Improving the stellarator through advances in plasma theory

C. C. Hegna[1], D. T. Anderson[1], A. Bader[1], T. A. Bechtel[1], A. Bhattacharjee[2], M. Cole[2], M. Drevlak[3], J. Duff[1], B. J. Faber[1], S. R. Hudson[2], M. Kotschenreuther[4], T. Kruger[1], M. Landreman[5], I. J. McKinney[1], E. Paul[2,9], M. J. Pueschel[6], J. S. Schmitt[7], P. W. Terry[1], A. S. Ware[8], M. Zarnstorff[2], C. Zhu[2]

[1]University of Wisconsin-Madison, [2]Princeton Plasma Physics Laboratory, [3]IPP-Greifswald, [4]University of Texas, [5]University of Maryland, [6]Eindhoven University of Technology, [7]Auburn University, [8]University of Montana, [9]Princeton University

IAEA Fusion Energy Conference
Session OV/3
May 10, 2021

Motivation of this work is to improve the stellarator concept

- Recent success in the stellarator program is driven by the era of optimization.
  - With a strong theoretical foundation, the concepts of quasi-symmetry (QS), quasi-omnigeneity (QO), quasi-isodynamicity (QI), etc. were produced to solve the problem of poor neoclassical transport at low collisionality

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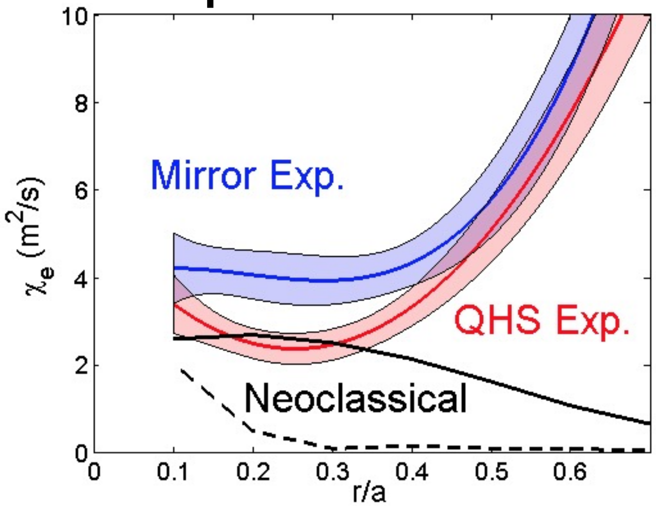
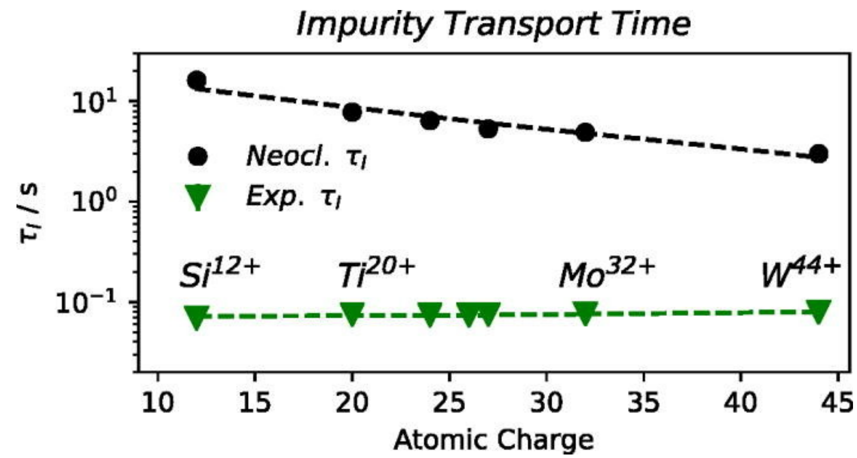
HSX experiments indicate electron heat transport is anomalous



Canik et al PRL ’07

Anomalous transport dominates impurity transport on W7X



Langenberg et al PoP ’20

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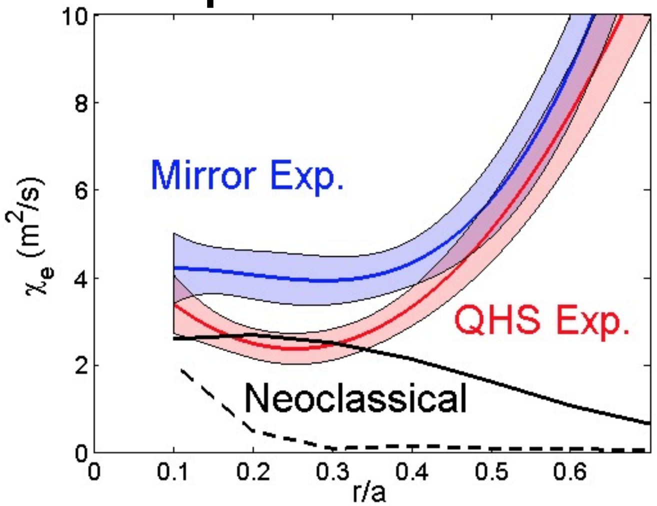

