A US Intermediate Scale Stellarator Experiment

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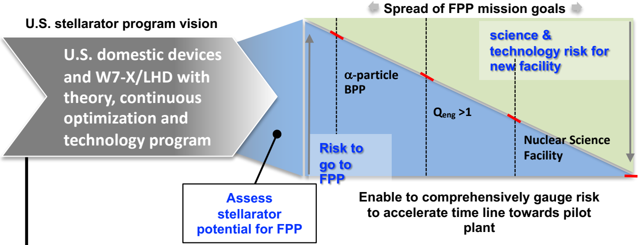
Assessing the stellarator as an option for a fusion pilot plant (FPP) requires retiring open risks and boosting the advantages of the concept



Four initiatives to foster an aggressive qualification strategy for the stellarator

- **Domestic facility (A. Bader):** "A U.S. Intermediate Scale Stellarator Experiment"
- **International collaboration (S. Lazerson):** "International Stellarator Research in Support of a Low Capital Cost Pilot Plant"
- **Technology and Concept Innovation (M. Zarnstorff):** "Initiative to Simplify Optimized Stellarators and Test Key Properties"
- **Stellarator Pilot Plant (D. Gates):** "The Stellarator Path to a Low Cost Pilot Plant"

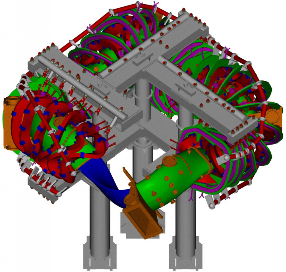
- **Strategic white paper as general background (A. Boozer):** "Strategic Implications of the Stellarator for Magnetic Fusion" (no talk)

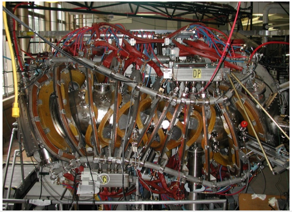
A US Intermediate Scale Stellarator Experiment

- The U.S. should have a strong stellarator program
  - Stellarators offer a path to a low recirculating power, ignited reactor
  - Advances in last decades have demonstrated success of stellarator optimization
  - Opportunity for a leadership position in the worldwide program
- Advantages of the stellarator in moving towards a pilot plant
  - Intrinsically steady state
  - No need for current drive/profile control
  - No disruptions or runaway electrons for low current stellarators
  - Density limits set by simple power balance; bigger design space at high density
    - Faster damping of energetic particles
    - Improved divertor operation/edge-radiation
    - Stable detached discharges observed on W7-X and LHD
  - Opportunity for optimized turbulent transport by design

Clear Opportunity Exists for US Leadership

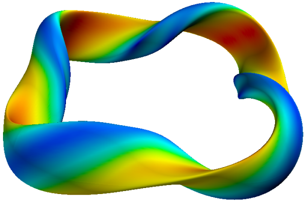
- The US has been instrumental in stellarator advancement
  - Pioneered quasisymmetry, distinct from the QO approach used on W7-X
  - Development of analytic theory, analysis/modeling codes, optimization techniques
- HSX has demonstrated benefits of quasihelical symmetry; unique advantages for stellarators in moving towards a reactor
  - Low q_{eff} (reduced neoclassical transport, lower bootstrap currents, smaller Shafronov shift)
  - Low ion flow damping (turbulence suppression, island healing...)





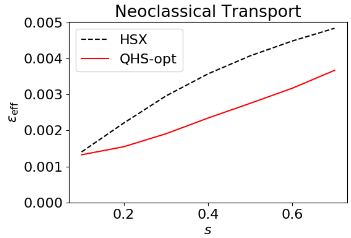
A Compelling Program can be Developed which **Looks Beyond** Present Capabilities

- Turbulent transport reduction by design
- Greatly improved energetic particle confinement
- Divertor structure/geometries that scale to a reactor; investigate impurity accumulation/expulsion
- Utilize advanced manufacturing and new coil design techniques to reduce time, cost, risk and complexity of fabrication

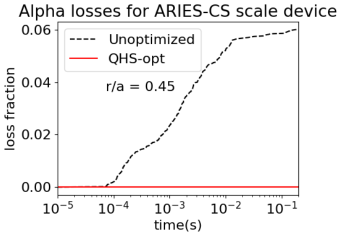


A mid-scale facility NOW would address these critical issues and provide the needed data to assess application to a pilot plant

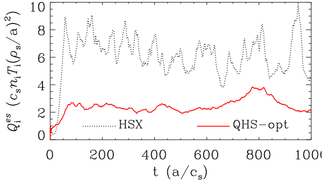
Configuration Identified with Excellent Confinement Properties



