Hard X-rays from Superthermal Electrons in the HSX Stellarator

Preliminary Examination for

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Objectives

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To study the confinement of energetic particles (superthermal electrons) in different magnetic geometries and plasma parameters during electron cyclotron resonance heating (ECRH) in the Helically Symmetric eXperiment (HSX) stellarator.

Outline of the Talk

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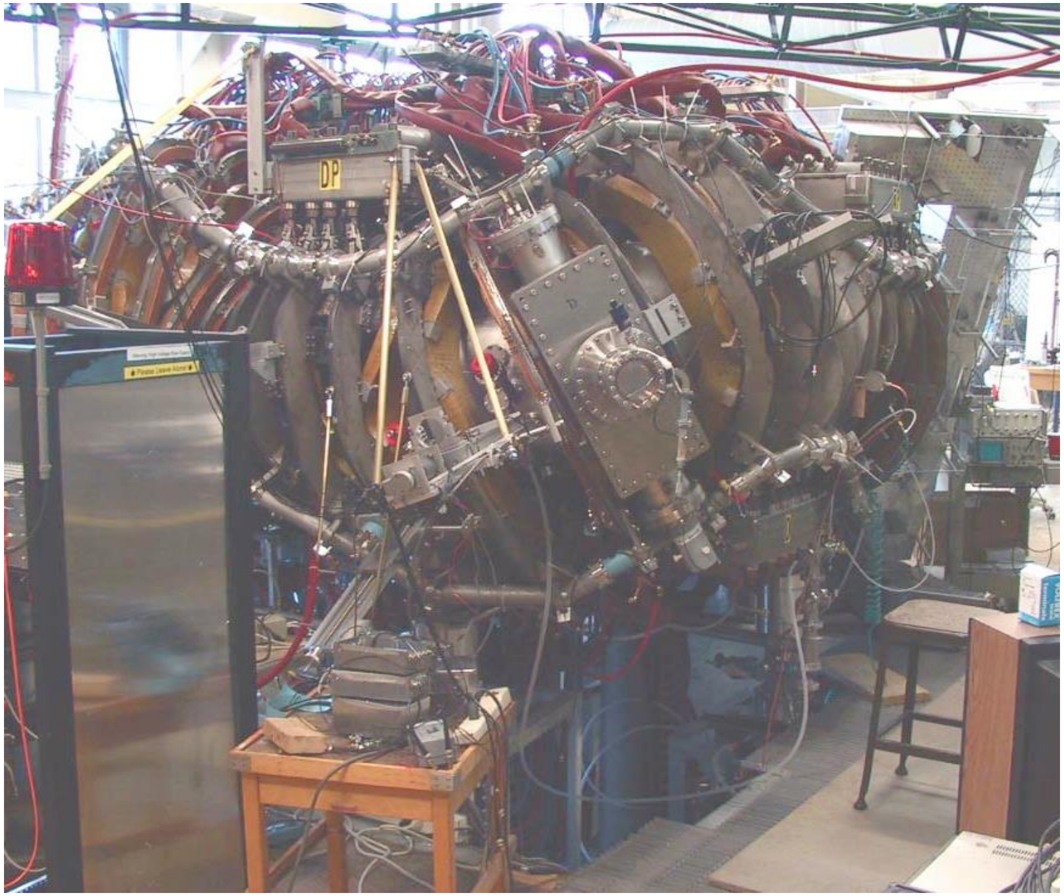
- The HSX experiment
- Hard x-ray diagnostics.
- Initial results.
- Future work.

  - Experimental work
  - Fokker-Planck simulation

The Helically Symmetric eXperiment (HSX)

