National Compact Stellarator Program

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representing the
US Compact Stellarator Community

DOE Budget Planning Meeting

Gaithersburg, MD **March 15, 2005**

Main Topics

- US compact stellarator program logic
- Experimental facilities and programs
- Contributions to FESAC's priority questions

Programmatic Approach

- US compact stellarator program uniquely integrates three features in experiments
  - compactness (low aspect ratio)
  - quasi-symmetry (low ripple and flow damping)
  - good flux surfaces (finite, low plasma current)
- Goal -- steady-state disruption-immune toroidal plasmas with performance comparable to, or better than, that of tokamaks
- Possible because recent advances in 3-D theory and computation allow design of optimized configurations
- Motivation -- excellent results from larger aspect ratio stellarators without benefits of quasi-symmetry

Compact Stellarators Offer Solutions to Steady-State Burning-Plasma Challenges

- **Steady-state compatible, quiescent high-beta plasmas already demonstrated without disruptions.**
  - – **provides alternate solution to high-bootstrap-fraction Advanced Tokamak**
  - ⇒ **allows ITER to lead to the next step (DEMO), even if disruption-mitigated, steady-state, high-bootstrap-current operation is not fully attained**
- **Soft operating limits, not disruptive. Allows higher density operation**
  - – **allows low temperature edge, should ease divertor design.**
  - – **decreases drive for fast ion instabilities**
  - ⇒ **provides alternative solutions for ITER challenges**
- **Orbit physics and turbulent transport physics of quasi-symmetric stellarators is directly connected to tokamak understanding. Thus, contributes to, and benefits from, ITER understanding.**

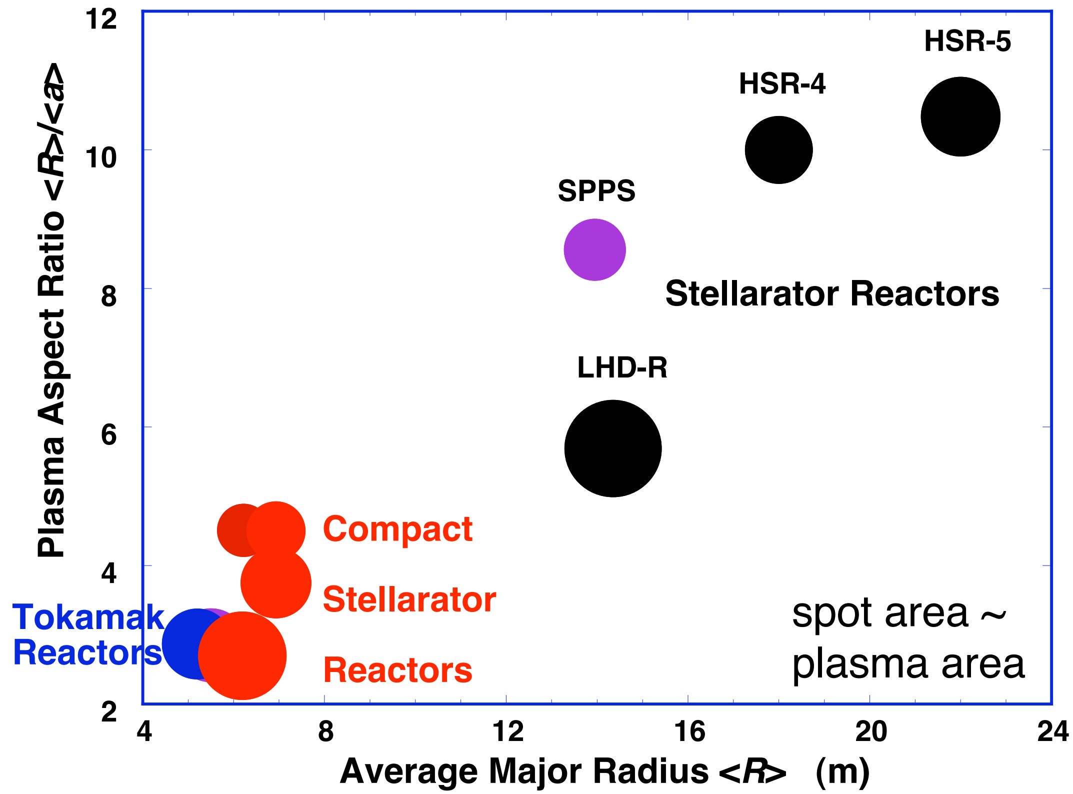
Energy Vision: a More Attractive Reactor

- A steady-state toroidal reactor with
  - No disruptions
  - No near-plasma conducting structures or active feedback control of instabilities
  - No current drive (⇒ minimal recirculating power)
  - High power density (~3 MW/m^2)
- Likely configuration features (based on present knowledge)
  - Rotational transform from a combination of bootstrap and externally-generated (how much of each?)
  - 3-D plasma shaping to stabilize limiting instabilities (how strong?)
  - Quasi-symmetric to reduce helical ripple transport, alpha-particle losses, flow damping (how low must ripple be?)
  - Power and particle exhaust via a divertor (what topology?)
  - $R/\langle a \rangle \sim 4$ (how low?) and $\beta > 4\%$ (how high?)
- Design involves tradeoffs -- need experimental data to quantify mix and assess attractiveness

Reactor Concept Improvement

- **Stellarator advantages**
  - inherent steady-state capability with no disruptions
  - fully ignited operation with no power input to the plasma
  - no need for rotation drive or feedback control of instabilities

- **Compact stellarator reactors can be comparable to tokamaks in compactness**



The US Compact Stellarator Program

The components of the integrated national compact stellarator (CS) program

- HSX and CTH (existing university experiments)
- NCSX (under construction)
- QPS (R&D and prototyping phase)
- Theory and modeling
- International collaborations, ARIES reactor study

address important US program issues using CS's unique features: quasi-symmetry and configuration flexibility

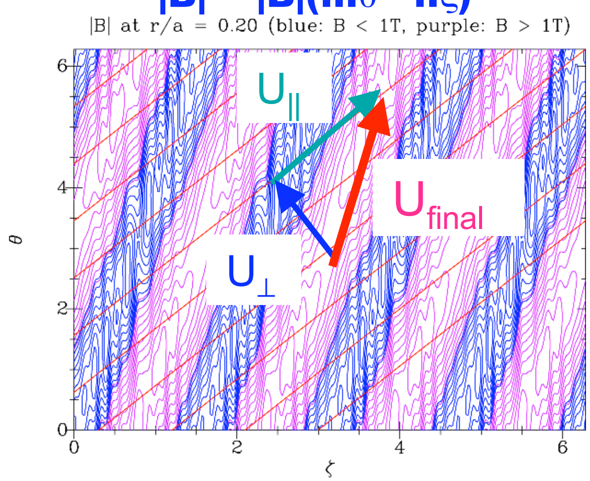
- to advance toroidal confinement understanding
  - MHD stability; disruption immunity without instability feedback
  - reduced neoclassical and anomalous transport
  - natural divertor for particle & power handling
- for concept improvement
  - quiescent steady state, without current or rotation drive
  - factor 2-4 lower aspect ratio than conventional stellarators
  - smaller reactor embodiment

Compact Stellarator Experiments Optimize Confinement Using Quasi-Symmetry

- **Quasi-symmetry: small |B| variation and low flow damping in the symmetry direction, which allows large flow shear**