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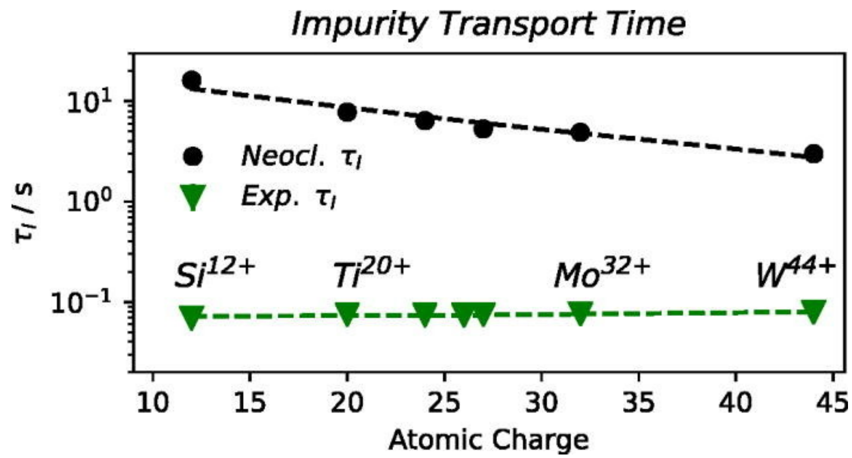


Langenberg et al PoP '20

- In the next generation of stellarator design, the promising features of neoclassical optimized high-beta stellarators can be united with new opportunities:
  - Improve high-energy particle confinement
  - Reduce turbulent transport
  - Avoid impurity accumulation
  - Simplify coil design
  - Develop robust divertor solutions

Thesis

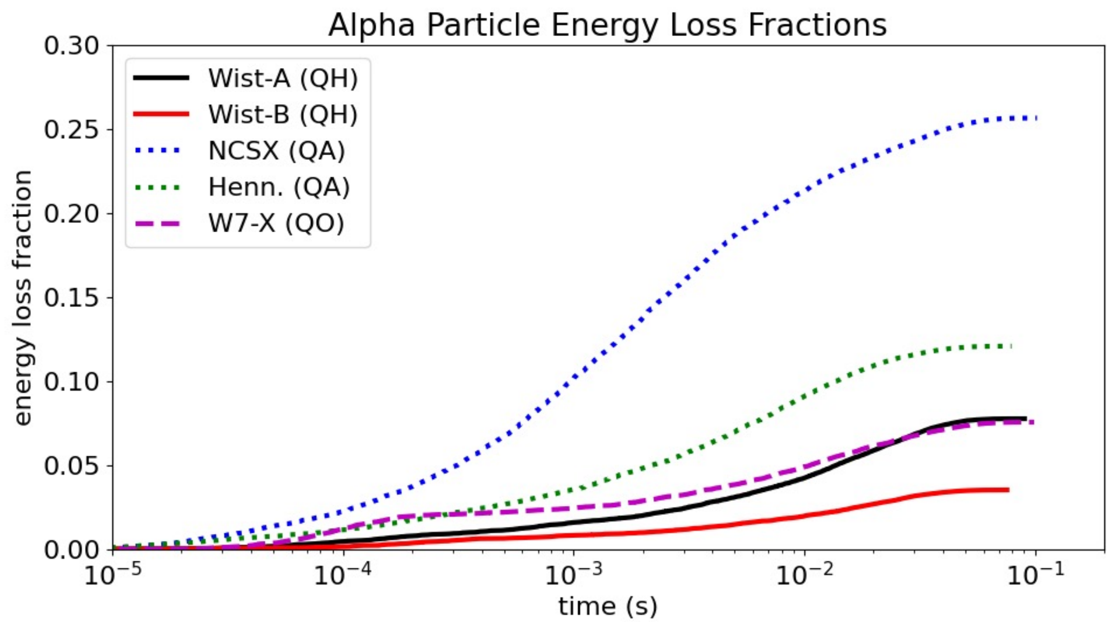
- Improvements to the stellarator concept can be realized through advancements in theoretical and computational physics

- Several recent advances are reported in the following topical areas aimed at:
  - Improving energetic ion confinement
  - Reducing turbulent transport
  - Reducing coil complexity
  - Providing novel optimization and design methods
  - Developing new 3D MHD tools

- Advances in physics understanding improves stellarator optimization efforts and enable the design of new stellarator configurations with excellent confinement properties.

Stellarator configurations with excellent energetic ion confinement have been designed

- Energetic ion confinement is a conventional weakness for stellarators.
  - 3D geometry can lead to net radial drifts of trapped energetic ions
  - Flagged as a crucial issue for stellarator reactors (Mau '08)
- Method to significantly improve energetic ion confinement in reactor-scale stellarators has been identified (Nemov et al '08, Bader et al JPP '19, JPP'20)
  - Recipe: optimize to quasi-helically symmetry and alignment of $J_{||} = \int m v_{||} dl$ with magnetic surfaces.
  - Configurations found with no collisionless losses for EP born inside $\frac{r}{a} \sim 0.5$
- Alpha losses are computed for a variety of stellarator configurations
  - $V = 450\, m^3, B = 5.6\, T$
  - Collisions enhance EP loss
- Quasi-helically symmetric (QHS) generally best performer $\sim 2\%$ alpha losses

