US Stellarator Proof-of-Principle Program

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for the US Stellarator Community

PoP Program Review June 8, 1998

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TOPICS

Need for Compact Stellarator Program

Readiness for a PoP Program

Compact Stellarator Strategy

Proposed Program

Existing Program Elements

NCSX Proof-of-Principle Facility

QOS Concept Exploration Experiment

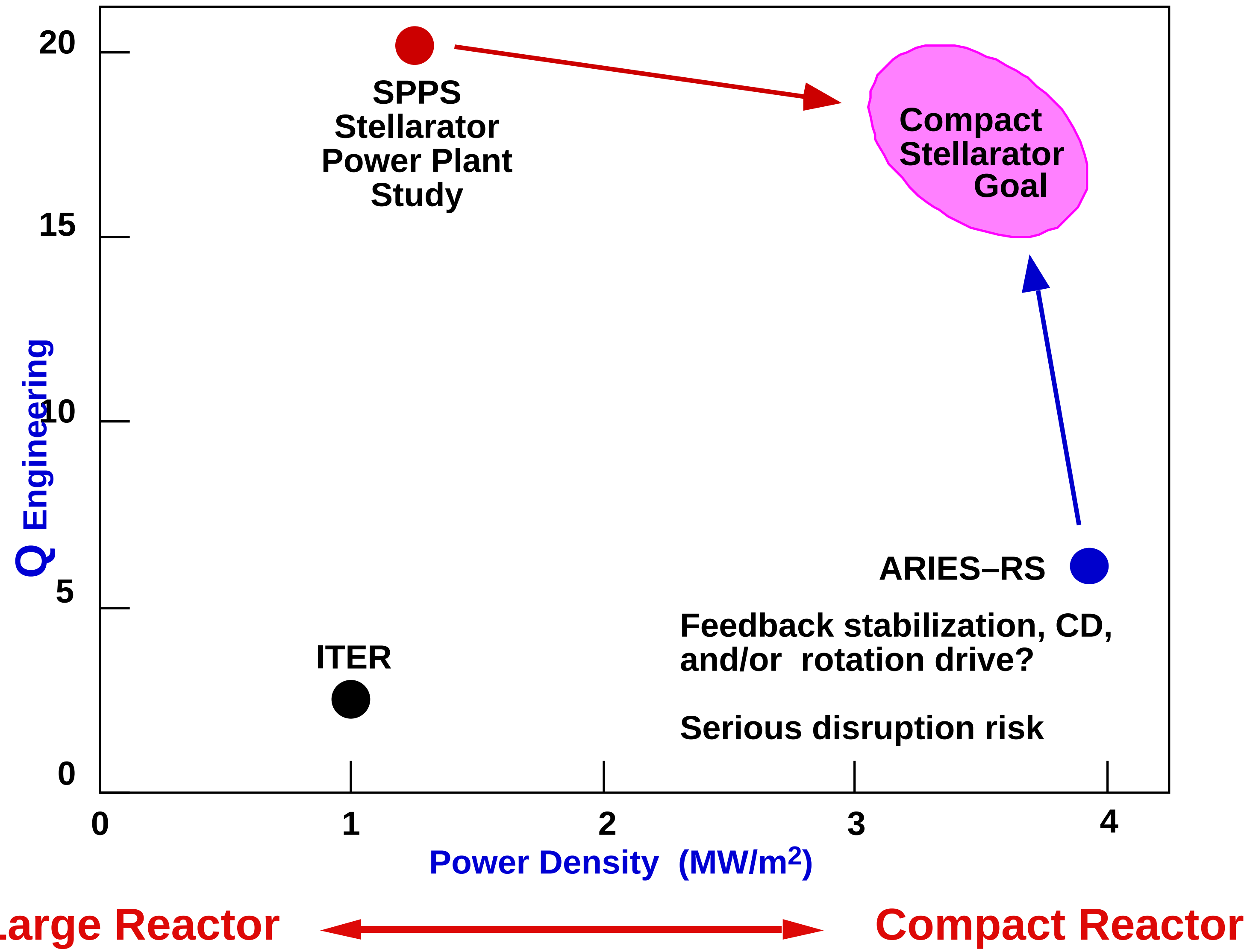
The U.S. Needs a Compact Stellarator Program

- **Stellarators have distinct advantages as reactors**
  - no disruptions, even at the highest β less margin needed
  - maximum density determined by power, not disruptions
  - no current drive low recirculating power, more flexibility and control in the operating point
- **U.S. program has developed 2 complementary strategies for attractive compact stellarators**
  quasi-axisymmetry (QA) & quasi-omnigeneity (QO)
  - optimized neoclassical transport, reduced below anomalous
  - bootstrap current incorporated in the optimization
  - aspect ratios ranging from 2 to 4 smaller, lower cost than present designs in the non-US program
  - $\beta > 5\%$ similar to latest tokamak reactor (ARIES-RS)
- **Need a Proof-of-Principle scale Program to assess whether these characteristics can be attained**
  - develop the basis for deciding whether to pursue at a larger (Proof-of-Performance) scale

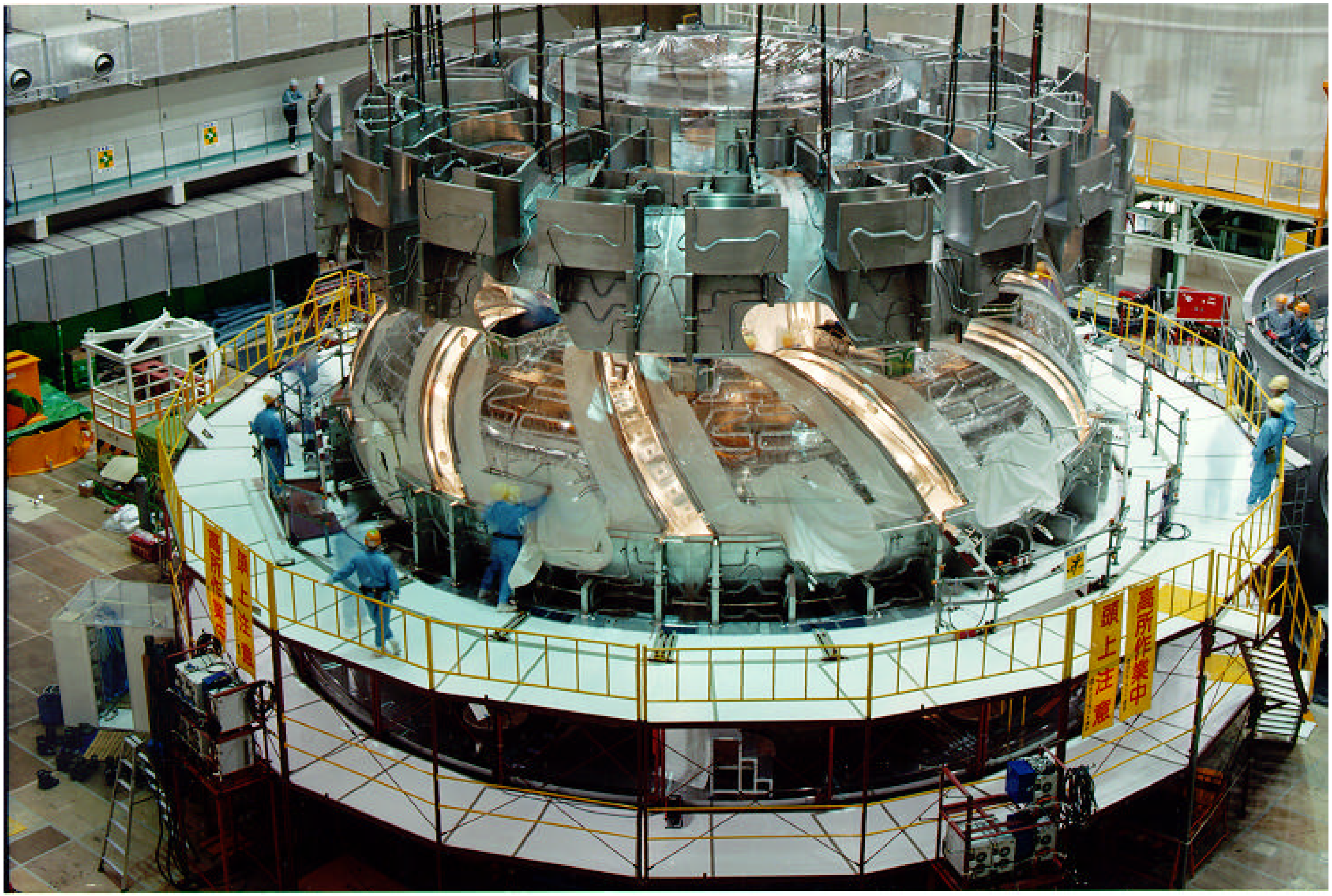
Major Focus is on β > 5% *without* Disruptions

