Compact Stellarator Proof-of-Principle Program

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representing
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FESAC Review of PoP Programs
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The Proposed Proof-of-Principle Programs Are Important for a Balanced, Restructured Fusion Program

- **Fusion community has responded to the need for innovative concepts to add the breadth called for in the restructured Fusion Energy Science program**

MTF (with FRC)	RFP	Compact Stell.
self-organized	self-organized (some ext. control)	external control (some self-organiz.)

- **MTF, RFP, and *Compact Stellarators* offer a portfolio that spans a wide spectrum of approaches**

Compact Stellarators Offer Innovative Solutions to Critical Problems of Magnetic Fusion

- Achieving steady-state operation at high beta without disruptions is a major challenge for toroidal confinement
- Advanced tokamaks are exploring one approach
- Compact stellarators provide an alternative solution
  - 3-D shaping for external kink and vertical stability without a close-fitting wall or active feedback
  - Reverse shear all the way to the edge (neoclassical tearing instability, external kink modes)
  - Sustainment without external current drive at tokamak-like plasma aspect ratios

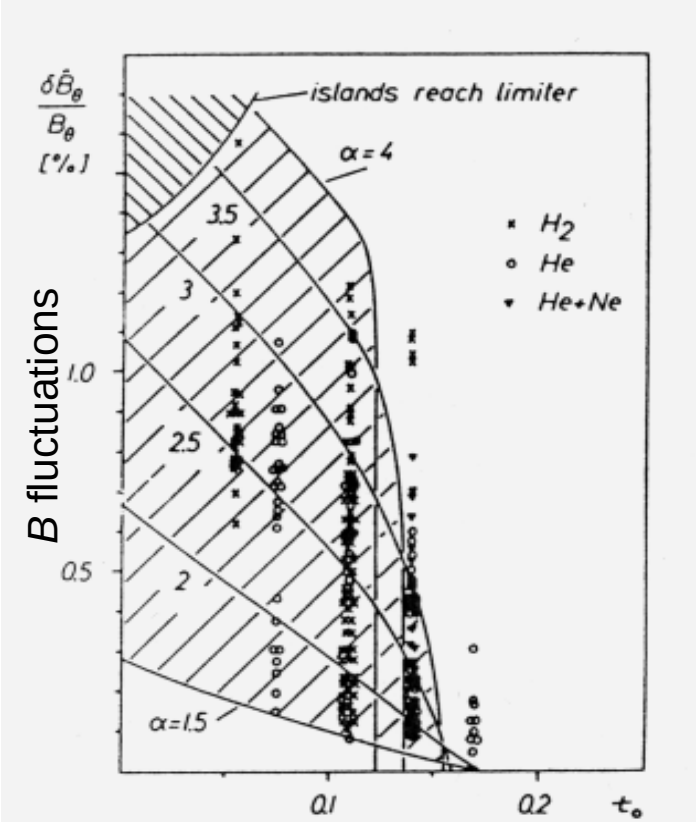
The Compact Stellarator PoP Program Complements the Two Major Toroidal MFE Approaches

- The advanced tokamak approach (conducting structures, current drive, feedback control) -- CS's are needed to broaden the attack in this area
- The large world stellarator program that focuses on currentless plasmas at high aspect ratio -- CS's are needed to reduce the size of these reactors
- Compact stellarators build on both of these approaches
  - compactness, (partial) bootstrap current, good confinement, and symmetry features of tokamaks
  - 3-D shaping, (partial) production of poloidal field using external currents, disruption immunity of stellarators
  - uses international collaboration to address issues not covered in the U.S program
  - fills niche in world program not otherwise covered

Compact Stellarators Have the Potential for an Attractive Reactor

- Tokamak-like plasma aspect ratio and bootstrap current leads to more compact stellarator reactor with economical wall power loading
- Stellarator features (3-D shaping, stellarator shear) lead to
  - * steady-state operation without external current drive
    low recycled power
  - * disruption immunity at highest plasma parameters
  - * stability at high beta without close conducting wall or active feedback systems for
    - – external kink modes
    - – ballooning instability
    - – neoclassical tearing modes
    - – vertical instability

Stellarator Fields Successfully Used to Avoid High Density Limit Disruptions



added external transform

- ι(a) =0.35
- Murakami-normalized density increased by a factor of three by the application of external transform

- **Also did not observe q<2 disruptions with ohmic current on W7A and CLEO.**
- **Further work required on high pressure MHD limits.**

From: WVII-A Team, Nuclear Fusion, 20, 1093 (1980).