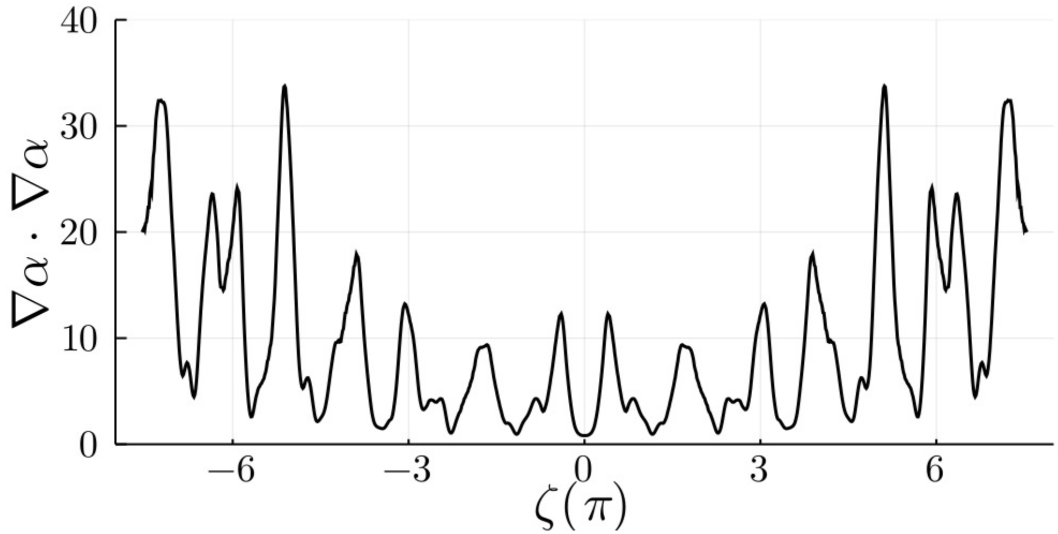


Bader et al, P1 Poster, FEC 2021

Reduced turbulent transport is a goal of the next generation of stellarators

- Transport in neoclassical optimized stellarators is anomalous
  - Micro-instabilities (ITG, TEM, KBM, ETG ...) are thought to be responsible
- Stellarator theory benefits from improvements in Gyrokinetics modeling (GENE,EUTERPE, XGC-S, Stella) and analytic understanding in past decade
  - Stellarator has more complex geometric properties
  - Optimization approaches target reduced growth rates
    - Lower linear growth rates via manipulating magnetic geometry (Mynick PRL ’10; Xanthopolous et al ‘14, Proll et al PPCF ‘16)
    - Maximum-J configurations (Helander et al, PoP ‘13)
      - Benefit to TEM stability
      - Guide for favorable W7X operation

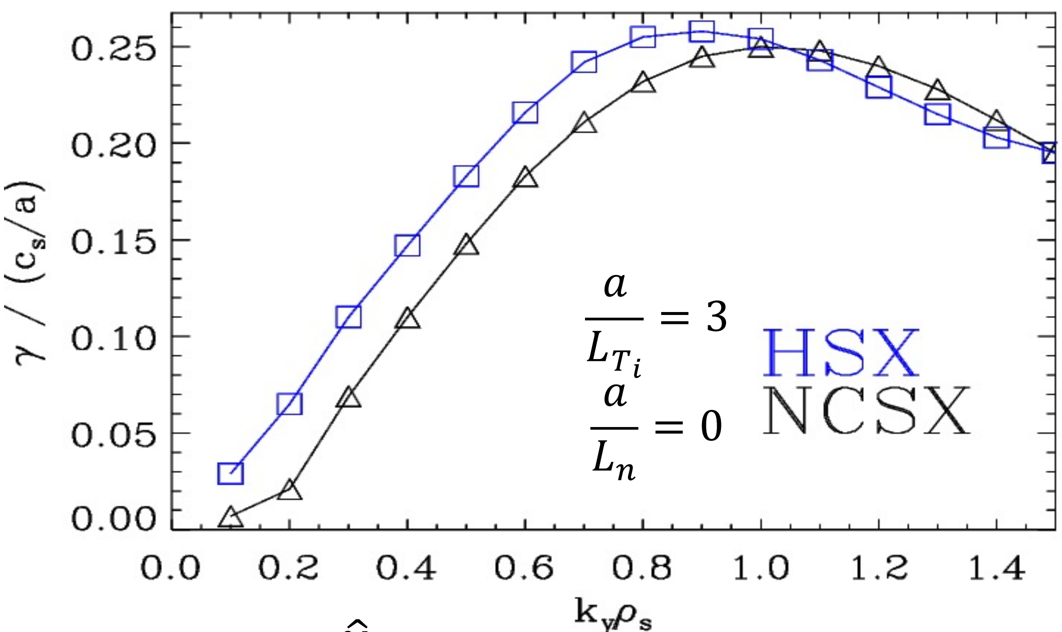
(Integrated local magnetic shear)^2 of along field line in flux tube geometry



Quasi-linear models has limited applicability for predicting turbulent transport in quasi-symmetric stellarators