- **Disruptions are the dominant issue for the design of a tokamak reactor**
  - **Thus far, advanced tokamak regimes are more disruptive than ITER-like regimes**
  - **ARIES Industriual Team: goal is 1 disruption per decade!**
- **Stellarators offer a potential solution**
  - **can design for ballooning and kink stability without a close conducting wall**
  - **past experiments with OH currents and modest external rotational transform (È = 1/*q* ≈ 0.15) have observed stabilization of density-limit and low-*q* disruptions**
- **Can this work at high β with bootstrap currents?**

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

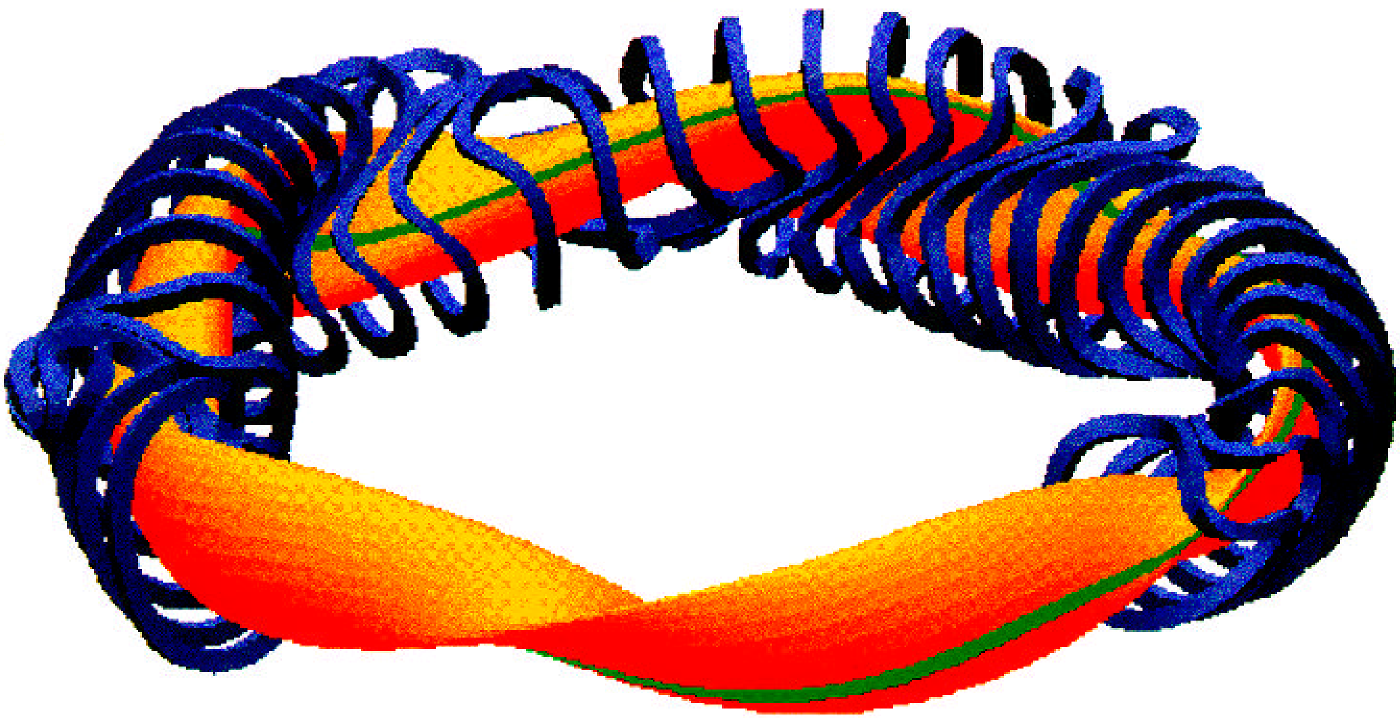


LHD Has Started Operation



- **Only initial commisioning phase so far**
- **τ_E = 250 ms at 6 x 10^{18} m^{-3}, 80 kW ECH**

W7-X Will Test High *R*/<*a*> QO Approach in 2006



Extrapolates to HSR reactor (*R* = 22-24 m)

Foreign Stellarator Programs Address Important Issues, but not Compactness

- **Large Helical Device: *R* = 3.9 m, <*a*> = 0.65 m, *P* = 30 MW**
  - steady-state (superconducting coils), helical & island divertors
  - bootstrap current, energetic orbit confinement, transport
  - performance that can extrapolate to a burning plasma
- **W7-X (2006): *R* = 5.5 m, <*a*> = 0.52 m, *P* = 30 MW**
  - minimization of Pfirsch-Schlüter and bootstrap currents
  - QO-like optimization and β limits at high aspect ratio
- **W7-AS (until 2001): *R* = 2 m, <*a*> = 0.18 m, *P* = 3 MW**
  - confinement improvement, electric field effects, island divertor
- **CHS (until 1999): *R* = 1 m, <*a*> = 0.2 m, *P* = 3 MW**
  - confinement, electric field effects at medium aspect ratio
- **TJ-II and H-1 -- large helical axis excursions**

A PoP-Scale Experiment is Needed to Address Critical Issues for Compact Stellarators

- **Stellarator scaling laws set *P*, *R* constraints**

  τ_E^{ISS95} $R^{2.86}P^{-0.59}n^{0.51}B^{0.83}$ (fixed $R/<a>$ & È); n_{max} $(PB/R^3)^{0.5}$

  – $\underline{È_{BS}/È_{ext}}$ $\underline{\beta}$ H $R^{-0.14}\underline{P}^{0.4}n^{0.5}B^{-1.17}$ H $R^{-0.9}\underline{P}^{0.67}B^{-0.92}$

  – $\underline{T_{i,e}}$ H $R^{-0.14}\underline{P}^{0.4}n^{-0.5}B^{0.83}$ (for confinement studies)

  – $\underline{1/\nu^*}$ H^2 $R^{-1.28}\underline{P}^{0.82}n^{-1.98}B^{1.66}$

  – $\underline{\beta/\nu^*}$ H^3 $R^{-1.42}\underline{P}^{1.23}n^{-1.47}B^{0.5}$ (for high $È_{BS}/È_{ext}$ at low ν^*)

  Need high *P* to reach β, $È_{BS}/È_{ext}$, $T_{i,e}$, $1/\nu^*$ goals

  – Confinement improvement H is critical, easier at high *T* (*P*)?

