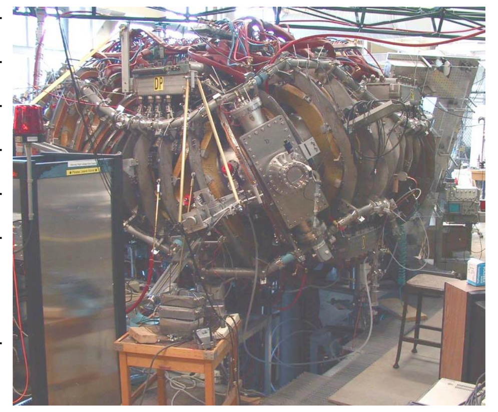
Study of the Hard X-rays from Superthermal Electrons in the HSX Stellarator

A. E. Abdou, A. F. Almagri, D. T. Anderson, J. Radder, V. Sakaguchi, J. N. Talmadge
HSX Plasma Laboratory, U. of Wisconsin, Madison

1. The Helically Symmetric Experiment (HSX)

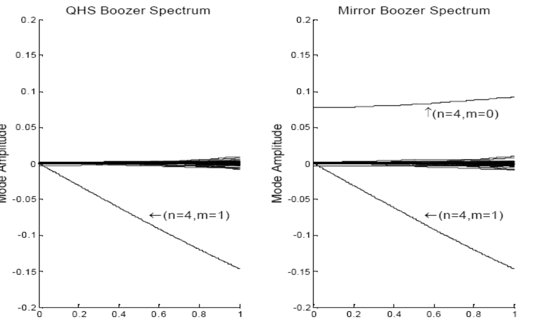
a. Machine Parameters

Major Radius	1.2 m
<r>	0.12 m
Volume	~.44 m^3
Field periods	4
ι_{axis}	1.05
ι_{edge}	1.12
Coils/period	12
B_0 (on axis)	.4-.6 T 1.25 T Max
ECH Pulse length (up to now)	Up to 50 msec.
Heating Power (up to now)	Up to 100 kW



b. Magnetic Field Structure

- HSX is the worlds first Quasi-Symmetric Stellarator, based on a dominant n = 4, m = 1 component of the magnetic spectrum.
- This symmetry can be broken by the addition of a large toroidal mirror term (n = 4, m = 0)
- All symmetry breaking terms below 1% of average field.

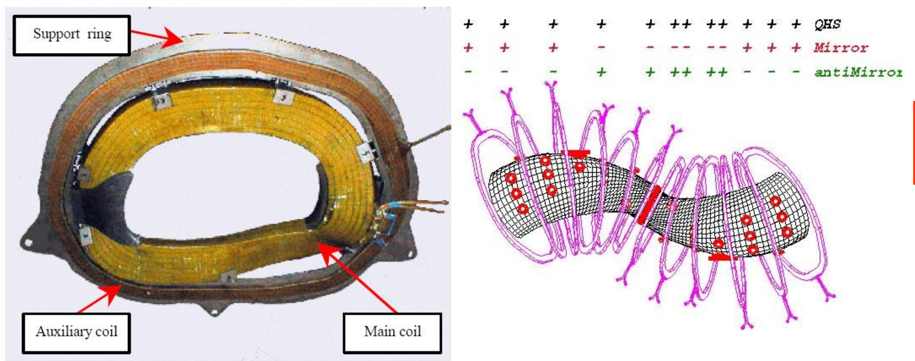


$$B = B_0\left[1-\varepsilon_h\cos(N\phi - m\theta)\right]$$

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

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

c. Modes of Operation

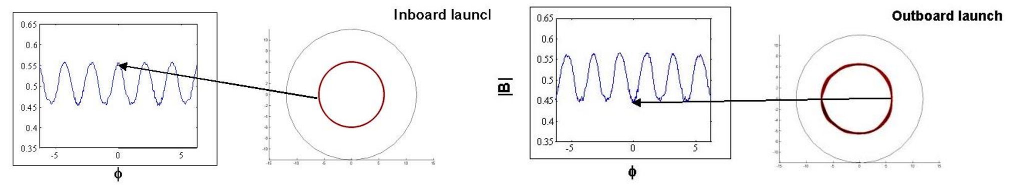


Configuration	Auxiliary Coil Currents	Dominant Feature
QHS	None	Lowest neoclassical transport; Quasi-symmetry
MIRROR	3 coils on ends add to main; center 6 opposite	Neoclassical transport similar to conventional stellarator
ANTI-MIRROR	Opposite phasing to mirror	Similar neoclassical transport to Mirror. Deep ripple on low-field side at ECH launcher