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



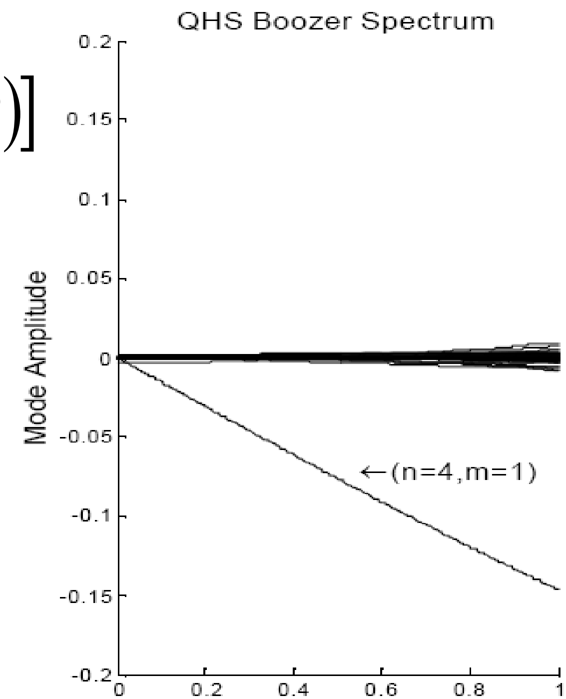
Magnetic Field Structure

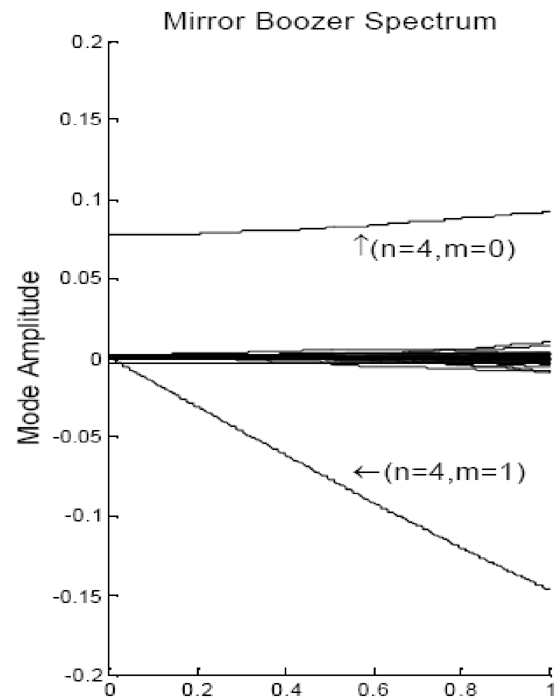
$$B = B_0\left[1 - \varepsilon_h \cos\left(N\phi - m\theta\right)\right]$$

In straight line coordinates

$$\theta = \iota\phi$$

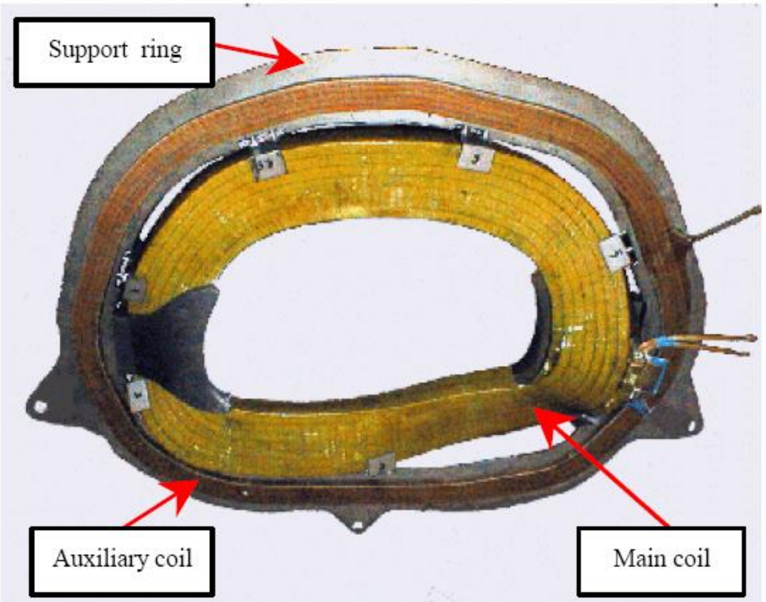
$$B = B_0\left[1 - \varepsilon_h \cos\left(N - m\iota\right)\phi\right]$$

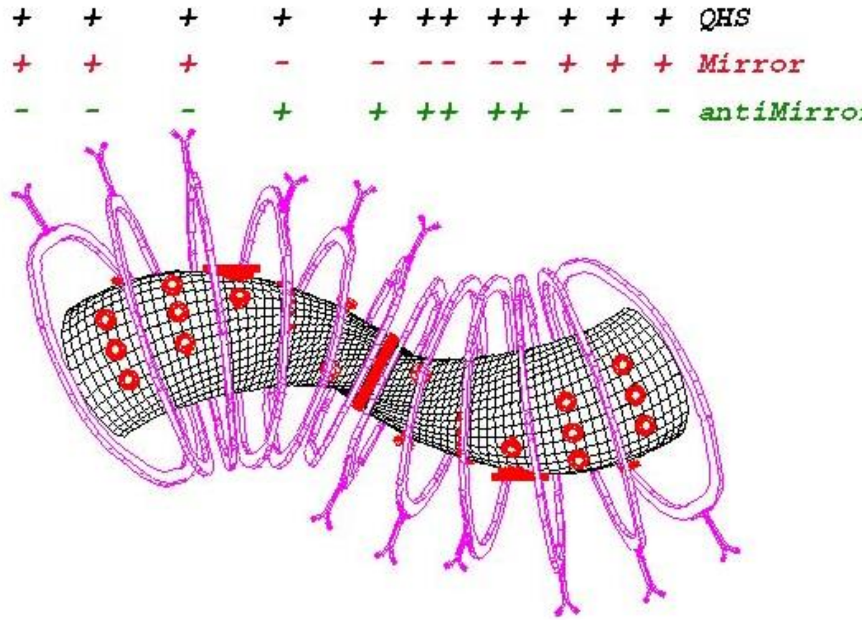




- HSX is the worlds first Quasi-Symmetric Stellarator, based on a dominant n = 4, m = 1 component of the magnetic spectrum.
- This symmetry can be broken by the addition of a large toroidal mirror term (n = 4, m = 0)
- All symmetry breaking terms below 1% of average field.

