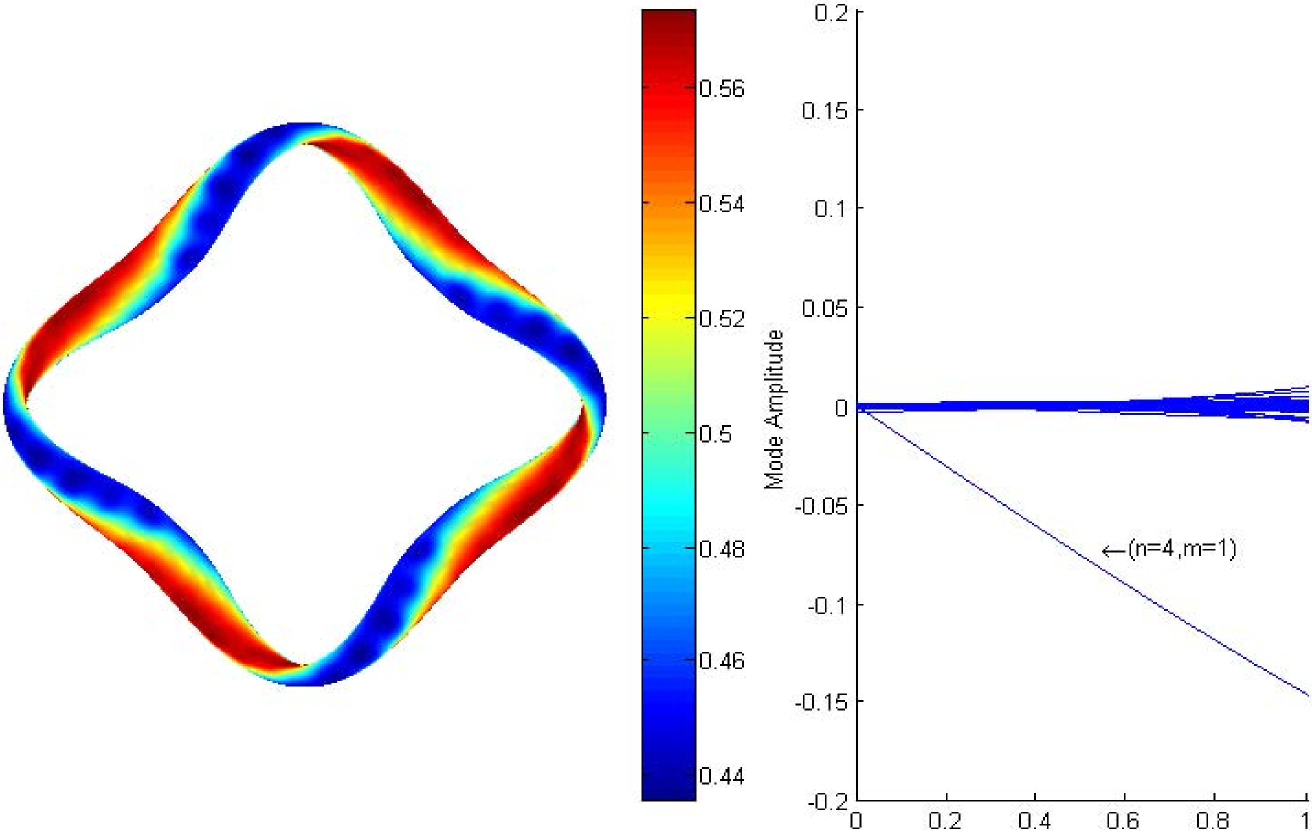
Experimental Evidence for Improved Confinement with Quasisymmetry in HSX

S. P. Gerhardt, A. Abdou, A. F. Almagri, D.T. Anderson, F.S.B. Anderson, D. Brower, J. Canik, C. Deng, W. Guttenfelder, K. Likin, S. Oh, P.H. Probert, V. Sakaguchi, J. Schmitt, J. Tabora, J.N. Talmadge, and K. Zhai

Abstract

Plasmas produced by second harmonic electron cyclotron heating (ECH) in HSX provide the first evidence of transport improvement due to quasisymmetry in a stellarator. Comparisons are made between plasmas in the base quasihelically symmetric (QHS) configuration and two neoclassically degraded configurations which lack quasisymmetry (Mirror configurations). It is found that the plasma breakdown occurs more easily in the QHS configuration, indicating improved confinement of the breakdown electrons. The stored energy in the QHS configuration is up to six times larger than in discharges in the Mirror configurations, and evidence is shown for enhanced prompt loss of trapped particles when the Mirror field applied. The flow damping rate in the Mirror configuration is a factor of three to four times higher than in the QHS configuration.

The Helically Symmetric eXperiment



Quasihelical: Fully 3-D, BUT

Symmetry in |B| : $B = B_0\left[1 - \varepsilon_h \cos(N\phi - m\theta)\right]$

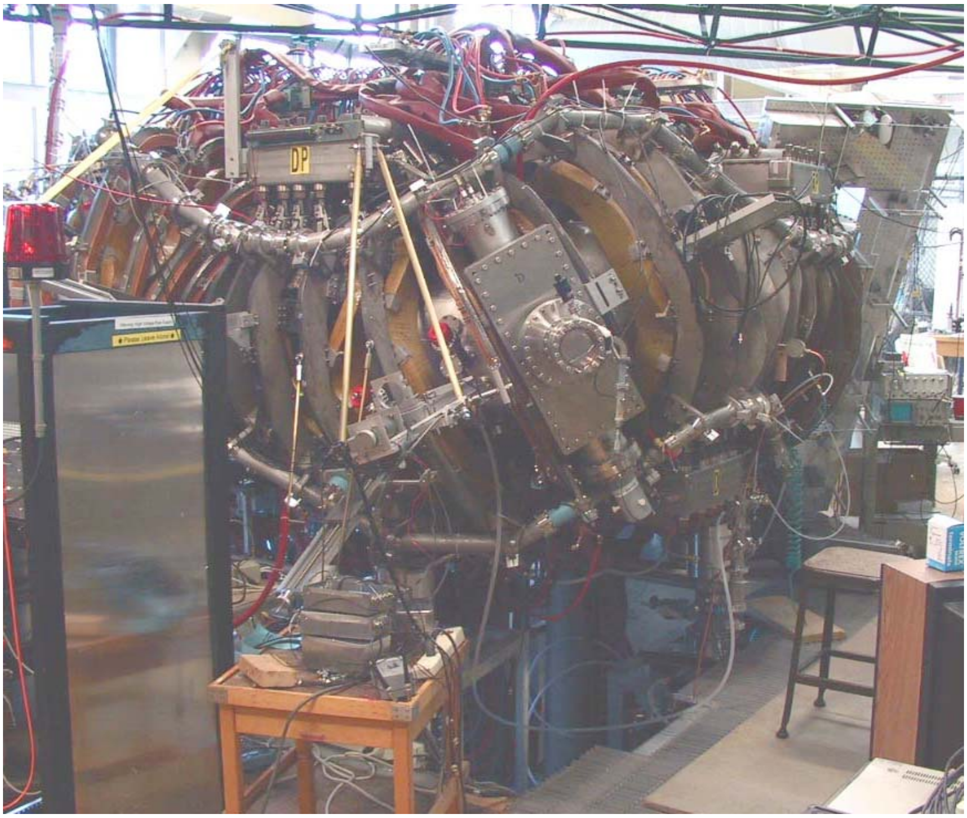
In straight line coordinates $\theta = \iota\phi$,

