Overview of HSX Experimental Program

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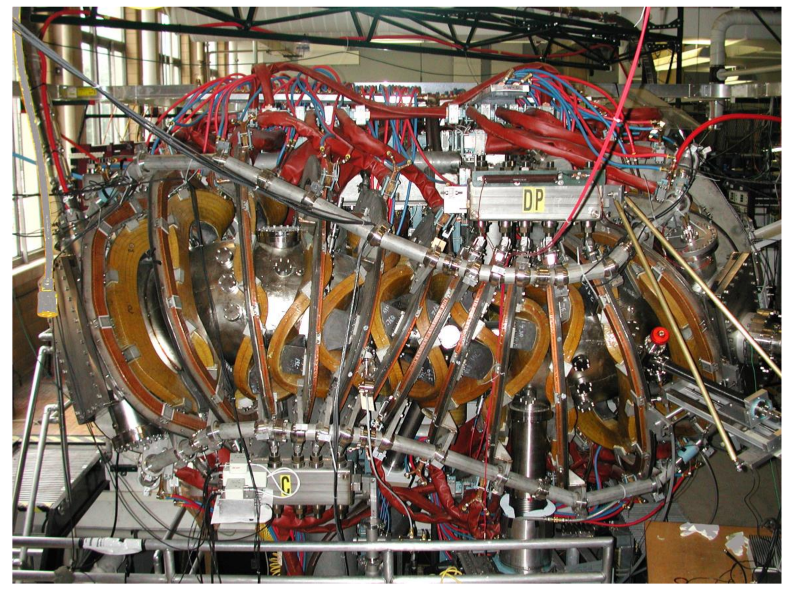
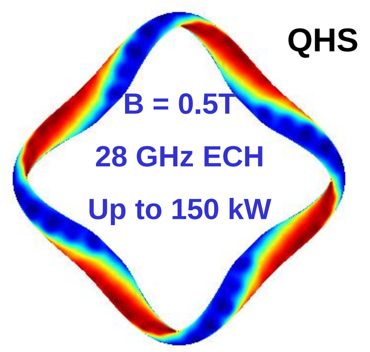
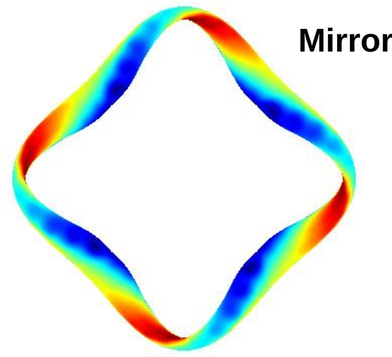
1. The HSX Experiment

HSX is the World's First Test of QuasiSymmetry





$B = B_0[1+\varepsilon_h\cos(N-m\iota)\phi]$



$B = B_0[1+\varepsilon_h\cos(N-m\iota)\phi+\varepsilon_M\cos(N\phi)]$

- HSX has a helical axis of symmetry in |B|
  - Reduction of direct loss orbits
  - Low level of neoclassical transport
  - Small viscous damping of plasma flow
- For experimental flexibility, the quasi-helical symmetry can be broken by adding a mirror field.