Modes of Operation

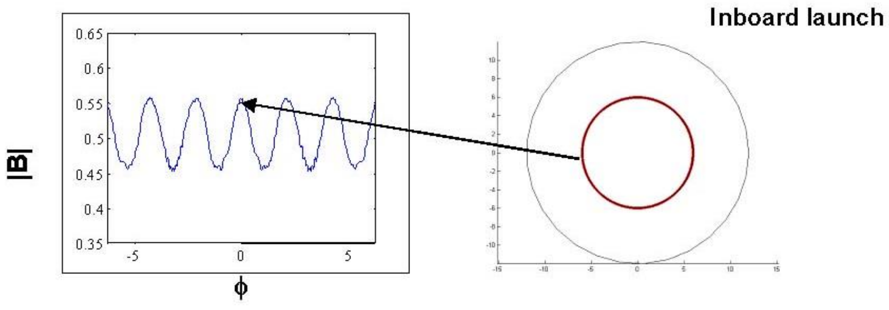


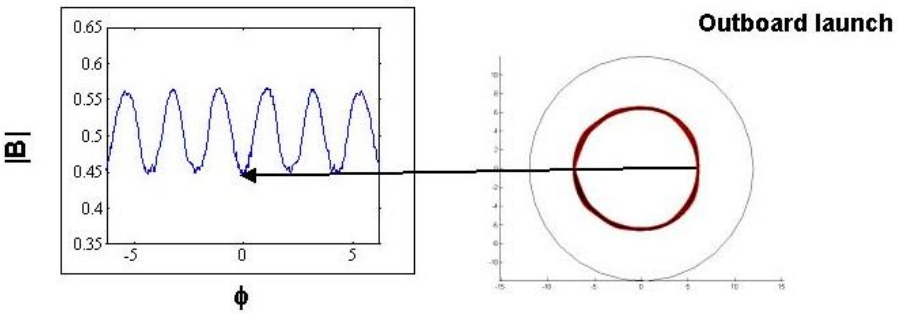


Configuration	Auxiliary Coil Currents	Dominant Feature
QHS	None	Lowest neoclassical transport; Quasi-symmetry
MIRROR	3 coils on ends add to main; center 6 opposite	Neoclassical transport similar to conventional stellarator
ANTI-MIRROR	Opposite phasing to mirror	Similar neoclassical transport to Mirror.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

Particle Orbits in QHS Configuration

20 KeV electrons with 80º pitch angle, launched at $\phi = 0$, and r/a = ½

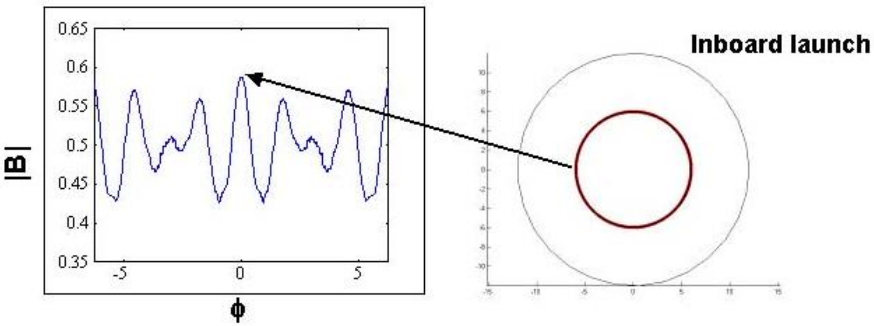


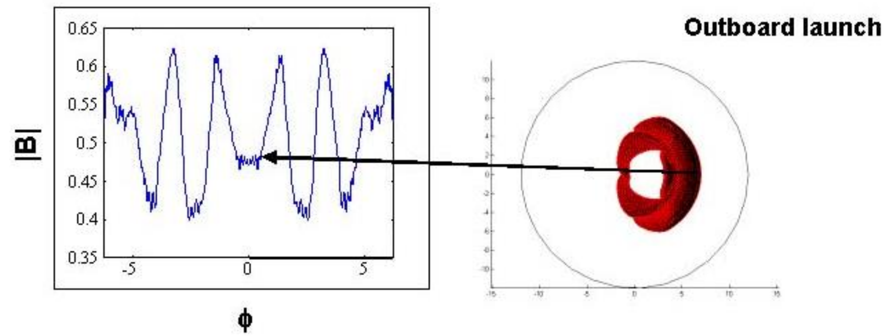


- When electrons are launched at the inboard side (the top of magnetic well) they are passing particles
- When they are launched at the outboard side (the bottom of the magnetic well) they are trapped with their orbits deviation from home flux surface being small compared to Mirror and antiMirror cases.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

Particle Orbits in Mirror Configuration

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





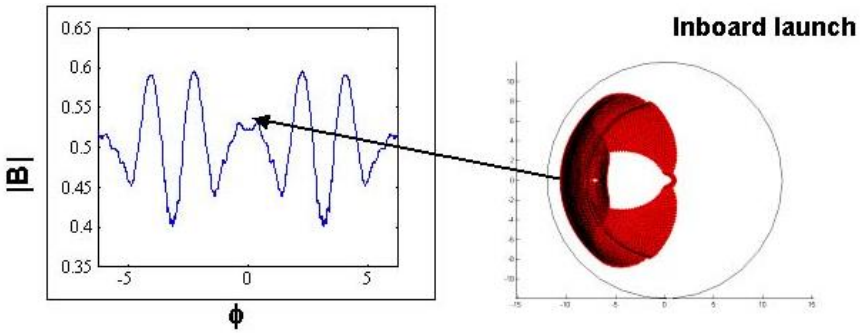
• When electrons are launched at the inboard side (top of the magnetic well) they are passing particles. Similar to the QHS inboard case.

