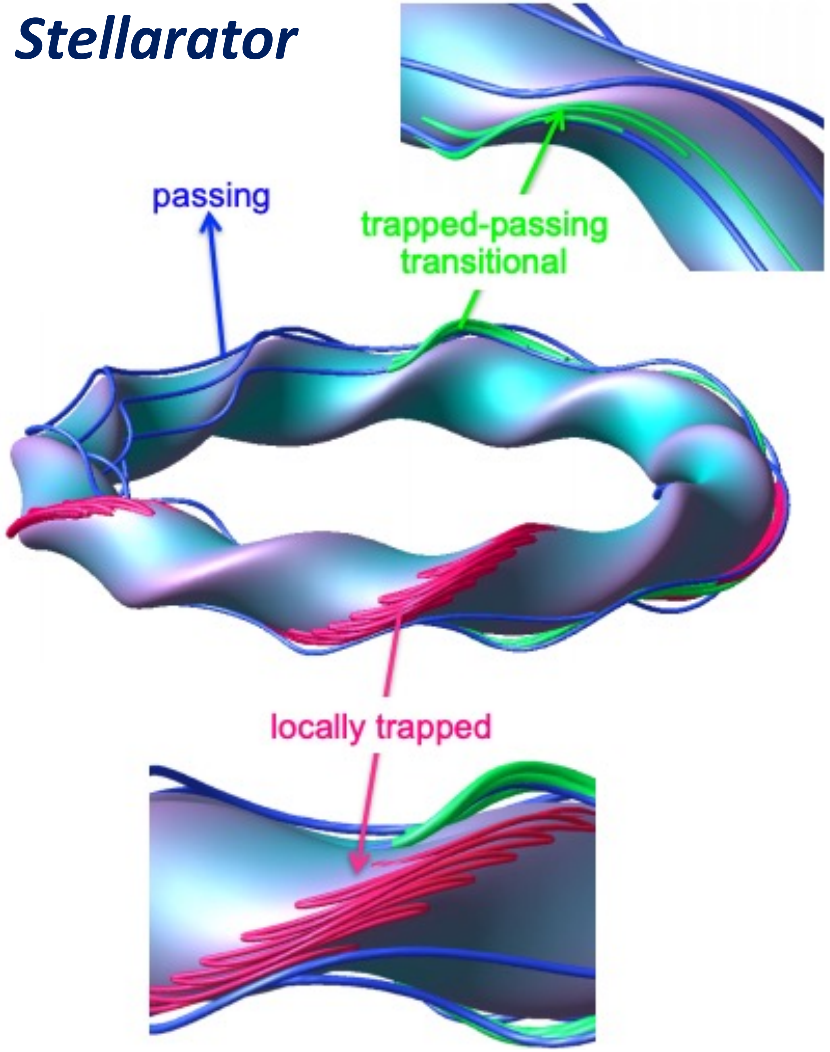
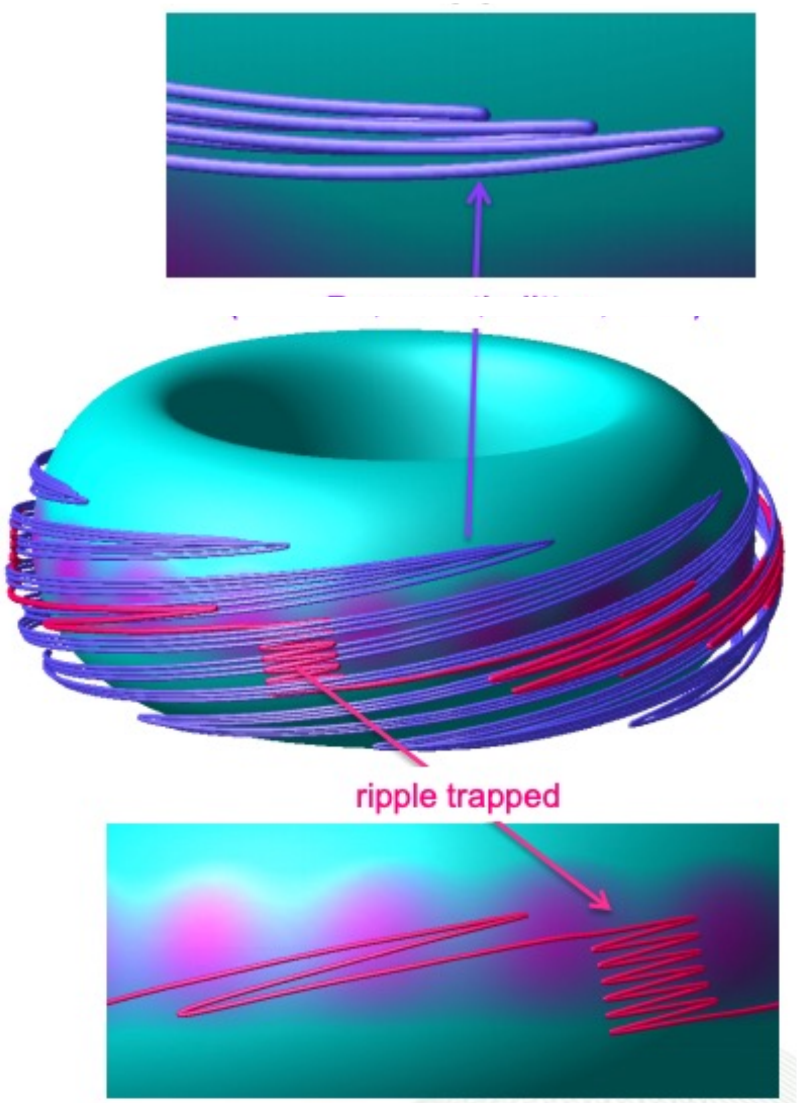
The zoology of particle orbits in 3D fields

Stellarator



Perturbed tokamak

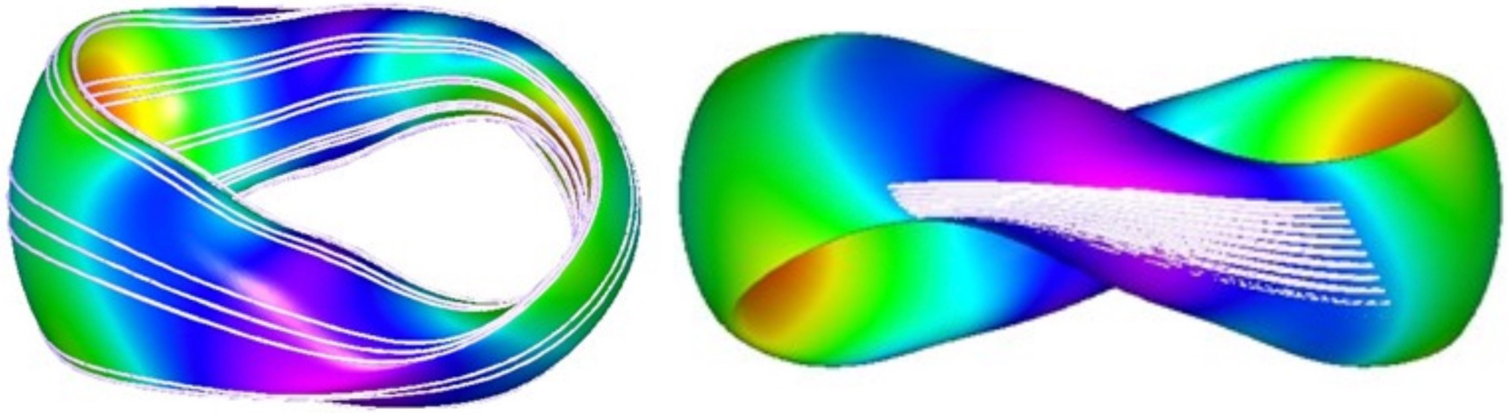


Can we confine them all?

D.A. Spong et al, *APS DPP* (2014).

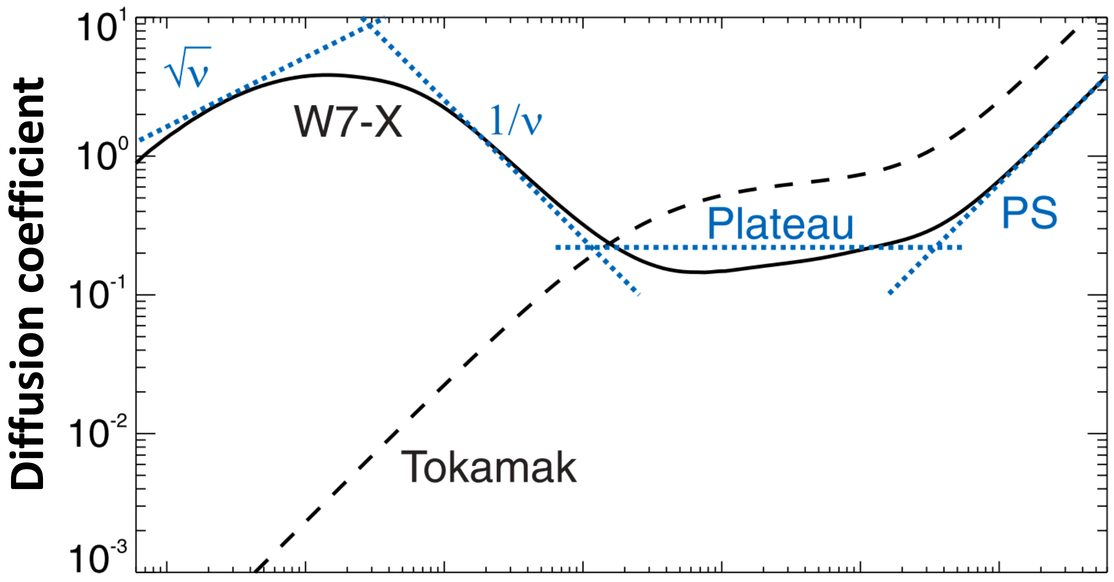
Ingredients of stellarator confinement

Collisional guiding center confinement



D.A. Spong et al, *IAEA* (2003).

P. Helander, *Rep. Prog. Phys.*, 77 (2014).



$$\nu_* = \nu R/(\iota v)$$

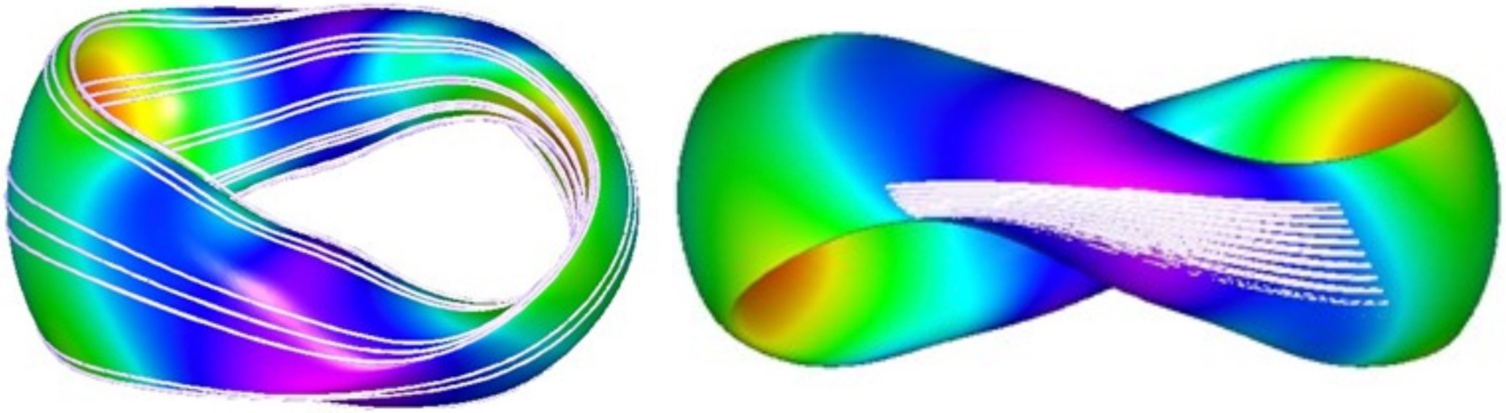
"drift kinetic equation"

$$(v_{||}\hat{\boldsymbol{b}} + \boldsymbol{v}_{\mathrm{drift}}) \cdot \nabla f = C(f)$$

