Stellarator Initiative and New Approaches

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Initiatives on Stellarators for Fusion

- PPPL Strategic Initiative
  - W7X and LHD collaborations
  - Theory 5-year Plan: advances in stellarator modeling
  - LDRD activities on experiment design
- Simons Foundation: Hidden Symmetries and Fusion Energy" study

- *DPP/Community Planning Initiative*
  - Aim for the minimum cost, steady-state fusion pilot plant (NAS recommendation)
  - As recommended by the recent NAS report
  - Strategy: Simplify

- *Proposal for new experiment: SAS*

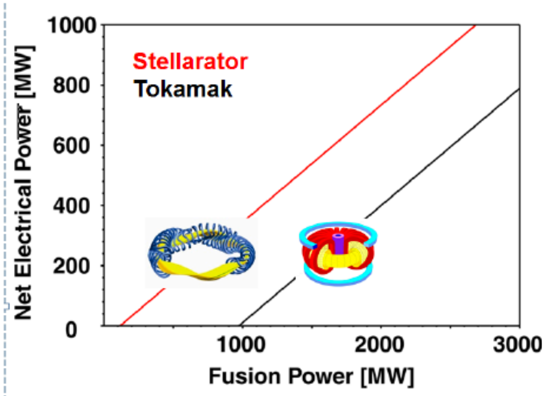
Why Stellarators?

Stellarators simplify fusion systems:

- Steady, low risk operation: Intrinsically avoid disruptions, runaways EM loads.
- Efficient, Compact Facility: No need for current drive (v.low recirculating power, smaller unit size)
- MHD Stability at high β: higher power density without complexity of v. high field
- Reduced risk: Fields are from coils, not self-organization
- Easier first wall: Stellarators have longer connection length divertors, higher plasma density (lower heat loads)

2010 Pilot Plant Studies Identify Opportunities

- Eliminate CD need & systems
  - Increase energy efficiency
  - Reduce required $nT\tau$ for fixed P-electric
  - Retire η_{CD} risk, disruption risks
  - Simplify and increase TBR



[H. Zohm et al., 2017]

- Produce net power at moderate scale and plasma power flux. Aim for
  - ~50 - 100 MWe
  - 30-100 MW plasma heating, JET/W7X scale
  - low tritium inventory

- *Need compatible high-β, high confinement & PFC solution*

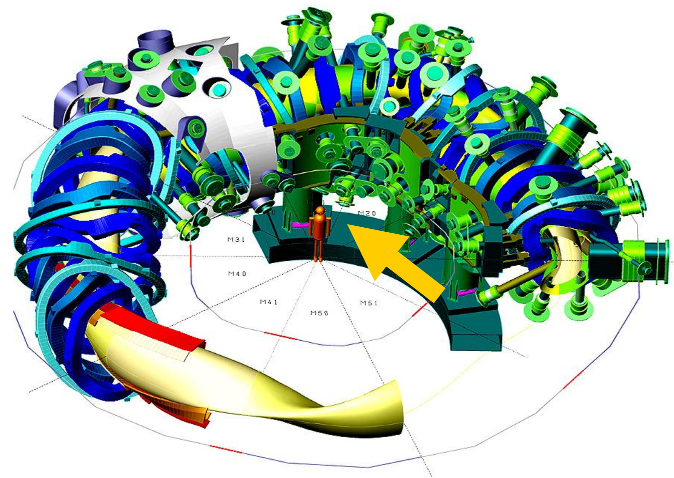
	AT Pilot	ST Pilot	CS Pilot
$A = R_0 / a$	4.0	1.7	4.5
R_0 [m]	4.0	2.2	4.75
B_T [T]	6.0	2.4	5.6
I_P [MA]	7.7	20	2.1
q_{95}	3.8	7.3	1.5
f_{BS} or iota from BS	0.69	0.90	0.23
$n_e / n_{Greenwald}$	1	0.7	-
H_{98} or H_{ISS04}	1.22	1.35	1.75
β_T [%]	4.8	39	6.9
β_N	3.7	6.1	-
P_{fus} [MW]	674	1016	529
P_{aux} [MW]	79	50	12
Q_{DT}	8.5	20.3	44
Q_{eng}	1.0	1.0	2.5
Net Electric [MW]	0	0	110

