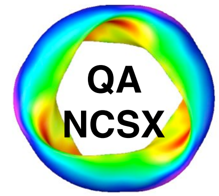
US Compact Stellarator Program *without* NCSX

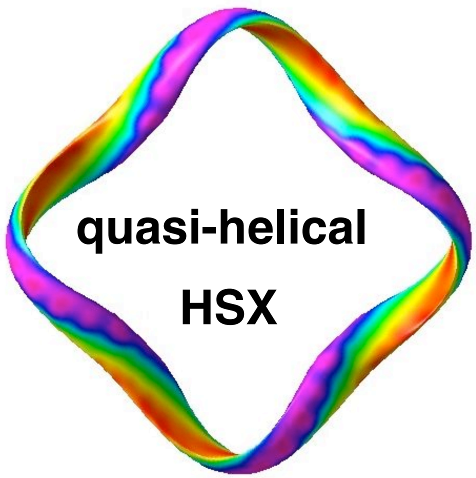
J.F. Lyon for the US stellarator community

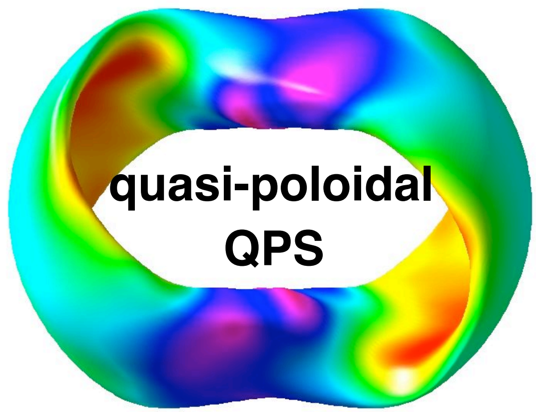
FESAC Subcommittee Sept. 15, 2007

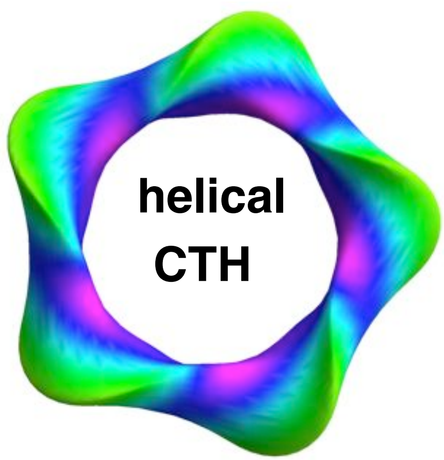
Topics

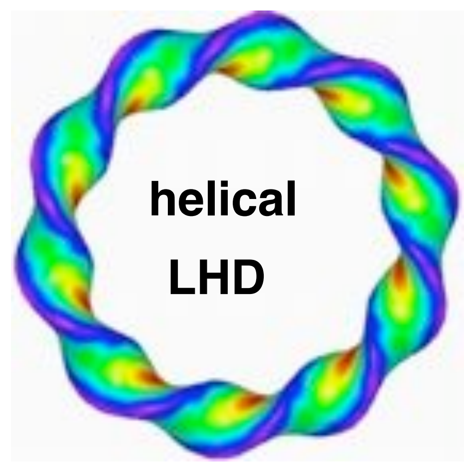
- Program elements in addition to NCSX
- How key physics issues are addressed











Compact Stellarator Program

- The US compact stellarator program has been designed as an integrated whole to assess the attractiveness of compact stellarators and to advance the physics related to non-axisymmetric shaping
- Compact stellarators are not addressed in stellarator work abroad, so there is a clear opportunity to maintain the leading US role in this area in both experiment and theory
- The loss of NCSX as an integrated PoP facility with connection to the tokamak program would fundamentally change the character of the U.S. stellarator program
- Enhancement of the other U.S. stellarator program elements could address important compact stellarator issues, albeit in a less complete way without NCSX

Unique Program Elements Add to the Knowledge Base from Different Perspectives

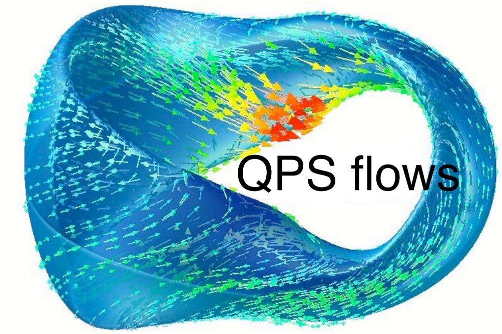
- Theory and computation are critical integrating elements connecting the physics of quasi-symmetry and axisymmetry (tokamaks, STs, RFPs)
- HSX, the only operating quasi-symmetric stellarator in the world program, provides a fundamental test of quasi-symmetry and very low ripple; it obtains high effective transform through QH symmetry at $R/a = 8$
- The non-symmetric CTH with $R/a > 4$ studies equilibrium and stability in current-carrying stellarators with a focus on disruption avoidance, 3-D equilibrium reconstruction, and control of magnetic islands
- QPS with $R/a \sim 2.5$ tests a very compact QP symmetric configuration (low bootstrap current, increased flows/shear to suppress turbulence, robust magnetic surfaces) and connection to W 7-X with $R/a = 10.4$
- Collaborations on LHD and W 7-X give access to large (30 m^3), high-power (20–30 MW) plasmas & high plasma parameters, superconducting coils, steady-state operation, and power & particle handling at high power

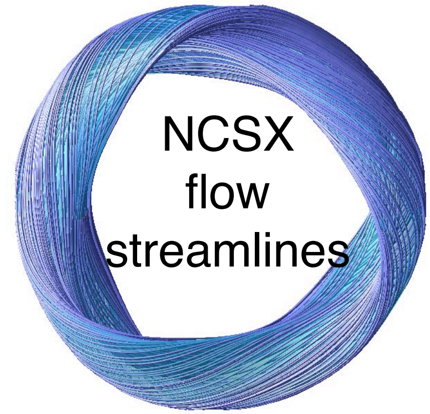
Program Elements

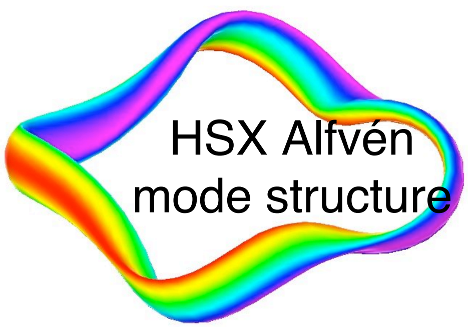
Theory and Computation Are Critical Innovating and Integrating Elements

US theory has provided world-class tools for stellarator interpretation and configuration improvement

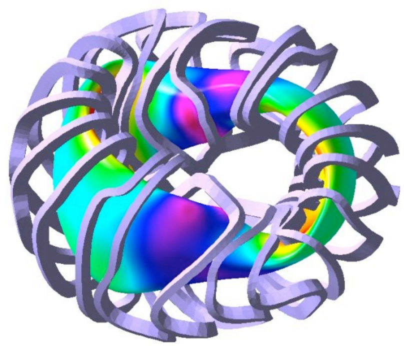
- 3-D MHD equilibrium (VMEC, PIES, SIESTA) and stability (COBRA, Alfvén mode codes, M3D)
- Transport (DKES, Monte Carlo codes, PENTA)
- Plasma heating (NBI, full wave/ray tracing codes)
- Concept improvement (STELLOPT); reactor optimization (MHHOPT)
- These codes have been used to optimize NCSX & QPS
  - direct optimization from coils to free boundary equilibrium
- Benchmarked with tokamak results
  - integrates common understanding of these devices