so that $B = B_0\left[1 - \varepsilon_h \cos(N - m\iota)\phi\right]$

In HSX: N=4, m=1, and $\iota \sim 1$

$\iota_{eff} = N - m\,\iota = 1/q_{eff} \sim 3$

The HSX Device

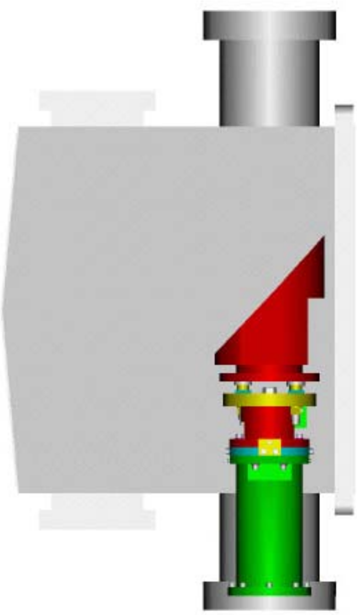


Major Radius	1.2 m
<r>	0.11 m
Volume	~.44 m^3
Field Periods	4
ι_{axis}	1.05
ι_{edge}	1.12
Coils/period	12
B_0 (max.)	1.25 T
Magnetic Field Flattop Length	0.2 s
Auxiliary Coils	48

Plasmas Produced by 28GHz ECH System.

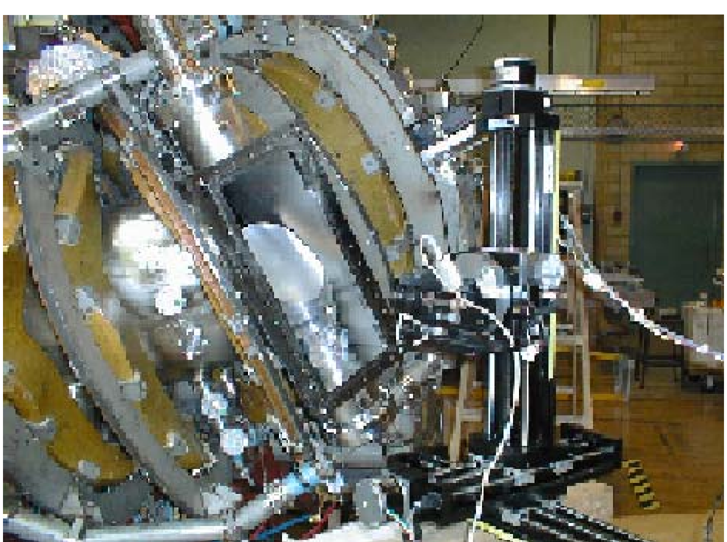
• Approximately 50 kW of power at 28 GHz in present experiments.

• Second harmonic X-mode at .5 Tesla generates a tail in the electron distribution function.



•ECH is focused to 4cm spot size using an ellipsoidal mirror.

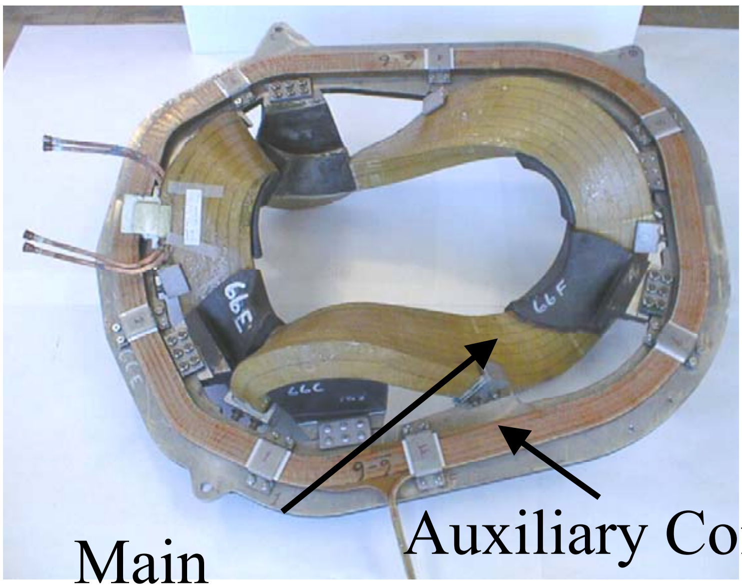
•Heating location chosen to minimize refraction.

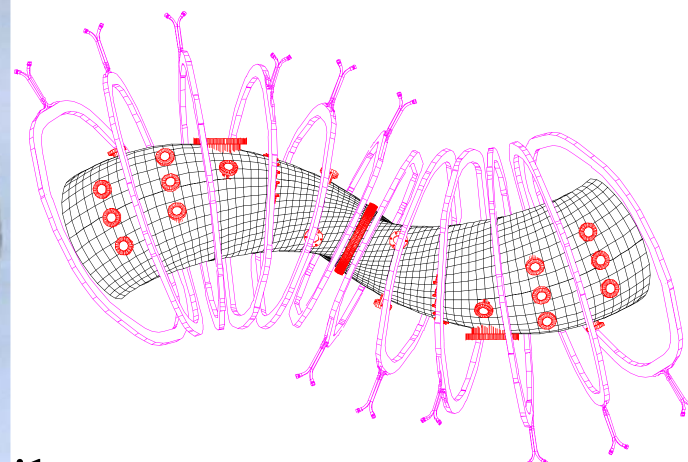


• Calculated beam waist of 4cm confirmed by measurements.

•ECH power in vessel monitored by three microwave diodes.