Guiding center motion **Collisions**

Ingredients of stellarator confinement

Collisional guiding center confinement



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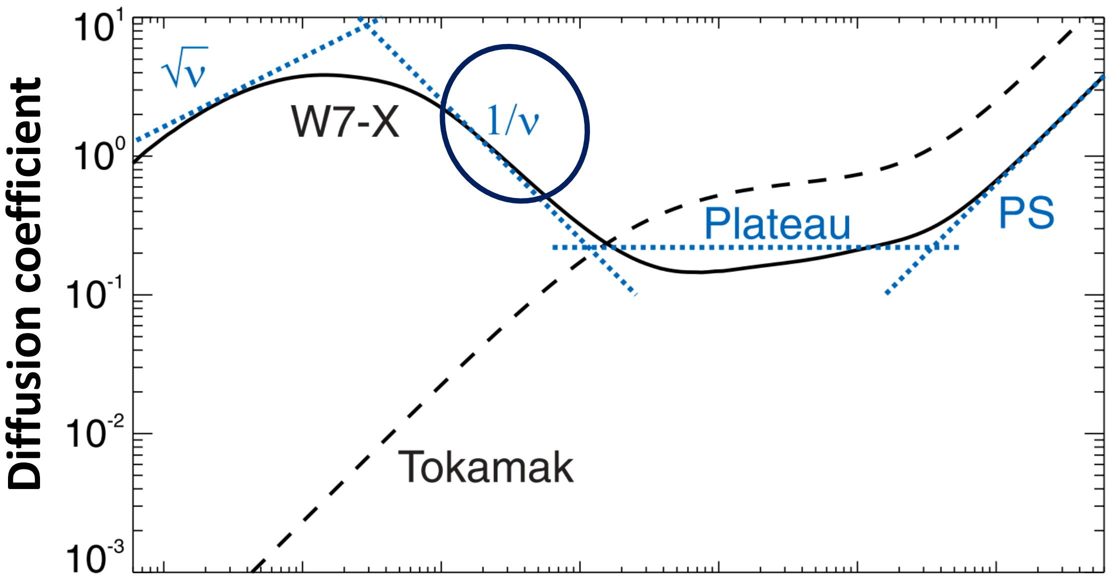
P. Helander, *Rep. Prog. Phys.*, 77 (2014).



$\nu_* = \nu R/(\iota v)$

$$D \sim \frac{\Delta r^2}{\Delta t} \sim \frac{\left(\boldsymbol{v}_{\mathrm{drift}} \cdot \nabla r/\nu\right)^2}{1/\nu} \propto T^{7/2}$$

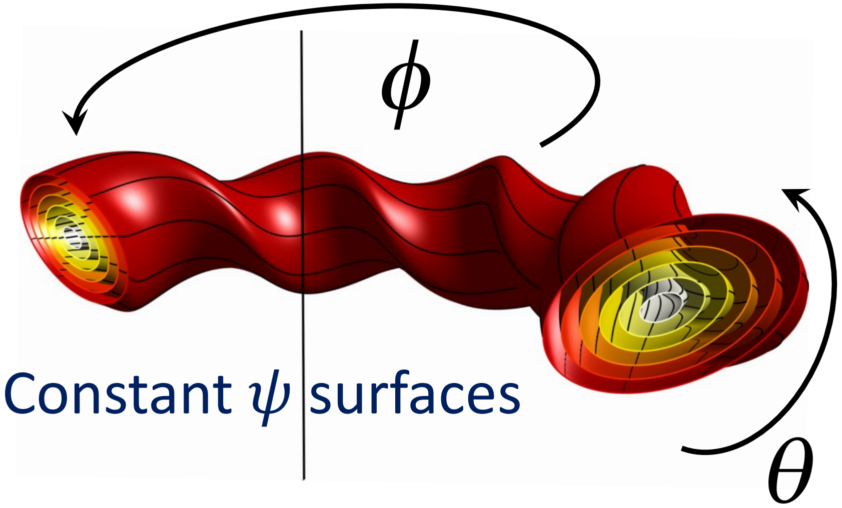
$$(v_{||}\hat{\boldsymbol{b}} + \boldsymbol{v}_{\mathrm{drift}}) \cdot \nabla f = C(f)$$

Symmetry of field strength yields particle confinement in 3D

$$\mathcal{L}(\boldsymbol{x}, \dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + q\boldsymbol{A}(\boldsymbol{x}) \cdot \dot{\boldsymbol{x}}$$

$\Big\downarrow$ **Strongly magnetized**

$$\mathcal{L}\big(\psi, \theta, \phi, \dot{\psi}, \dot{\theta}, \dot{\phi}\big) = \mathcal{L}\big(\psi, \color{red}{B(\psi, \theta, \phi)}, \dot{\psi}, \dot{\theta}, \dot{\phi}\big)$$

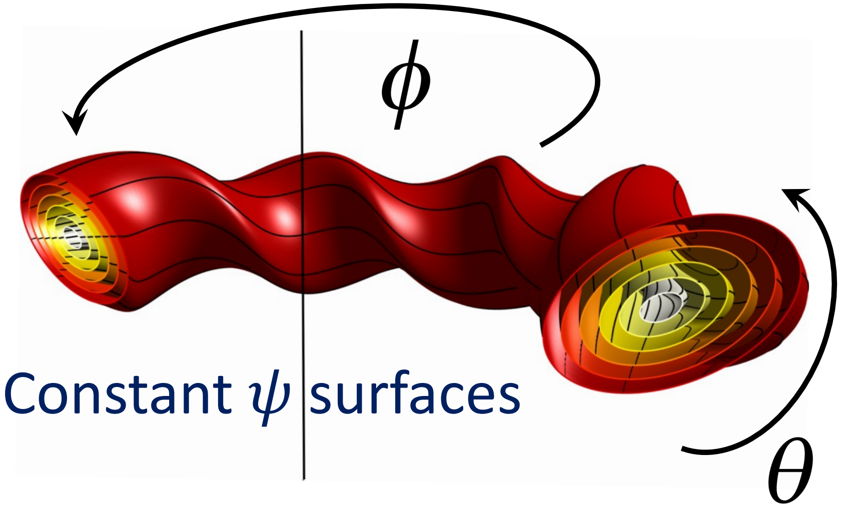


Symmetry of field strength yields particle confinement in 3D

$$\mathcal{L}(\boldsymbol{x}, \dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + q\boldsymbol{A}(\boldsymbol{x}) \cdot \dot{\boldsymbol{x}}$$

Strongly magnetized

$$\mathcal{L}\left(\psi, \theta, \phi, \dot{\psi}, \dot{\theta}, \dot{\phi}\right) = \mathcal{L}\left(\psi, B(\psi, \theta, \phi), \dot{\psi}, \dot{\theta}, \dot{\phi}\right)$$



$$\frac{\partial B(\psi, \theta, \phi)}{\partial \phi} = 0 \longrightarrow \frac{dp_\phi}{dt} = 0$$

Ignorable coordinate

Conserved momentum

Symmetry of field strength yields particle confinement in 3D

$$\mathcal{L}(\boldsymbol{x},\dot{\boldsymbol{x}}) = m\frac{|\dot{\boldsymbol{x}}|^2}{2} + q\boldsymbol{A}(\boldsymbol{x})\cdot\dot{\boldsymbol{x}}$$

Strongly magnetized

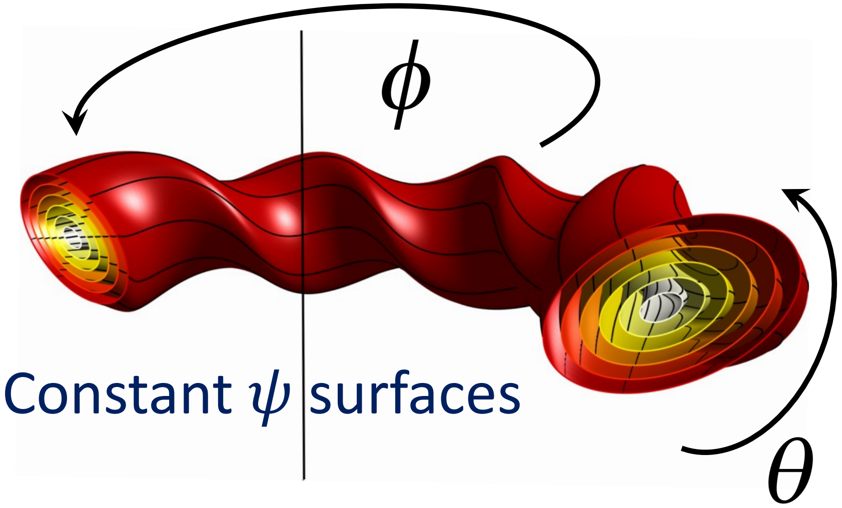
$$\mathcal{L}\big(\psi,\theta,\phi,\dot\psi,\dot\theta,\dot\phi\big) = \mathcal{L}\big(\psi,{\color{red}B(\psi,\theta,\phi)},\dot\psi,\dot\theta,\dot\phi\big)$$

$$\frac{\partial B(\psi,\theta,\phi)}{\partial\phi} = 0 \longrightarrow \frac{dp_\phi}{dt} = 0$$

Ignorable coordinate **Conserved momentum**

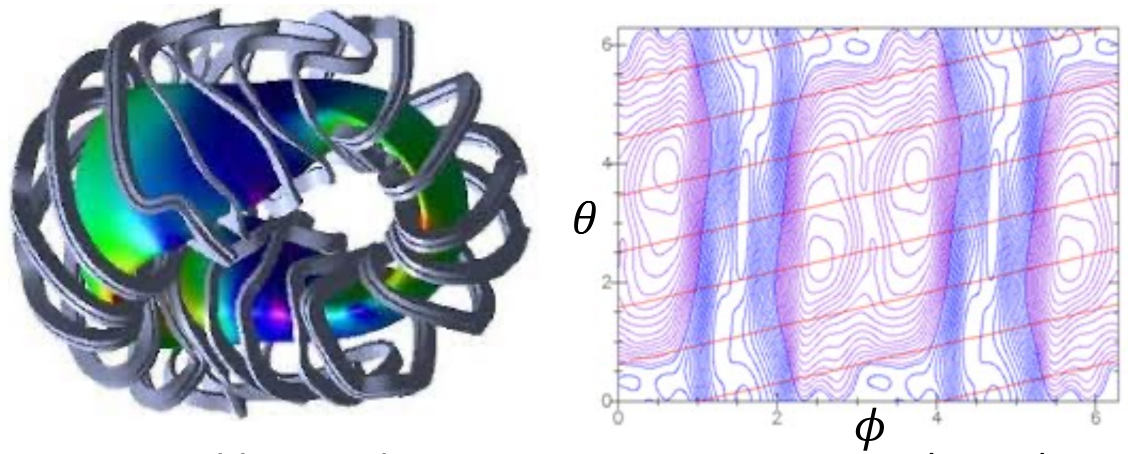
$$p_\phi = \cancel{\frac{mv_\phi}{qB}} + \underbrace{F(\psi)}$$