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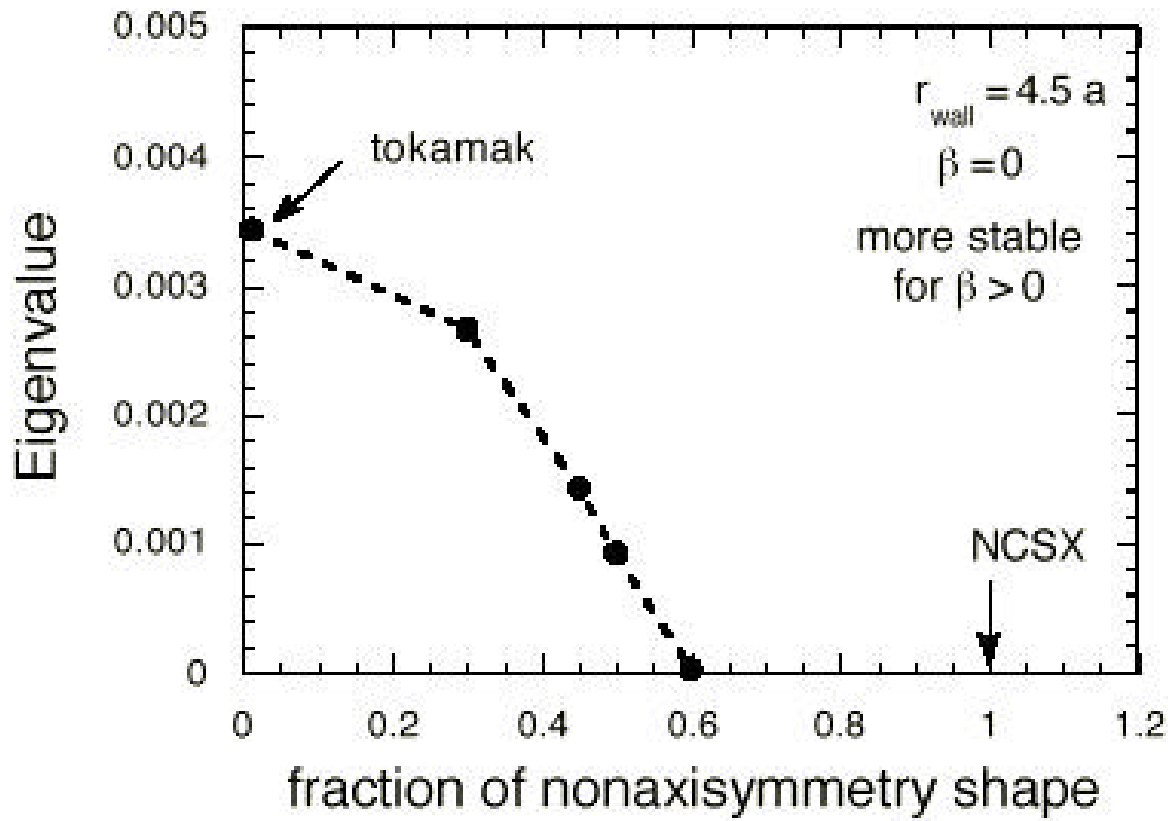
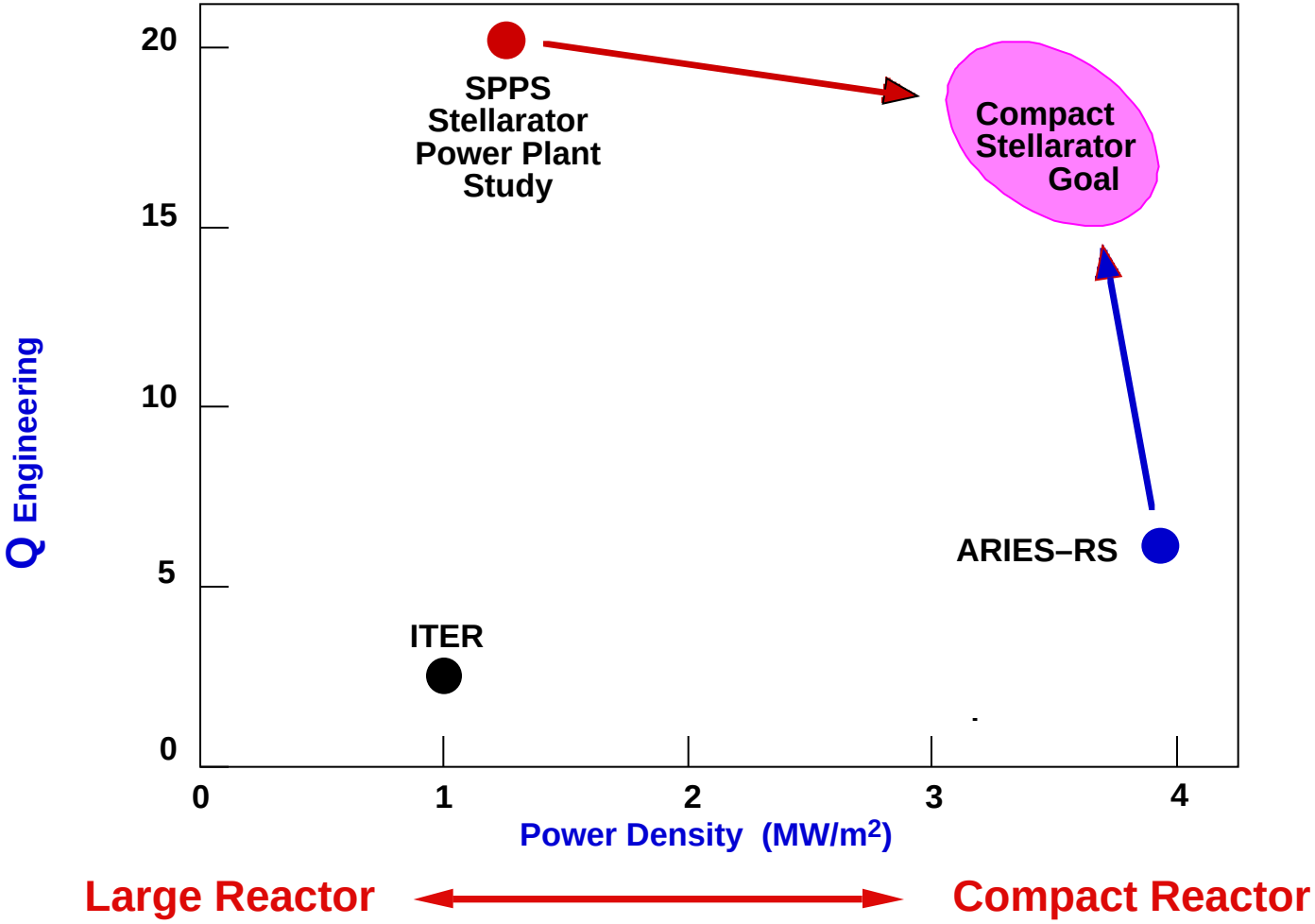
NCSX Configuration Is Robustly Stable Against Vertical Instability



- ***n* = 0 growth rate decreases from tokamak value as plasma boundary is varied toward NCSX shape**

Collaboration with CRPP-Lausanne and IPP-Griefswald

A Compact Stellarator Could Combine the Best Features of Tokamaks and Stellarators!



Large Reactor ⟷ Compact Reactor

- Compact, power density similar to tokamaks
- Without disruptions, feedback, or external current drive

FESAC Program Evaluation Criteria

0 **Quality of Science**

1 **Confidence for Next Step**

2 **Plasma Science/Technology Benefit**

3 **Issue Resolution -- physics & technology requirements**

4 **Leading Edge Research**

5 **Energy Vision**

6 **Program Issues**

7 **Portfolio Balance**

8 **Science/Technology Goals**

9 **Milestones**

These issues are addressed throughout the talk. A complete response is attached at the end of the handout.

