Effects of Symmetry-Breaking on Plasma Formation and Stored Energy in HSX

Presented by D.T. Anderson

for the HSX Team

University of Wisconsin-Madison

2001 APS-DPP Annual Meeting, Long Beach CA

Outline

Principles of Quasi-helical Symmetry

The HSX Device and Goals

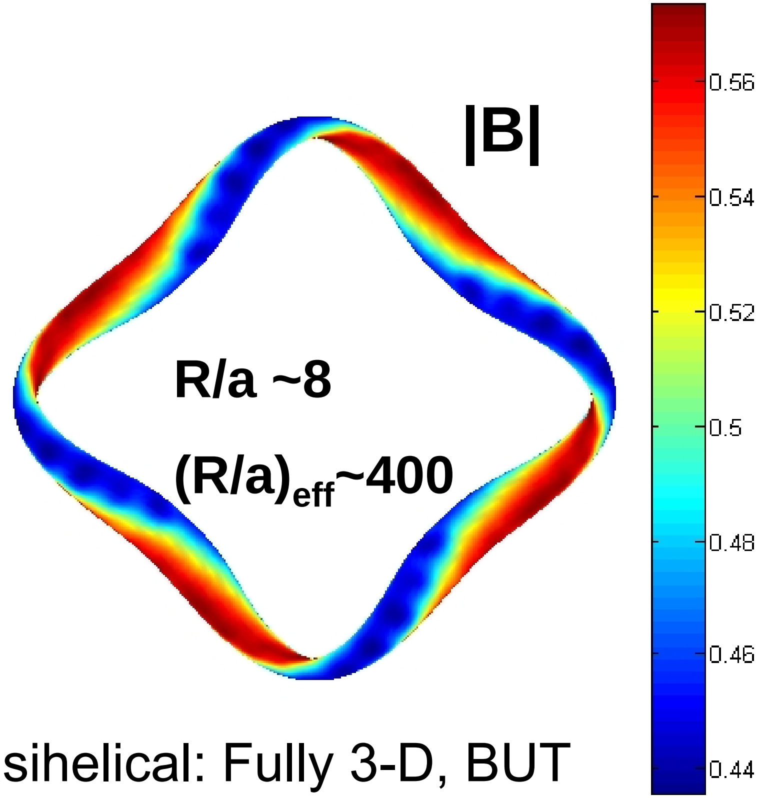
2^{nd} Harmonic ECH Breakdown

Effects of Magnetic Field Spectrum on Stored Energy

Plasma Rotation with Electrode Biasing

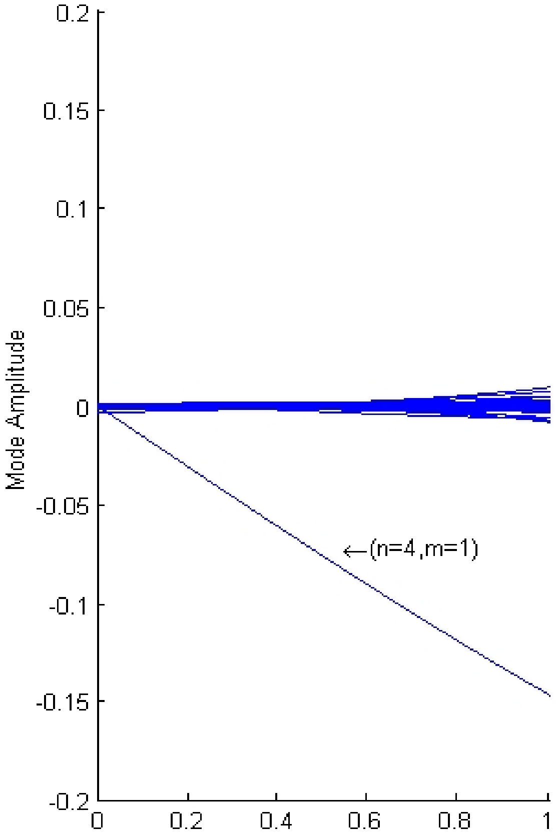
Posters on HSX website http://hsxa.ece.wisc.edu

The Helically Symmetric Experiment



R/a ~8

$(R/a)_{eff}$~400



Quasihelical: Fully 3-D, BUT

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

In straight line coordinates $\theta = \iota\phi$, so that $B = B_0\left[1-\varepsilon_h \cos\left(N - m\iota\right)\phi\right]$

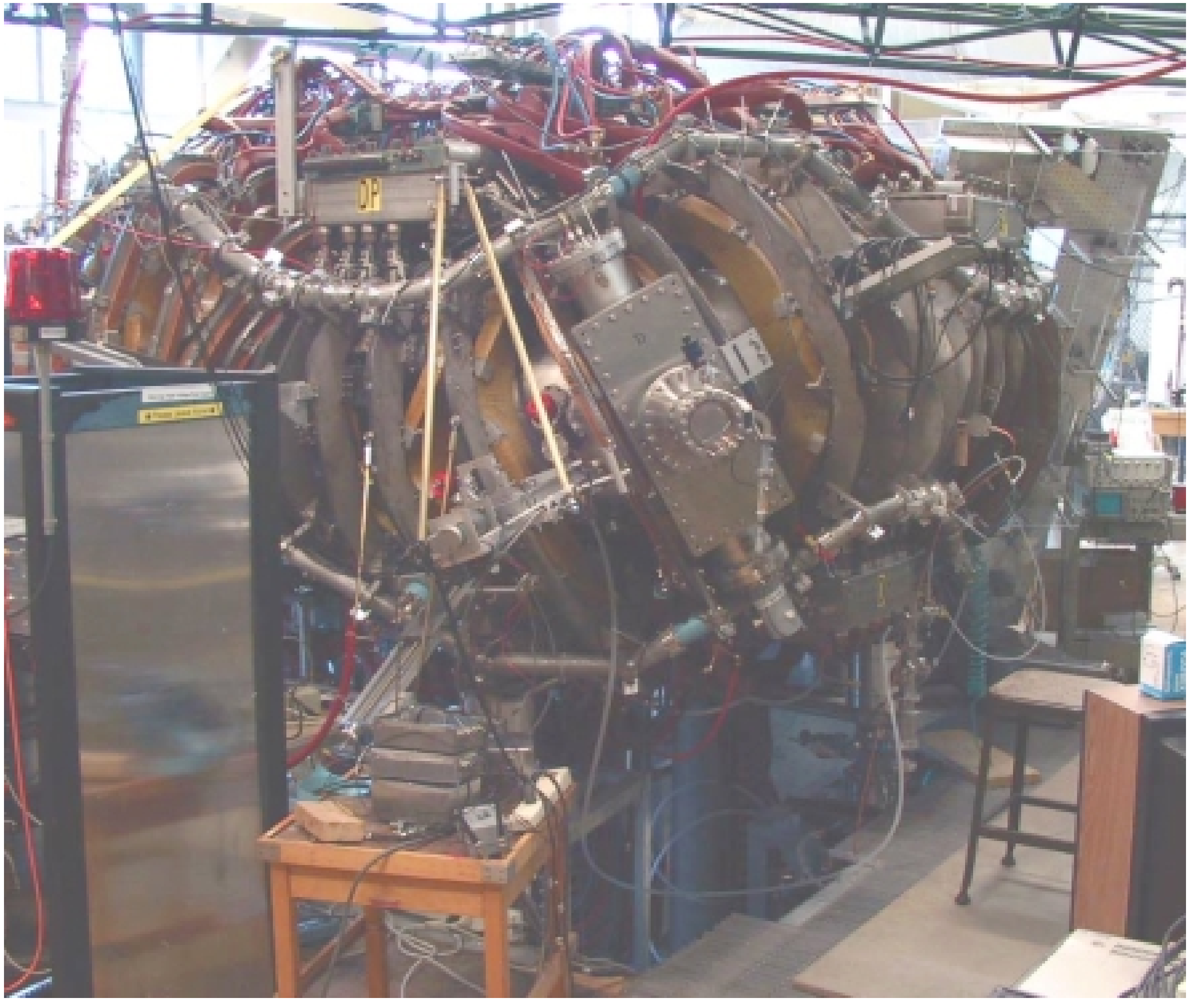
In HSX: N=4, m=1, and $\iota \sim 1$

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

High Effective Transform and Quasi-helical Symmetry Lead to Unique Properties

- **Low neoclassical transport**
  - **Small deviations from magnetic surfaces, small banana widths**
  - **Minimal direct loss particles, reduction in '1/ν' tansport, very small neoclassical thermal conductivity**
- **Plasma currents are small**
  - **Small Pfirsch-Schluter and bootstrap currents**
  - **Robust magnetic surfaces, high β_{eq} limit**
- **Low parallel viscosity in the direction of symmetry**
  - **Possibility of high E x B shear to reduce turbulence**
- **Lower anomalous transport (?)**
  - **L-2 experimental results $\chi_{e,anom} \sim 1/\iota$**