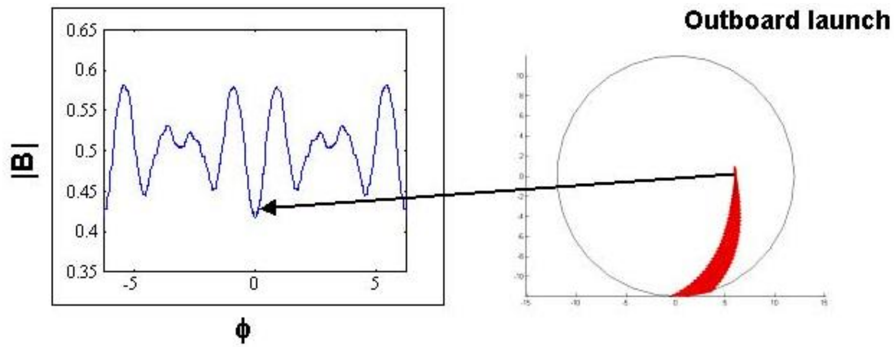
• When they are launched at the outboard side (bottom of the magnetic well) they are trapped with their orbits deviation from home flux surface being large compared to QHS (because of the asymmetry in the magnetic ripples).

• Different hard x-ray emission is expected in inboard and outboard sides.

Particle Orbits in antiMirror Configuration

20 KeV electrons with 80° pitch angle, launched at $\phi = 0$, 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.

Hard X-ray Diagnostics

Hard X-ray Detector

- Detector Type: CdZnTl
- Good energy resolution (*3% – 10 %*).

  Peak/Valley: > 8:1 @ 59.5 Kev

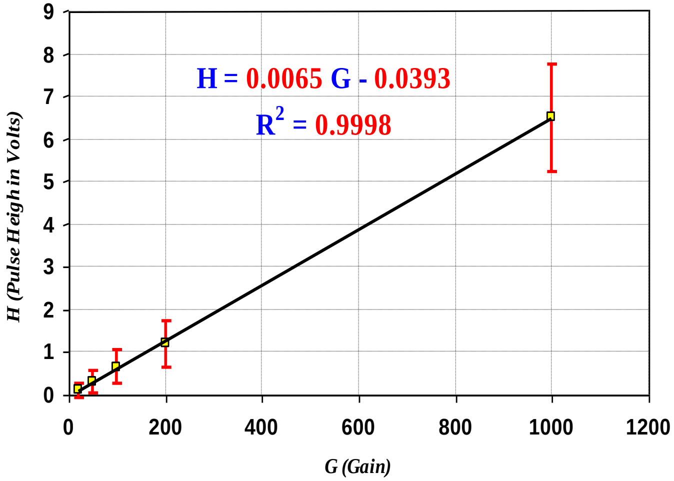
  Resolution: < 10% (6 KeV)@ 59.5 KeV (FWHM)

  Peak/Valley: > 3:1 @ 122 Kev

  Resolution: < 6% (8 KeV)@ 122 KeV (FWHM)

  Peak/Valley: > 1.8:1 @ 622 Kev

  Resolution: < 3% (20 KeV)@ 622 KeV (FWHM)
- 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.



Pulse Height Analysis

•Why direct digitization?

1- Dynamic timing binning

2- Better noise rejection/pile up detection

3- simple hardware implementation

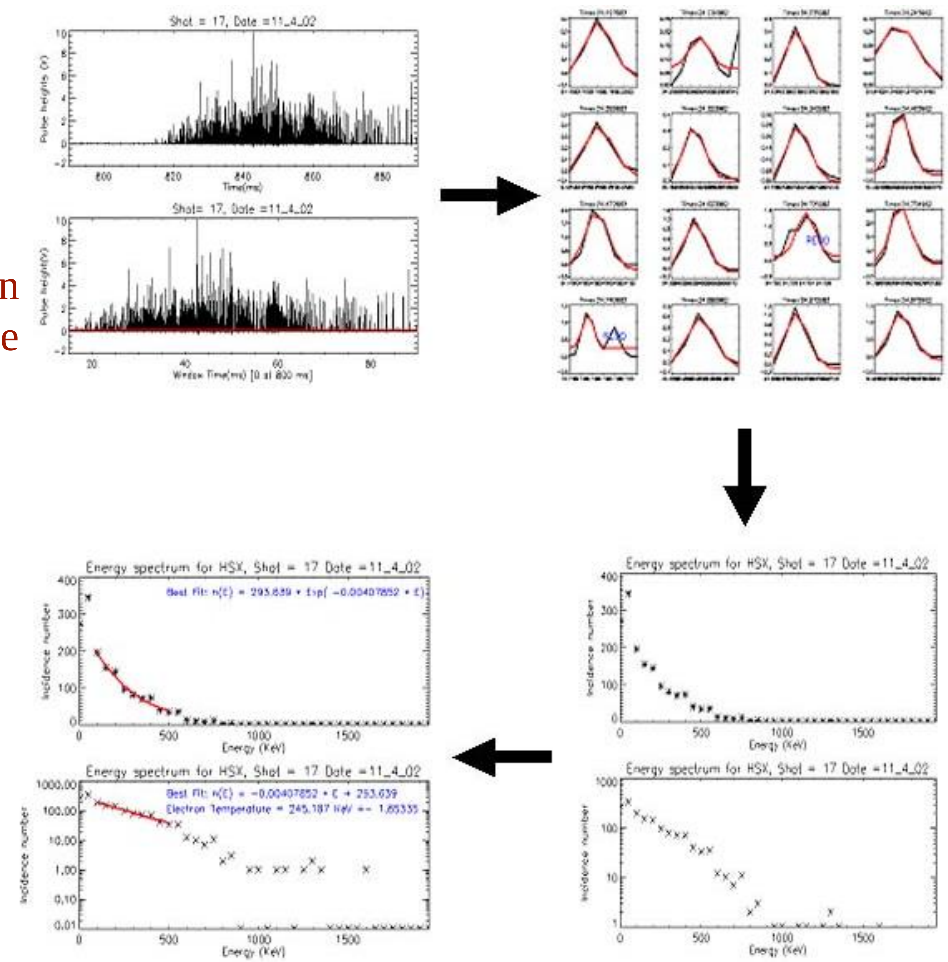
•The pulse height analysis program is written in IDL. The program mainly evaluate the following:

1- Resolving the Gaussian signals (single & double).

2- Least square fitting for the signals

3- Spectral Analysis of the signal

4- Calculation of the electron Temperature

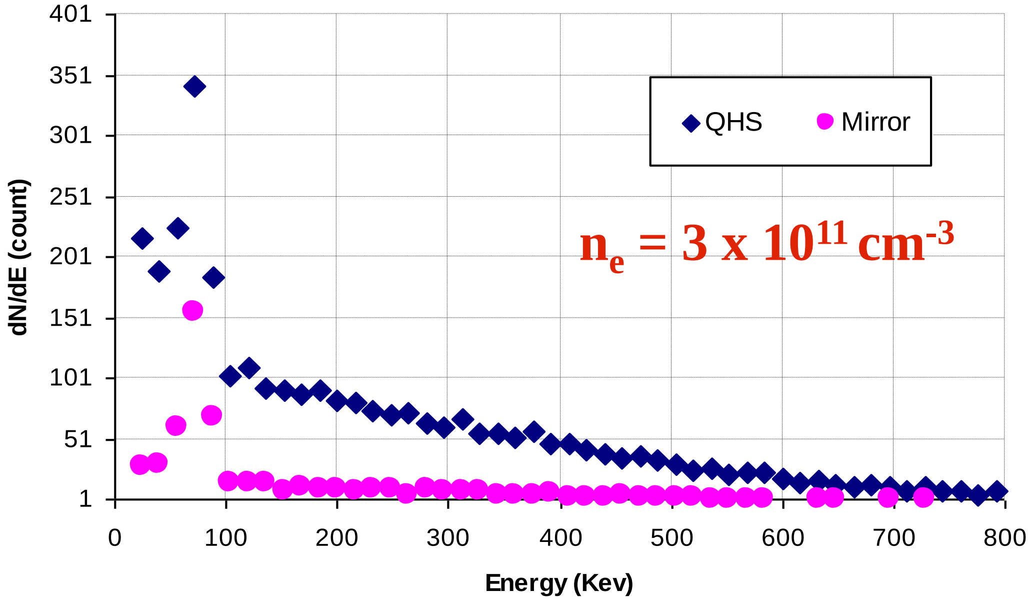


Initial Results

Different Hard X-ray Characteristics in QHS and Mirror

The Hard X-ray spectrum for QHS and Mirror, central heating shows:

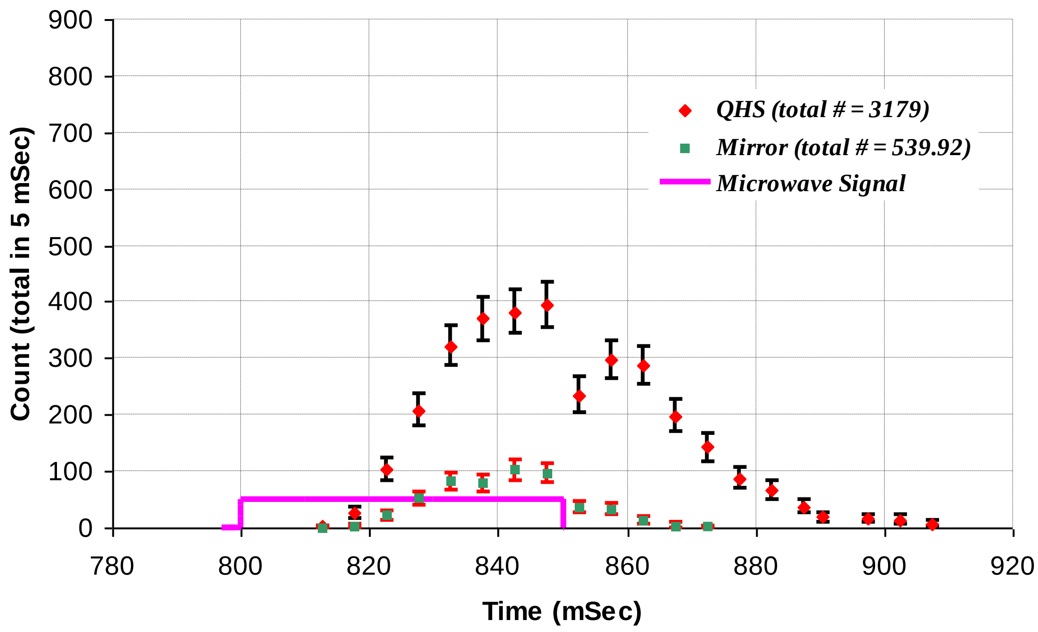
- Density of superthermal electrons is higher in QHS than in Mirror.
- Electrons are heated to higher energies in QHS than in Mirror
- The antiMirror case has a very small signal – in the noise