Neo-classical transport improved relative to HSX



ALL alpha particles confined within r/a = 0.45 when scaled to ARIES-CS volume and field strength



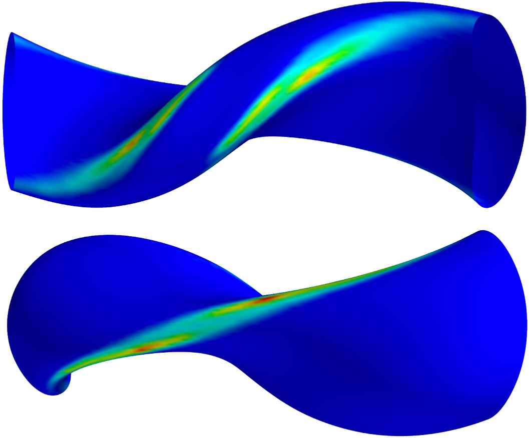
Nonlinear turbulent heat flux factor of three lower than in HSX

Bader submitted to JPP

Hegna PoP 2018

Non-Resonant Divertors are an Untested Design for Stellarators

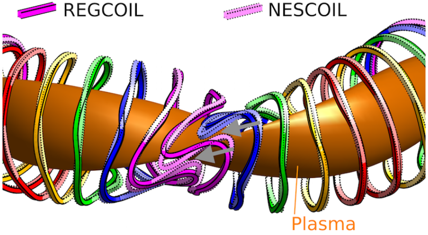
- Non-resonant divertors promise similar performance from vacuum to operational point
  - Insensitive to bootstrap current and profile evolution
  - Distinct from W7-X island divertor which is very sensitive to current profiles
- Non-resonant divertors require empirical tests on a mid-scale device

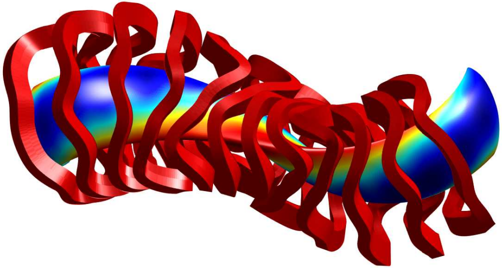


Bader PoP 2017, Boozer PoP 2018, picture courtesy of H. Frerichs

New Coil Tools and Manufacturing Capabilities Have Emerged

- New coil capabilities, (FOCUS, REGCOIL), have been developed
- These new tools produce simpler coils and looser tolerances for W7-X, HSX





- FOCUS produced coils for new configuration
- Technology advances like additive manufacturing or new materials can possibly aid mission and reduce cost

Landreman NF 2017, Zhu NF 2017, pictures courtesy of M. Landreman, T. Kruger

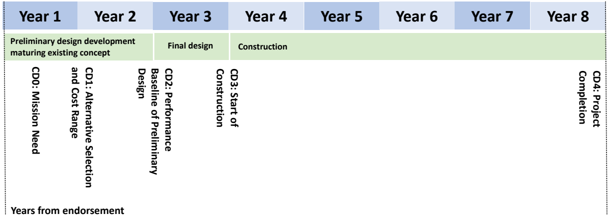
Scope of Mid-Scale Device is Set By Physics Goals

Minor radius	0.25 m
Magnetic field	2.5 T
Aspect ratio	6-8
Density	$<2.5 \times 10^{20}$ m^{-3}
Heating Power	1.5-2 MW
Heating Source	75 GHz - 140 GHz

- Hot thermal ions, low ν^*, test neoclassical ion transport and flow
- High density capability with neutral burnout and detached operation
- Adequate space for non-resonant divertor with low impurity source
- NBI available with upgrade, planned in initial design

A W7-AS scale device can provide a basis for an exciting and needed physics program

Operational in 8 Years at Initial Cost of $40-50 M



- Initial operation 1.25 T, 70 GHz gyrotrons $40-50 M
- Upgradable to 2.5 T, 140 GHz gyrotrons, NB additional $40-50 M

- Cost estimate scaled from HSX upwards and W7-X downwards (does not include cost savings available from advanced manufacturing)

US program has new ideas for improving the stellarator,
world-leading theory and modeling, strong international collaborations,
but needs new domestic experiments

