Stellarators

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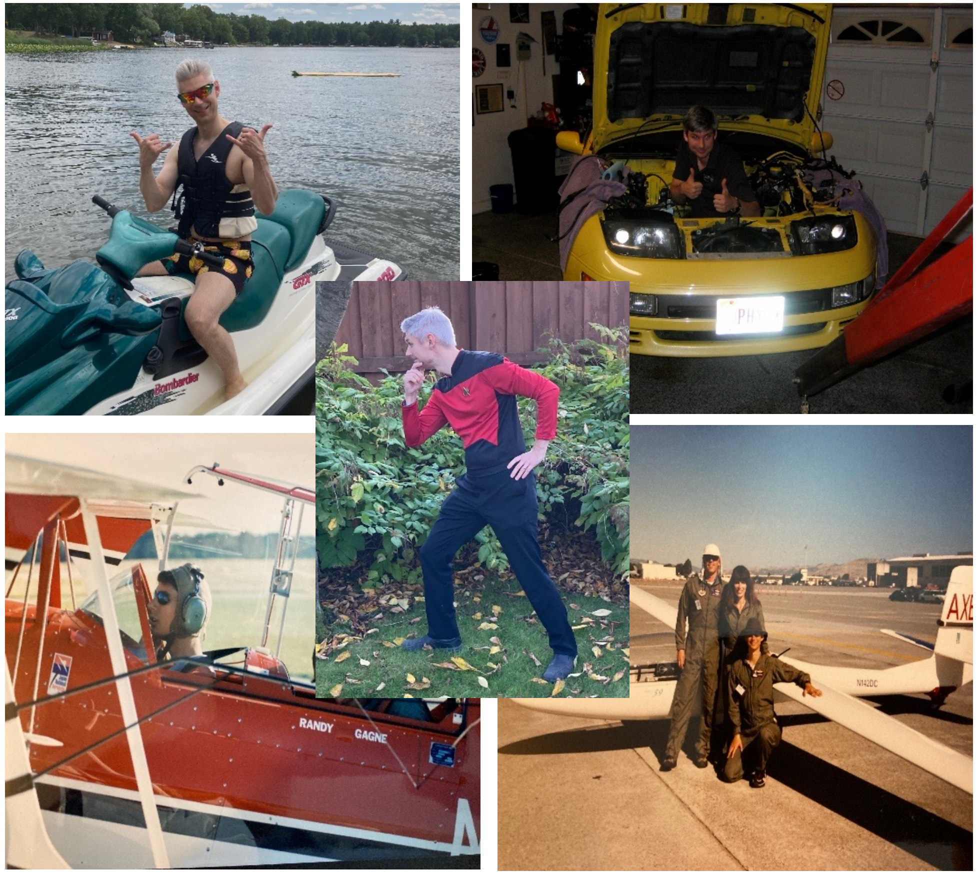
ABOUT ME

Samuel Aaron Lazerson, Ph.D.

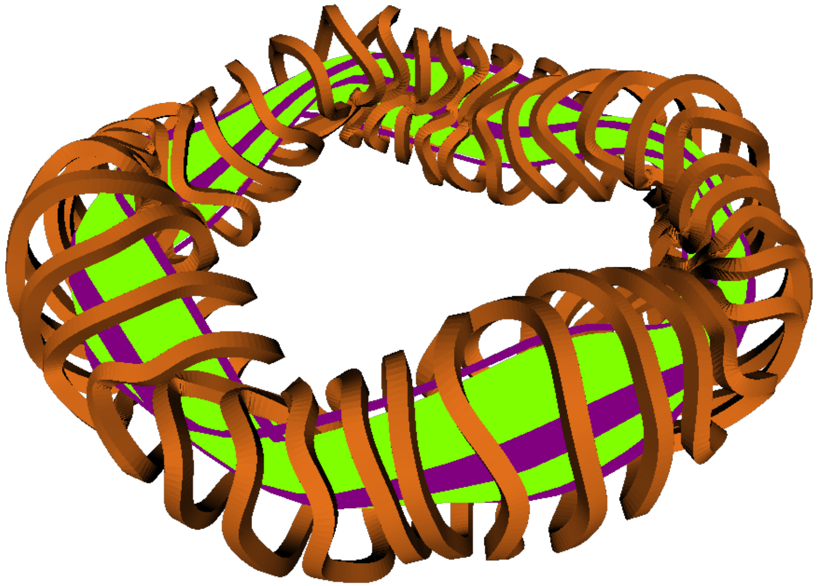
GAUSS FUSION



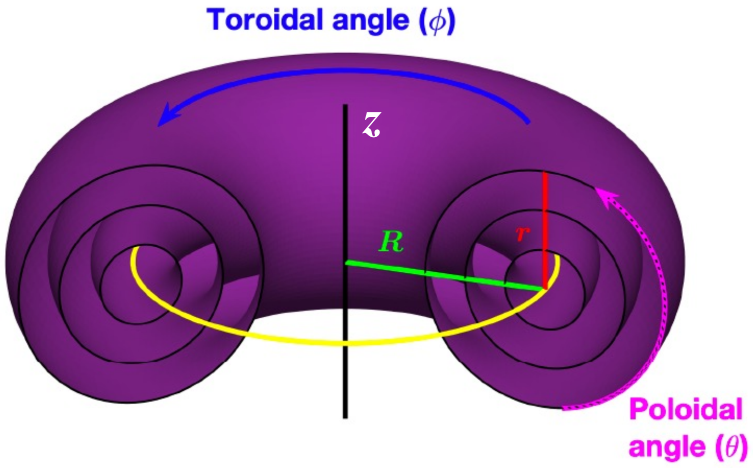
- 1998 Graduated from Jesuit High School in Sacramento, CA
- 2000 Started working the Space Physics Research Lab as an undergraduate.
- 2002 Graduated from Embry-Riddle Aeronautical University with B.S. in Engineering Physics. (Daytona Beach, FL)
- Spent a year bartending outside of Las Vegas, NV
- 2004 Started in the Space Physics Doctoral Program at the University of Alaska
- 2010 Graduated with my Ph.D. Space Physics and started my Postdoctroal research at PPPL working on LHD
- 2014 Spent 11 months at Wendelstein 7-X for the very first campaign.
- 2017-2019 Served as the Scenario and Integration Task Force Leader for the OP1.2 W7-X experimental campaign.
- 2019 Joined IPP as a research scientist
- 2024 Joined Gauss Fusion GmbH as the Stellarator Physics Lead

What is a stellarator?

1. Toroidal magnetic plasma confinement concept
2. Magnetic field generated solely by external coils
3. Nested magnetic flux surfaces are formed only in twisted shapes…stellarators are 3D



Some basic geometrical concepts of toroidal devices



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

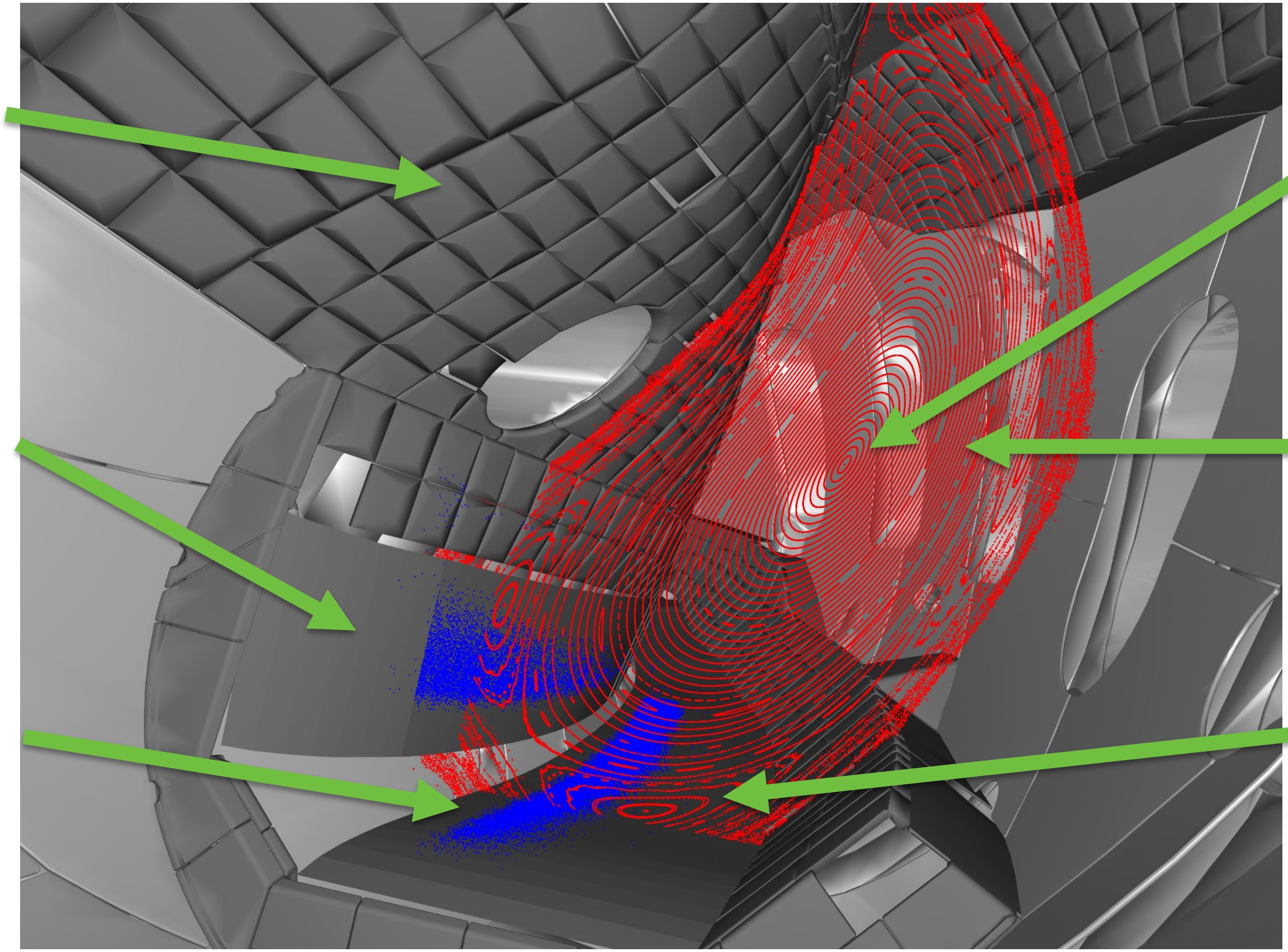
FUSION VOCABULARY

Wendelstein 7-X as a stereotypical configuration

First Wall

Divertor

Strike Lines



Magnetic Axis

Magnetic Flux Surface

Magnetic Island

Samuel A. Lazerson *et al* 2019 *Nucl. Fusion* **59** 126004

We can use magnetic fields to control the orbits of charged particles

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1. Motion of particles is governed by the Lorentz force
2. Free to move in the direction of the magnetic field
3. Motion across the magnetic field governed by orbit