2. Particle Orbits in HSX

a. Particle Orbits in QHS

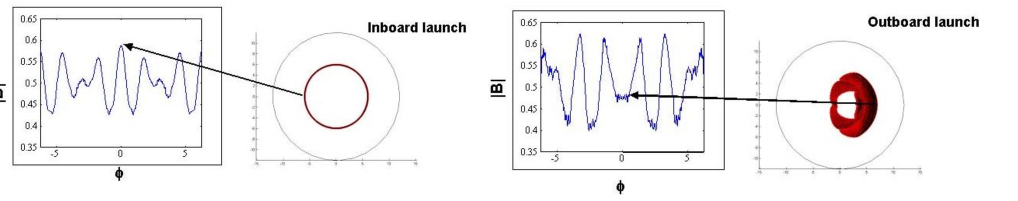
20 KeV electrons with 80° pitch angle, launched at ϕ = 0, and r/a = ½



- When electrons are launched at the inboard side (the top of magnetic well) they are passing particles
- When they are launched at the outboard side (the bottom of the magnetic well) they are trapped with their orbits deviation from home flux surface being small compared to Mirror and antiMirror cases.
- No or minor difference in hard x-ray emission is expected between inboard and outboard sides.

b. Particle Orbits in Mirror

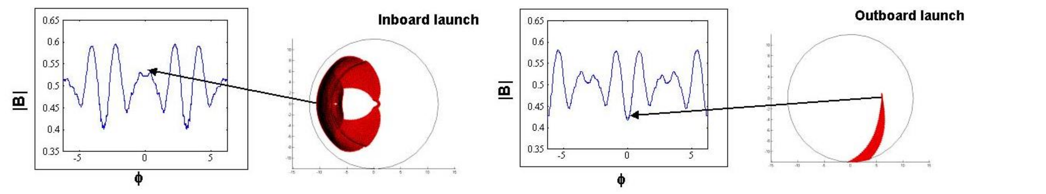
20 KeV electrons with 80° pitch angle, launched at ϕ = 0, and r/a = ½



- When electrons are launched at the inboard side (top of the magnetic well) they are passing particles. Similar to the QHS inboard case.
- When they are launched at the outboard side (bottom of the magnetic well) they are trapped with their orbits deviation from home flux surface being large compared to QHS (because of the asymmetry in the magnetic ripples).
- Different hard x-ray emission is expected in inboard and outboard sides.

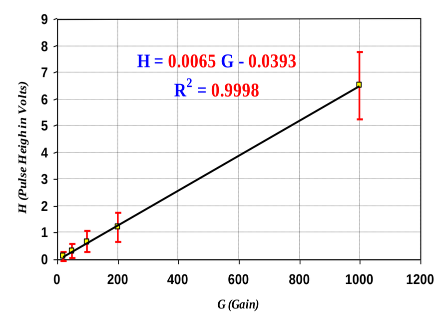
c. Particle Orbits in antiMirror

20 KeV electrons with 80° pitch angle, launched at ϕ = 0, and r/a = ½



- When electrons are launched at the inboard side (local maximum of the magnetic field) they are trapped with their orbits deviation from flux surface being large compared to QHS and Mirror cases.
- When electrons are launched at the outboard side (bottom of the magnetic well) they are in direct loss orbit.
- Very low hard x-ray intensity is expected in both cases for antiMirror.

3. Hard X-ray Diagnostics



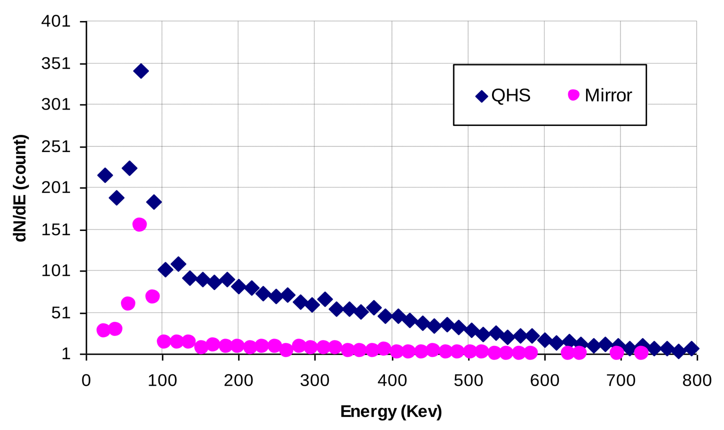
- Detector Type: CdZnTl
- Good energy resolution (*3% – 10 %*).
  Fast timing characteristics (*rise time 0.05 – 0.5 μs*).
- High x-ray stopping efficiency (*Compact size 10 mm x 10 mm x 2 mm*).
- No sensitivity to magnetic field (*no magnetic shields required*)
- Operate at room temperature (*no need for cooling*)
- Fulfills our experimental needs.