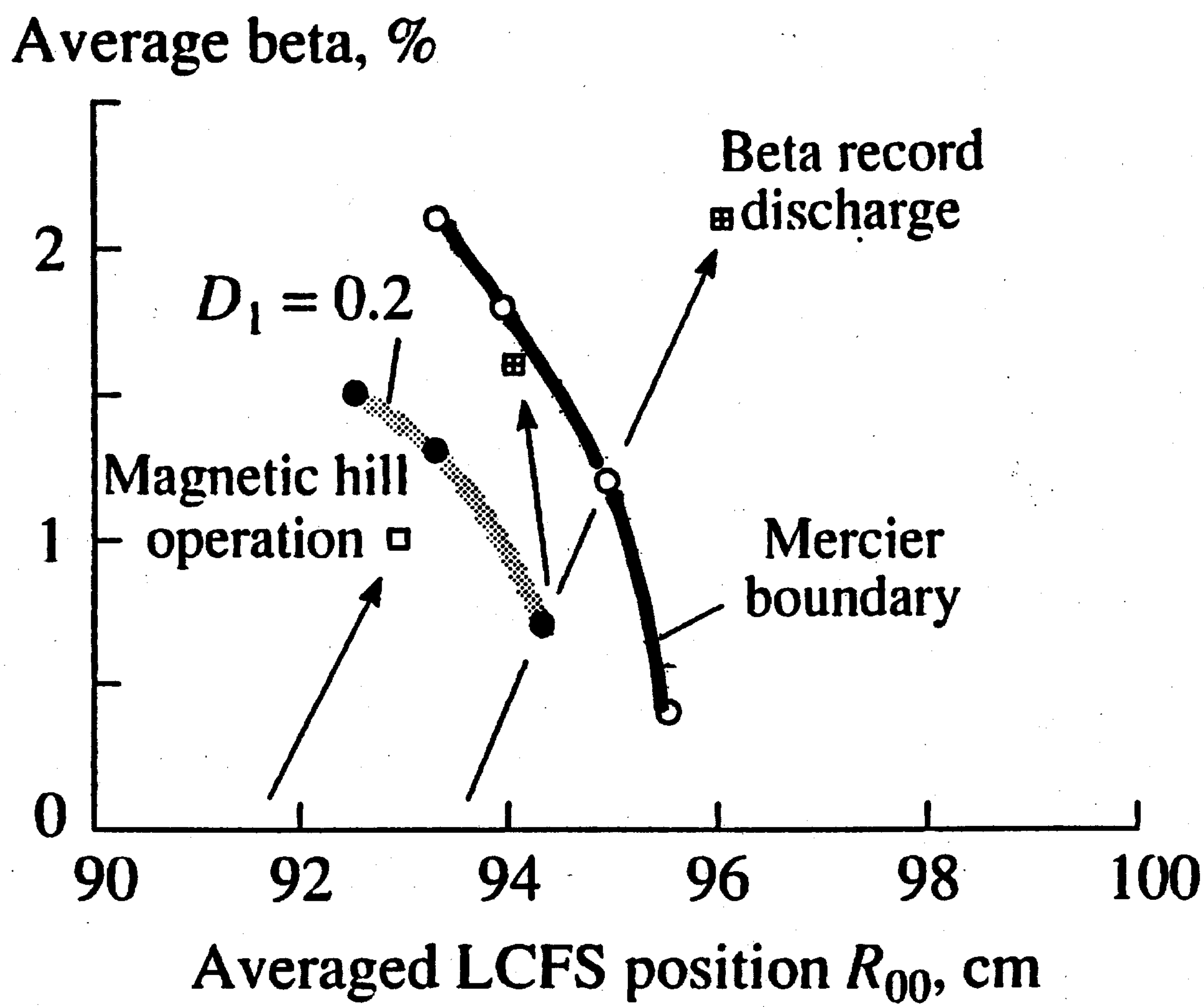
- **High *P* (neutral beam heating) sets constraints**
  – $BR > (BR)_{min}$ for good orbit confinement
  – $nR > (nR)_{min}$ for acceptable charge-exchange losses
  – access (*R*) and wall power density (P/R^2)

- **Time scales set pulse length constraints**
  – long enough to see bootstrap current effects

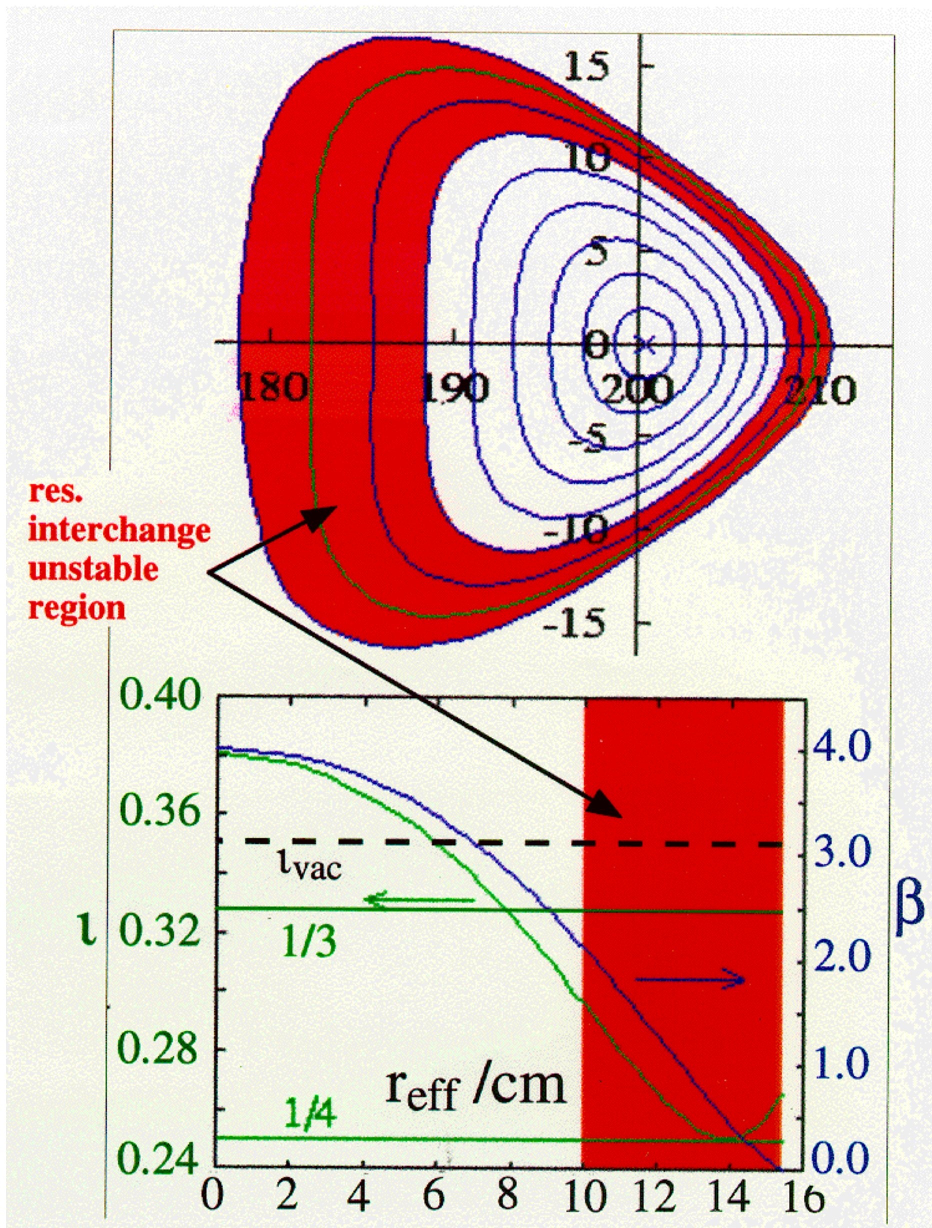
Data Base is in Hand for a PoP Program

- **Present stellarators exceed simple β limit estimates**
  - Δ/<*a*> = 2/3 at β = 1.8% in W7-AS; no change in behavior
  - Mercier instability criterion exceeded over most of CHS plasma radius at β = 2.1% without significant change in confinement
- **Bootstrap current control demonstrated: ATF, W7-AS**
- **Experiments show immunity from disruptions with modest amounts of external rotational transform (≈0.15)**
  - W7-A, CLEO (at high aspect ratio and low beta)
- **Anomalous transport has been reduced in present stellarator experiments (improved confinement modes)**
- **W7-AS/W7-X and CHS/LHD are developing control of particle and heat exhaust**
- **ARIES Team showed that a modular stellarator was competitive with the second-stability ARIES IV tokamak reactor, even at 2x the aspect ratio being targeted**