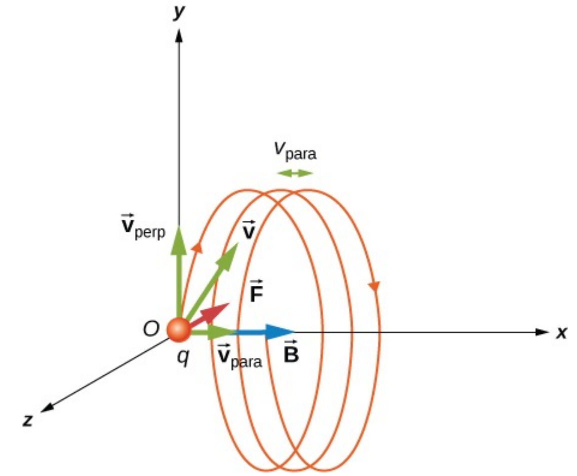
$$F = q(\vec{E} + \vec{v} \times \vec{B})$$ *Lorentz force*

$$\alpha = \frac{v_{\parallel}}{|\vec{v}|}$$ *Pitch parameter*

$$\omega_g = \frac{|q|B}{m}$$ *Gyro-frequency*

$$\mu = \frac{m v_{\perp}^2}{2B}$$ *Magnetic moment*

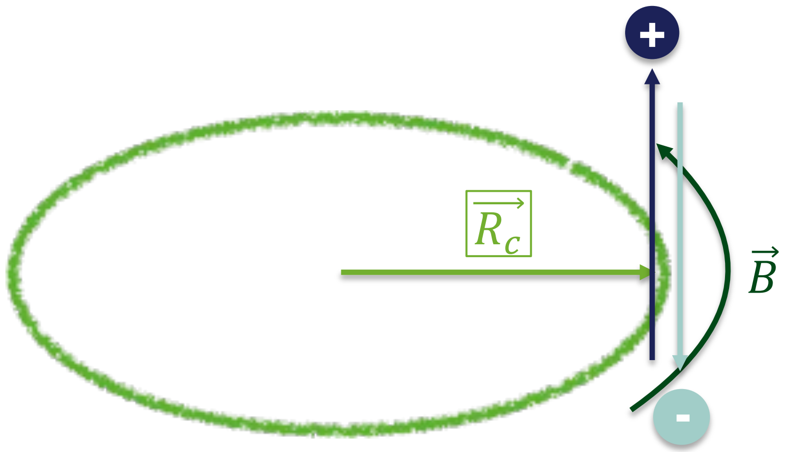
$$r_g = \frac{m v_{\perp}}{|q|B}$$ *Gyro-radius*



Motion of a Charged Particle in a Magnetic Field. (2022, September 13). https://phys.libretexts.org/@go/page/4416

Inhomogeneities in the magnetic field result in drifting motions

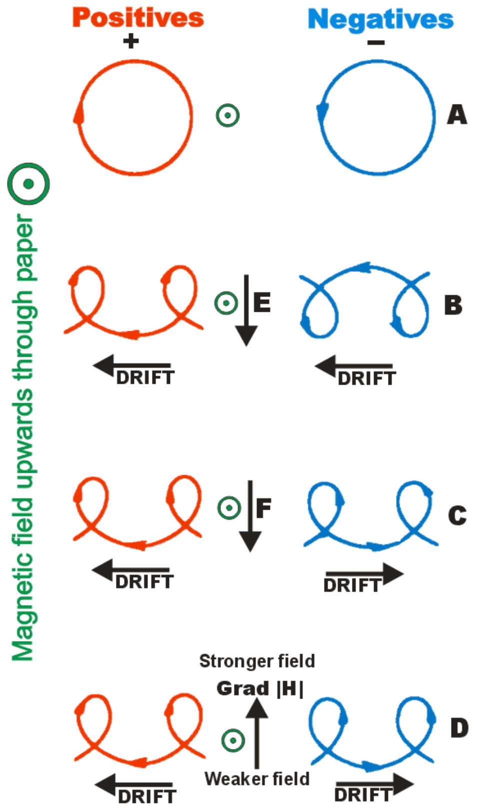
1. Electric fields drive particles across field lines.
2. Bending of the field drives electrons and ions apart
3. Gradients in the field also drive drift motion



$$\vec{v}_{E\times B} = \frac{\vec{E}\times\vec{B}}{B^2}$$

$$\vec{v}_R = \frac{2K_\parallel}{qB}\frac{\vec{R}_C\times\vec{B}}{R_C^2 B}$$

$$\vec{v}_{\nabla B} = \frac{K_\perp}{qB}\frac{\vec{B}\times\nabla B}{B^2}$$



https://www.plasma-universe.com/charged-particle-drift/

Conservation of magnetic moment results in a mirroring behavior

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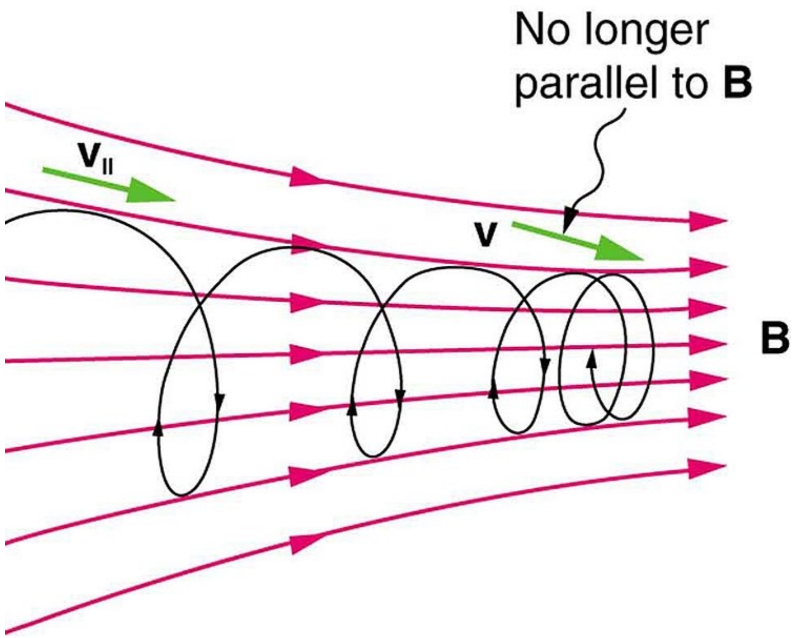
1. Magnetic moment and energy can be adiabatic invariants
2. As the field increases so must the perpendicular velocity
3. This implies parallel velocity can reach zero

$$\mu = \frac{mv_\perp^2}{2B} \qquad K = q\phi_{es} + \frac{mv_\parallel^2}{2} + \frac{mv_\perp^2}{2}$$

Note that early fusion devices based on this concept were heavily explored



Particle confinement requires twisted field lines in a torus

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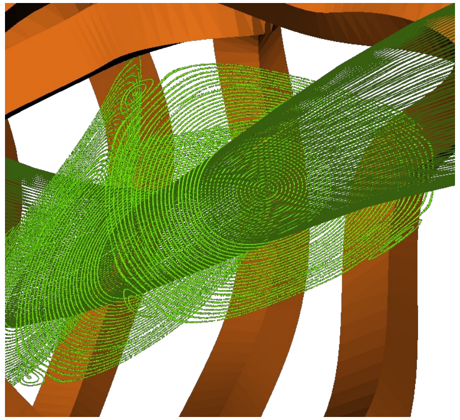
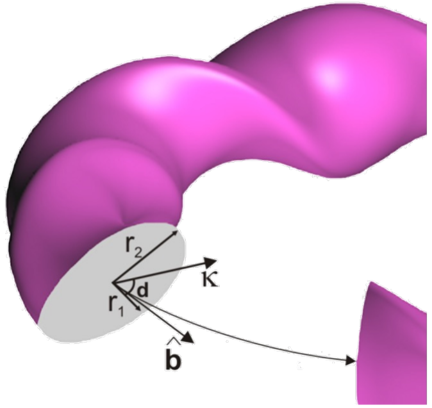
1. A pure toroidal field cannot confine a plasma.
2. A twisted toroidal field fixes this problem.
3. The twist of the field lines can come from three effects

$$\iota = \frac{1}{2\pi}\int_0^L \Bigg[\underbrace{\frac{\mu_0 I}{2B_0}}_{\text{Current}} - \underbrace{(\cosh\eta - 1)d'}_{\text{Rotation}} - \underbrace{\tau}_{\text{Torsion}}\Bigg]\frac{dl}{\cosh\eta}$$

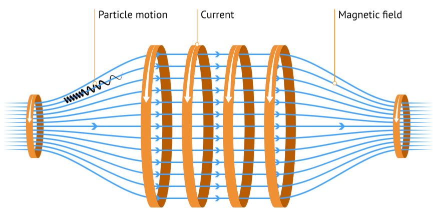


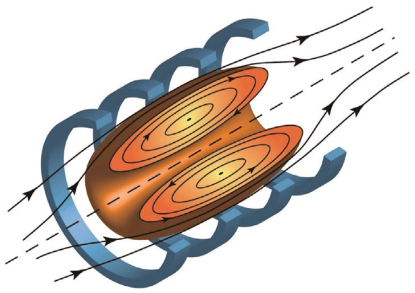


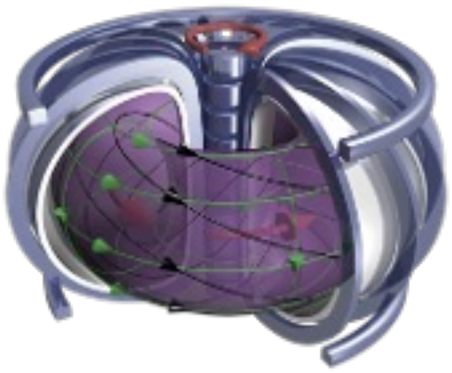
P. Helander, Rep. Prog. Mod. Phys., 2014

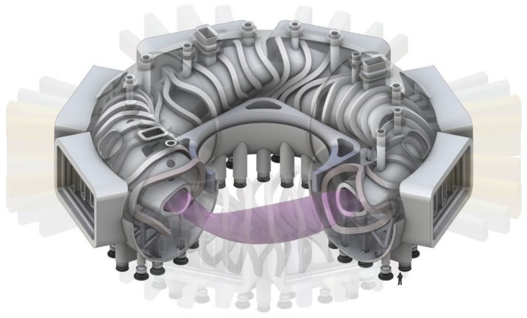
Magnetic confinement fusion spans a multitude of concepts

Mirror	FRC	Tokamak	Stellarator









Mirror
- Uses Mirror effect
- End losses

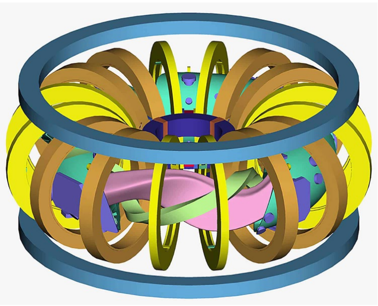
FRC
- Pure poloidal field

Tokamak
- Use plasma current to twist the field

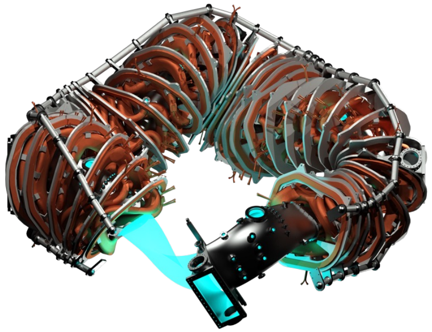
Stellarator
- Twist the magnetic field with coils

