# A Brief Introduction to Stellarators

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SULI Summer School 2020

1. Arturo: Please put a slide about yourself
2. What is a stellarator?
3. Why should we use stellarators?
4. How do we build a quality stellarator?
5. The present and future of stellarator research

# A career in plasma physics can start here!

- Undergrad: Cooper Union (Mech. Engineering)
- 2003 - NUF/SULI program at PPPL
- 2D phase: PhD from MIT in Applied Plasma Physics working on Alcator C-Mod tokamak
- 3D phase: PostDoc to research staff at UW-Madison working on stellarators

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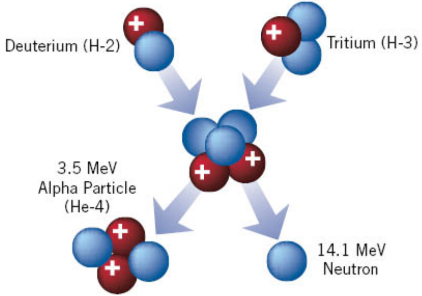
Tokamak

Stellarator

# Nuclear fusion requires large $nT\tau$

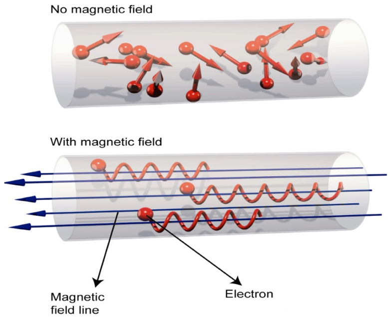
- $n$ = Density: how likely nuclei collide
- $T$ = Temperature: Ensures nuclei have enough energy
- $\tau$ = Confinement time: Make sure particles are not lost before collisions

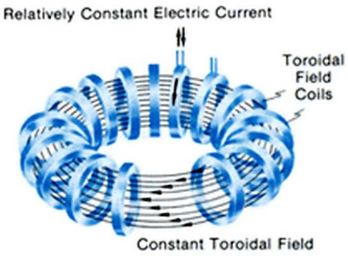



Picture from ANS

Magnetic Confinement Fusion tries to find better ways of improving, $\tau$, the confinement of the plasma using magnetic fields

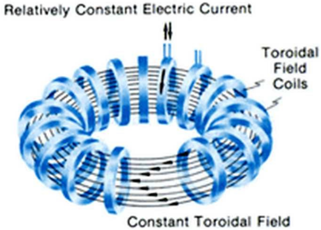
# Using magnetic fields to confine plasma

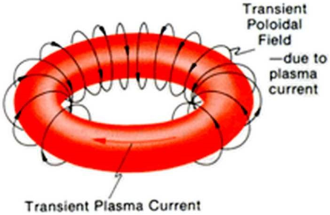


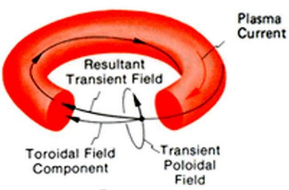




- Magnetic fields prevent motion perpendicular to a field, but allow parallel motion
- Confinement attempt 1: Make field lines into circles!