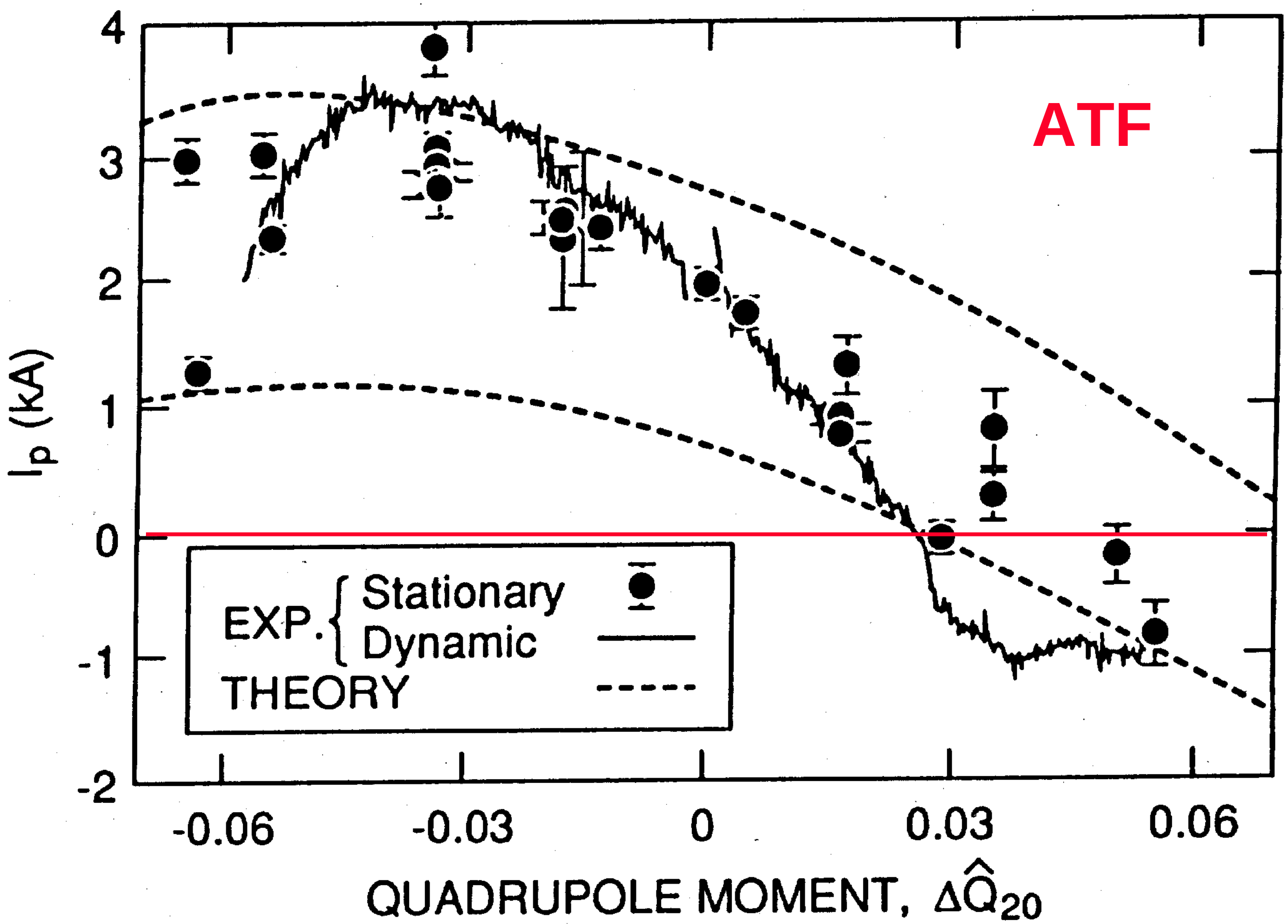
CHS Exceeds Mercier β Limit



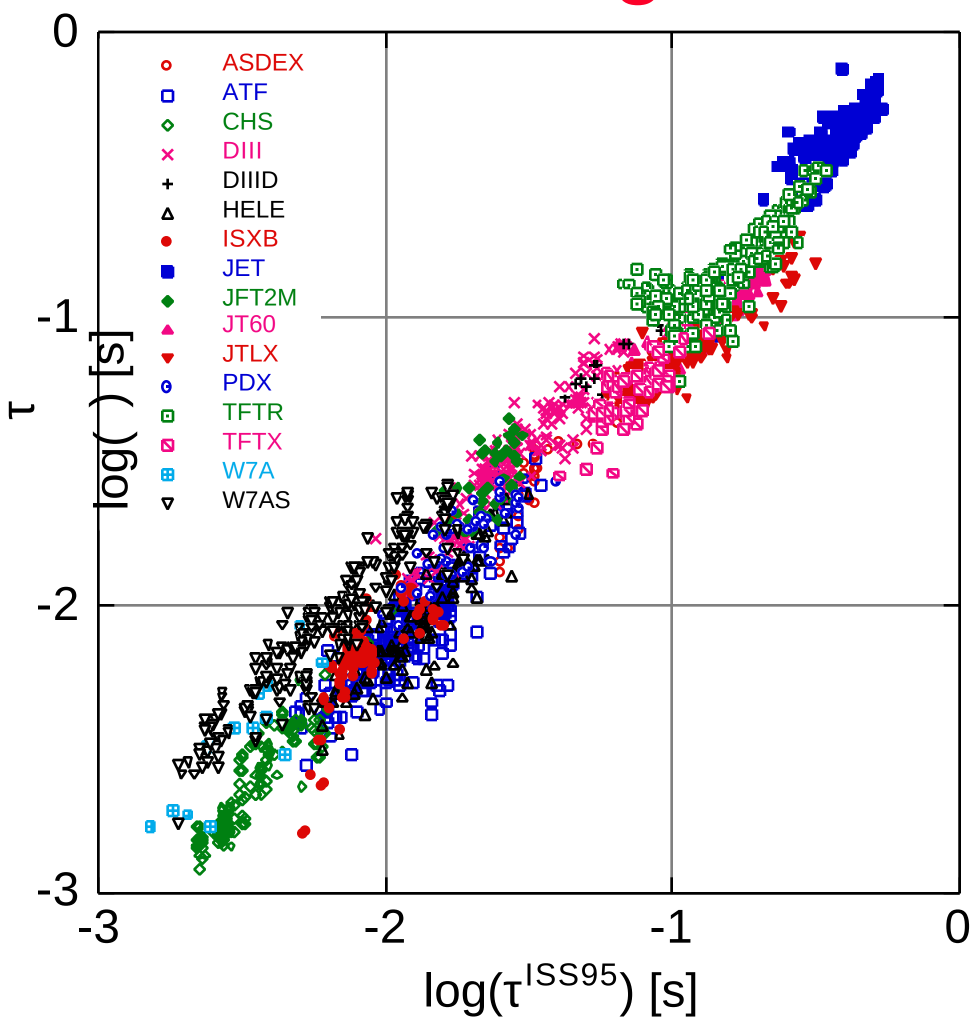
No Instabilities Seen at $\beta = 1.8\%$ in W7-AS