Stellarators are a steady-state route to fusion energy

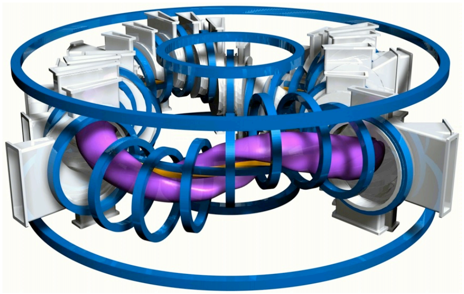
1. No external current current drive required
2. Stability limits are soft
3. The challenge is one of design not plasma control



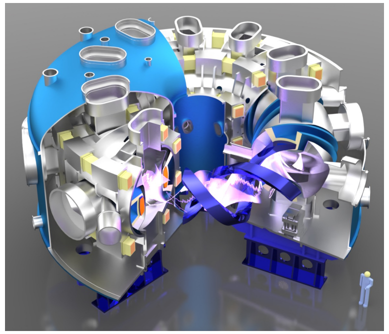
Heliotron-J



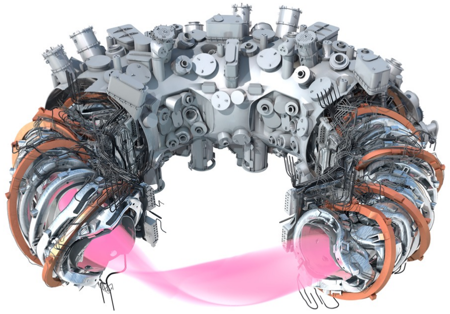
Helically Symmetric Experiment



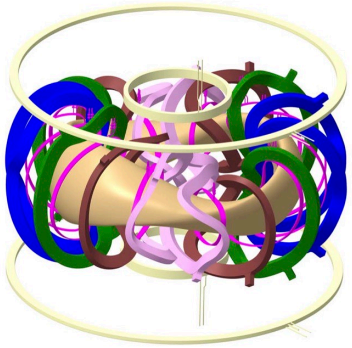
TJ-II



Large Helical Device



Wendelstein 7-X



CFQS

Stellarator design is a physics optimization process

- Equilibrium Shape
  - Rotational Transform
  - Neoclassical Transport
  - Alpha Confinement
  - Turbulent Transport
  - MHD Stability
  - Bootstrap Current

- Coil Shape
  - Curvature
  - Torsion
  - Coil Spacing
  - Divertor
  - Robustness

Stellarator design begins with computation of magnetic fields

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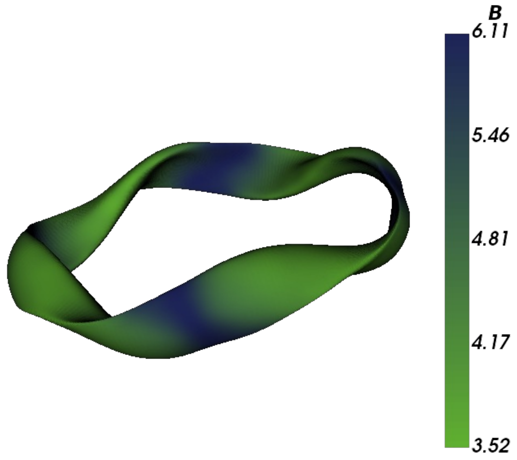
Ideal Magnetohydrodynamics provides a framework for computing magnetic fields

- Assume that within some toroidal surface there is no perpendicular magnetic field
- Field can then be represented in compact form
- Energy functional is minimized to find equilibrium magnetic field



$$\vec{F} = \vec{j} \times \vec{B} - \nabla p = 0$$

$$\nabla \times \vec{B} = \mu_o \vec{j}$$

$$\nabla \cdot \vec{B} = 0$$

$$W = \int \left(\frac{|B|^2}{2\mu_0} + \frac{p}{\gamma - 1} \right) dV$$

Inputs
Boundary Shape
Pressure Profile
Current Profile

→

Outputs
Magnetic Field

Transport is the relationship between the profiles and source terms

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The transport problem solves for the current and pressure in terms of the diffusive and source terms

Density

$$\frac{\partial n_k}{\partial t} = -\nabla \cdot \boxed{\Gamma_k} + \boxed{S_{wall} + S_{vol} + S_{pellet} + S_\alpha}$$

Temperature

$$\frac{3}{2}\frac{\partial}{\partial t}\left(\frac{n_k T_k}{Z_k}\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|^2\rangle \boxed{\chi_k} \frac{n_k}{Z_k}\frac{\partial T_k}{\partial \rho}\right) = \boxed{P_{AUX} + P_\alpha + P_c}$$

Current

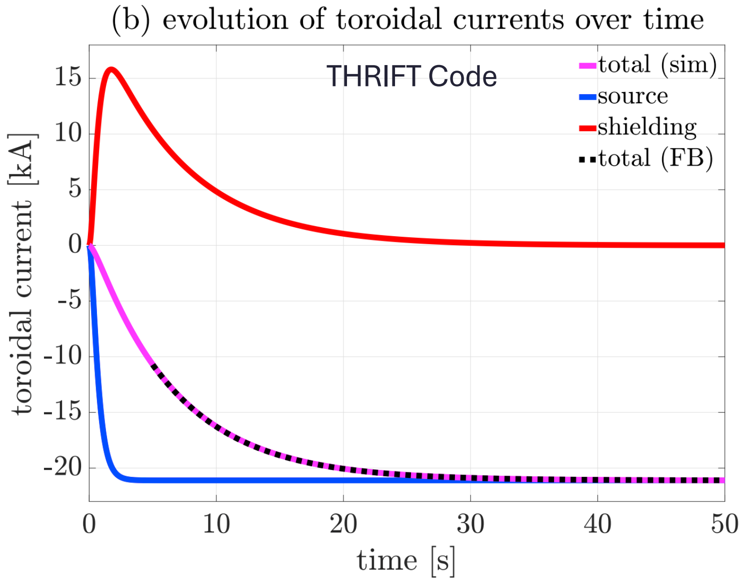
$$\frac{d\iota}{dt} = \frac{d\iota}{d\Phi}\frac{d\Phi}{dt} + \frac{d}{d\Phi}\left(\frac{\boxed{\eta_\parallel}}{\mu_0}\Phi'\left(S_{11}\iota + S_{12}\right)^2 \frac{d}{d\rho}\left(\frac{S_{11}\iota + S_{12}}{S_{21}\iota + S_{22}}\right) - \boxed{\eta_\parallel}\boxed{\langle J_s B\rangle}\frac{dV}{d\Phi}\right)$$

$$V' = \frac{\partial V}{\partial \rho}$$

The challenge is determining the **coefficients** and **source terms**

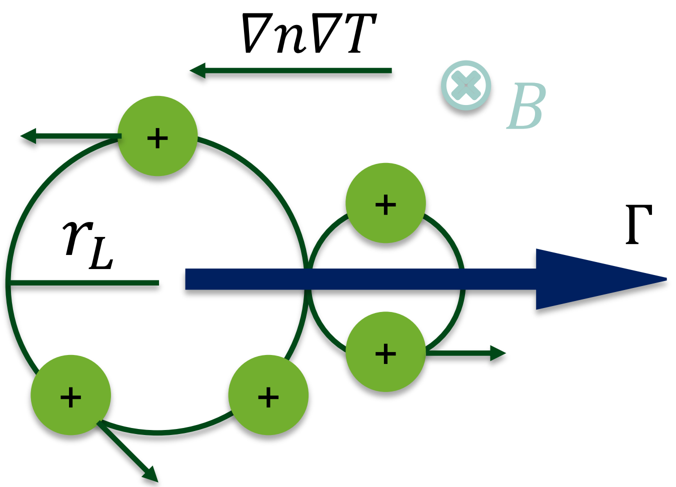
$S_{12})$

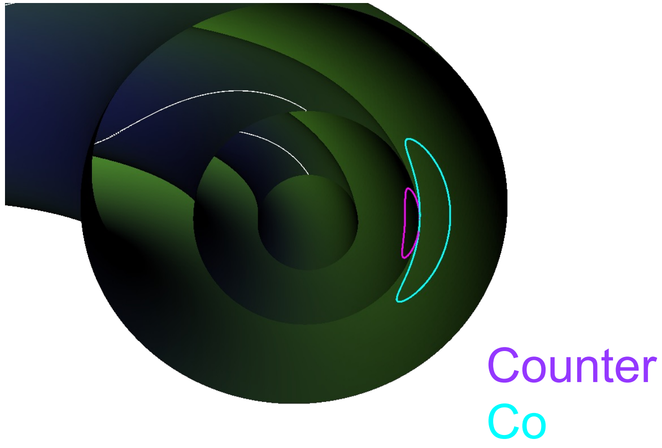
$$\frac{\iota}{2\pi} = \frac{\Psi'}{\Phi'}$$

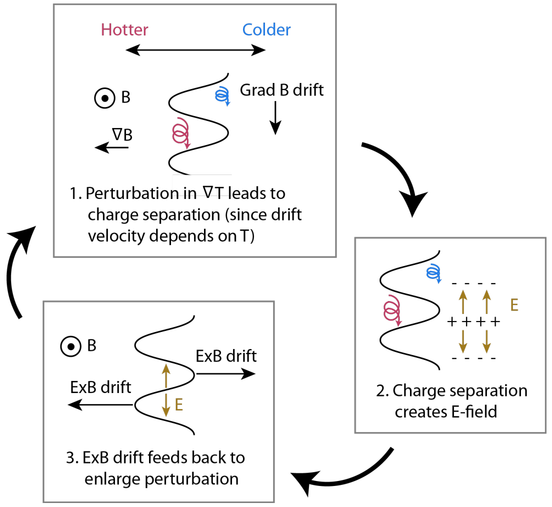


L. van Ham *et al.* Nucl. Fusion **65** 036001

Transport in stellarator arises from a number of phenomena







Classical Transport

- Particle transport in a magnetic field
- Frictions between different particles drive radial flux
- Dominated by motion of particles perpendicular to the magnetic field

Neoclassical Transport

- Curved magnetic fields give rise to mirroring motion of particles.
- Mirroring particles couple the parallel and perpendicular velocities so that parallel friction dominates.
- Gives rise to additional radial transport, electric fields, and self-generated current

Turbulent Transport

- Arises from drifting waves on flux surfaces driving radial transport
- Can be driven unstable by density and temperature gradients
- Ultimately responsible for particle and energy confinement in optimized stellarators

https://wiki.fusion.ciemat.es/wiki/Ion_Temperature_Gradient_instability

Transport determines how well the plasma is confined

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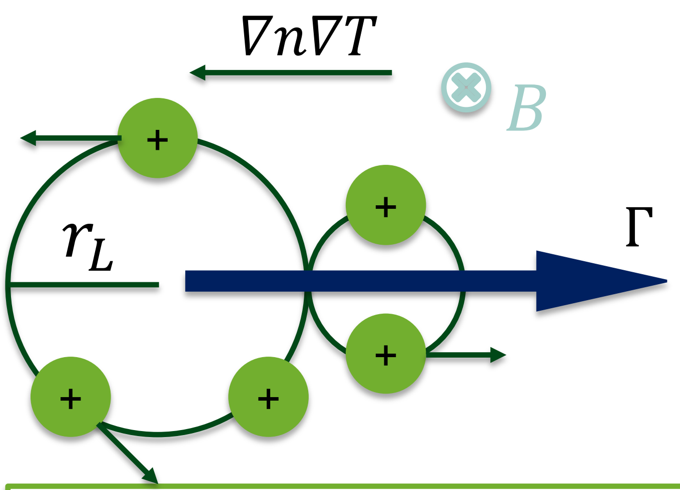
Classical Transport