4. Initial Results

a. Different Hard X-ray Characteristic in QHS and Mirror

The hard x-ray spectrum for QHS and Mirror, central heating shows:

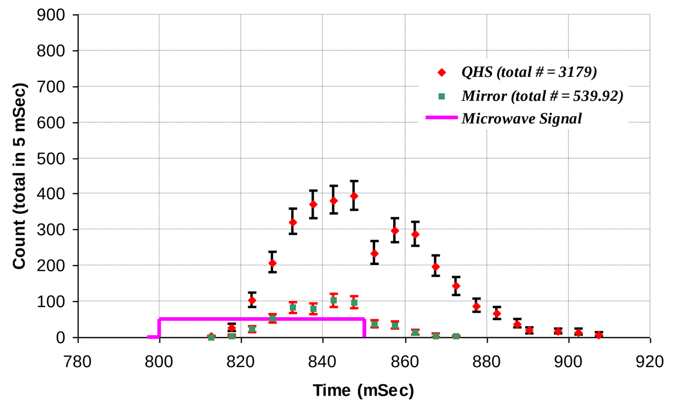
1. Density of superthermal electrons is higher in QHS than in Mirror.
2. Electrons are heated to higher energies in QHS than in Mirror
3. The antiMirror case has a very small signal



Property	QHS	Mirror
Max. Intensity (number)	~ 351	~ 151
Max. Energy (KeV)	~ 600	~ 100

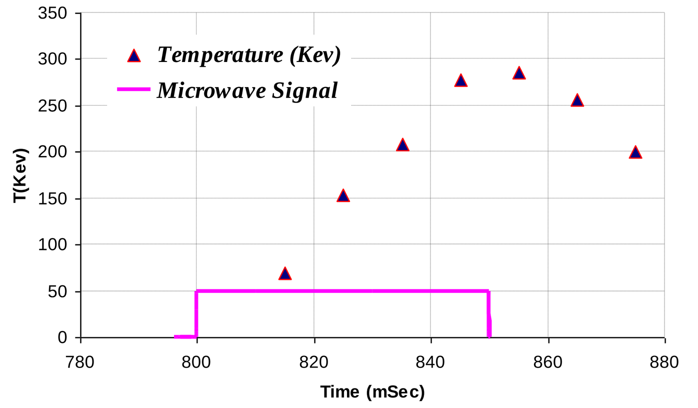
b. Hard X-ray Intensity Shows Improved Confinement in QHS Over Mirror Mode

- HXR signal shows strong evidence of the existence of superthermal electrons in both QHS and mirror configurations (central heating).
- Similar power density in both cases.
- The confinement of superthermal electrons in QHS is better than Mirror case.