TOPICS

- Physics Basis for Compact Stellarators
- Compact Stellarator Proof-of-Principle Program
- Programmatic Issues

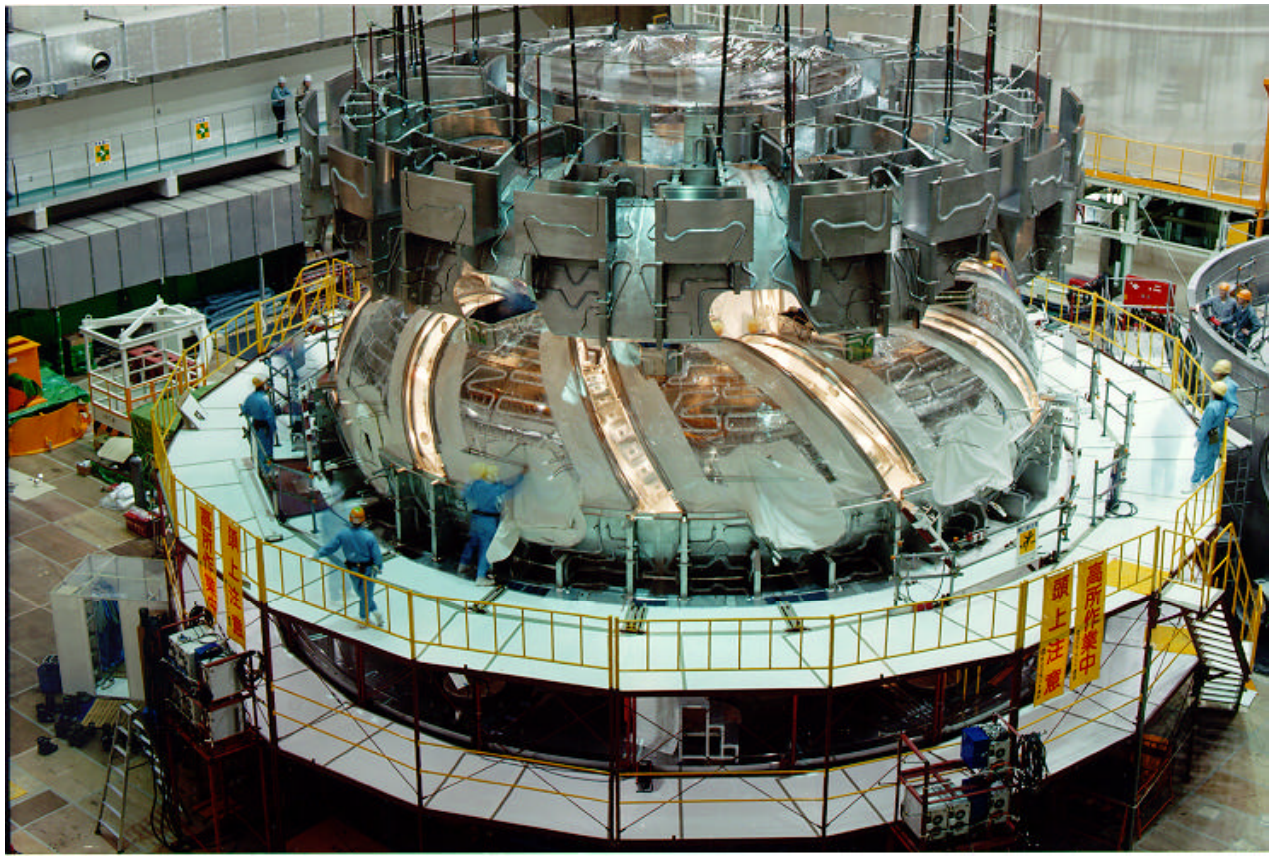
The Physics Base for the PoP Program Is Well Established

- **Equilibrium and plasma sustainment**
  - **Understanding of MHD equilibrium and stability from tokamaks and stellarators allows design of improved configurations**
  - **High-*R*/*a* stellarators with plasma current do not disrupt at density limit, β limit, or at low q (inductive) when fraction of rotational transform generated externally is >20%**
  - **Control (and reversal) of the bootstrap current and its agreement with theory has been demonstrated**
  - **>1-hour operation on ATF**

The Physics Base for the PoP Program Is Well Established (cont.)

- **Transport and divertors**
  - **3-D neoclassical transport and energetic orbit confinement is understood well enough to optimize experimental design**
  - **Global confinement scaling based on data sets from the world stellarators also fits tokamak data**
  - **Enhanced confinement techniques developed on tokamaks can be applied to stellarators (esp. QA)**
    - * edge control, flow shear
  - **Divertors have been demonstrated on CHS and will be further developed on W7-AS, LHD, and W7-X**

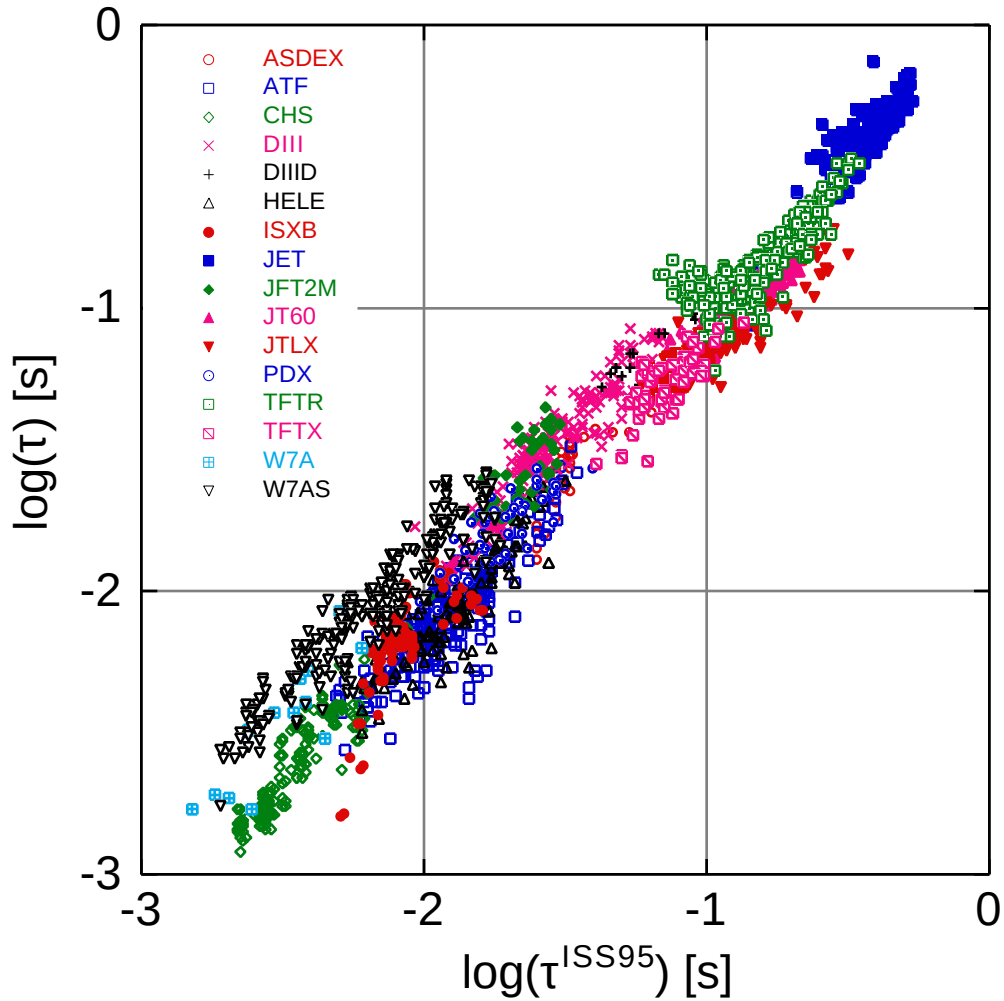
Japanese Large Helical Device Will Provide Important Data for Stellarator Development