Particles stay confined to ψ surfaces



Quasisymmetry - a hidden symmetry of magnetic fields

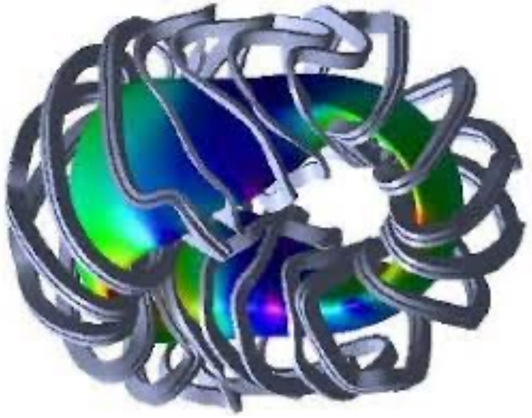
Quasi-poloidal symmetry

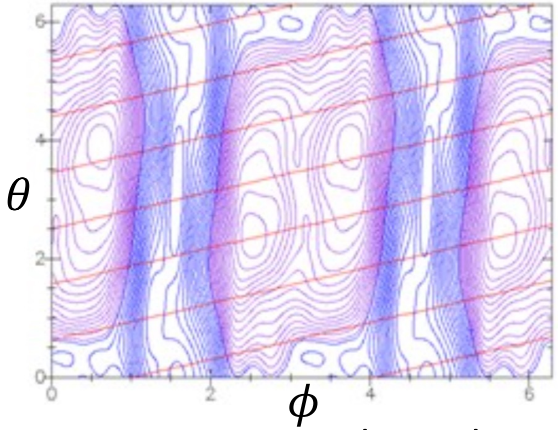


D. Strickler et al, *Fusion Eng. & Design,* 66 (2003).

Quasisymmetry - a hidden symmetry of magnetic fields

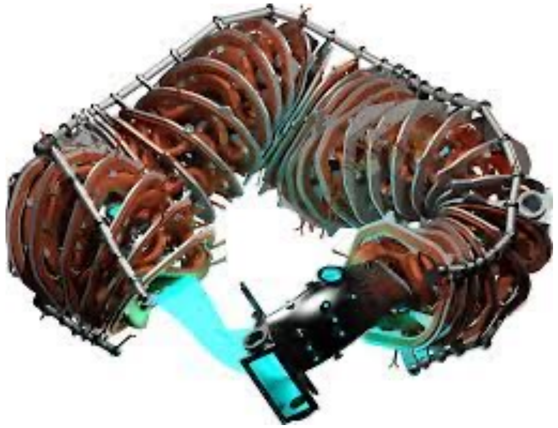
Quasi-poloidal symmetry

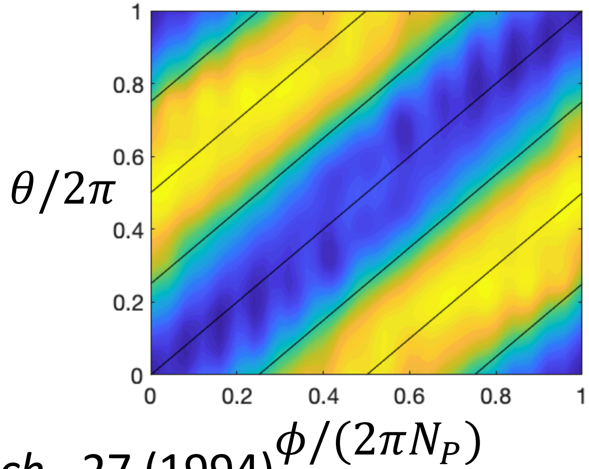




D. Strickler et al, *Fusion Eng. & Design,* 66 (2003).

Quasi-helical symmetry

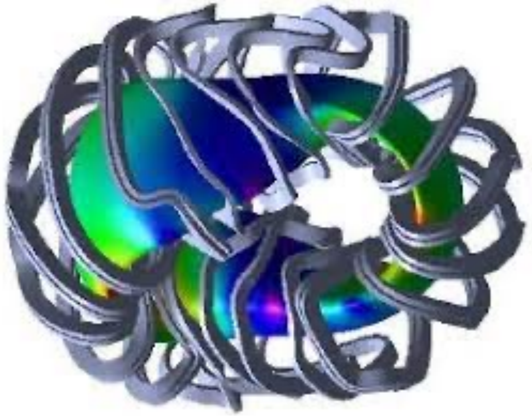


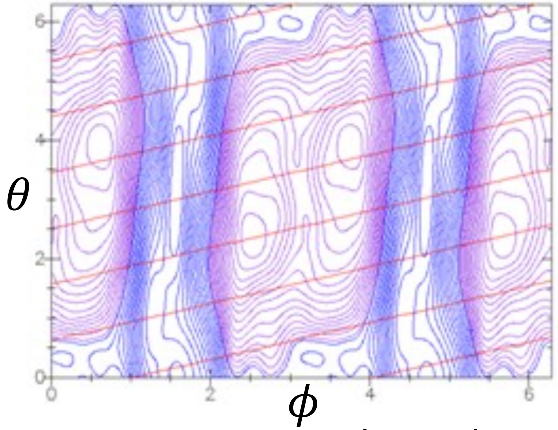


F. Anderson et al, *Fusion Tech.,* 27 (1994).

Quasisymmetry - a hidden symmetry of magnetic fields

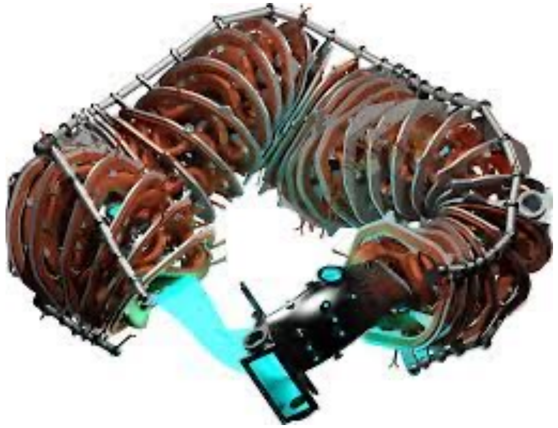
Quasi-poloidal symmetry

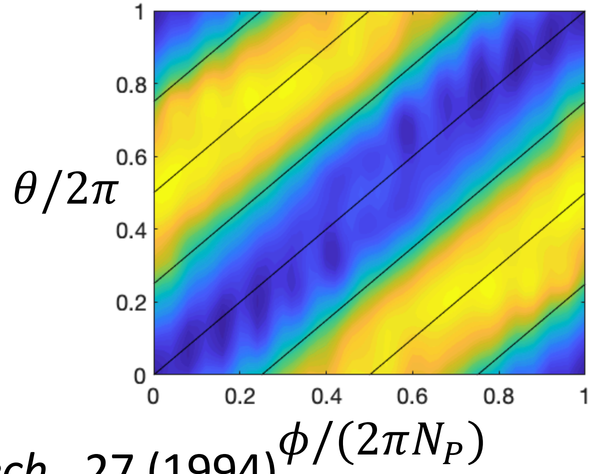




D. Strickler et al, *Fusion Eng. & Design,* 66 (2003).

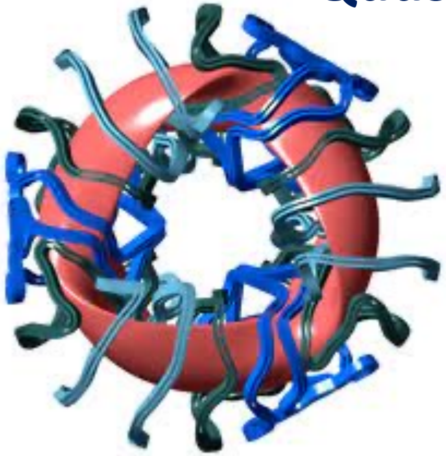
Quasi-helical symmetry

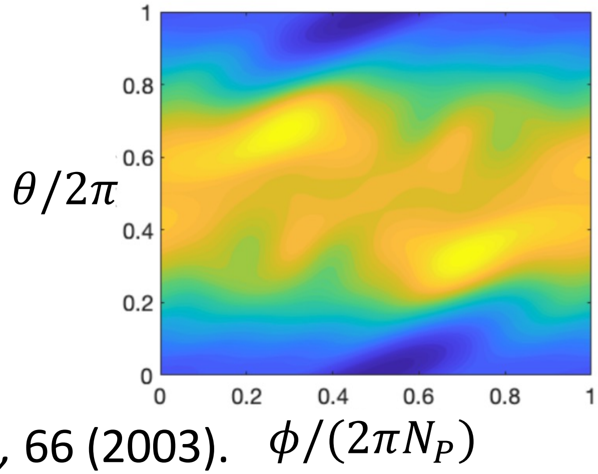




F. Anderson et al, *Fusion Tech.,* 27 (1994).

Quasi-axisymmetry





B. Nelson et al, *Fusion Eng. & Design,* 66 (2003).

Ingredients of stellarator confinement

…and many more

- ✓MHD stability
- ✓Collisional “bootstrap” current
- ✓Energetic particle confinement
- ✓Equilibrium β limit
- ✓Divertor configuration
- ✓Reduction of turbulent transport
- ✓Coil feasibility

Ingredients of stellarator confinement

…and many more

- ✓MHD stability
- ✓Collisional “bootstrap” current
- ✓Energetic particle confinement
- ✓Equilibrium β limit
- ✓Divertor configuration
- ✓Reduction of turbulent transport
- ✓**Coil feasibility**

ASG Superconductors

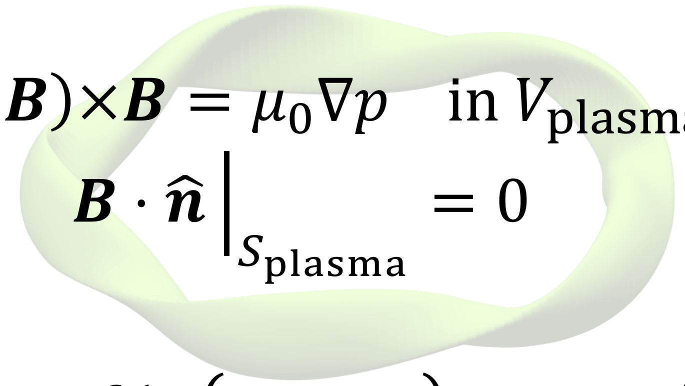
Outline

- Magnetic confinement without symmetry
- Ingredients of stellarator confinement
- **How do we “cook” a stellarator?**
- Stellarators in context

Traditional two-step optimization

1. MHD equilibrium optimization

Boundary of equilibrium optimized for confinement



$$(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \mu_0 \nabla p \quad \text{in } V_{\text{plasma}}$$

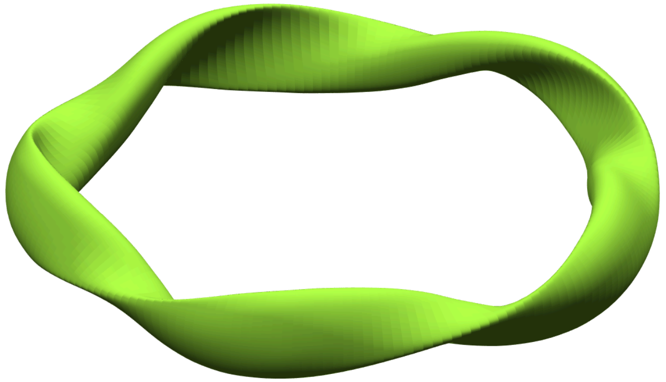
$$\boldsymbol{B} \cdot \hat{\boldsymbol{n}} \Big|_{S_{\text{plasma}}} = 0$$

$$\min_{S_{\text{plasma}}} f\left(\boldsymbol{B}\left(S_{\text{plasma}}\right), S_{\text{plasma}}\right)$$

Traditional two-step optimization

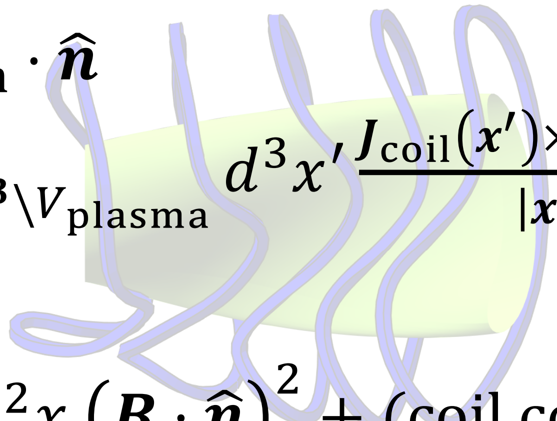
1. MHD equilibrium optimization

Boundary of equilibrium optimized for confinement



2. Coil design

Inverse problem solved to find coils to support equilibrium



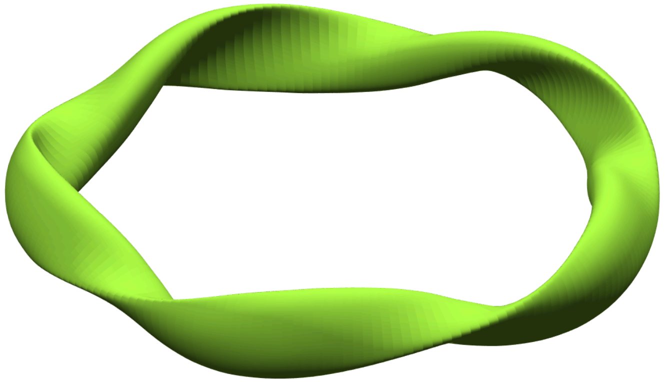
$$\boldsymbol{B}\cdot\hat{\boldsymbol{n}} = \boldsymbol{B}_{\text{plasma}}\cdot\hat{\boldsymbol{n}} + \frac{\mu_0}{4\pi}\int_{\mathbb{R}^3\setminus V_{\text{plasma}}} d^3x' \frac{\boldsymbol{J}_{\text{coil}}(\boldsymbol{x}')\times(\boldsymbol{x}-\boldsymbol{x}')\cdot\hat{\boldsymbol{n}}(\boldsymbol{x})}{|\boldsymbol{x}-\boldsymbol{x}'|^3}$$

$$\min_{\boldsymbol{J}_{\text{coil}}}\left(\int_{S_{\text{plasma}}} d^2x\,(\boldsymbol{B}\cdot\hat{\boldsymbol{n}})^2 + (\text{coil complexity})\right)$$