The HSX Device

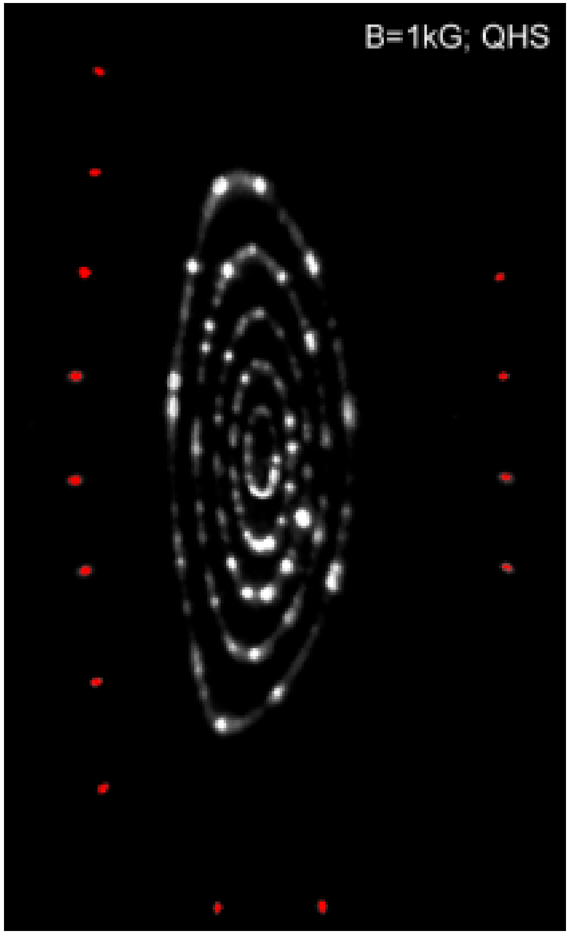


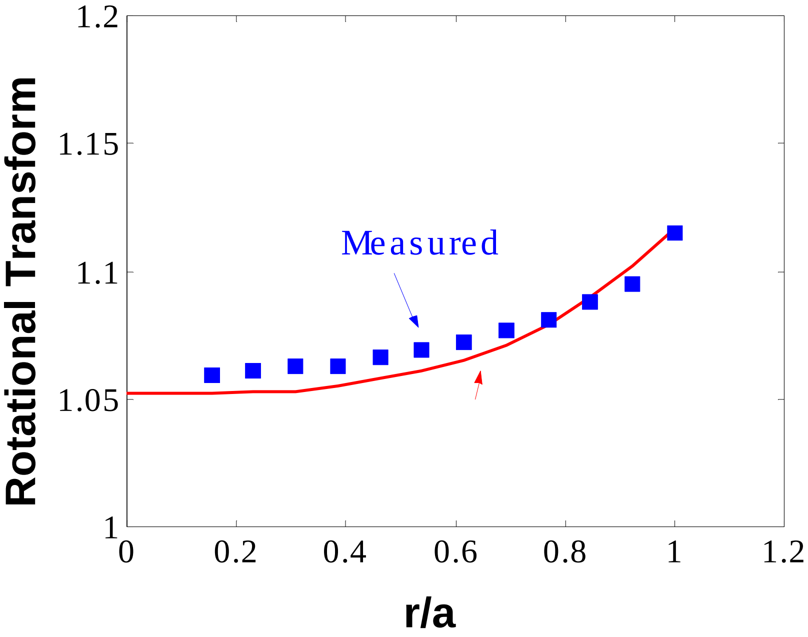
Major Radius	1.2 m
<r>	0.15 m
Volume	~.44 m^3
Field periods	4
ι_{axis}	1.05
ι_{edge}	1.12
Coils/period	12
B_0 (max.)	1.25 T
Pulse length	0.2 s
Auxiliary Coils	48

ECH heating at 28 GHz to investigate low collisionality electron transport

Experiments to date utilize 2nd harmonic heating at B=0.5 T to generate hot trapped electron population

Designed Magnetic Structure Confirmed Experimentally





Low energy electron beams and fluorescent mesh used to map the magnetic surfaces

- **Well-formed nested magnetic surfaces observed**
- **Rotational transform within 1% of design value**

Passing Particle Orbits Contain Information about $m \neq 0$ Spectral Components of B

High energy passing electron orbits, measured at several toroidal angles, mapped into Boozer space using neural network

➡ **Shifts from flux surface related to spectrum**

$$r^2 = r_0^2 + \frac{2Mv_\parallel g}{eB_0^2} \sum b_{nm} \frac{m}{n - m\iota} [\cos(n\phi - m\theta) - \alpha_{nm}]$$

Method ideal for measurement of nearly resonant spectral components which cause large deviation of orbit from flux surface.

Details can be found in Physics of Plasmas (Dec., 2001)

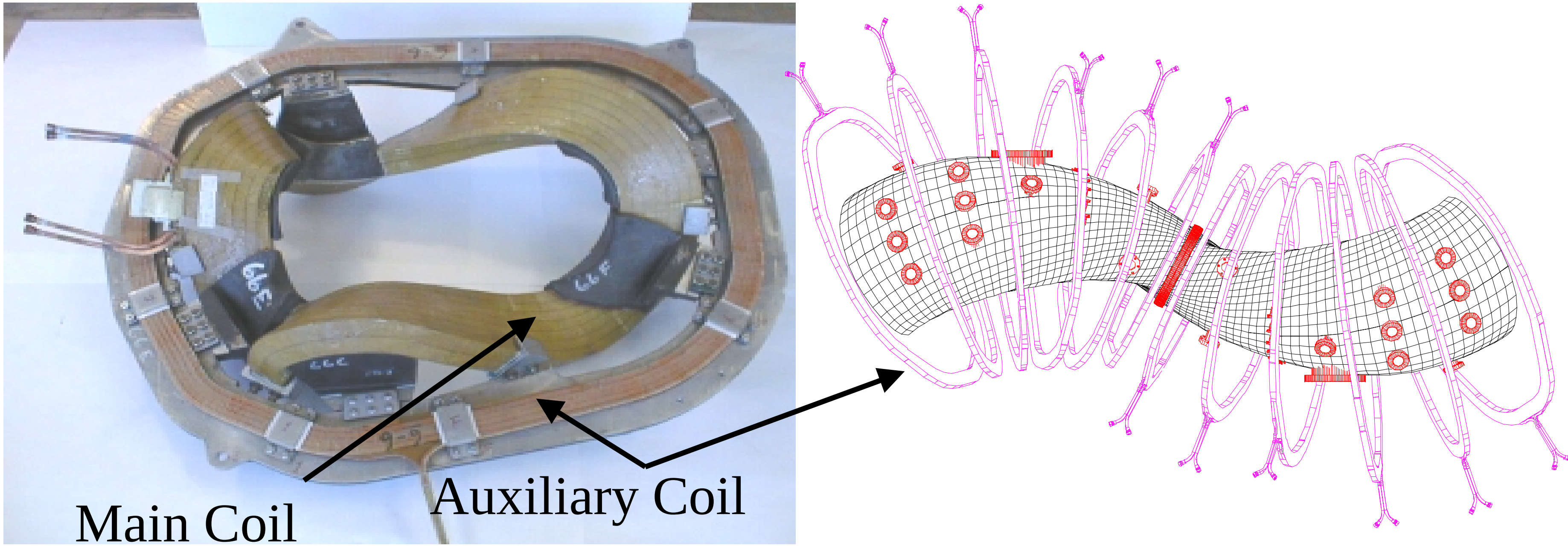
Results in HSX confirm that:

Toroidal curvature is very small

Very large effective transform results in small excursions of passing particles from flux surface

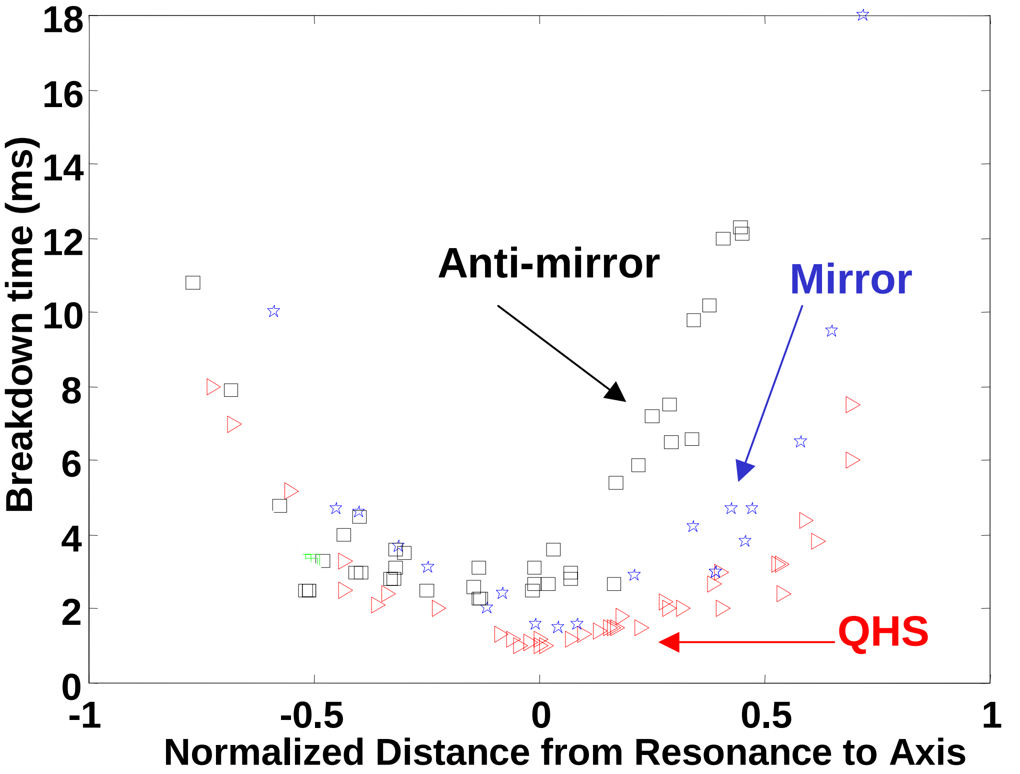
Mapping and Drift Orbit Studies Confirm the Designed HSX/QHS Structure Has Been Achieved

Auxiliary Coils Provide Flexibility for HSX



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; same global transport**	**Deep ripple on low-field side at ECH launcher**
WELL	**All currents opposite to main coil currents**	**Well depth and stability increase**