1998

- ***R*** **= 3.9 m, <*a*> = 0.5-0.65 m, *B* = 3(4) T (SC coils), *P* ~ 40 MW**
- **steady-state, high-T_i physics, size scaling, divertor physics**

Stellarator-Based Confinement Scaling Compatible with Tokamak Data



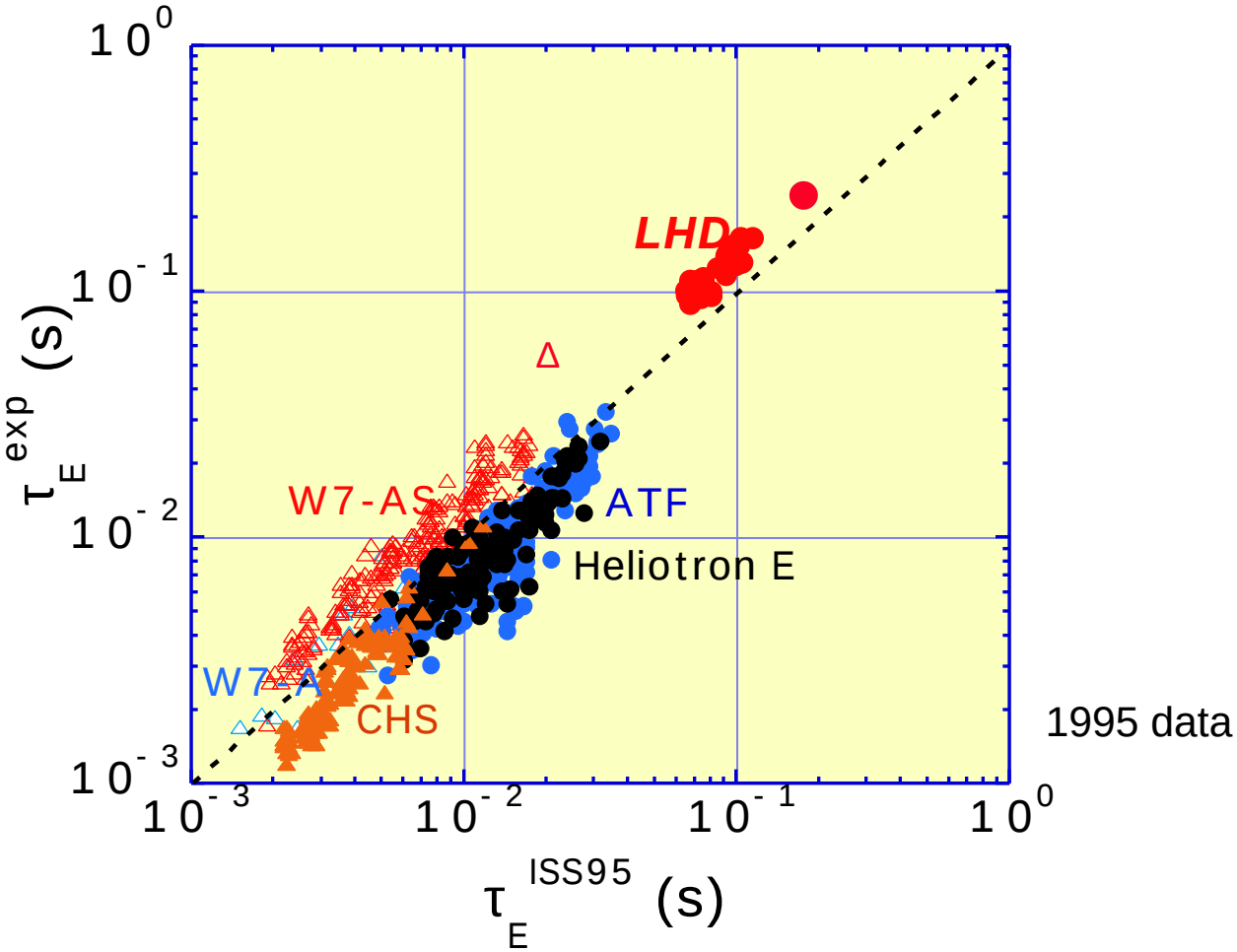
1995 stellarator data

ITER-89P tokamak data base

$$\tau_E^{ISS95} = 0.079 \langle a \rangle^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{0.4}$$