Traditional two-step optimization

1. MHD equilibrium optimization

Boundary of equilibrium optimized for confinement



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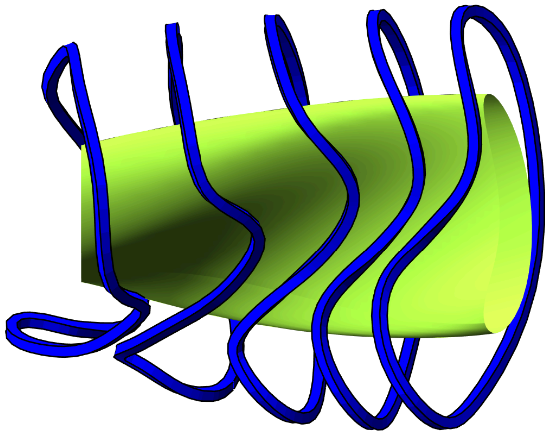
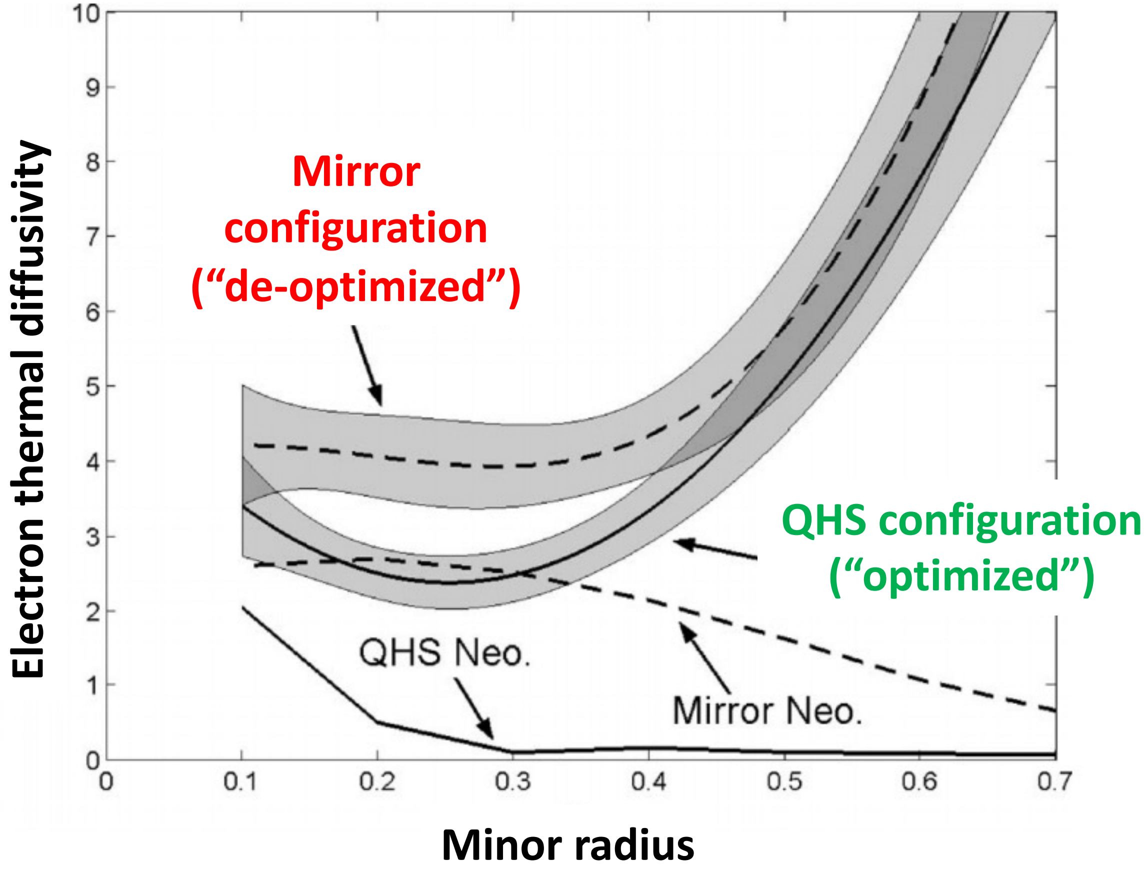


Stellarator optimization has been experimentally verified

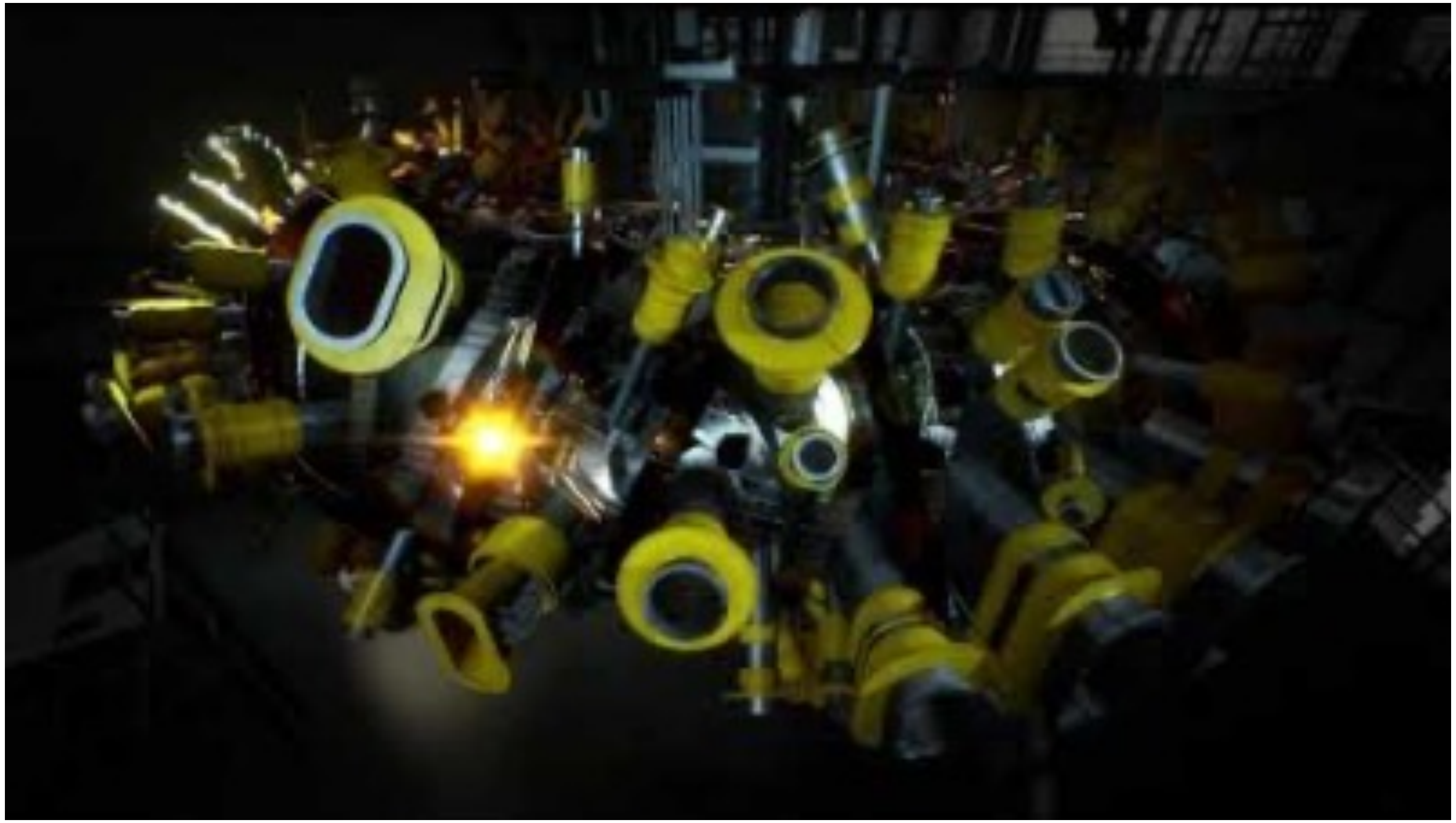
Helically Symmetric Experiment (HSX)



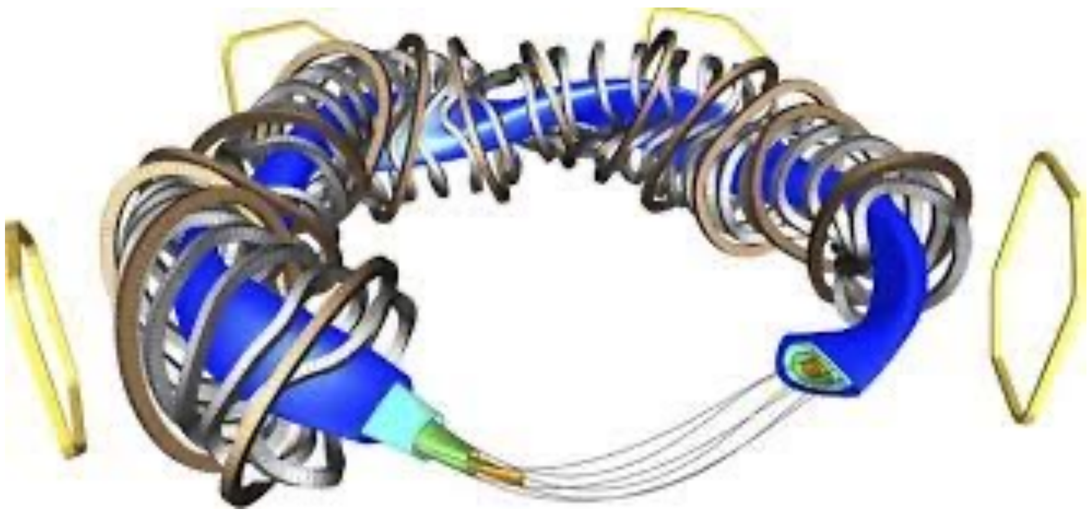
J. M. Canik et al, *Phys. Plasmas* 14, (2007).

Stellarator optimization at scale – Wendelstein 7-X

- ✓ Stable equilibria up to $\beta = \frac{p}{B^2/2\mu_0} = 5\%$
- ✓ Improved particle confinement
- ✓ Reduced plasma current



Stellarator optimization at scale – Wendelstein 7-X



nature

Article

Demonstration of reduced neoclassical energy transport in Wendelstein 7-X

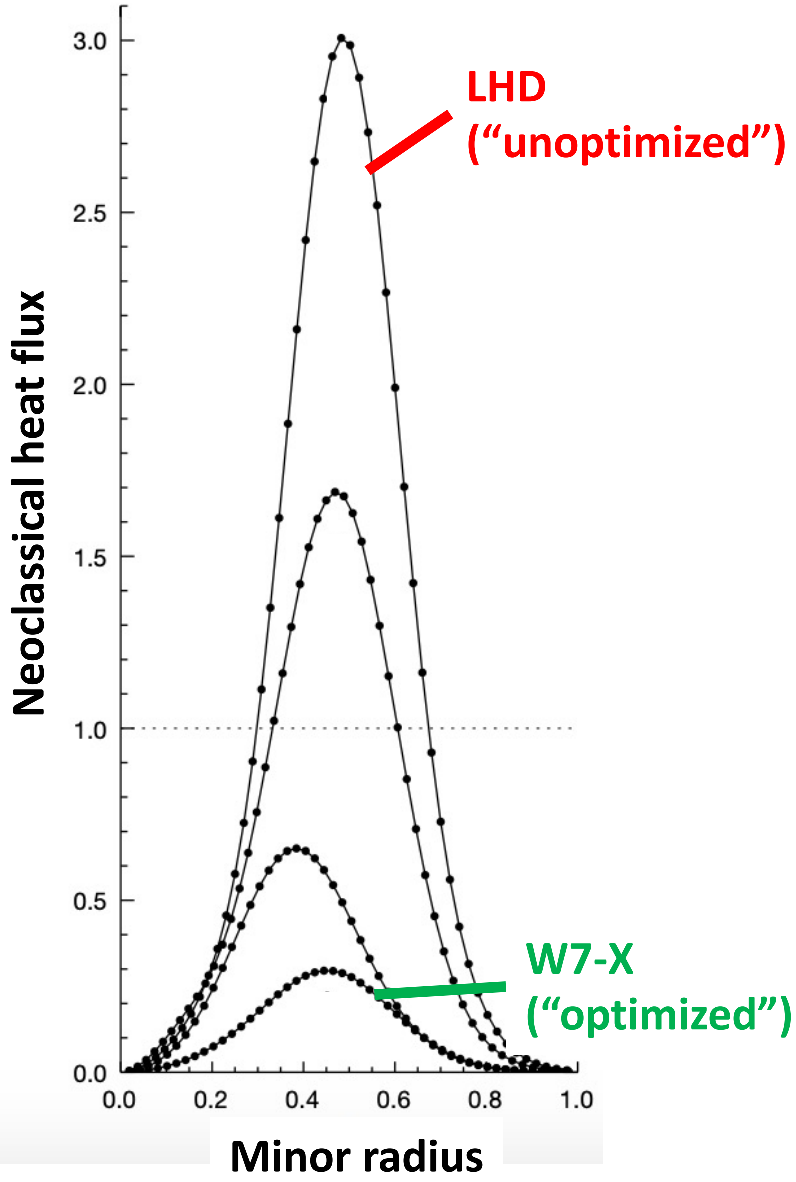
https://doi.org/10.1038/s41586-021-03687-w