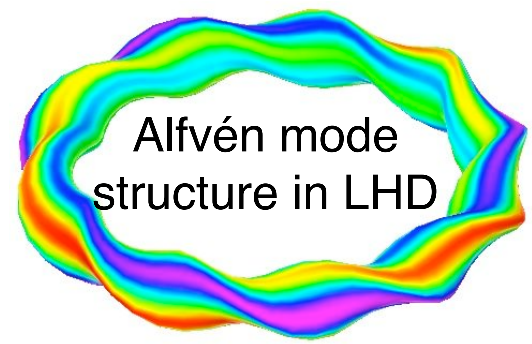






QPS IBI
structure
and coils

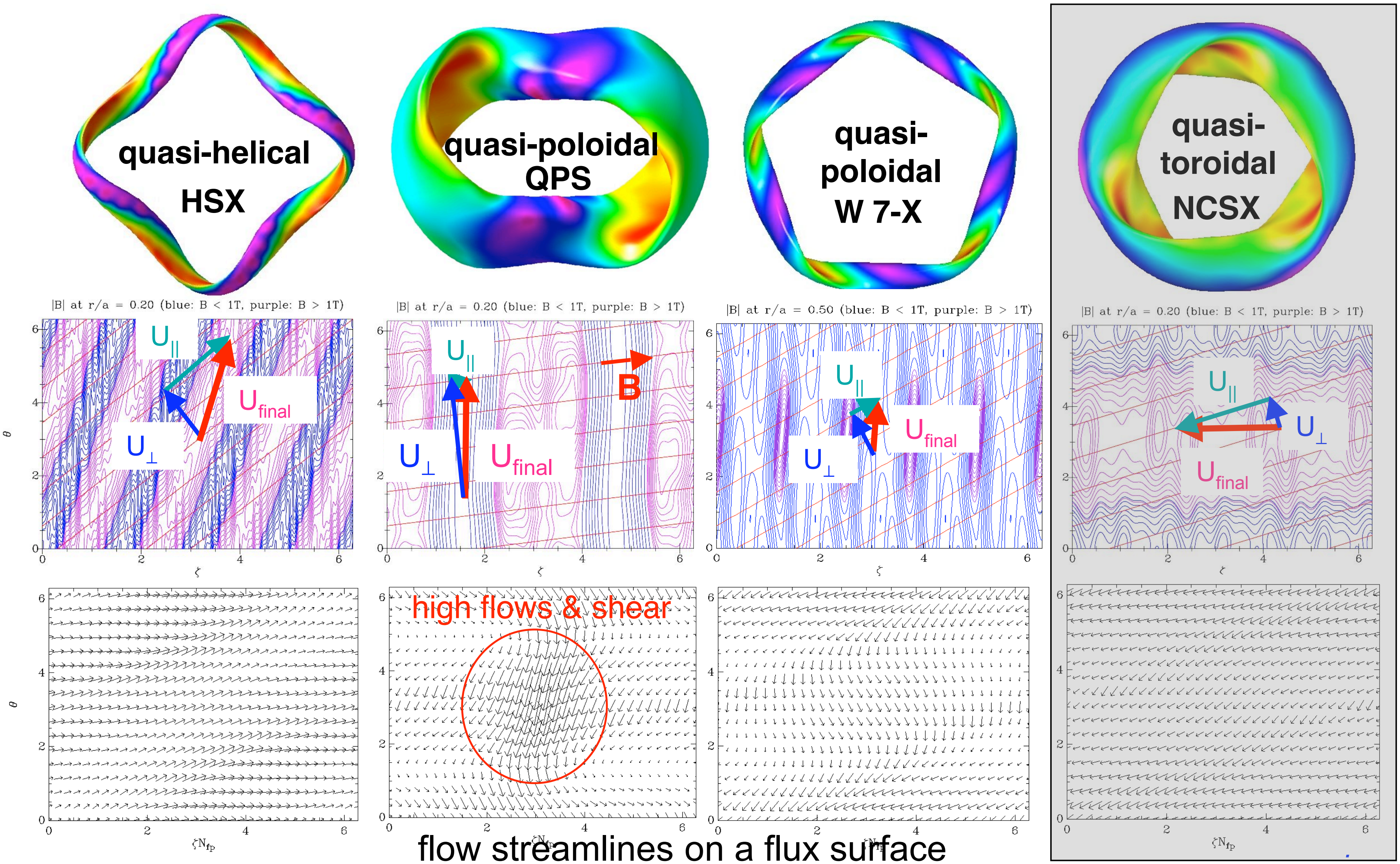




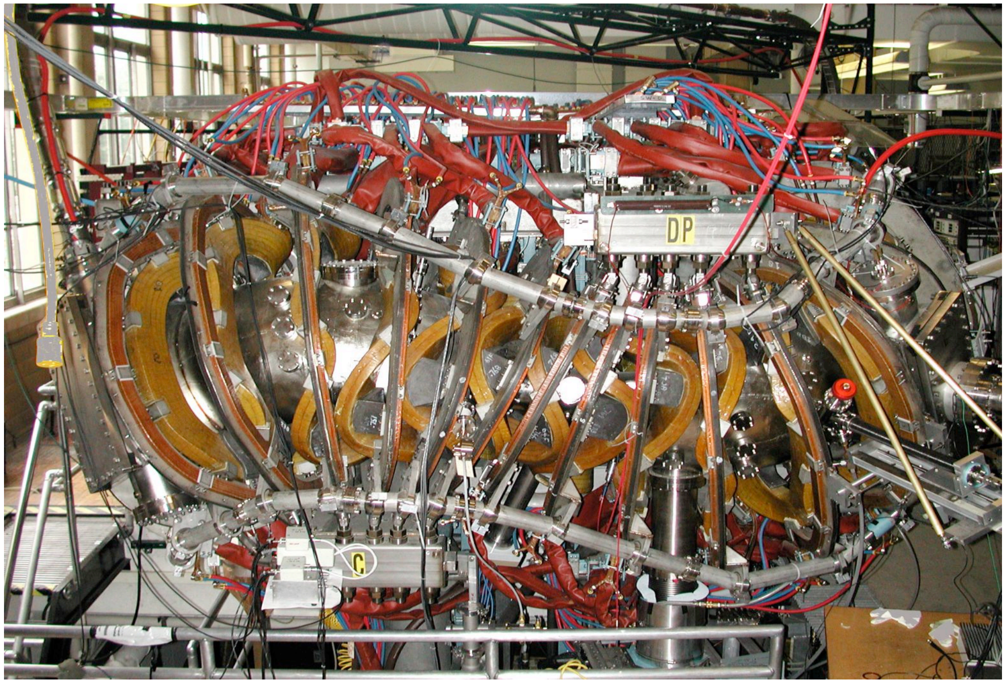
Theory and Computation Need Strengthening

- **Advance U.S. leadership in stellarator theory and modeling**
  - Improve understanding of recent high-β and high-density regimes
  - Bridge gap between neoclassical and turbulent transport: meso-scale physics
  - Optimization: develop new physics targets, simplify compact stellarator coils
- **Significant near-term opportunities for advancing toroidal confinement physics:**
  - 3-D MHD equilibrium modeling and reconstruction
    - continue adaptation to existing experiments
    - fast codes incorporating islands for optimization studies
  - Edge physics/divertor development
  - 3-D MHD stability: nonlinear ideal/resistive/extended MHD codes
  - Turbulence: gyrokinetic transport, zonal flows, configuration variation
  - Neoclassical transport
    - Include higher dimensionality/islands, extend to lower collisionality
  - Energetic particle physics (Alfvén and resonant wave-particle modes)