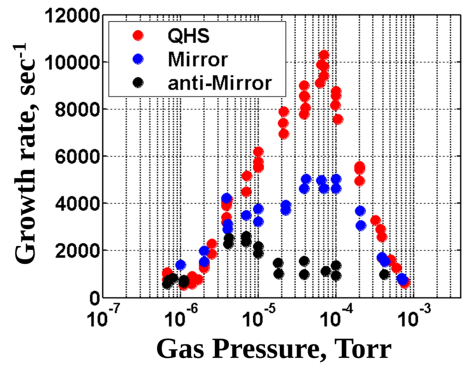
Overview

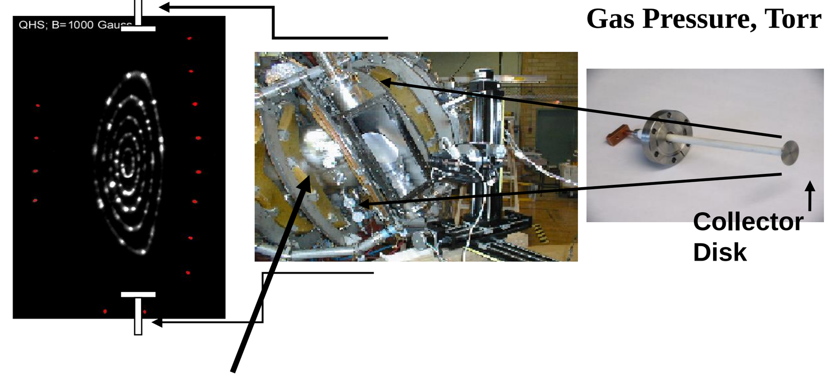
- Quasihelically symmetric stellarators have high effective transform, given by $N - m\iota = 3$ for N = 4, m = 1 helical field and a transform just above 1.
- Previously demonstrated B spectrum does not contain toroidal curvature and that high effective transform reduces drift from flux surface.
- We have shown that quasisymmetry is effective in reducing direct orbit losses and viscous damping of plasma flow.
- 2nd harmonicECH with 28 GHz gyrotron produces central T_e up to 1 keV with 150 kW, measured by 10 chord Thomson scattering.
- Nonthermal electron population is evident in ECE, TS and X-ray measurements. This population skews HSX scaling studies with respect to International Stellarator database.
- However, good confinement of the nonthermal population in QHS configuration has led to unforeseen MHD activity (with no effect on confinement): Global Alfven Eigenmode.
- Presently concentrating on determining whether neoclassical transport influences particle and heat diffusivities.
  - Thermodiffusion possibly flattens density profile in Mirror configuration. In QHS, this term is very small and profiles are peaked.
  - Preliminary evidence that T_e is higher in QHS than for Mirror.
- Anomalous transport dominates towards plasma edge.
  - Turbulent driven flux measured with probes only loosely correlates with H_α measurements of particle flux.
  - Initial modeling suggests drift wave turbulence dominates transport.
- Future plans include more flow measurements, higher magnetic field, power and density. Also, more extensive turbulence measurements.

2. Symmetry Matters!

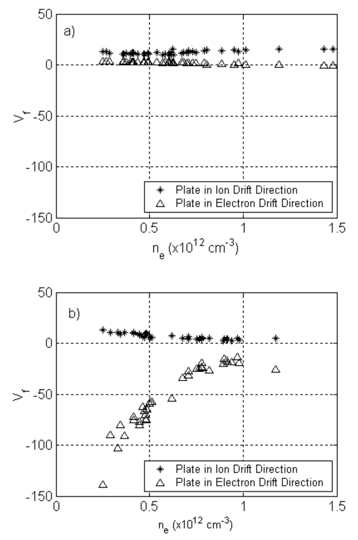
2.1 Reduction of Direct Loss Orbits

Faster breakdown, more rapid plasma density growth rate with QHS





ECH Mirror

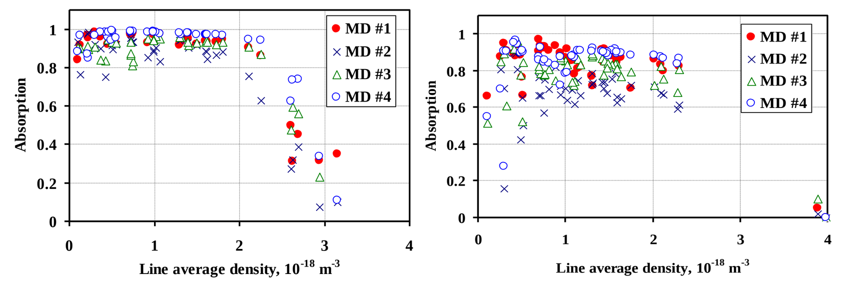


QHS

Mirror

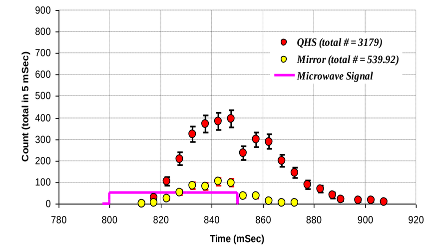
- Collector plates positioned at the top and bottom of the torus (in the B X VB directions) at the ECH location
- Floating potential monitored as indicator of directed fluxes
- For mirror mode, plate in electron drift direction driven to large negative potential