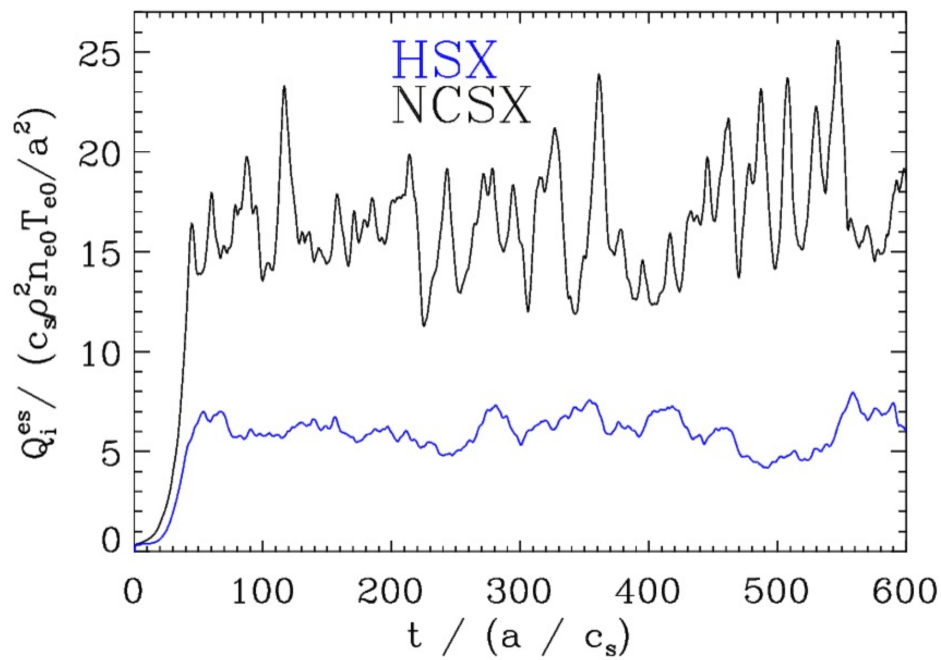
- Comparison of Quasi-Helically and Quasi-Axisymmetric configurations
- Linear and nonlinear GENE ITG simulations (McKinney et al JPP ‘19)

Linear Growth Rates for HSX and NCSX



$$\frac{\left(\sum \frac{\hat{\gamma}}{< k_\perp^2 >}\right)^{HSX}}{\left(\sum \frac{\hat{\gamma}}{< k_\perp^2 >}\right)^{NCSX}} \sim 4.2$$

GENE simulations of turbulent transport



$$\frac{\hat{\chi}^{HSX}}{\hat{\chi}^{NCSX}} \sim \frac{1}{3}$$

- HSX has higher linear growth rates than NCSX, but lower turbulent transport
- Differences due to nonlinear turbulent saturation physics

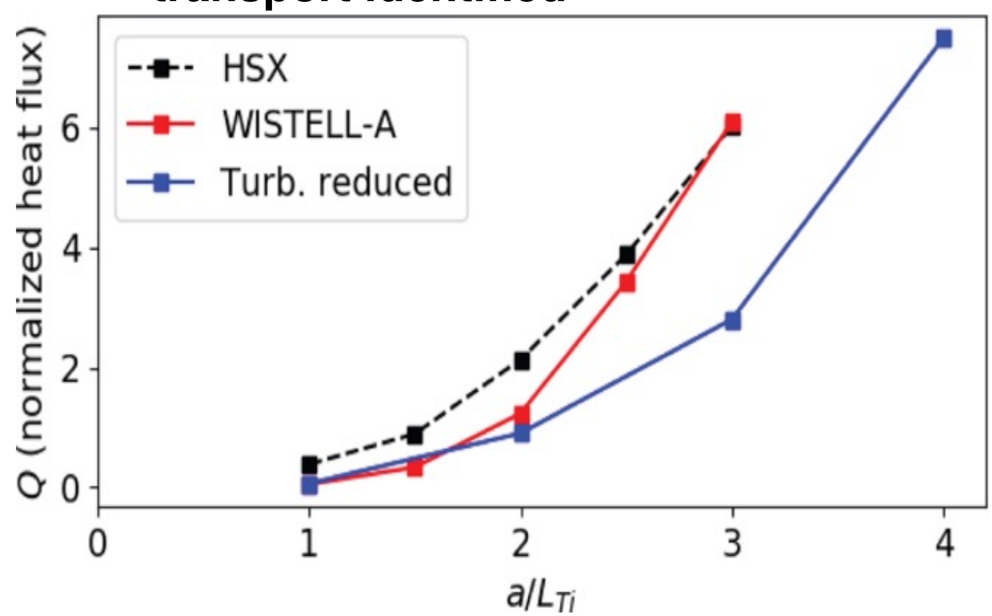
Understanding turbulent saturation is a route to reduced turbulent transport

- Nonlinear gyrokinetic simulations provide important insights on stellarator turbulence (Faber et al ‘18)
  - Sizeable number of sub-dominant instabilities at each **k**
  - Fastest growing instability is not always the most prominent nonlinearly
  - Prevalence of damped eigenmodes

- Paradigm for nonlinear saturation (Terry et al ‘18; CCH et al ‘18)
  - Nonlinear energy transfer from unstable to damped eigenmode
  - Quantified by triplet correlation time
  - Partial explanation for “Turbulence Reduced” configuration

- Turbulent transport reduction is a target in future stellarator design

Configurations with reduced turbulent transport identified



Near axis expansion is an efficient method to generate optimized stellarator configurations

- Significant progress has made in optimization and design methods for stellarators.
  - New method to generate and parameterize optimized configurations using analytic expansion about the magnetic axis (Landreman et al, JPP '18,'19)

$$R(r,\theta,\phi) = R_0(\theta) + rR_1(\theta,\phi) + r^2R_2(\theta,\phi) + \ \ldots$$