Differences in Flows & Flow Shearing among Quasi-Symmetric Stellarator Configurations



HSX Mission: to Experimentally Confirm the Potential Benefits of Quasi-Symmetry



HSX research addresses critical issues to the stellarator concept

- **Quasi-symmetry as solution to large neoclassical transport**
- **Variation of flows/damping and plasma currents**
- **Dependence of turbulent transport with magnetic structure**

Program Role:

- First experimental test of quasi-symmetry worldwide
- Importance of high effective transform; low effective ripple at moderate aspect ratio

<u>Parameters</u>

$R = 1.2$ m, $\langle a_p \rangle = 0.15$ m
$B = 1.0$ T
P_{ECH}: 200 kW, 28 GHz now
200 kW in progress
To date: $T_{e0} \sim 2.3$ keV
$\langle n_{el} \rangle = 6 \times 10^{18}$ m^{-3}

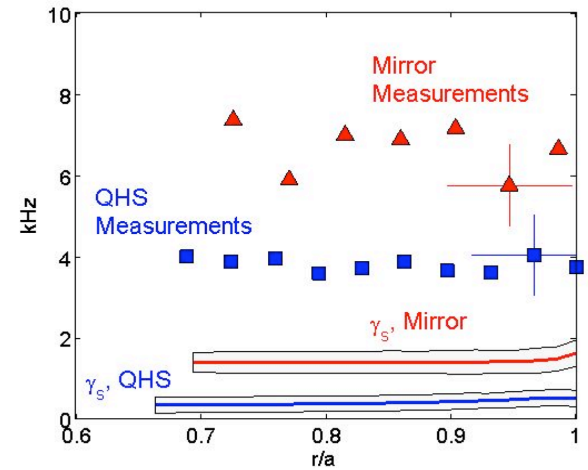
HSX can span the range between QH symmetric and non-symmetric configuration

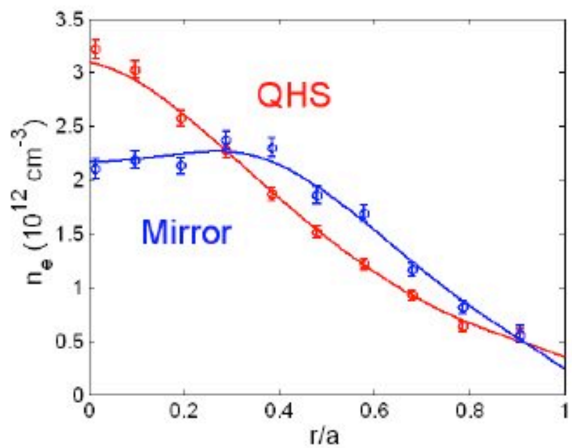
HSX Demonstrates Advantages of Quasi-symmetry

- Benefits demonstrated using auxiliary mirror coils to spoil QH symmetry

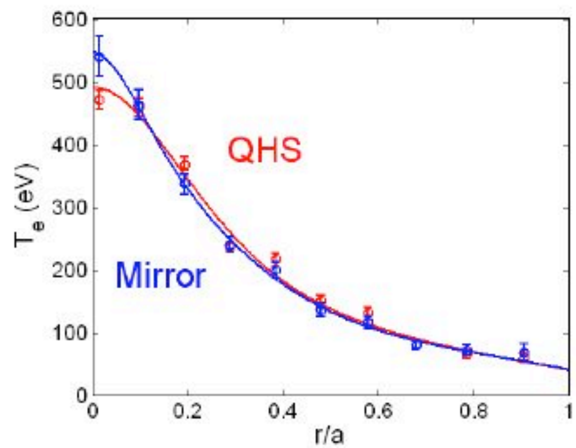
- Parallel viscous damping is reduced with QH symmetry (more rotation/shear)

- Reduced thermo-diffusion and lower χ_e

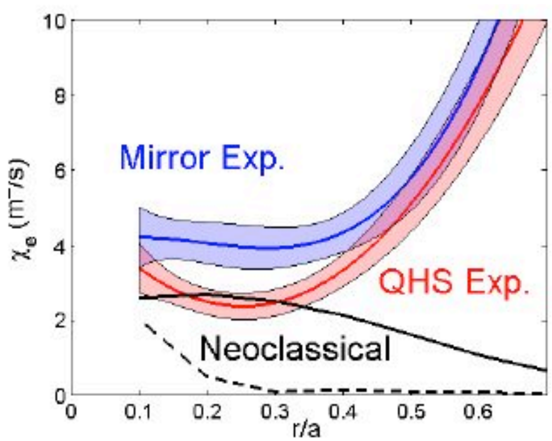




Reduced thermodiffusion with quasisymmetry



2.5 times the power needed in mirror to match T_e profiles



Calculated reduced central χ_e even in electron root (T_e>>T_i)

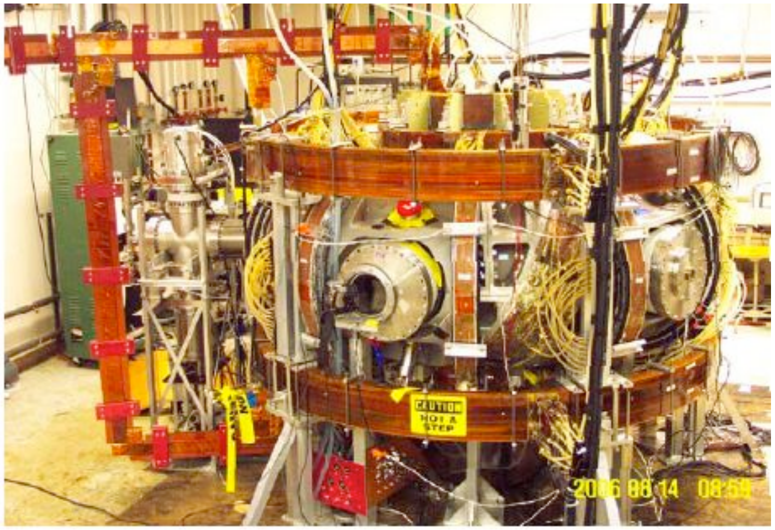
Near-Term Plans

- Confirm neoclassical improvements over wider range, more thermal plasmas; investigation of equilibrium currents
- Measurement of E_r with DNB on loan from MST; collaboration with RPI on novel HIBP
- Begin augmentation of edge fluctuation studies with central measurements with ECE and reflectometer; role of anomalous transport in QH symmetric configurations
- Continue work on 2nd 200-kW 28-GHz ECH system
  - power modulation experiments; heat pulse χ_e in addition to power balance
  - steerable launcher for T_e profile variation
  - EBW for overdense operation

Opportunities for Enhanced HSX Program

- ICRF program on HSX
  - plasmas in the ion root to maximize differences in neoclassical and anomalous transport between QH symmetric and mirror plasmas
  - position HSX for future β-limit studies
- High-field-launch fundamental X-mode heating
  - double the plasma density
  - direct XB Bernstein wave heating
- Doppler reflectometry: density fluctuations and plasma rotation
- Microwave scattering: fluctuation k-spectrum
- HIBP with energy analysis (with RPI) for fluctuation measurements for turbulent transport with effective ripple

