US Compact Stellarator Program

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Presentation to:
Fusion Energy Sciences Advisory Committee

PPPL
August 1, 2001

What is the US Compact Stellarator PROGRAM and WHY?

- **The stellarator is a fully 3-D system; provides challenges and opportunities to basic science**

- **Stellarator provides a solution to problems in toroidal confinement**
  - **Disruption elimination**
  - **Current drive; density limitations (W7AS ~ 3 x n_{gw})**

- **Two historical problems for conventional stellarators as reactors:**
  - **Neoclassical transport at low collisionality**
  - **Stability β limits**

→ High aspect ratio

Large size

Through Advances in Theory, Computation, and Modeling a Better Understanding is Emerging

→ **Better Experiments**

The World Stellarator Program

- A diverse portfolio of stellarator experiments has produced encouraging results.

- One operating and one planned PE experiment, both with significant technology focus
  - **LHD**: Conventional superconducting stellarator
    - 3% β achieved; >2 x ISS95 scaling
  - W7X: Optimized superconducting stellarator
    - Low plasma currents; β~4.5%; low neoclassical losses by adding mirror term to align drift/flux surfaces => R/a = 10.6

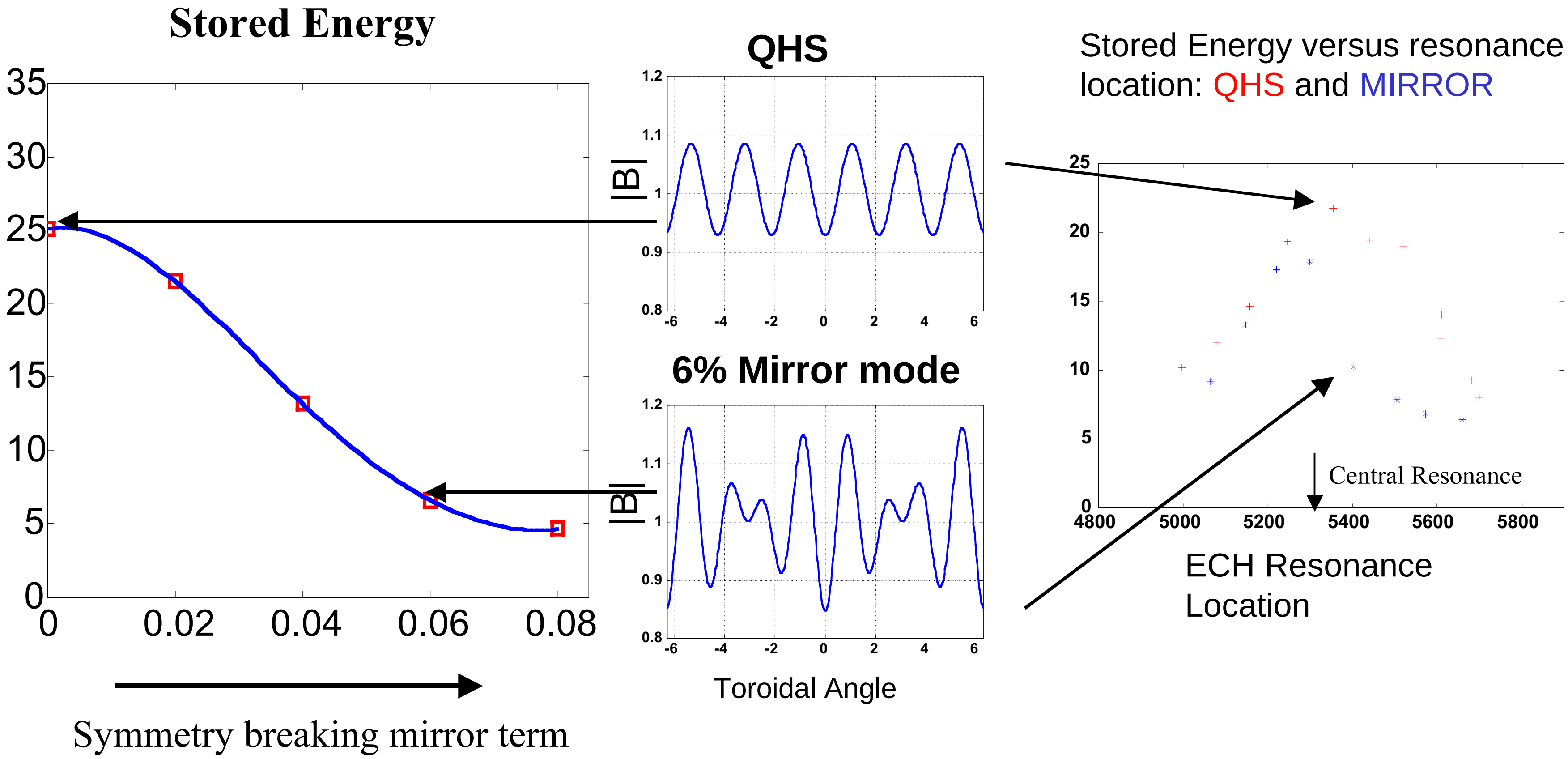
Problem: Large reactors projected, 18-22m (HSR)