- Based on a Maxwellian particle distribution
- Frictions between different particles drive radial flux
- Dominated by motion of particles perpendicular to the magnetic field.



$$D_{CL}^{ab} = \frac{\rho_a^2}{2}\nu_{ab} \qquad \nu_{ab} = \frac{4\sqrt{2\pi}}{3(4\pi\epsilon_0)^2}\frac{e_a^2 e_b^2\sqrt{m_a b}\ln\Lambda_{ab}}{(k_B T)^{3/2}}\frac{n_b}{m_a}$$

$$\Gamma_{CL}^{a} = -\nabla n_a \sum_{b\neq a} D_{CL}^{ab} + n_a \sum_{b\neq a} D_{CL}^{ab}\frac{e_a}{e_b}\left(\frac{\nabla n_b}{n_b} - \frac{\nabla T}{T}\left[\frac{3m_{ab}}{2m_b} - 1 - \frac{e_b}{e_a}\left(\frac{3m_{ab}}{2m_a} - 1\right)\right]\right)$$

Diffusive

Inward

Outward
Temperature Screening

Early stellarators and tokamaks did not behave classically!

Neoclassical transport accounts for the trapping dynamics of the particles

Neoclassical Transport

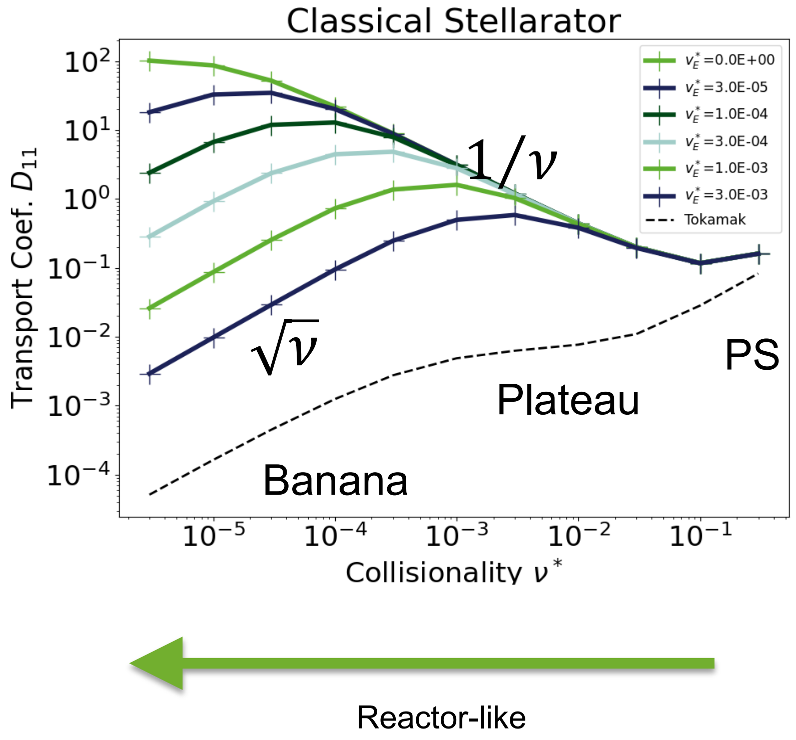
- Curved fields couple parallel and perpendicular velocities, so parallel friction dominates
- Trapping gives rise to a self-generated current: bootstrap current
- Ambipolarity condition gives rise to radial electric field and perpendicular drifts

$$\Gamma_{neo}^{k} = -n^k L_{11}^{k} \left(\frac{1}{n^k}\frac{dn^k}{dr} - \frac{q^k E_r}{T^k} + \delta_{12}\frac{1}{T^k}\frac{dT^k}{dr} \right)$$

$$L_{11} = \frac{2}{\sqrt{\pi}} \int_0^\infty K^{1/2} e^{-K} D_{11}(K)\, dK \qquad K = \frac{mv^2}{2T}$$

$$L_{12} = \frac{2}{\sqrt{\pi}} \int_0^\infty K^{3/2} e^{-K} D_{11}(K)\, dK \qquad \delta_{12} = \frac{L_{12}}{L_{11}} - \frac{3}{2}$$

$$L_{22} = \frac{2}{\sqrt{\pi}} \int_0^\infty K^{5/2} e^{-K} D_{11}(K)\, dK$$



Optimization achieves configuration with good neoclassical transport

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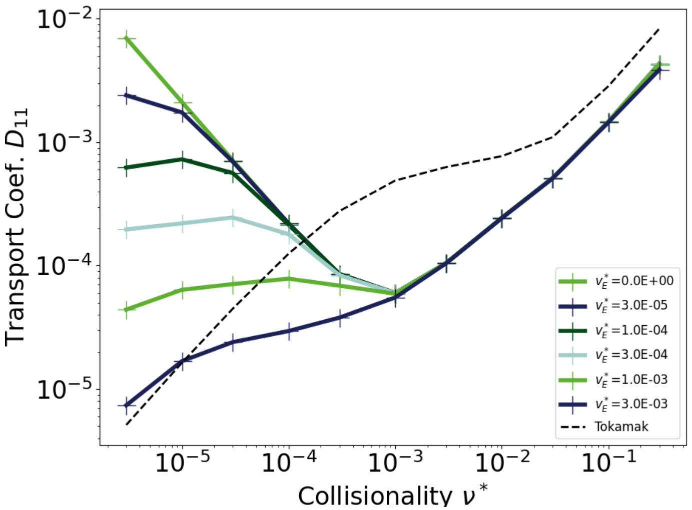
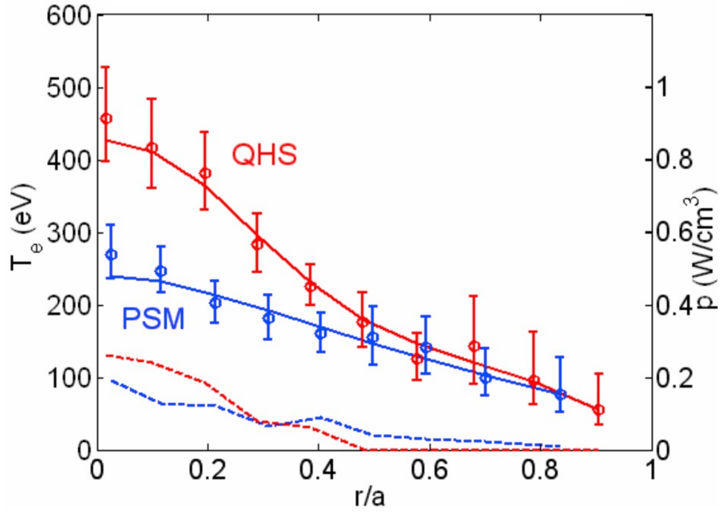
- Early works pointed toward tailoring magnetic fields for improved neoclassical confinement
- The Helically Symmetric Experiment showed optimized stellarators could achieve low neoclassical transport levels.
- The Wendelstein 7-X experiment demonstrated confinement not achievable in similar un-optimized stellarators.

Optimized Stellarator

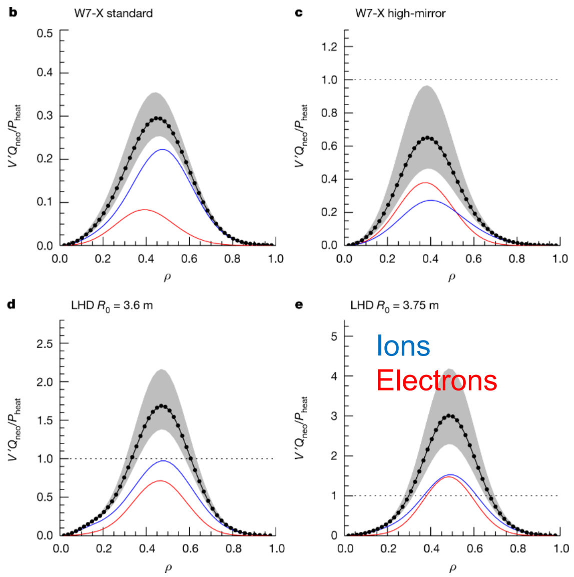


Gauss Fusion optimized plasma configuration indicating improved neoclassical transport.

HSX Stellarator



High electron temperature in HSX QHS configuration than in unoptimized configuration.
https://ncsx.pppl.gov/Physics/NSTT/HSXTheory.pdf

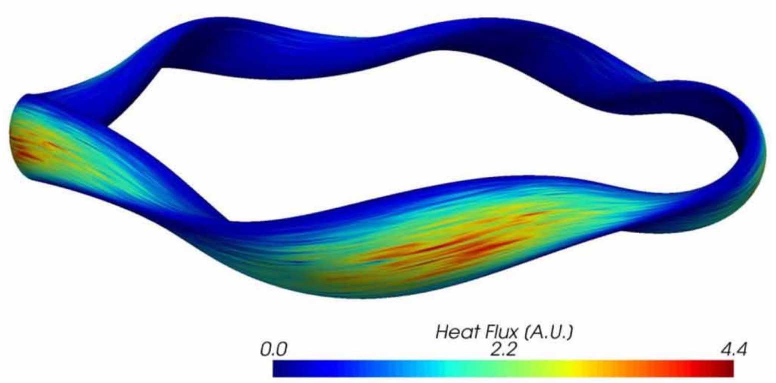


Normalized heat conduction in W7-X and LHD showing neoclassical optimization effect.
Beidler, C.D. et al., Nature **596** 7871 (2021) 221.