CTH Studies Equilibrium and Stability in Stellarators with Current



$R = 0.75$ m, $\langle a_p \rangle = 0.18$ m

$B = 0.65$ T, $I_{OH} \sim 50$ kA

vacuum $\iota_a = 0.1 - 0.5$, 5 periods

one helical coil; TF & PF coils

$\Rightarrow$ large variation possible in ι_{pl}/ι_{ext}

100-kW OH + 18-GHz 15-kW ECH

adding soon 14-GHz 30-kW

- Not quasi-symmetric, but uses 3-D shaping, vacuum transform to passively control MHD instabilities
- Validating new V3FIT method of magnetic equilibrium reconstruction in 3-D plasmas
- Detection and control of magnetic islands
- Innovative procedures to determine most accurate model for as-built coils

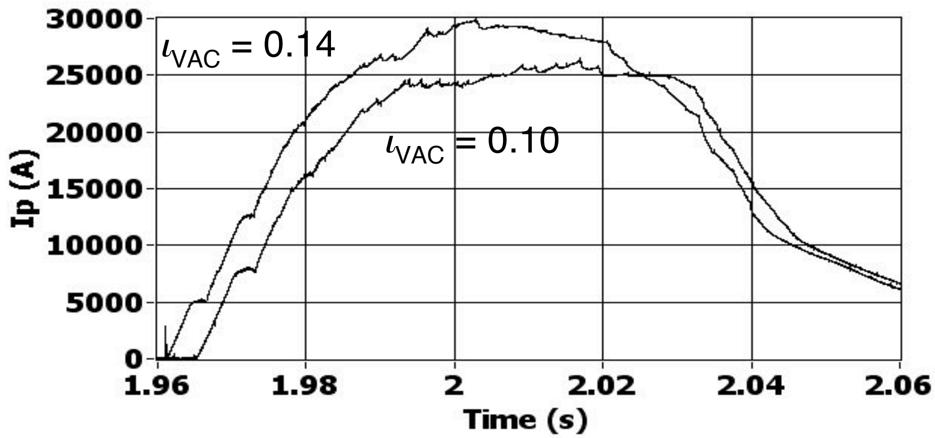
  These topics central to robust equilibrium and stability control of compact stellarator plasmas
- Extended program:

  ICRF electron heating $\Rightarrow$ higher pressure MHD studies

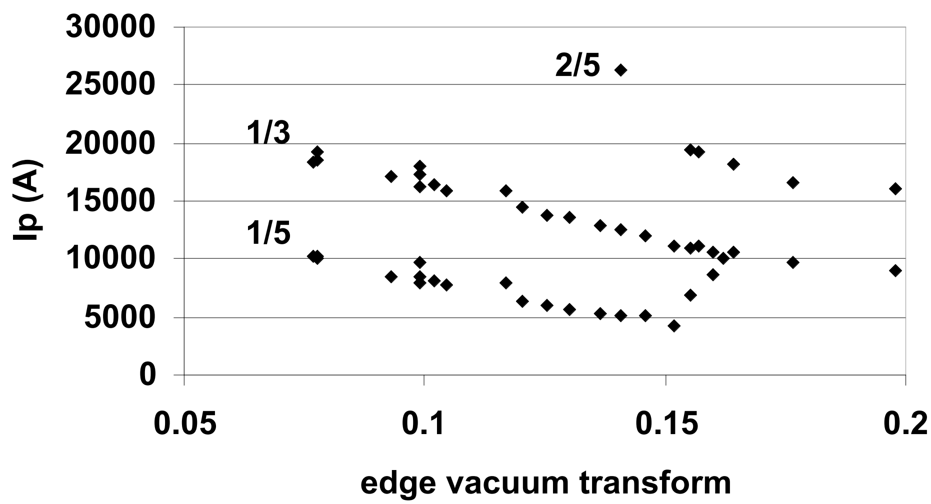
CTH Current-driven Instability Studies Underway

- Transient instabilities and current hesitations observed during current rise
- Instabilities occur at/near rational edge transform
- Discharges with $\iota_{TOT}(a) > 0.7$ obtained with $\iota_{VAC}(a) \sim 0.2$
- Some unstable behavior, but no complete current collapse
- NEAR TERM GOALS:
  - extend range of vacuum transform and plasma current
  - model with V3FIT 3-D equilibrium reconstruction

Plasma current for 2 different vacuum transforms



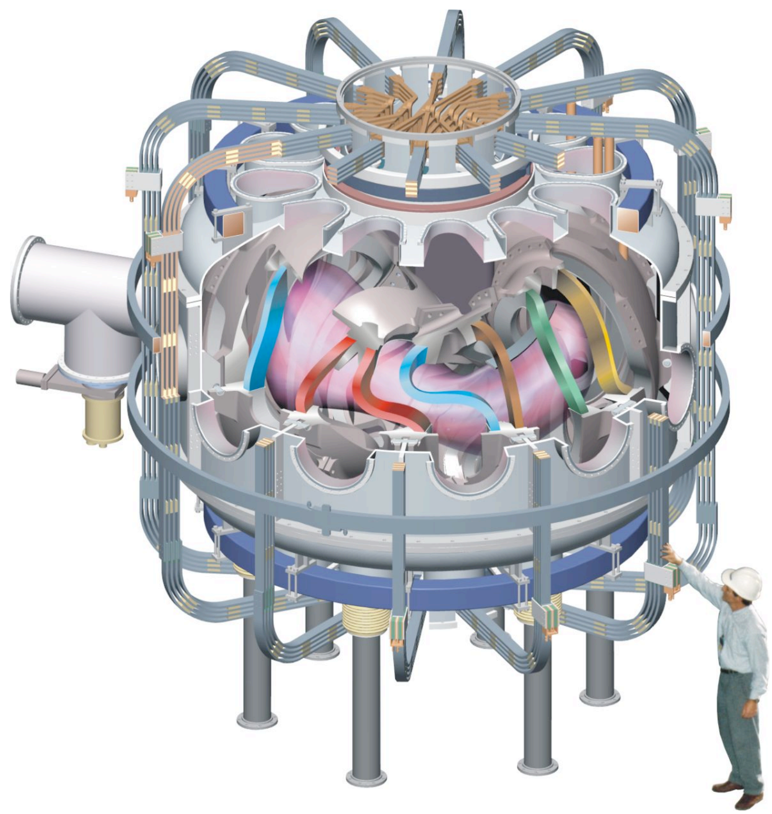
Net transform at edge determines onset of instability



QPS: Quasi-Poloidal Symmetry at Low *R/a*

Linked-mirror configuration is orthogonal to axisymmetric experiments

- low neoclassical and anomalous transport (low effective ripple; low poloidal viscosity ⇒ large sheared E x B flows)
- robust equilibrium and healing of magnetic islands
- reduced growth rates for trapped particle, ITG modes



Can vary key physics features by >10x

- quasi-poloidal symmetry, poloidal flow damping, neoclassical transport
- stellarator/tokamak shear
- trapped particle fraction