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

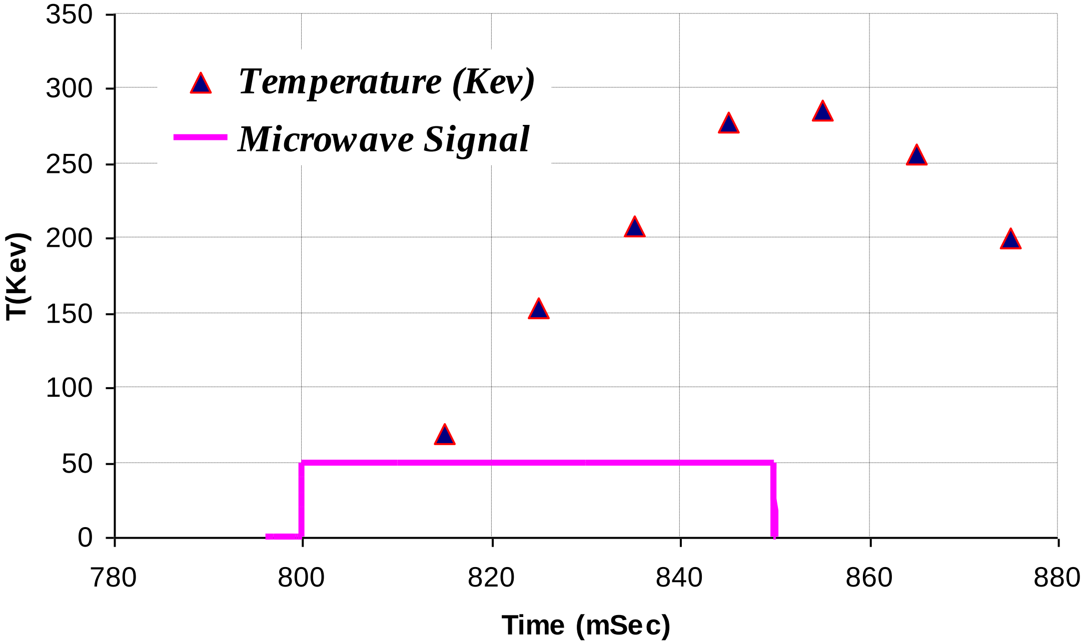
Hard X-ray Intensity Shows Improved Confinement in QHS Over Mirror Mode

- Hard X-ray signals show strong evidence for the existence of superthermal electrons in both QHS and mirror configurations (central heating).
- Similar input power density in both cases.
- The confinement of superthermal electrons in QHS is better than Mirror case.



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

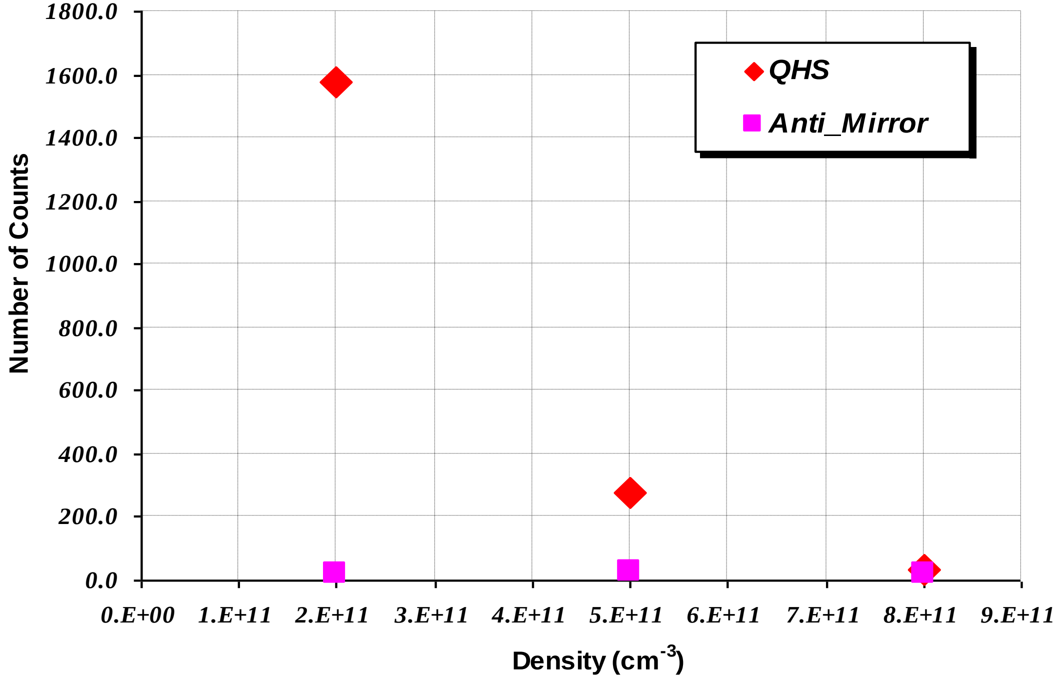
“Temperature” Evolution Shows Good Confinement of Superthermal Electrons in the QHS Mode