The Breakdown Time is a Function of Spectrum and Resonance Location

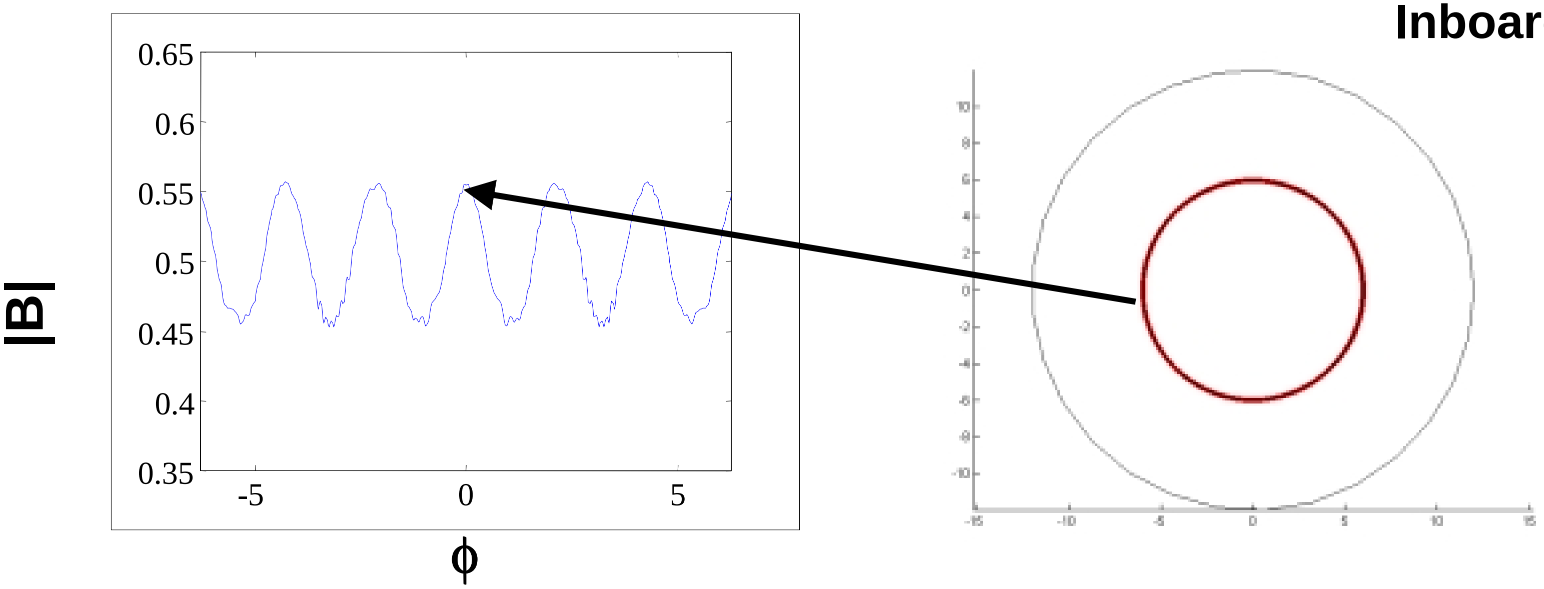


- 2^{nd} Harmonic ECH (B=0.5T)
- P_{RF} = 50 kW
- Constant puff (1 x 10^{-6} torr)
- Breakdown time defined as time to $\langle n_e \rangle = 2 \times 10^{11}$ cm^{-3}

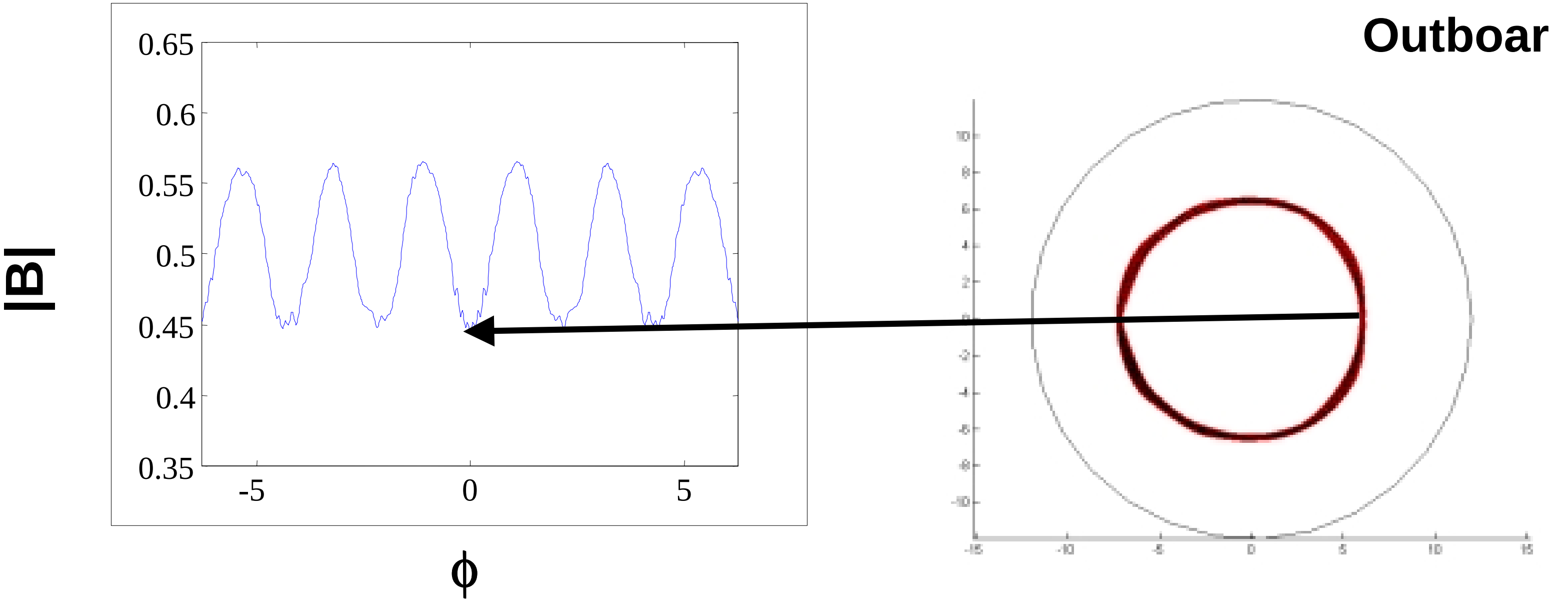
- **QHS** symmetric about on-axis heating
- Increased τ_b for **mirror** on outboard side; longer for **anti-mirror**