# Why we need rotational transform

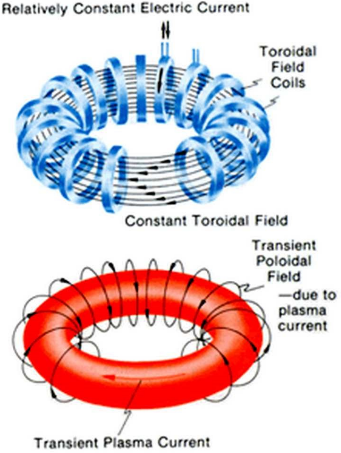


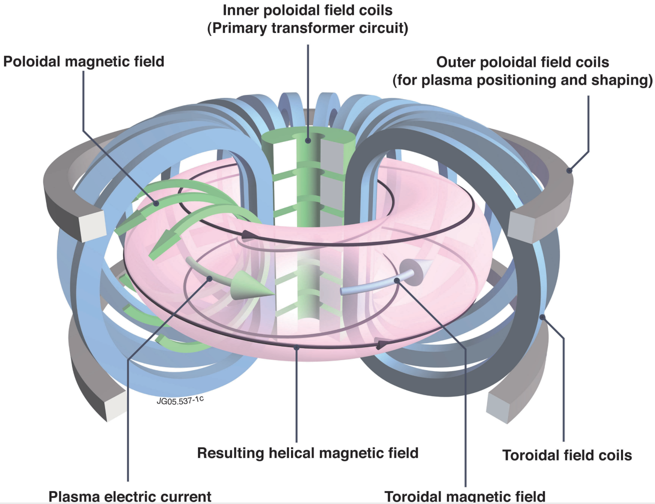



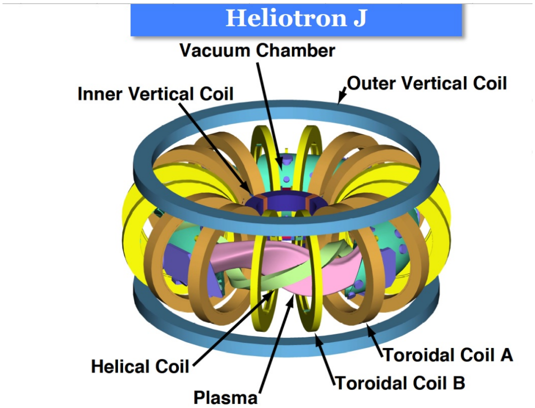

- With only toroidal fields, plasma will drift right out of the machine and into the wall
- Need a field in the other (poloidal) direction
- Rotational transform: $B_{\text{pol}}/B_{\text{tor}} \propto \iota \propto 1/q$

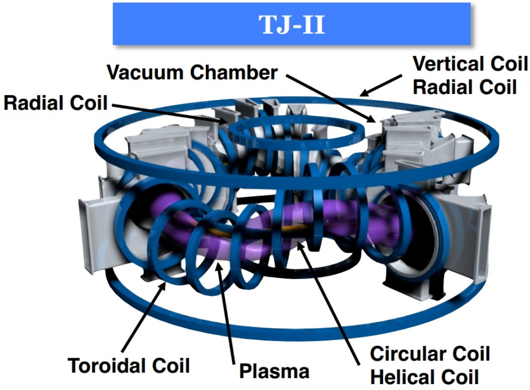
# Tokamaks use plasma current to generate rotational transform



# Stellarators use coil shapes and arrangements to generate transform



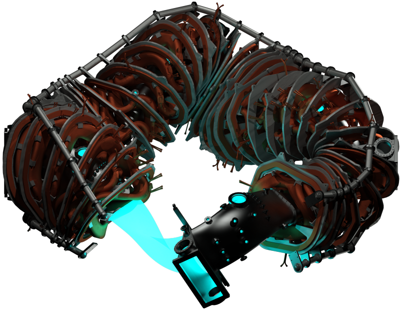




Pictures from S. Yamamoto IAEA 2012

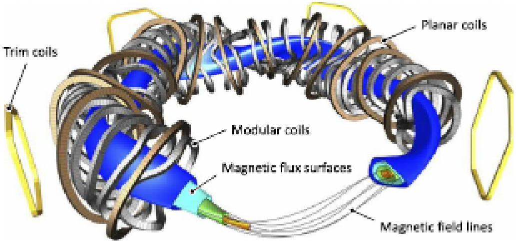
"Simple" stellarators combine circular coils with helical coils

# Stellarators use coil shapes and arrangements to generate transform

HSX



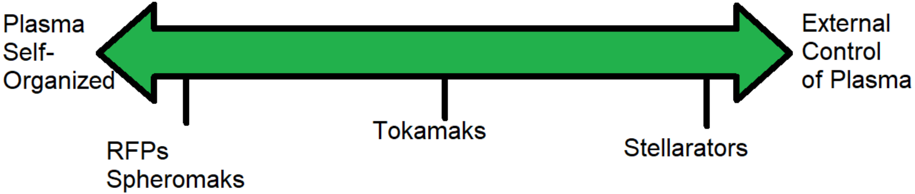
W7-X




W7-X picture from Wolf PoP 2019

Stellarators can be built with complicted 3D coils

# Stellarators try to externally control the plasma as much as possible




- Self-organized: Use plasmas self-generated fields to confine itself as much as possible. Make the plasma work for you!
- Externally controlled: Make the confinement fields independent of plasma behavior. Plasmas cannot be trusted!

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# Stellarators do not rely on plasma current for confinement

- Inherently steady state
- Long pulse operation possible
- LHD can operate a 24 million degree Kelvin plasma for over half an hour
- No current-driven disruptions or runaway electrons!

