Effects of Symmetry-Breaking on Stored Energy and density scaling in HSX

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Outline

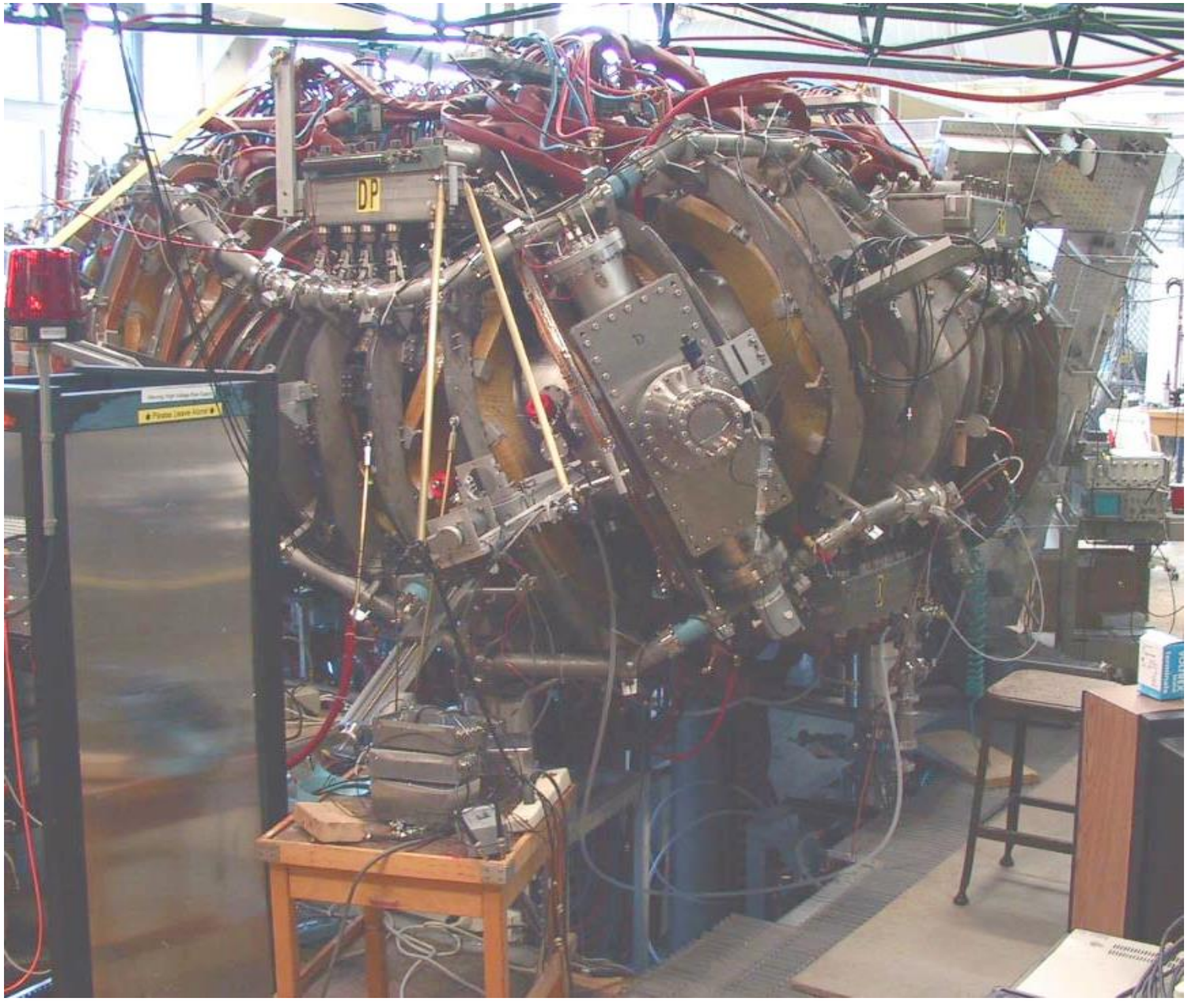
- Stored energy and resonance location.

  With and without symmetry.

- Stored energy and density scaling.

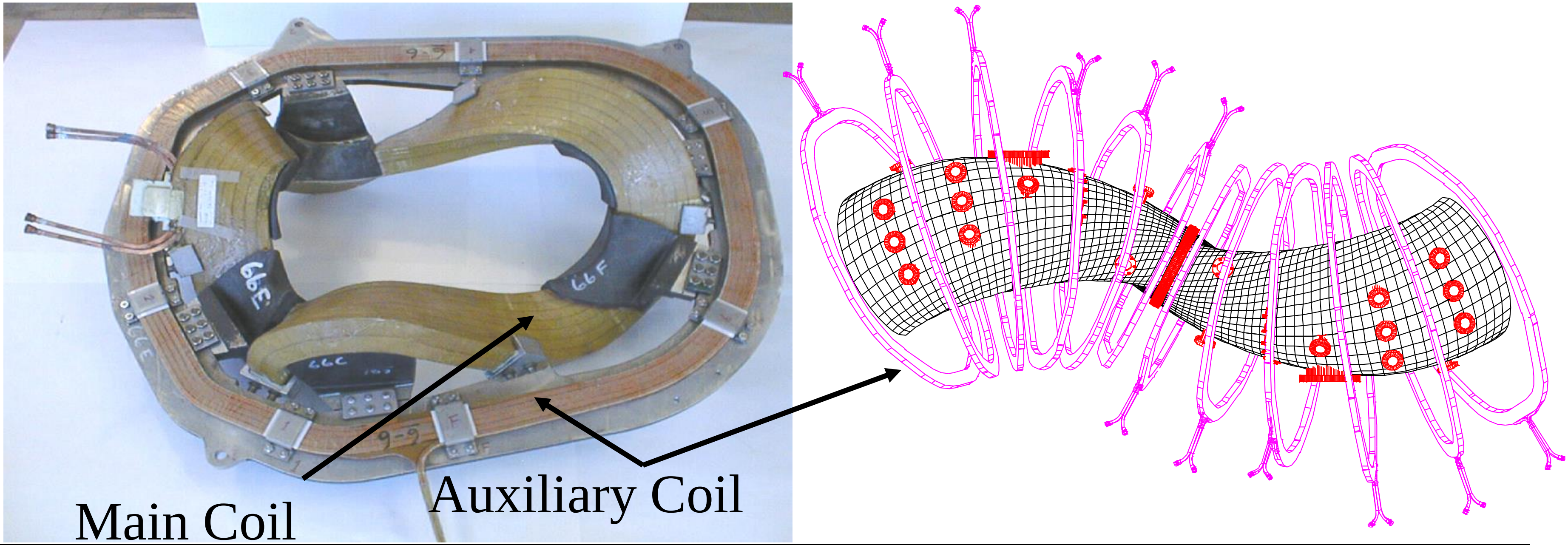
- Energy confinement scaling.

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

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

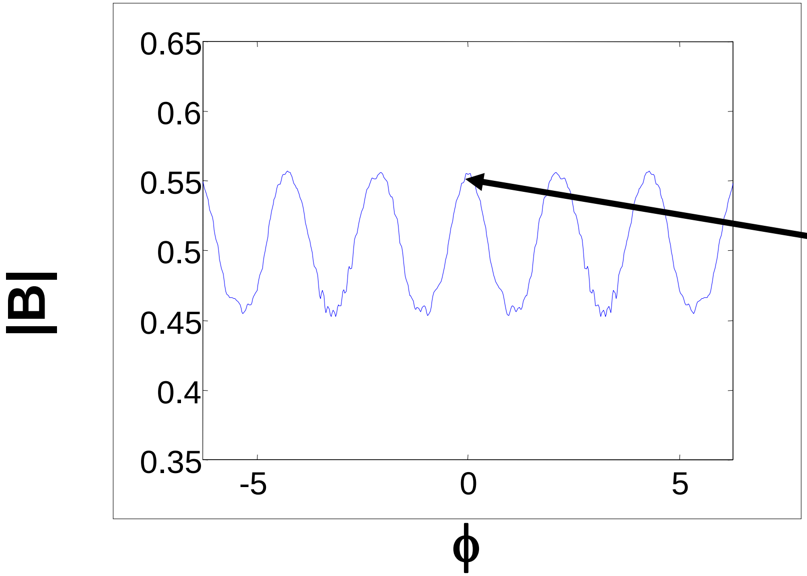
Present experimental program focuses on improvement of electron transport through quasi-helical symmetry

- 28 GHz gyrotron (200kW) is used to heat electrons into low collisionality regime where conventional stellarators have very large neoclassical losses.