Potential for optimization not fully explored in the present World Program

World Program Has Not Addressed Low Aspect Ratio with Improved Neoclassical Transport and Finite Plasma Current

- **Improved 3-D codes are capable of finding configurations with good flux surfaces at low aspect ratio**
- **Quasi-symmetry ⇒ symmetry of |B|, gives neoclassical transport analogous to (or better than!) the tokamak**
- **Compact stellarator program elements include symmetry of |B| in the toroidal (NCSX), helical (HSX), and poloidal directions (QPS).**
- **Quasi-axisymmetric configuration (NCSX) will have a significant bootstrap current, but much less than Advanced Tokamaks**
  - **Bootstrap current provides 25% of the rotational transform**
  - **Disruption control, kink stability and neoclassical MHD need to be investigated experimentally**
- **Quasi-symmetric stellarators also have direction of low parallel viscous damping for E_r shear stabilization of turbulence**
  - **Deviations from symmetry allow E_r shear without external momentum drive through proximity of electron/ion roots (W7-AS and CHS)**

HSX Demonstrates Quasi-symmetry Improves Confinement



- ~50 kW of 2nd harmonic ECH used to produce energetic deeply-trapped electrons (B = 0.5T, 28 GHz)
- Stored energy drops by a factor ~5 as mirror term is introduced

Theory Has Been Critical to Advancing the Stellarator Concept

- **US has had a leadership role in worldwide 3-D theory and modeling**
    - **- analytic/numerical transport, quasi-symmetry concept**
    - **- 3-D equilibrium and stability**
- **World-wide efforts have drawn heavily on these tools in developing stellarator optimization codes**
    - **Theory has led experiment design (W7-X, HSX)**
- **PPPL/ORNL Team have advanced tools beyond W7-X levels to optimize configurations with plasma currents and low aspect ratios**

A strong stellarator theory effort is required as a major component of the CS PoP Program

The Goals of the Compact Stellarator Program

Evaluate the benefits and implications of the three forms of quasi-symmetry; stimulate and provide focus for 3-D theory and modeling for application to basic physics and toroidal confinement

=> The Real World is 3-D

A steady-state toroidal system at low aspect ratio with:

- **No disruptions**
- **Good neoclassical confinement; potential for flow control, ITB's**
- **High β limits**
- **No near-plasma conducting structures or active feedback control of instabilities**
- **No current or rotation drive (⇒ minimal recirculating power in a reactor)**

Likely compact stellarator features:

- **Rotational transform from bootstrap and externally-generated currents: (how much of each? Needed profiles? Consistency?)**
- **3D plasma shaping to stabilize limiting instabilities (how strong?)**
- **Quasi-symmetric to reduce helical ripple transport, energetic particle losses, flow damping (how low must ripple be? Other flow drive mechanisms?)**
- **Power and particle exhaust via a divertor (what topology?)**
- **$R/\langle a\rangle \sim 4$ (how low?) and $\beta \sim 4\%$ (how high?)**

The US stellarator community has mapped out a balanced program to capitalize on recent advances in stellarators not covered in the international program.