In QHS, the time evolution of the superthermal electron temperature deduced from Hard X-Ray data

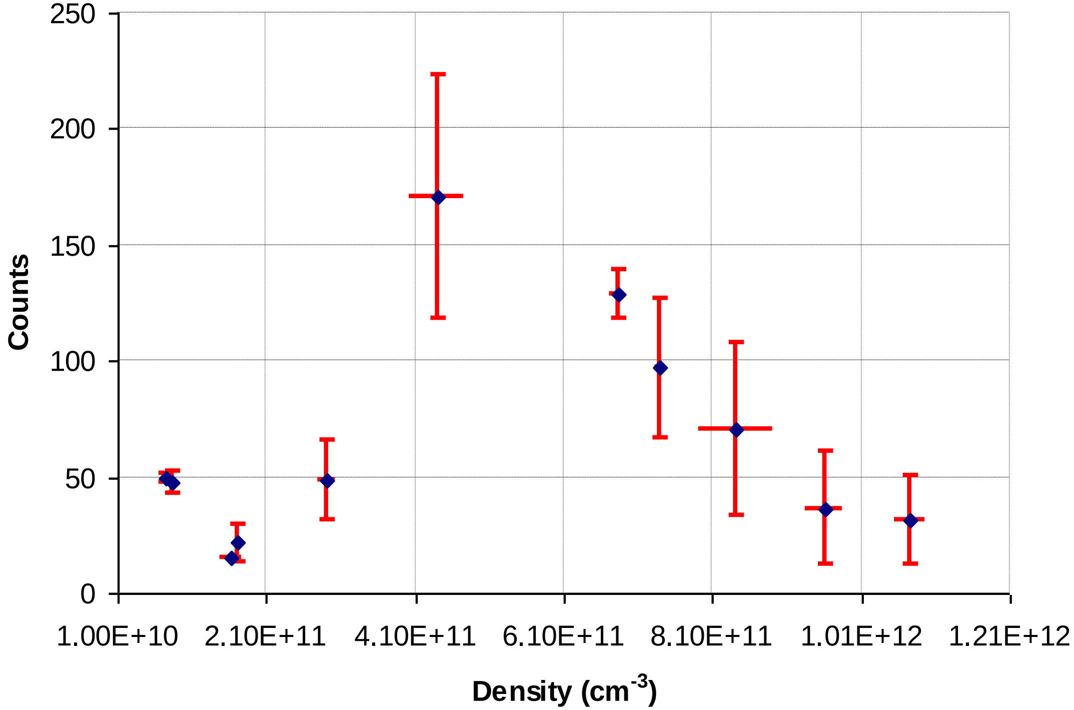
1. Good confinement
2. High energy super-thermal electrons

Hard X-ray Intensity Decreases with Plasma Density



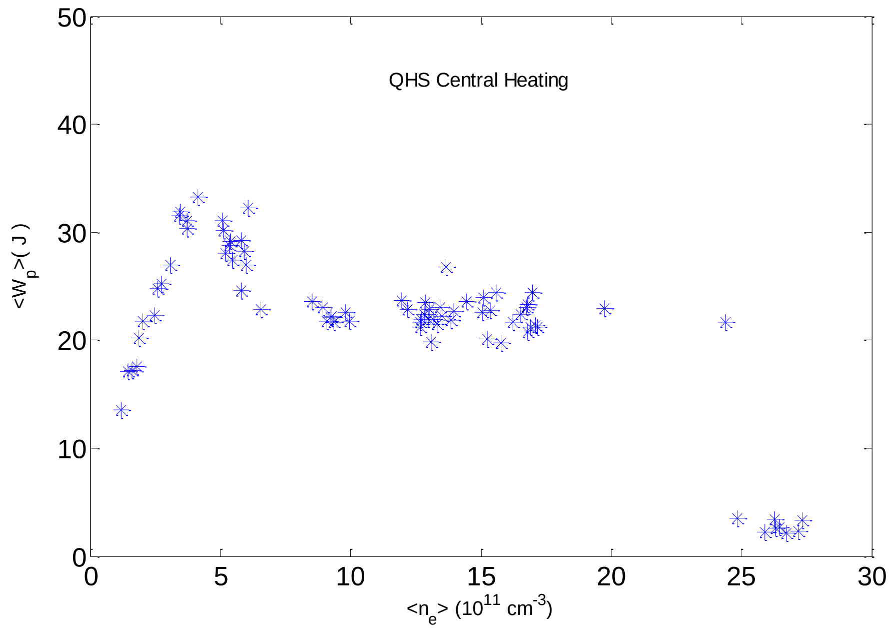
- In QHS The Hard X-Ray intensity decreases with density.
- For the Anti-Mirror case we have very low count rate.