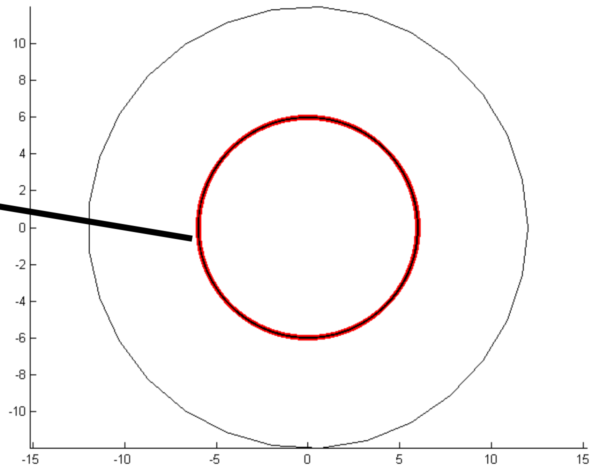
- We are presently focusing on second harmonic x-mode heating at B = 0.5 T to generate ***hot tail electrons*** for energetic particle confinement studies.

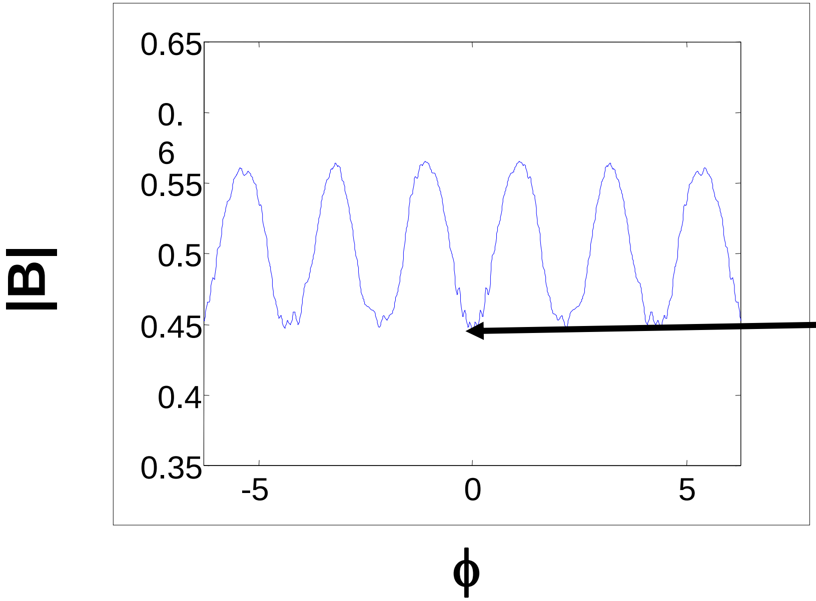
- We are only injecting 50 kW and coupling no more than about 10-20 kW. This is in rough agreement with estimates based on the optical depth and ray-tracing calculations.