Elements of the U.S. Compact Stellarator Program

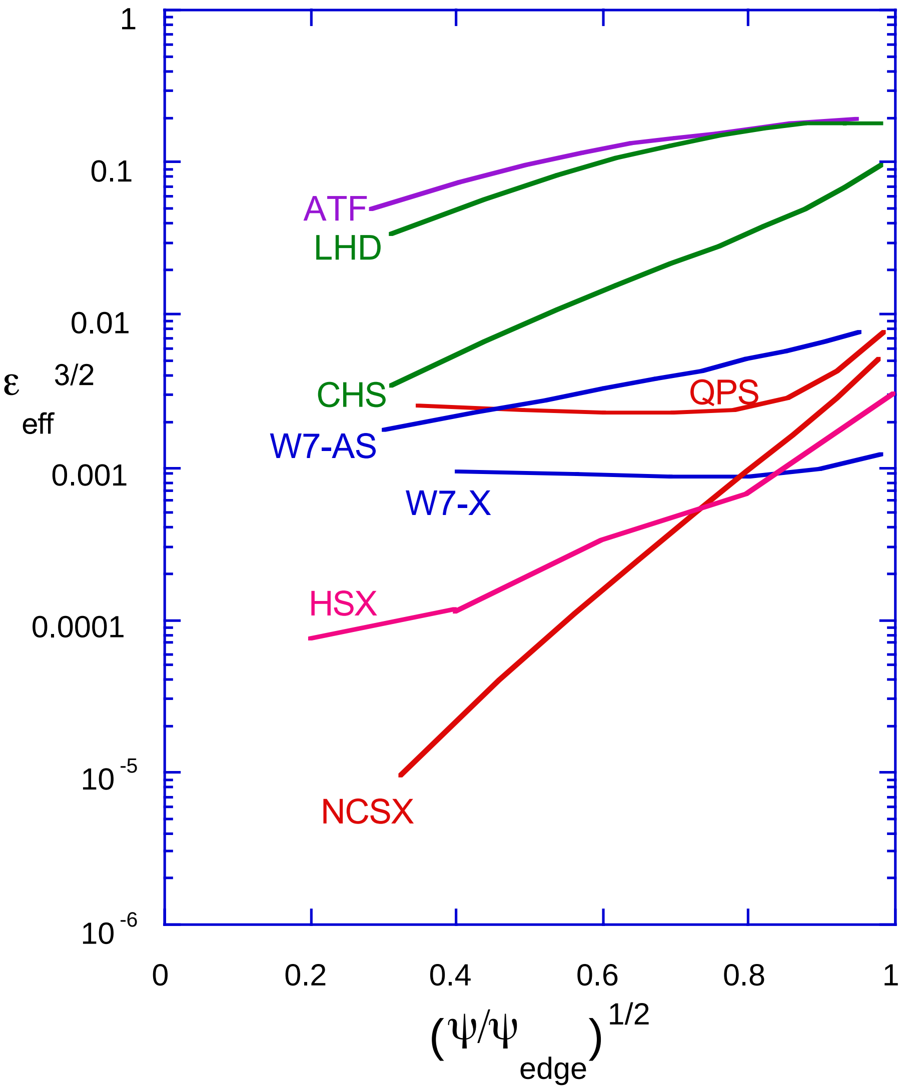
Focus on Quasi-symmetries and Plasma Current

- CE Experiments, Existing and Under Construction
  - HSX - Quasi-helical symmetry, low collisionality electron transport
  - CTH - Kink and tearing stability
- Proposed New Projects: NCSX, QPS
  - NCSX – Low collisionality transport, high beta stability, quasi-axisymmetry, low R/a – Integrated facility (main PoP Element)
  - QPS - Quasi-poloidal symmetry at very low R/a; complement NCSX
- Theory
  - Confinement, Stability, Edge, Energetic Particles, Integrated Modeling – Strong coupling to experimental program!
- International Collaboration
  - LHD, CHS, W7-AS ⇒ W7-X, Theory
- Reactor Studies
  - Assess concept potential for fusion energy