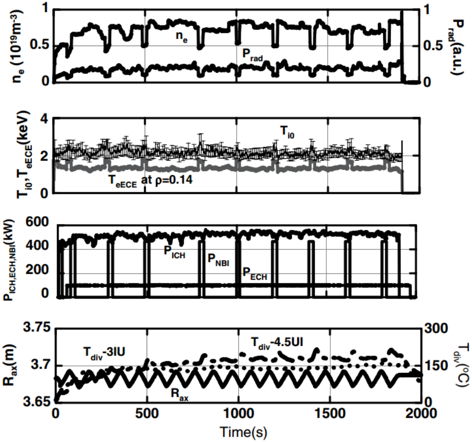
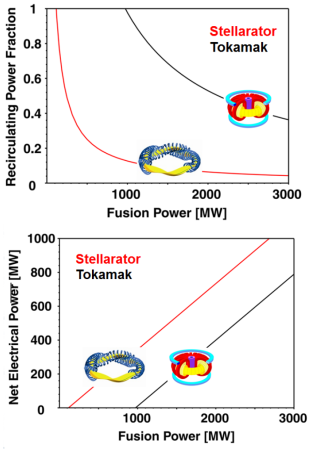



Figure from
Kumazawa Nuclear Fusion 2006

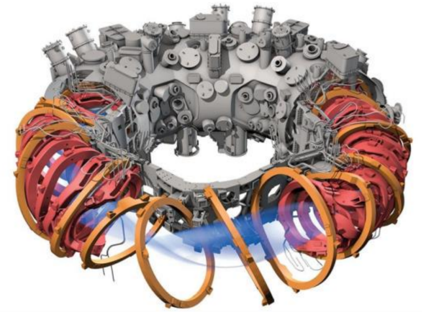
# Low recirculating power - improve reactor payout




Zohm Nuclear Fusion 2017

- Tokamak central solenoid can only provide current drive for so long
- Driving plasma current in steady-state is very inefficient
- Removing current drive allows for smaller scale devices that produce net power

# What are the difficulties?



Klinger IAEA 2018

- 3D nature makes it more difficult to design and construct
  - Still learning how to design the best possible stellarator
  - Opportunities exist for tailoring the configuration to the exact reactor needs
- No axisymmetry makes simulation and analysis more difficult

Video of W7-X construction:

https://www.youtube.com/watch?v=CJ_OBoEs3uU

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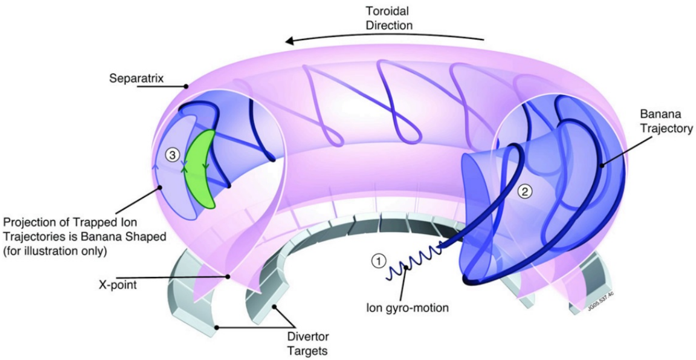
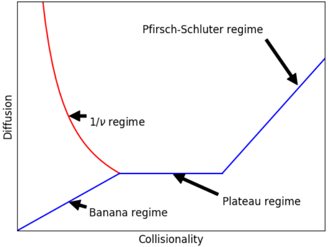
# In axisymmetry precessional drifts are in the toroidal direction

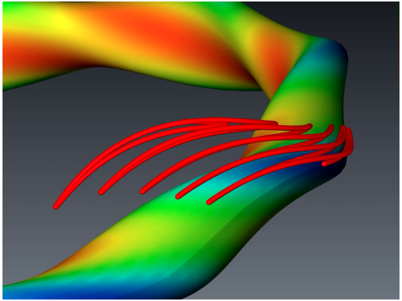



Picture from Briesemeister SULI 2015

- ”Trapped” particles reflect on the high field side making ”banana” orbits
- In addition particles undergo ”precessional” drift, which moves them in the toroidal direction