Significantly improved microwave absorption in QHS configuration

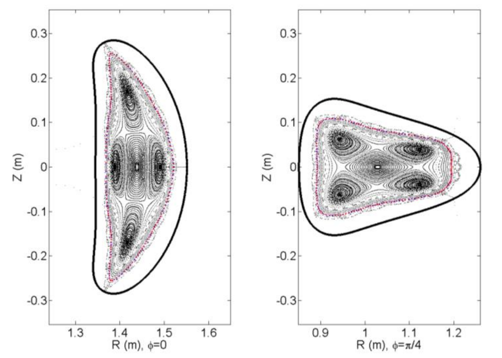


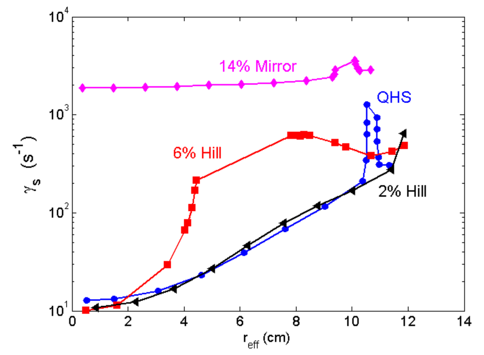
QHS Mirror

Decreased x-ray flux when symmetry is broken



2.3 Breaking symmetry with islands increases viscous damping





- Decreasing rotational transform leads to (4,4) islands in plasma
- (4,1) spectral component of field interacts with (4,4) island structure to give rise to (8,5) and (0,3) terms
- The quasisymmetry is broken by these additional spectral components and the viscous damping rate increases
- Process is similar to rotation damping due to resistive wall modes in tokamaks.

Poster by Schmitt PP1.048

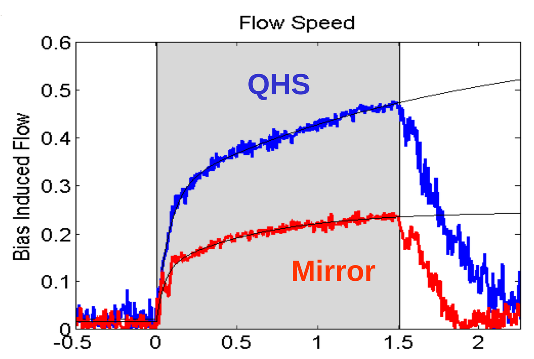
2.2 First evidence that parallel viscous damping is reduced with quasi-symmetry

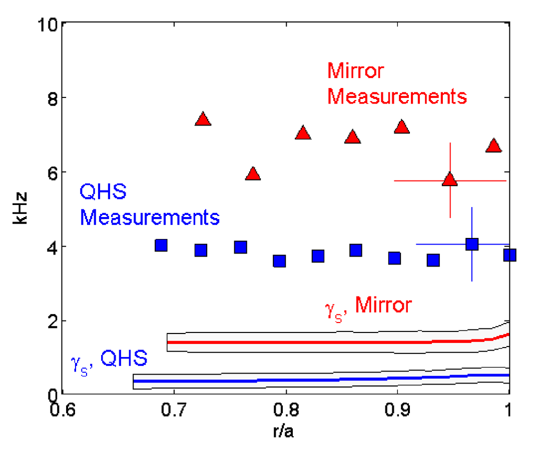
For equivalent drive QHS has slower rise and fall and reaches a higher flow velocity

Two time scales observed; slow corresponds to the damping in the direction of symmetry

Although quasi-symmetry reduces neoclassical damping, there remains a residual anomalous damping mechanism similar to tokamaks