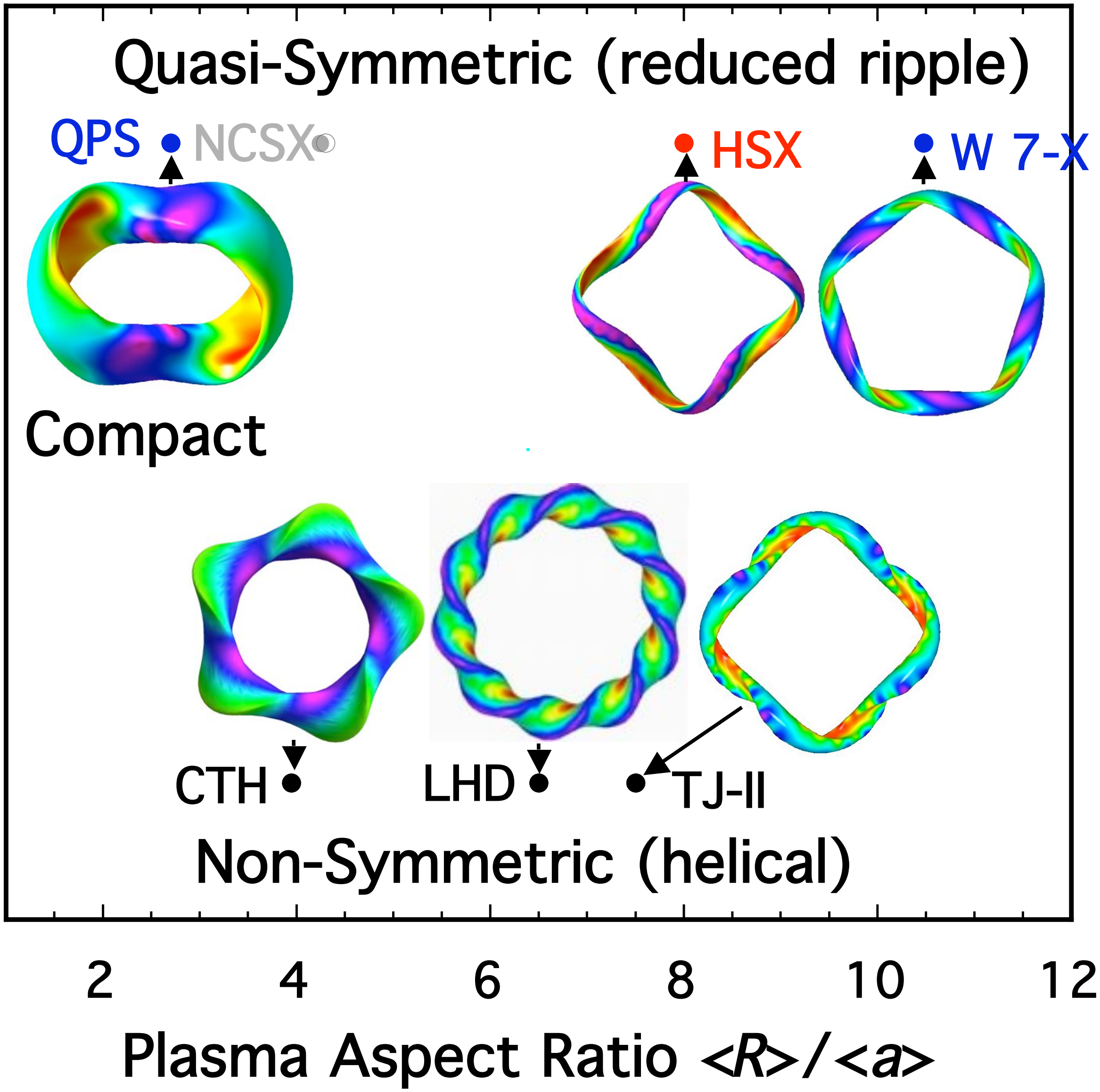
$\langle R \rangle = 0.95$ m

$\langle a \rangle = 0.3$–0.4 m

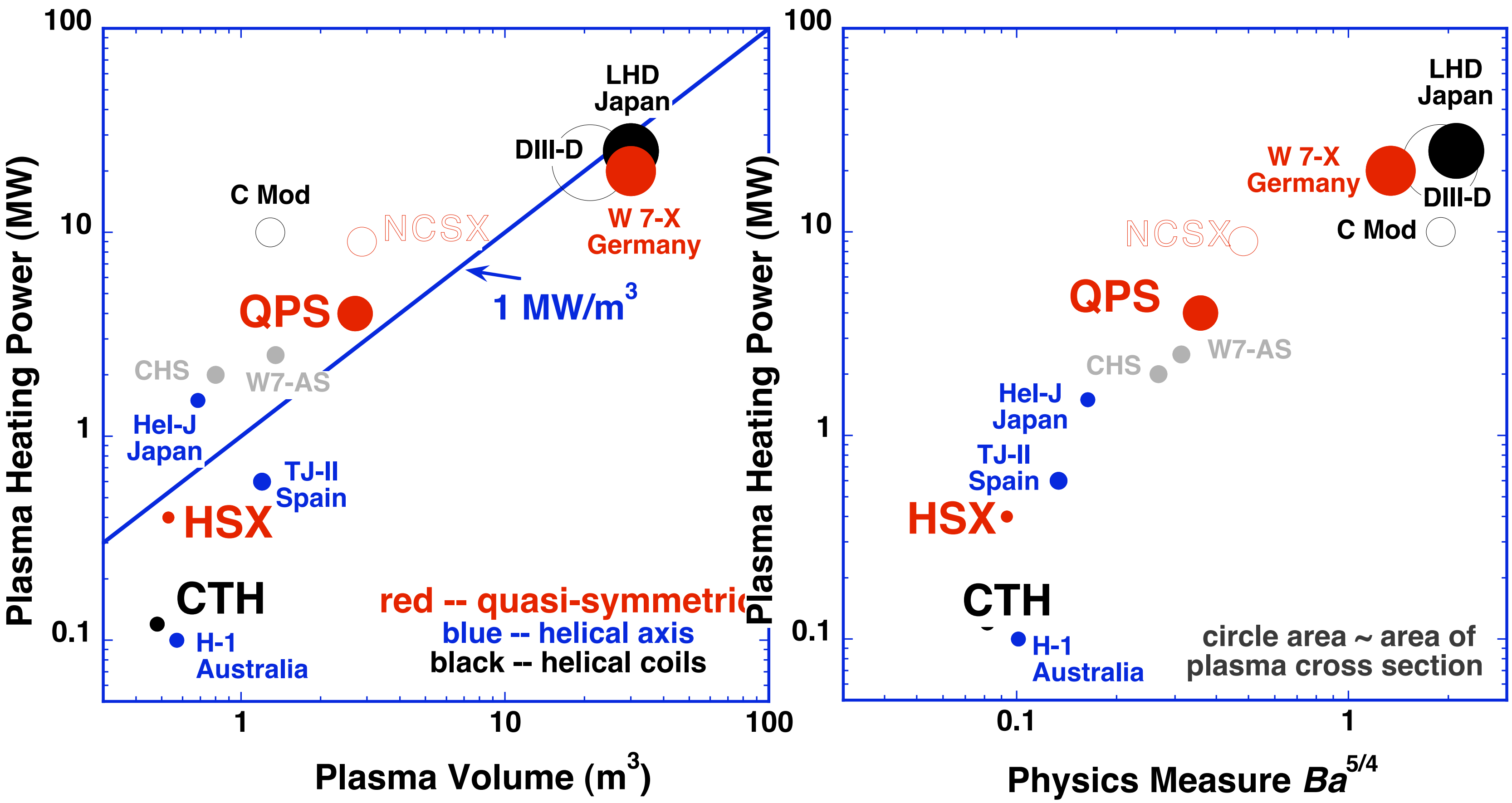
$\langle R \rangle / \langle a \rangle \sim 2.5$