[J.E. Menard et al., NF 2011)]

What has changed?   Understanding

W7-X has Rapidly Exceeded Expectations: (Klinger et al, NF 59 (2019) 112004)

- $T_e(0)$ ~ 10 keV; τ_E up to ~0.24 sec
- Initial validation of neoclassical optimization
- Turbulence dominated confinement
- No impurity accumulation
- Well functioning 3D divertor, controlled detachment



Building on results from HSX and LHD

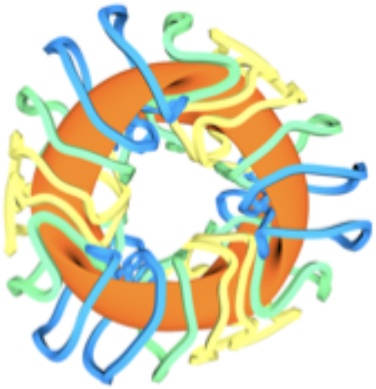
Conclusion: Stellarator optimization works!

Theory and modeling-based understanding improved:

- How to design for fast ion orbit confinement (2 methods)
- Unifying tokamak and stellarator understanding and codes (esp. turbulence)

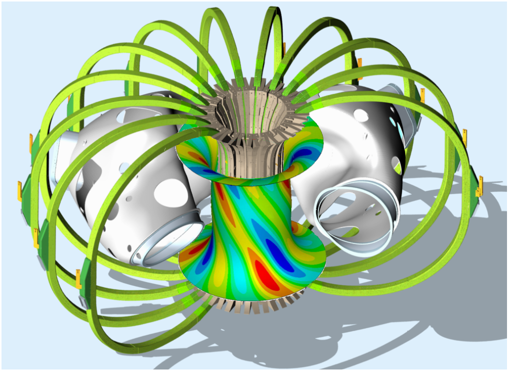
Tokamak exploration of PFC materials (high Z; low Z; liquids)

What has changed?   Coil Simplification



- Highest priority need in previous assessments
  - Crucial for maintenance and availability
  - Construction costs

- Three approaches, likely used in combination
  - Permanent magnets for 3-D shaping
  - Bulk superconductors, for simple 3D shaping at high B
  - Improved coil-design codes, enabling coil shape simplification

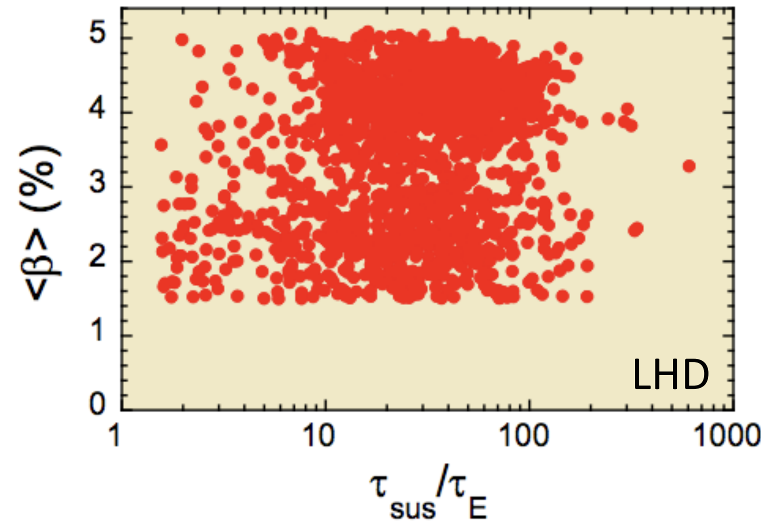


- Permanent magnets: simplify engineering & design
  - Equivalent to saddle coils (early design for NCSX)
  - Primarily on inside, outer thickness ~zero
  - Planar coils for TF (simplest possible)
  - At highest B, may only be usable on outer half of torus
    Guarantee straight coil outer legs for maintenance access

- *Need to get experience with these methods, mature engineering approaches*

Outstanding Needs for Pilot Plant

- What β-value to design for?
  - β =5.4% (LHD), β=3.4% (W7-AS) sustained; soft-maximum; *limit?*
  - Much higher than predicted by linear MHD
  - *Can high-β with high-H be extrapolated?*
- Integration with metal PFCs *(pref. low-Z, liq.)*