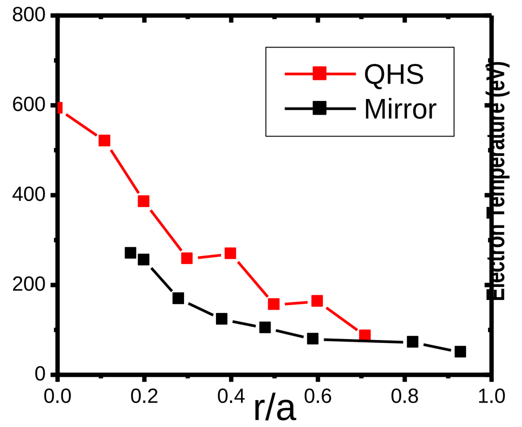
Invited talk by Gerhardt EI1.003



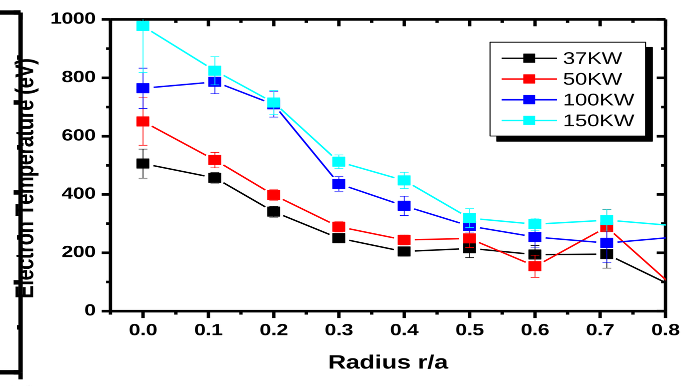


3. Nonthermal Population Observed During ECH Excites MHD Mode

3.1 Thomson Scattering and ECE measure T_e profiles

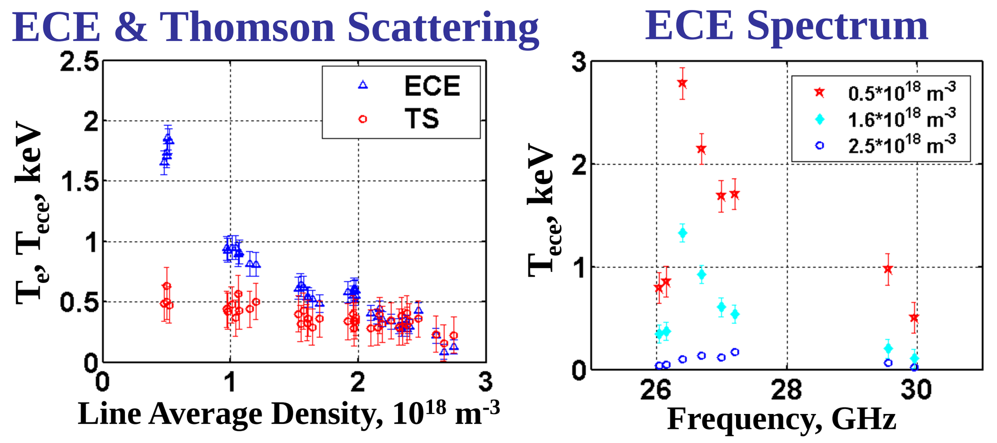


- Some preliminary data indicating difference in QHS/Mirror T_e profiles.
- Neoclassical thermal conductivity in QHS is about 3 orders of magnitude smaller than Mirror configuration.