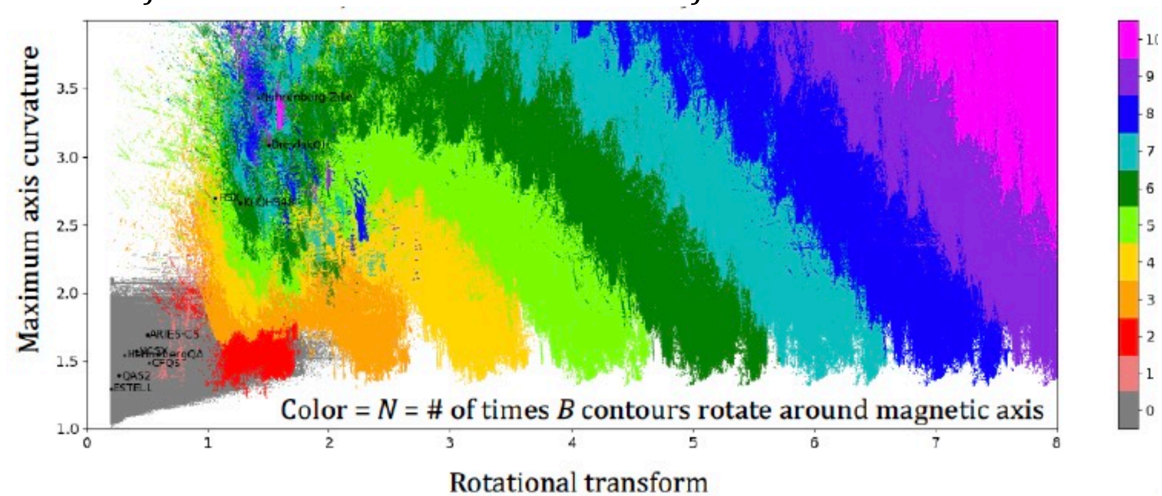
$$\mathrm{Z}(\mathrm{r},\theta,\phi) = Z_0(\phi) + rZ_1(\theta,\phi) + r^2Z_s(\theta,\phi) + \ \ldots$$

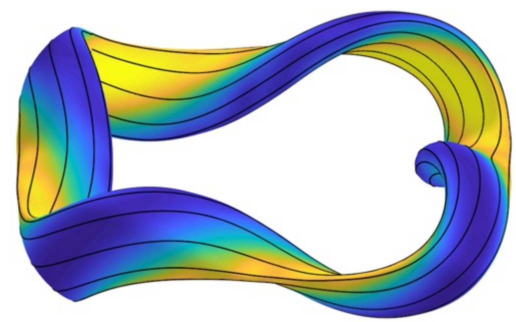
....

  - Computational efficient method to generate quasi-symmetric equilibria

$$R_0(\phi) = 1 + \sum_{j=1}^{3} R_j \cos(jn_{fp}\phi)\ , Z_0(\phi) = \sum_{j=1}^{3} Z_j \sin\left(jn_{fp}\phi\right)$$

2.4×10^8 configurations



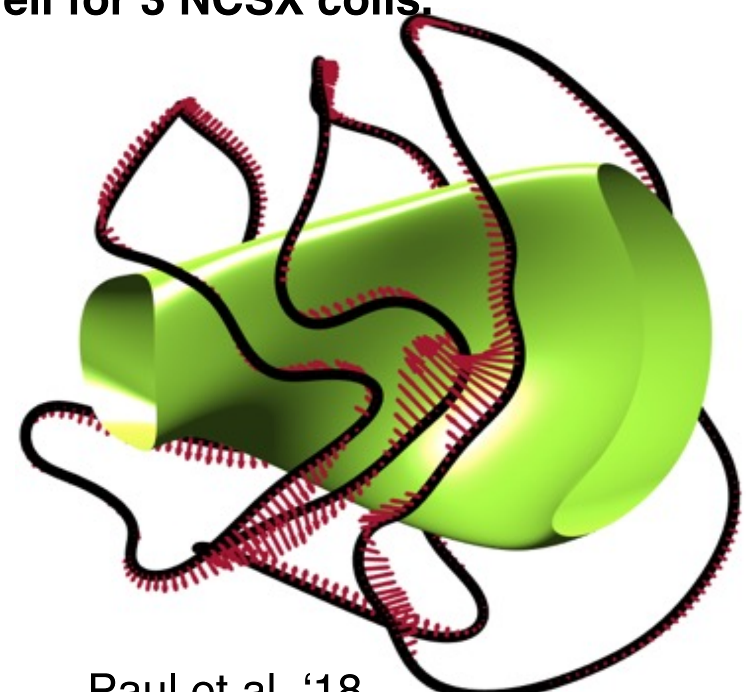


  - Many physical properties of interest can be computed directly from near-axis expansion