Bootstrap Current Agrees with Experiment in ATF and W7-AS



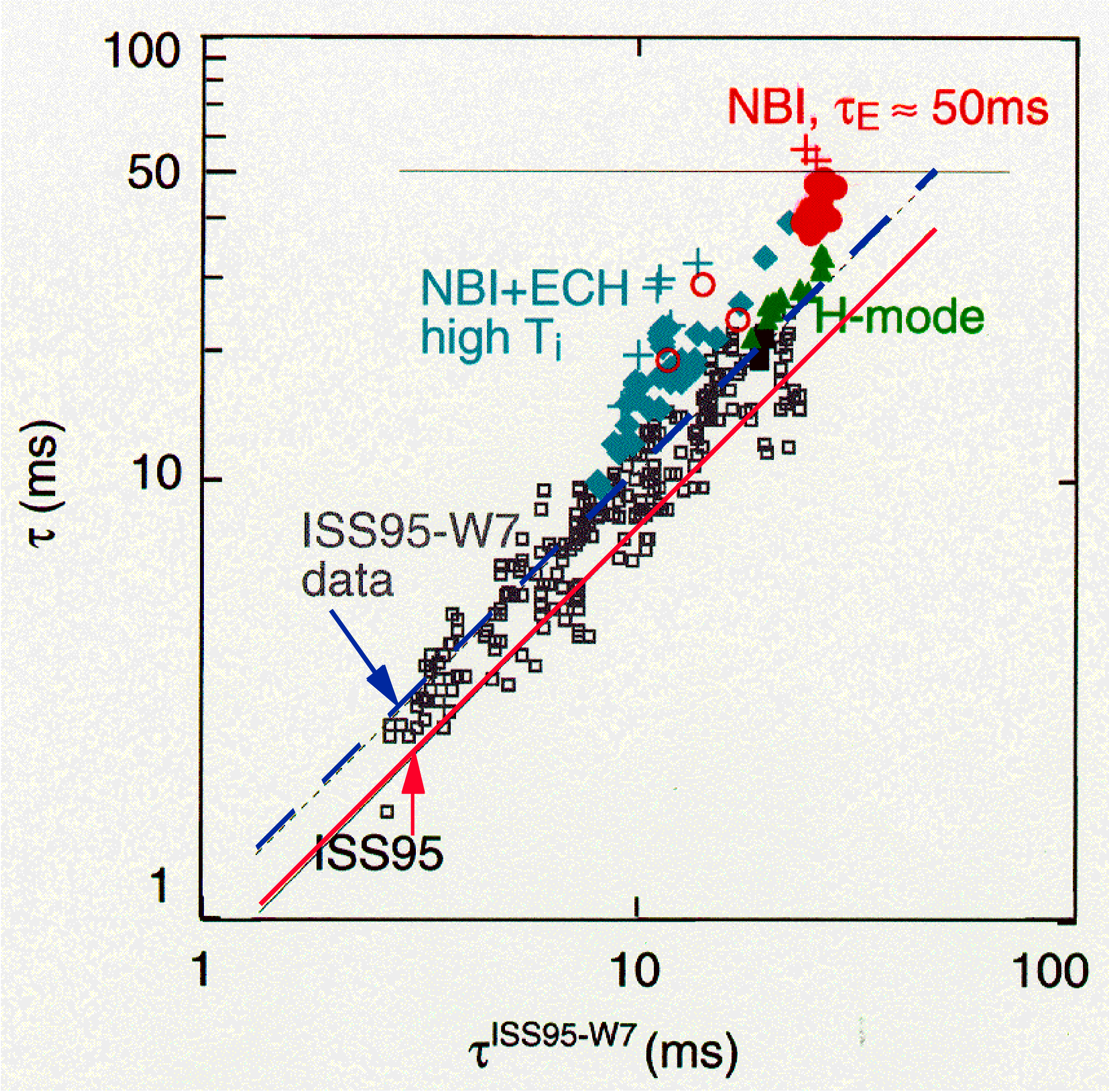
Confinement Scaling in Stellarators



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

- **Low-shear W7-AS factor ~2 above the trend**

W7-AS Improves on ISS95 Scaling



Validated 2-D and 3-D Tools Are Available for Optimization and Design of PoP and CE Experiments

- **Configuration Design**
  - Field line and flux surface codes
  - MHD equilibrium codes
  - Bootstrap current codes
- **Configuration Performance/Analysis**
  - MHD stability codes (Mercier, ballooning, kink)
  - Monte Carlo transport codes
  - Time-dependent transport codes
  - Calculation of ambipolar electric field
  - Neutral beam and RF modeling
- **Device Design**
  - Calculation of coils from magnetic configuration
  - Complex coil design, analysis, and fabrication codes
  - Vacuum vessel design, analysis, and fabrication codes
- **Auxiliary Systems**
  - ICRF antenna design codes
  - Diagnostic analysis codes

Two Optimization Strategies Have Been Developed for Compact (A = 2 – 4) Stellarators

- **Quasi-axisymmetry (QA)**
  - * Quasi-symmetric stellarators conserve a component of the canonical momentum and have neoclassical transport properties that are tokamak-like: 1st test in HSX
  - * Quasi-axisymmetric stellarators can have aspect ratios and bootstrap currents typical of tokamaks, so they resemble hybrids of stellarators and advanced tokamaks
- **Nonsymmetric quasi-omnigeneous (QO) stellarators**
  - * achieve reduced neoclassical losses by approximately aligning the collisionless trapped particle drift orbits with the magnetic surfaces
  - * provides a larger fraction of the rotational transform by external coils, reducing the fraction that must be created by the bootstrap current
- **Both can have a deep magnetic well and high beta limits for ballooning and external kinks**

Quasi-Axisymmetry

- **In magnetic coordinates, has topology similar to tokamak (few % non-axisymmetric components)**
  - **expect similar transport, bootstrap current, rotation shear, etc.**
- **Strong axisymmetric component of shaping used to obtain good ballooning stability**
- **Should have good MHD properties**
  - **Designs with kink and ballooning β limit > 7% without close wall. "Reversed shear" across entire profile.**
- **~40% of È (= 1/*q*) from external coils to avoid disruptions**
- **Configuration can be produced with modular coils (reactor) or with saddle coils + TF + PF (experiment)**

Quasi-Omnigeneity

- **In magnetic coordinates, has topology more like W7-X (large non-axisymmetric components)**
  - expect similar transport, global magnetic well, etc.
- **However, factor of 3 lower aspect ratio than W7-X, higher bootstrap current (>70% of È from external coils)**
  - Should ease control from low to high β
- **Can achieve good orbit confinement by optimizing variation of the second adiabatic invariant J***
  - neoclassical $\tau_E > 100\tau_{ii}$ at 1 keV, 5 x 10^{13} cm^{-3}
  - alpha-particles confined by J*-contour closure
- **Should have good MHD properties**
  - Ballooning, Mercier, and external kink stable at $\beta = 7\%$ with monotonic j(r) and self-similar bootstrap current profiles

Compact Stellarator Optimization

- **Both the QA and QO concepts make use of the bootstrap current, but to different degrees, to create a configuration with <1/3 the aspect ratio of the currentless W7-X stellarator**
- **The new QA and QO stellarator configurations are aimed at $\beta \geq$ the 5% value projected for LHD, W7-X, and the ARIES-RS tokamak reactor**
- **Both look attractive for more compact reactors, but each has distinct complementary advantages**
- **Both must be developed experimentally to establish the needed scientific base for the program's ultimate success.**
- **A determination of the optimum strategy to pursue is one of the U.S. stellarator program's goals**

