Prospects and alternatives for development of US stellarator program

Jeffrey H. Harris[6]

on behalf of U.S. stellarator collaborators*

*D.T. Anderson[1], A.H. Boozer[2], D. Curreli[3], D. A. Ennis[8], J.P. Freidberg[4], D.A. Gates[5], S.R. Hudson[5], M. Landreman[7], J.D. Lore[6], D.A. Maurer[8], H. E. Mynick[5], G.H. Neilson[5], A. Reiman[5], D. Ruzic[3], D.A. Spong[6], J.N. Talmadge[1], F.A. Volpe[2], H. Weizner[9], G.A. Wurden[10], M.C. Zarnstorff[5]

1 – University of Wisconsin
2 – Columbia University
3 – University of Illinois
4 – Massachusetts Institute of Technology
5 – Princeton Plasma Physics Laboratory
6 – Oak Ridge National Laboratory
7 – University of Maryland
8 – Auburn University
9 – New York University
10 – Los Alamos National Laboratory

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Stellarators: external confinement

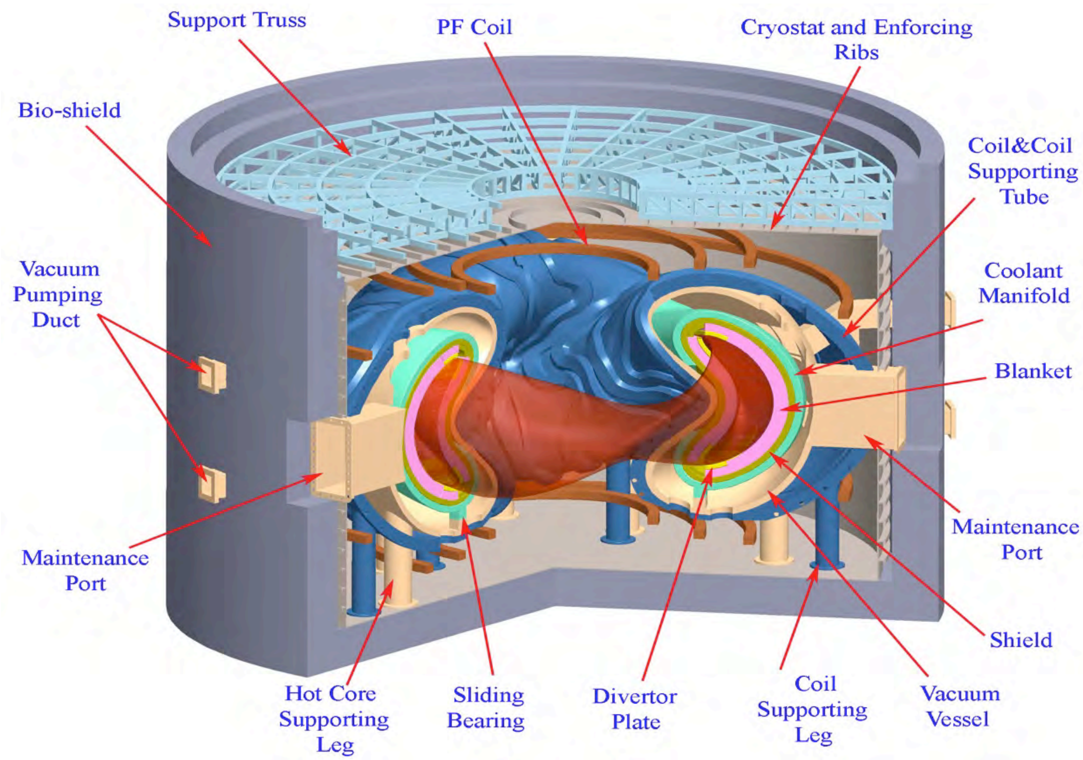
- Goal: steady-state, ignited, disruption-free reactor operation with predictable performance and minimum possible requirements for external control.
- Performance determined by 3-D stellarator field
  - MHD equilibrium and stability
  - Energy, particle, and impurity transport
  - Alpha particle confinement
  - Divertor
- Challenge: develop and validate techniques which allow optimization and confident extrapolation of designs to reactor-scale devices.
- US can use its unique capabilities to lead in this area, if it acts soon.