$B = 1$ T, $P = 3$–5 MW

With No NCSX, QPS Would Be the Only Compact Quasi-Symmetric Stellarator



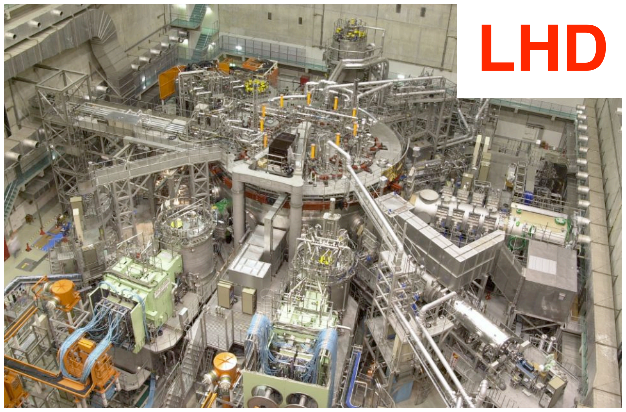
With No NCSX, QPS Would be the Only Quasi-Symmetric Stellarator between HSX and W 7-X in Capability

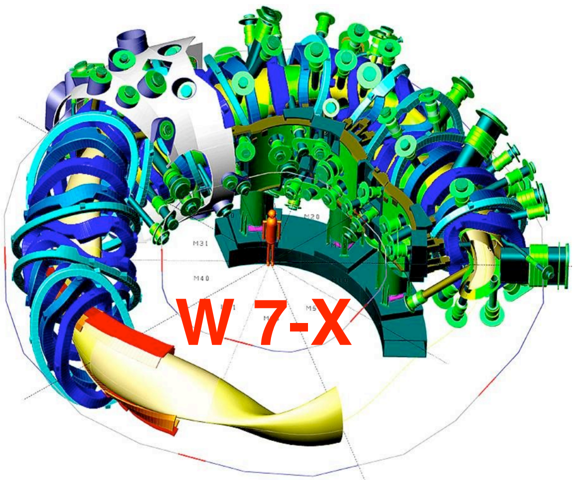


- QPS bridges gap between HSX and W 7-X: factors of 60 in volume, 50 in power and 14 in $Ba^{5/4}$

International Collaboration

- Allows access to stellarators with capabilities well beyond the scope of the US program
- Although not compact stellarators (R/a = 6-7 in LHD and 10.4 in W 7-X vs 2.5 in QPS), they can obtain important information on
  - plasma behavior at high parameters: density (>10^{21} m^{-3}), ion and electron temperatures (5-13 keV), $\beta \sim 5\%$ for $50\tau_E$
  - energetic-ion stability and transport
  - steady-state operation and β maintenance at high power (3 MW)
  - 3-D power and particle exhaust methods
- They are additional sources of information on
  - the effect of lower effective ripple on neoclassical and anomalous transport
  - density and β limits and mechanisms





B = 3 T superconducting coils, V_{pl} = 30 m^3
a_{pl} = 0.53–0.6 m
$P_{heating}$ = 15–30 MW

Key Physics Issues

Different US Program Elements Add to the Knowledge Base From Different Perspectives

Key physics issues in reduced compact stellarator program are similar to what would have been addressed in a more integrated fashion in NCSX

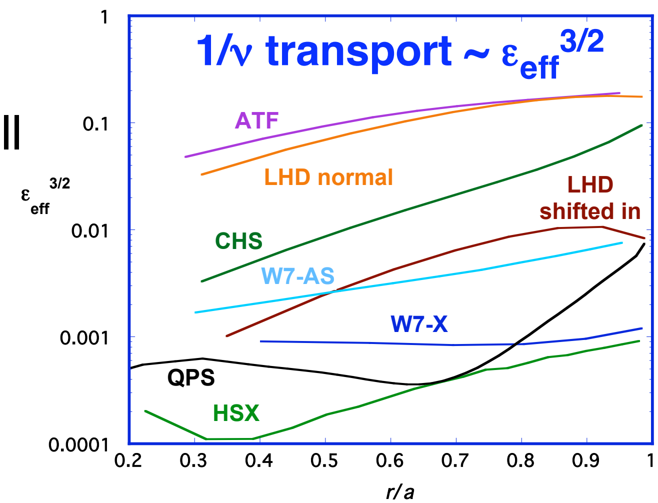
Basic Physics Issues	QPS	NCSX	HSX	CTH
Compactness (plasma aspect ratio)	2.7	4.4	8	4
Quasi-symmetry	pol.	tor.	hel.	none
Effects of reduced effective ripple on energy confine.		X		
Reduction of turbulent transport by flows		X		
Improved energetic-ion stability and confinement		X		
Pressure limits & limiting mechanisms at moderate $\langle\beta\rangle$		X		
Stabilization of equilibrium islands & tearing modes		X		
Disruption stabilization and avoidance		X		
3-D power and particle exhaust methods		X		
High plasma parameters		X		

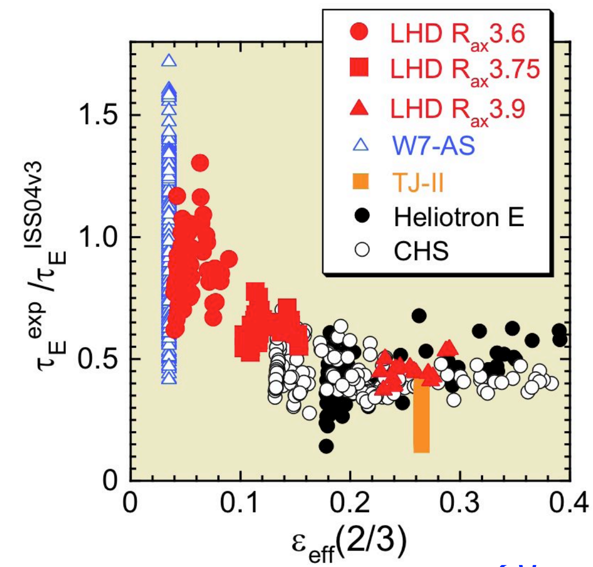
Darkness of blue indicates indicates relative contribution to physics issue

Performance-extension LHD and W 7-X make major contributions in all areas

Effects of Strongly Reduced Effective Ripple on Energy Confinement

- 2004 stellarator τ_E scaling study found improvement of confinement with lower effective ripple (ε_{eff})
- Quasi-symmetric designs have the lowest ripple of all configurations
- Various experiments address this issue for different symmetries: HSX (QH), QPS (low-*R*/*a* QP), W 7-X (high-*R*/*a* QP) and LHD (non-symmetric)
- Orbit deviations from flux surfaces are greatly reduced in LHD by shifting the magnetic axis inward, which produces a large reduction in microturbulent transport
- HSX contributes by varying the effective ripple using an auxiliary coil set with matched temperature and density profiles
- QPS can provide similar information at higher plasma parameters by varying the effective ripple over a wide range.