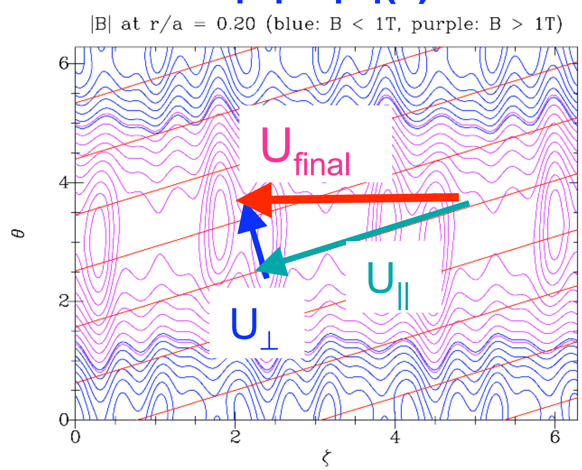
Quasi-helical symmetry

$|B| \sim |B|(m\theta - n\zeta)$



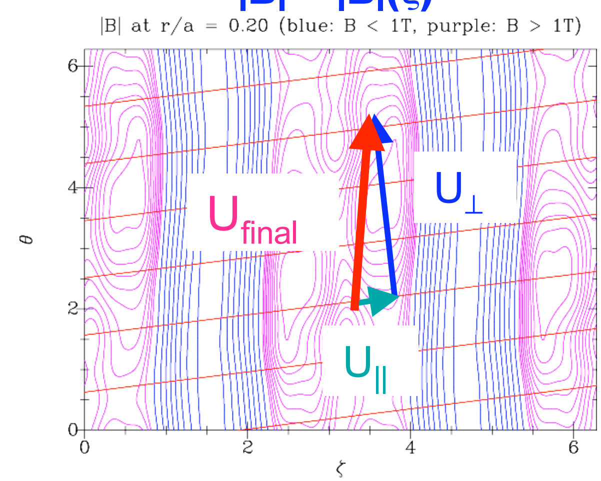
Quasi-toroidal symmetry

$|B| \sim |B|(\theta)$



Quasi-poloidal symmetry

$|B| \sim |B|(\zeta)$



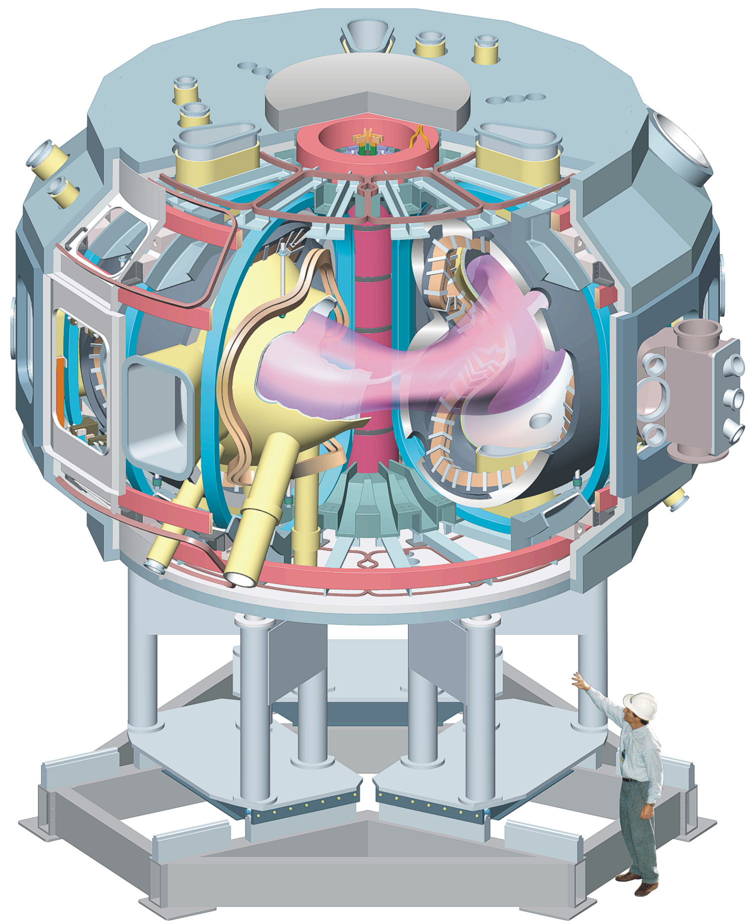
- **Low effective field ripple for low neoclassical losses**
- **No/low plasma current for good flux surfaces at both low and high beta**

3-D Optimized Experiments Designed With Particular Magnetic Configuration Features

- NCSX -- stellarator-tokamak hybrid with quasi-axisymmetry
- QPS -- stellarator-mirror hybrid with quasi-poloidal symmetry
- HSX -- quasi-helical symmetry and low neoclassical transport
- CTH -- equilibrium and stability with plasma current at low R/a

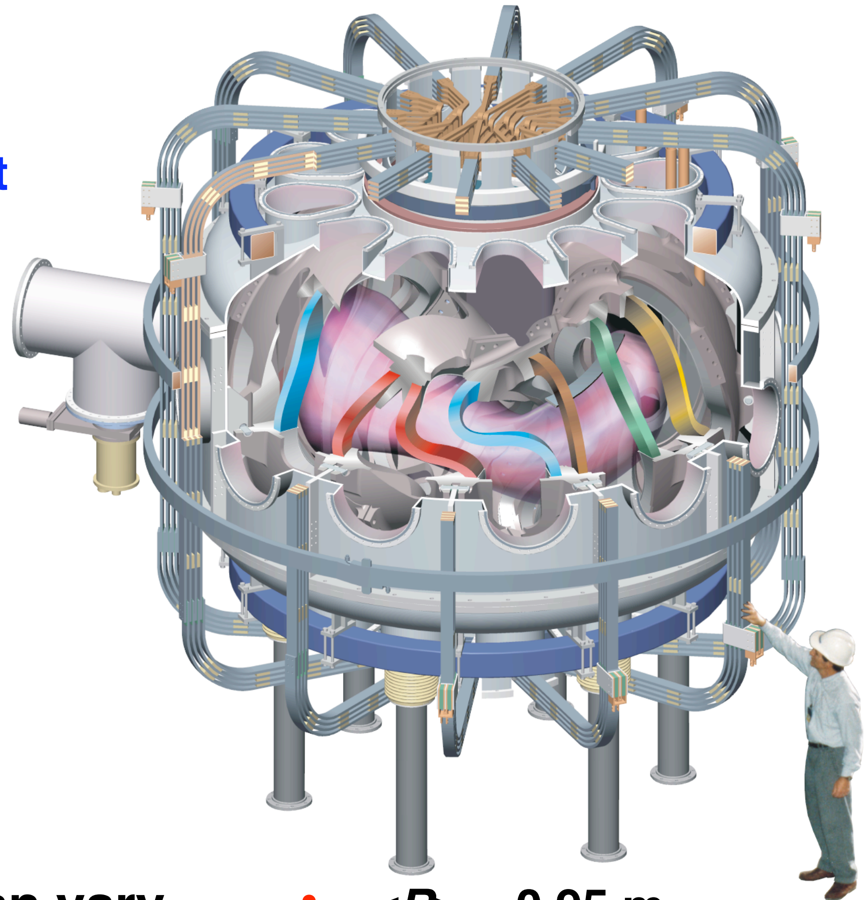
NCSX Explores Advantages of Quasi-Axisymmetry