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

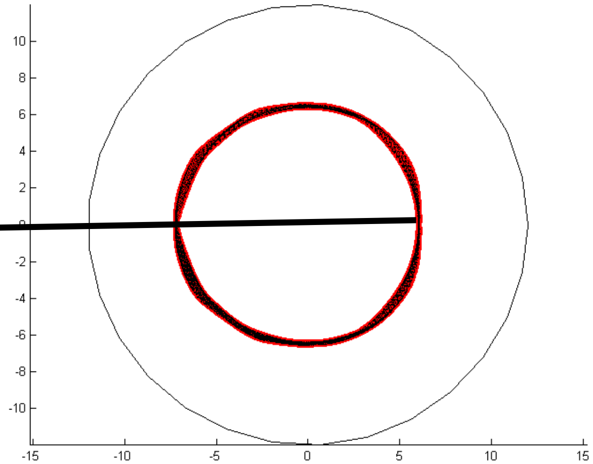


Inboard launch

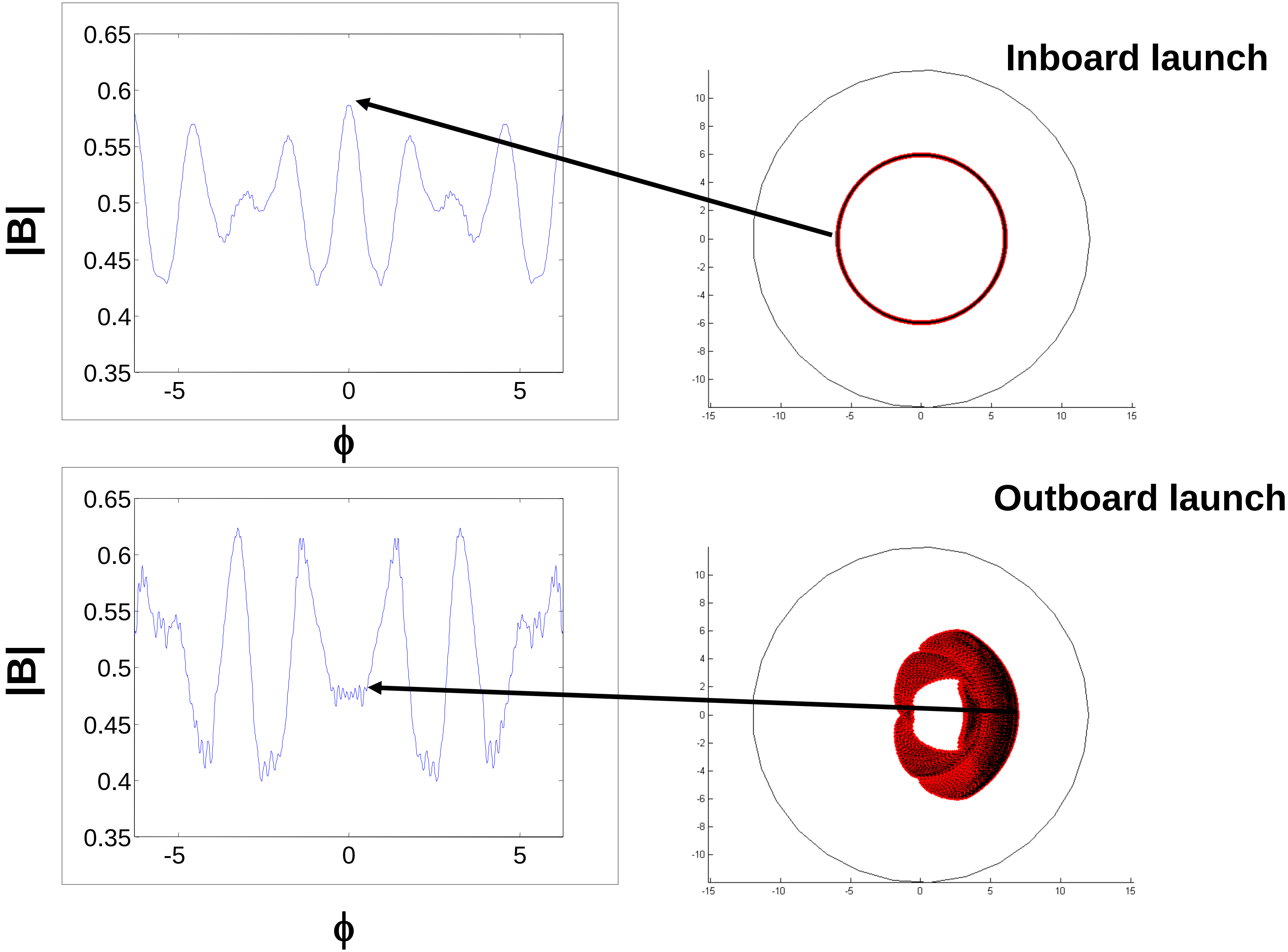




Outboard launch

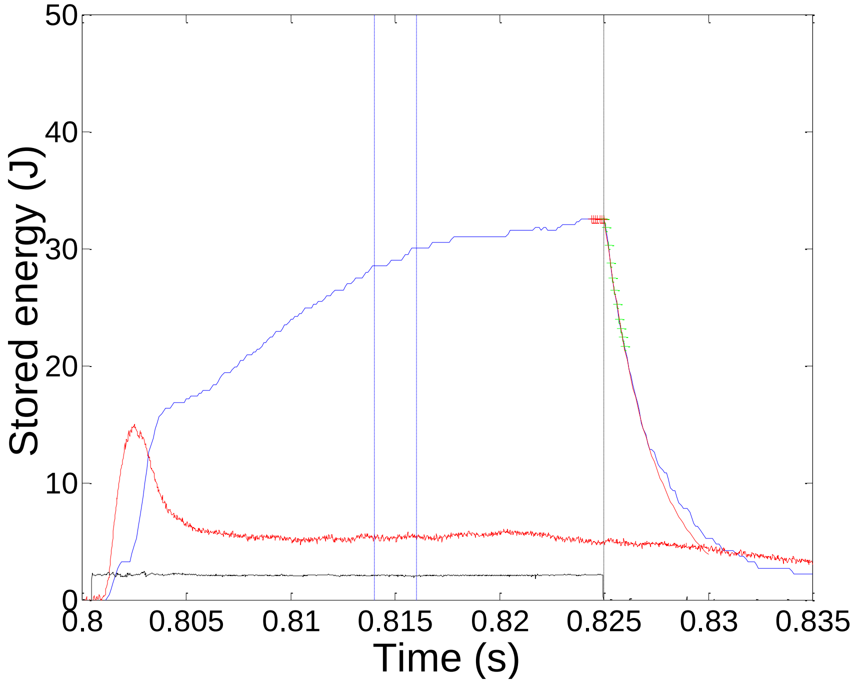


Particle Orbits at ECH Launch (ϕ=0) : Mirror Mode

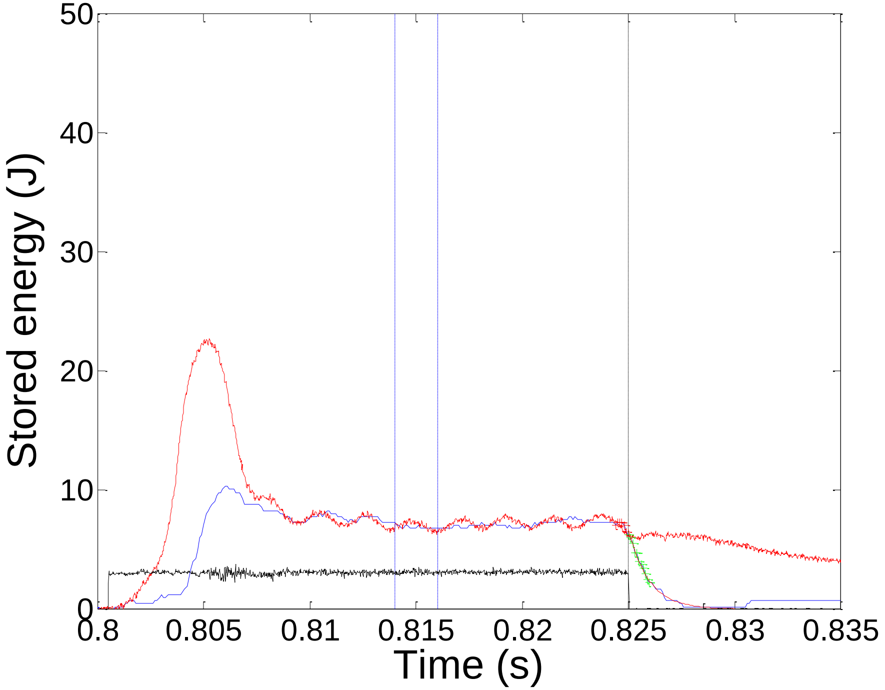


Higher Stored Energies Can be Achieved in the QHS Mode of Operation

QHS

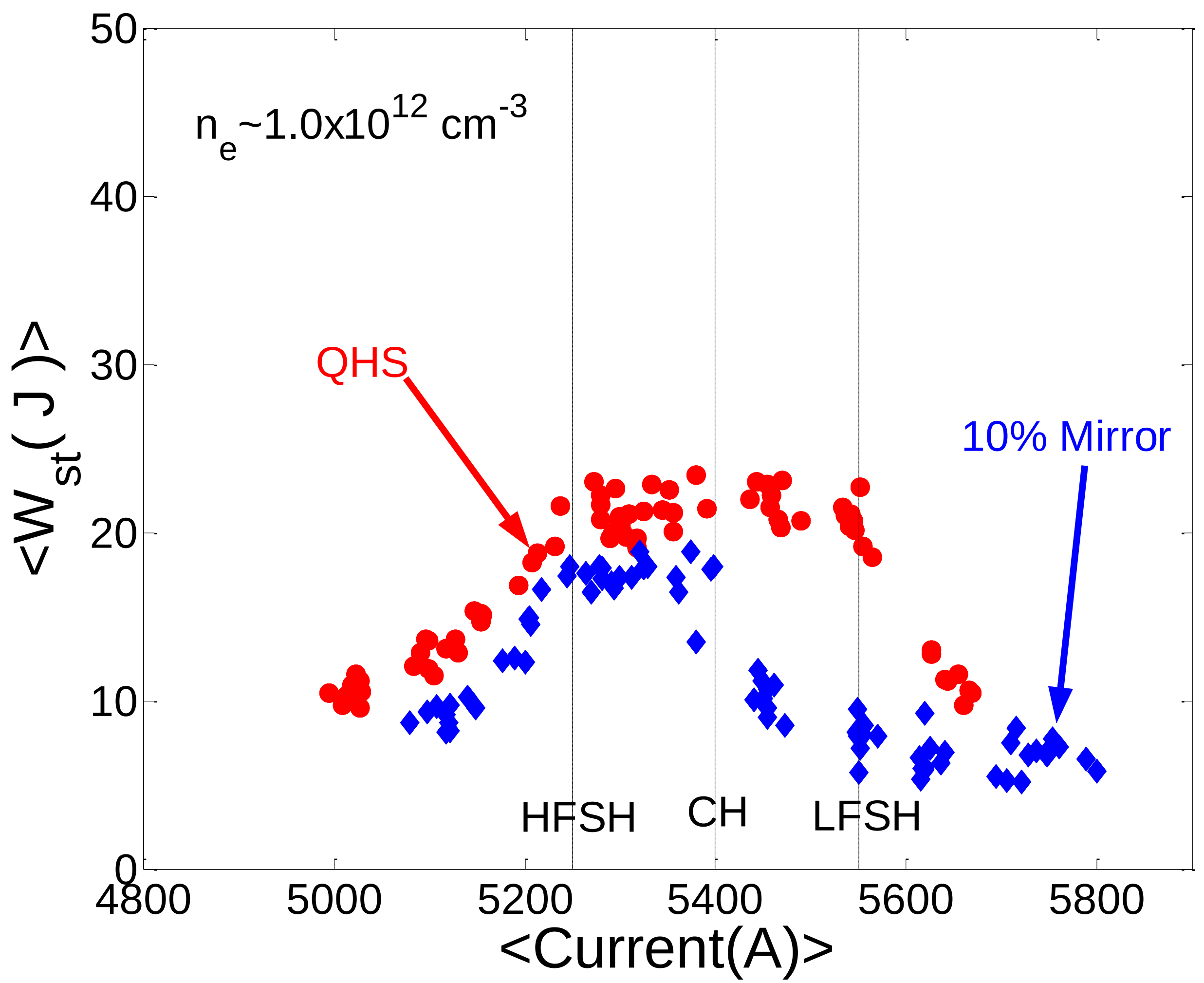


Mirror Mode



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