# Unoptimized stellarator can have drift losses



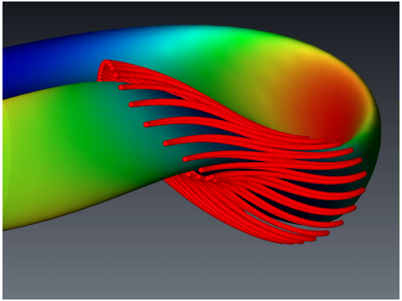



Picture courtesy if IPP-Greifswald

- With no symmetry direction, precessional drifts may cause particles to leave flux surfaces
- This can create large ”neo-classical” collisionless losses - thought to be a showstopper for stellarators

# With optimization, trapped particles can be confined

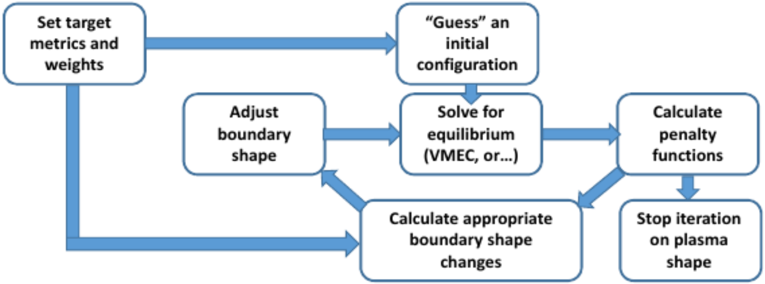
- The net drift for a particle of a flux surface is called the ”bounce-averaged radial drift”
- With effort it is possible to choose a shape such that some trapped particles are confined: bounce-averaged radial drift = 0
- Focus mainly on deeply trapped particles since they are the biggest problem



Picture courtesy if IPP-Greifswald

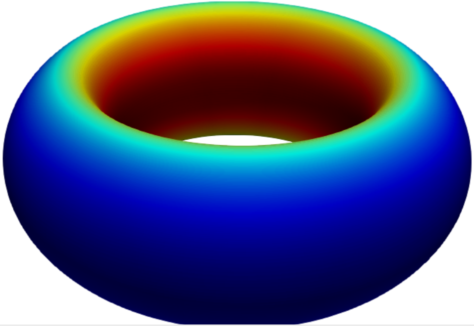
# So you want to design a stellarator?

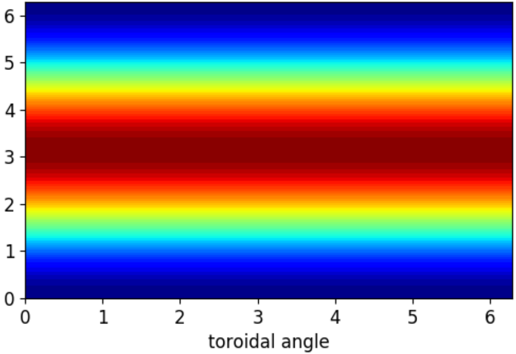
- Define targets to optimize and set weights for targets
- Solve for equilibrium, evaluate target functions
- Perturb $\mathbf{R}, \mathbf{Z}$ in an optimization scheme



# Axisymmetric devices have all drift orbits confined

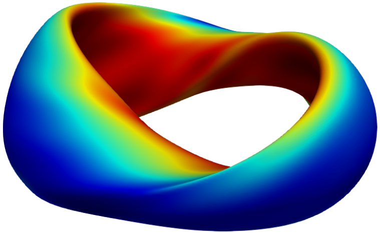
Calculations can show that a coordinate system exists where bounce-averaged drifts depend only on magnetic field strength (Boozer coordinates)

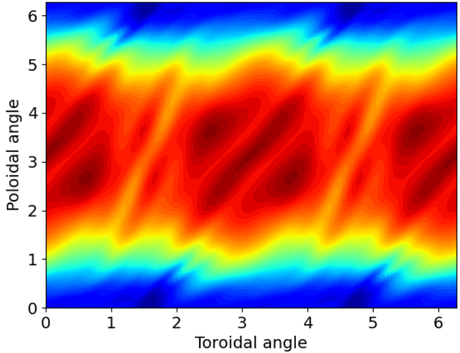




# Can approximate axisymmetry even with non-axisymmetric shapes

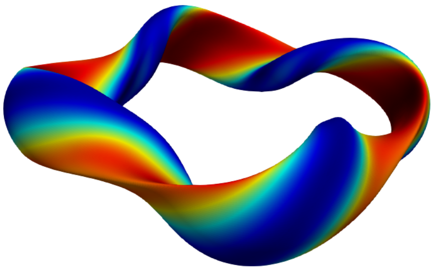
If magnetic field strength is axisymmetric in Boozer coordinates, bounce-averaged drifts are eliminated and particles are confined: Quasi-axisymmetry (ex. from Henneberg 2019)