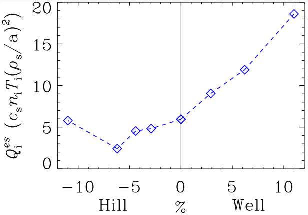
We are ready to begin now

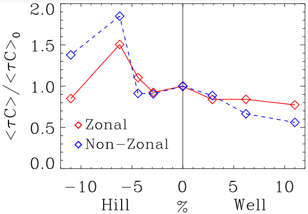
Extra Slides

List of Stellarator Optimization Collaborators

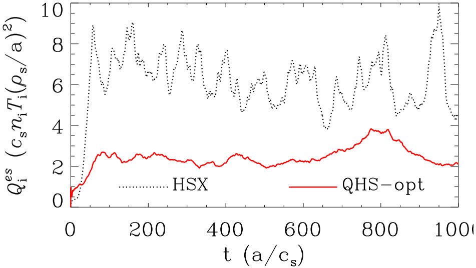
- **UW-Madison:** D.T. Anderson, A. Bader, B.J. Faber, C.B. Forest, H. Frerichs, B. Geiger, C.C. Hegna, K.M. Likin, I. McKinney, S.T. Kumar, T. Kruger, J.S. Sarff, O. Schmitz, P.W. Terry
- **PPPL:** S.R. Hudson, S.A. Lazerson, C. Zhu
- **Auburn:** G.J. Hartwell, D.A. Maurer. J.C. Schmitt
- **ORNL:** D.A. Spong, M. Cianciosa
- **U. Maryland:** M. Landreman, E. Paul
- **UCLA:** C. Deng
- **NIFS:** M. Nakata, Y. Suzuki
- **Kyoto U:** S. Murakami, K. Nagasaki
- **IPP-Greifswald:** M. Drevlak, S. Henneberg

Neoclassical and Turbulent Transport Details



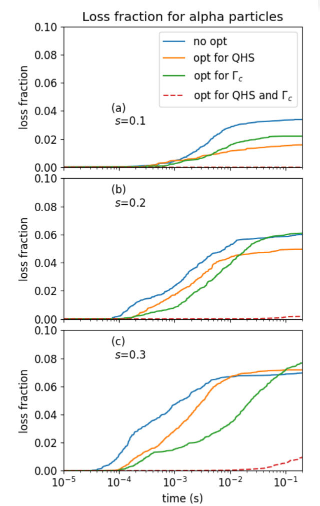


- Turbulent saturation metrics have been developed
- Can allow for optimization of *nonlinear* turbulent transport for first time
- Experimental data in many configurations needed to validate turublent models

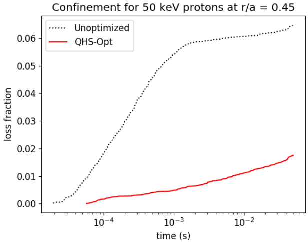


Hegna PoP 2018, Terry PoP 2018

Energetic Particle Confinement Details

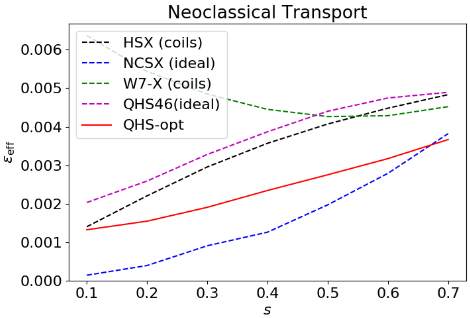


- QHS configurations exist which eliminate all core losses on ARIES-CS scale devices
- We know how to generate these configurations - optimize for QHS and Γ_c



Nemov PoP 2008, Bader submitted to JPP

Neoclassical transport comparisons for many configurations



- ϵ_{eff} is difficult to compare across configurations because some configurations are idealized (no coils) and some are realistic (with coils)
- For constructed machines (HSX, W7-X) the idealized target configurations are not readily available

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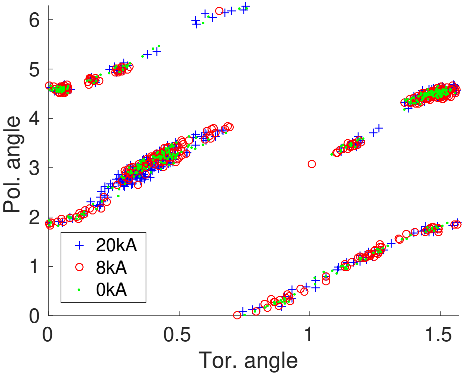

Bader PoP 2017, Boozer PoP 2018

Expanded Timeline

Year 1	Year 2	Year 3	Year 4-8	Year 9-10	Year 11-12
Preliminary design development maturing existing concept		Final design	Construction	First Operation Phase	Upgrade to high power and full field

CD0: Mission Need

CD1: Alternative Selection and Cost Range

CD2: Performance Baseline of Preliminary Design

CD3: Start of Construction

CD4: Project Completion

Continuous Device Operation

Years from endorsement