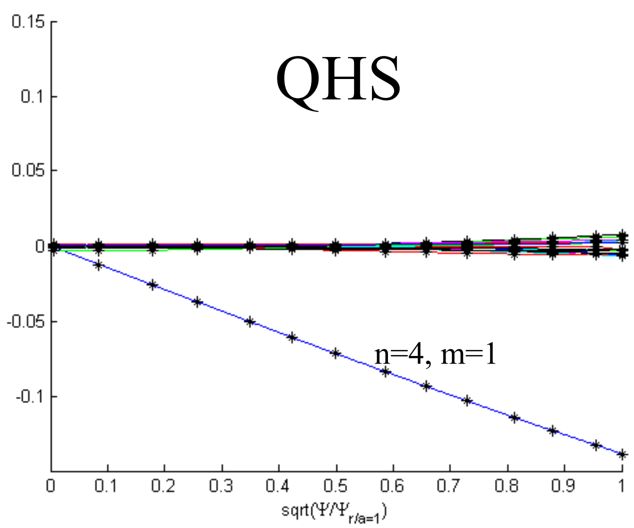
Auxilliary Coils Provide Flexibility

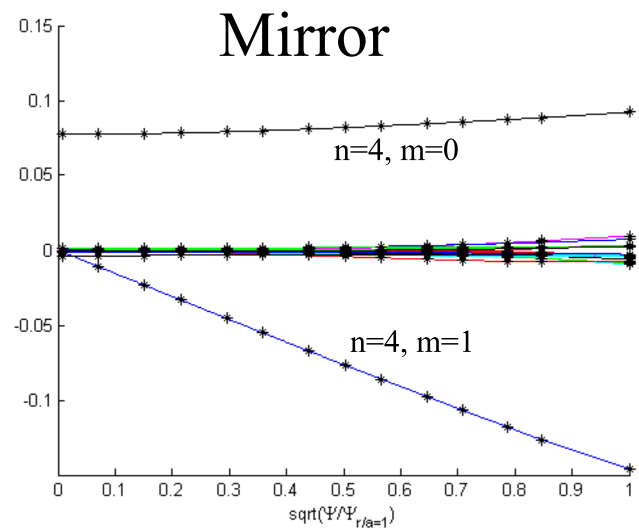




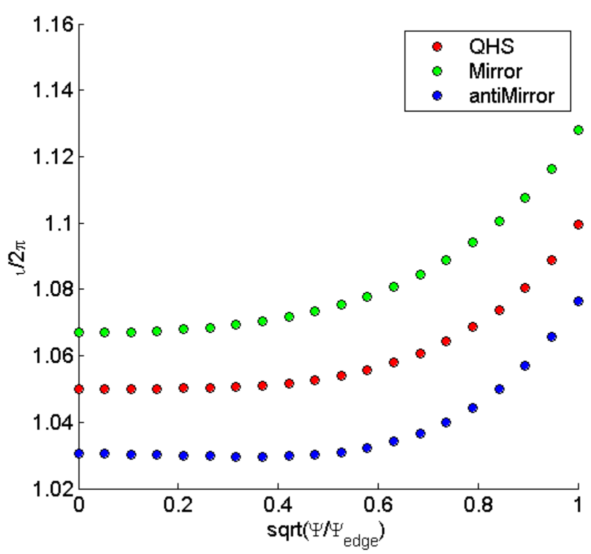
Configuration	Auxiliary Coil Currents	Dominant Feature
QHS	None	Best transport; symmetry
MIRROR	3 coils on ends add to main; center 6 opposite	Transport similar to conventional stellarator
ANTI-MIRROR	Opposite phasing to mirror;	Deep ripple on low-field side at ECH launcher
WELL	All currents opposite to main coil currents	Well depth and stability increase

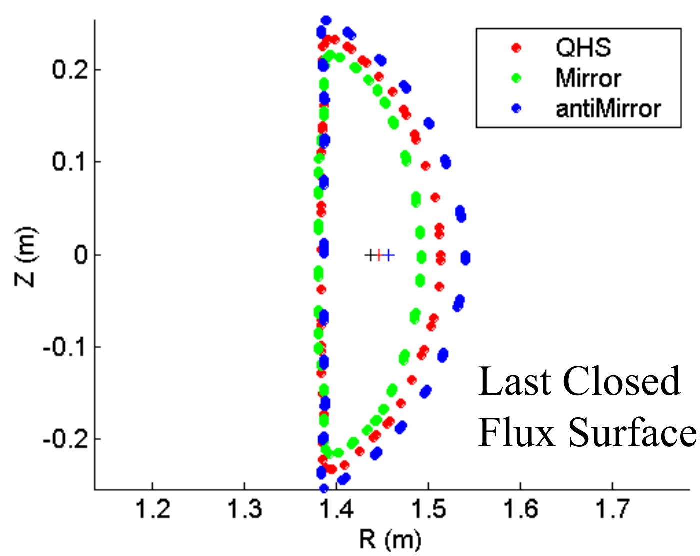
QHS and Mirror have different magnetic field spectra...





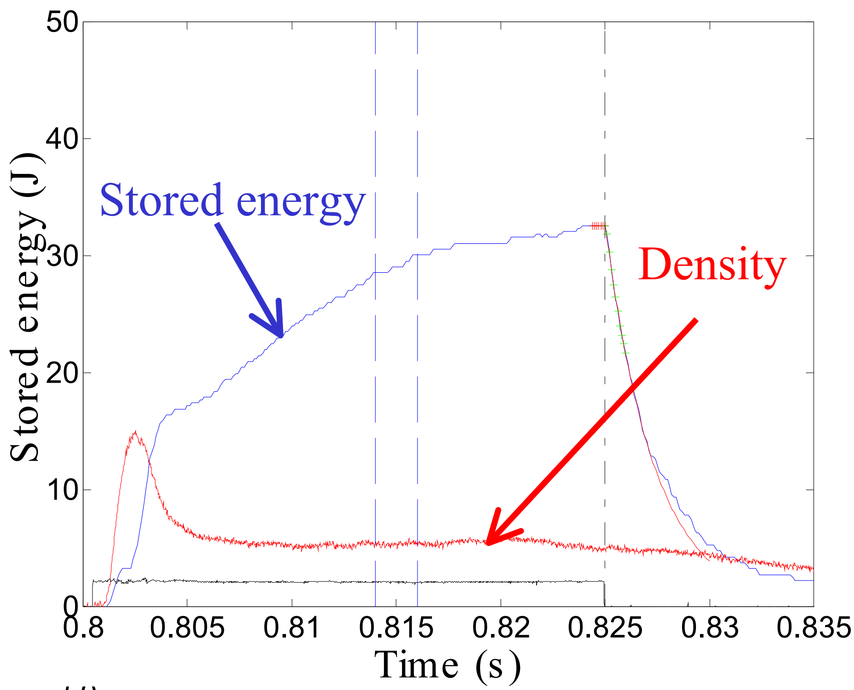
…but similar well depth, rotational transform, surface shape, and plasma volume.



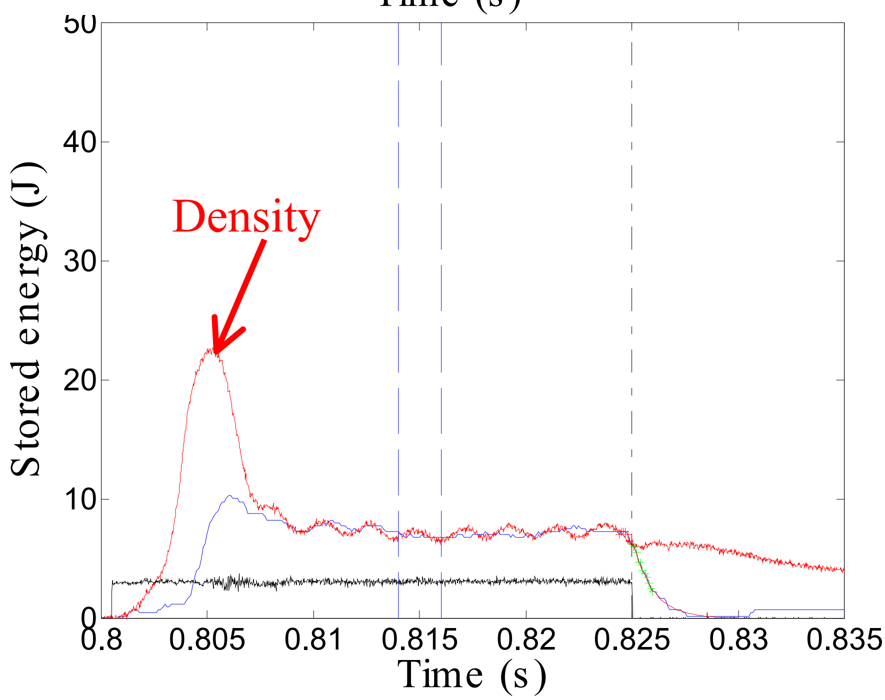


Low Density QHS has Much More Stored Energy than Mirror

QHS: Stored energy increases throughout the discharge, to >30J.