- Integrated *simplified* designs
  - Engineering
  - Stellarator plasma physics design & boundary approach (metal PFCs)
  - Rest of fusion energy system
- Integration validation (TRL advance)

SAS: Advance Stellarator Innovation, 3 ideas

Overall goal: Develop basis toward reduced-cost practical fusion energy stellarator (e.g. NAS study)

- Leverage stellarator advances
  - Improved understanding from recent stellarator (W7X,…) and tokamak experiments
  - Synergy with Simons "Hidden symmetries and fusion energy" study results: focus on QS
- Extreme simplification of 3-D Stellarator coils using permanent magnets
  - Resolve primary engineering risk and barrier for stellarators
  - Disruptive technology to simplify construction, reduce costs, greatly reduce maintenance complexity
  - Made possible by modern, neodymium/RE magnets
- Liquid-metal first wall, building on LTX-β and other initiatives
  - Increase confinement
  - Path to robust handling of power exhaust
  - Use increased confinement to explore β limit and physics

Proposal Opportunities & Timeline

- Simons Foundation has expressed interest in providing partial funding
  - In partnership with Hidden Symmetries project
  - At modest finding scale
  - In partnership with DOE and other funders
  - “SAS”: Simons Advanced Stellarator

- ARPA-E will solicit new proposals for next round of fusion proposals
  - Fusion energy development and technology focused
  - Solicitation expected Sept. 2019. Proposals probably Oct. 2019. Funding ~ 1/1/2020 ?
  - Requires co-funding, effectively requires private participation

SAS Approach

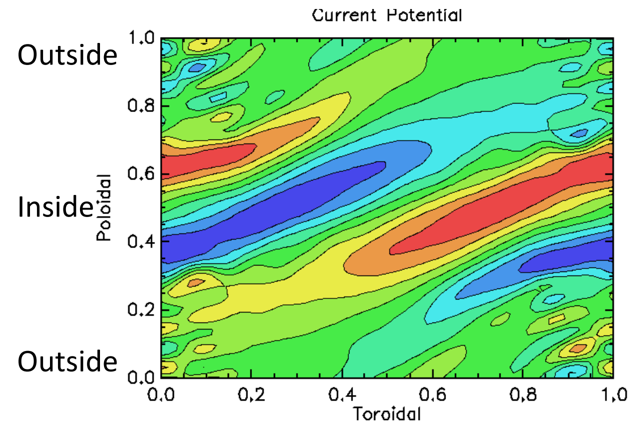
- Establish initial progress at minimum cost,
  - World's first simple optimized stellarator!
  - Improved confinement, through optimized QS and Lithium-boundary
  - Target key topics
- Re-use components, when possible
  - Some parts from NCSX (TF coils, vacuum vessel), but room-temperature
  - Li-approach, NB (1.5MW, 20kV) and some diagnostics from LTX-β
  - Make improved equilibrium – beyond NCSX. Most likely QA.
- Make re-configurable (via re-arranging magnets)
  - Vehicle for testing Hidden Symmetries results
  - For research flexibility
  - Increase capabilities (incl. B) over time

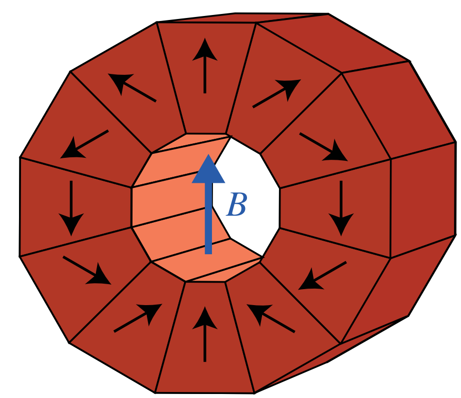
Permanent Magnets Dramatically Simplify Engineering & Design

- Shell of magnets around plasma
  - "Current potential" (NESCOIL, REGCOIL) calculations give simple indication of needed surface-magnetization

- Advanced magnet technology approach
  - Halbach array (1980): for higher magnet efficiency.
  - Uses tangential magnetization to reduce magnetic reluctance, increase field strength at plasma
  - Used in high efficiency motors, generators
  - Open NMR magnet systems

Solutions by C.Zhu & M.Landreman for finite thickness calculations.