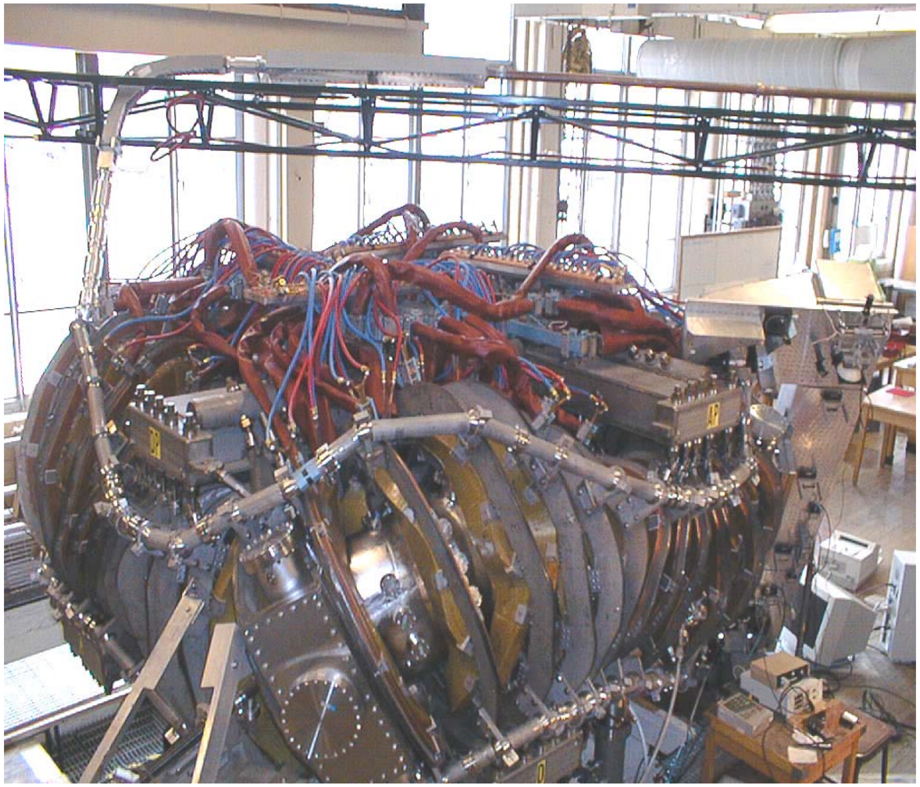
New Quasi-symmetric Stellarators have Low Neoclassical Transport – Examine Effects of I_p

- In $1/\nu$ regime, asymmetrical neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- Initial (successful!) test in HSX, studies continuing.
- Stability with finite current also a key issue for PoP program:

  CTH focused on kink & tearing stability with external transform.
- Low ν_*, high β test of quasi-axi -symmetry and current in NCSX.
- Very low R/a test of quasi -poloidal symmetry and current in QPS.