Particle Orbits at ECH Launch (ϕ=0): QHS

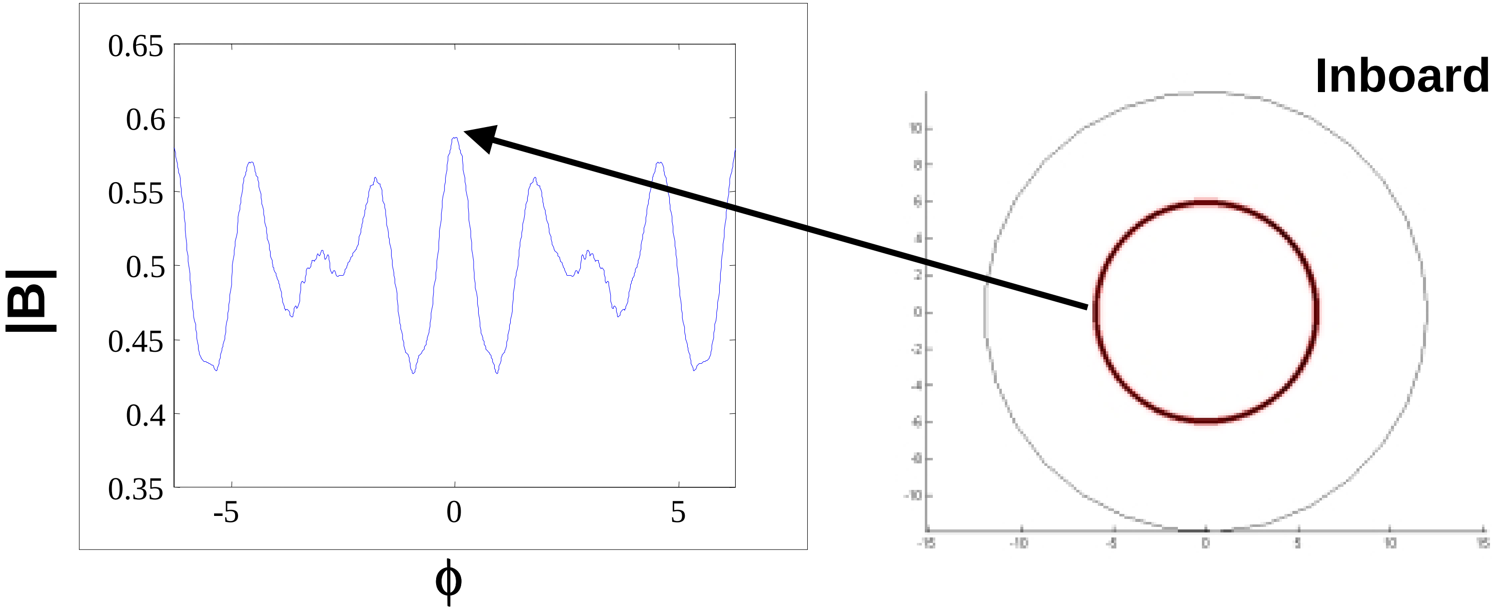
Inboard launch



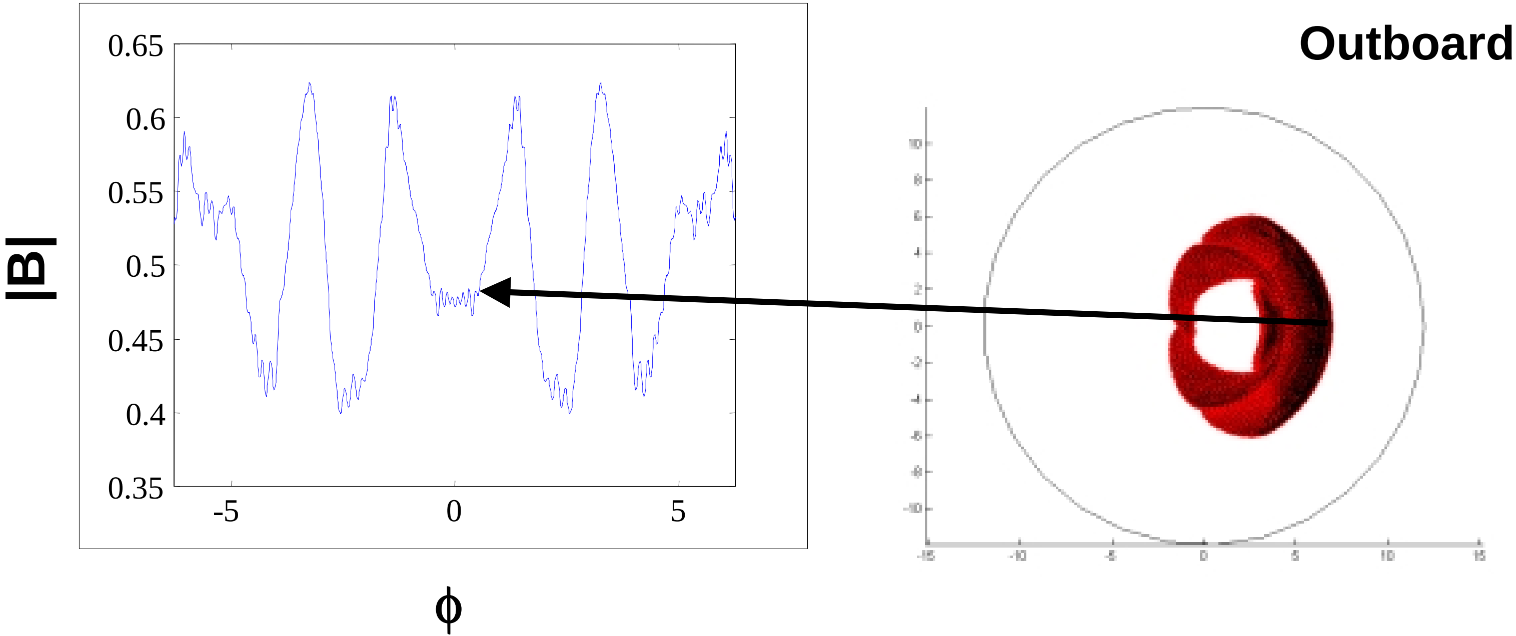
Outboard launch



Particle Orbits at ECH Launch (ϕ=0) : Mirror Mode

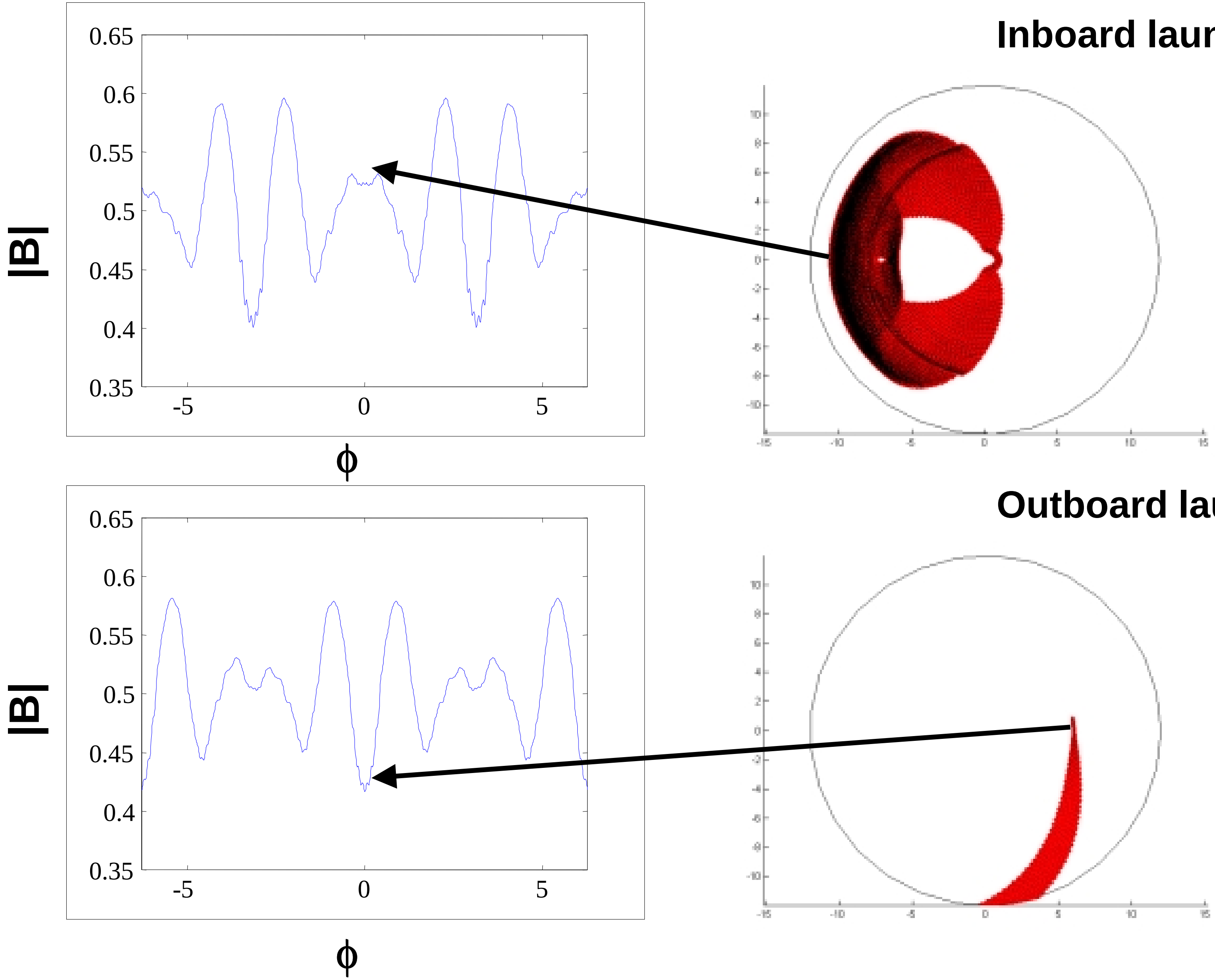


Inboard launch

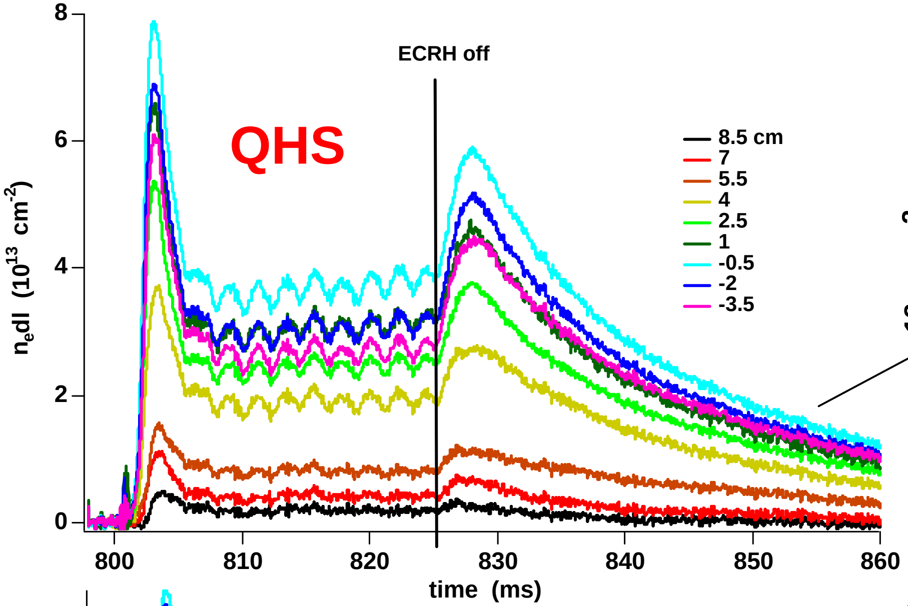


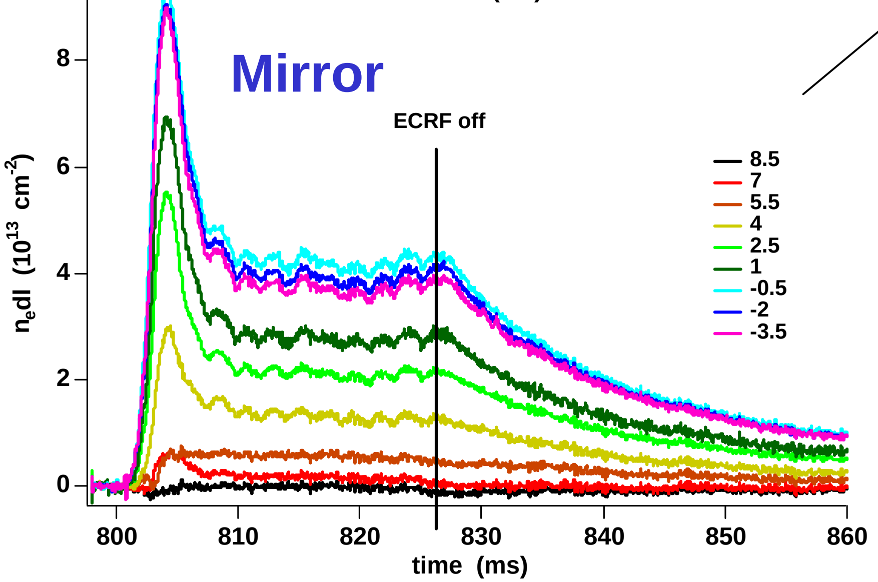
Outboard launch

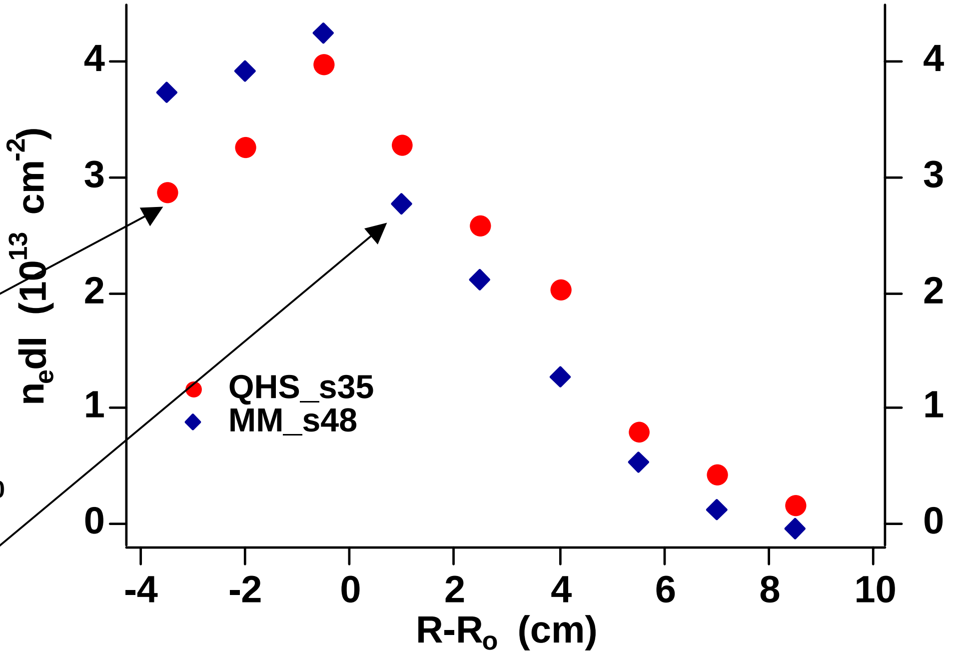
Particle Orbits at ECH Launch (ϕ=0) : Anti-Mirror