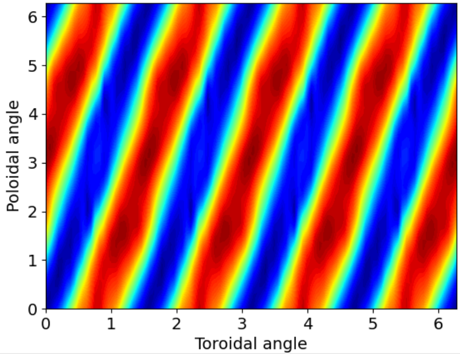




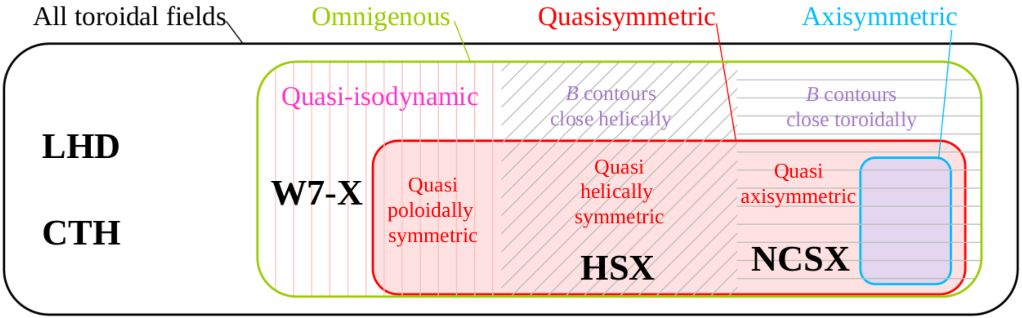
# Can produce same good properties in helical systems

Quasihelical symmetry is when magnetic field strength is symmetric in the helical direction (ex. HSX)





# The zoology of stellarators




Landreman PhD Thesis 2011

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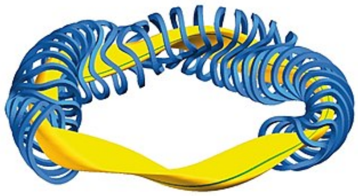
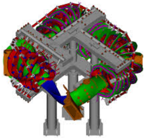
# Stellarator experiments are an international effort

W7-X (Optimized QO) $R$=5.5 m, $a$=0.53 m, $B$=3T

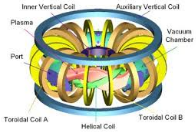


LHD (Unptimized Torsatron) $R$=3.5 m, $a$=0.6 m, $B$=3T

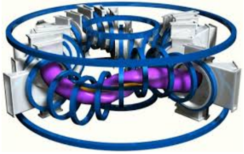
HSX (Optimized QH)
$R$=1 m, $a$=0.15 m, $B$=1 T



Heliotron-J (Unptimized)
$R$=1.2 m, $a$=0.15 m, $B$=1.5 T

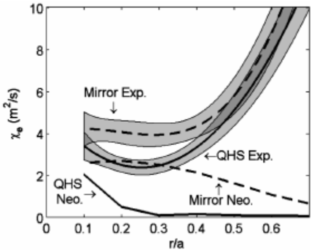



TJ-II (Unoptimized Heliac)
$R$=1.5 m, $a$=0.22 m, $B$=1 T

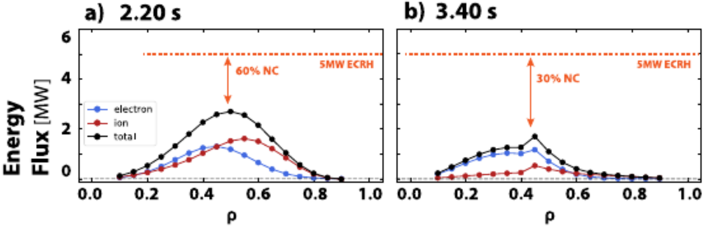


# Optimized stellarators show reduction of ”neo-classical” transport

HSX




W7-X




- Optimization has reduced neo-classical transport in optimized stellarators HSX and W7-X
- Improving transport further requires reducing turbulent transport