Received: 30 April 2020

Accepted: 2 June 2021

Published online: 11 August 2021

C. D. Beidler[1✉], H. M. Smith[1], A. Alonso[2], T. Andreeva[1], J. Baldzuhn[1], M. N. A. Beurskens[1], M. Borchardt[1], S. A. Bozhenkov[1], K. J. Brunner[1], H. Damm[1], M. Drevlak[1], O. P. Ford[1], G. Fuchert[1], J. Geiger[1], P. Helander[1], U. Hergenhahn[1,5], M. Hirsch[1], U. Höfel[1], Ye. O. Kazakov[3], R. Kleiber[1], M. Krychowiak[1], S. Kwak[1], A. Langenberg[1], H. P. Laqua[1], U. Neuner[1], N. A. Pablant[4], E. Pasch[1], A. Pavone[1], T. S. Pedersen[1], K. Rahbarnia[1], J. Schilling[1], E. R. Scott[1], T. Stange[1], J. Svensson[1], H. Thomsen[1], Y. Turkin[1], F. Warmer[1], R. C. Wolf[1], D. Zhang[1] & the W7-X Team*



Outline

- Magnetic confinement without symmetry
- Ingredients of stellarator confinement
- How do we “cook” a stellarator?
- **Stellarators in context**

Stellarators in context

Overview of stellarators & tokamaks

Tokamaks

- ✓ Automatic guiding center confinement
- ✓ Automatic integrability
- ✓ “Simpler” design
- ✗ Requires large plasma current
- ✗ Steady-state is challenging/inefficient

Stellarators

- ✗ Confinement optimization required
- ✗ Shaping by complicated coils/magnets
- ✓ Low recirculating power
- ✓ No plasma-terminating disruptions
- ✓ No Greenwald density limit
- ✓ “softer” pressure/β limit

Plasma Phys. Control. Fusion **54** (2012) 124009 (12pp) doi:10.1088/0741-3335/54/12/124009

Stellarator and tokamak plasmas: a comparison

P Helander, C D Beidler, T M Bird, M Drevlak, Y Feng, R Hatzky, F Jenko, R Kleiber, J H E Proll, Yu Turkin and P Xanthopoulos

Max-Planck-Institut für Plasmaphysik, Greifswald and Garching, Germany

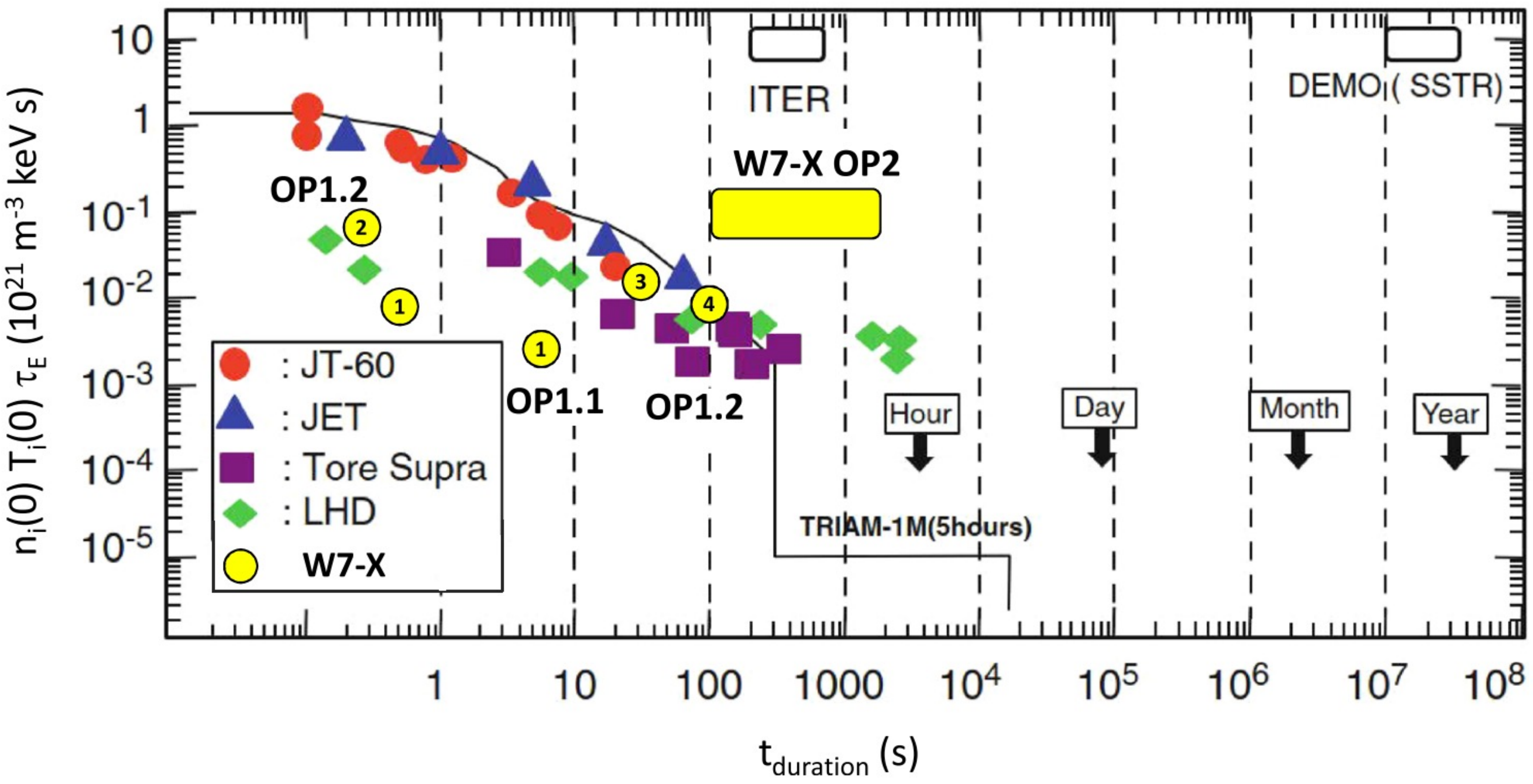
Stellarators in context

Comparison with tokamak performance

"Triple product"

$nT\tau_E \gtrsim 4{\times}10^{21}\text{m}^{-3}\text{ keV s}$

$P_{\text{fusion}} \geq P_{\text{loss}}$

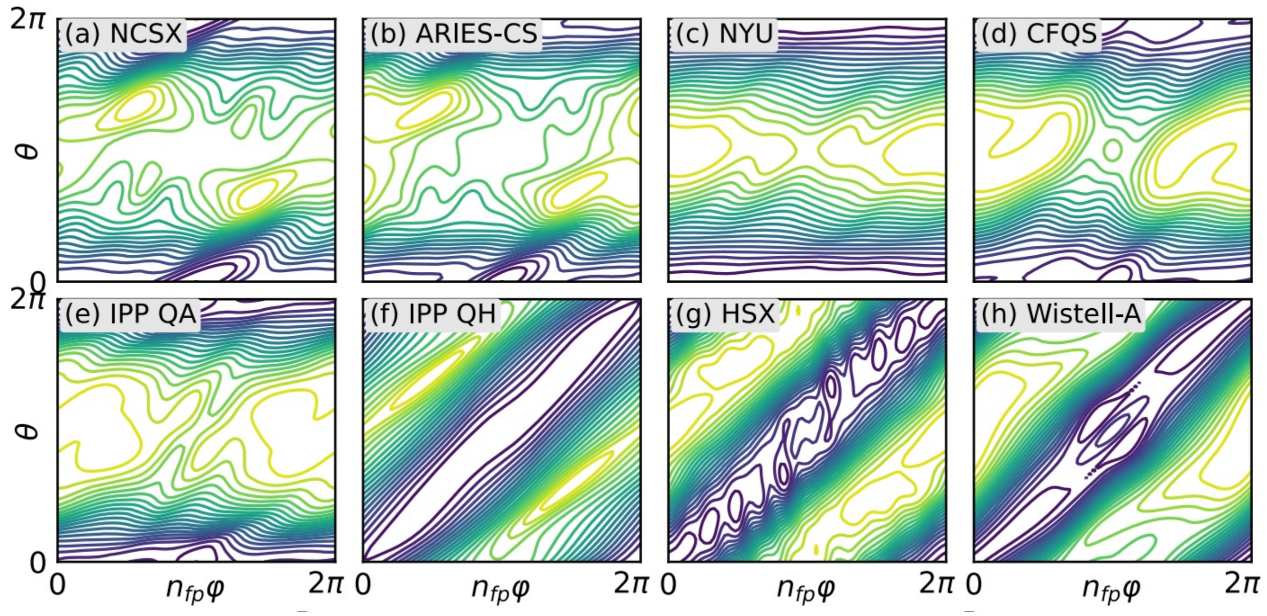


R. C. Wolf et al, *Phys. Plasmas* 26, (2019).

Stellarators in context

Stellarators with "precise quasisymmetry" have been uncovered

B as a function of "Boozer" coordinates



Stellarators in context

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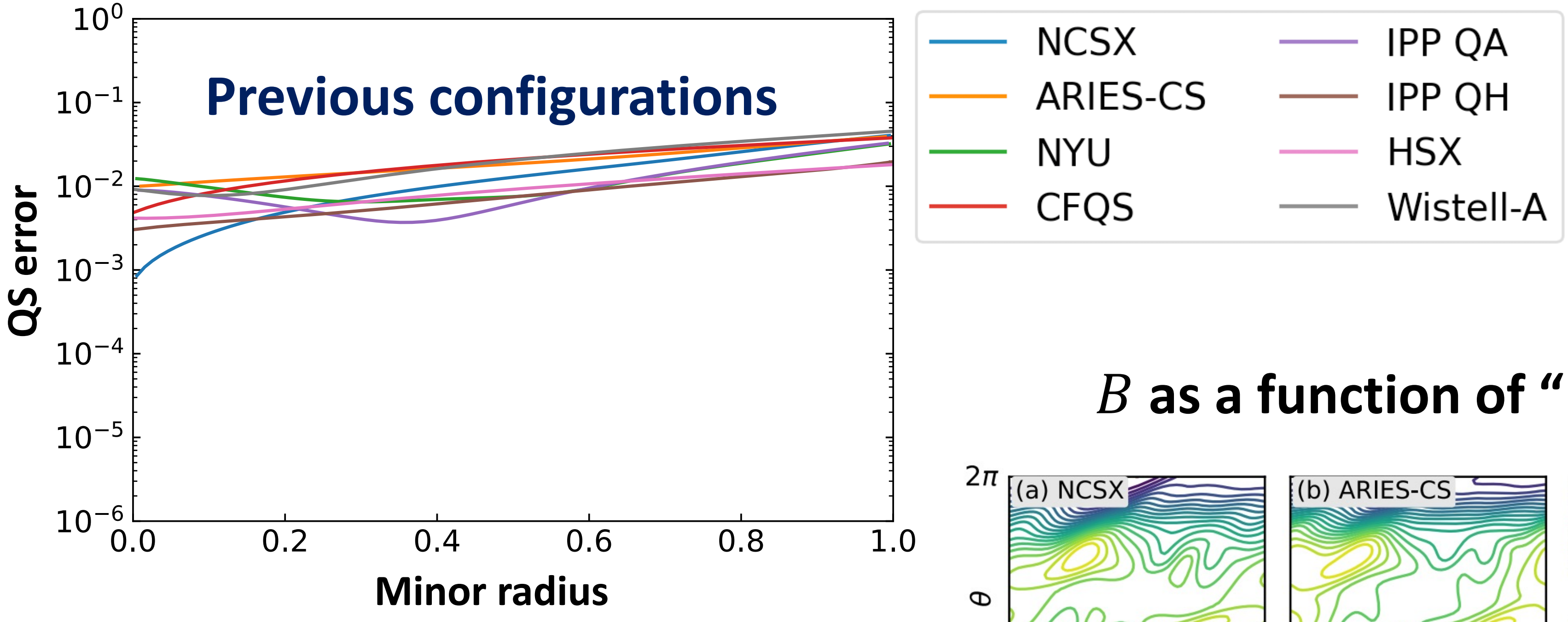