Line-Density Signals and Profiles for QHS and Mirror-Mode Plasmas; Central Heating



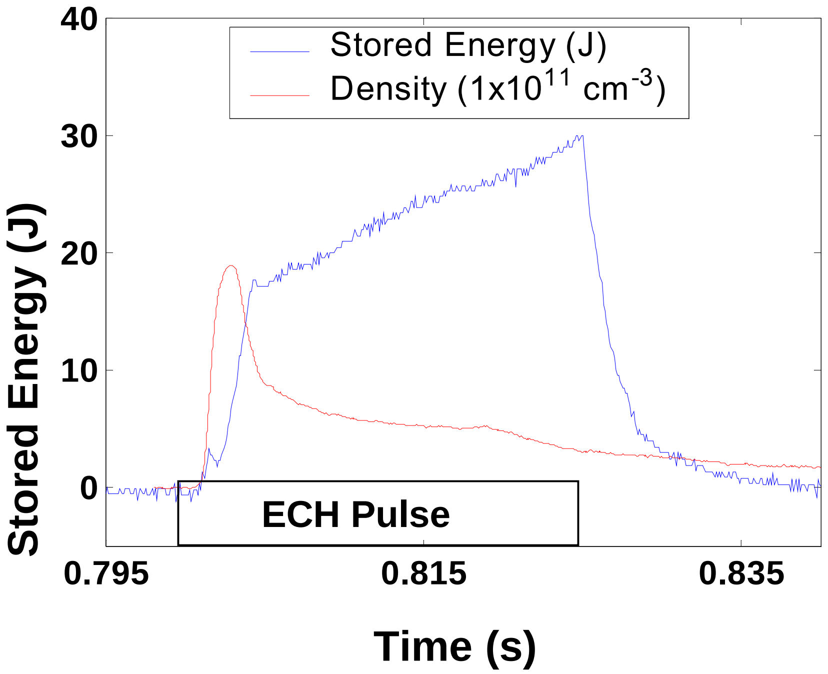




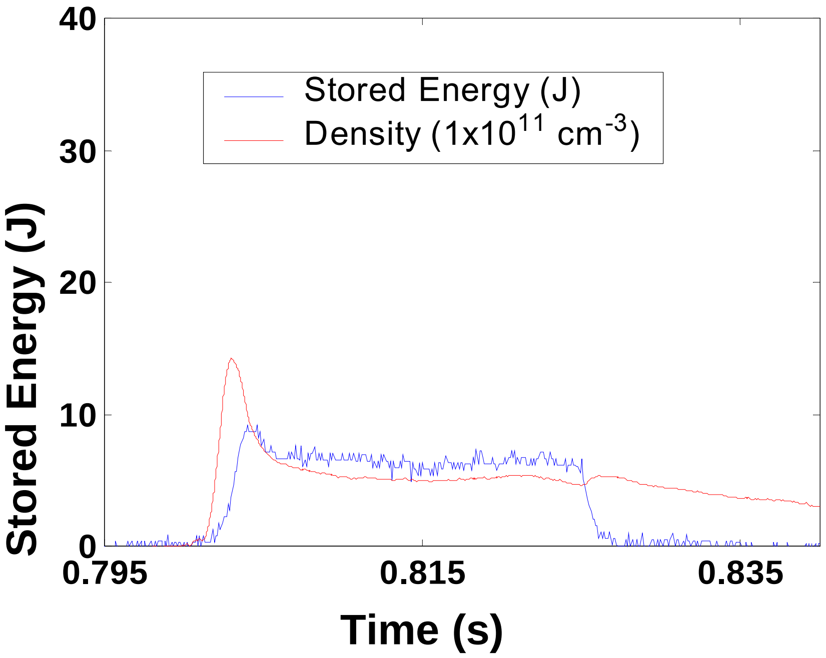
- QHS has density rise for ~5 ms after ECH turn-off
- Density decay comparable after initial rise (cold afterglow)
- Line-density profiles insensitive to heating location

Higher Stored Energies Can be Achieved in the QHS Mode of Operation

QHS

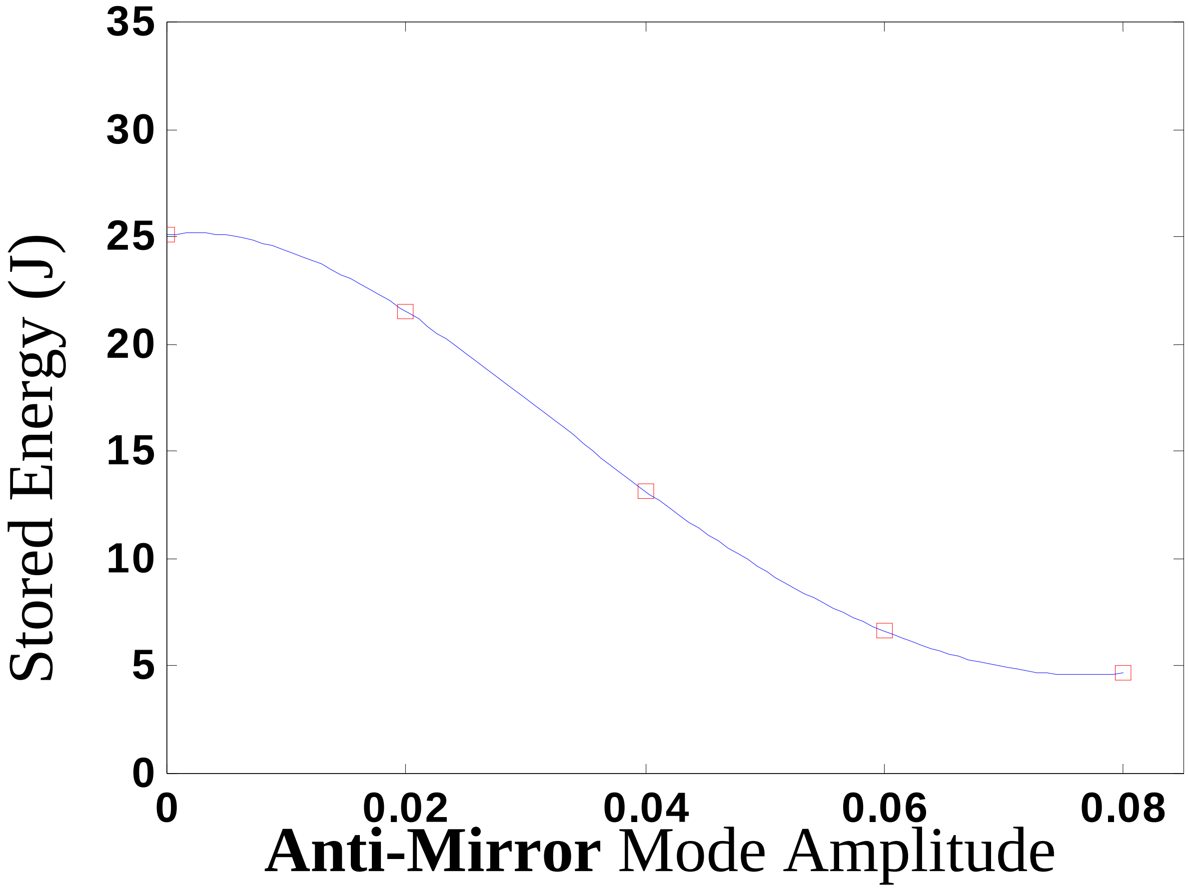


Mirror Mode



- With similar densities, large variations are observed in the stored energies measured by a diamagnetic loop
  - Variations with magnetic field spectrum, resonance location, and line-averaged density

Clear Reduction in Stored Energy at Constant Density and P_{RF} as Anti-Mirror Term is Increased



All data for scans taken with P_{RF}=50kW input

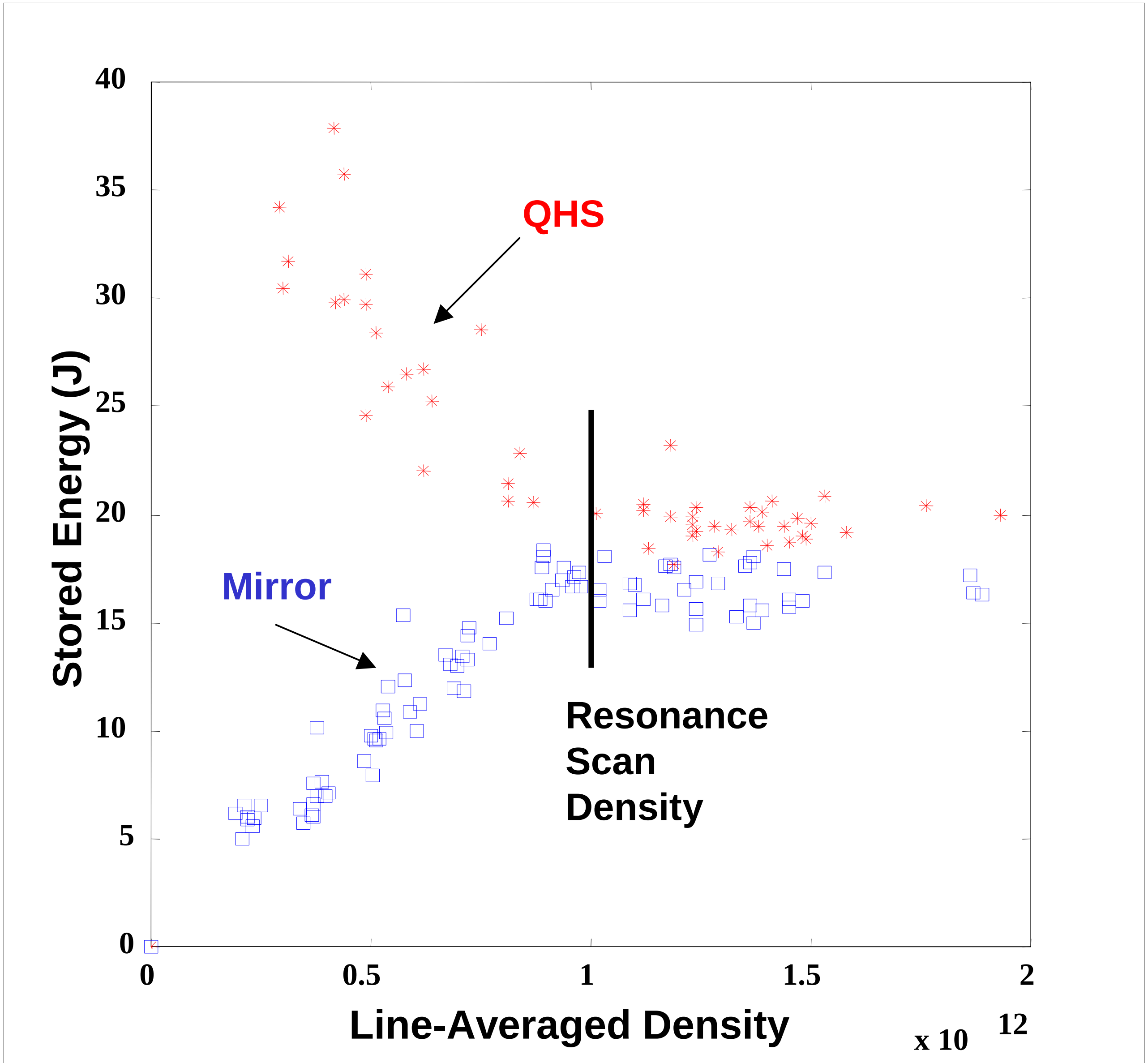
Gas programmed to maintain $<n_e>$ constant