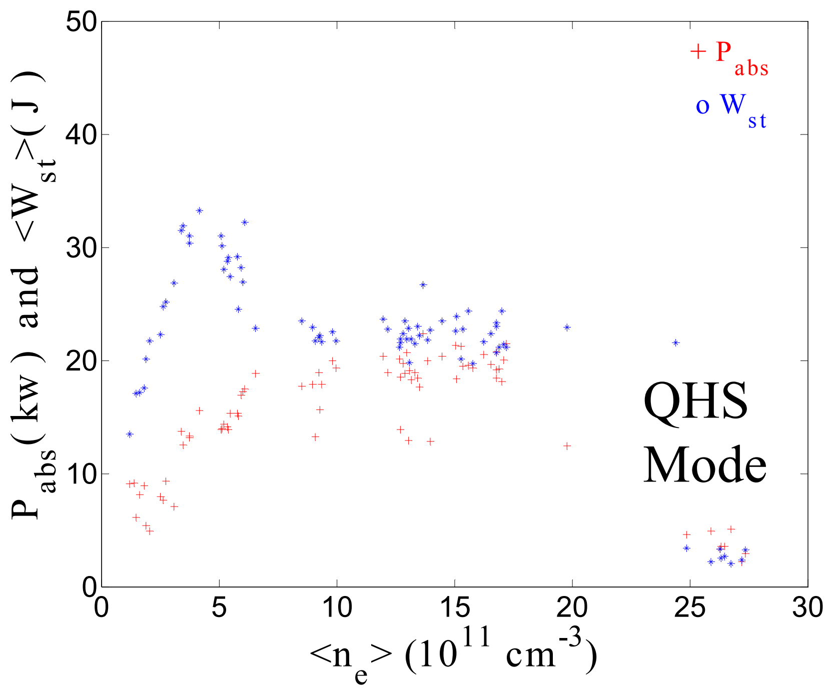


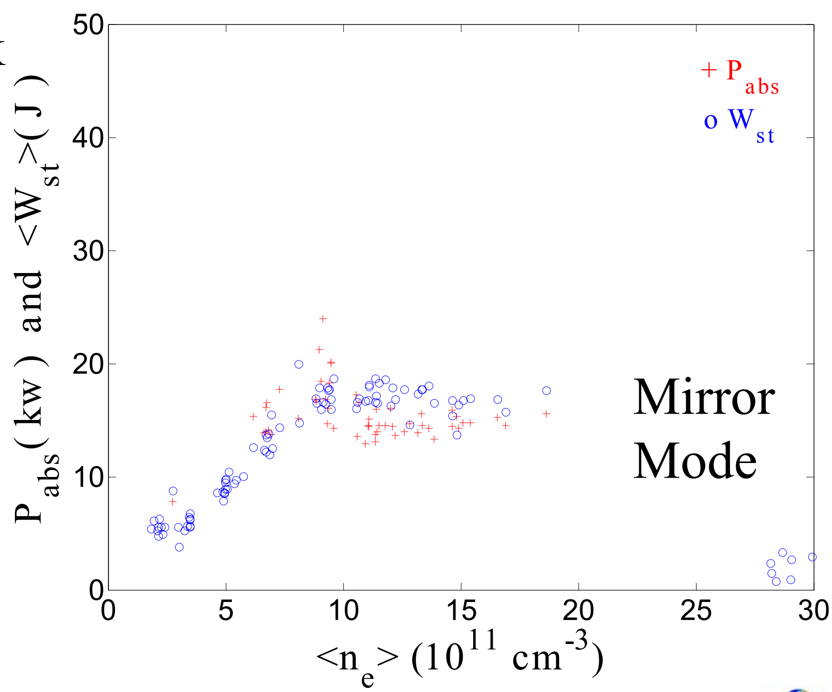
Mirror: Stored energy saturates at <10 J.



The Stored Energy is Similar at Higher Density, but Diverges at Low Density

- Shown are the Stored energy and absorbed power in the QHS and Mirror configurations.
- Absorbed Power from change in slope of diamagnetic loop at ECH pulse termination.
- Absorbed power similar between two modes at similar density.
- QHS shows a large peak at $5x10^{11}$ cm^{-3}, possibly related to the improved confinement of energetic particles.
- The two configurations are similar at higher density, but diverge at low density.

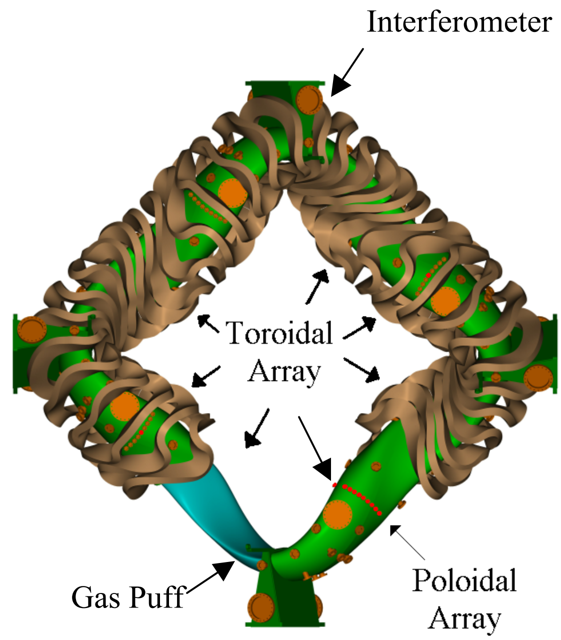


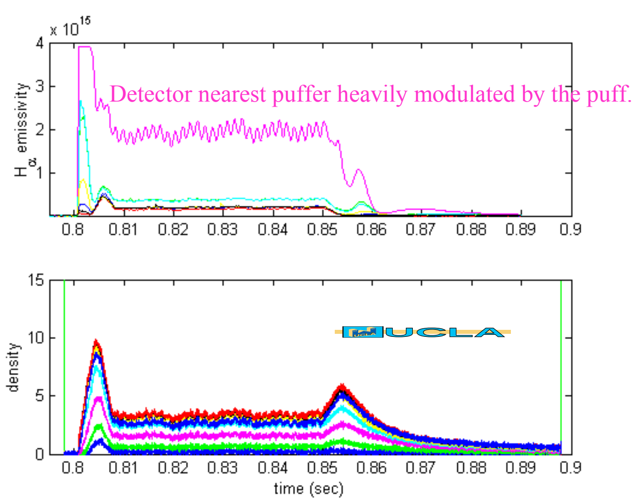


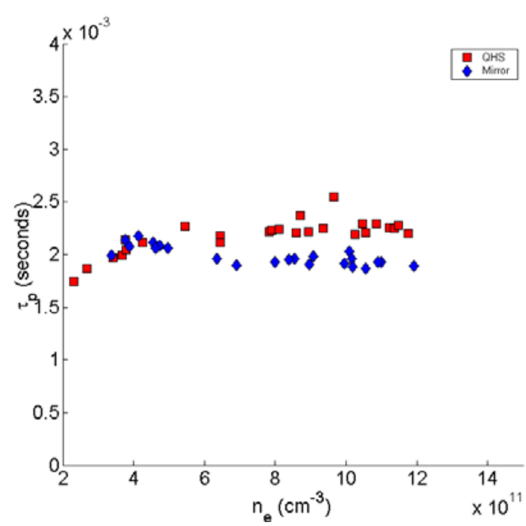
HSX

Particle Confinement Studies Yield Estimates of D and Neutral Density

- 16 absolutely calibrated H_α detectors viewing the plasma.
- Can use these signals to calculate a volume averaged ionization rate[1], which, along with the total number of electrons, can be used to estimate the average neutral density and the particle confinement time.
- Similar neutral densities and particle confinement times in QHS and Mirror configurations.