Adjoint methods improves stellarator optimization

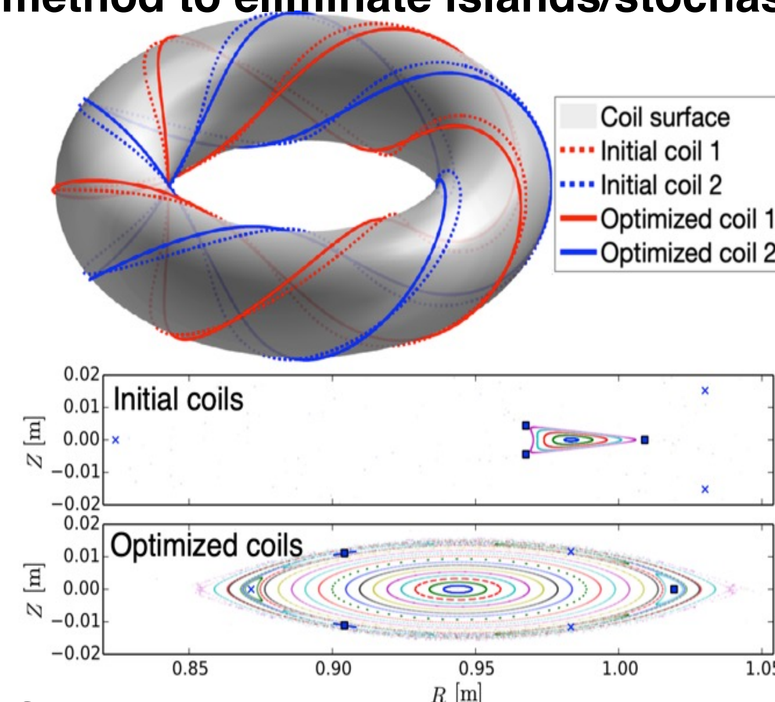
- Adjoint methods for computing shape gradients (Paul et al, NF '18)
  - Numerically efficient tool for computing derivatives --- invaluable for optimization and sensitivity studies in stellarator design
  - Shape gradient provides a local contribution to some scalar figure of merit caused by normal displacement of the shape
  - Adjoint methods have recently been derived for many quantities of interest for stellarator design --- collisional transport, coil complexity, island widths

Shape gradient for the magnetic well for 3 NCSX coils.



Paul et al, '18

Optimization using analytic derivatives and adjoint method to eliminate islands/stochasicity



Geraldini et al '21

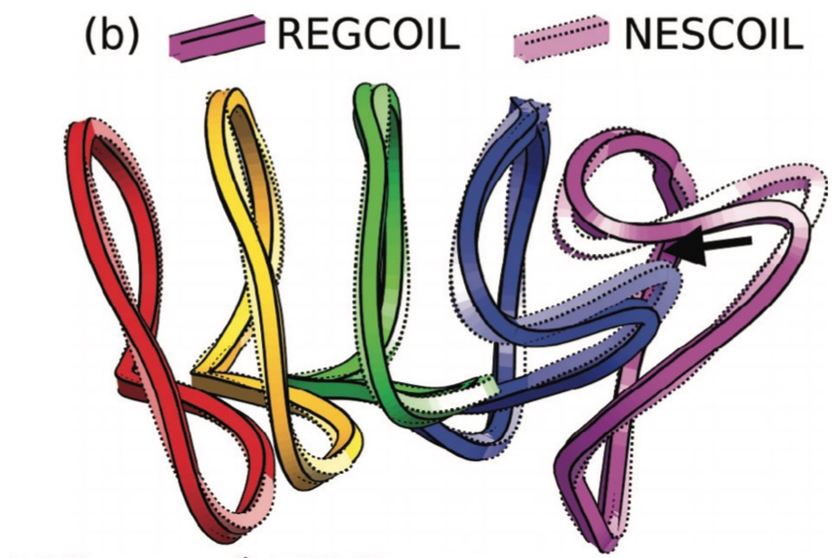
Methods to simplify coil design are emerging

- Designing and fabrication complicated non-planar coils are a significant challenge to the stellarator programs ---- complex geometry, tight tolerances
- New coil design methods have been developed
  - REGCOIL --- employs a winding surface, Tikhonov regularization (Landreman NF'17)
  - FOCUS --- fully 3D representation w/o winding surface, analytic derivatives (Zhu et al, NF '18)
  - FOCUS-FINITE BUILD --- considers finite build of the coil (Singh et al JPP '20; McGreivy et al NF '21)
  - MAGPIE --- Permanent magnets, beyond electromagnetic coils (Hammond et al NF '20)
  - Combining plasma optimization and coil design --- (Hudson et al PLA '18, Giuliani et al '20)

New design tools significantly improve stellarator coils

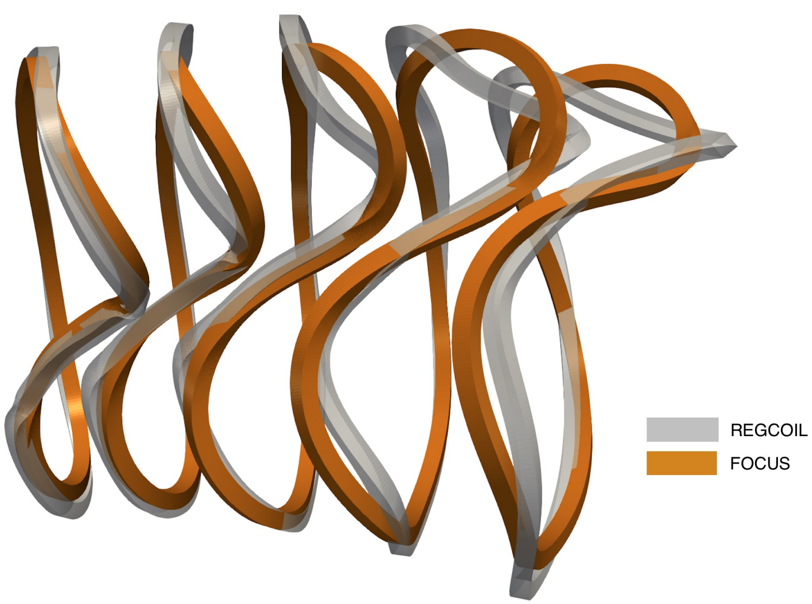
- New coil tools:
  - Improves free-boundary reconstruction of target plasma shape
  - Increases the minimum distance between coils.
  - Pulls coils away from plasma boundary (reduces “ripple”, frees up space)
    - FOCUS used for improved EP