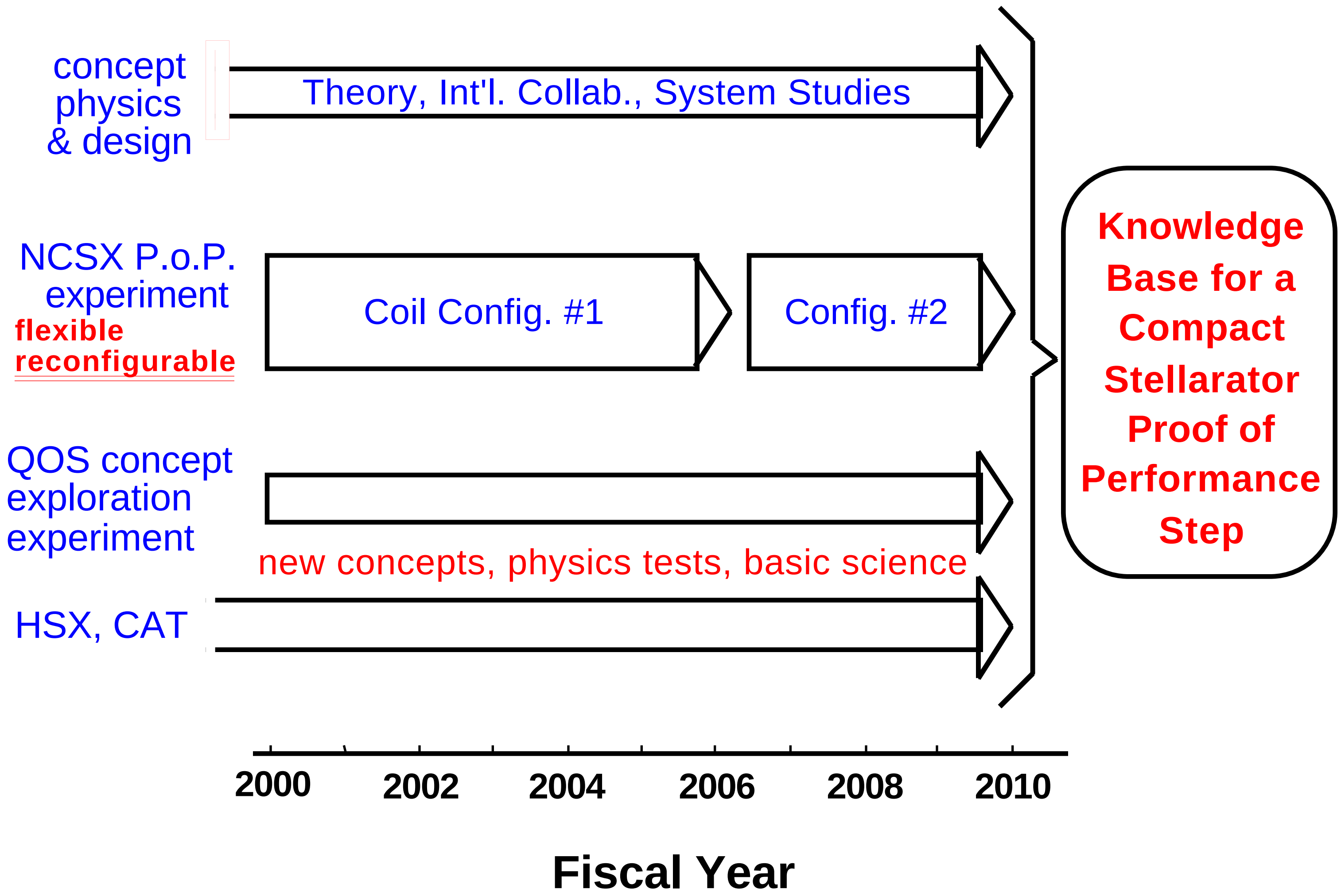
QA and QO Testing Approach

- In order to minimize cost, it is planned to construct the NCSX PoP facility by modifying an existing device, the PBX-M tokamak, and using its supporting infrastructure
- The QA designs are likely more compatible with the PBX-M constraints, so QA been chosen as the initial PoP configuration for NCSX
- A new concept exploration experiment (QOS) will test the basic principles of the QO optimization strategy
- This will provide a better data base for optimum design of a PoP-level QO configuration which could be tested as the second magnetic configuration in the NCSX facility

Compact Stellarator PoP Program Approach

- **Use existing higher *R*/<*a*> US stellarators**
  - **HSX (quasi-symmetry), CAT (disruption studies)**
- **Take advantage of existing resources (PBX-M) to reduce cost of a PoP-level experiment "with a plasma of sufficient size and performance that a range of physics issues can be examined" to test QA approach**
- **Construct a Concept-Exploration experiment to test complementary QO approach**
- **Use international collaboration on higher *R*/<*a*> currentless stellarators to study specific issues**
- **Enlarge theory effort for comprehensive understand-ing, extrapolation from experiments, tool/analysis development, and further concept development**
- **Use ARIES Team for reactor assessments**

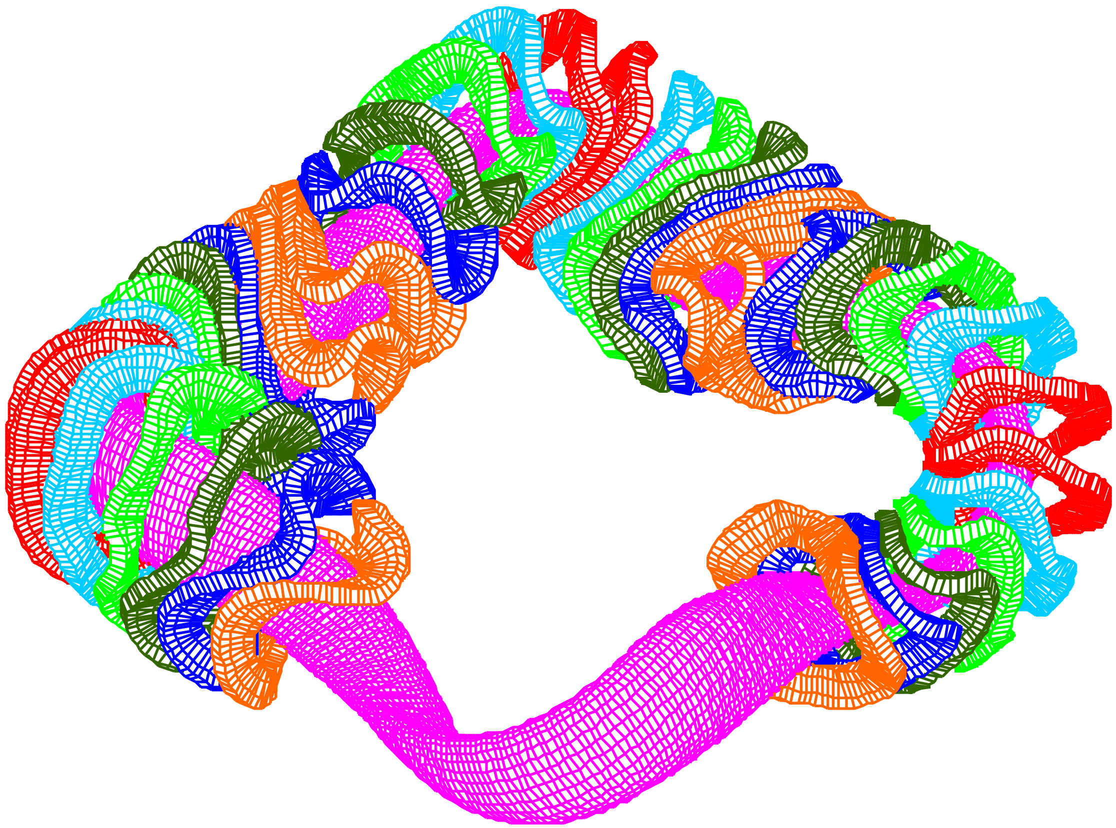
Compact-Stellarator Proof-of-Principle Program



All PoP program elements are complementary, interconnected, and essential for a later Proof-of-Performance decision

The HSX Experiment

Quasi-helically symmetric magnetic configuration



$R_0/\langle a\rangle \approx 8$, but effective aspect ratio ~ 400

The Existing HSX Stellarator Will Provide the First Results on Quasi-Symmetry

- **HSX has a high "effective" rotational transform: small Pfirsch-Schlüter currents; small poloidal gyroradius; and neoclassical transport that can be smaller than in a comparable tokamak**
- **The primary objectives of the HSX program are to study**
  - **reduction of neoclassical transport in QHS configurations and the role of anomalous transport**
  - **reduction in direct loss of deeply trapped particles**
  - **decreased viscous damping of rotation on a flux surface**
- **HSX has low $j_{||}$ at high aspect ratio, which complements large $j_{||}$ at low aspect ratio in the QA configuration**
- **Extending quasi-helical symmetry to quasi-axisymmetry at half the plasma aspect ratio will be the task of NCSX**