Low stored energy observed uniformly for anti-mirror mode

Subsequent data presented for QHS/Mirror modes

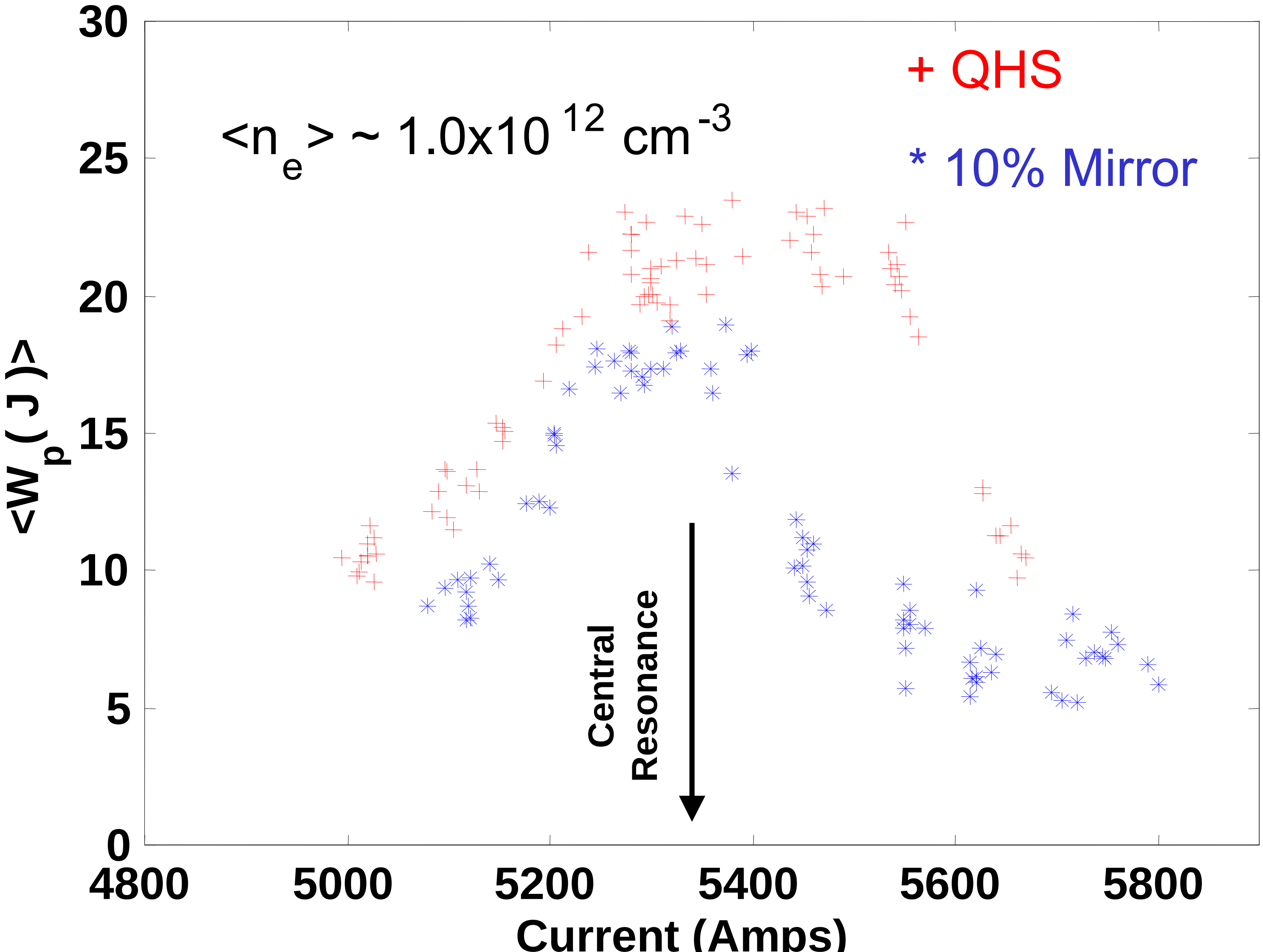
Role of direct loss for anti-mirror under investigation

The QHS Mode has Higher Stored Energies than the Mirror Mode at Low Densities

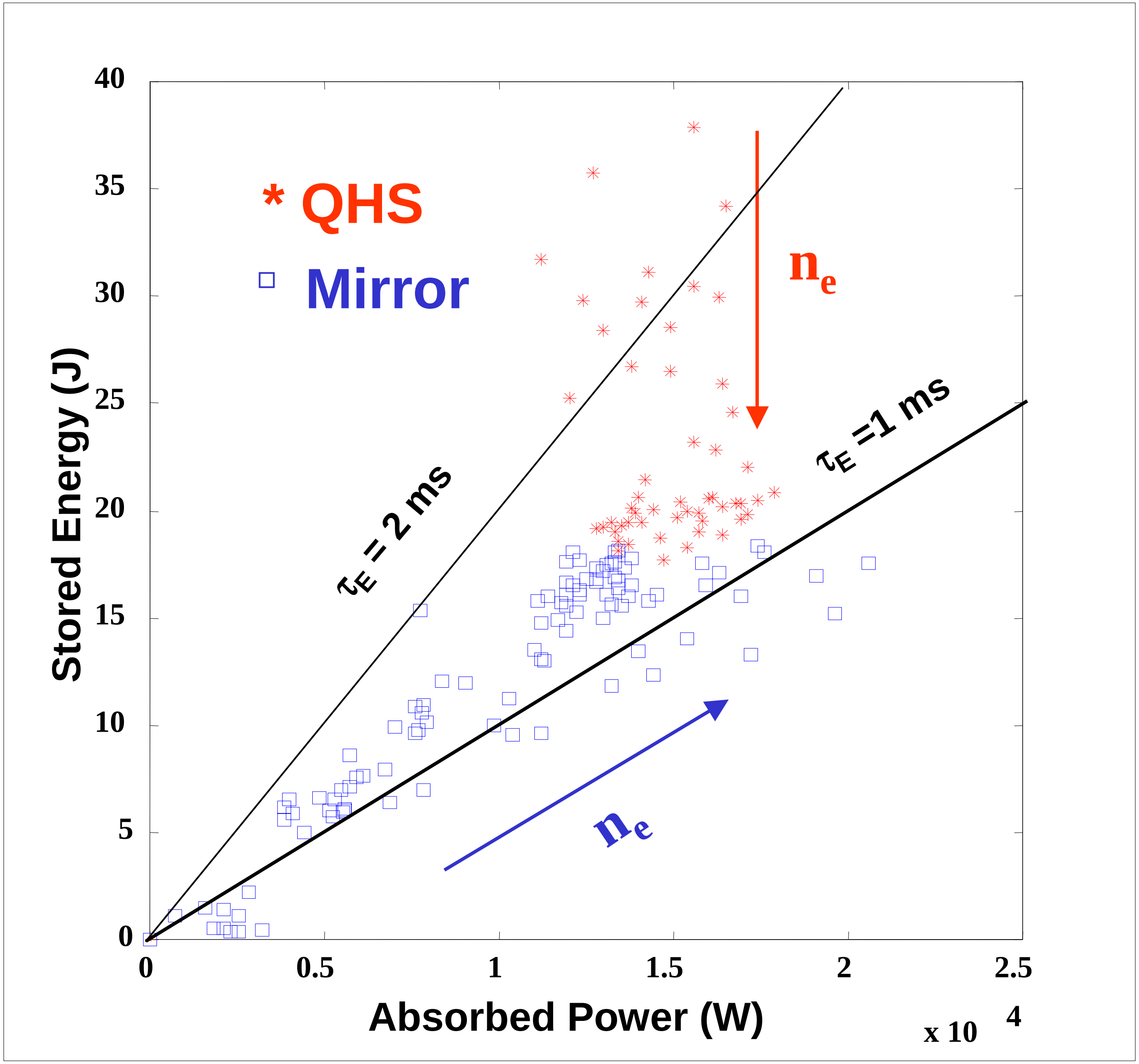


- **Central Heating**
- **QHS stored energy drops with increasing density while mirror increases below 1 x 10^{12} cm^{-3}**
- **Stored energy independent of density above this value**