Stored Energy in the Mirror Mode is asymmetric with resonance location

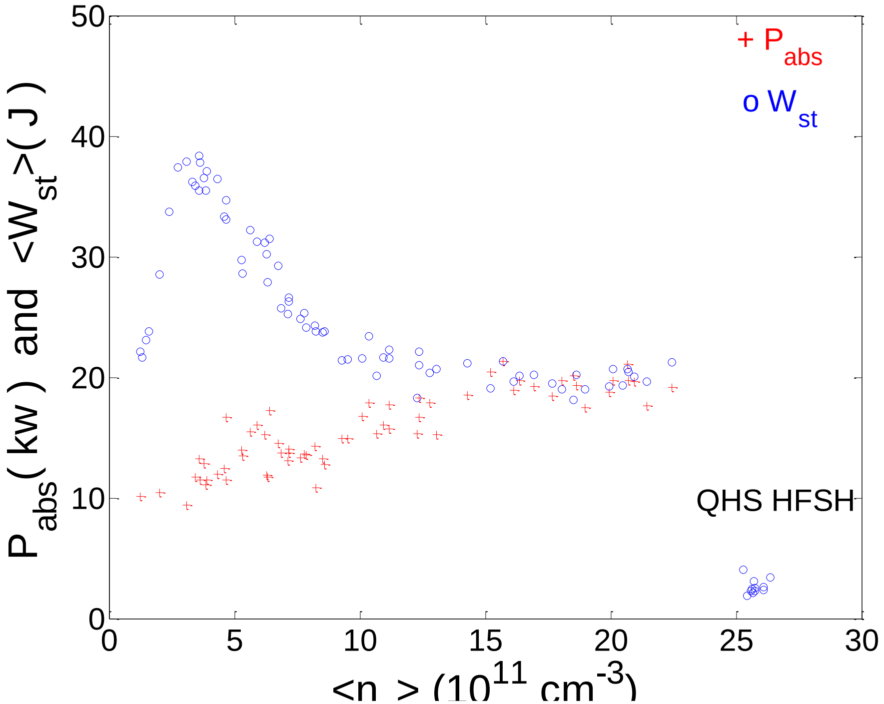


Restoration of symmetry is important

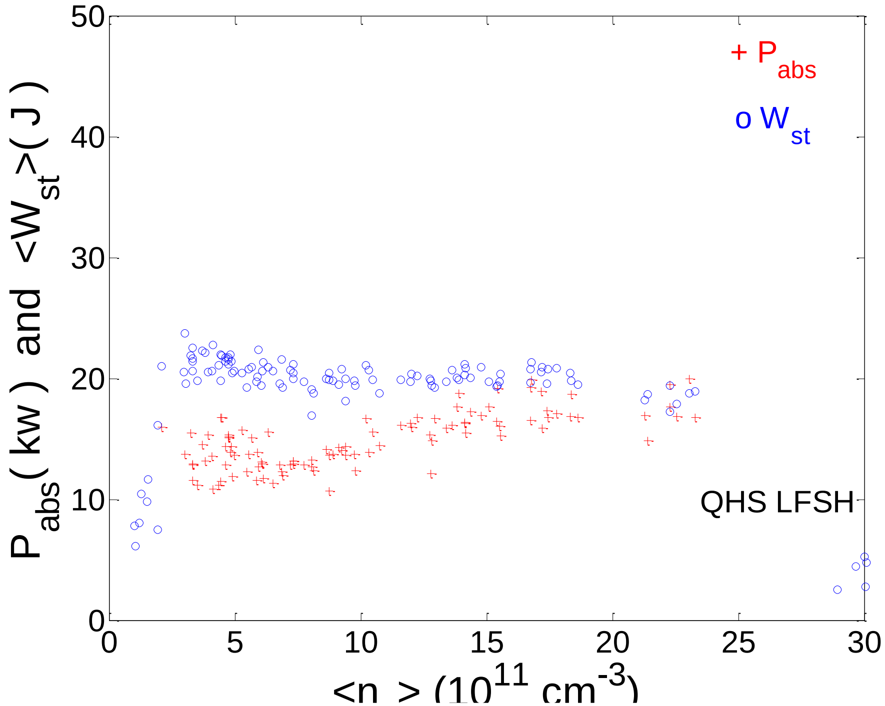
Low field side heating: there is a strong dependence on the mode of operation reflecting the importance of trapped particles.

High field side heating: the energy content is similar in both modes. The small decrease may be due to change in plasma volume.

Stored energy has a peak in the high field side resonance QHS.