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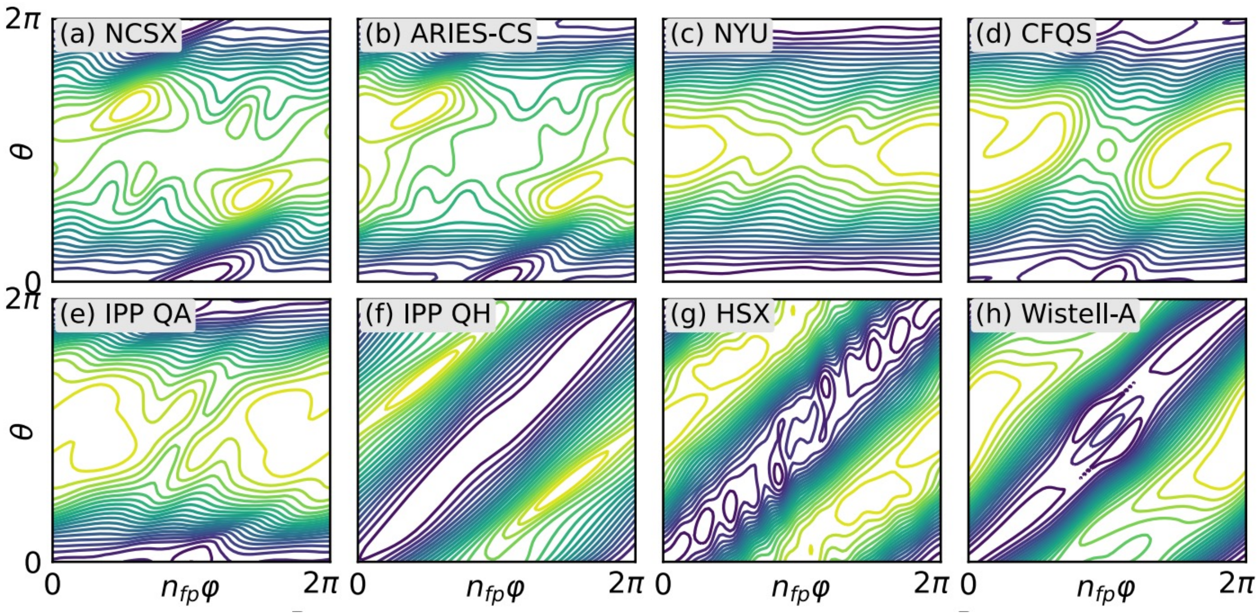

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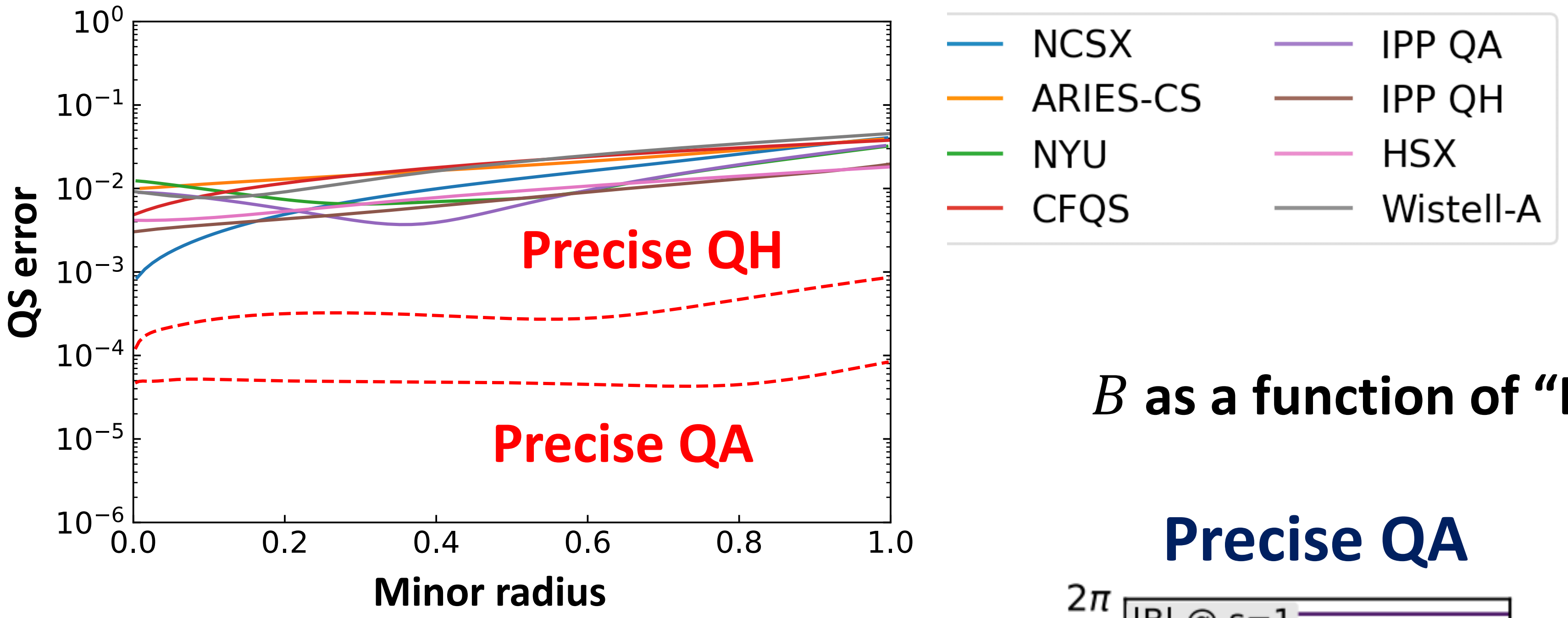
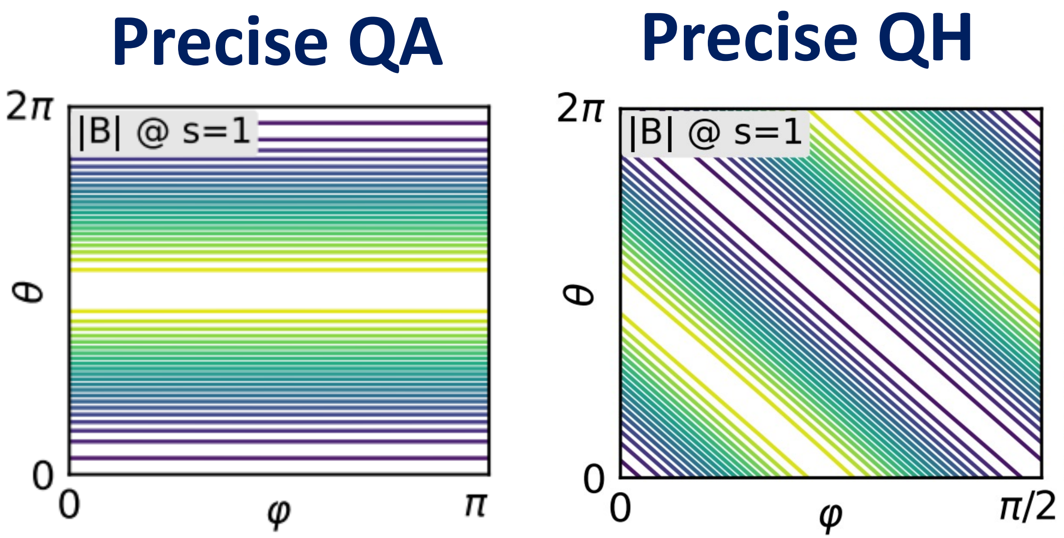
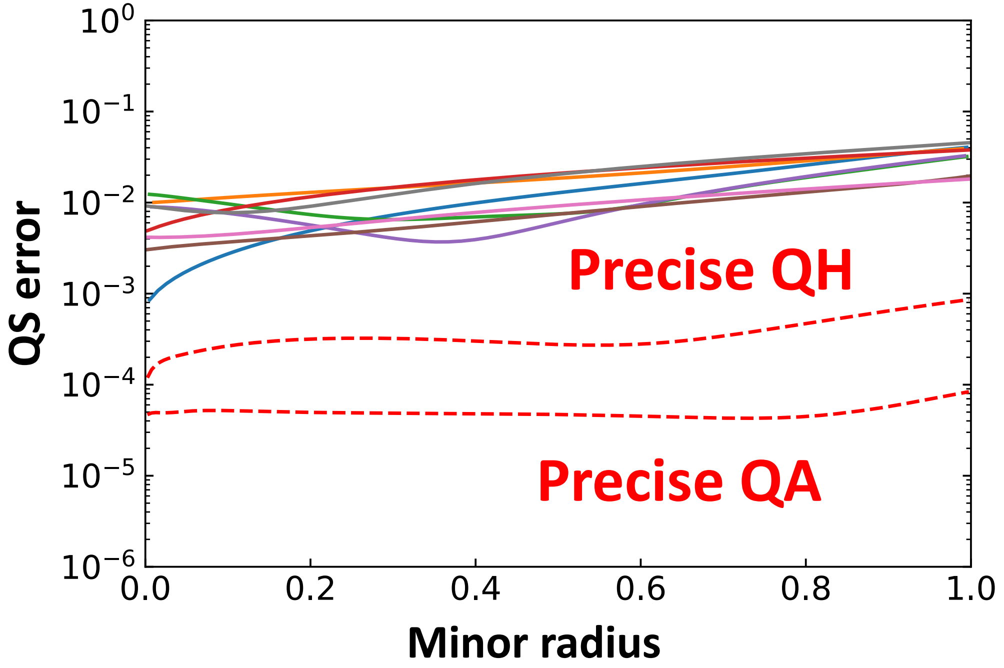


B **as a function of "Boozer" coordinates**

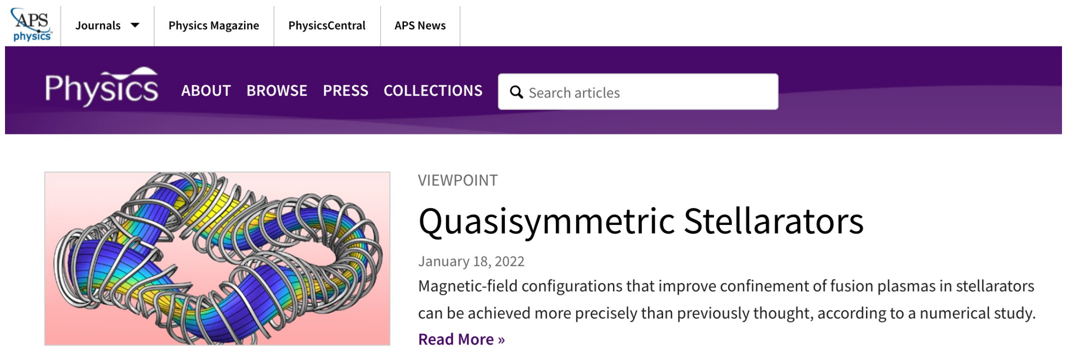


Stellarators in context

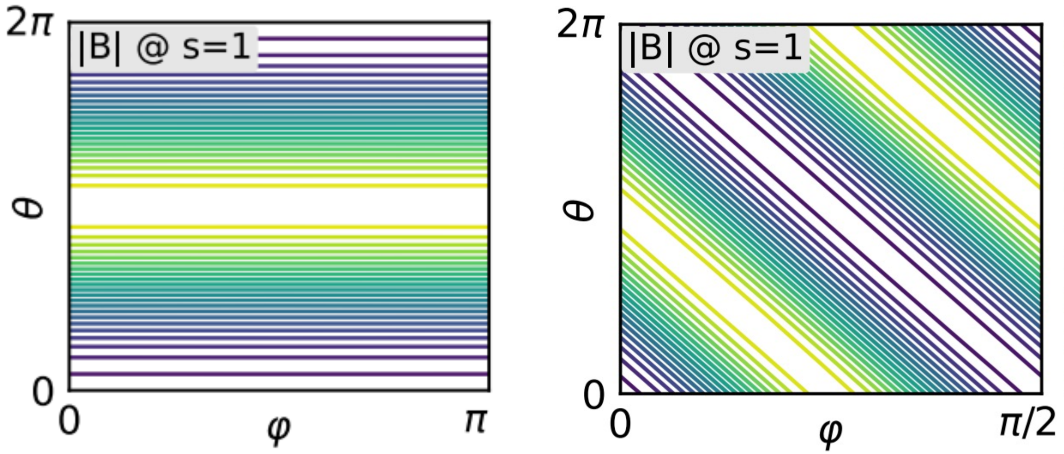
Stellarators with "precise quasisymmetry" have been uncovered