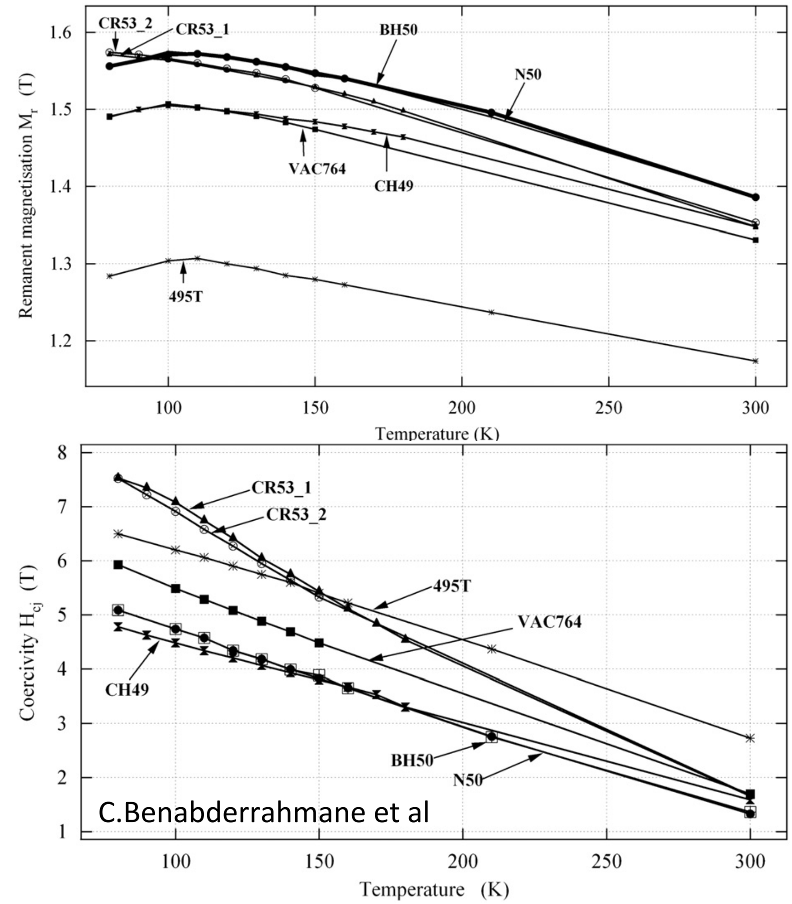
“Rare Earth” magnets are almost ideal

- μ_r = 1.01 – 1.05. Highly anisotropic.
- Remnant magnetic field and coercivity depend on detailed recipe and processing
- Both increase as temperature drops
- Nd-Fe-B has a phase change at 100-150K
  Arnold: NdFeB at 293K with Br=1.49T
- Pr-Fe-B goes to higher performance < 100K
- Commercially available in lg. quantity
- Fe-N may (someday) offer B_r > 2.5T