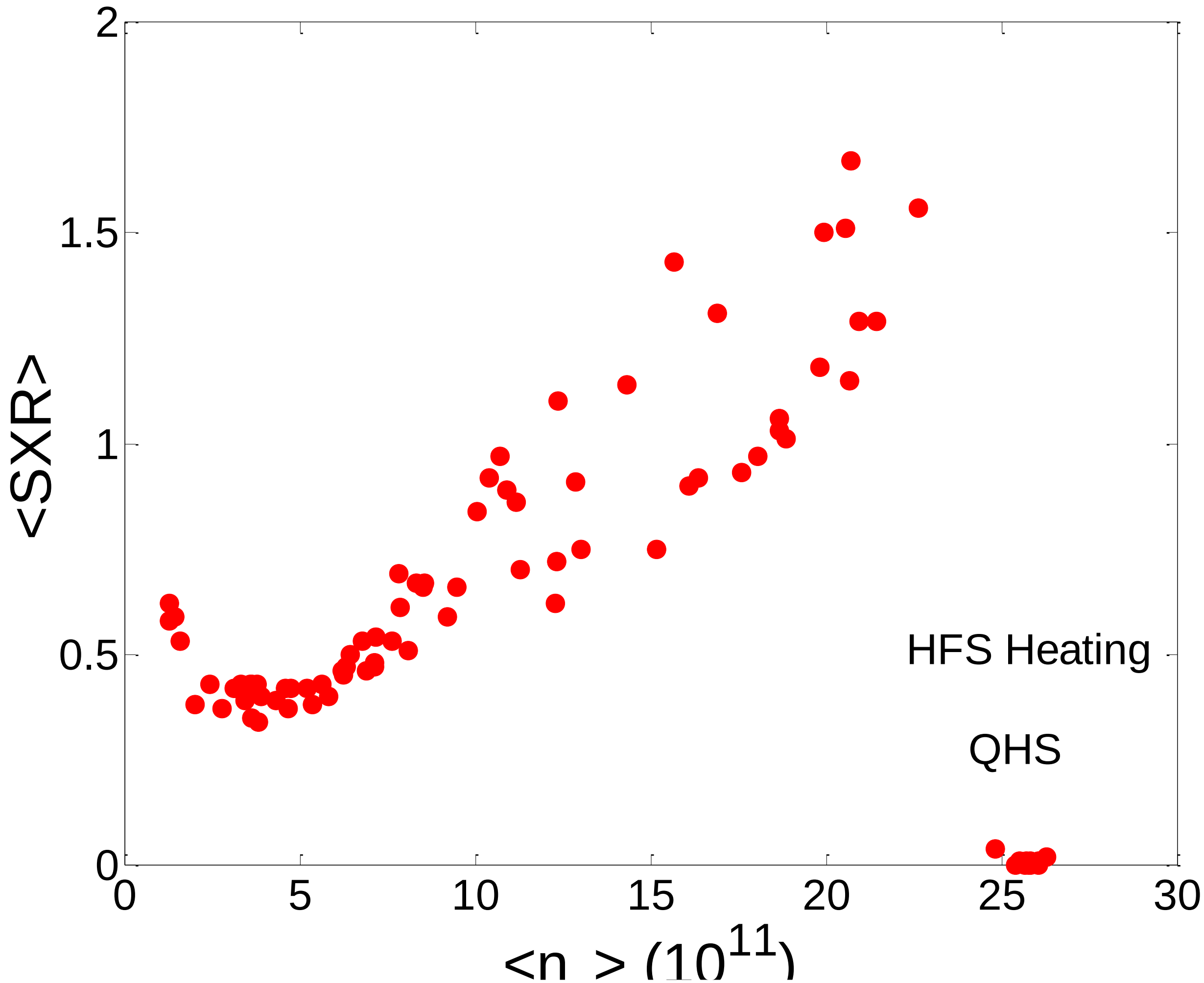


QHS HFS

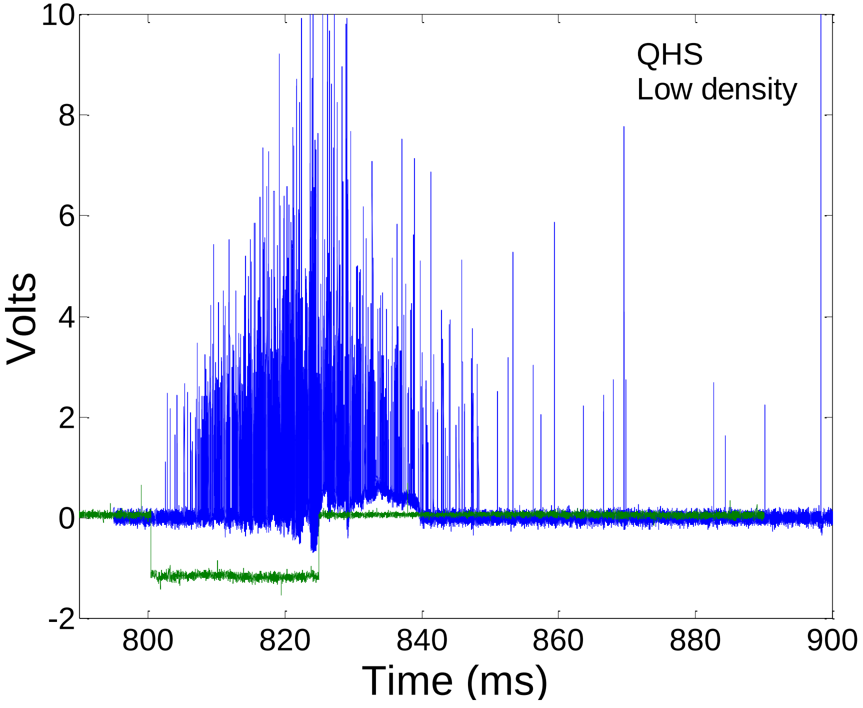


QHS LFS

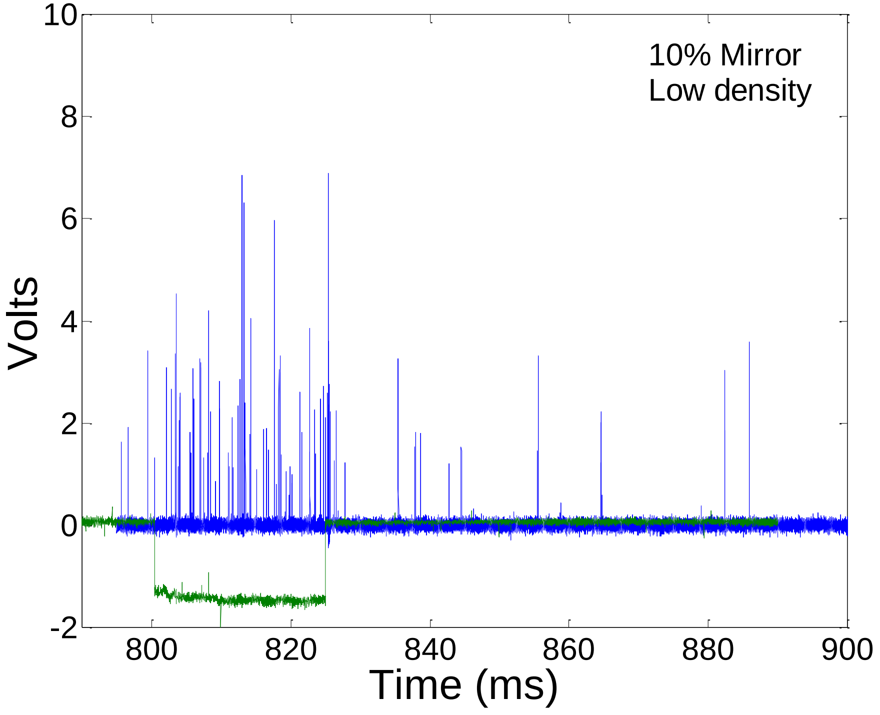
Soft x-ray does not show the low density peak (Bulk plasma).



Hard x-ray (CdTe detector) shows high energy tail in the QHS.

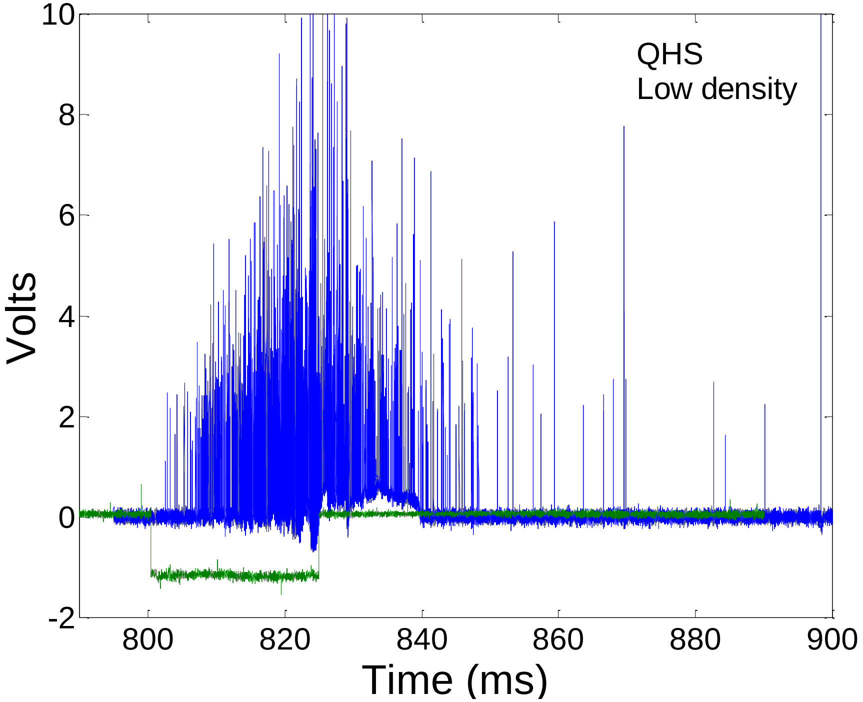


QHS

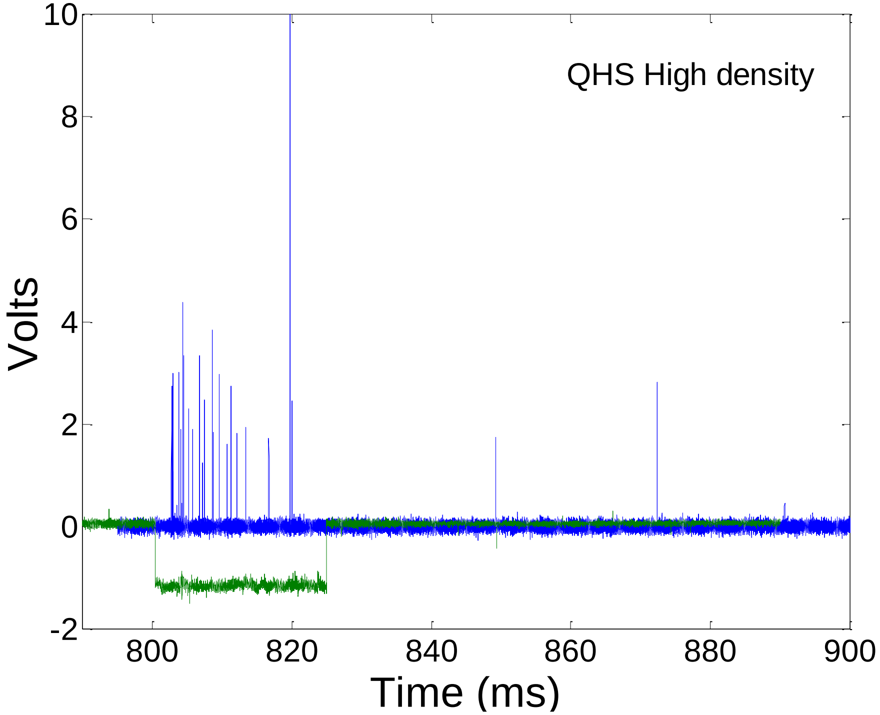


10% Mirror

Hard x-ray shows no high energy tail in the QHS at high density.