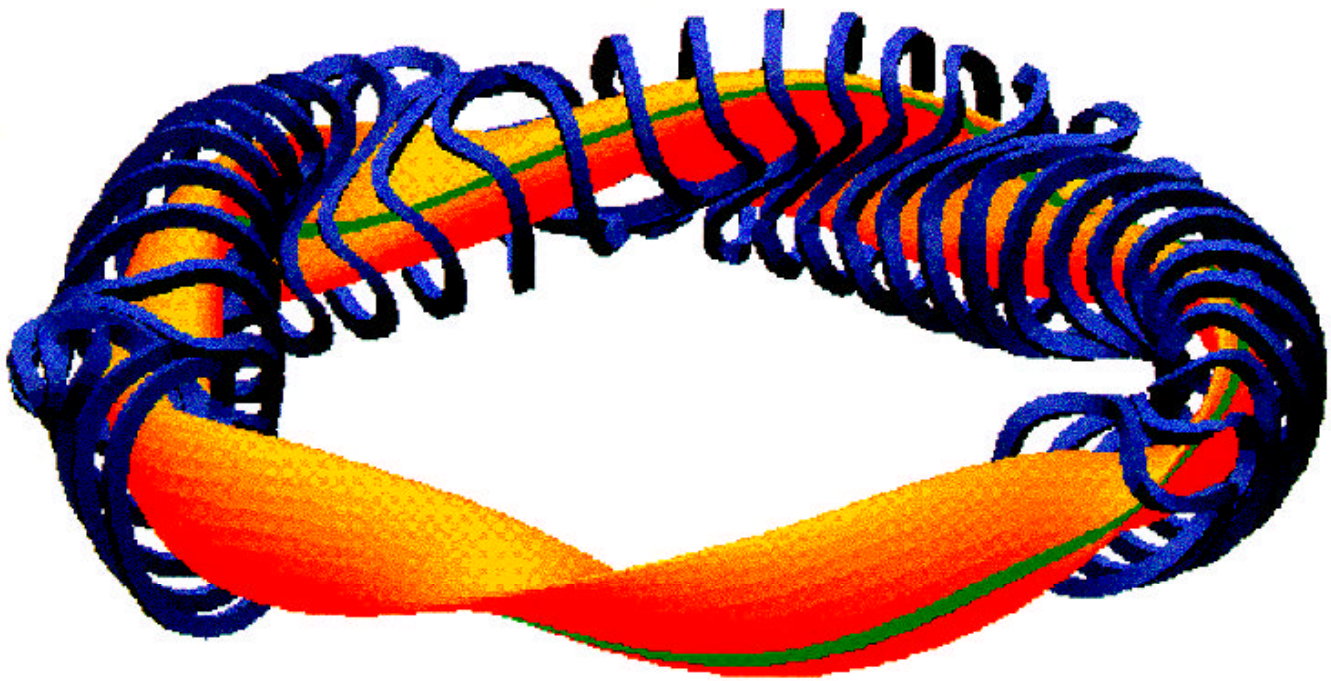
- **Provides basis for machine design**

Enhanced Confinement Has Been Observed in Stellarators



- **Newer data points fromW7-AS at 50 ms (2.5 x τ_E^{ISS95}) and initial LHD results (τ_E = 0.26 s) already above ISS95 scaling**
- **gyro-Bohm-like scaling attractive for reactor extrapolation**

Wendelstein 7-X Will Test High *R*/<*a*> QO-like Approach in 2006



- ***R*** **= 5.5 m, <*a*> = 0.52 m, *B* = 3 T (SC coils), *P* ~ 30 MW**
- **test high-β, zero-current, transport-optimized design**
- **leads to HSR reactor with *R* = 22 m**

PoP Program Will Address the Key Issues for Compact Stellarator Development

- Can a high-β stellarator with net plasma current and external transform avoid disruptions?
- What are the β limits and the limiting mechanisms?
  - test ballooning, external kink, neoclassical tearing modes, vertical instability
- Can neoclassical transport be reduced to an acceptable level by compact stellarator configuration design strategies?
- Can turbulent transport be controlled (e.g., by flow shear), leading to enhanced global confinement?

Compact Stellarator Optimization

2 complementary approaches will be tested

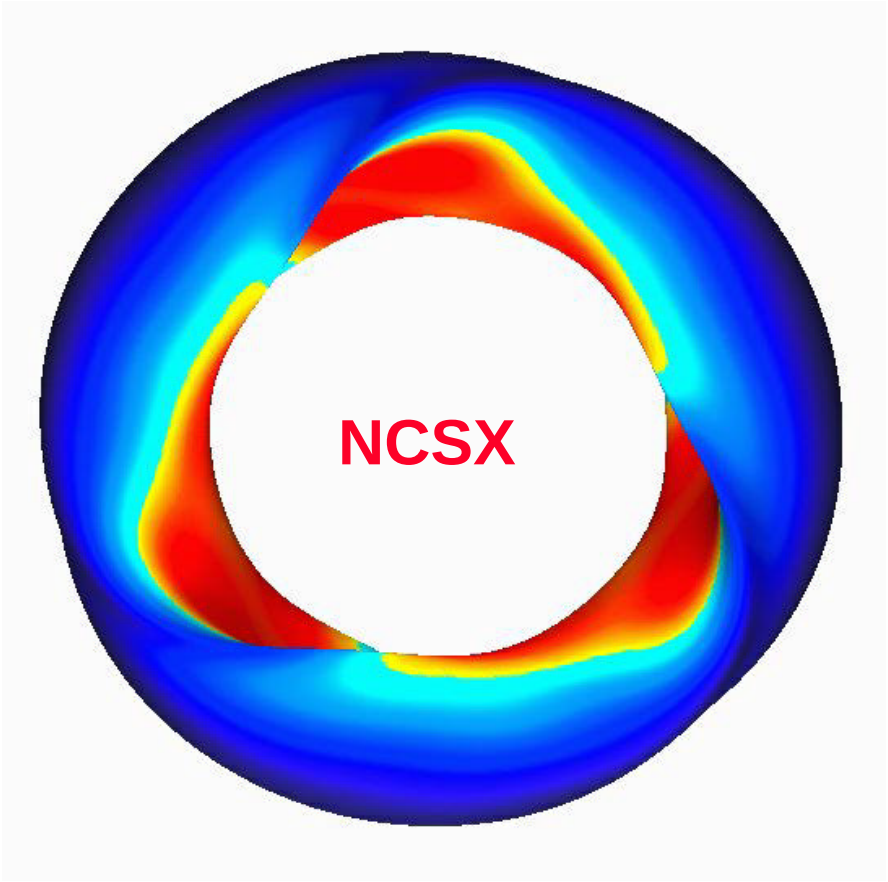
- **quasi-axisymmetry (QA)**
  - **uses the bootstrap current to produce ~1/2 of the poloidal field**
  - **hybrid of stellarator and advanced tokamak**
- **quasi-omnigeneity (QO)**
  - **approximately aligns bounce-averaged drift orbits with magnetic surfaces**
  - **advanced stellarator-like approach with some bootstrap current**
- **both are needed to develop the knowledge base to choose the best configuration for a next step**