- **<R> = 1.42 m, <a> = 0.33 m (0.37 m max)**
  <R>/<a> = 4.4, wide range of configurations
- **B = 2 T, P = 3-12 MW**
- **Operation in 2009**
- **Objectives: integrated demonstration and understanding of**
  - **high-beta disruption-free operation with bootstrap current and external transform**
  - **beta limits and limiting mechanisms in a low-R/a current-carrying stellarator**
  - **reduction of neoclassical transport by quasi-axisymmetric design**
  - **confinement scaling and reduction of anomalous transport by flow-shear control**
  - **islands and stabilization of neoclassical tearing modes by magnetic shear**
  - **power and particle exhaust compatibility with good core performance**



QPS Explores Quasi-Poloidal Symmetry

- Will study effect of low R/a and quasi-poloidal symmetry on
  - reduction in neoclassical transport (low effective ripple)
  - reduction in anomalous transport (large poloidal flows, E_r)
  - equilibrium robustness with strong toroidal/helical coupling
  - healing magnetic islands
  - $\langle\beta\rangle$ limits and instability character
  - edge divertor topology
- Extends stellarator database to lowest aspect ratio
- 9 independent coil current sets; can vary
  - quasi-poloidal symmetry by a factor of 9
  - poloidal flow damping by a factor of 25
  - neoclassical transport by a factor of 20
  - stellarator/tokamak shear
  - trapped particle fraction



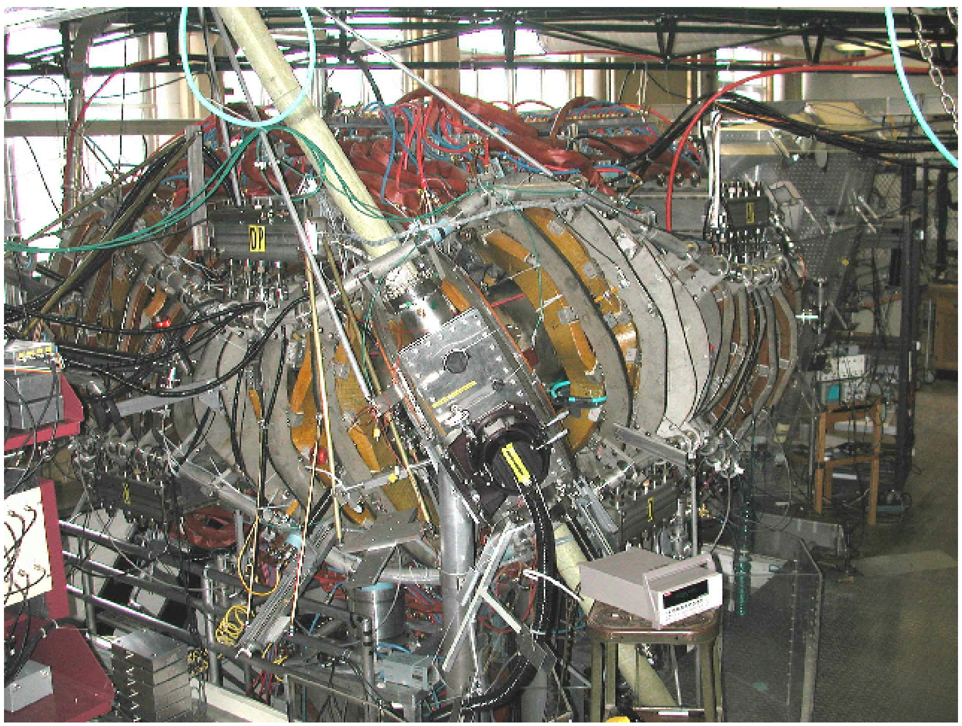
- $\langle R \rangle = 0.95$ m
- $\langle a \rangle = 0.3\text{-}0.4$ m
- $\langle R \rangle / \langle a \rangle = 2.7$
- B = 1 T, P = 2-4 MW
- 0.15-T ΔB, $I_p = 50$ kA
- Operation in 2010

The HSX Program: World's First Experimental Test of Quasi-symmetry

Mission: Explore Improvement of Neoclassical Transport in Stellarators

Quasi-helical stellarators have high effective transform, $\iota_{eff} \sim 3$ ($q \sim 1/3$)

- Reduced particle drift
- Small neoclassical transport
- Low plasma currents; robust magnetic surfaces



- **First experimental verification of reduced flow damping with quasi-symmetry**
- **Confirmation of high effective transform and reduction of direct loss orbits**
- **Fast particle effects on MHD modes observed due to improved confinement**
- **Observation of reduced neoclassical thermodiffusion**
- **Experimental verification of 3-D neutral code DEGAS**

<R> = 1.2 m, <a> = 0.15 m, B = 1.0 T, 4 periods, 400-kW 28-GHz ECH

CTH: Compact Toroidal Hybrid

Addresses equilibrium & stability in stellarators with current

Objectives:

- **Reconstruct 3-D plasma equilibrium with V3FIT code & magnetic measurements**
- **Determine stable operating scenarios and disruption behavior in current-carrying plasmas**
- **Control static islands in low-aspect ratio helical plasmas**

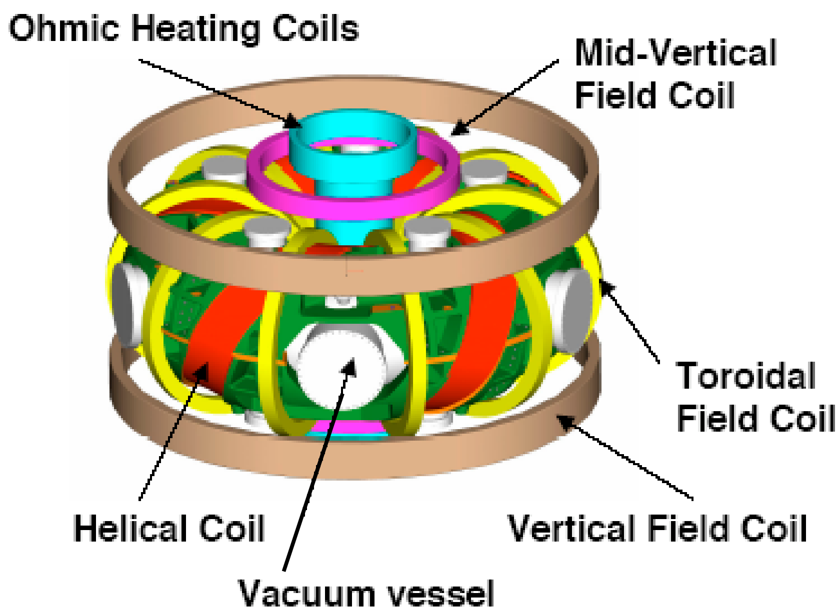
Addresses key physics areas:

- **Physics underlying external stability control**
- **Understanding current-driven instabilities in stellarators**
- **Limits of disruption-free operation**

Parameters:

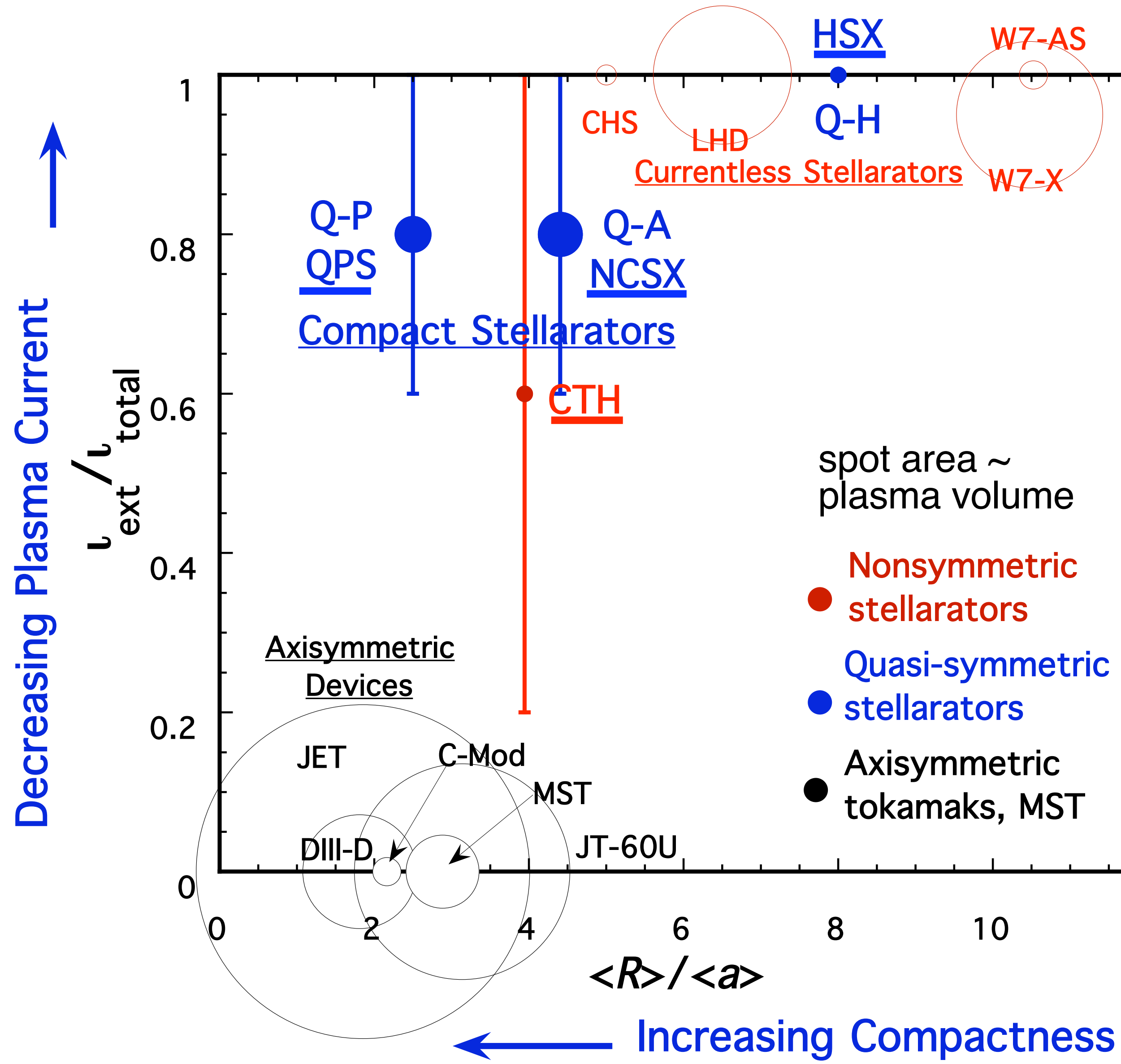
- $R = 0.75$ m, $a_{Plasma} \leq 0.18$ m, $R/a \geq 4$
- $B = 0.5$T, $I_p = 50$ kA, ($\Delta\iota \sim 0.5$), $P \sim 120$ kW

$\Rightarrow$ **First plasma Feb. 22, 2005 (ECH at 0.1T)**



CTH in late January, prior to 1st plasma

Compact Stellarators Bridge between Currentless Stellarators and Lower *R/a* Tokamaks



Compact Stellarator Program Contributes Unique Information on FESAC's High Priority Scientific Questions

1 **How does magnetic field structure impact fusion plasma confinement?**

2 **What limits the maximum pressure that can be achieved in laboratory plasmas?**

3 **How much external control versus self-organization will a fusion plasma require?**

4 **How does turbulence cause heat, particles, and momentum to escape from plasmas?**

5 **How are electromagnetic fields and mass flows generated in plasmas?**

9 **How to interface with room temperature surroundings?**

- **Advantage is wide range of configuration properties**

1. How Does Magnetic Field Structure Impact Fusion Plasma Confinement?

Understanding the role of plasma shaping on:

a plasma confinement

b effects of self-generated currents and flows

c effects of magnetic structure within the plasma

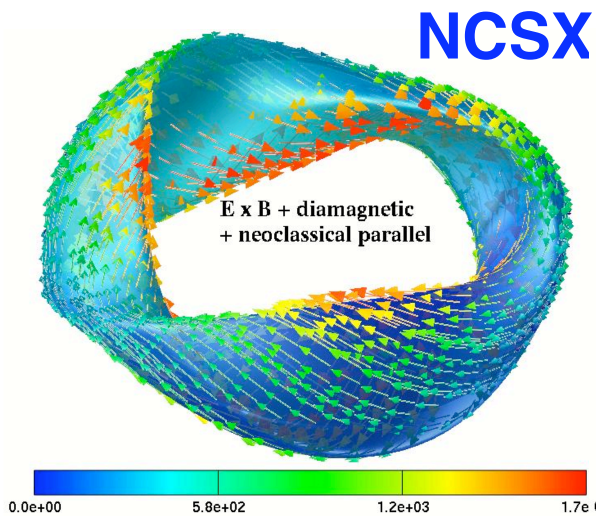
Wide variation of configuration properties is possible in compact stellarators for transport & stability studies

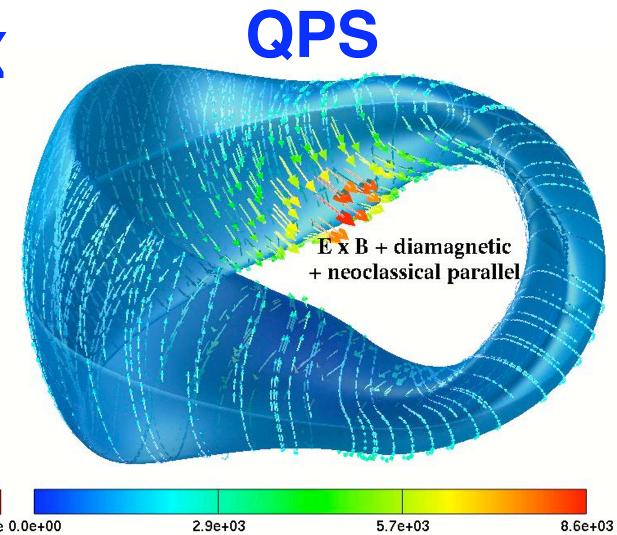
- 3-D shaping and effective magnetic field ripple
- trapped particle fraction
- amount and sign of shear
- type and degree of quasi-symmetry
- degree of viscous damping and flow shear
- ambipolar electric field and internal transport barriers
- magnetic island size and ergodic regions
- internal vs. external transform