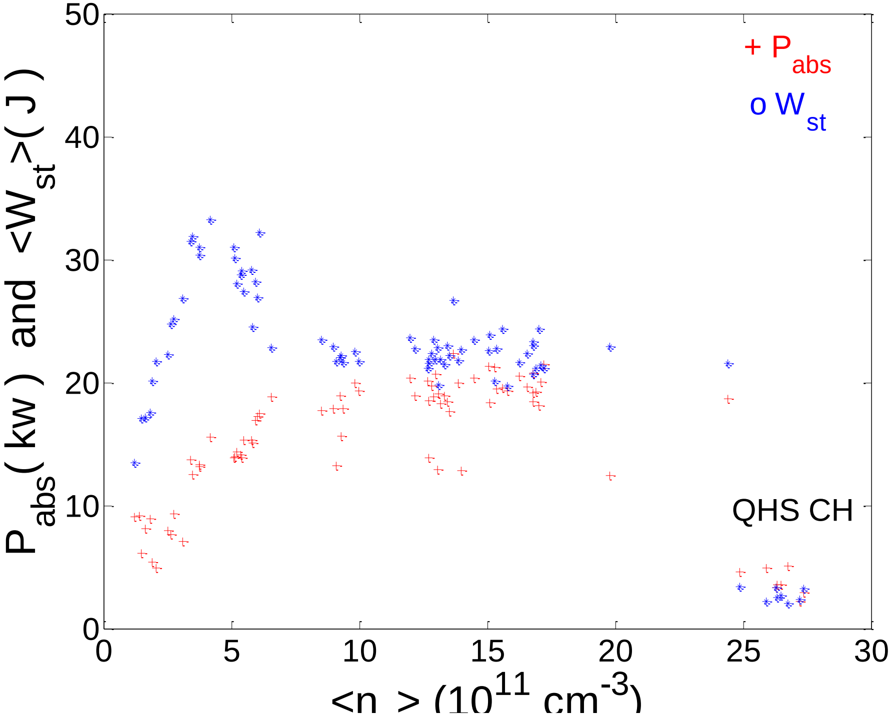


QHS Low Density

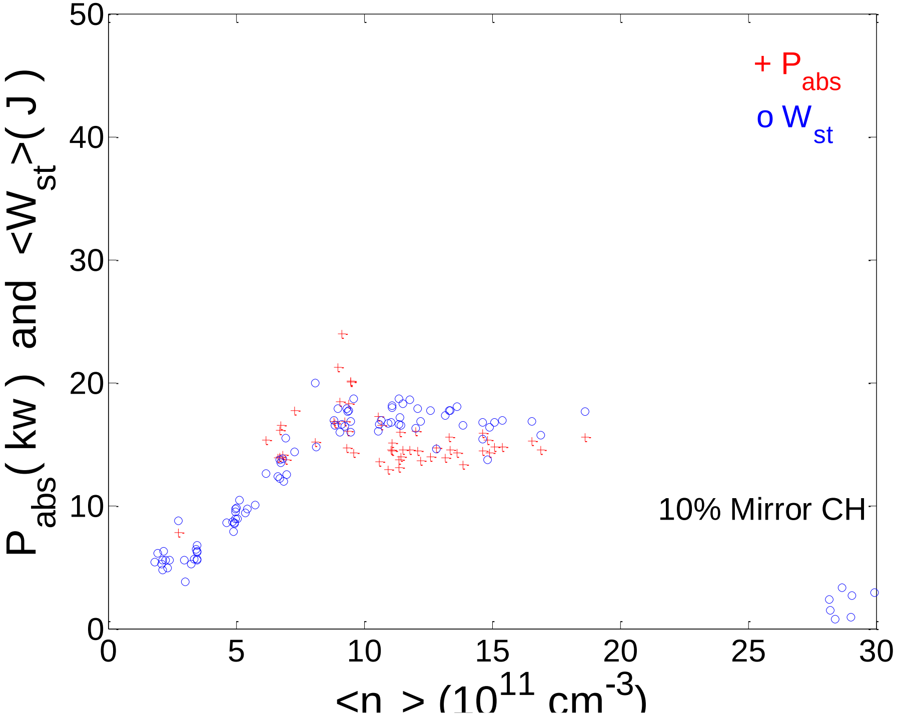


QHS High Density

Stored energy at low density decreases with the amplitude of symmetry-breaking-ripple.

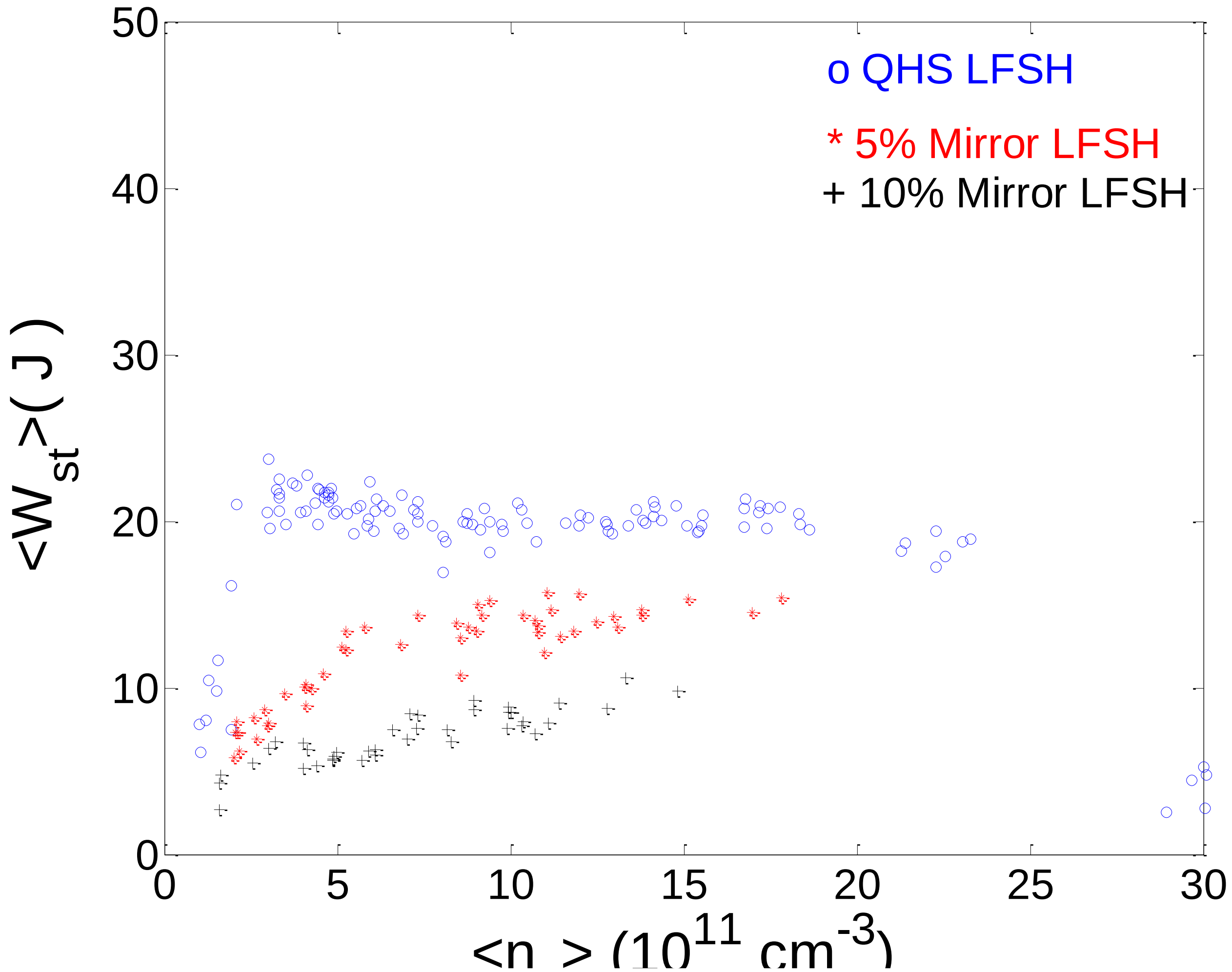


QHS CH



10% Mirror CH

Stored energy at low density decreases with the amplitude of symmetry-breaking-ripple.