Property	QHS	Mirror
Max. Intensity	~ 391	~ 102
decay time τ (msec)	~ 13.0	~ 5.3

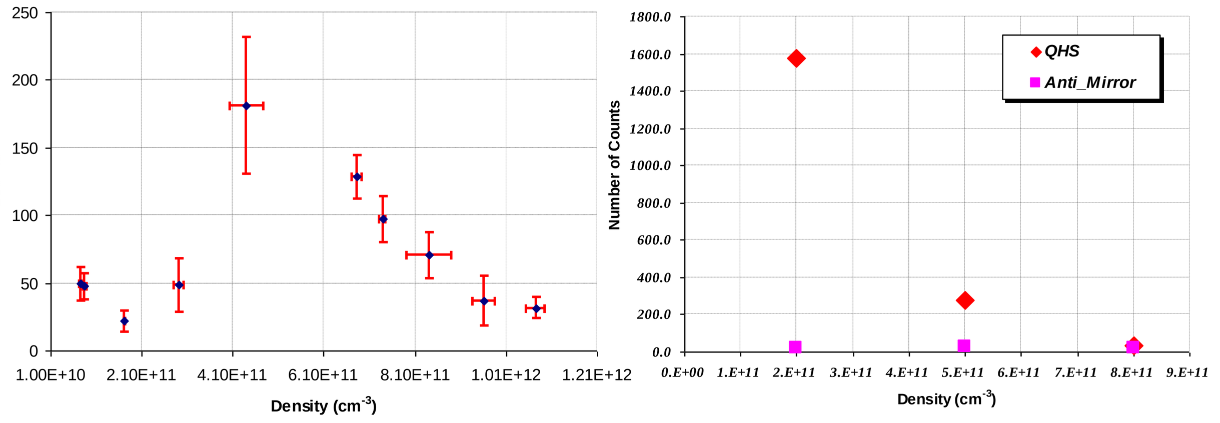
c. "Temperature" Evolution Shows Good Confinement of Superthermal Electrons in the QHS Mode



In QHS, time evolution of the superthermal electron temperature deduced from HXR under the assumption of Maxwellian distribution, shows:

1. Good confinement
2. High energy of superthermal electrons

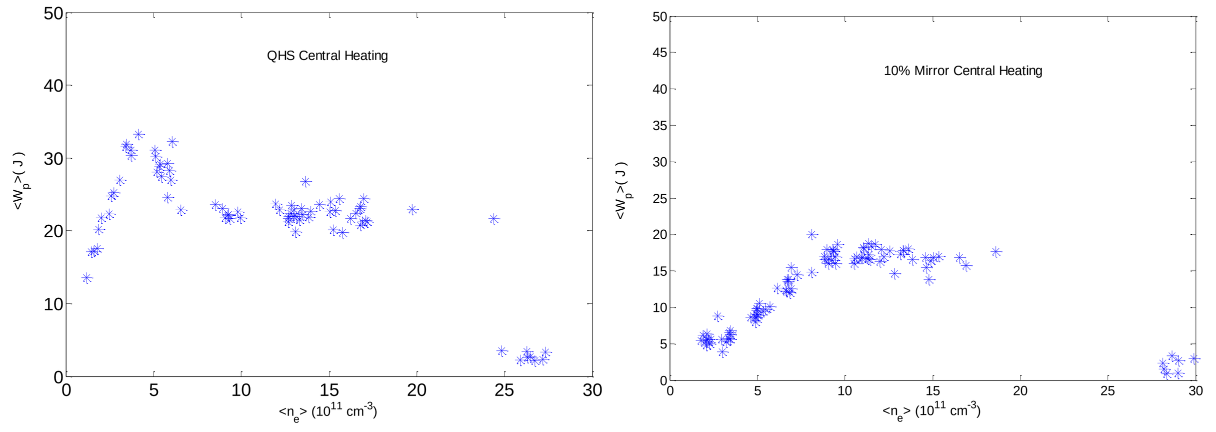
d. Hard X-ray Intensity variation with Plasma Density



1- In QHS The HXR Intensity decreases with density.
2- While in the Anti-Mirror case we have very low count rate.
3- Hard x-ray intensity is nearly flat at $n_e < 4 \times 10^{11}$, then increases suddenly to a maximum at $n_e \sim 4.2 \times 10^{11}$, and begin to decrease with increasing electrons density.