HSX Explores Improved Neoclassical Transport with Quasi-helical Symmetry



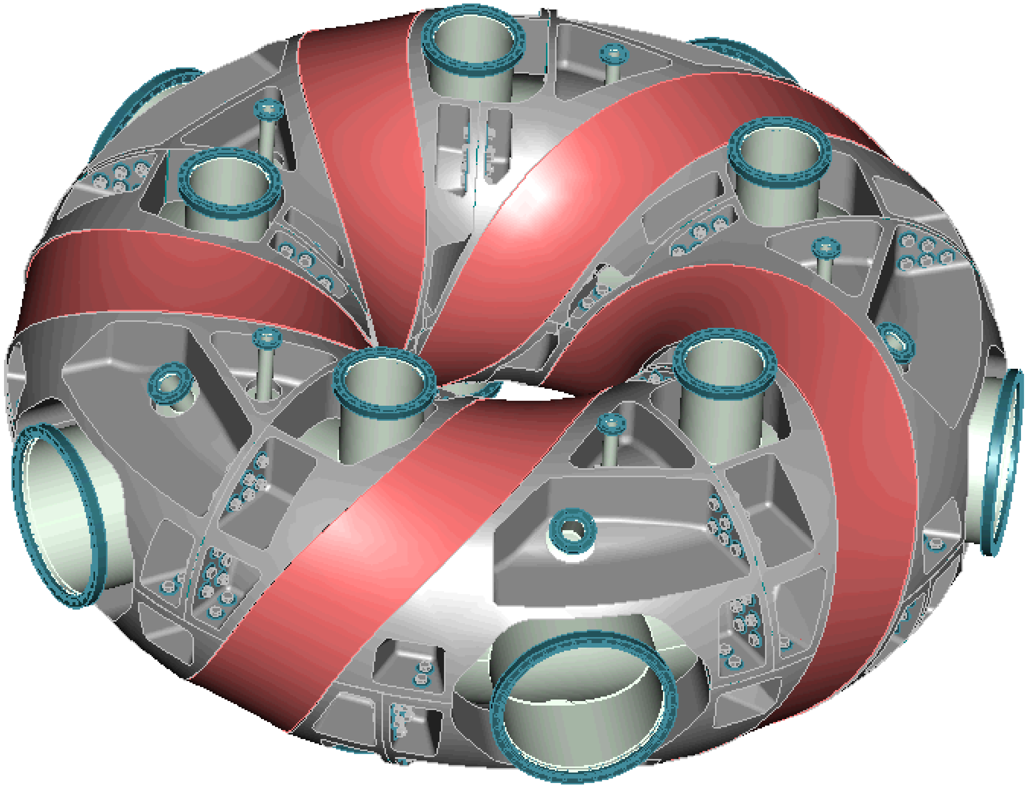
R=1.2m, <a>=0.15m B = 1.0 T
4 periods, ECH 28GHz 200 kW
(additional 350 kW at 53 GHz in progress)
University of Wisconsin-Madison

- Worlds first (and currently only) operating quasi-symmetric stellarator
- High effective transform (q_{eff}=1/3)
  - -large minor radius/banana width
  - -very low plasma currents
  - -very low neoclassical transport
- Neoclassical transport, stability and viscous damping can be varied with auxiliary coils

Goals

- Test reduction of neoclassical electron thermal conductivity at low collisionality
- Test E_r control through plasma flow and ambipolarity constraint
  - -low viscous damping in the direction of symmetry may lead to larger flows
- Investigate anomalous transport and turbulence
- Test Mercier and ballooning limits

Compact Toroidal Hybrid (CTH) Targets Current-Driven Disruptions at Low Aspect Ratio



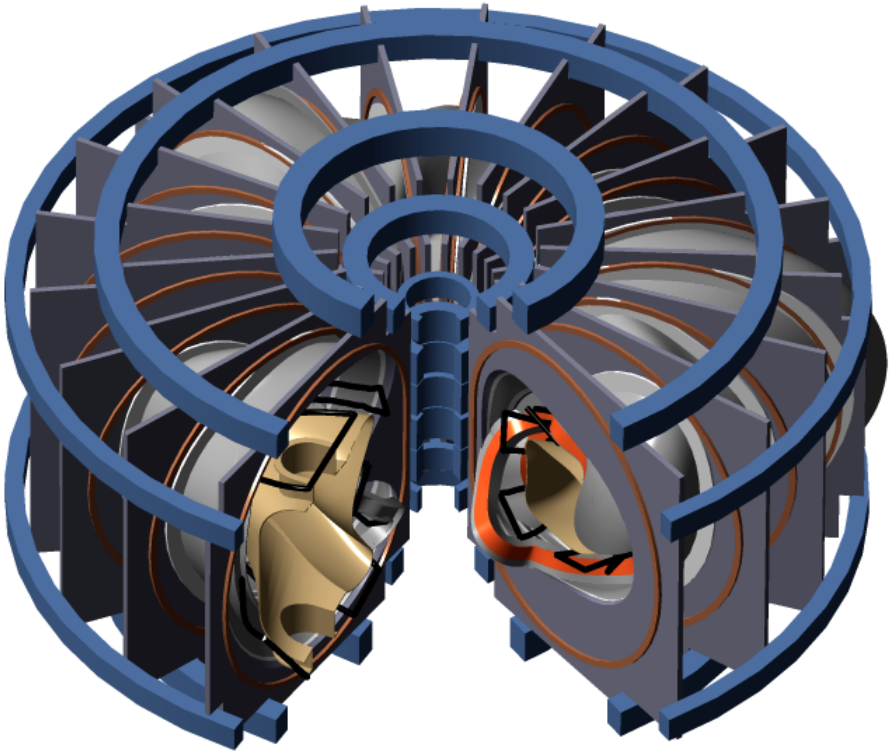
Auburn University
R=0.75m, <a> =0.18m, B=0.5T, I_p=50 kA
Approved Sept. 2000; Operations planned in FY03