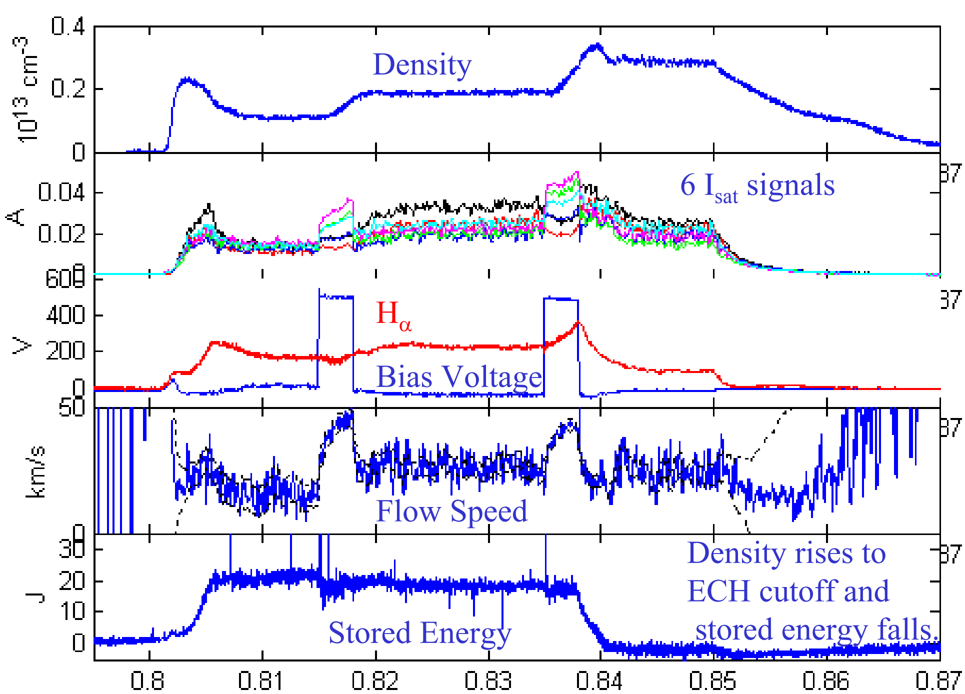
•This estimate for $\tau_p \approx 2$ msec implies D=1 m^2/s, which agrees well with estimates from perturbative transport analysis which predict D=1.4 m^2/s.

•Bulk particle confinement is similar between the configurations, but the energetic trapped particle confinement is very different.

HSX

Plasma Flows are Induced with a Biased Electrode and Measured with Mach Probes

- Biased electrode system draws up to 30 A of electron saturation current at 550 V.
- Can be switched on and off very quickly (20μs).
- Flows are measured with a 6 tip Mach probe; data analyzed using the unmagnetized model of I. Hutchinson.[2]
- Typical evolution of biased discharge shown below.



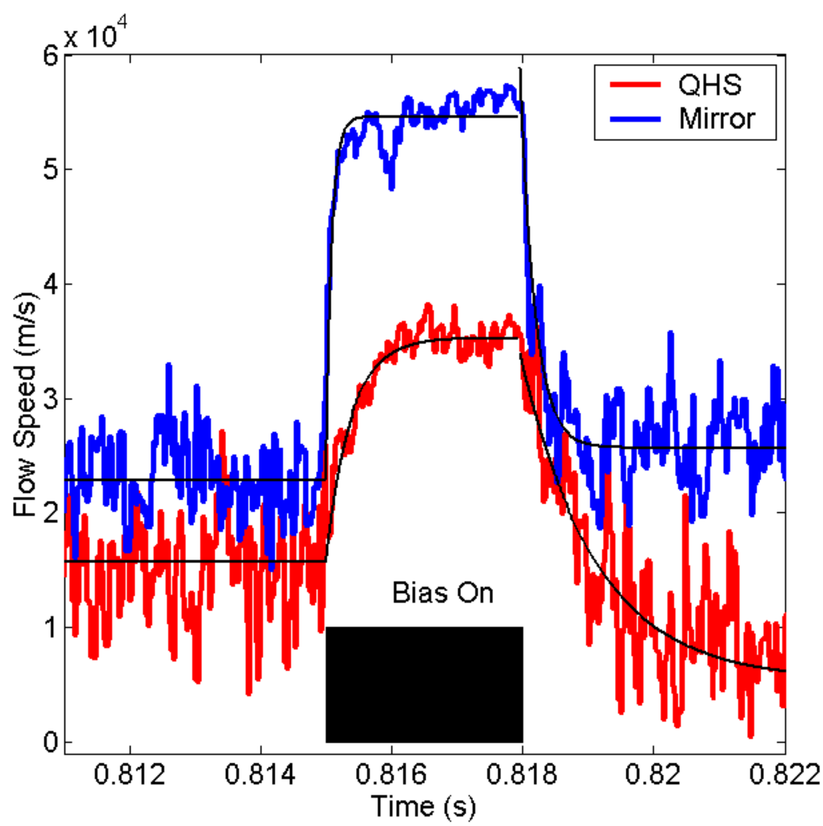
Experiments Show a Large Difference in Damping Rates Between QHS and Mirror Configurations

- Similar discharges at densities of $1x10^{12}$ cm^{-3}, QHS and Mirror configurations.
- Mach probe is approximately at r/a=.8 in both configurations.

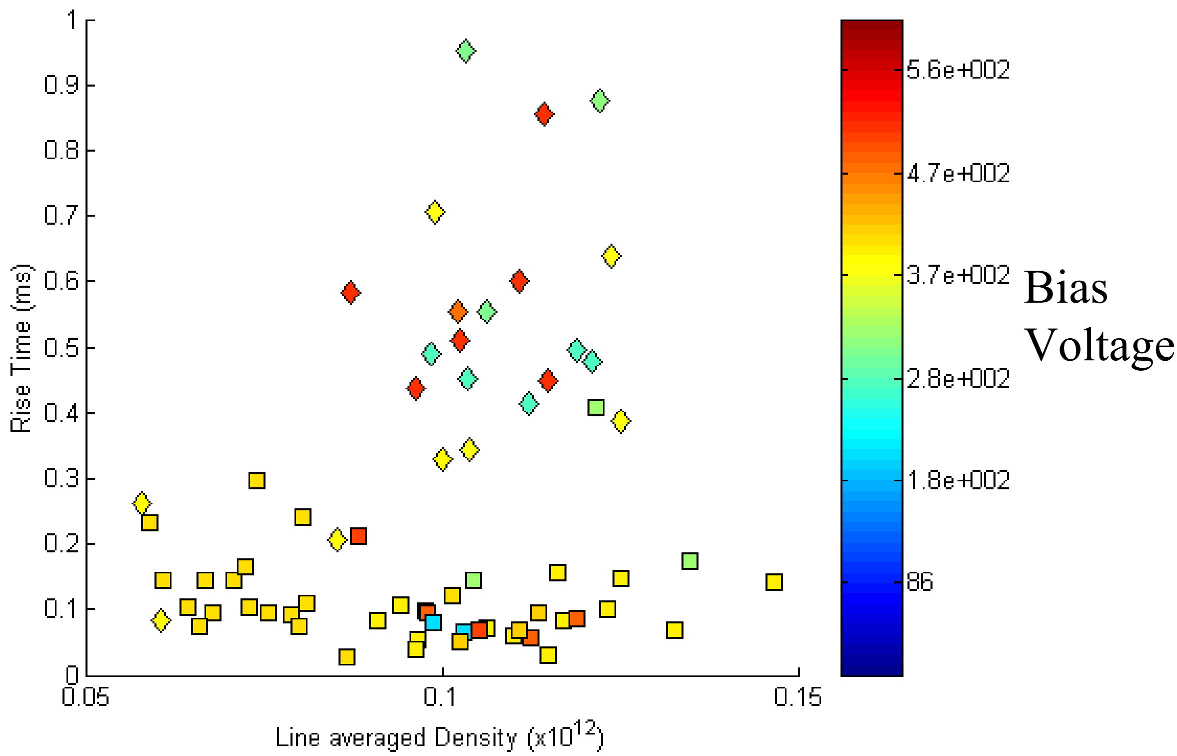
• QHS configuration biased to 275 V drawing 5.1 A, Mirror to 425 V drawing 10.5 A.