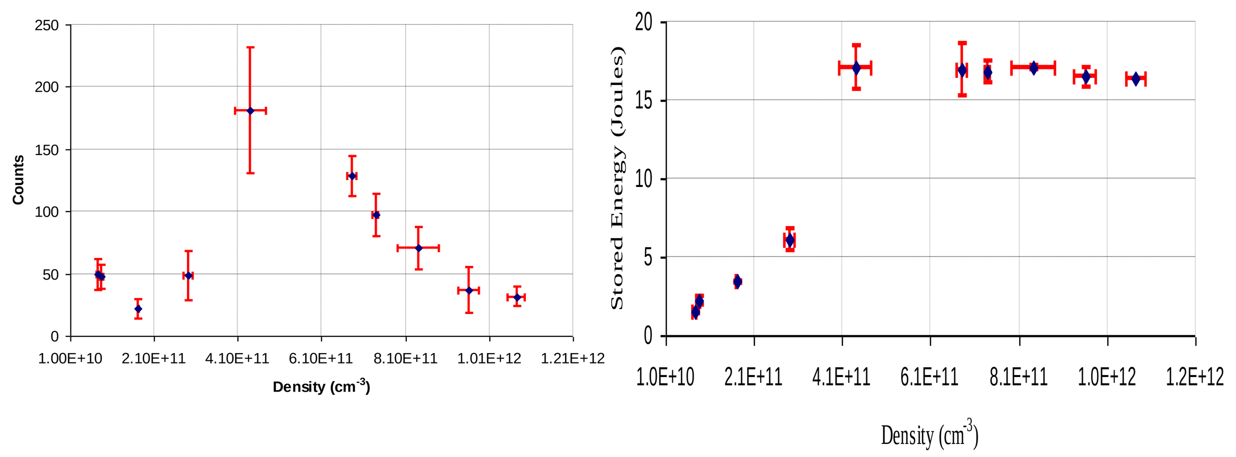
4- QHS and Mirror have similar behavior for $n_e > 5 \times 10^{11}$ cm^{-3}.

e. Different Stored Energy Behavior in QHS and Mirror Modes



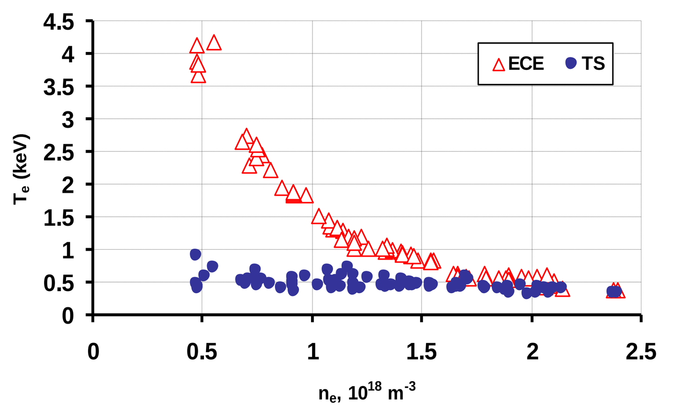
- In QHS, the stored energy increases with density ($n_e < 4 \times 10^{11}$ cm^{-3}), then it begin to decrease with further increase in density, and become flat for $n_e > 9 \times 10^{11}$ cm^{-3}.
- In Mirror, the stored energy increases with density ($n_e < 9 \times 10^{11}$ cm^{-3}), and become constant for $n_e > 9 \times 10^{11}$ cm^{-3}.

f. Stored Energy may be Correlated with Hard X-ray



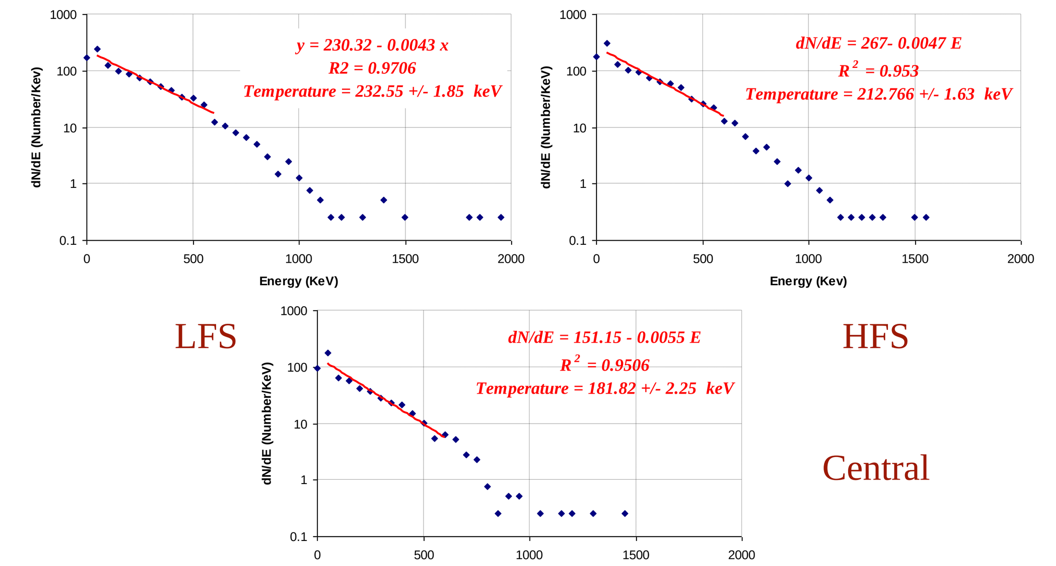
- In Mirror, stored energy increases with density for $n_e < 4.2 \times 10^{11}$ cm^{-3}, and become constant for $n_e > 4.2 \times 10^{12}$ cm^{-3}.
- Hard x-ray and stored energy change their behavior at the same density (i.e. $n_e \sim 4.1 \times 10^{11}$ cm^{-3}).