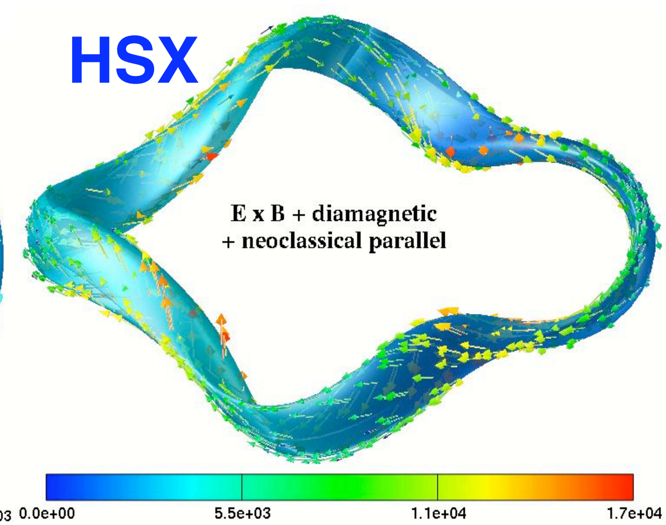
+ integrated effort in experiment, modeling, and theory

Quasi-Symmetry Determines Flow Magnitude and Direction

- **Low flow damping in symmetry direction allows large flows that can shear apart turbulent eddies and reduce anomalous transport**
- **Corresponding electric fields and their effect on flows can also affect neoclassical and anomalous transport**



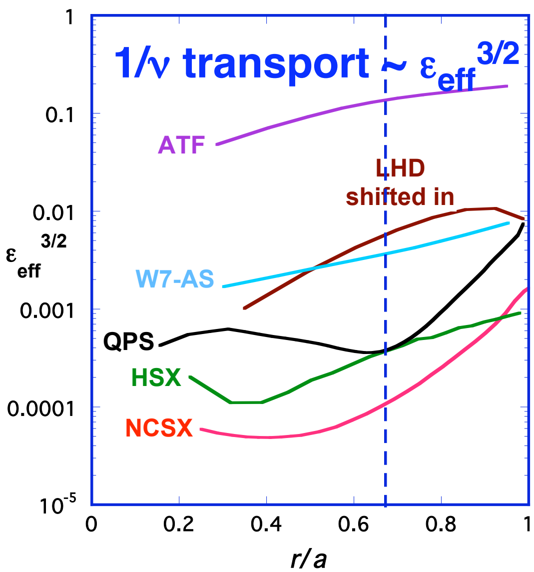




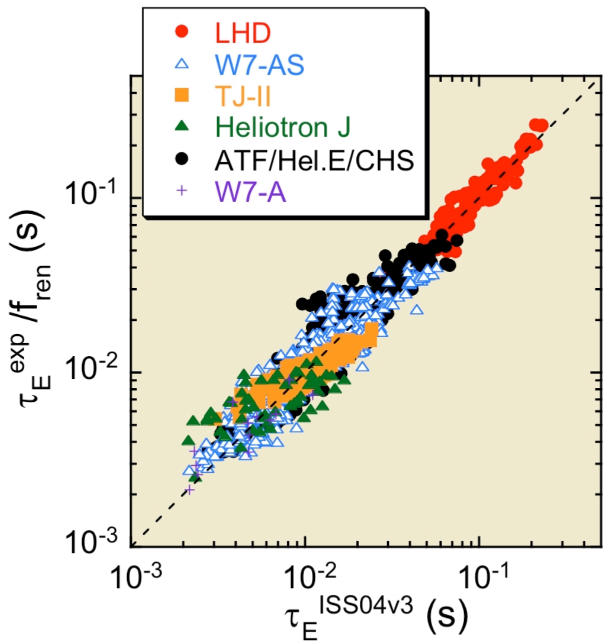
⇒ Can vary damping through external control

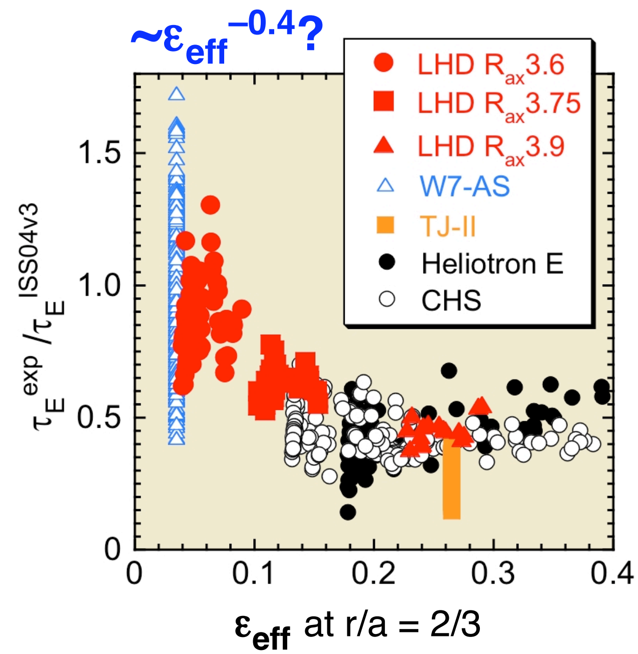
Anomalous Transport May Depend on ε_{eff}

- **The large reductions in effective helical ripple ε_{eff} in compact stellarators is expected to greatly reduce neoclassical transport**



- **Stellarator database suggests that lower effective ripple may also reduce anomalous transport -- electric field effect?**

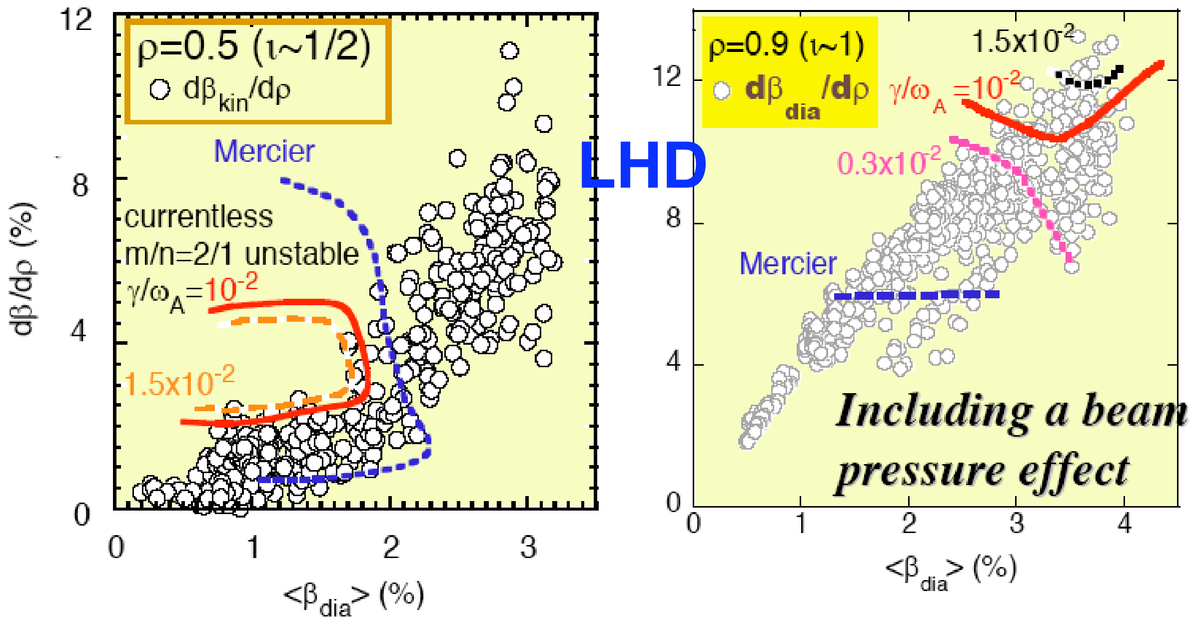




- **New research area: scaling of confinement with configuration parameters (ε_{eff}, aspect ratio, degree of quasi-symmetry, etc.) has not been explored at low aspect ratio or in quasi-symmetric configurations**
- **Provides insight for other configurations**
  - **might be tied to flow damping physics**
  - **ε_{eff} can be varied over a very wide range in a single experiment**