•Rise time of .4 msec in the QHS configuration.

•Rise time of .1 msec in the Mirror configuration.



The Damping Time is Longer for the QHS Configuration for All Densities and Bias Voltages



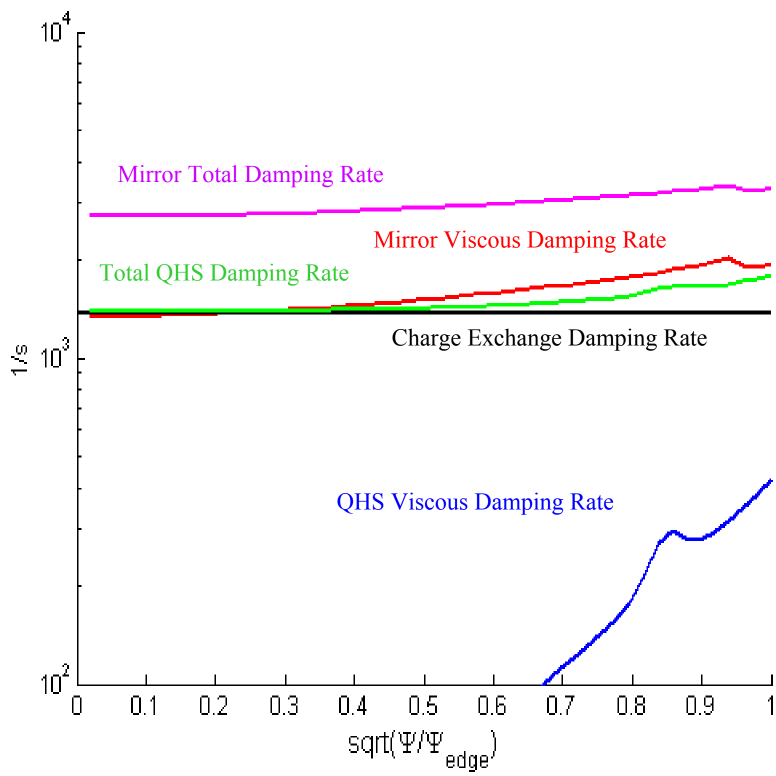
• Rise time plotted vs. density, parameterized by voltage on bias electrode.

•Scatter of about a factor of 2.

•QHS configuration always has longer damping time than Mirror configuration.

Experimental Damping Time Compares Well with Neoclassical Estimates

- Calculations done using model of Coronado and Talmadge.[3]
- Solves ion and electron continuity and momentum equations in the limit of no heat flux.
- Model includes linear parallel viscosity and charge exchange as damping mechanisms.
- Calculations done in Hamada coordinates, using the basis vectors for a large aspect ratio tokamak.[4]
- Parabolic density profile and flat ion temperature profile are used. Volume averaged neutral density as calculated earlier..

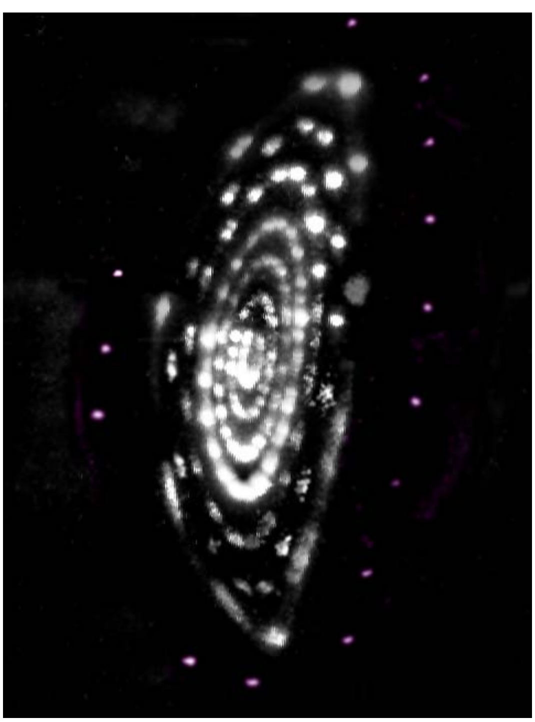


- Predicts an edge QHS damping rate of ≈2000 s^{-1}→damping time ≈.5 msec.
- The Mirror prediction is ≈3000 s^{-1}→damping time ≈.3 msec.

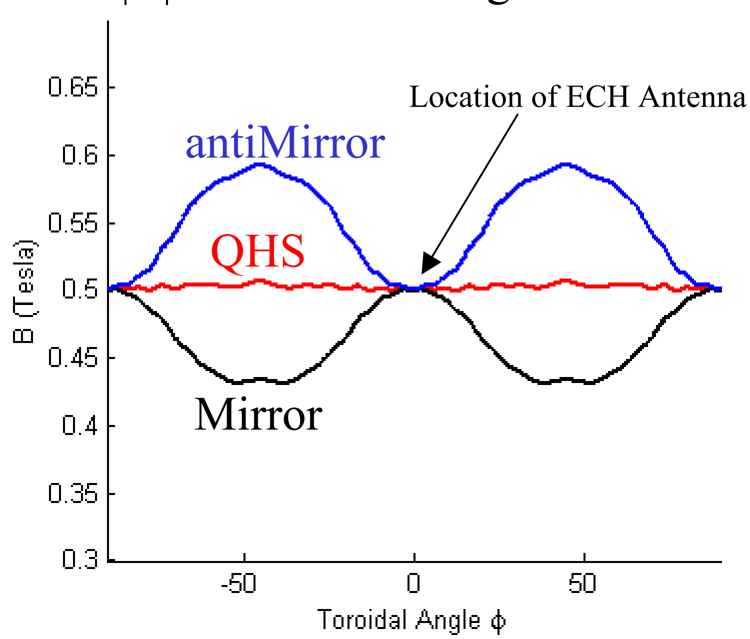
Structure of Field Ripple at ECH Antenna Important for ECH at Low Density in HSX

• Mirror configuration has maximum of n=4, m=0 spectral component at the ECH antenna.
• antiMirror configuration minimum of n=4, m=0 spectral component at the ECH antenna.
•Bottom right shows |B| along the magnetic axis with the ECH resonance on axis for the 3 configurations.
•QHS has no modulation on axis, while Mirror and antiMirror have the opposite toroidal phase.

antiMirror Surfaces



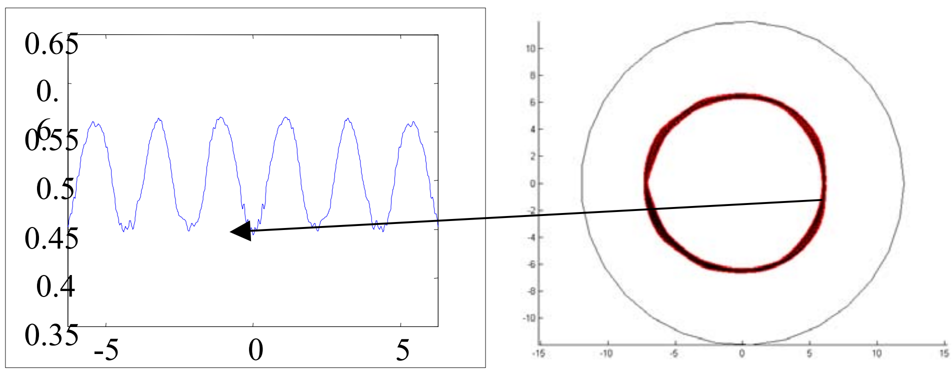
|B| vs. Toroidal Angle on Axis.