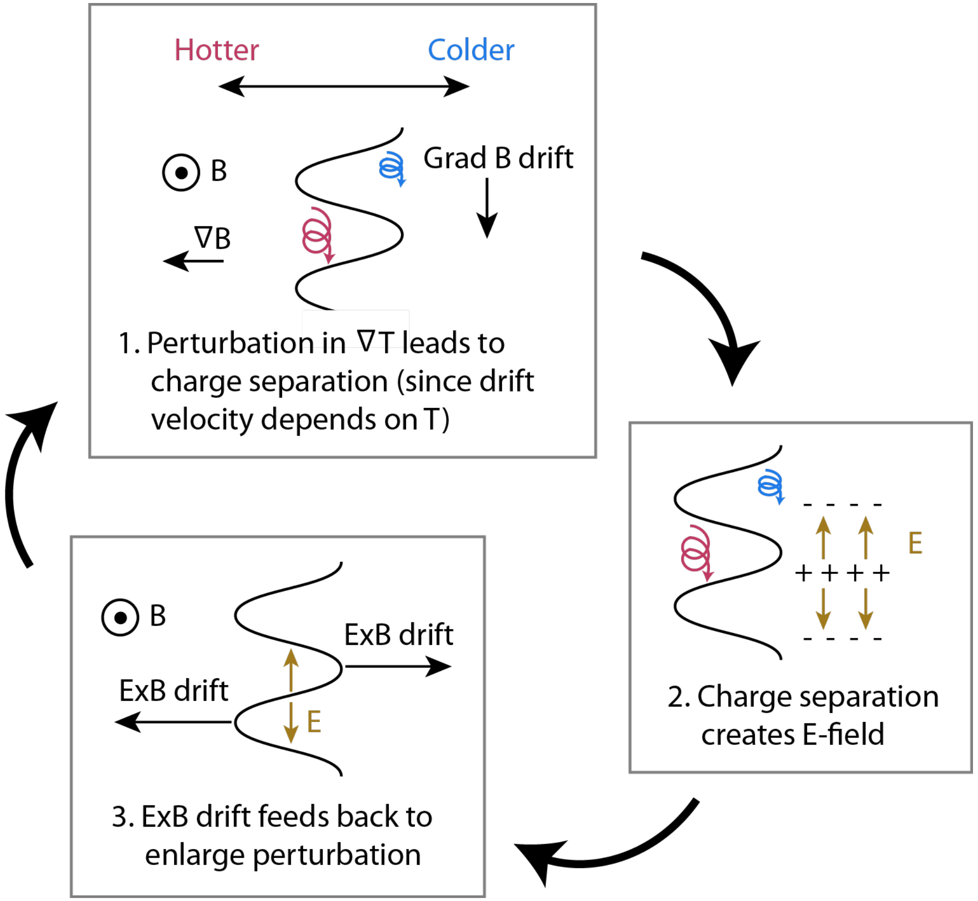
Gradients and drifts drive transport as well

Ion temperature gradient (ITG) and trapped electron mode (TEM)

- Driven by alignment of grad(B) drifts and temperature / density gradients
- Grad(B) drift velocity depends on particle energy (temperature)
- This in turn drives ExB which can enlarge the perturbation
- Net result is radial transport



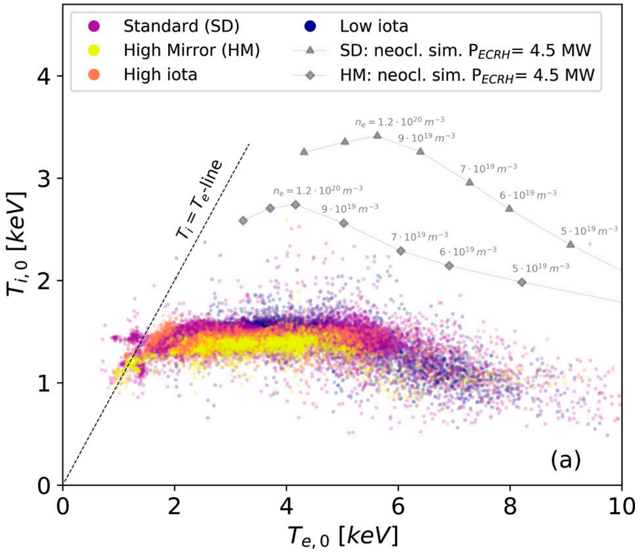
A Bañón Navarro et al 2020 Plasma Phys. Control. Fusion **62** 105005



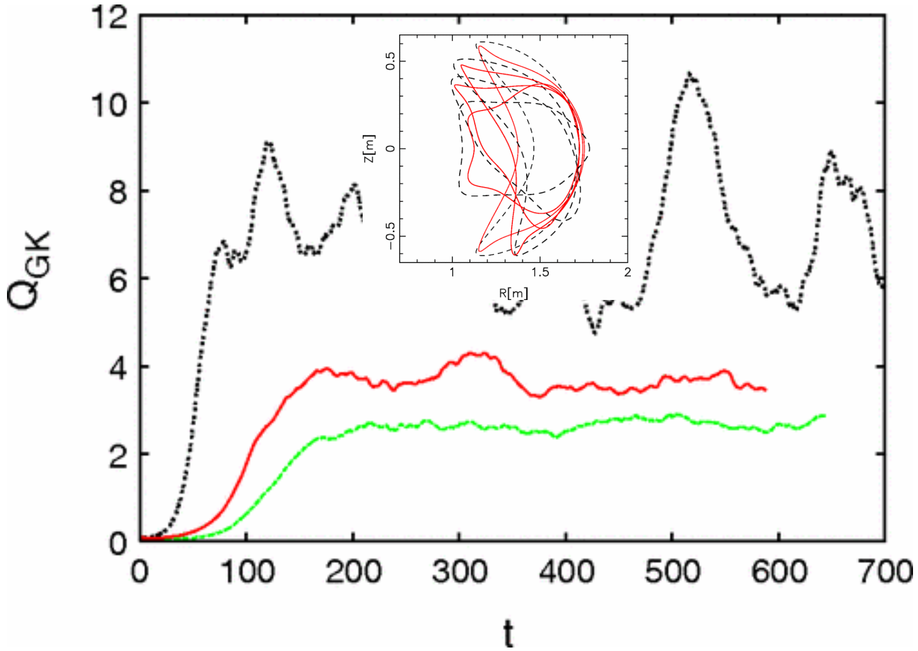
https://wiki.fusion.ciemat.es/wiki/Ion_Temperature_Gradient_instability

Turbulence can be controlled in stellarators through design

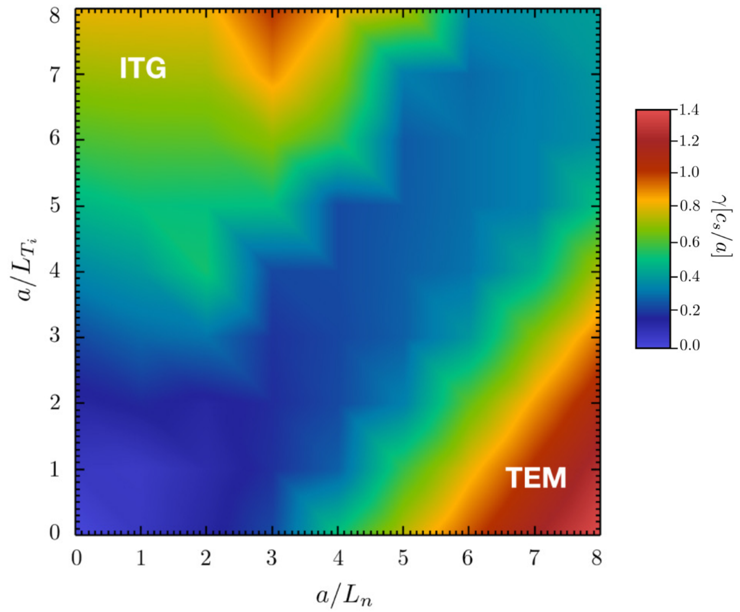
- Turbulence has been shown to limit achievable ion temperatures in stellarators and tokamaks
- Optimization using proxy functions is showing a path towards improved confinement.
- The Wendelstein 7-X experiment has experimentally show suppression of turbulence through density profile control



Achievement of experimental temperatures in W7-X.
Beurskens, M.N.A. et al., Nucl. Fusion **61** (2021) 116072.



Suppression of turbulence through stellarator shaping.
Mynick, H.E. et al., Phys. Rev. Lett. **105** (2010) 095004.

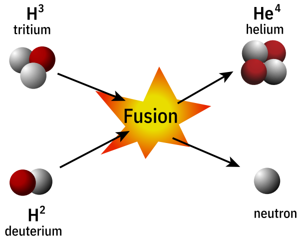


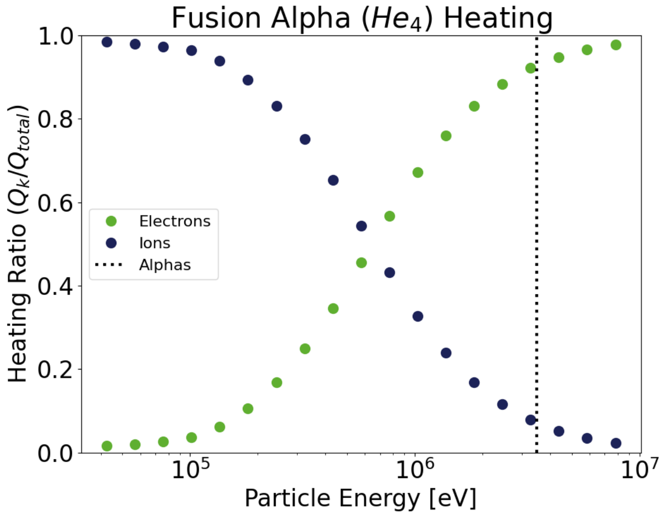
Stability valley in W7-X showing tradeoff between temperature and density gradient.
Alcusón, J.A. et al., Plasma Phys. Control. Fusion **62** (2020) 035005.

Fusion born alphas must also be confined

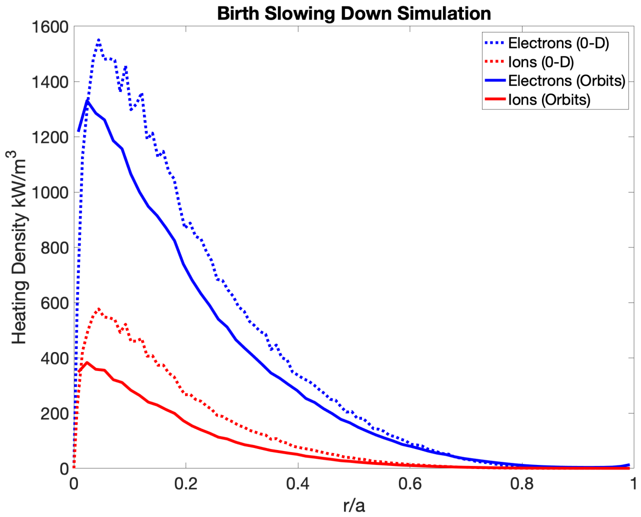
Alpha particles are born with energies well above the thermal background

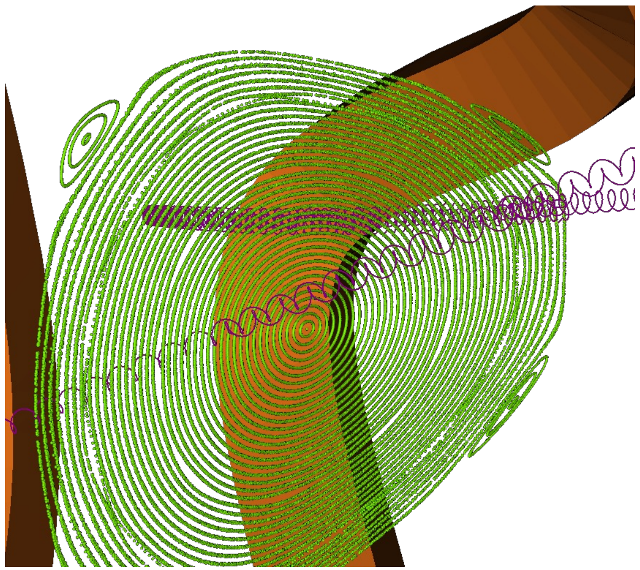
- Must be confined long enough to heat the electrons
- Passing particles are well confined but trapped particles can drift radially outward
- Alfvénic activity can be destabilized by energetic particle species.