Stellarator configuration design requires integrated optimization across multiple domains . . . in 3-D

Confinement volume:
Flux surface quality
MHD equilibrium, stability
Neoclassical transport
Turbulent transport

Divertor:
Particle/heat exhaust
Heat flux control
Impurity control

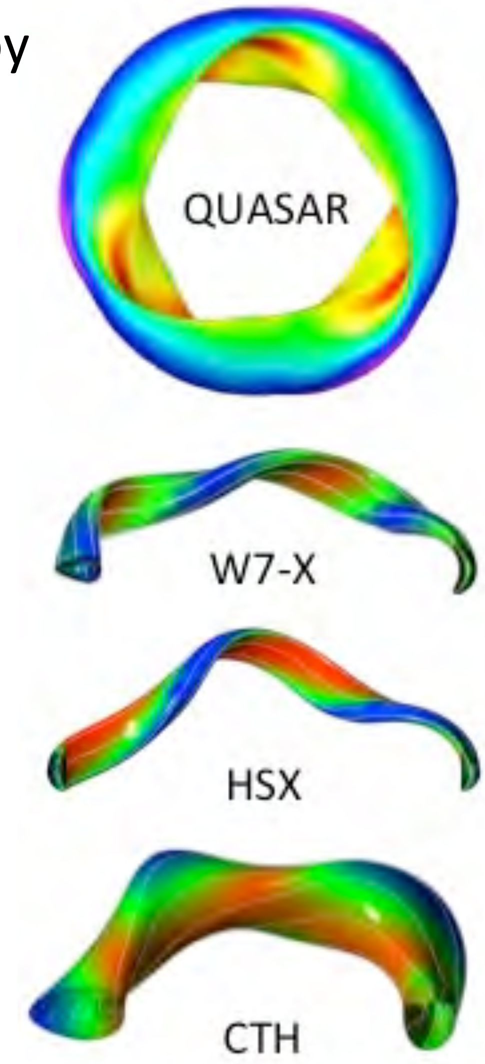
Coil/blanket system:
Performance
Support
Construction
Access, maintenance



ARIES-CS reactor concept quasi-axisymmetric stellarator (based on NCSX/QUASAR design)

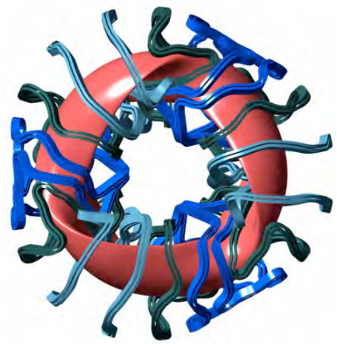
A US world-leading program in 3-D configurations is critical for finding optimum fusion solutions

- U.S. design tools optimize plasma/coil configurations by evaluating properties against physics and engineering targets.
- Configurations optimized to reduce neoclassical transport, increase flow shear, achieve high-beta were available by 2007.
- Studies since 2007 have been extended to improve coils, access, and targeted transport processes.
- *Extension of all aspects of stellarator optimization is the defining goal of the US stellarator initiative for the next decade.*
  - *Experimentally test and validate theory.*
  - *Extend understanding and design capabilities.*
  - *Continue to improve designs*



There is more than one way to optimize a stellarator

QUASAR (*né* NCSX)



R = 1.4m

R/a ≃ 4.4

$\iota_{total} \sim 0.4\text{-}0.7$

$\iota_{bootstrap} \leq 0.15$

$\beta_{stab} \geq$ 6%

Helical ripple = 0.1-0.4%

(reduced neoclassical xport)

Quasi-axisymmetry (RS tokamak)

Compact system size

W7-X

R = 5.5m

R/a ≃ 11

$\iota_{total} \sim 0.83\text{-}1.25$

$\iota_{bootstrap} \leq 0.05$

$\beta_{stab} \geq$ 5%

Helical ripple ≃ 1%

(reduced neoclassical xport)

Isodynamic (Shafranov shift ~ 0)

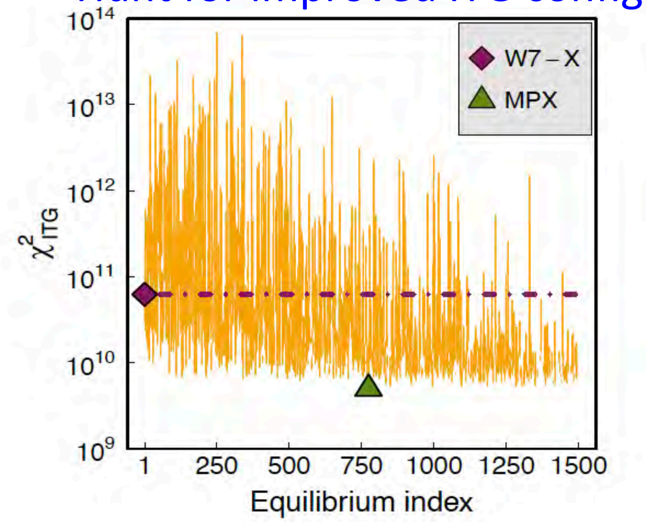
Large system size

- **Which is better??????**
- **Same physics basis, different design choices**
- **Depends on actual vs predicted performance ⇒ *experiments!***