- Power scan shows up to 1 keV measured in 10 channel Thomson scattering diagnostic.
- Comparing signal in different spectral channels indicates nonthermal population

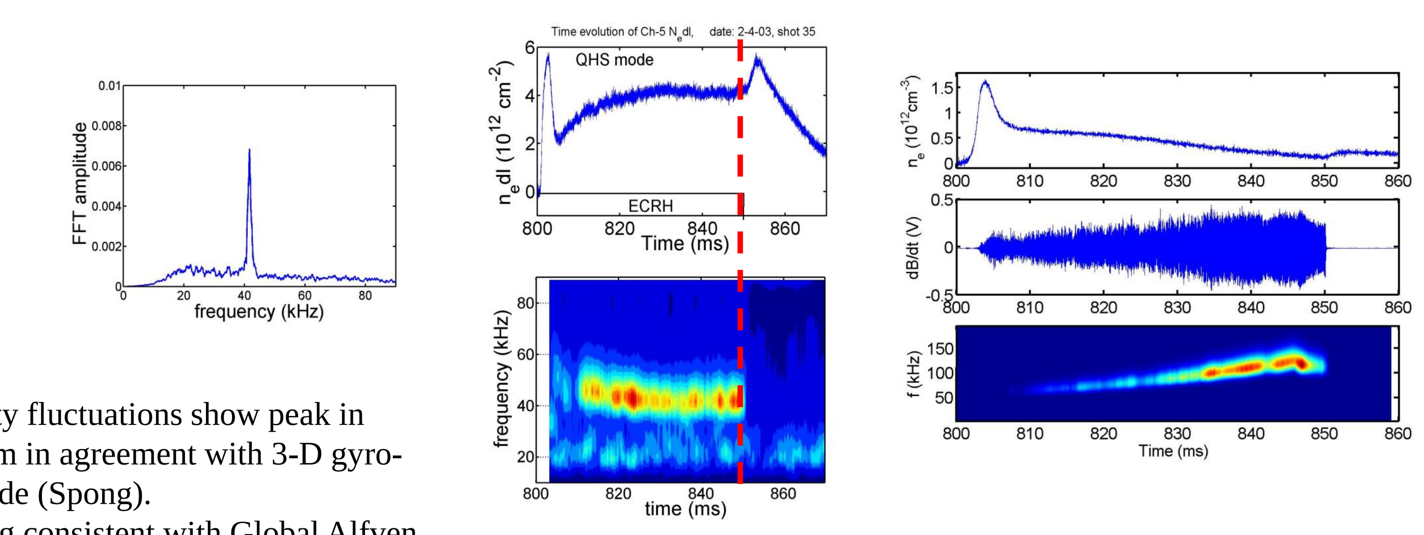
Poster by Zhai PP1.042



- ECE shows nonthermal population at low density
- Bi-Maxwellian plasma can model high absorption and ECE emission.

Poster by Likin PP1.041

3.2 Nonthermal population drives GAE MHD mode in QHS plasmas



- Density fluctuations show peak in spectrum in agreement with 3-D gyro-fluid code (Spong).
- Scaling consistent with Global Alfven Eigenmode.

Poster by Deng PP1.044

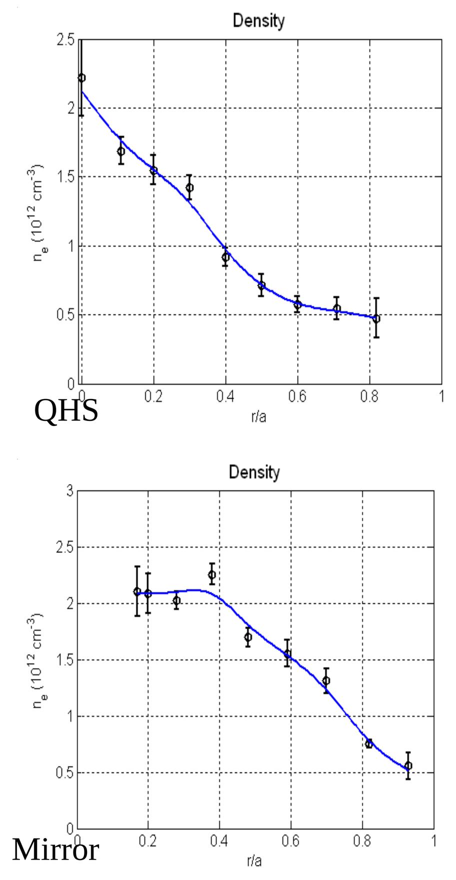
$$\omega_{GAE} \le k_{//} v_A = \frac{(m\iota - n)}{R}\frac{B}{\sqrt{4\pi n_i m_i}}$$