Under what conditions are current-driven disruptions suppressed by helical field?
- Variable vacuum rotational transform & shape

How do we measure 3-D magnetic equilibrium of current-driven stellarator?
- Measurement of rotational transform by novel MSE/LIF

How do magnetic stochasticity & islands influence stability?
- External control of magnetic errors, measurement of islands in plasma

NCSX Mission: Addresses Integrated Issues of the Compact Stellarator



R=1.42m <a>=0.33m

B > 2 T (1.7 T at full ι_{ext})

P_{NBI} 3 => 6 MW

Macroscopic Stability:

- Disruptions - when, why, why not?
- High β, 3-D stability of kink, ballooning, neoclassical tearing, vertical displacement.

∀ ⇒ High heating power

Microturbulence and Transport:

- Is quasi-symmetry effective at high T_i?
- Challenge E_r shear understanding via ripple control.
  ⇒ High T_i, flexible coil system

Wave-particle Interactions:

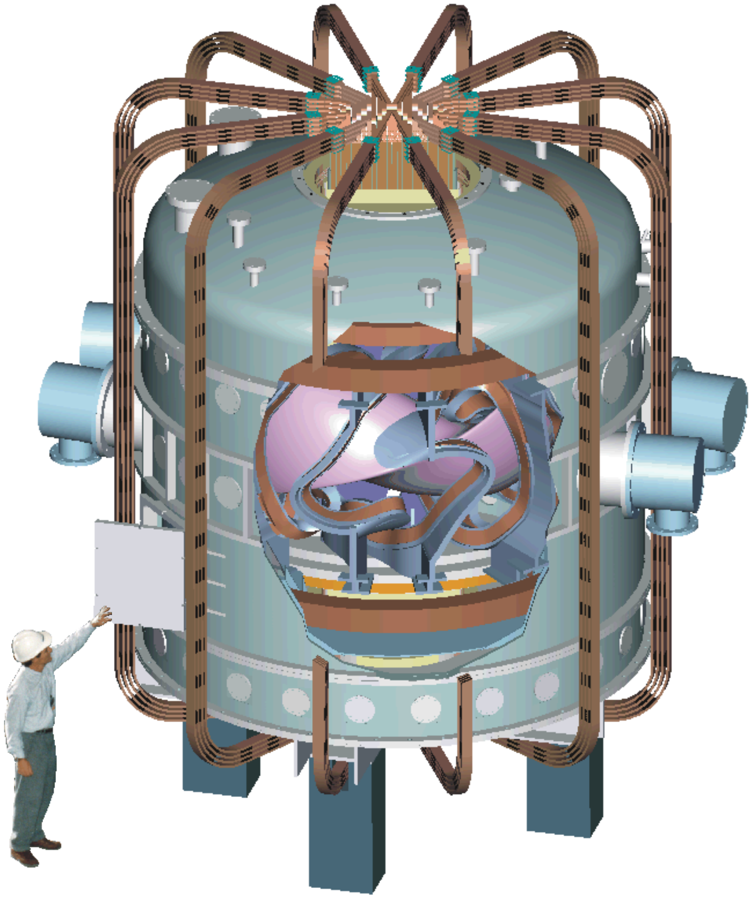
- Do we understand 3-D fast ion resonant modes & Alfvenic modes in 3-D?
  ⇒ Good fast ion confinement