Canik Phys. Rev. Let. 2007, Pablant Nuc. Fus. 2020

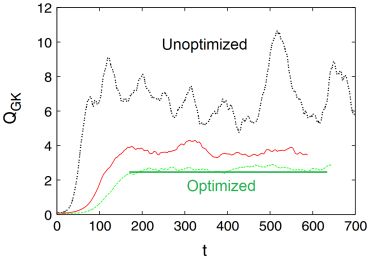
# Key areas of stellarator physics going forward

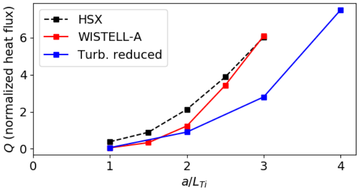
- Reduce both turbulent and neo-classical transport at the same time
- Make sure the plasma can exhaust heat without destroying the walls (day 6)
- Confine energetic particles, like those produced from fusion reactions
- Make sure impurities don't build up in the plasma
- Design simpler machines that are easier to construct

# Can we design a device optimized for turbulent transport?

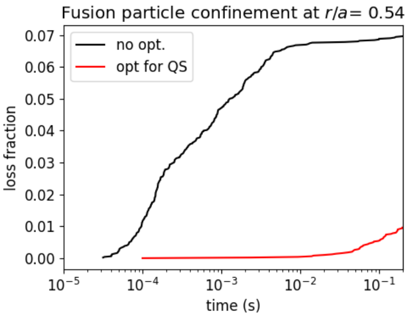
- Different stellarators have different turbulent transport properties
- Non-linear heat flux too expensive for an optimization loop
- Several possibilities for how to reduce turbulence
  - Target growth rates, how ”powerful” the transport channel is
  - Target correlation times, mitigate powerful channels by moving energy to others

Mynick Phys. Rev. Let. 2010, Bader submitted to J. Plas. Phys.



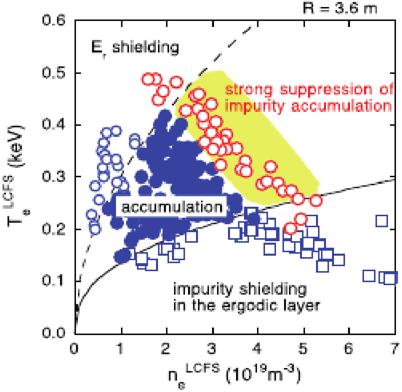
# Must confine fusion products to heat the plasma




- Must confine fusion products long enough so that they deposit energy in plasma
- 3.5 MeV fusion alpha particles can damage the wall if lost immediately
- Having good thermal particle confinement does not guarantee good energetic particle confinement
- Stellarators must be optimized to confine both thermal and energetic particles

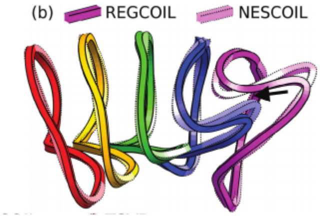
# All fusion devices need to expel impurities from the plasma

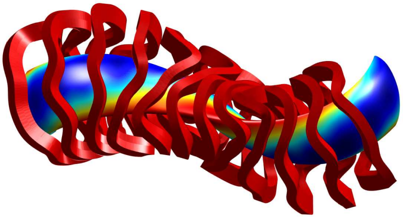
- Fusion products must be expelled after energy has been deposited
- Heavy ions from wall structures must be prevented from entering
- Theory predicts that stellarators should accumulate impurities (bad) but experiments show different behavior (good!)




Nakamura Nuclear Fusion 2017

# Can we build better and simpler coils



- New codes such as REGCOIL (Landreman 2017) and FOCUS (Zhu 2018) leverage computational power to simplify coils
- Can expand coils in non-sensitive areas
- Can mix different coil types
- Loosen engineering tolerance by stochastic optimization
- Next step: bringing coils into the overall optimization loop

# Stellarators: convincing those sneaky plasmas to behave

- Stellarators are magnetic confinement devices that use shaped coils with 3D magnetic fields to confine the plasmas
- Through optimization, stellarators like HSX and W7-X can confine thermal particles well
- Improved methods of optimization allow for substantial improvements in performance