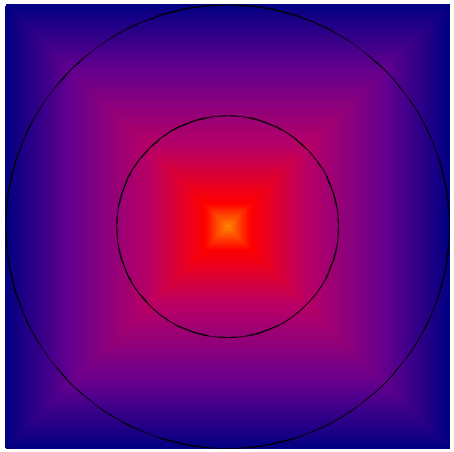
QA and QO Approaches Should be Pursued at Different Levels

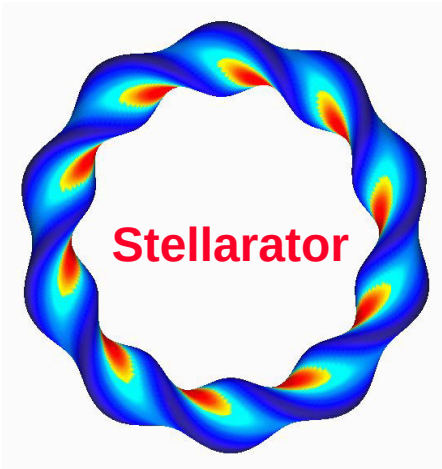
- Key issue is high-beta operation without disruptions
  - adequate power and size is needed to test β limits and transport
- QA approach chosen for PoP test (NCSX)
  - a new direction rather than refinement of an existing approach; not tested elsewhere
  - allows cost-effective use of PBX-M equipment
- QO approach chosen for CE-level test (QOS)
  - early test of W7-X-like optimization at much lower aspect ratio
- Understanding which is the better approach is needed before proceeding to the next step

NCSX: a Proof-of-Principle Experiment to Test High-β Disruption-free Operation

- **Quasi-axisymmetric (QA) design**
  - **adaptable to existing high-β tokamak experimental facility**
  - **extends quasi-symmetry thrust**







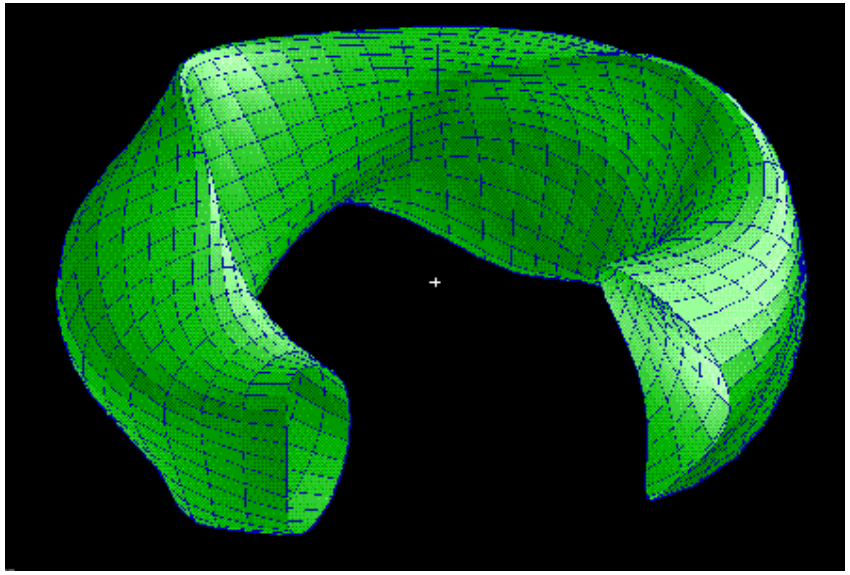
NCSX: National Compact Stellarator Experiment

PPPL, ORNL, Auburn U., Columbia U., NYU, U.Texas, U.Wisconsin

- ***R*/<*a*> = 3.4**

- **Design has no need for**
- **conducting wall, feedback, or rotation**
- **Design is stable at $\beta \geq 4\%$ to**
  - * **external kink modes**
  - * **ballooning instability**
  - * **neoclassical tearing mode**
  - * **vertical instability**

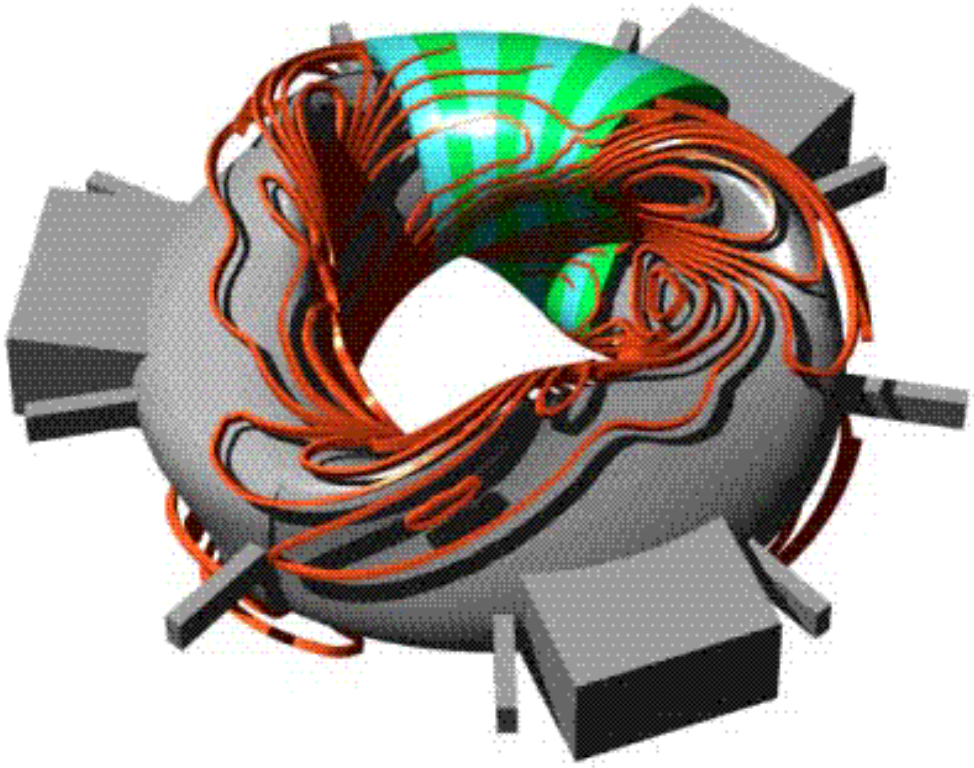
  $\Rightarrow$ **simpler system**



- **Experiment: test stability, immunity to disruptions at high β, neoclassical transport reduction, confinement improvement**