Plasma-boundary interaction:

- Effects of edge magnetic stochasticity?
  ⇒ High power, flexible coil system

Quasi-axisymmetric Design to Build upon Tokamak and Stellarator Physics

QPS Will Pioneer Good Confinement in Very Low Aspect Ratio Stellarators



$\langle R \rangle = 0.9$ m; $\langle a \rangle = 0.35$ m

$B = 1$ T (0.5 s); $P_{RF} = 1\text{-}3$ MW

- **Only ~2x ripple transport for W 7-X but at 1/4 the aspect ratio**
- **Consequences of poloidal symmetry**
  - **may lower H-mode power threshold (like W 7-AS)**
  - **lower parallel bootstrap current compared to quasi-axisymmetry leads to robust equilibrium with β**
- **Can study fundamental issues common to low-β and high-β quasi-poloidal configurations**
  - **flux surface robustness**
  - **reduction of neoclassical transport**
  - **scaling of the bootstrap current with β, magnetics**
  - **ballooning instability character & limits**

Directly addresses FESAC goal of compactness

Role of 3-D Theory

- **The theoretical and computational program is a key element in the US Stellarator Program**

- **Provides strong connection with world-wide program in both basic physics and fusion science**

- **Key issues which need to be addressed in PoP Program:**
    - **Understand from first principles MHD β limits, transport, flux surface islands and stochasticity as applied to 3-D magnetic fields**
    - **Develop method to compare experimental and computational 3-D MHD equilibria**
    - **Understand microturbulence in 3-D versus 2-D systems**
    - **Modeling power and particle handling in non-symmetric edges/divertors; edge field structure**
    - **Explore role of energetic particles in MHD stability in a 3-D system**

Adequate Support of 3-D Theory is Essential to a Successful Compact Stellarator Program!

Strong Connection Between Stellarators and Other 3D Plasma Physics Problems

- Most plasma problems are three-dimensional
  - Magnetosphere; astrophysical plasmas
  - free-electron lasers; accelerators
  - perturbed axisymmetric laboratory configurations

- Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods.
  - methods to reduce orbit chaos in accelerators based on stellarator methods
  - chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators
  - astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  - tokamak and RFP resistive wall modes are 3D equilibrium issues
  - transport due to symmetry breaking was developed with stellarators

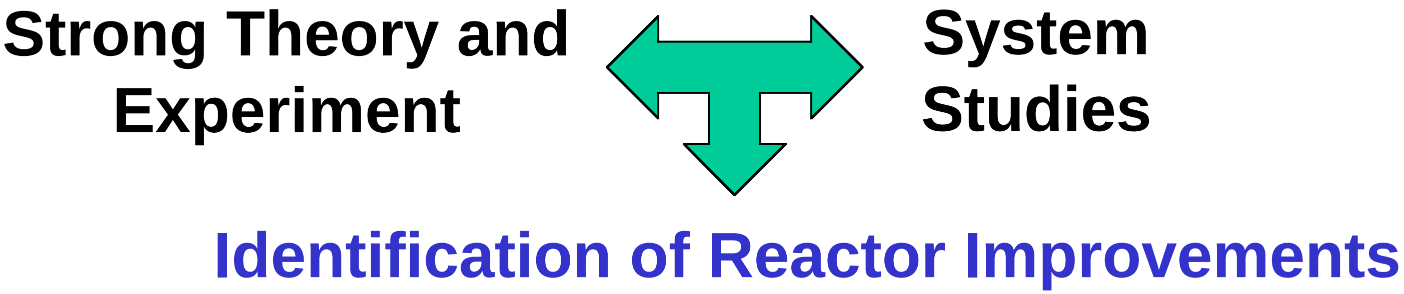
The Compact Stellarator Program will stimulate Development and Connections to Basic 3-D Plasma Physics