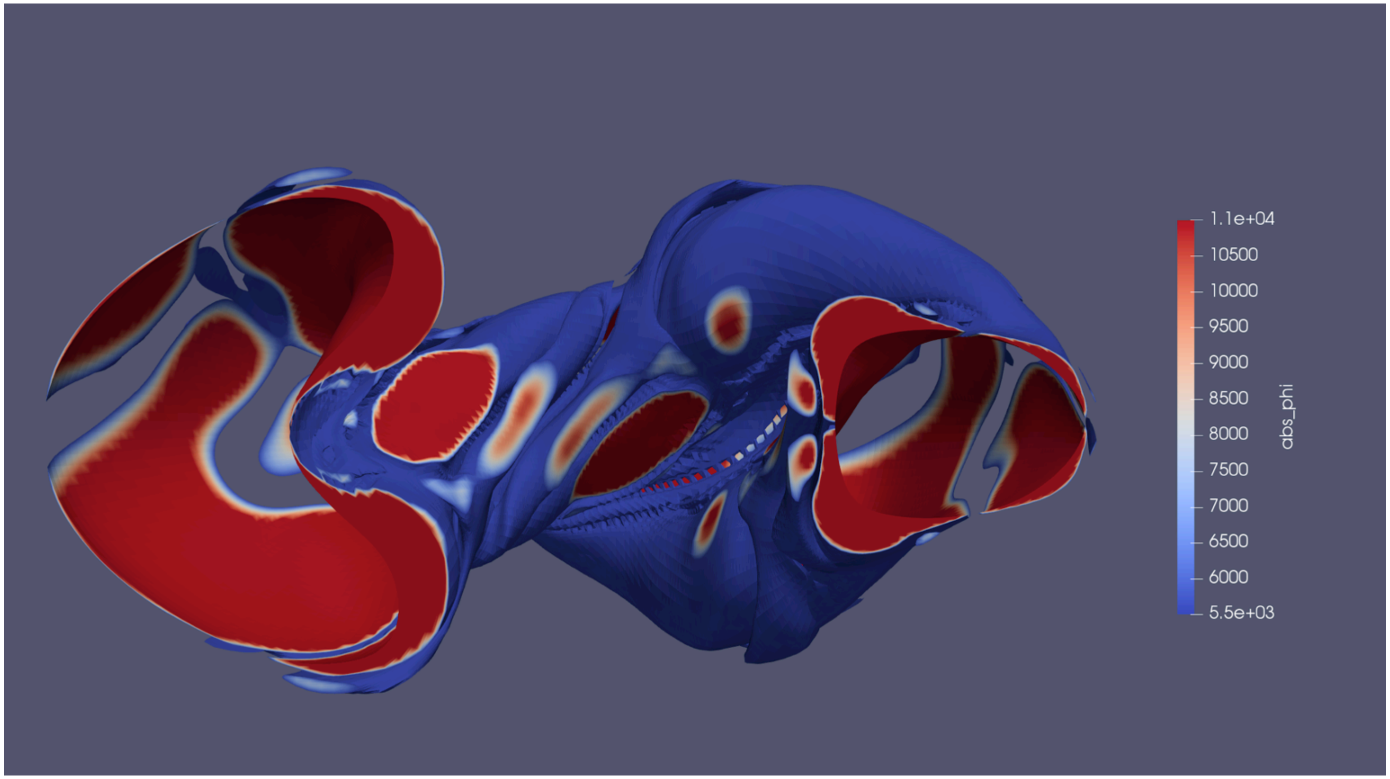
Material	Temp	B_r (T)	H_{cB} (kA/m)	H_{cB} (Oe)	H_{cJ} (kA/m)	H_{cJ} (Oe)
PrFeB NMX-68CU	77 K	1.67	1240	15582	6200	77911
PrFeB NMX-68CU	295 K	1.40	1010	12692	1680	21112
NdFeB NMX-S45SH	150 K	1.50	1137	14288	4000	50265
NdFeB NMX-S45SH	293 K	1.30	970	12200	1671	21000

E.Moog et al, ANL

Typical curves



Initial Finite-Thickness Solution
Perpendicular only (C.Zhu)