Samuel A Lazerson et al 2021 Plasma Phys. Control. Fusion **63** 125033



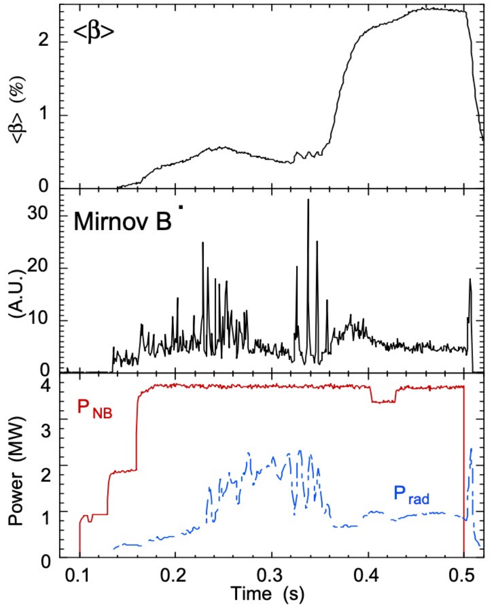


Instabilities and non-ideal effects can degrade performance

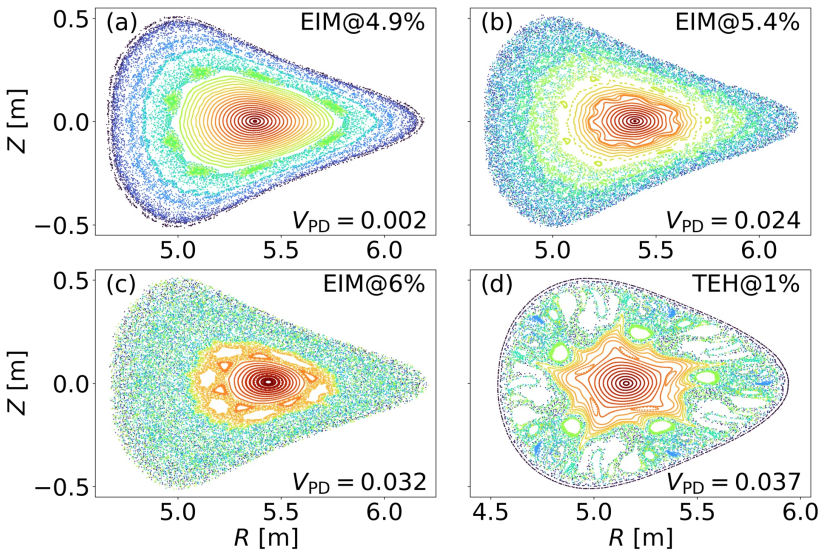
Stellarators exhibit beta limiting MHD stability phenomena

- The lack of toroidal current significantly improves stability
- Ballooning, interchange, and kink instabilities can still limit stellarator performance
- Generally, limits are soft and can be overcome

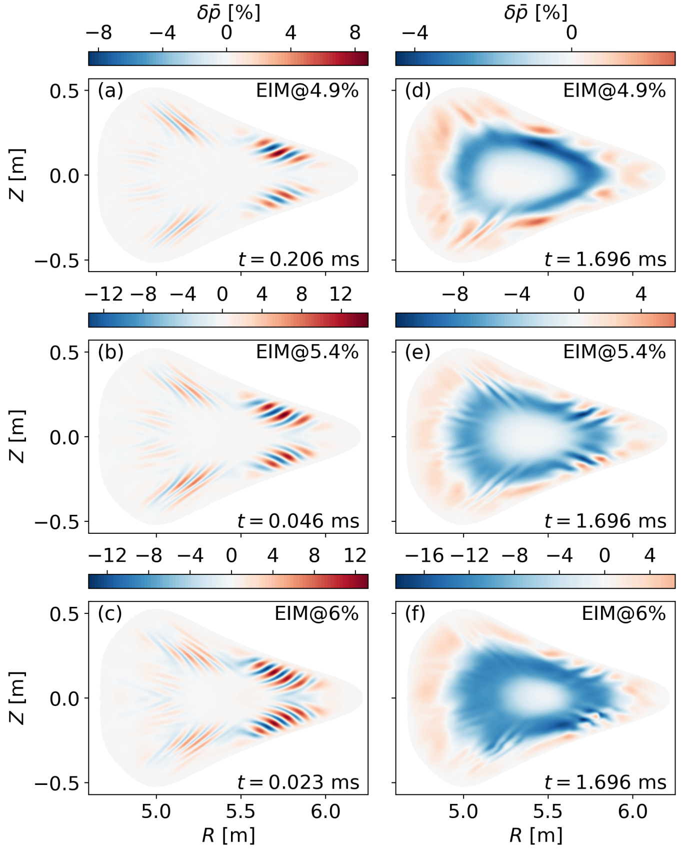
W7-AS



W7-X



W7-X

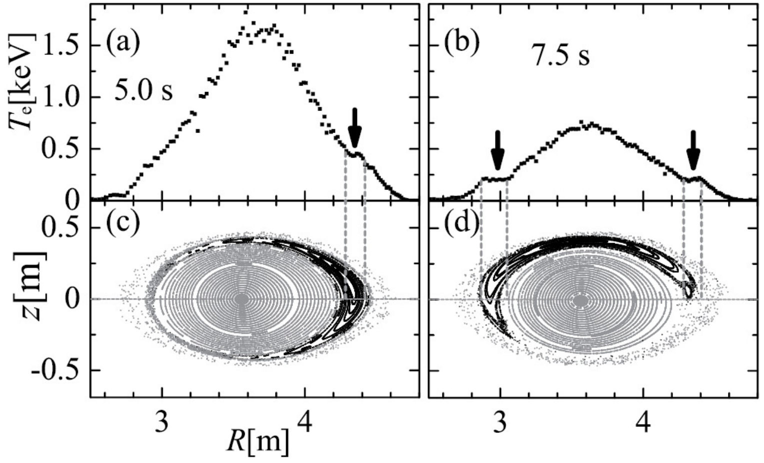


Geiger, Joachim E., et al. *Fusion science and technology* 46.1 (2004): 13-23.

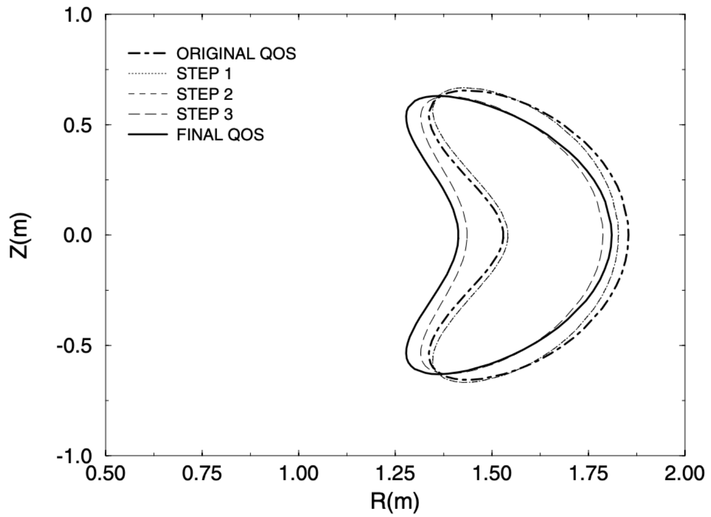
Y. Zhao *et al., 2024* Phys. Rev. Letter **133**, 135102

Shaping allows achievement of higher plasma betas

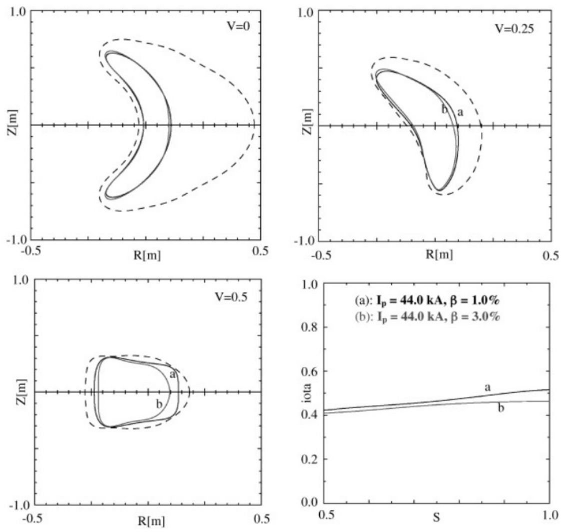
- Magnetic shear and avoidance of low order rational magnetic surfaces in plasmas.
- Shaping can be used to improve overall ballooning stability and achievable plasma beta.
- Shaping can also be used to improve finite toroidal mode number stability (kink).



Degradation of confinement due to island formation in LHD.
Y. Narushima *et al.* 2017 *Nucl. Fusion* **57** 076024



Boundary Shape optimization for ballooning stability.
R. Sanchez *et al.* 2000 *Plasma Phys. Control. Fusion* ***42*** 641



Achievement of higher plasma beta through shaping.
N. Pomphrey *et al.* 2007 *Fusion Sci. and Tech.* **51** 181

Omnigenious magnetic fields generally improve particle confinement

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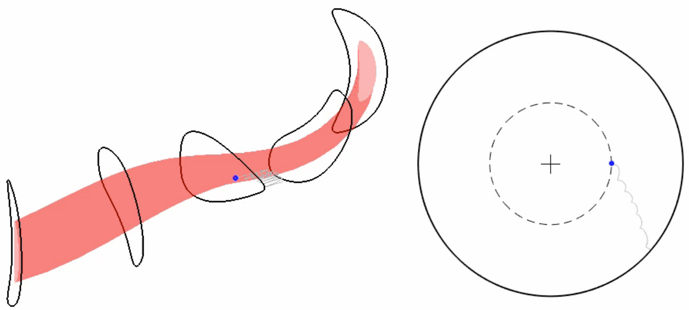
1. Three-dimensional flux surfaces generally result in large radial drifts which give rise to large neoclassical transport.
2. Magnetic field can be tailored to minimize these collisionless drifts.