Reduction of Turbulent Transport by Flows

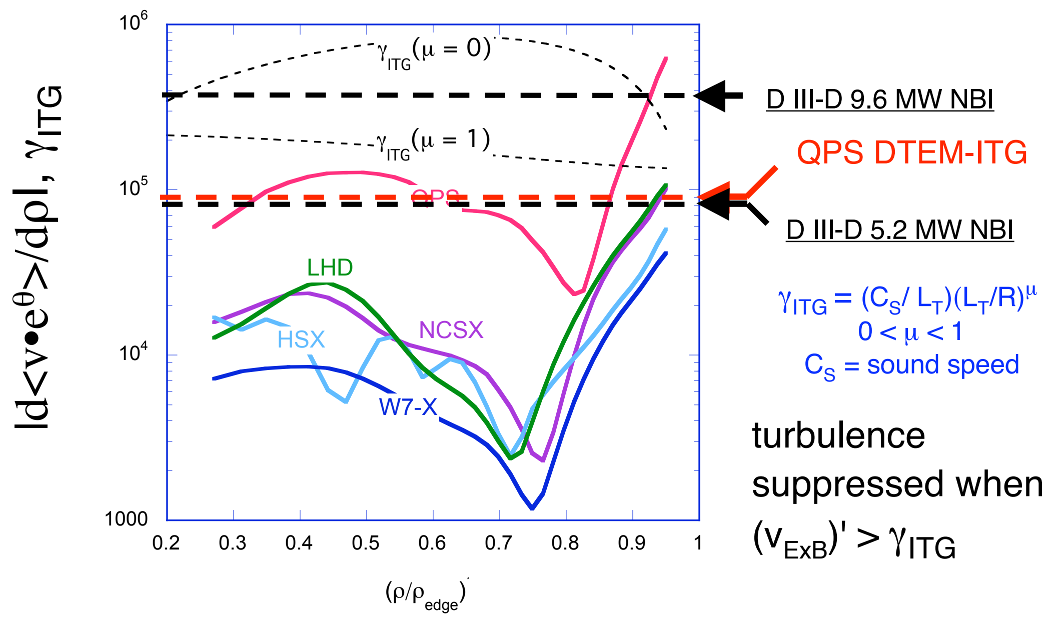
- HSX can understand the underlying mechanism of configuration-dependent changes in turbulence by examining zonal flow dynamics and equilibrium flows and radial electric fields, coupled with fluctuation measurements and microstability calculations
- Theoretical & computational studies of these effects in quasi-symmetric configurations is stimulating experiments on LHD to look for flows associated with improved confinement regimes in very high density plasmas obtained with pellet injection

Reduction of Turbulent Transport by Flows

QPS exploits low R/a, low ι and QP symmetry to obtain large flow shearing

$\Rightarrow$ reduces anomalous transport and increases stability

Without external momentum input, QPS has larger poloidal flow shear than other toroidal devices



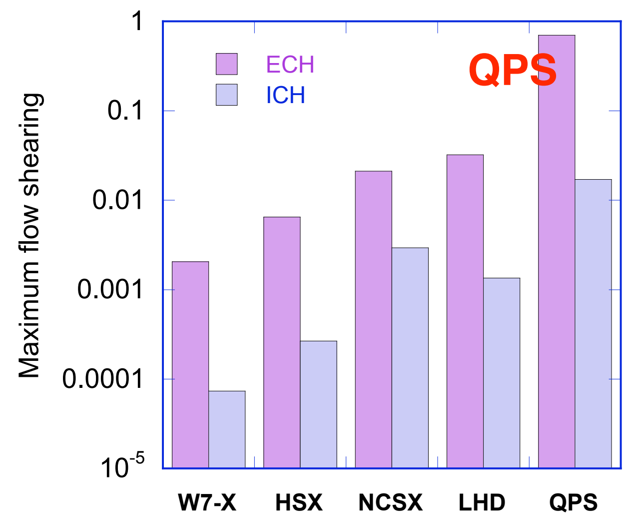
$\gamma_{ITG} = (C_S/L_T)(L_T/R)^{\mu}$

$0 < \mu < 1$

C_S = sound speed

turbulence suppressed when $(v_{ExB})' > \gamma_{ITG}$

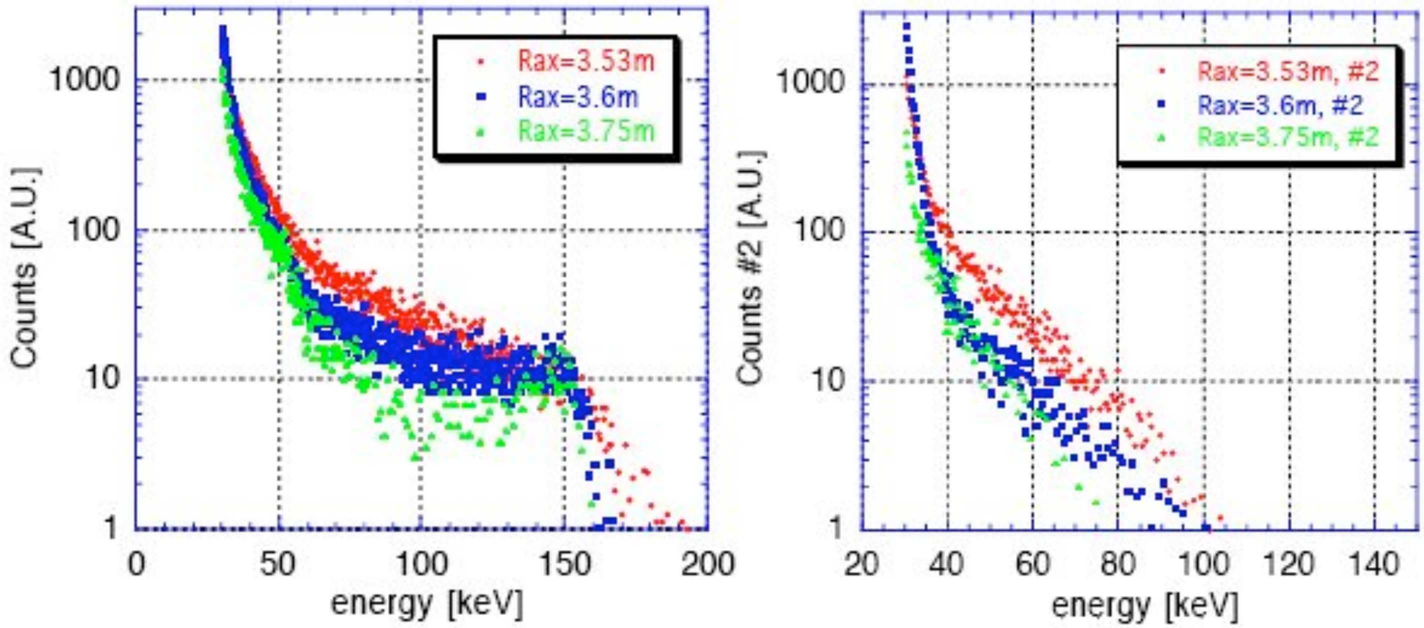
Flow shearing rates within flux surfaces, measured by $\frac{R_0}{v_A}(b \bullet \nabla)V$ are large enough to impact MHD:



- Simple extrapolation from Concept Exploration Experiment to reactor:
- Real E_r scale lengths generally $< \langle a \rangle$
- Going from model case (0.3 keV) to reactor, ρ_* drops by ~8 (10 keV)
- Continuing studies show that v_{ExB} shearing in QPS exceeds simple scaling by a factor ~10
- If trend maintained, equilibrium flow shearing is sufficient in a reactor