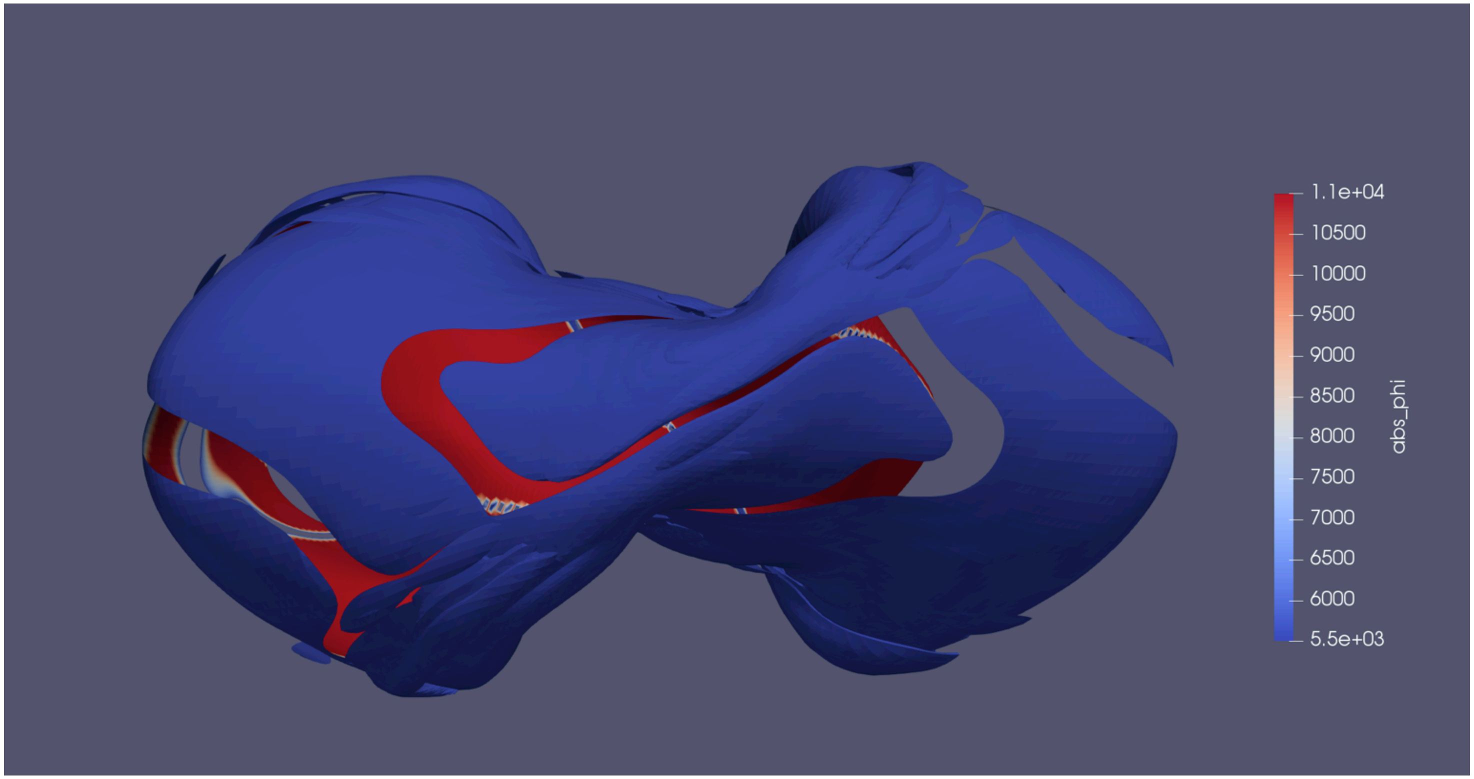
Volume: 2.96 m^3 (~24 tons ~ $1.2M)

Bn residual error:
3.76E-4 (clipped)
2.70E-4(whole)