2. What Limits the Maximum Pressure That Can Be Achieved in Laboratory Plasmas?

- **Current data indicates that β in stellarators is not limited by instabilities**
  - **quiescent plasmas are routinely observed well above linear stability thresholds**

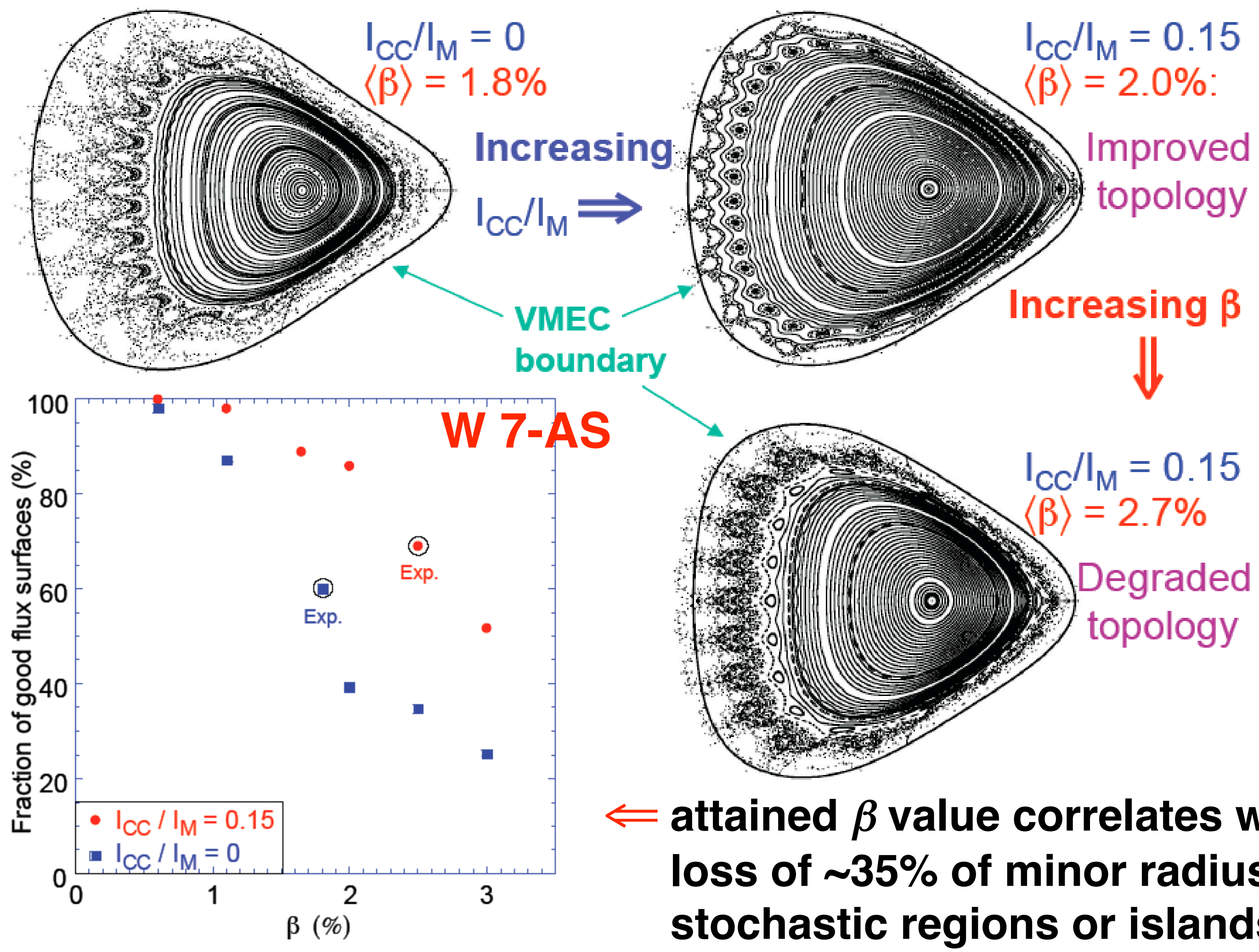


- **Character of MHD instabilities is different in stellarators**
  - **e.g., ballooning instability occurs simultaneously on a surface in tokamaks but occurs progressively line-by-line with different growth rates as β increases in stellarators**
- **Provides new insight into non-linear character of MHD instabilities**

Observed β Limits May Be Due to Equilibrium Limits

Equilibrium is limited by the onset of magnetic stochasticity:

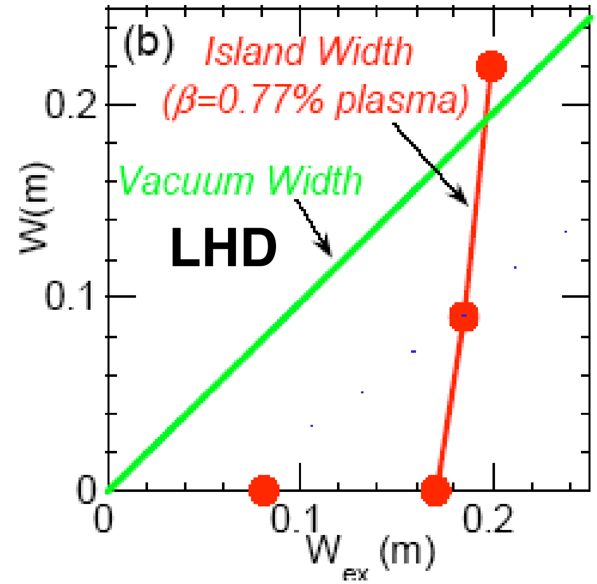
$\Rightarrow$ Compact stellarators designed to maintain good surfaces at high β



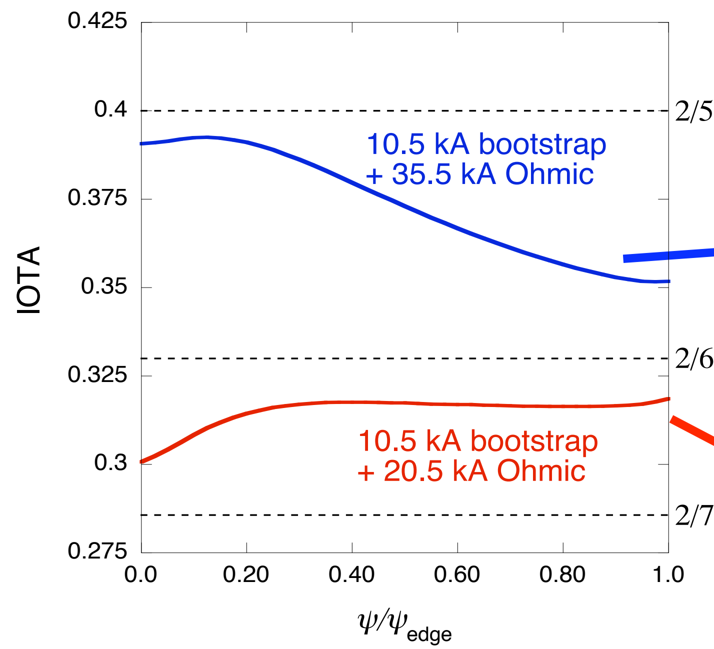
$\Leftarrow$ attained β value correlates with loss of ~35% of minor radius to stochastic regions or islands