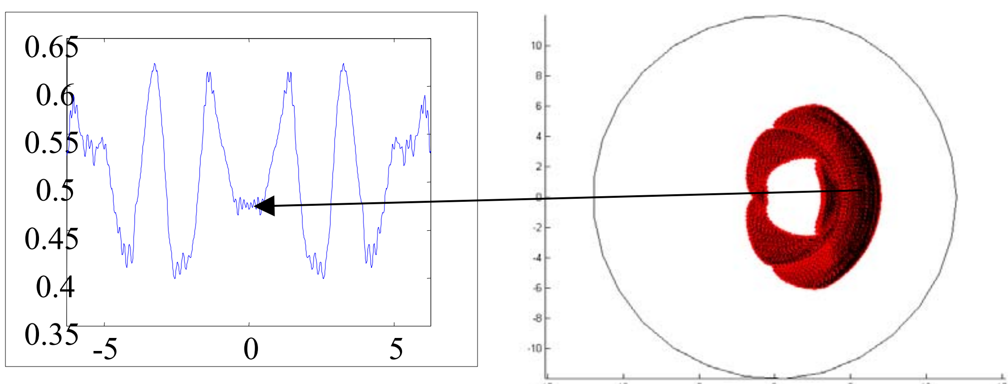
AntiMirror Particle orbits at ECH Location are the Worst of All Three Configurations

- Electron orbits computed in Boozer coordinates
- Particles have a pitch angle of 80 degrees and an energy of 20keV, launched on <u>outboard</u> side of torus.

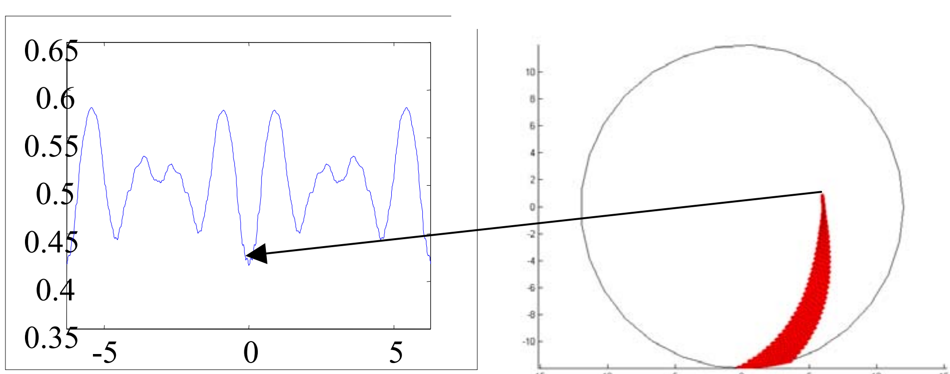
QHS: Bannanna orbit never deviates far from it's birth surface.



Mirror: Trapped particle has large drift off of it's birth surface.

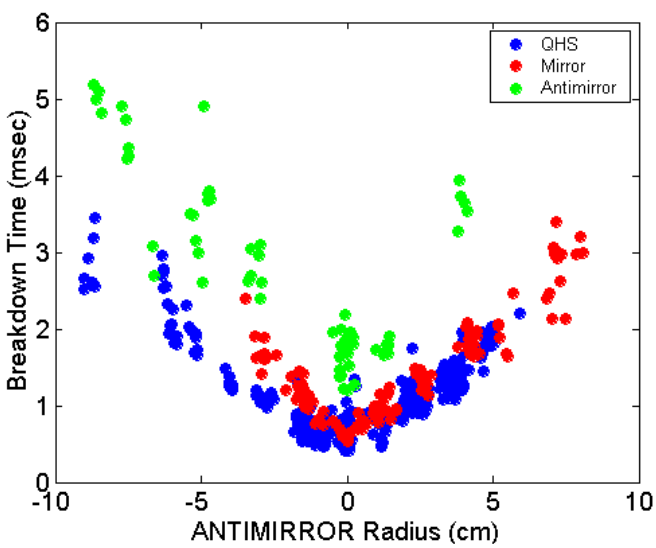


antiMirror: Particle leaves the confinement region without collisions.

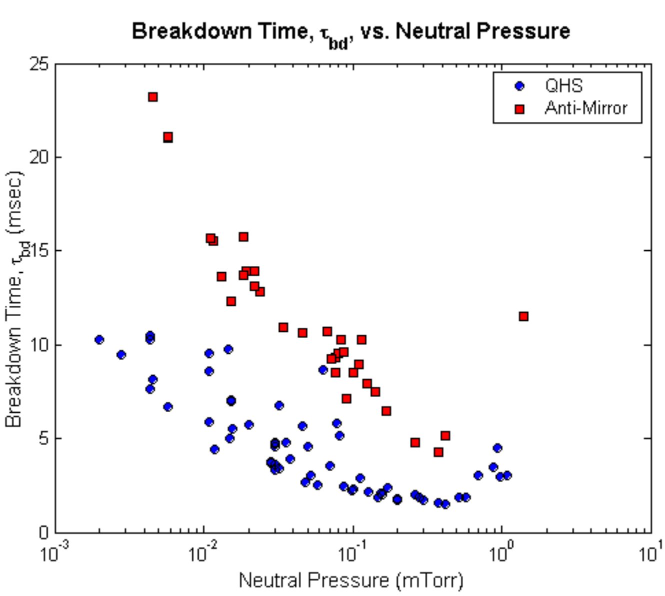


Studies of the Breakdown Time Show Difference Between QHS and antiMirror

• HSX filled with constant bleed of hydrogen gas.
• Time difference between ECH turn on and measurable density studied as a function of resonance location and fill pressure.



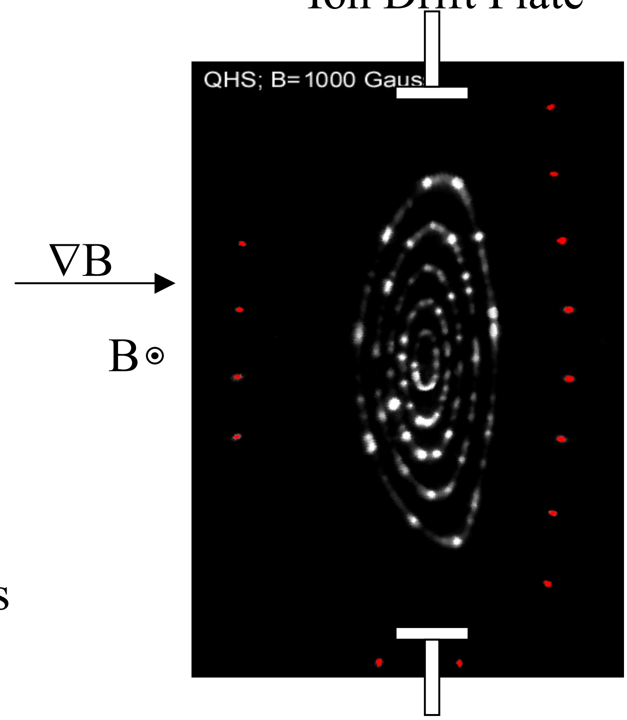
•Breakdown time measured versus location of ECH resonance layer.
•Minimum of breakdown time centered on the magnetic axis for all configurations.
•QHS and Mirror have comparable breakdown times, with antiMirror much longer.