collaboration on tools with Germany, Japan, Switzerland

3-D Shaping Fields Produced by Saddle Coils Wound on a Structural Shell



Machine Parameters

R = 1.45 m, $\langle a \rangle$ = 0.42 m

$B \geq$ 1.2 T

Plasma Heating

NBI: 6 MW

ICRF: 6 MW available

- Saddle coils provide configuration flexibility; not meant to be reactor prototypical
- NCSX Core Assembly will be pre-assembled and installed in PBX-M axisymmetric magnet set
- Cost-effective approach for a PoP facility using existing coils, heating systems, power supplies, etc. at PPPL

3. ISSUE RESOLUTION

- **Transport assessment -- 2 years after 1st plasma. Assess confinement optimization and density limits at moderate beta.**
- **Short-pulse beta-limit assessment -- 3-4 years after 1st plasma. Assess short-pulse β-limit operation (4%). Decide on:**
  - **implementing the facility enhancements to complete remaining mission,**
  - **modifications to test a different Compact Stellarator configuration, *or***
  - **termination of the program**

6. PROGRAM ISSUES

What are construction & operating costs and their basis?

- **NCSX Budget Profile** (FY 1999 M$) for Proposed Scenario
  (Title I start in FY-2000, 1st plasma Sept., 2004)

Fiscal Year	1999[a]	2000	2001	2002	2003	2004	TOTAL[b]
Tot. Proj. Cost		7.2	9.0	9.7	9.3	8.7	44.0
Exper. Prep.	4.2	0.5	0.5	0.7	1.3	2.0	5.0
Total Funding	4.2	7.7	9.5	10.4	10.5	10.7	49.0

  - Based on preconceptual design information, a 5-year construction schedule, experience with previous projects, and detailed knowledge of the PBX systems
  - Operating costs are 20 M$ per year after first plasma, including facility operations, enhancements, and research

[a] For reference
[b] Total for Construction period, FY 2000 – FY 2004

- **NCSX Budget Profile (FY 1999 M$) for "Slow Start" Scenario (Title I starts in FY-2002, 1st plasma Sept., 2005)**

Fiscal Year	1999[a]	2000	2001	2002	2003	2004	2005	TOTAL[b]
Tot. Proj. Cost		4.9	5.4	6.7	10.1	9.6	9.3	46.0
Exper. Prep.	4.2	0.0	0.0	0.7	0.8	1.8	2.7	6.0
Total Funding	4.2	4.9	5.4	7.4	10.9	11.4	12.0	52.0

  - **Results in 1-year delay in first plasma, 2 M$ increase in TPC, and higher peak annual costs before first plasma**

[a] For reference

- [b] Total for Construction period, FY 2000 – FY 2005

QA and QO Approaches Should be Pursued at Different Levels

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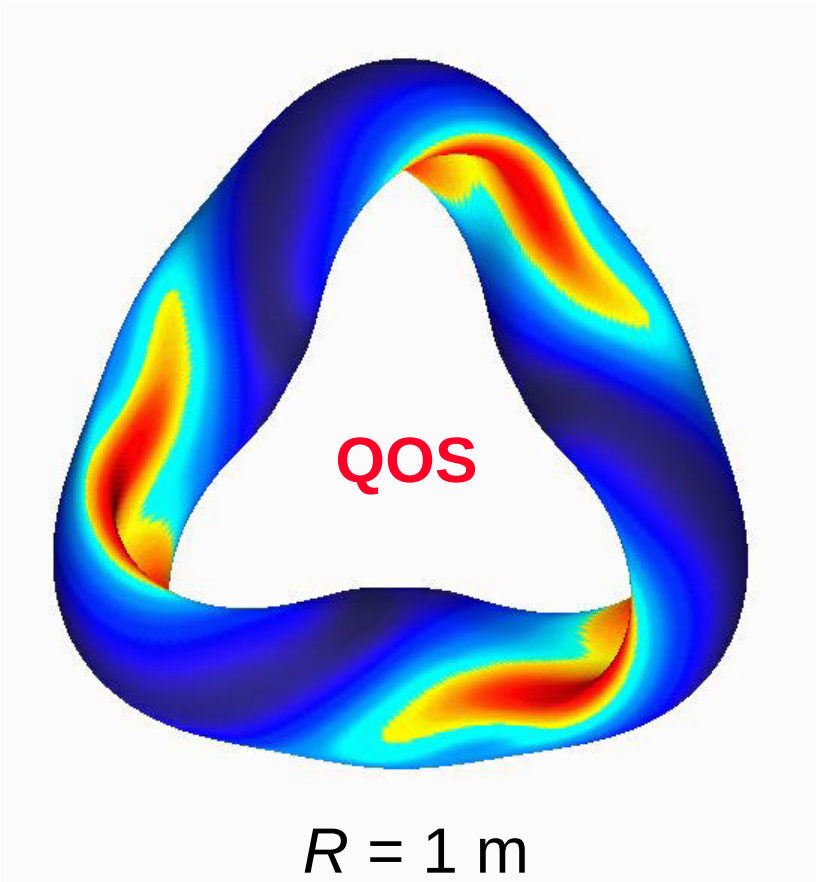
- QA approach chosen for PoP test (NCSX)
  - a new direction rather than refinement of an existing approach; not tested elsewhere
  - allows cost-effective use of PBX-M equipment
- QO approach chosen for CE-level test (QOS)
  - early test of W7-X-like optimization at much lower aspect ratio
- Understanding which is the better approach is needed before proceeding to the next step

QOS: a Hybrid Combining Features of W7-X at ~1/3 the Aspect Ratio with Some Bootstrap Current