International Collaborations

- **Cooperation on the development of the HSX, NCSX and QPS designs (Australia, Austria, Germany, Japan, Russia, Spain, Switzerland, Ukraine)**
  - **TOOL DEVELOPMENT**
- **Participation in ongoing experiments**
  - **Fast ion and neutral particle diagnostics on LHD and CHS**
  - **Pellet injection, ICRF heating, bolometry and magnetic diagnostics on LHD**
- **Joint theory/code work to understand basic science of 3-D systems…**
  - **Microinstabilities (FULL), nonlinear GK (GS-2 & GTC under 3-D development)**
- **…and promote better understanding of experiments**
  - **3-D MHD without assumed flux surfaces (PIES and HINT); 3-D equilibrium reconstruction – code development, application & benchmarking (LHD and CHS)**
- **Benefit from physics and technology experience of PE level experiments**
  - **Divertors**
  - **Long-pulse operation; power handling**
  - **Superconducting coils**
  - **Negative-ion-based neutral beam injection**

Reactor Studies

- Stellarator Power Plant Study (SPPS-'scoping study') carried out by the ARIES Team (1997) concluded the MHH4-based power plant was economically competitive with the 2nd stability ARIES-IV tokamak
  - MHH4, a variant of HSX by Garabedian, extrapolated to R = 14 m reactor
  - Complexity and larger R of reactor offset by reduction in recirculating power
- Recent assessment of low-R/a QA and QP configurations as reactors (IAEA 2000) used same assumptions as for other stellarator reactors
  - B_{max} = 12 T, $<\beta>$ = 5%, ARIES-AT blanket and shielding assumptions
  - Smaller size, higher wall loading; QA 8.8m, QP 7.3m
- What are the true potential advantages & design issues for quasi-symmetric configurations as applied to reactors?
  - Cost/benefit tradeoffs for aspect ratio, β limits, energetic/bulk confinement
  - Access, maximum field, practical power and particle handling



Strong Theory and Experiment

System Studies

Identification of Reactor Improvements

What Do We Expect to Learn from the CS Program?

- What are the conditions for disruption immunity?
- Develop an understanding of β stability limits in 3-D for pressure and current driven modes.
  - True understanding between theory, codes and experiment
- What is the cause of anomalous transport in stellarators?
  - How can it be reduced (flow shear and/or adjacent location of electron and ion roots for E_r)?
- What level of symmetry is needed/acceptable to
  - 1) ensure energetic particle confinement,
  - 2) keep neoclassical losses less than anomalous, and
  - 3) keep flow damping low?
- What are the benefits of high effective transform (low-q)?
- How robust can configurations at low aspect ratio be to finite pressure, field errors and plasma current?
- How to diagnose and reconstruct 3-D equilibria (3-D EFIT)?
- Is a PE experiment advisable based upon what we learn in the Compact Stellarator Program? If so, what is the best approach?

Concluding Remarks

- **Balanced program focused on the 10-Year IPPA Goal:**

  "Determine Attractiveness of Compact Stellarator"

- **Has a strong science element**
  - ***Benefits of quasi-symmetry***
  - ***Advantages and limitations of plasma current in 3-D systems***
  - ***Real plasmas are 3-D***

- **Set of UNIQUE devices in world-wide program**
  - **HSX:QHS, high ι_{eff}, anomalous transport, pressure-driven instability**
  - **CTH: Current-driven instabilities at low aspect ratio, detailed equilibrium/current measurements, disruption limits**
  - **NCSX: Integrated PoP test of compact stellarator; connects to and complements the AT**
  - **QPS: Very low aspect ratio test of quasi-poloidal symmetry**

- **The Compact Stellarator Program is an exciting opportunity for unique fusion science.**
  - **Stabilize high-β instabilities with 3D shaping; understand 3D effects**
  - **Reduced transport in low-collisionality 3-D systems**

- Strong linkages with all of magnetic fusion science, with theory playing a central role.
  - Integrates well scientifically with international program

- Physics basis is sound, attractive configurations identified
  - Building upon large international stellarator and tokamak programs

- Compact Stellarators provide innovative solutions to make magnetic fusion more attractive.
  - Combine best characteristics of stellarators and tokamaks.
  - Potentially eliminate disruptions; intrinsically steady state

Tremendous opportunity to expand our scientific understanding of 3-D systems and identify potential reactor improvements using 3-D Shaping