- Magnetic fluctuations coherent with density

- **Poster by Oh PP1.045**

4. Neoclassical vs Anomalous Transport: Crucial Issue for Quasisymmetric Stellarators

4.1 Neoclassical transport shapes density profile



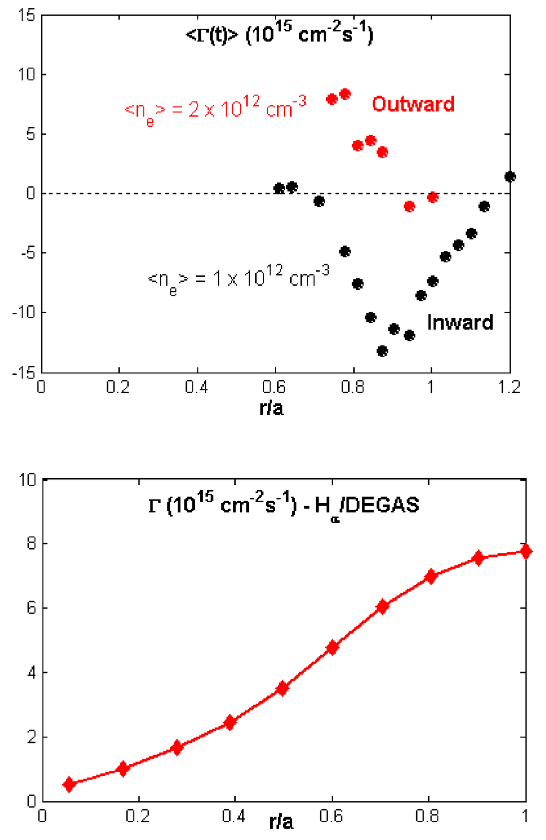
QHS

Mirror

- Density profile peaked in QHS, flat in Mirror configuration
- Thermodiffusive particle transport always small with symmetry, but dominates when symmetry is broken
- With off-axis heating and flattened T_e profiles, density is peaked again in Mirror configuration.

Poster by Canik PP1.043

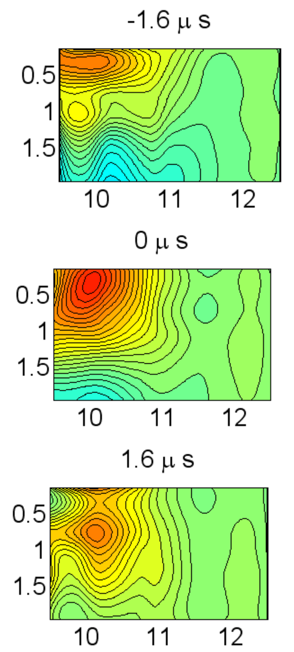
4.2 Does turbulence dominate at the edge?



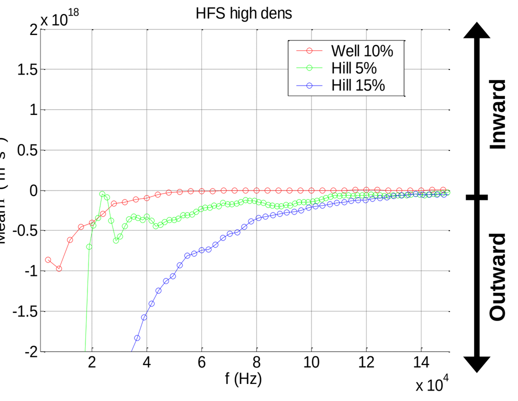
- Turbulent driven flux, measured with probe, is comparable to that measured with H_α detectors and DEGAS code.
- Trapped electron model provides rough agreement with particle and heat diffusivities.