- **Mirror structure, helical axis similar to W7-X**



R = 1 m

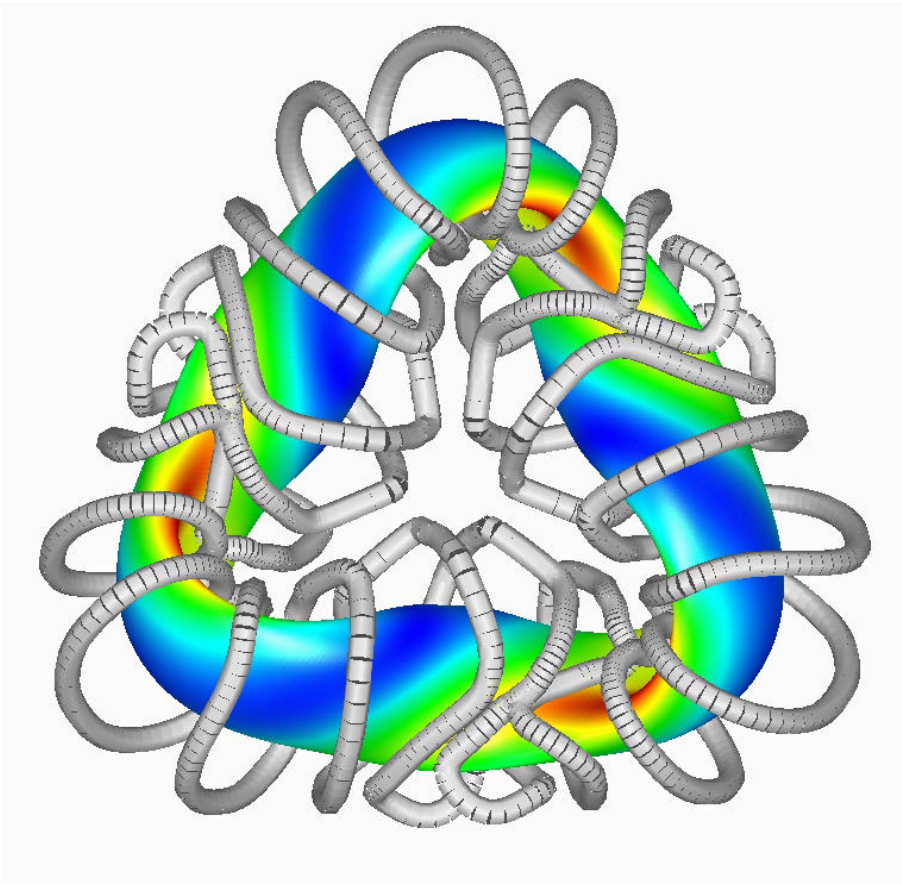
R = 5.5 m

QOS Research Goals

Test key QO physics at Concept Exploration scale as a complement to NCSX

- **Reduction of energetic orbit losses and transport in low-A non-symmetric configurations**
- **Control and reduction of the bootstrap current, configuration invariance with β**

Quasi-Omnigenous Stellarator



Plasma Configuration

- $\langle\beta\rangle \approx 4\%$ (not at CE-level)
- $\iota(r) = 1/q$ 0.78–0.91

Scoping Study Parameters

- R_0 1.0 m
- $\langle a\rangle$ 28–33 cm
- $R_0/\langle a\rangle$ 3–3.6 (1/3 W7-X)
- B_0 1 T

Plasma Heating Available

- 0.6 MW ECH
- 3 MW ICRF

ornl

QOS Costs and Schedule Less Well Defined

- **Scope defined by concept-exploration-level budget**
- **Total Project cost ≈ 8 M$ in FY-99 $ (2001-2003)**
  - **based on comparisons with HSX and ATF**
- **Total budget rising to ≈4 M$ after first plasma**
- **First plasma in June 2003 for Proposed Scenario (1.3 M$ budget in FY-2000)**
- **First plasma in Sept. 2003 for "Slower Start"Scenario (0.65 M$ budget in FY-2000)**

9. KEY PROJECT MILESTONES

- **NCSX:**
  - **Physics Validation Review in September 1999**
  - **Conceptual Design Review in March, 2000**
  - **1st Plasma in Sept. 2004 with 3.5 M$ increment in FY 2000**
  - ***1st Plasma in Sept. 2005 with 0.65 M$ increment in FY 2000***

- **QOS:**
  - **Physics Validation Review in April 2000** ***(June 2000)***
  - **Conceptual Design Review in Sept. 2000** ***(Dec. 2000)***
  - **1st Plasma in June 2003 with 1.3 M$ increment in FY 2000**
  - ***1st Plasma in Sept. 2003 with 0.65 M$ increment in FY 2000***

- **Appropriate reviews of NCSX and QOS should be conducted by DOE**

– **Are there adequate resources to accomplish the proposed program goals?**

* **NCSX: project scope includes the device, adapting the 4 PBX-M neutral beam lines, and facility modifications to operate at *B* = 1.2 T with a basic diagnostic set**
* **Equipment provided is sufficient for the highest-priority goal of disruption-free operation at high β**
* **Enhancements to accomplish the full mission would come out of the 20 M$/year operating budget**

* **QOS: project scope includes the device, adapting the ATF ECH system, and facility modifications to operate at *B* = 1 T with a basic diagnostic set**
* **Additional diagnostics and ICRF heating are available from the ATF and TEXT programs**

SUMMARY

- Compact Stellarators provide a route to steady-state, disruption-free reactors
- NCSX addresses high β without disruptions and has tokamak-like symmetry properties to improve confinement
- QOS avoids disruptions by minimizing bootstrap current and has W7-X like transport optimization
- Combined program with supporting research satisfies FESAC PoP program evaluation criteria
- FY 2000 increases of 3.5 M$ for NCSX and 1.3 M$ for QOS are needed to proceed as proposed
- FY 2000 increase of 1.3 M$ would delay both experiments but would permit start of required NCSX R&D and QOS design

CONCLUSIONS

- **Recommendation: the proposed Compact Stellarator PoP program provides concept innovations that address critical fusion science issues**
  - **steady state and disruptions at high β**

  and should be supported to proceed as proposed

- **Even if Compact Stellarators receive only 1/3 of the 3.9 M$ set aside for PoP programs in FY-2000, the program would proceed on a slower schedule, but important and useful steps forward could be taken**