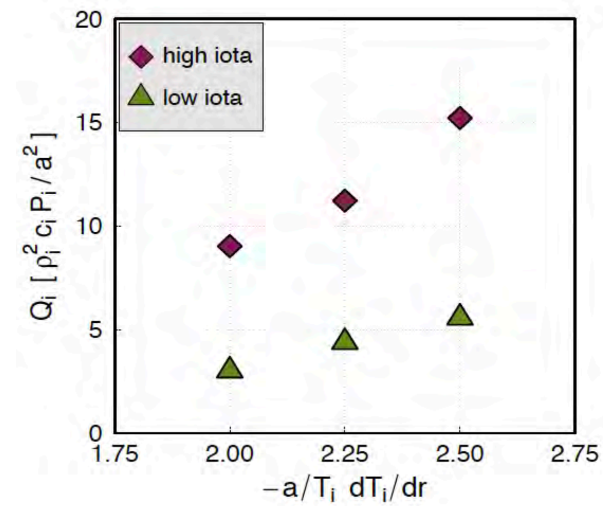
Stellarator optimization continues even after devices are built

- STELLOPT coupled with GENE turbulence calculations reveals neighbors of W7-X with reduced ITG-driven transport.
- Similar configurations can then be realized in W7-X for experiments by varying coil current ratios.
- These techniques allow anomalous transport mechanisms to be identified in experiments and then reduced by improved design of the external field.
- Similar types of configuration “tweaking” used to improve MHD stability, alpha confinement, etc.

Hunt for improved ITG config.



Realization in actual W7-X



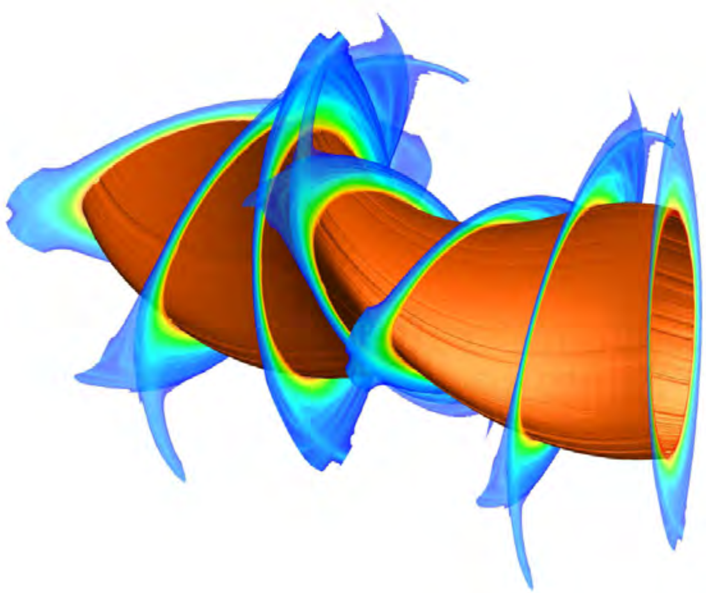
P. Xanthopoulos, et al, submitted to PRL

Divertor design is the next target for optimization

- Divertors are outside the closed flux surfaces: new methods needed.
- Integration of 3-D plasma and PMI modeling, iterative shaping of divertor plates.
- Experimental validation essential.
- Focus of US activity on W7-X: high heat flux, PMI; coord. w/university exp'ts
  See talk by O. Schmitz
- ⇒Divertor optimization tools for inclusion in design process

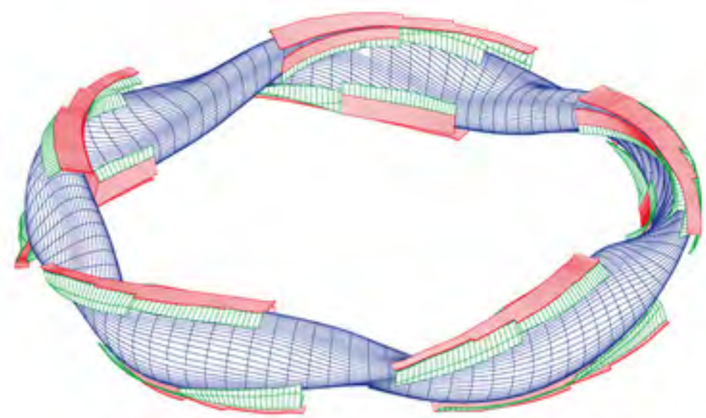
Large Helical Device (LHD)

Test helical divertor performance with stochastic layer



Wendelstein 7-X (W7-X)

Test island divertor performance vs. topological stability



US has near-term opportunities to excel in stellarator optimization and validation

Present US stellarator funding ~$5-6M/year, but could rapidly expand in steps:

1. **Increased support for 3D theory/computation [Increment $3-4M/yr]** *Talk M. Landreman*
2. **Expand US partnership on W7-X** Immediate expansion to **$5M/yr and then to $10-12M/yr** over next 5 years would allow US to to increase involvement in divertor and core physics, deploy pellet fueling (ITER prototype) and take advantage of steady-state capabilities. *Talk G. Wurden*
3. **Upgrade 2 existing, add 1 new facilities to explore 3-D divertor physics.** HSX: Heating, flexible divertor; CTH: Increase ohmic heating; HIDRA(WEGA): PMI studies in stellarator environment. **[Increment $6-7M/yr]** *Talk O. Schmitz*
4. **Mid-size US stellarator experiment.** Fastest implementation (QUASAR, **$130M construction over 5 yrs, ~$60M/yr operation**) would use NCSX design and coils. *Next slides.*
5. **Develop design options and mission-need for next-step U.S. stellarator.** Possible missions range from a DD JET-scale device to an FNSF. (**≥ 5 years, ~$5M/yr**) *Talk: M. Zarnstorff.*

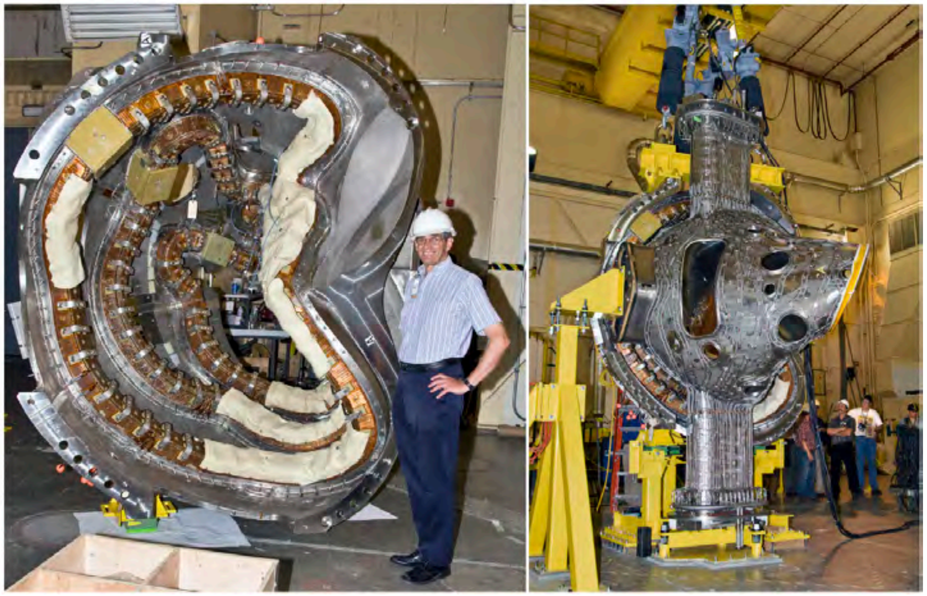
QUASAR research goals

- Assess/refine 3-D quasi-axisymmetric (QA) configuration
- Unique in world, mimics tokamak symmetry in B-field
- Configuration with ~25% of transform from plasma current (bootstrap).
- Search for disruption thresholds
- Pressure limits and mechanisms
- Confinement, transport with very low QA ripple
  - Comparison with tokamak
- Role of equilibrium islands, tearing modes, reversed shear
  - 48 trim coils for island production or compensation
- Develop 3-D ergodic divertor configuration
- How much 3-D shaping (external transform) is really needed?
  - Simpler design possible?
  - Continuum with tokamak
- Use configuration flexibility to explore innovations in optimization, e.g. reduction of anomalous transport

B = 2 T
Δt = 0.5 (2T)–2 s (1.25T)
P_{NBI} = 6 MW
P_{RF} = 6 MW (upgrade)

Possible QUASAR implementation

- Scoping study (1 year, $5M)
  - Use NCSX design and coils
    - Refine unbuilt components
      - Trim coils, etc
  - Update physics basis
    - Mission enhancements
    - Partnerships
      - ORNL, MIT, universities, . . .
      - China, others



  - Update cost, schedule estimates
    - Construction: ~$130M, 4-5 years (China: offer to contribute 1/3)
    - Operation: $60M/yr
- QUASAR could deliver data needed for optimization within the decade.
- Design of follow-on experiments should proceed in parallel and incorporate emerging improvements.

Conclusions

- Integrated design optimization is essential to developing the stellarator as an steady-state, ignited, disruption-free reactor candidate.
- Powerful numerical optimization techniques for complex 3-D fields have been developed, but need experimental validation, and new optimization challenges (e.g., divertors) must be met.
- The US has led the development of optimization tools, and has attractive opportunities to extend its leadership in the next 5-10 years by leveraging domestic and international partnerships in experiments and theory/computation. This will require timely increases in support from present low levels.
- Failure to act will reduce the US to the role of a spectator in a field it largely created.