B **as a function of "Boozer" coordinates**



Precise QA **Precise QH**

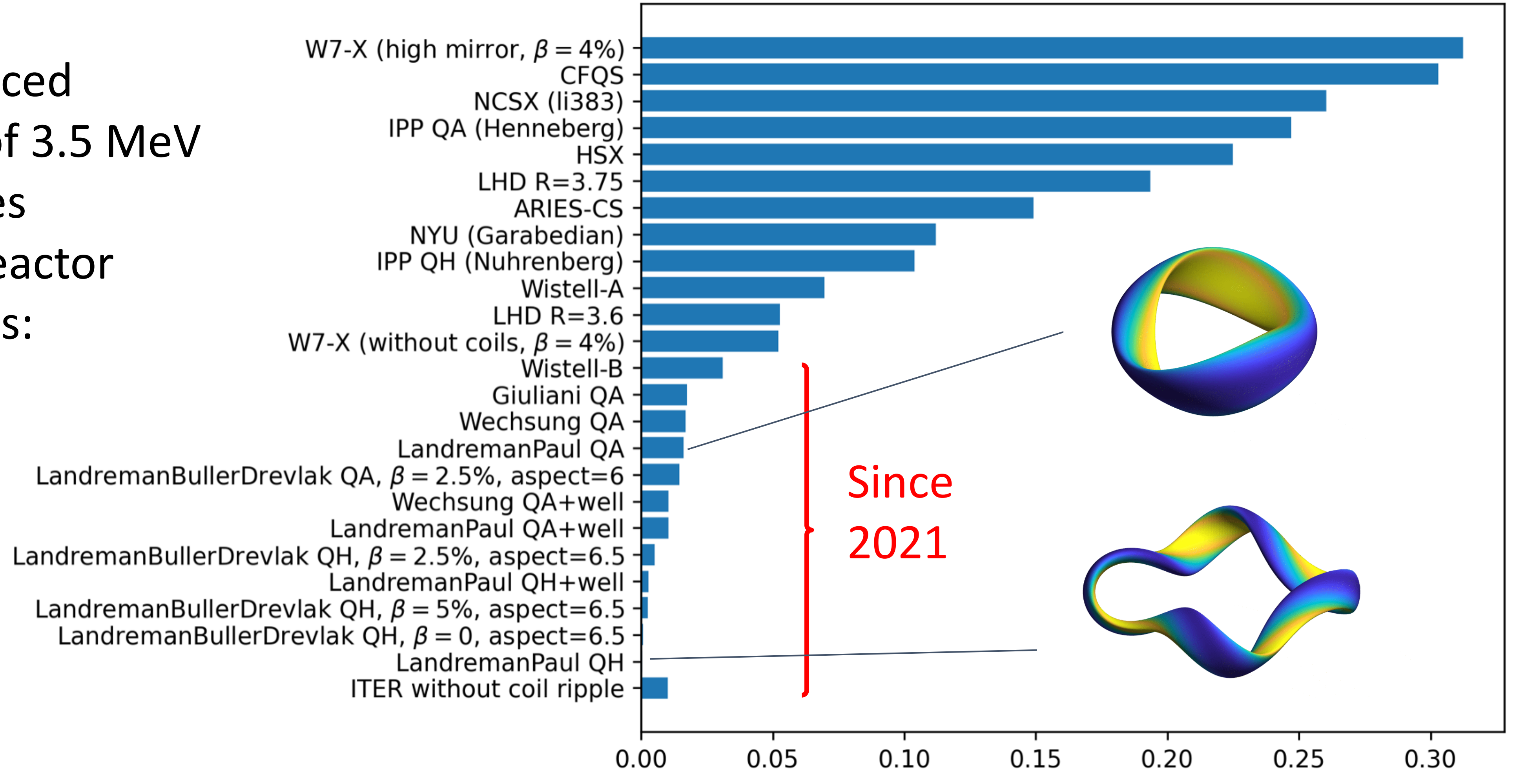


M. Landreman & E. J. Paul, *Phys. Rev. Lett.* 128 (2022).

Stellarators in context

Stellarators can be designed to confine energetic fusion products

Fusion-produced distribution of 3.5 MeV alpha particles followed in reactor configurations:

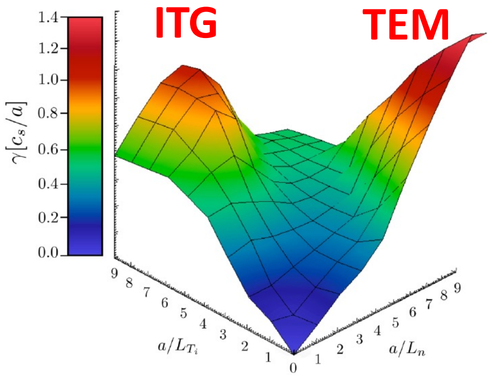


Fraction of alpha-particle energy lost before thermalization

Stellarators in context

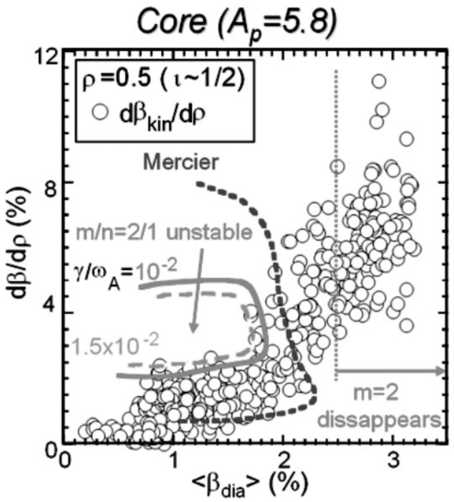
Open questions and new frontiers

Can we optimize stellarators for reduced turbulence?



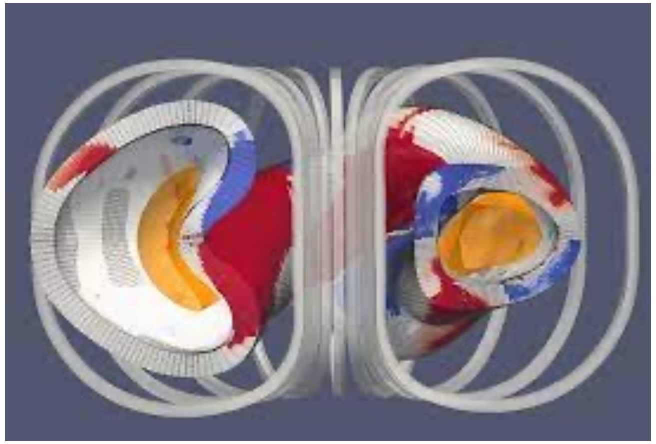
J. Alucon et al, *PPCF* 62 (2020).

Why can stellarators routinely violate linear MHD stability limits?



A. Weller et al, *Fusion Science & Tech.,* 50 (2006).

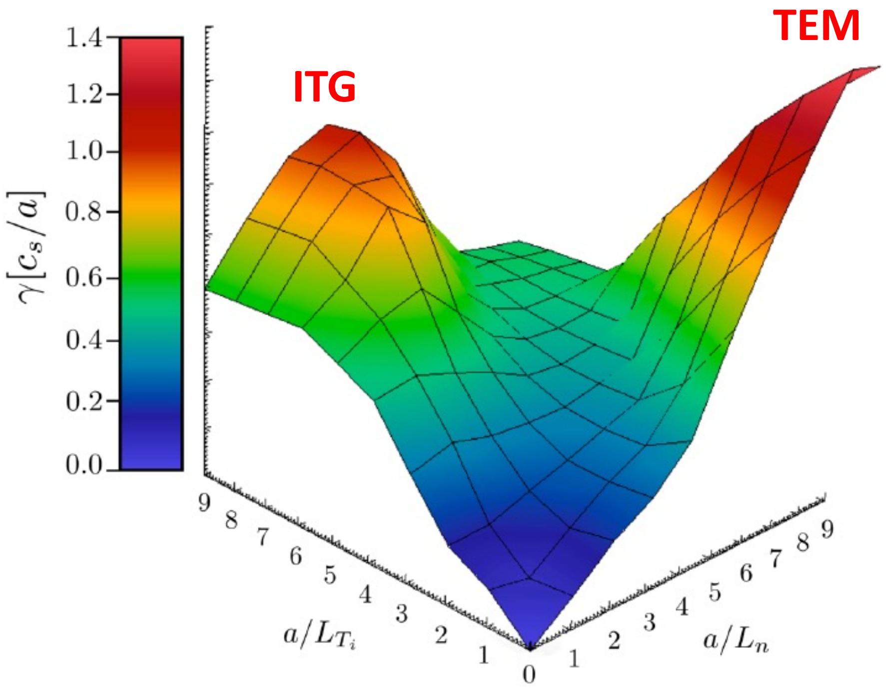
Can we simplify stellarator magnets?



C. Zhu et al, *Nuclear Fusion,* 60 (2020).

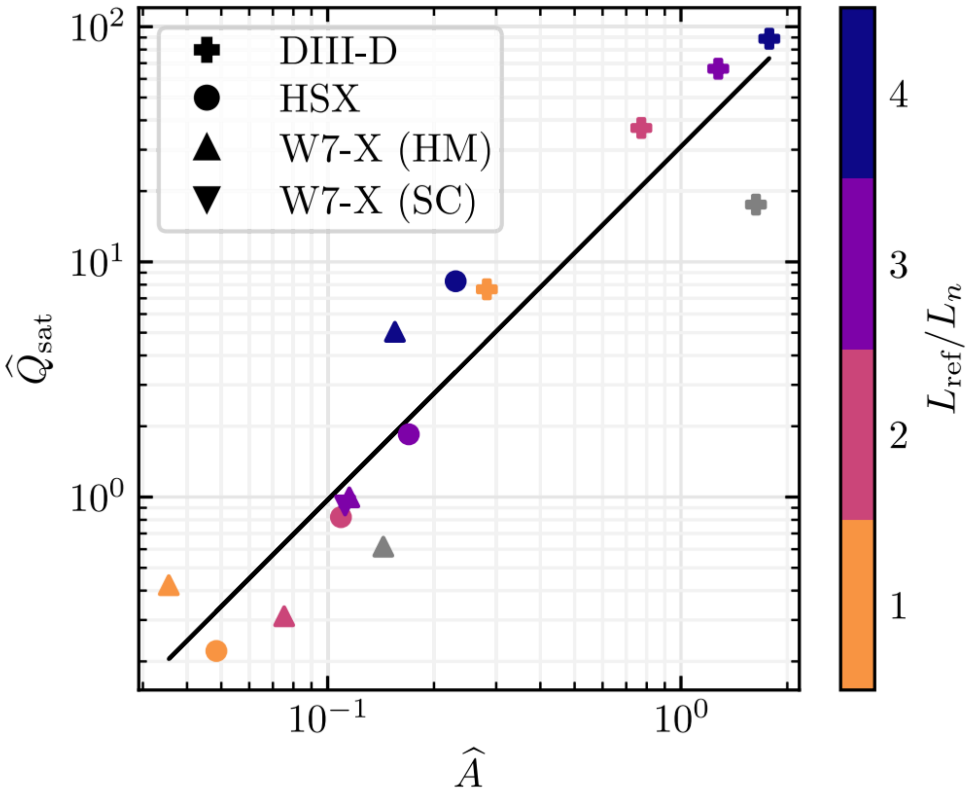
Stellarators in context

Can we optimize stellarators for reduced turbulence?