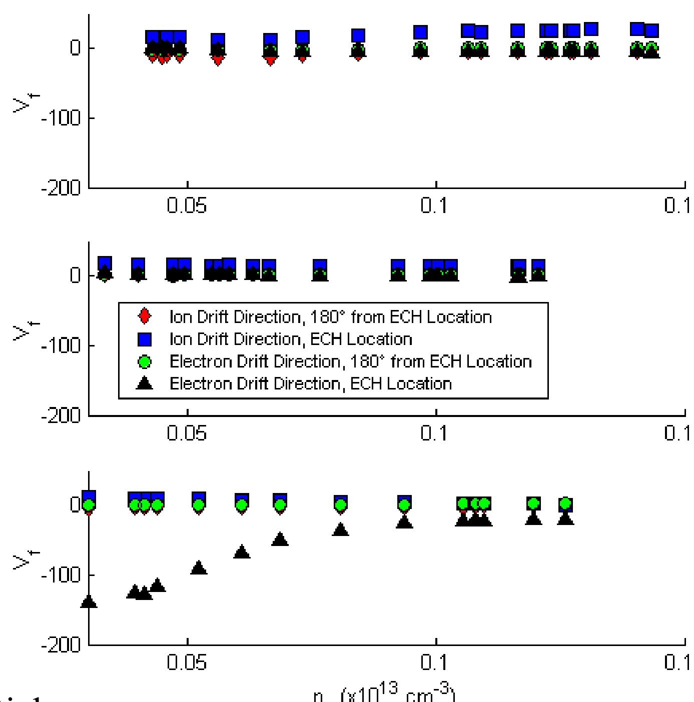


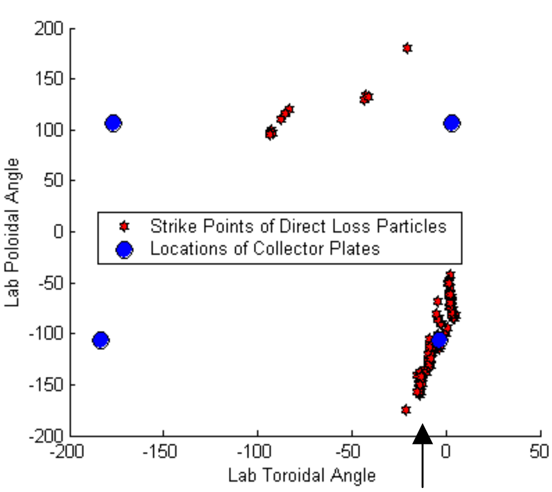
•Breakdown time measured versus fill pressure for the QHS and antiMirror configurations, with the ECH resonance on axis.
•QHS breaks down faster for all pressures.
•Upper limit of pressure set by arcing at gyrotron window.
•Both of these results imply better confinement of the initial breakdown electrons in the QHS configuration.[5]

Collector Plates Detect Direct Loss Orbits

- Two edge collector plates at ECH antenna location, one in electron drift direction and one in ion drift direction.
- Two more plates in similar poloidal location, but 180 degrees around the torus.
- In antiMirror configuration, the plate in the electron drift direction goes very negative as the density is lowered.
- In QHS configuration, all plates have similar voltage, independent of density.
- Deeply trapped particle orbits computed in the antiMirror configuration till the particles strike the wall.

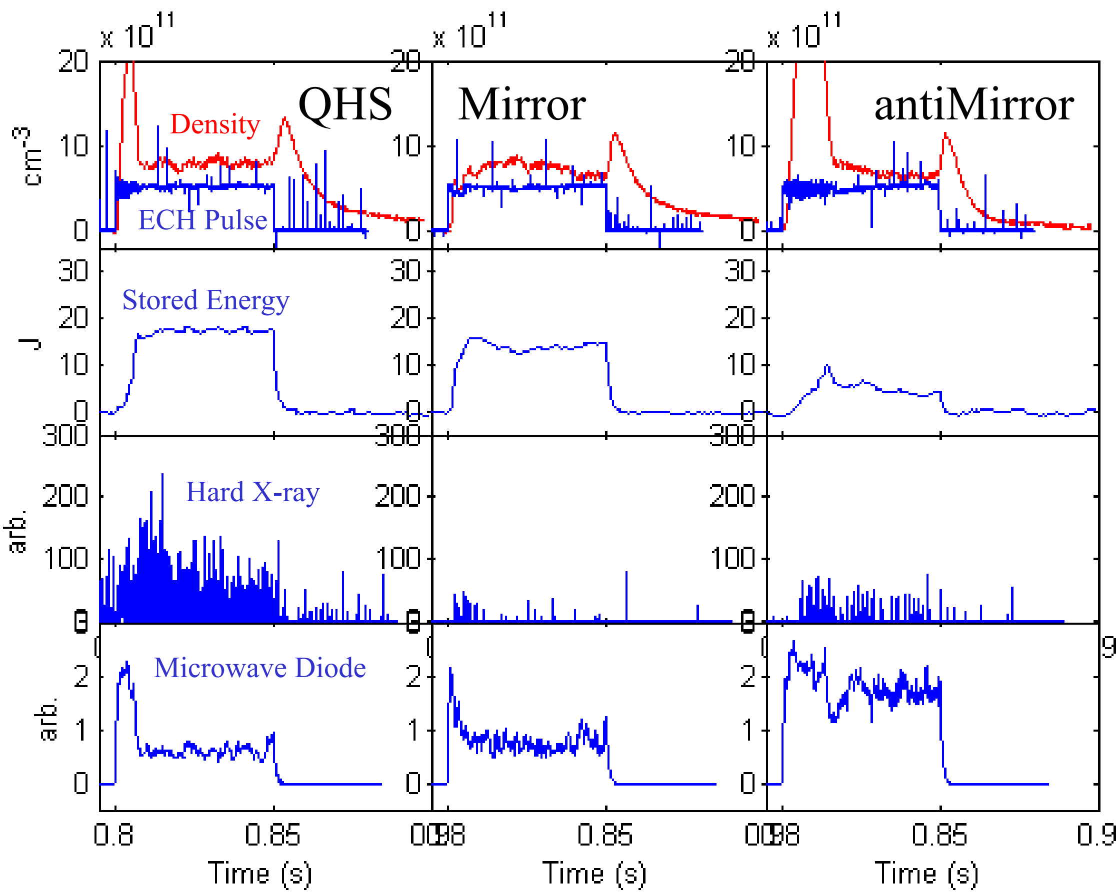






Collector plate coincides trapped particles.

Significant Differences in Confinement Between the Three Different Configurations.



As a general trend, going from QHS to Mirror to antiMirror

1. Stored energy decreases.
2. Hard X-ray flux drops.
3. Absorption of the ECH decreases.
4. Signal to electron drift plate increases.

Conclusions

- Low density plasmas in the QHS configuration of HSX have higher stored energy, better ECH absorption, and better confinement of trapped particles.
- The hard X-ray flux is higher in the QHS configuration and persists longer after the discharge.
- Damping of plasma flows is reduced in the QHS configuration.

References

[1] JOHNSON, L.C., HINNOV, E., J. Quant. Spectrosc. Radiat. Transfer **13**, 133 (1973)
[2] HUTCHINSON, I.H., Plasma Phys. Control. Fusion **44**, 1953 (2002).
[3] CORONADO, M., TALMADGE, J.N., Phys. Fluids B **5**, 1200 (1993).
[4] CORONADO, M., GALINDO TREJO , J., Phys. Fluids B **2**, 530 (1990)
[5] CARTER, M.D., BATCHELOR, D.B., ENGLAND, A.C., Nuclear Fusion **27**, 985 (1987).