Stored energy exhibits a complicated density scaling

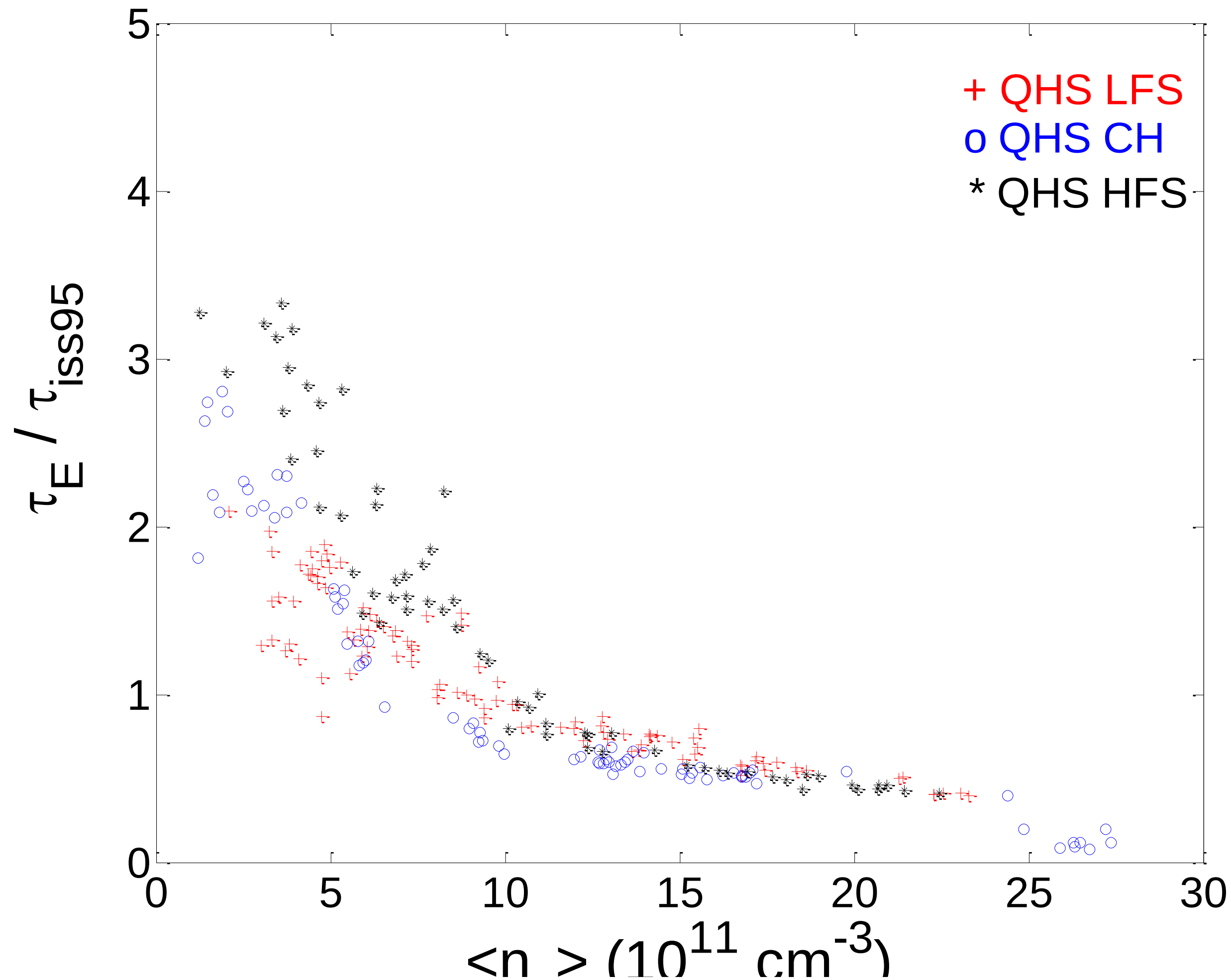
Store energy has a peak at low density. *This peak strongly dependent on resonance location*

$$4\text{x}10^{11}\ \text{cm}^{-3} < n_e < 10^{12}\ \text{cm}^{-3}$$

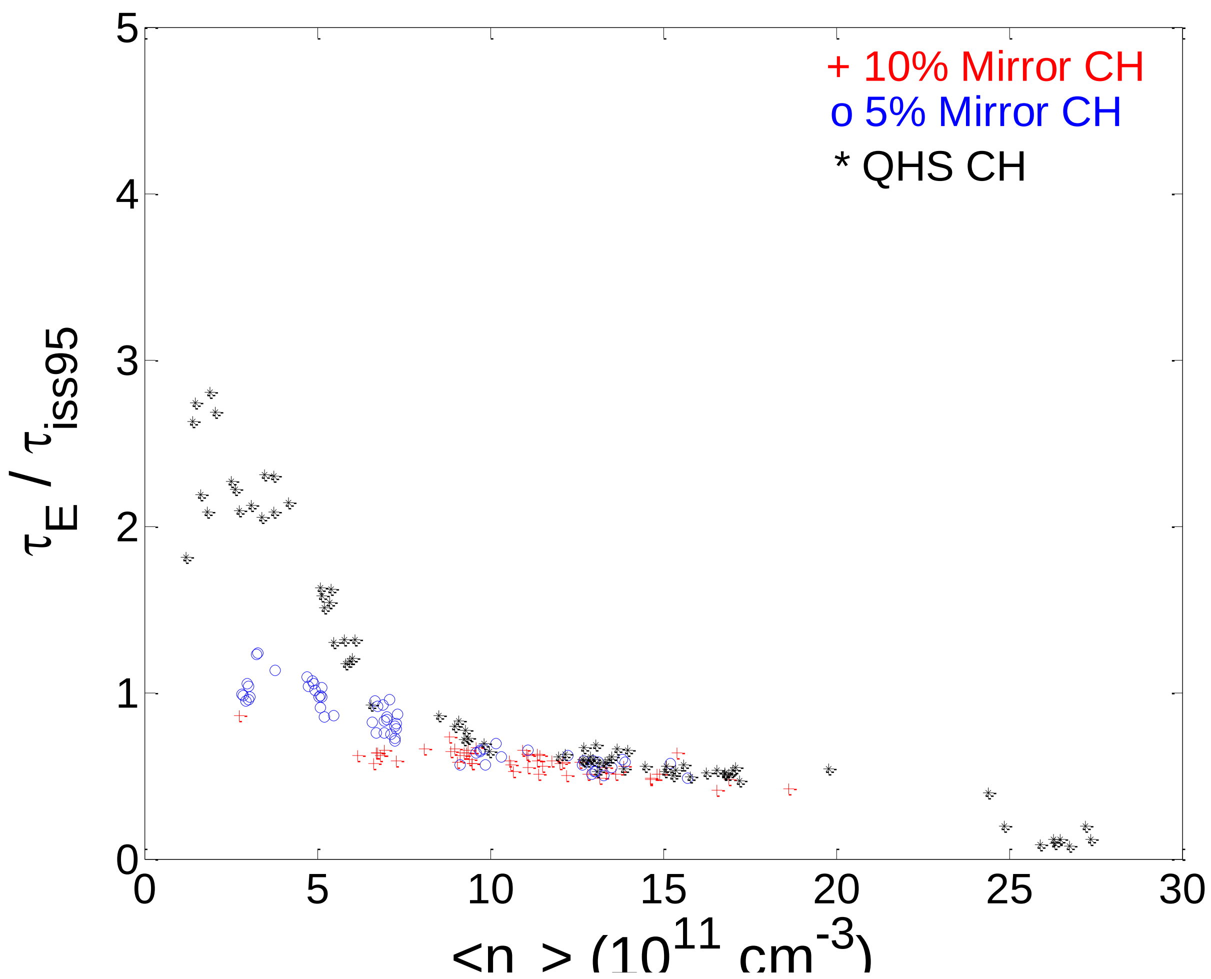
Stored energy increases with density. *Strongly dependent on amplitude of symmetry breaking*

$$n_e < 4\text{x}10^{11}\ \text{cm}^{-3}$$

At low density we have well confined energetic electron tail for all resonance locations