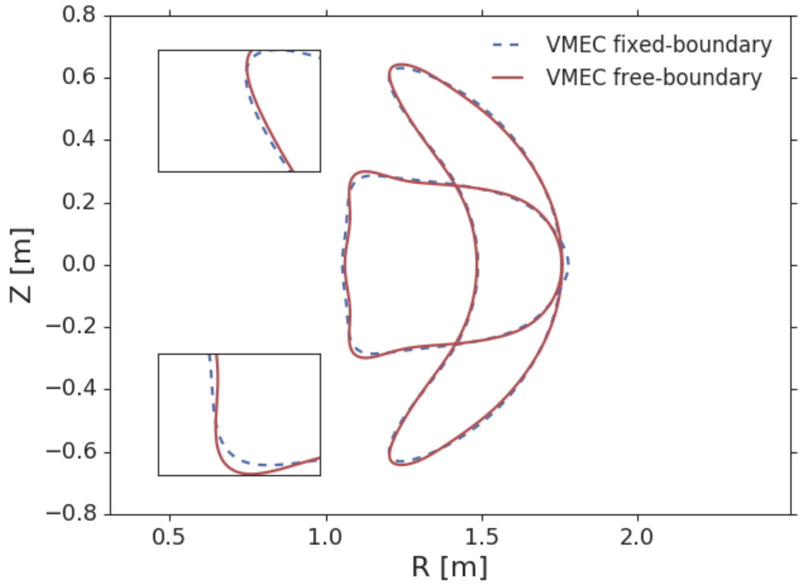
Max thickness ~20cm

With non-perp. elements, Landreman has max-thickness ~13cm

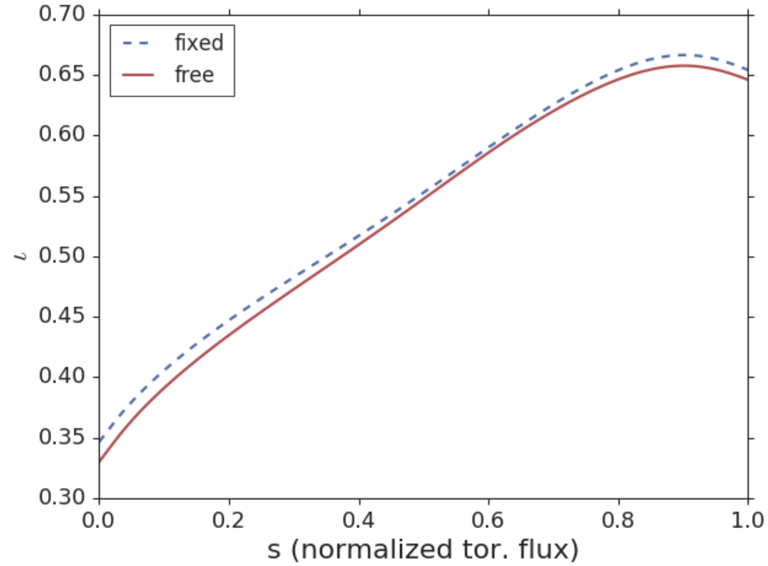
Viewing from the outboard.



Free-boundary VMEC shows good approximation.



Comparisons of plasma surfaces.



Rotational transform profile comparisons.

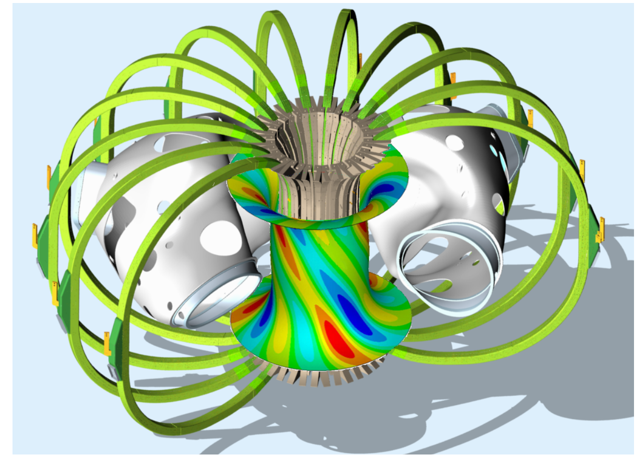
Opportunities for Configuration Improvement

- Improve fast particle confinement (ala Nemov or Henneberg)
- Reduce turbulent transport
- Maximize β
- Divertor design

- Optimize for PM approach (different than coils!)
  - Reduce needed on plasma
  - Reduce elongation(?)

- Incorporate guidance from Pilot Plant studies

We welcome suggestions and contributions, on all aspects



Lots of work to come:

Overall Mission and Expected Impact

- Research goals, plan, and basis
  - Design, heating, confinement, diagnostics
  - Phased research goals/plan and milestones
- Engineering goals, plan, basis
  - Enough design to be confident in approach and risk control
- Cost estimate

By Sept./Oct. 2019

Initiate a Path to a Pilot Plant

1. Near term experiment(s)
    - Test & develop engineering of simpler coils
    - Test confinement & β with low-Z metal PFCs
    - Test ability to design for reduced turbulence
    - *Our plan is to start this with the permanent magnet stellarator*
    - *Rapid deployment of design improvements*
2. Integration validation experiment (TRL advance)
    - Integrated Engineering
    - Plasma physics (i.e. coils) & boundary (plumbing & cooling)
    - Mainly DD, perhaps *trace T to validate reactivity?*
3. Pilot Plant, demonstration