Stored Energy in the Mirror Mode Falls Rapidly with Outboard Heating



QHS Mode Effectively Absorbs Power for all $\langle n_e \rangle$

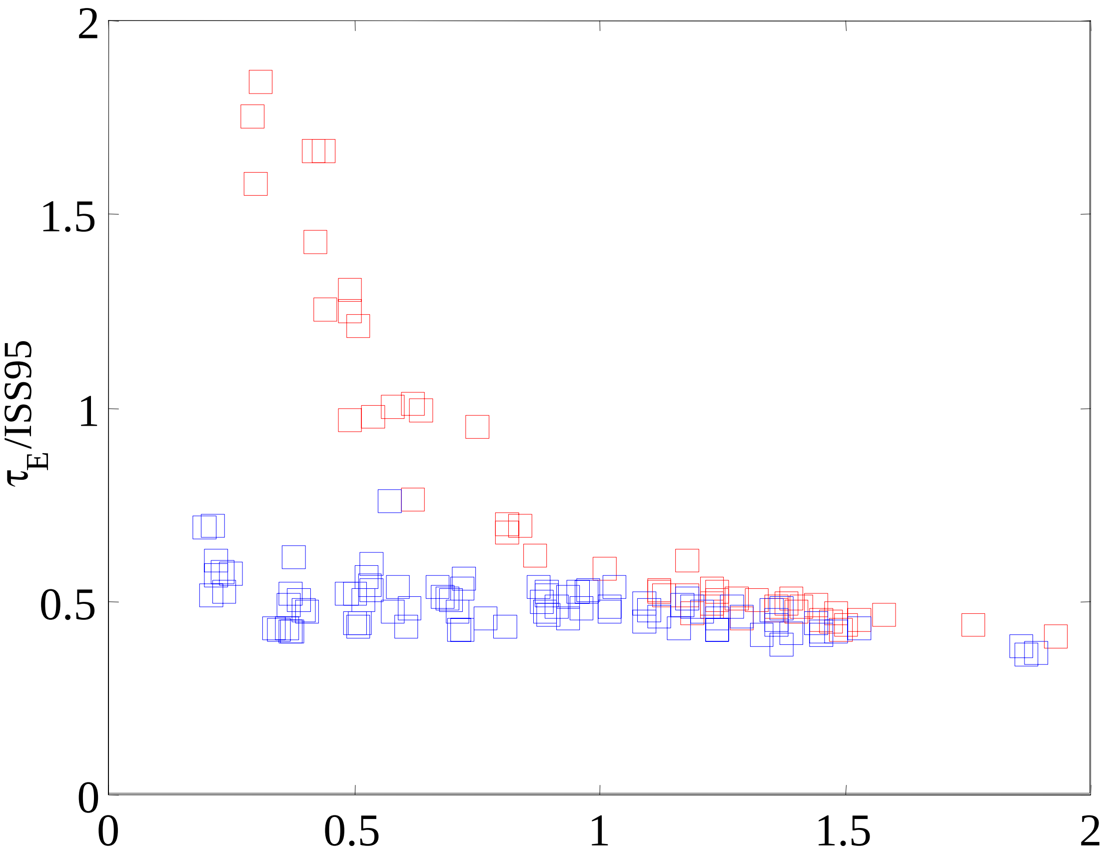


Absorbed power inferred from ΔW_p at ECH turn-off

Absorbed power increases with density in the mirror mode

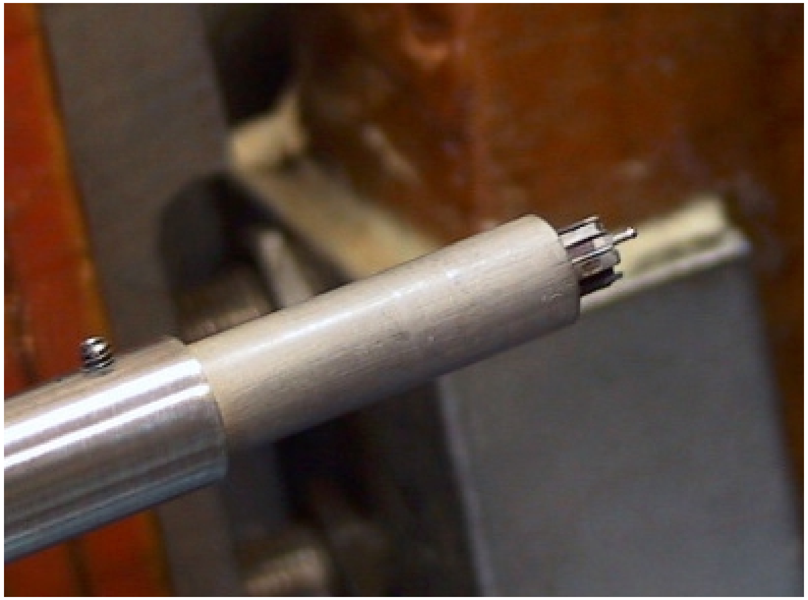
Increases in confinement time observed in *low* density QHS plasmas

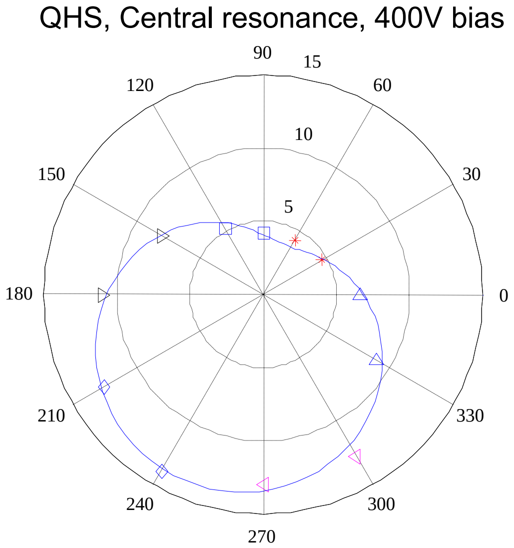
Mirror and High Density QHS Follow ISS95 Scaling



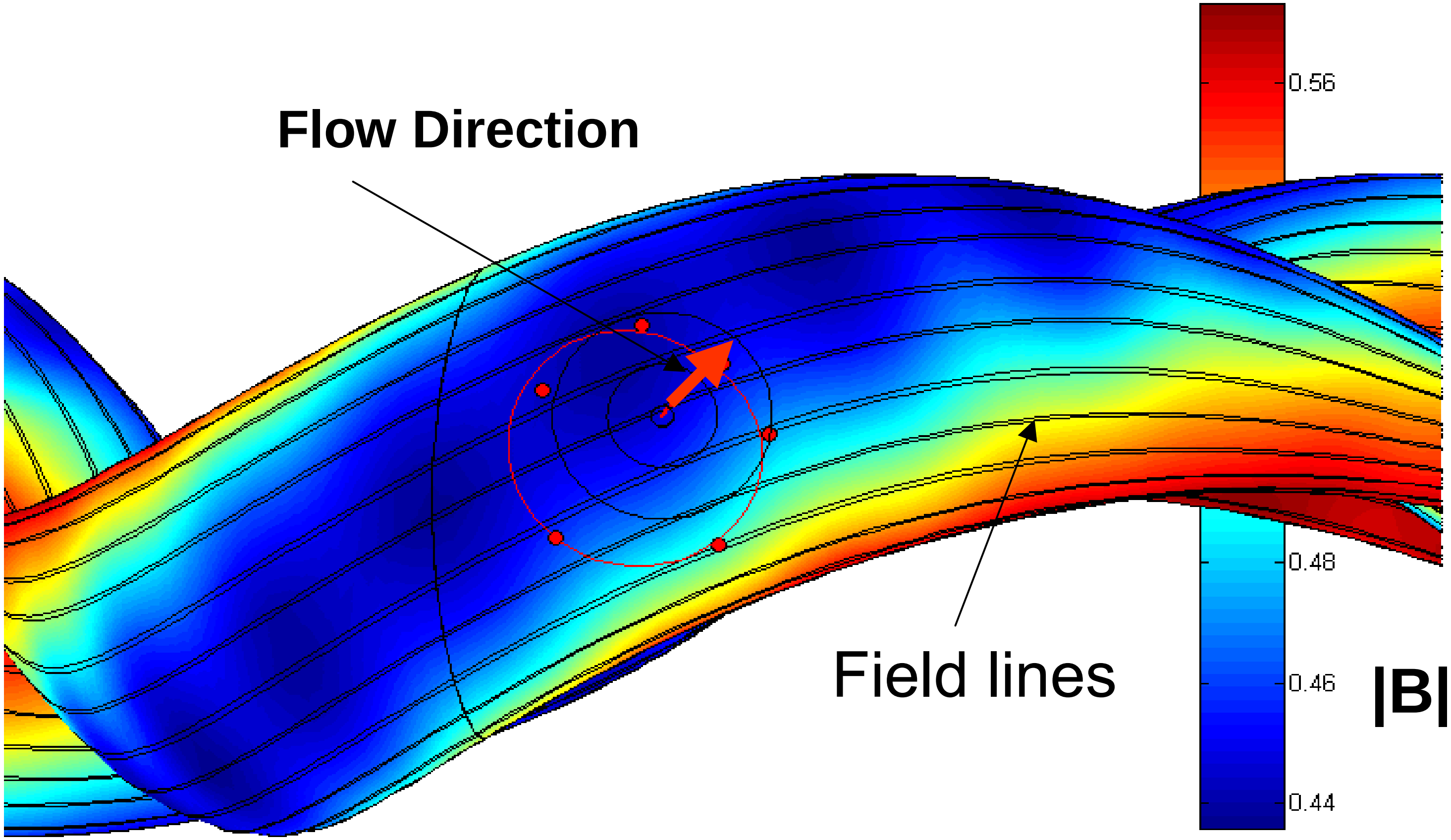
Initial Measurements of Plasma Flow Induced Using a Biased Electrode

- QHS plasmas should have low parallel viscous damping in the direction of symmetry
- Biased electrode used in edge region to drive flow
- Flow measured with a six-element Mach probe