Total Energy

$$H = \frac{mv^2}{2}$$

Magnetic Moment

$$\mu = \frac{mv_\perp^2}{2B}$$

Para. Velocity

$$v_\parallel = \pm\sqrt{2\frac{H-\mu B}{m}}$$

2nd Adiabatic Invariant

$$J = \int_{l_1}^{l_2} mv_\parallel dl = \sqrt{2Hm}\int_{l_1}^{l_2}\sqrt{1-\lambda B}\,dl$$

In-surface drift

$$\Delta\alpha = -\frac{1}{Ze}\frac{\partial J}{\partial \psi}$$

Radial Drift

$$\Delta\psi = \frac{1}{Ze}\frac{\partial J}{\partial \alpha}$$

$\Rightarrow$

$$\frac{\partial J}{\partial \alpha} = 0$$ Omnigenity

Magnetic symmetries make omnigenous fields accessible

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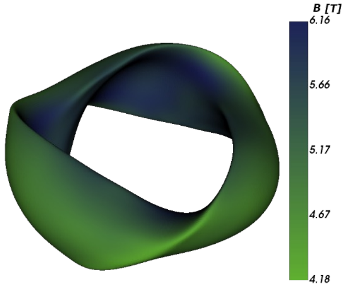
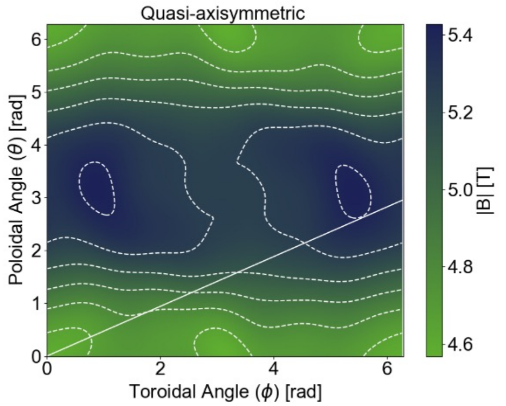
Quasi-symmetric fields

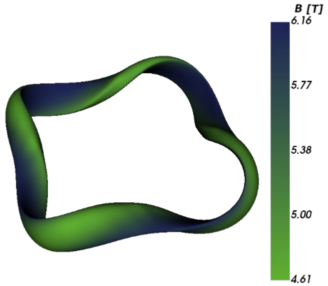
- Magnetic fields where despite having 3D shape, the magnetic field possesses a clear symmetry
- These are quasi-omnigeneous as they generally confine particle through their symmetry

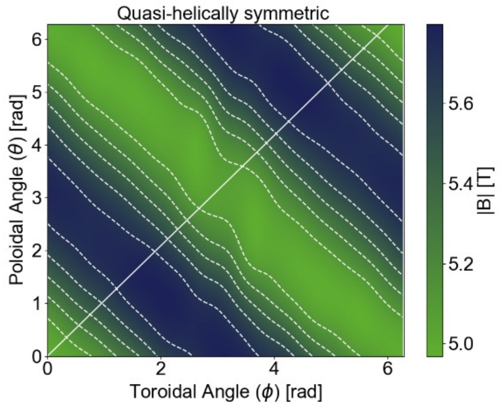
Quasi-axisymmetry



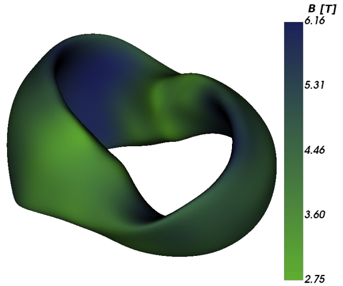


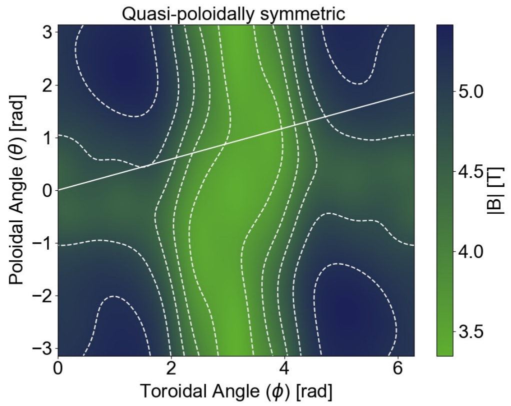
Quasi-helical symmetry





Quasi-poloidal symmetry

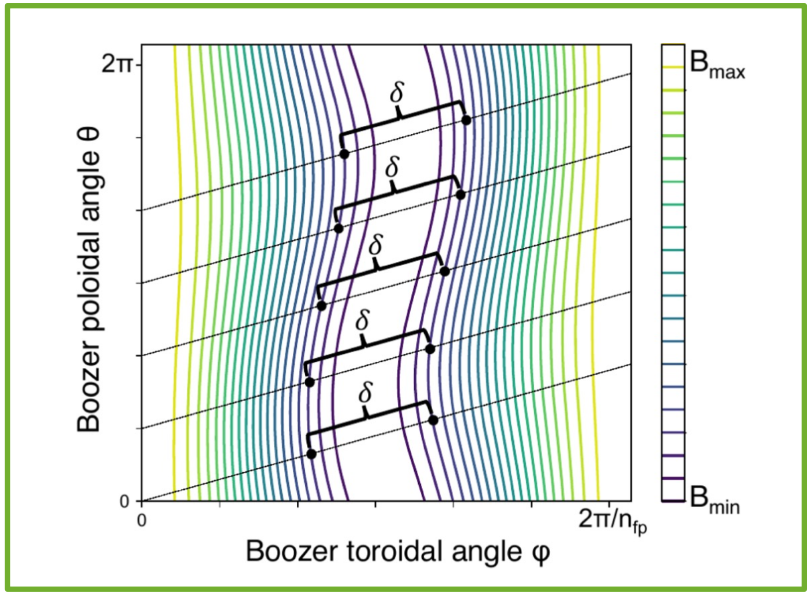




Most recently quasi-isodynamic configurations have been of interest

Quasi-isodynamic fields

- Only one minimum in magnetic field strength along any field line.
- All contours of |B| must close poloidally
- The bounce distance delta should be independent of field line label

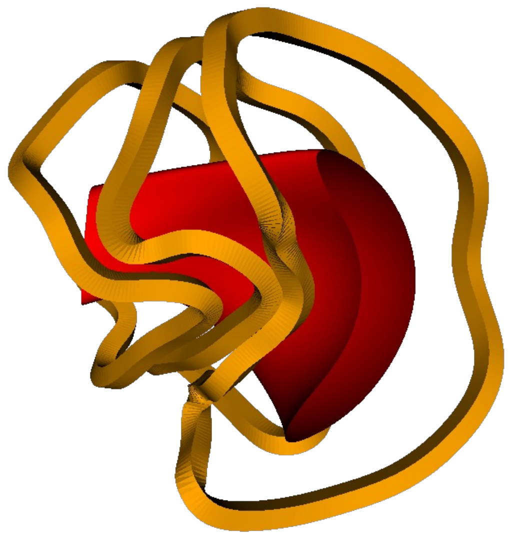


A. G. Goodman *et al.*, *Journal of Plasma Physics*, vol. 89, no. 5, p. 905890504, 2023. doi:10.1017/S002237782300065X

A coil must be optimized which produces an optimized plasma

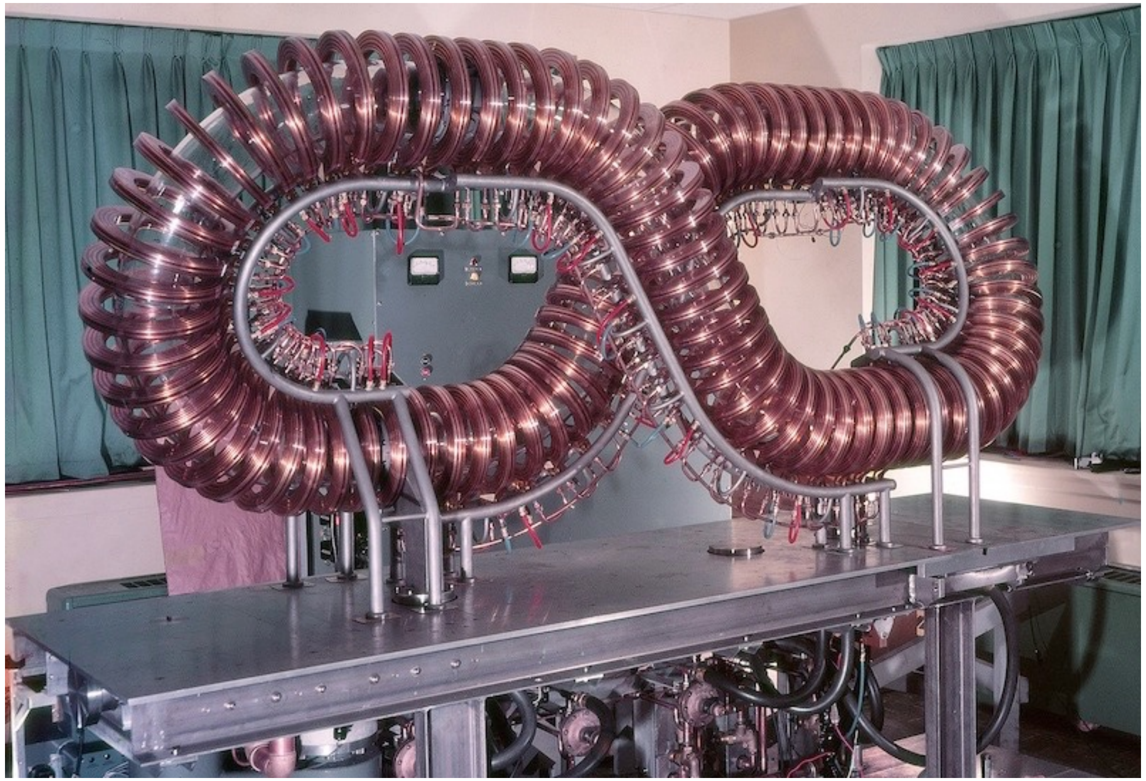
1. The plasma is defined by a closed surface which encodes the desired physics.
2. A flux surface is defined as a surface with no normal magnetic field.
3. The problem is to find a set of coils which generates that flux surface shape.

$$\boxed{\vec{B} \cdot \hat{n} = \left(\vec{B}_{plasma} + \vec{B}_{coil}\right) \cdot \hat{n} = 0}$$



Early coil designs were based on analytic formulas for magnetic fields

Lyman Spitzer with the Model A stellarator
Image: PPPL

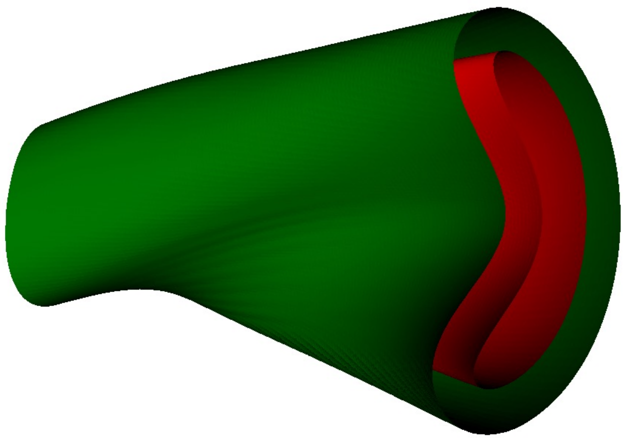


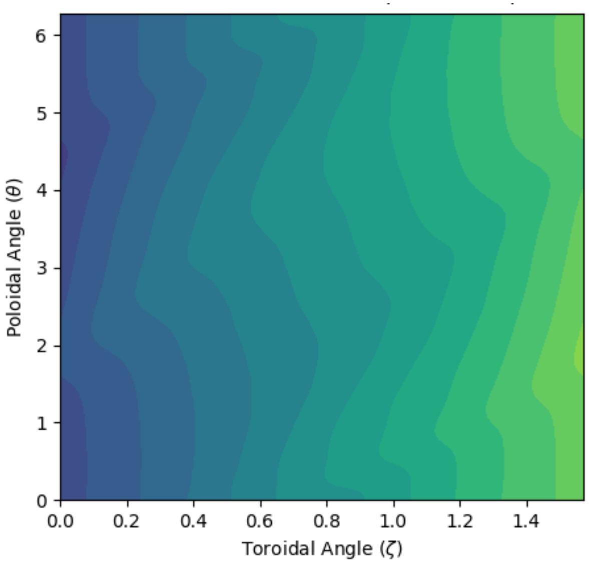
PPPL file photo

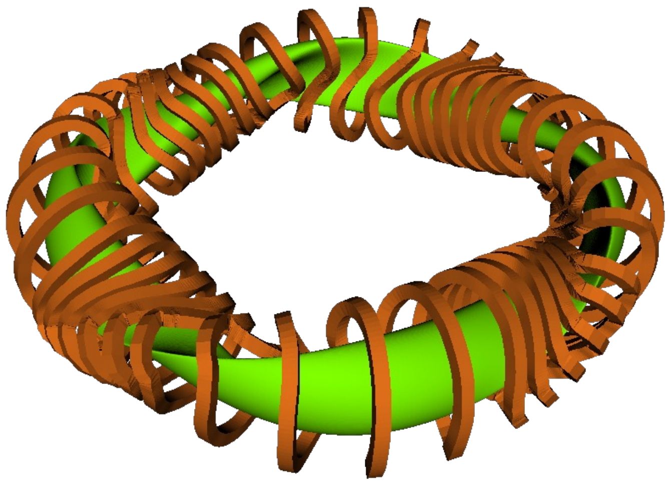
Modular coils were made possible by numerical methods