Magnetic Islands Can Be Controlled

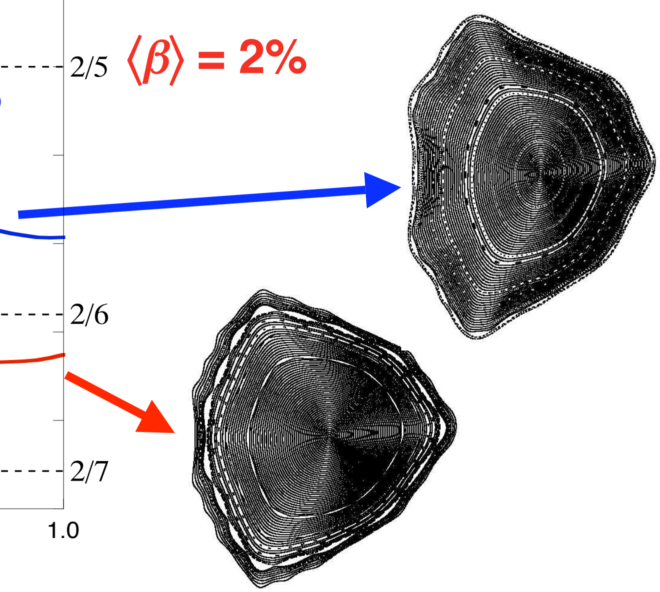
- **Compact stellarators are designed to have good flux surfaces**
- **Self-stabilizing effect of a plasma current (for *w/a* < 0.3), related to tearing modes in tokamaks**



- **Bootstrap and Ohmic current tailoring of the *q* profile to avoid low-order resonances**
- **Can control with external coils**



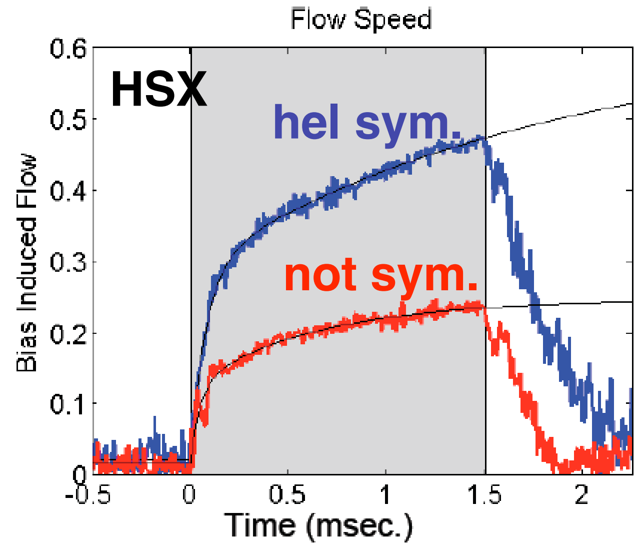
$\langle\beta\rangle$ = 2%



3. How Much External Control Versus Self-organization Will a Fusion Plasma Require?

a **Understanding the use of dominant external control (*e.g.* externally generated confining magnetic fields or flows)**

b **Understanding and controlling pressure-gradient-driven plasma currents and flow self organization**

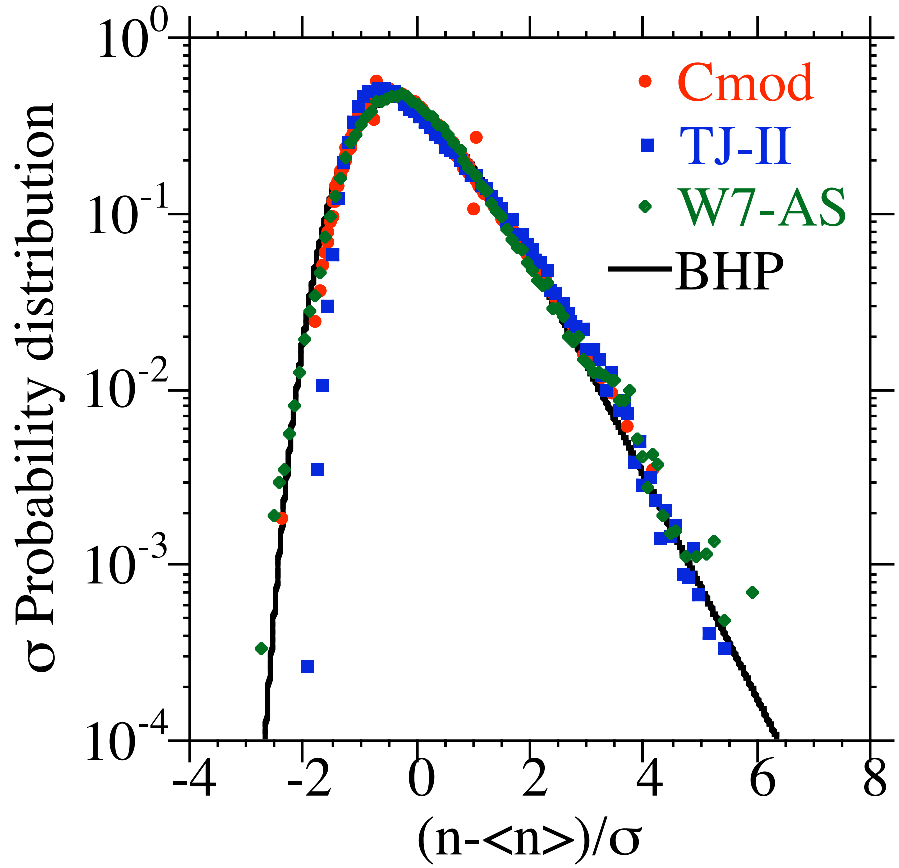


- **W 7-AS shows that externally controlled plasmas allow quiescent, long-lasting, non-disruptive plasmas at high beta, even without compact stellarator optimization**
- **LHD shows that can control electron-root to ion-root transition and internal transport barriers**
- **The field can be tailored to control current-driven and pressure-driven instabilities**

⇒ **External control reduces self-organization and nonlinearity in equilibrium and stability, avoids kink instabilities**

4. How Does Turbulence Cause Heat, Particles & Momentum to Escape From Plasmas?

- The functional form of the normalized probability distribution of edge fluctuations in different toroidal devices is very similar
- This behavior is seen in other systems close to a critical point, implying correlations
- Does the behavior of the edge layer in toroidal plasmas belong to this universal class?
- Does it differ for quasi-symmetric compact stellarators?
- What is the physics behind this?