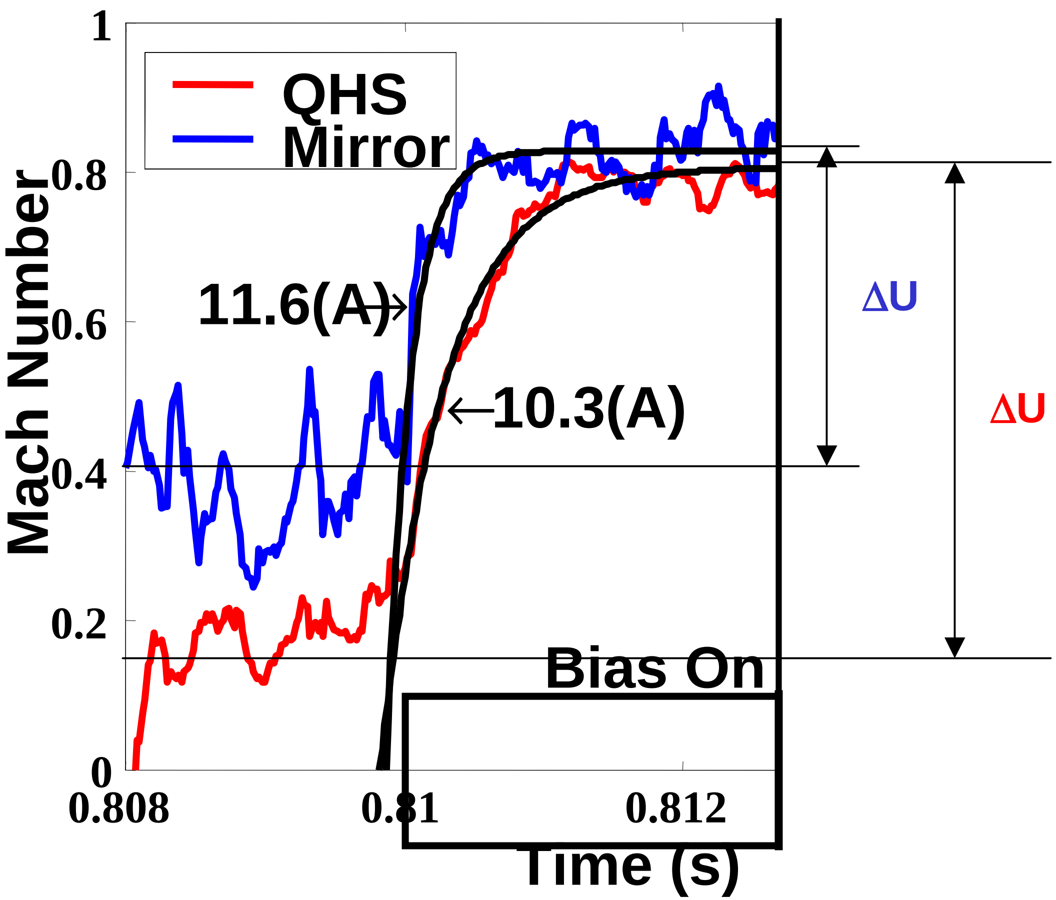




The Measured Induced Plasma Flow is in the Direction of Quasi-symmetry



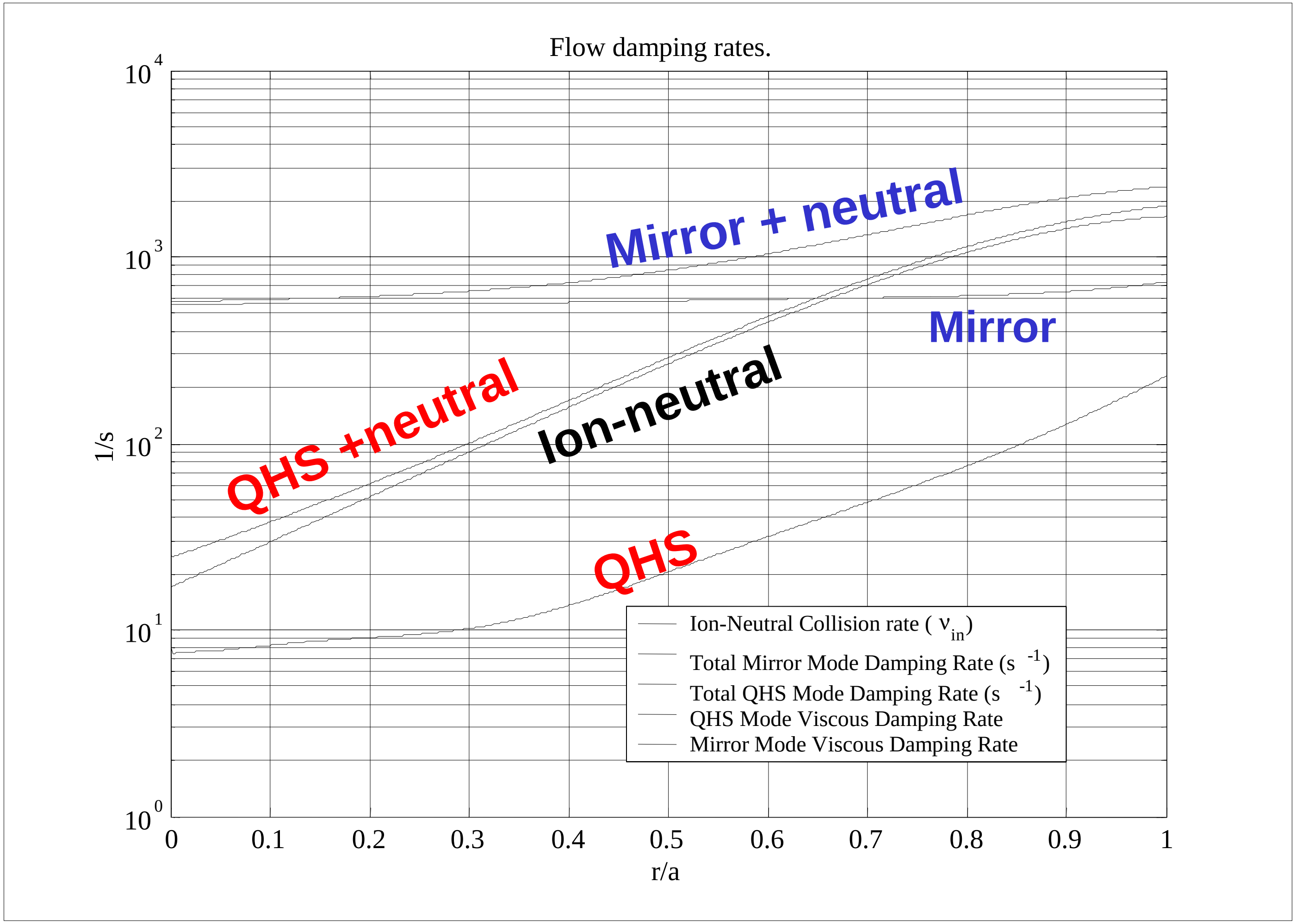
QHS Has a Larger Flow Velocity Change for Less Drive than the Mirror Mode



ΔU ~ 50% larger for QHS; slower rise

Higher radial conductivity observed for mirror mode

Damping Due to Parallel Viscosity for QHS 1-2 Orders on Magnitude Less Than Mirror

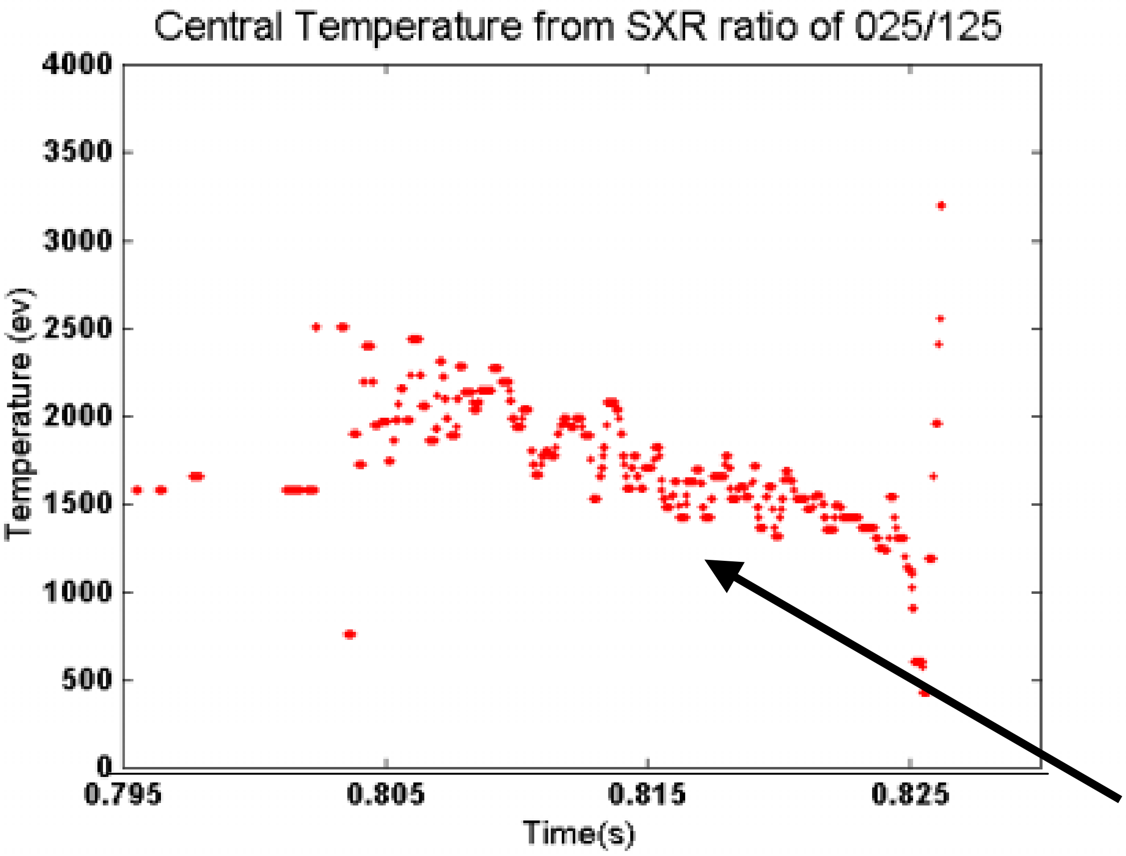


Factor of two difference in damping rates near the plasma edge explained by damping due to neutrals

Concluding Remarks

- Stellarators can be designed for targeted physics properties
- Specifically for quasi-helical symmetry
  - ➡ Virtual elimination of toroidal curvature
  - ➡ $|N - m\iota|$ reduction of orbit shifts (high ι_{eff})
- **Quasi-Symmetry Matters!**
  - Shorter breakdown times
  - Higher stored energy/better absorption
  - Reduced rotation damping

What is T_e in HSX?



Stored energies of 30 J routinely attained at $\langle n_e \rangle \sim 1 \times 10^{12}$ cm^{-3}

$3/2\ nkT_eV = 30$ =>

$T_e \sim 300$ eV

Density profile peaked; with T_e peaking, factor of 3-4 in T_{e0} possible =>

$T_{e0} \sim 900\text{-}1200$ eV

SX, calibrated against MST Thomson system, gives ~1500 eV

Resolution awaits additional diagnostics: HSX Thomson (mid 2002), fast electron diagnostics and ECE (soon!) and time-resolved spectroscopy (now)