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 $\sim 3 \times n_{gw}$)

- Two historical problems for conventional stellarators as reactors:
  - Neoclassical transport at low collisionality
  - Stability $\beta$ limits

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

Better Experiments

High aspect ratio

Large size
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% $\beta$ achieved; $>2 \times$ ISS95 scaling
  – **W7X**: Optimized superconducting stellarator
    • Low plasma currents; $\beta \sim 4.5\%$; low neoclassical losses by adding mirror term to align drift/flux surfaces $\Rightarrow \ R/a = 10.6$

**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 2\textsuperscript{nd} 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 $\beta$ 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 \( \varepsilon_{\text{eff}}^{3/2} \)

- 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 $\nu$, high $\beta$ 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

- Worlds first (and currently only) operating quasi-symmetric stellarator
- High effective transform \((q_{\text{eff}}=1/3)\)
  - 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

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

Macroscopic Stability:
- Disruptions - when, why, why not?
- High $\beta$, 3-D stability of kink, ballooning, neoclassical tearing, vertical displacement.

$\forall \Rightarrow$ High heating power

Microturbulence and Transport:
- Is quasi-symmetry effective at high $T_i$?
- Challenge $E$, shear understanding via ripple control.
  $\Rightarrow$ High $T_i$, flexible coil system

Wave-particle Interactions:
- Do we understand 3-D fast ion resonant modes & Alfvénic modes in 3-D?
  $\Rightarrow$ Good fast ion confinement

Plasma-boundary interaction:
- Effects of edge magnetic stochasticity?
  $\Rightarrow$ 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

- 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 $\beta$
- Can study fundamental issues common to low-\(\beta\) and high-\(\beta\) quasi-poloidal configurations
  - flux surface robustness
  - reduction of neoclassical transport
  - scaling of the bootstrap current with $\beta$, magnetics
  - ballooning instability character & limits

\(<R> = 0.9\) m; \(<a> = 0.35\) m

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

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 $\beta$ 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
  – \( B_{\text{max}} = 12 \text{ T, } <\beta> = 5\% \), 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, \( \beta \) 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 $\beta$ 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 $\iota_{\text{eff}}$, 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-$\beta$ 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