REGCOIL simultaneously Improves reconstruction of target boundary and coil shapes for W7X



Landreman NF ‘17

FOCUS simplifies REGCOIL coils further



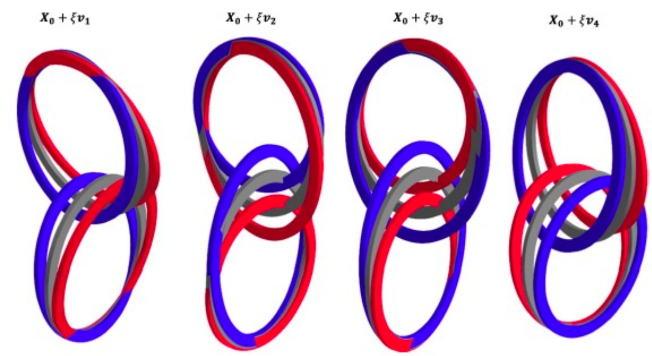
Zhu et al NF ‘18

Novel methods emerging to address coil tolerances

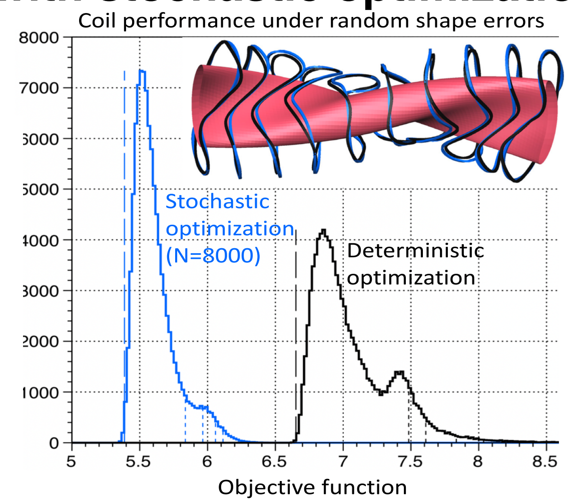
- Coil tolerances are crucial in design --- sensitivity to small field errors --> consequences for confinement
  - Hessian matrix provides sensitivity information (Zhu et al PPCF ‘18)
  - Shape gradient techniques (Paul et al NF ‘18)
  - Stochastic optimization (Lobsien et al JPP ‘20)

- Permanent magnets can simplify geometry
  - Cannot create toroidal flux, but can create poloidal flux (Helander PRL ’20)