g. Evidence for a Non-thermal Electron Population



- Comparison of ECE and TS data suggests the existence of non-thermal electrons at lower density plasmas.
- Discrepancy disappears near line averaged densities of ~1.7 - 2.0 × 10^{12} cm^{-3}.
- See K. Likin's poster for more information on ECE, and K. Zhai for Thomson Scattering.

h. Similar HXR Emission at Different Resonance Locations in QHS



As predicted before from the energetic electrons drift orbit analysis in QHS (at n_e = 4 x10^{11} cm^{-3}), there is nearly no difference in hard x-ray emission at different resonance location.

5. Future Work

a. Future Experiment

•What is the effect of changing resonance location on HXR emission?

At the same plasma density, investigate the hard x-ray emission at different resonance locations (LFS, Central, HFS) for QHS, Mirror and antiMirror.

At fixed resonance location, what is the density dependence of the superthermal electrons population?

At each resonance location (LFS, Central, HFS) investigate the hard x-ray emission as density increases.

•What is the effect of changing ripple amplitude on HXR emission?

Investigate the hard x-ray emission in the Mirror mode for different ripple amplitudes (Mirror and antiMirror %).

•Is there any nonthermal component in the stored energy?

Investigate the stored energy dependence on density and resonance location and compare it to the hard x-ray emission.

What is the effect of changing the ECRH power level on the HXR emission?

At fixed resonance location and plasma density, investigate the hard x-ray spectrum as a function of ECRH power level.

b. Fokker-Planck Modeling

The CQL3D code

- **3D, Multi-species, toroidal, fully relativistic code**
- **Accepts the measured plasma parameters (T_e and n_e) as simple input variables to calculate the spatial and temporal distribution functions.**
- **Ray tracing codes TORAY and/or GENRAY are used to derive the ray tracing of the EC beams**
- **The diffusion coefficient as function of radius and energy is calculated in CQL3D using the power deposition and wave electric fields calculated from ray tracing codes.**
- **The code includes highly benchmarked bremsstrahlung diagnostic calculations. The line of site integrals measured by x-ray diagnostics are computed in CQL3D for direct comparison.**
- **CQL3D has a limited applicability to model the Mirror and antiMirror configurations.**

The Marushchenko code

- **5D Fokker-Planck, studies electron cyclotron resonance heating ECRH of fusion plasmas**
- **Periodic magnetic field**
- **The solution for the distribution function is obtained by means of conservative, finite difference, two-step operator scheme.**

c. Experimental method to Model the Superthermal Electron Distribution Function

Another way to model superthermal electron distribution function is to use hard x-ray pulse height analysis diagnostics.

Solution procedures

- Experimental data

Two features of the data the modeling should reproduce

1- The asymmetry in x-ray between small and large viewing angles.

2- The slope of the plot of the photon counts versus photon energy at each viewing angle

- Bremsstrahlung emission $\frac{dN(k,\theta_v)}{dk\,dt} \propto \int d^3\vec{p}\, f(\vec{p},\theta_p)\frac{d\sigma(k,\theta_v,P_e,Z_i)}{dk\,d\theta_v}v_e$

- Bremsstrahlung cross-section

- Model electron distribution function $f(\vec{p}) = C_N e^{\left(-\frac{p_\perp}{2T_\perp}-\frac{p_\parallel}{2T_\parallel}\right)}$

6. Conclusion

- **Hard x-ray analysis of the initial results up to now show better confinement of superthermal electrons in QHS compared to Mirror and antiMirror configuration.**
- **The future experimental work will involve modeling the superthermal electron distribution function, investigating the hard x-ray emission in different magnetic configurations and understanding the nonthermal component of the stored energy.**
- **The Fokker-Planck simulation will help us understand the experimental results and calculate how much energy is carried by superthermal electrons during the ECRH discharges.**