Improved Energetic-Ion Stability and Confinement

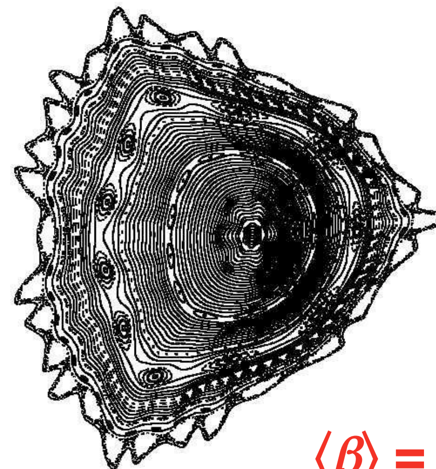
LHD NBI



- LHD and W 7-X are best suited to provide information on this topic with high-power neutral beam heating
  - shifting the axis in on LHD reduces ripple (QP-like) and improves fast-ion confinement
- TAEs observed in W 7-AS and LHD at low density with NBI
- QPS can study energetic ion confinement through high-energy tails created with 2-MW ICRF heating

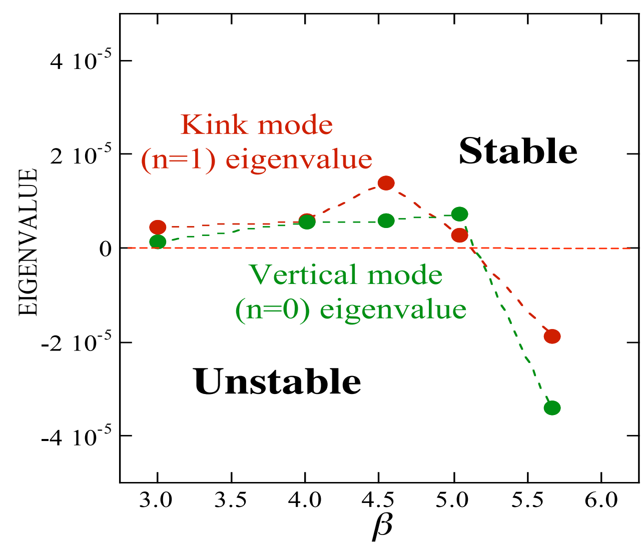
Pressure Limits and Limiting Mechanisms

- LHD and W 7-X will address this issue at high aspect ratio and QPS at low aspect ratio
- Beta limits in stellarators appear to be set by degradation in confinement rather than by disruptive plasma instabilities
  - ballooning 'limit' may not constrain β
- QPS is predicted to be stable to drift wave turbulence over range of temperature & density gradients without additional momentum input
  - should reduce anomalous transport even in absence of flow shearing
- Trapped particle mode stability
  - QPS has a large fraction of trapped particles in regions of low/favorable field line curvature to suppress trapped-particle instabilities
  - QPS is the only device with region of stability for the collisionless trapped particle mode



$\langle\beta\rangle = 4\%$

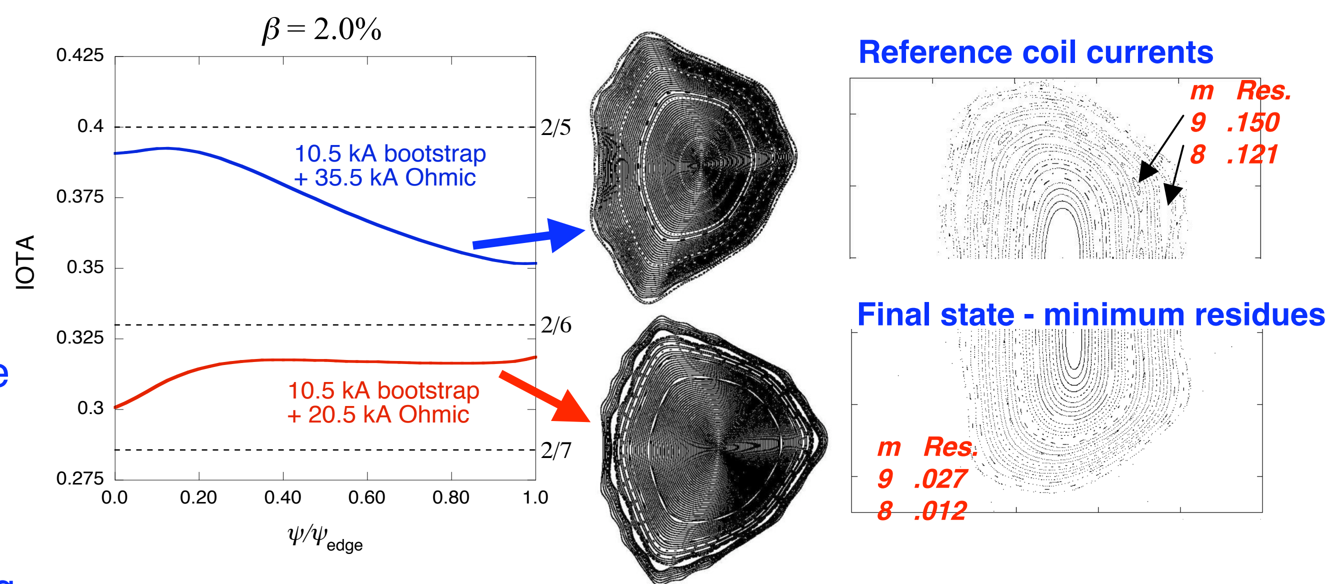
QPS



Stabilization of Equilibrium Islands and Tearing Modes

- An important issue for both stellarators and tokamaks is their response to small magnetic perturbations
  - LHD has examined these effects in low-order islands near the plasma edge, but these results need to be extended to higher-order internal islands in different configurations
- CTH studies will address the consequences and need for control of static magnetic islands in helical plasmas with significant toroidal current
- At higher β, QPS and W7-X could investigate finite pressure modifcation of islands

- Induced currents in QPS could also be used to study passive stabilization of neo-classical tearing modes
  - of special interest is the shielding of islands when neoclassical effects are stabilizing rather than destabilizing



Disruption Stabilization and Avoidance

- CTH is the only experiment in the world program that can study elimination of disruptions using large (factor ~ 10) variations in the ratio $\iota_{\mathrm{external}}/\iota_{\mathrm{plasma}}$
  - the circular cross-section vacuum vessel accommodates plasma equilibria with rotational transform (ι_{vacuum}) from 0.05 to ~ 0.5
- CTH stabilization and mitigation studies can span the range from near-tokamak geometry to helically-dominated configurations
- Other experiments (HSX, W 7-X, QPS, LHD) can avoid disruptions through no or low plasma (bootstrap) current and tailoring the rotational transform profile

Options for U.S. Stellarator Program *without* NCSX

3a *What options would exist or be possible to address the key issues of quasi-symmetric stellarators in general and the compact stellarator in particular?*

3b *What program elements would be required to maintain the U.S. as a significant participant in the international stellarator program? Identify potential opportunities for U.S. leadership with more international collaboration as appropriate*

- The US has a clear international leadership role NOW in quasi-symmetry which should be maintained and strengthened through
  - an enhanced theory program to connect the physics of quasi-symmetry with axi-symmetry and improve coil configurations
  - an enhanced HSX program to further demonstrate advantages of quasi-helical symmetry, high effective transform and very low ripple
  - an enhanced CTH program to study equilibrium and stability in stellarators with current focusing on disruption, 3-D equilibrium and control of magnetic islands
  - QPS to test a very compact quasi-poloidal symmetric configuration with large flows and flow shearing and connection to large-aspect-ratio W 7-X
  - strengthened and targeted collaborations on issues important to US program
  - considering how to pursue the quasi-axisymmetric approach