Perturbed coils for first 4 principal eigenvectors of CNT

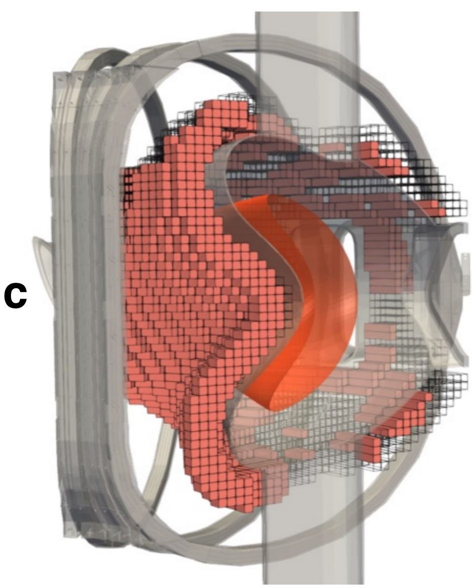


Robust coils can be found with stochastic optimization



Lobisen et al, NF ‘18

1/6 of 0.5 T NCSX experiment with permanent magnetic

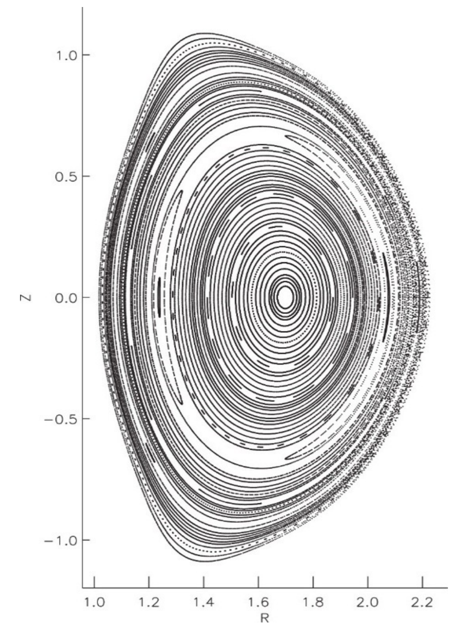


C. Zhu et al, P3 Poster, FEC 2021

Improved 3D MHD tools are developing for stellarator applications

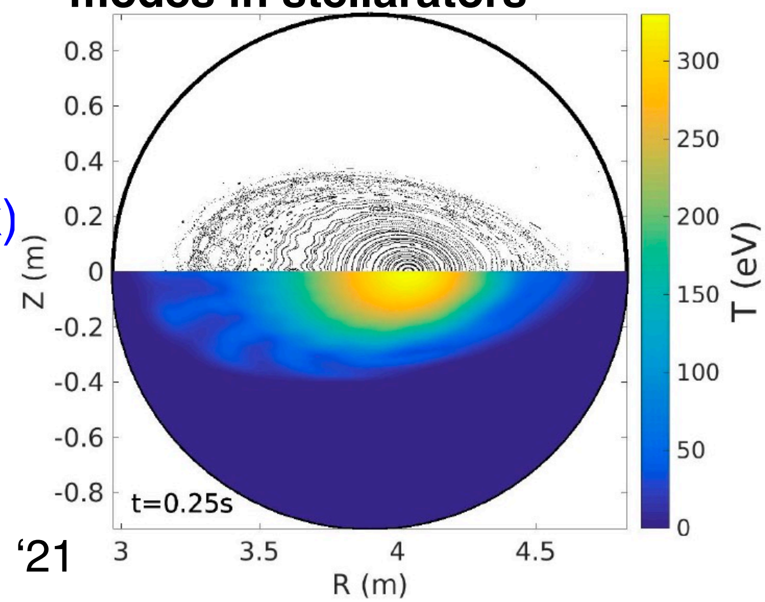
- 3D MHD equilibria have mathematical pathologies at rational surfaces
  - Nested toroidal surfaces are not guaranteed, islands/stochasticity
- SPEC computes a special class of sharp boundary equilibria (Hudson et al '12)
  - Minima of energy functional in N_v regions
  - Ideal MHD constraints only imposed at interfaces with discontinuous p and **B**
  - General magnetic topology, islands allowed
  - SPEC being incorporating into optimization approaches

SPEC reconstruction of DIII-D equilibria with RMP



- Extended MHD tools are being adapted for stellarator applications (M3D-C1, NIMROD, Jorek)

NIMROD models interchange modes in stellarators

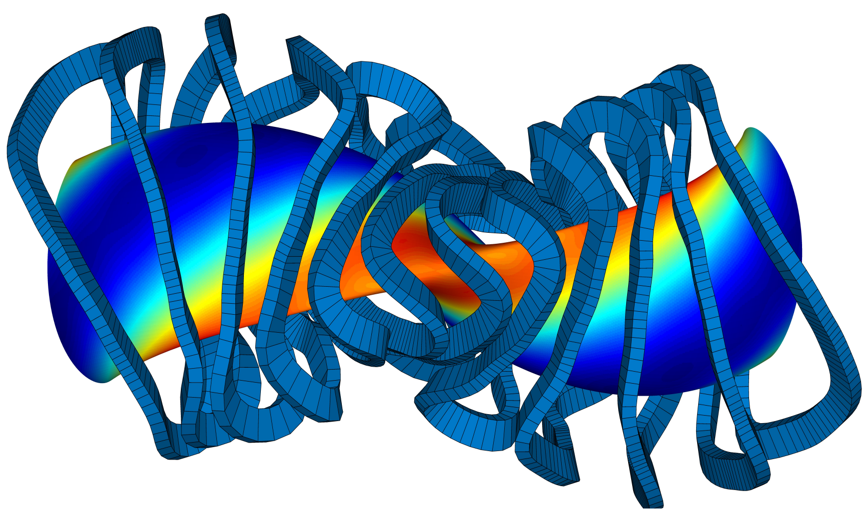


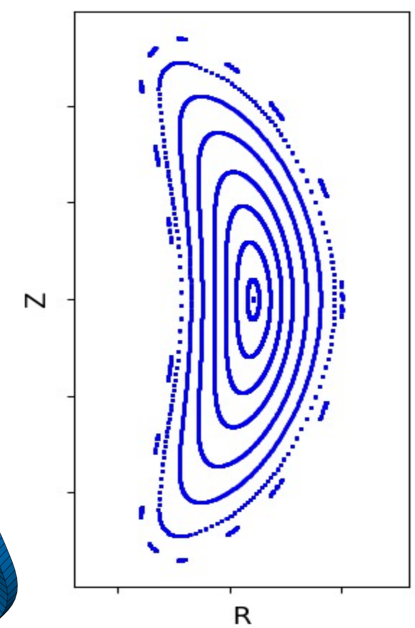
Bechtel et al '21

Advances in physics understanding, computational tools used to generate new configurations

- Various advances in physics modeling and design tools can be employed in optimization schemes to generate new configurations
  - Example configurations based on :
    - quasi-helically symmetric (Bader et al JPP ‘20)
    - quasi-axisymmetric (Henneberg et al PPCF ‘19)
  - Wistell-A configuration has:
    - Excellent energetic particle and neoclassical transport properties, Quasi-symmetry, Magnetic Well, Buildable coil set
  - Future designs will seek:
    - Reduced turbulent transport
    - High-beta stability
    - Robust divertor solution

Representation of the coil set for Wistell-A configuration





Hegna, IAEA FEC 2021
University of Wisconsin-Madison

Summary

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