Poster by Guttenfelder PP1.046

4.3 2-D correlation measurements show blob propagation



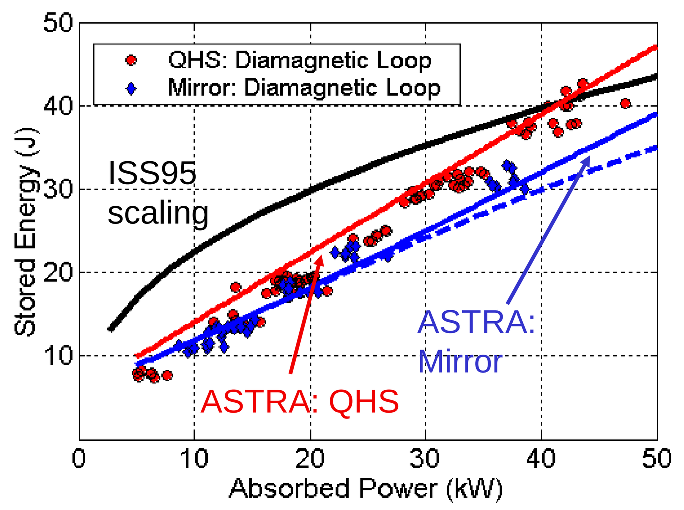
- Correlation of multi-pin probe with fixed reference shows downward propagation of blobs at plasma edge
- No phase difference between density and potential points to drift waves.

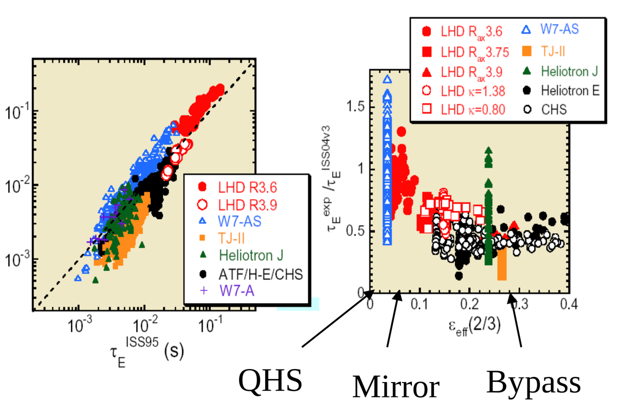


- Turbulent driven flux increases with magnetic hill.

Poster by Lechte PP1.047

4.4 Stellarator Modeling and Scaling





QHS	Mirror	Bypass Coil #3
0.007	0.06	

- Stellarator Database shows offsets dependent on configuration. Machine dependent normalization factor indicates confinement degrades as effective ripple increases.
  - Occurs even for high collisionality
  - Could energetic particle confinement or viscous damping of flow be responsible?
- HSX can vary effective ripple over broad range and investigate confinement, viscous damping, diffusivities and energetic particle confinement

- ASTRA modeling shows T_e and stored energy are consistent with anomalous $\chi_e \sim 1/n$.
- Stored energy increases linearly with power, contrary to stellarator database in which W ~ $P^{0.4}$
- Mirror neoclassical transport very much dependent on E_r
- Nonthermal population possibly skewing HSX scaling

5. Future Plans

- Build on present plasma flow results by measuring flow damping near magnetic islands and across separatrix; correlate with turbulence.
- Install magnetic probe arrays and measure poloidal, toroidal mode numbers of GAE mode.
- Compare CQL3D Fokker-Planck results to X-ray measurements.
- Increase power, density and magnetic field to minimize nonthermal population and accentuate neoclassical transport
- Increase operating field to B=1.0 T
  - O-mode operation at 1 T gives factor of 2 in n_e and reduction of tail population.
  - Reduce anomalous transport and increase neoclassical.
- Implement a 2nd 28 GHz gyrotron
  - Available power increased from 200 to 400 kW.
  - Vary heating profiles, allow for pulse propagation.
- Identify characteristics of anomalous transport in quasi-symmetric configurations through diagnostic improvements
  - ECEI for temperature fluctuations
  - Reflectometry for density fluctuations
- It would be desirable to measure the radial electric field since neoclassical transport in Mirror very much depends on E_r.