Previous machines (W7-AS and W7-X) use current surface potential method to design coils

- Winding surface chosen a fixed distance away from plasma
- Coils cut from current potential
- Engineering constraints as afterthought



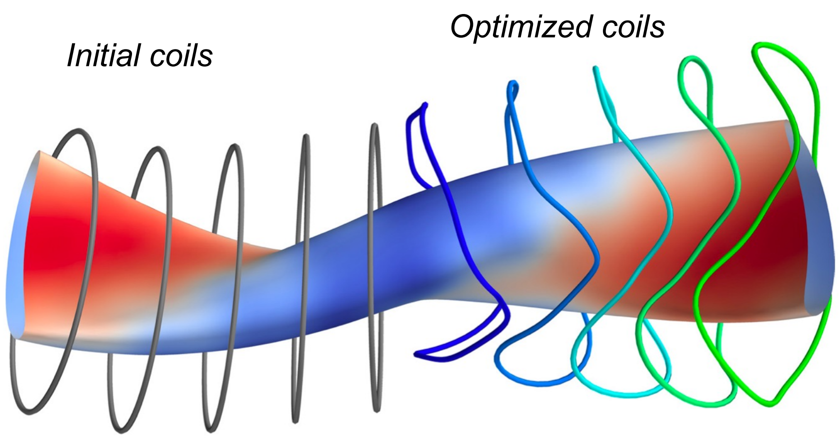




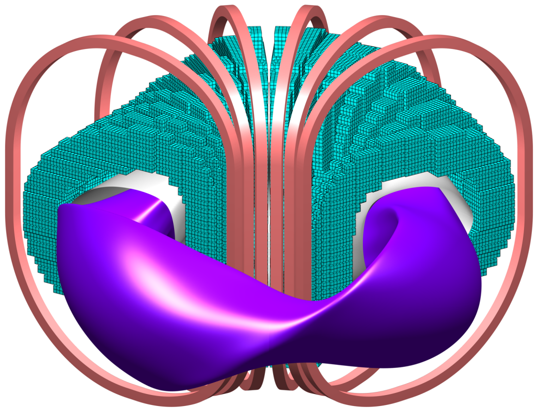
Modern techniques are incorporating engineering and divertor constraints

The desire for inclusion of space for blankets and remote access is driving coil design

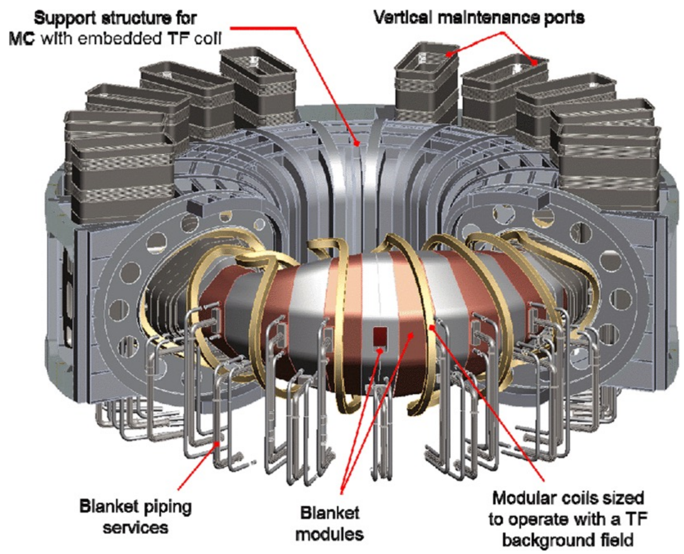
- Winding surface free optimization
- Robust optimization techniques for limiting error fields
- Inclusion of saddle coils and permanent magnet fields for novel designs



C. Zhu, Nucl. Fusion 2018



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



T. Brown et al., 2015 IEEE 26th SOFE, 1-6

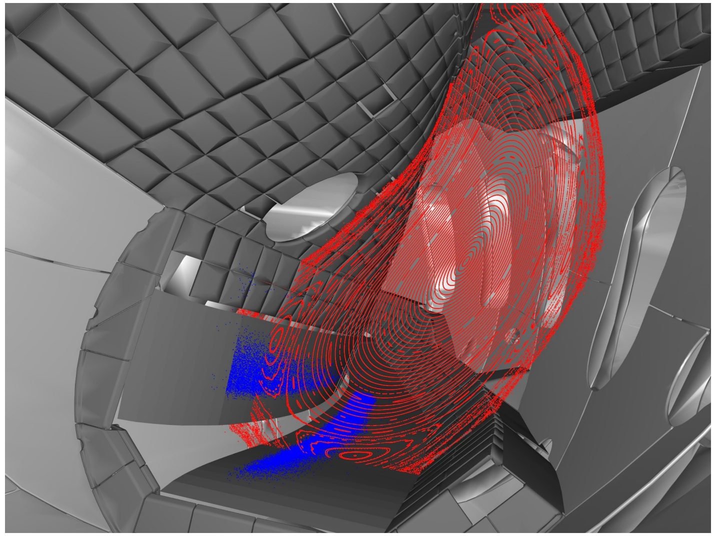
Stellarator divertor concepts are have grown in maturity

Magnetic island divertor

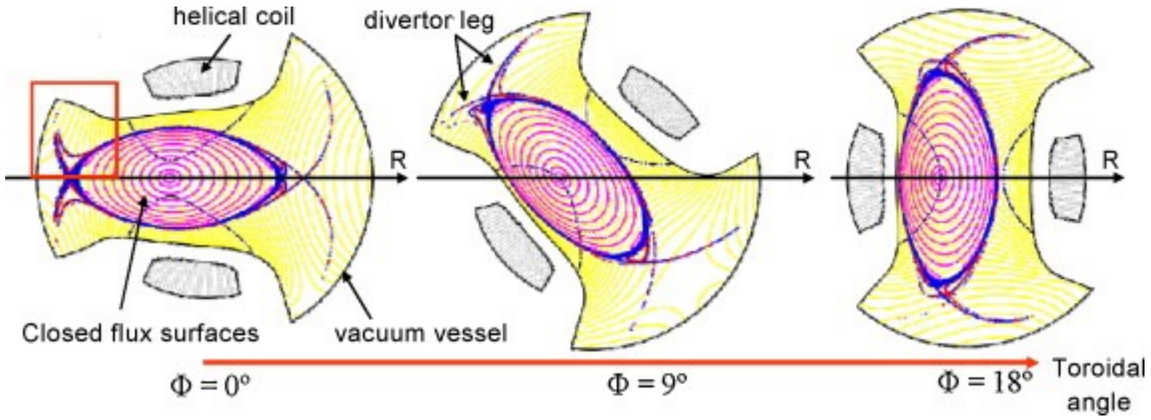
- Low order rational surface used to generate edge island chain
- Interaction between plasma wall and island chain helps control heat and particle exhaust

Helical Divertor

- Helical coil generates a divertor leg-like structure.
- Divertor plates placed to intersect leg-like structures.



Samuel A. Lazerson *et al* 2019 *Nucl. Fusion* **59** 126004



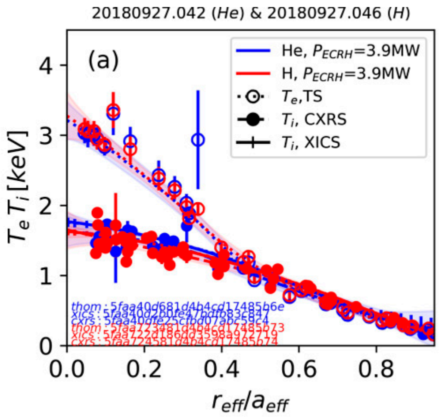
S. Masuzaki *et al* 2010 *Fusion Eng. and Design* **85** 940

Stellarators are now viable power plant candidates

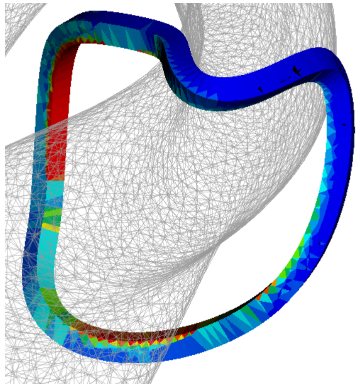
1. Optimization suppresses neoclassical transport achieve tokamak levels of confinement.
2. Optimization improves fast ion confinement beyond acceptable levels.
3. Magnetic quasi-symmetries provide a framework for understanding underlying physics
4. Bootstrap currents are generally low and paths to compete suppression are available.
5. Stability limits are generally soft and can be overcome.
6. Modular coil designs demonstrated at scale and have advantages over tokamak coil sets

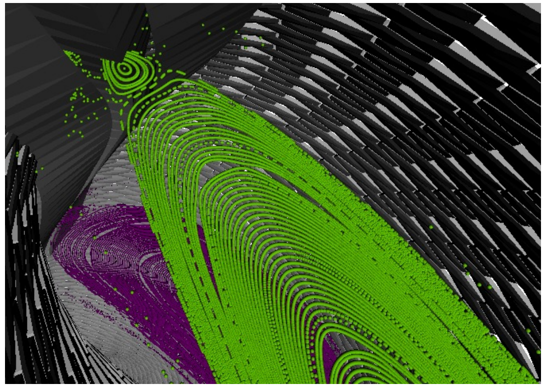
The future of stellarator research is focusing on the power plant environment

1. Achievement of fusion relevant ion temperature with electron heating an open topic
2. The nuclear environment is setting requirements on coil-plasma distances
3. Divertor pumping and detachment research is motived by materials and fuel cycle needs



Beurskens, M.N.A. et al., Nucl. Fusion **61** (2021) 116072.





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