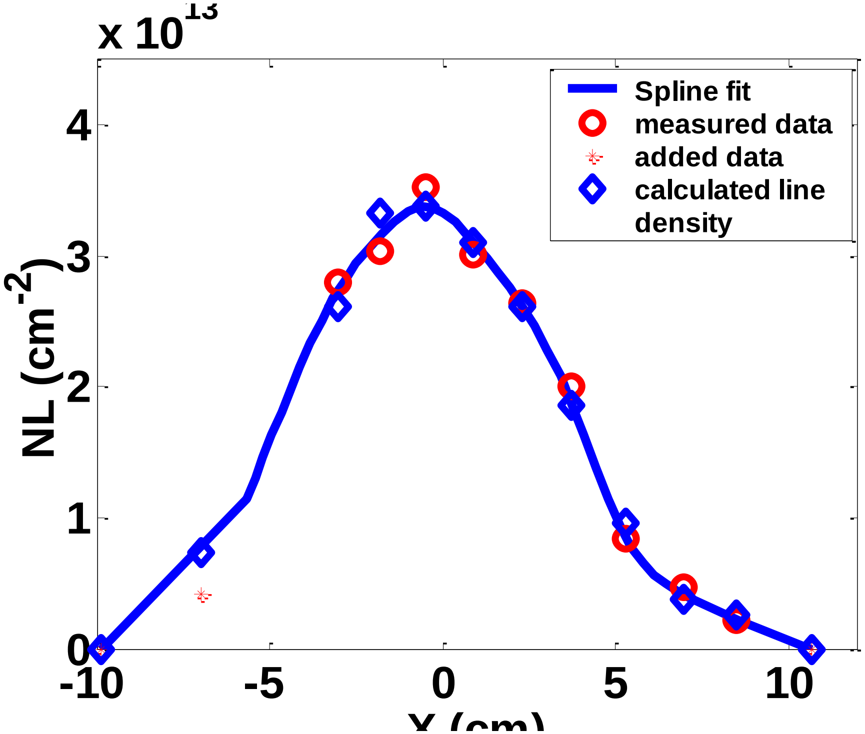
The confinement of energetic electron tail degrades with increased ripples.



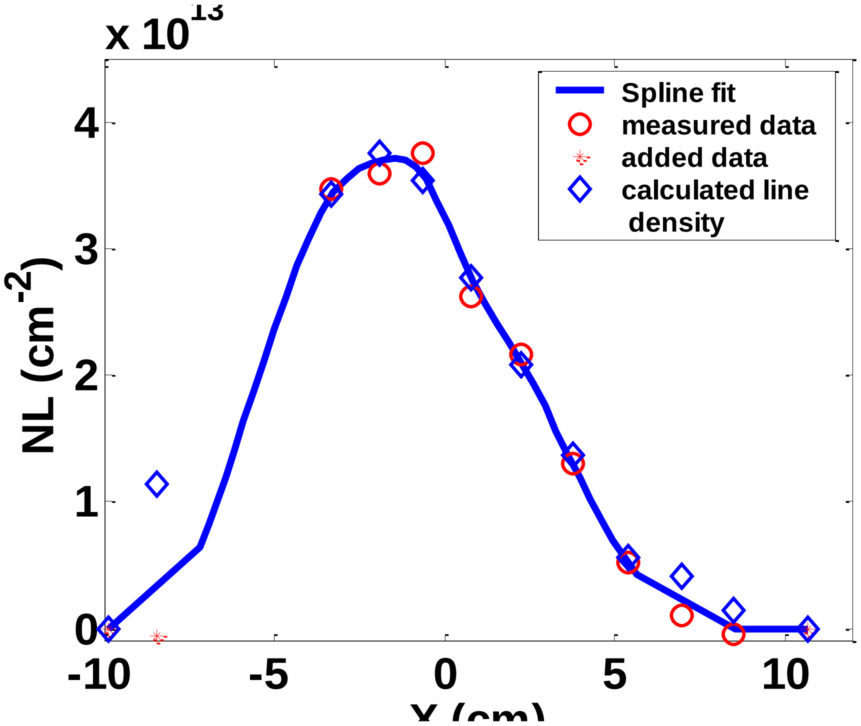
Confinement and scaling

- At low density, QHS confinement time is a factor of 2 or so higher than Mirror.
- At higher density, confinement times are similar.
- Mirror scales roughly like ISS95, but a factor of 2 lower. QHS has different scaling

Similar Density Profiles for QHS and Mirror



QHS



Mirror Mode

- Line-density profiles insensitive to heating location

The Helically Symmetric Experiment Is the First Stellarator to Have an Axis of Symmetry

- Quasi-helical symmetry (QHS) is symmetry ONLY in the magnitude of B. In a straight field line coordinate system where $\theta = \iota\phi$

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

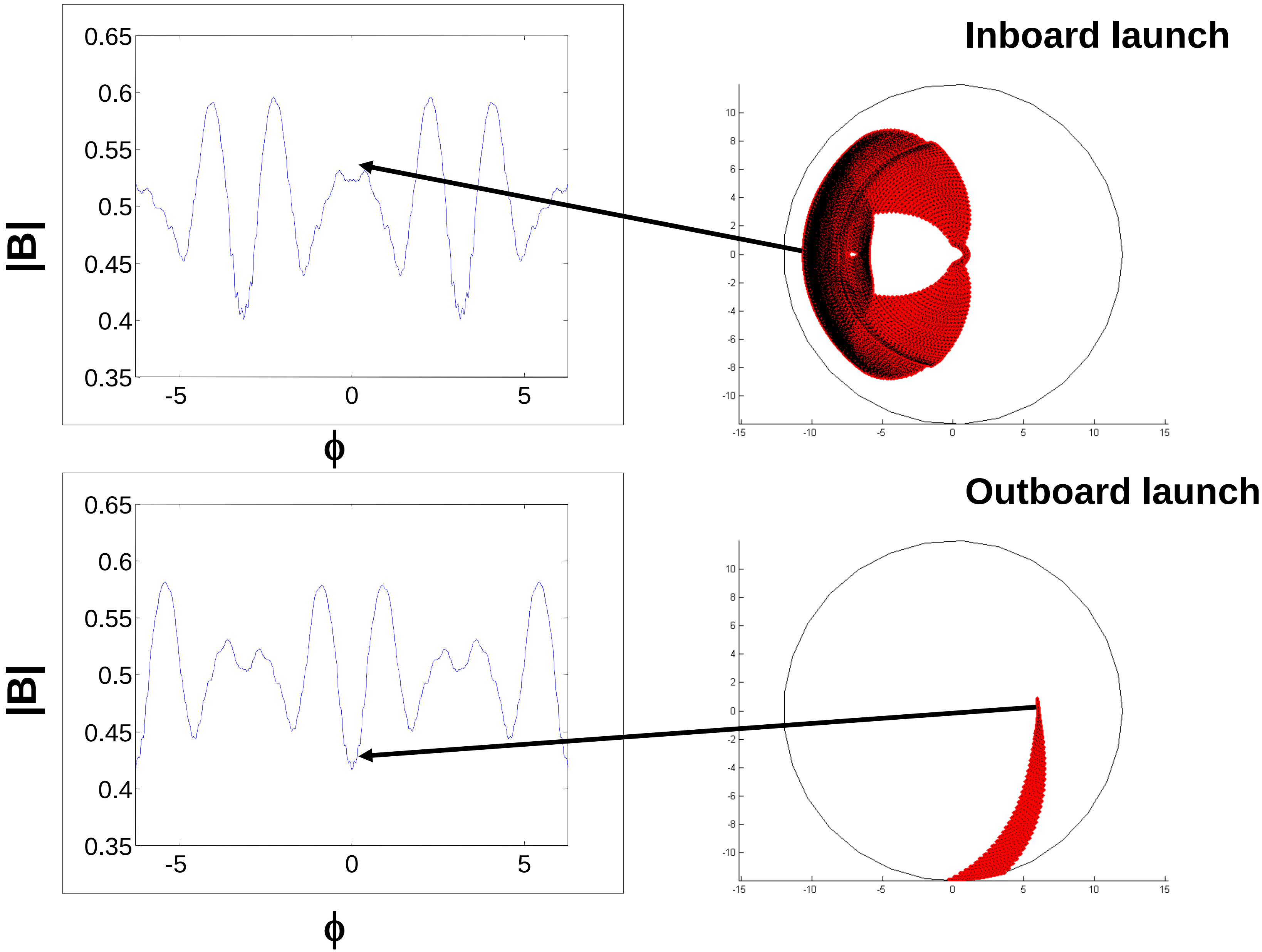
$\Rightarrow$ Equivalent to a tokamak with transform given by $N - m\iota$

- In HSX: N = 4, m=1 and $\iota \sim 1$ the effective transform is approximately 3.

High Effective Transform and Helical Symmetry Is Responsible For:

- Low Neoclassical Transport
- Small deviations from magnetic surfaces, small banana widths
- Minimal number of direct loss particles
- Small Pfirsch-Schlüter and bootstrap currents
- Robust magnetic surfaces, high equilibrium beta limit
- Low parallel viscosity in the direction of symmetry

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



Variation of stored energy with resonance.