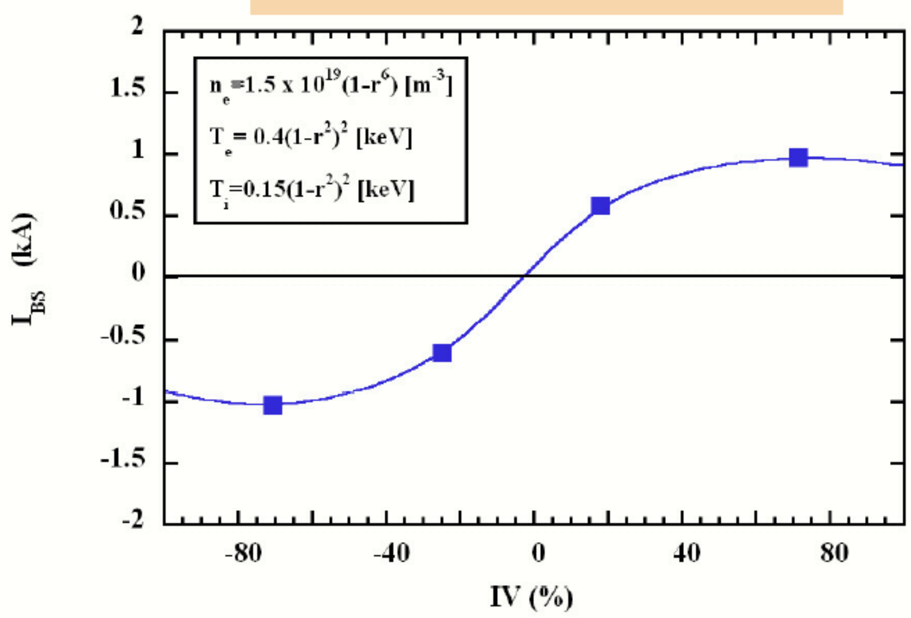
Differences in Magnetic Structure Influence Core Turbulence and Confinement

- **Low flow damping with quasi-symmetry allows zonal flow stabilization**
- **Reversed magnetic shear can stabilize trapped particle instabilities, increase damping of ITG modes**
- **Internal islands can produce E x B shearing, generating transport barriers**

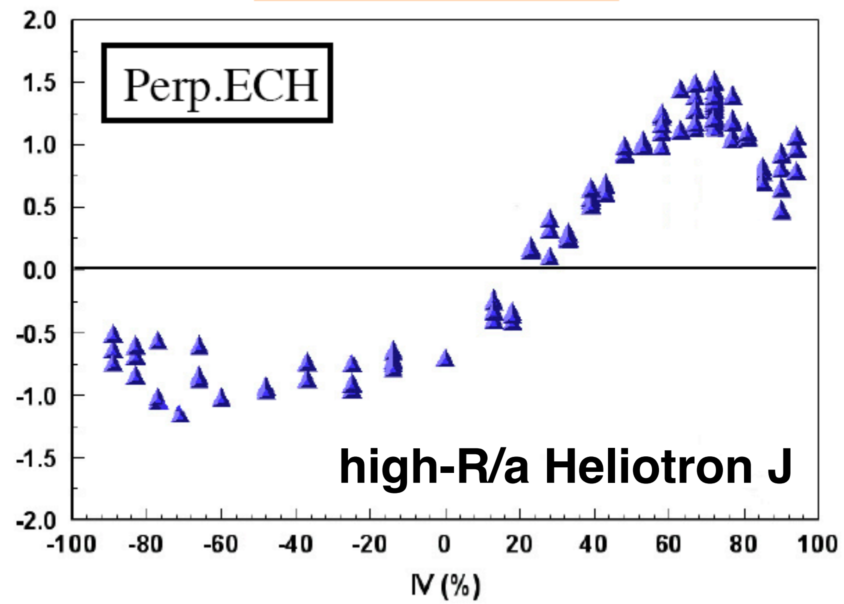
5. How Are Electromagnetic Fields and Mass Flows Generated in Plasmas?

- **Examples: E x B flows (discussed earlier), control/reversal of bootstrap currents**

MODEL CALCULATION



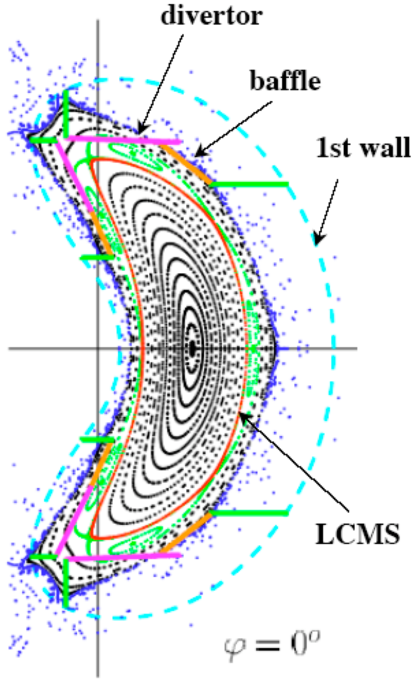
EXPERIMENT

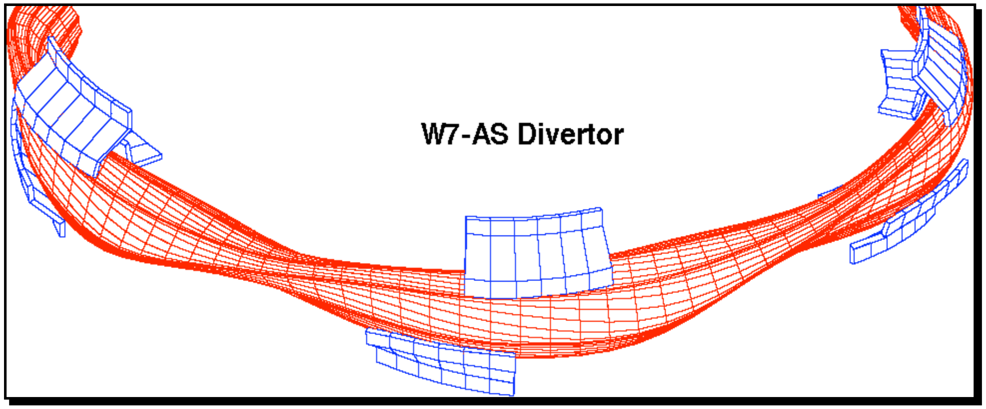


- **The type of quasi-symmetry and low aspect ratio affect the magnitude of the bootstrap current**

9. How to Interface to Room Temperature Surroundings?

- **3-D shaping flexibility allows different edge strategies:**
  - diverted field lines, island divertors, ergodic edges, or combinations
- **W 7-AS and LHD divertors have successfully demonstrated density and impurity control, including high-β plasmas**
  - need to demonstrate in compact stellarators
- **Good or enhanced confinement obtained at very high density in stellarators**
  - combined with lack of need for current drive allows low temperature edge plasma, easing divertor design





3-D Geometry and Low Aspect Ratio Drive Theory Development

- **Plasma equilibrium**
  - toroidal and poloidal variation are strongly coupled -- need to improve representation, convergence more demanding
  - need to improve modeling of plasma response
- **MHD stability**
  - need to understand observed nonlinear mode saturation
  - interpretation of high-n ballooning stability differs because calculations don't apply to entire surface as in a tokamak
- **Transport**
  - need nonlinear simulations of expected turbulent transport
  - need to include magnetic islands and 2-D variations within a flux surface

Compact Stellarators Impact Other Areas

- **Confinement of non-neutral and e^+/e^- plasmas (Columbia Non-Neutral Torus)**
  - **simple coils and low-R/a plasma designed with tools developed in compact stellarator program**

- **3-D nature of space plasmas**
  - **uses theoretical methods for treating magnetic problems (solar flares, galaxy structure)**

SUMMARY

- **The components of the integrated national compact stellarator program are designed and coordinated to address important US program issues (FESAC)**
- **Unique features: quasi-symmetry, good flux surface with configuration flexibility, and compactness**
  - **to advance toroidal confinement understanding**
  - **for concept improvement**
- **Complements larger tokamak and international stellarator programs and aims at an improved reactor vision**