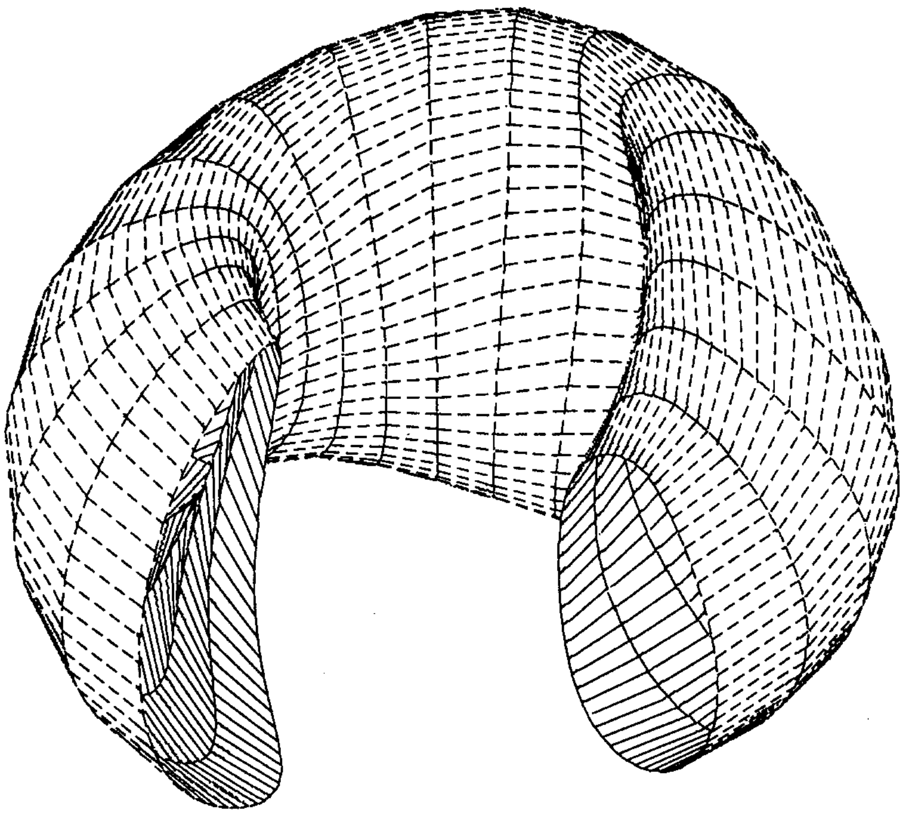
Modest-Cost Upgrade to the Existing Compact Auburn Torsatron Allows Additional Studies

- **CAT is a small (R = 0.53 m, <a> = 10 cm, B = 0.1 T), medium-aspect-ratio (5.6) conventional stellarator**
  - can vary transform from 0.08 to 0.6
  - can upgrade to I_p = 25 kA, B = 0.5 T and P_{ICRF} = 100 kW
- **Main objectives of the CAT program are to study**
  - role of transform from plasma current and pre-existing magnetic islands on current-driven instabilities
  - external kink stability and internal resistive modes
  - ICRF plasma generation and heating
- **Extending the studies of disruption avoidance and stability to a large bootstrap current fraction and to lower plasma aspect ratio in an optimized stellarator will be the task of NCSX**

Key Issues Need to be Resolved before a Proof-of Performance Decision

- **Can a $\beta > 5\%$ stellarator with bootstrap current and external transform avoid disruptions?**
- **What is the ultimate β limit and the limiting mechanism for compact stellarators?**
- **Can neoclassical transport and orbits losses be reduced sufficiently by the QA and QO optimization strategies?**
- **Can turbulent transport be controlled to give sufficient confinement for an attractive reactor?**
- **Is there a workable scheme to control particle and heat exhaust that is applicable to a reactor?**

Quasi-Axisymmetric NCSX



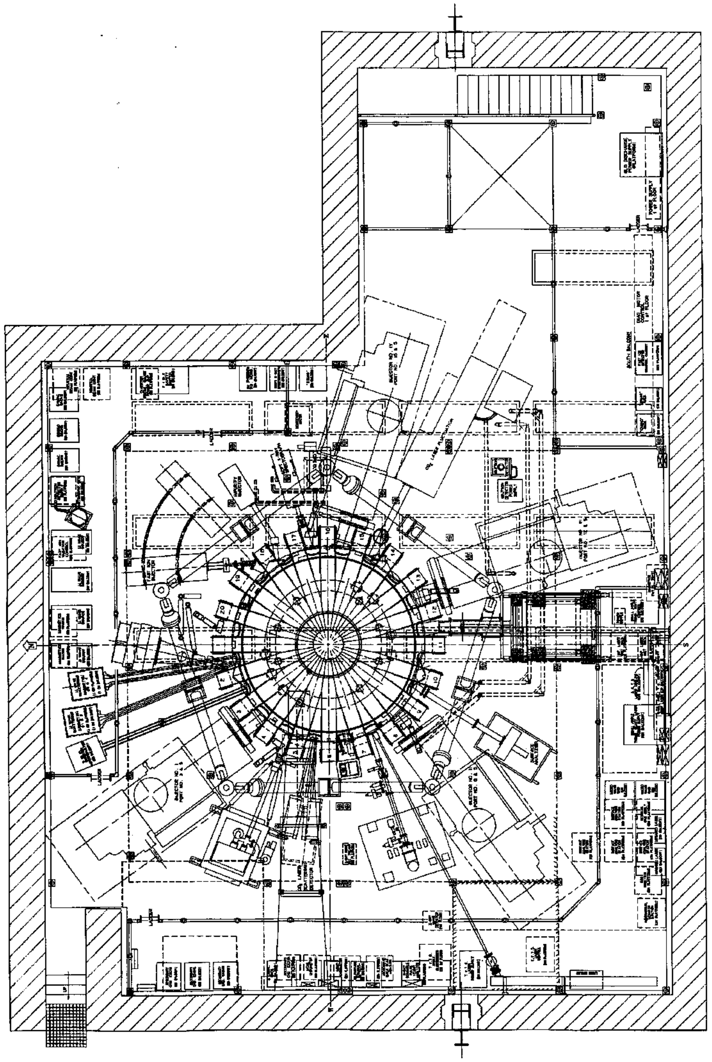
- R_0 1.5 m
- <*a*> 45 cm
- $R_0/\langle a \rangle$ 3.3
- Volume 6 m^3
- B_0 1 - 2 T
- I_p <400 kA
- Pulse 3 - 5 s
- Plasma Heating
  6-12 MW; NBI+ICRF

The NCSX PoP Facility

- Provides sufficient plasma performance and device capability for integrated testing of compact stellarator configurations that allow extrapolation to more reactor-relevant performance
- A PPPL-ORNL NCSX Project has been developed
  - conceptual design will be completed mid FY-99
  - construction start in FY-2000, 1st plasma in 2003
  - total project cost is estimated at $35M
  - $20M per year is needed for facility operations, physics research, and facility enhancements

PBX-M Facility Can Be Used to Reduce Cost of PoP Tests

- ***R*** **= 1.5 m;** ***B*** **= 1 T (22s), 2 T (1.5 s)**
- **6-MW, 0.3-s NBI; ≤ 6-MW ICRF**
- **Operational facility**
- **Has operated near parameters of interest**



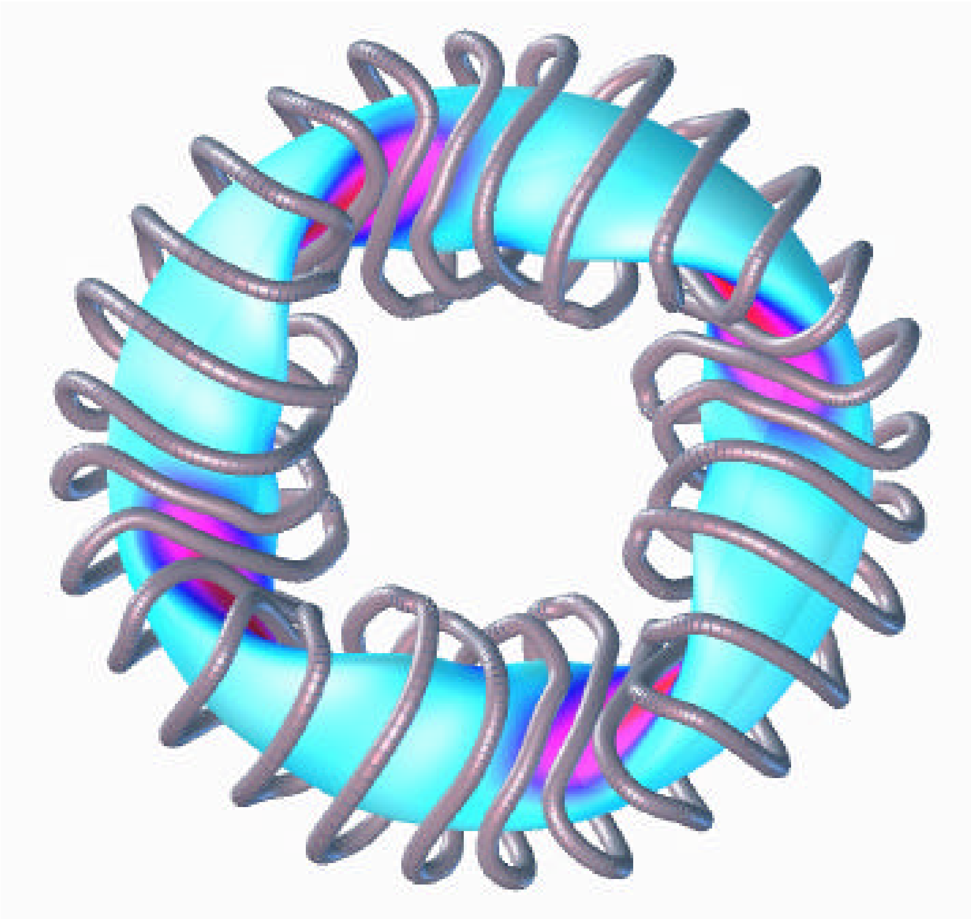
NCSX Will Address Key Issues for Compact Stellarator Development