W7-X can operate in a "stability valley"

New theory to diagnose "available energy" for turbulence

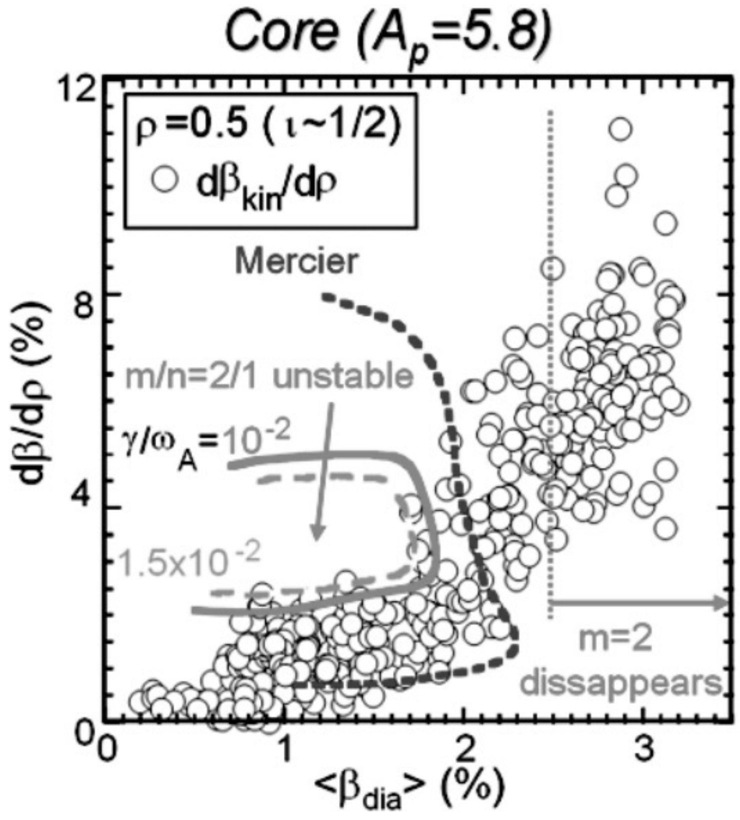


J. Alucon et al, *PPCF* 62 (2020).

R. Mackenbach et al, *PRL 128* (2022).

Stellarators in context

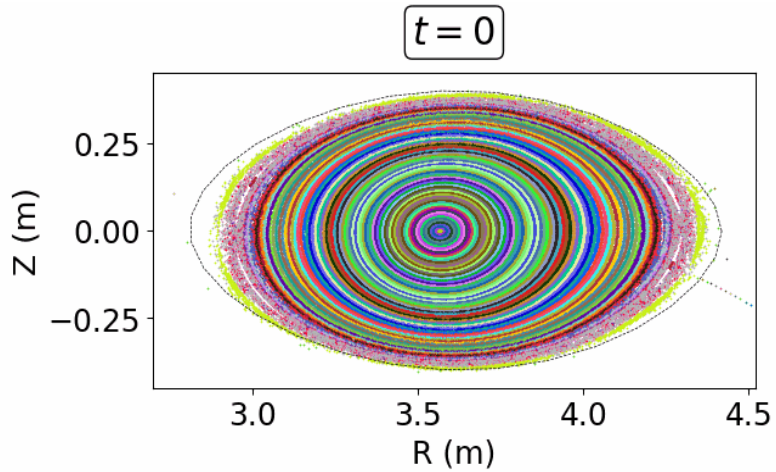
Why can stellarators routinely violate linear MHD stability limits?

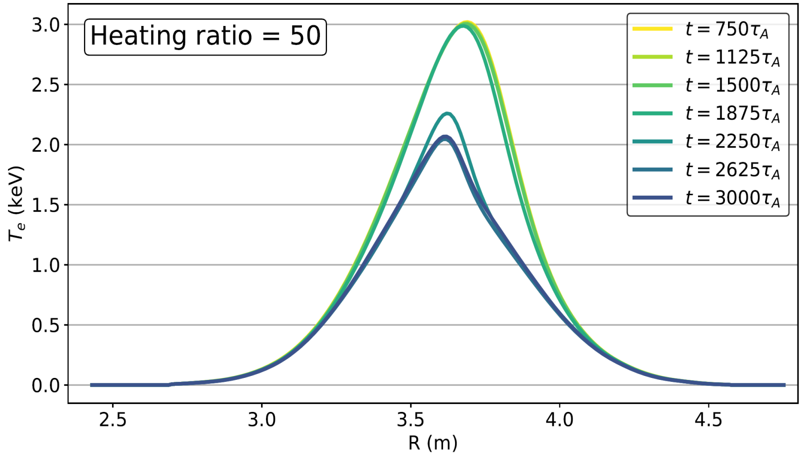


LHD operation beyond linear ideal MHD threshold

A. Weller et al, *Fusion Science & Tech.*, 50 (2006).

High-fidelity simulations leveraged at PPPL [A. Wright]

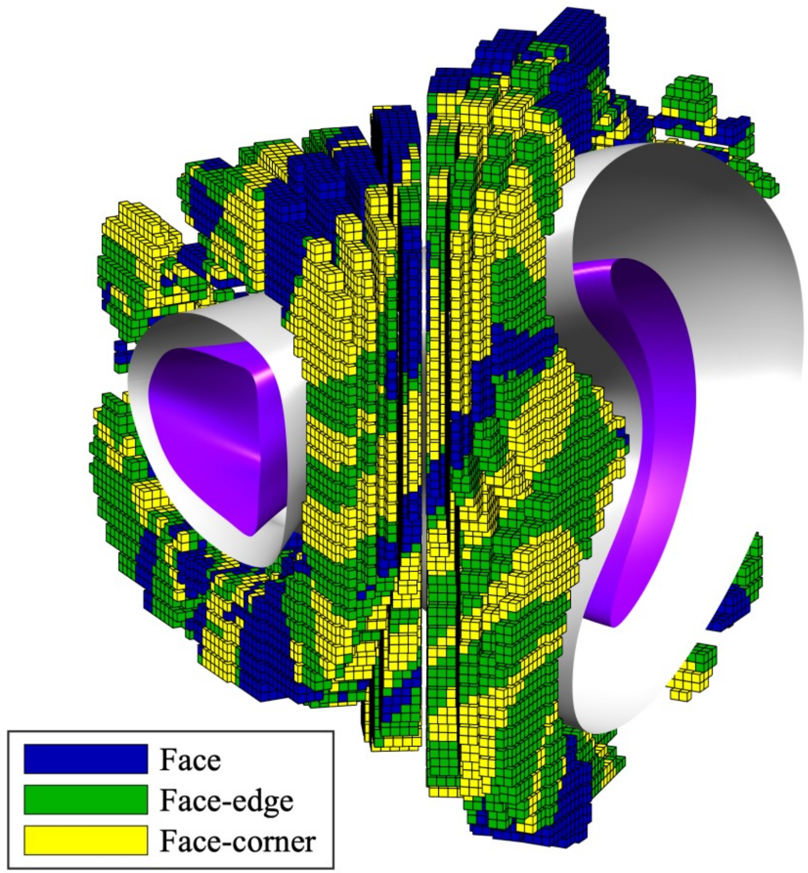


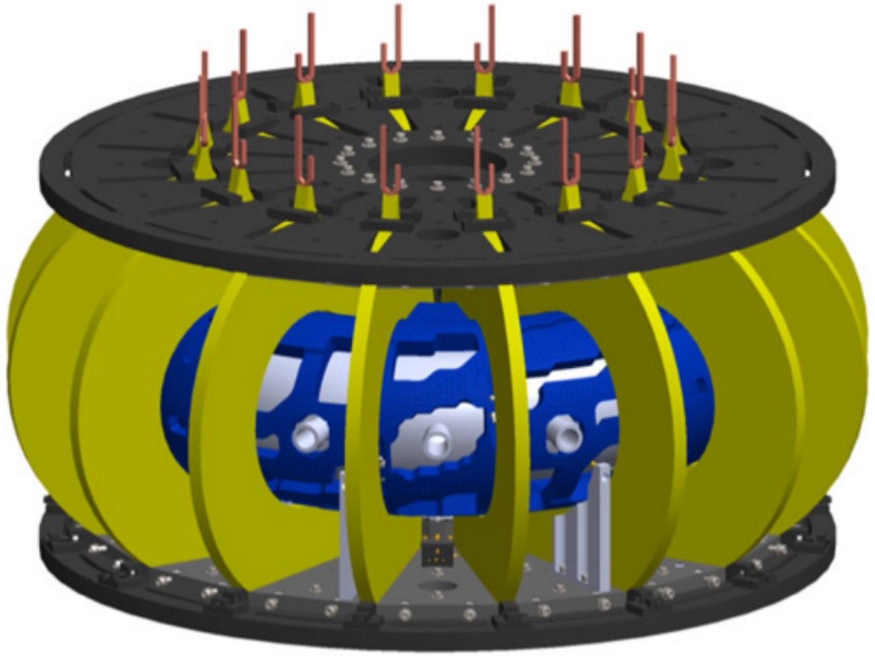


Stellarators in context

Can we simplify stellarator magnets?

PPPL projects use permanent magnets for confinement





C. Zhu et al, *Phys. Plasmas, 29* (2022).

T. Qian et al, *Nucl. Fusion, 62* (2022).

Stellarators in context

Growing private investment in stellarators

TYPE ONE ENERGY

RENAISSANCE FUSION

STELLAREX

Proxima Fusion

Princeton Stellarators

Summary

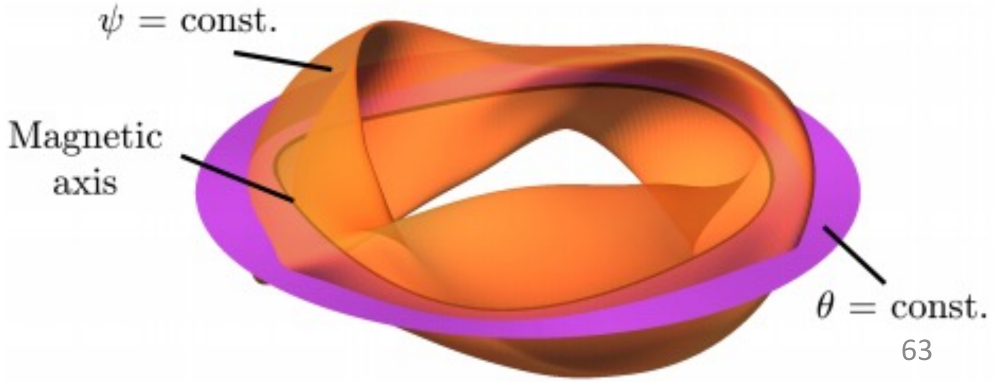
- Stellarators confine plasmas with non-symmetric magnetic fields
- Rotational transform (twisting field lines) can be produced through shaped magnetic fields
- Stellarators avoid headaches associated with having a large plasma current
- Although stellarators are not axisymmetric, they can be designed to have hidden symmetries
- Immense progress has been recently made, and there are exciting research opportunities

An introduction to stellarators: from magnetic fields to symmetries and optimization (arxiv:1908.05360)

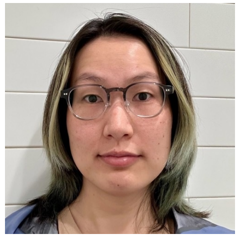
1. Introduction
2. Background
3. Electric and magnetic fields: Maxwell's equations
4. Classical mechanics
5. Single particle motion in electromagnetic fields
6. Coordinate systems
7. Toroidal magnetic confinement
8. Coupling of particles and electromagnetic fields: MHD models
9. Magnetic coordinates
10. Challenges associated with 3D equilibrium fields
11. Models of 3D equilibrium magnetic fields
12. Symmetries in stellarators
13. Optimization for stellarator design
14. New frontiers of optimization

	MHD equilibrium (surfaces assumed)	Force-free fields	Vacuum fields
Hyp.	$\boldsymbol{J}\times\boldsymbol{B}\neq 0$ $\nabla p\neq 0$	$\boldsymbol{J}\times\boldsymbol{B}=0$ $\nabla p=0$ and $\lambda=$ const.	$\boldsymbol{J}=0$ $\nabla p=0$
PDE model	$\boldsymbol{J}\times\boldsymbol{B}=\nabla p$ $\nabla\cdot\boldsymbol{B}=0$ $\mu_0\boldsymbol{J}=\nabla\times\boldsymbol{B}$	$\nabla\times\boldsymbol{B}=\lambda\boldsymbol{B}$ $\mu_0\boldsymbol{J}=\nabla\times\boldsymbol{B}$	$\Delta\widetilde{\Phi}_B=0$
Given	$p(\psi)$, $\iota(\psi)$, Ψ_T	λ, Ψ_T	I_P
Unkn.	$\boldsymbol{B}$	$\boldsymbol{B}$	$\widetilde{\Phi}_B$
With	$\boldsymbol{J}$ function of $\boldsymbol{B}$	$\boldsymbol{J}$ function of $\boldsymbol{B}$	$\boldsymbol{B}=\nabla\left(\widetilde{\Phi}_B+(\mu_0 I_P/2\pi)\,\phi\right)$
BC	$\boldsymbol{B}\cdot\hat{\boldsymbol{n}}=0$	$\boldsymbol{B}\cdot\hat{\boldsymbol{n}}=0$	$\hat{\boldsymbol{n}}\cdot\nabla\widetilde{\Phi}_B+(\mu_0 I_P/2\pi)\,\hat{\boldsymbol{n}}\cdot\nabla\phi=\boldsymbol{B}\cdot\hat{\boldsymbol{n}}$



Join the stellarator crew at Columbia!

UG/Masters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