- Can a high-β stellarator with bootstrap currents and external transform avoid disruptions?
- What are the β limits and limiting mechanisms?
- Can neoclassical transport be reduced to an acceptable level by proper configuration design?
- Can turbulent transport be controlled (e.g., by flow shear), leading to enhanced global confinement?
- Can transport and stability be controlled through external magnetic configuration control?
- Are neoclassical islands and tearing modes suppressed by bootstrap current and the proper choice of magnetic shear?

A New Concept Exploration Experiment, QOS, Is Needed to Test Quasi-Omnigeneity

- **broaden the scientific base on the quasi-symmetry being tested in HSX and NCSX into low-aspect-ratio non-symmetric stellarators**
- **test reduction of neoclassical transport via nonsymmetric quasi-omnigeneity, and the effect of radial electric fields on confinement**
- **test reduction of energetic orbit losses in non-symmetric low-aspect-ratio stellarators**
- **test reduction of the bootstrap current and the configuration independence on β**
- **test methods to affect anomalous transport, such as producing sheared E x B flow, and understand flow damping in non-symmetric configurations**

Quasi-Omnigeneous Stellarator



- R_0 1.0 m
- <*a*> 28 cm
- R_0/<*a*> 3.6
- Volume 1.55 m^3
- B_0 1 T
- I_p <150 kA
- Pulse 0.2 - 1 s
- Electron Heating
  0.4 MW; 53/60 GHz
- Ion Heating
  1 MW; ICRF

The Total Project Cost is $6.5 million, similar to that of HSX. Operating costs would be $2.5 million per year.

International Stellarator Collaboration

- **U.S. should take advantage of large foreign programs**
  - 0.5-1 B$ LHD and W7-X (2006); ~100 M$ W7-AS (to 2001)
- **Near-term collaboration is being pursued**
  - LHD -- order of magnitude increases in plasma volume, heating power, pulse length $\beta \geq 5\%$, T_i ~ 10 keV, τ_E ~ 0.3 s
  - energetic particle confinement, transport, β limits, divertor
  - W7-AS -- low shear, transport, confinement improvement
- **These complement US tests of physics & optimization principles for Q-A and Q-O concept development**
  - larger aspect ratio, helical axis, island divertors
  - ion heating, neoclassical transport, role of electric field, improved confinement modes, beta limits, divertors
- **International programs <u>do not</u> incorporate the bootstrap current and QA or QO at low aspect ratio**

A Stronger Stellarator Theory Program Needed

- **Changing perspective on stellarators is associated with advances in 3-D stellarator theory**
  - new physics concepts, new computational tools, and new magnetic configurations (Q-A and Q-O)
- **Theory is needed for compact stellarator studies**
  - differences between Q-A and Q-O; further optimization
  - maximize benefit from the experimental program
  - further "tool" development (e.g., more effective method for assessing magnetic surfaces)
  - 3-D MHD equilibrium and stability
  - neoclassical transport and drift orbits
  - microstability and anomalous transport
- **A stronger stellarator theory program allows US to**
  - address the key issues that are critical to further development of the stellarator concept
  - be a major contributor to innovative 3-D plasma physics
- **However, experimental tests are essential!**

Each Program Element Has a Unique or Complementary Programmatic Role

- NCSX -- assessment of QA optimization strategy
  - confinement improvement, access to high-β operating point, β limits, disruption limits
- QOS -- assessment of QO optimization strategy
  - confinement improvement, reduction of bootstrap current
- HSX -- tests of helical symmetry
  - reduction of neoclassical transport, small parallel current
- CAT -- disruption studies, ICRF tests
- International collaboration -- experiments and modeling of results from LHD, W7-AS, etc. in selected areas
  - energetic particle confinement, confinement improvement, bootstrap current
- Theory -- optimization and analysis tools, interpretation of experiment, new concept development
- System Studies -- ARIES assessments of reactor potential

Stellarator PoP Program Budget

	FY 98	FY 99	FY 00	FY 01	FY 02	FY 03	FY 04	FY 05
NCSX Proof-of-Principle Experiment								
Construction TPC ($35M)		3.5	9.0	12.0	10.4	-	-	-
NCSX Operations		0.4	0.7	1.3	4.0	15.0	15.0	15.0
NCSX Enhancements		0.0	0.3	0.7	1.5	5.0	5.0	5.0
NCSX Total	1.8	3.9	10.0	14.0	15.9	20.0	20.0	20.0
QOS Concept Exploration Experiment								
Construction TPC ($6.5M)		0.5	1.1	1.8	2.1	1.0		
QOS Operations		0.1	0.1	0.1	0.1	1.0	1.3	1.5
QOS Enhancements		0.0	0.1	0.1	0.1	0.4	1.2	1.0
QOS Total	0.3	0.6	1.3	2.0	2.3	2.4	2.5	2.5
Helically Symmetric Exper.	1.6	1.6	1.7	1.9	2.0	2.0	2.0	2.0
Compact Auburn Torsatron	0.2	0.5	0.5	0.3	0.3	0.3	0.3	0.3
Theory	1.2	2.0	2.5	3.0	3.5	3.5	3.5	3.5
International Collaboration	0.8	1.0	1.3	1.5	1.5	1.5	1.5	1.5
Program Total	5.9	9.6	17.3	22.7	25.5	29.7	29.8	29.8

The Program We Have Outlined Satisfies the 1996 FESAC-SciCom Alternative Concepts Review Panel Report Definition of a "Proof-of-Principle Program"

- It is the lowest cost program aimed at developing an integrated and broad understanding of basic scientific aspects of the concept which can be scaled with great confidence to provide a basis for evaluating the potential of this concept
- Experimental activity in this step requires at least one device with a plasma of sufficient size and performance ($5M to $30M per year) that a range of physics issues can be examined
- It is beneficial to include Concept-Exploration experiments which focus on certain key issues of the concept and help promote further innovations
- Theory, modeling, and benchmarking with experiments should be vigorously pursued to provide a theoretical basis for scaling the physics of the concept and evaluating its potential
- Power-plant studies, including in-depth physics & engineering analysis, should be carried out to identify key physics and technological issues and help define the research program

Summary

- **Compact stellarators are an exciting opportunity for the US Program 2 complementary strategies (QA & QO) developed that**
  - **combine best features of stellarators and advanced tokamaks**
  - **lead to a more attractive reactor concept -- like ARIES-RS, but with low recycled power and no disruptions**
- **US stellarator community has developed an effective, efficient program to capitalize on this opportunity that requires**
  - **a PoP facility (NCSX) to test β limits, disruptivity near the β limit, scaling of stability and transport for QA approach**
  - **a new CE experiment (QOS) to test confinement improvement, bootstrap current control for QO approach**
  - **HSX to test quasi-symmetry and CAT to study disruptions, ICRF**
  - **theory, international collaboration, and system studies to integrate results and understanding**
- **We are ready to proceed with this program**
  - **well established stellarator and tokamak knowledge base, both experiment and theory**
  - **well developed physics and engineering design capabilities**
  - **2 promising concepts that need experimental verification**

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