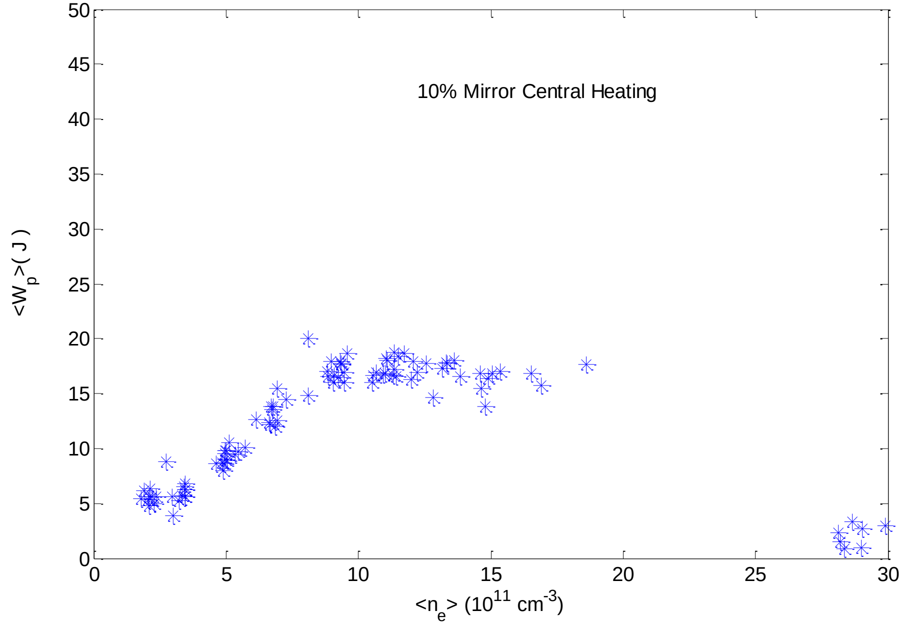
Hard X-ray Intensity has a Complicated Density Dependence in the Mirror Mode



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

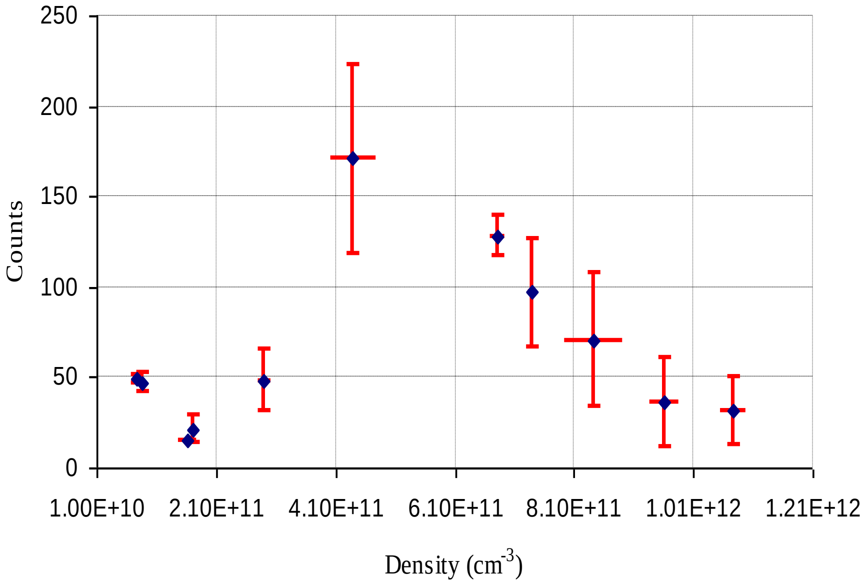
Different Stored Energy Behavior in QHS and Mirror Modes

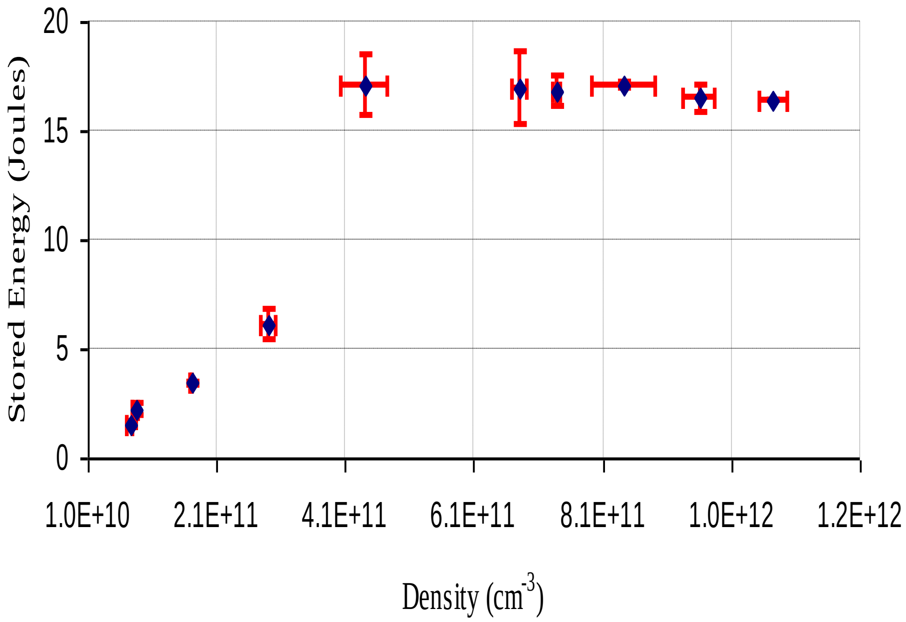




- In QHS, the stored energy increases with density ($n_e < 4 \times 10^{11}$ cm^{-3}), then it begin to decrease with further increase in density, and become flat for $n_e > 9 \times 10^{11}$ cm^{-3}.
- In Mirror, the stored energy increases with density ($n_e < 9 \times 10^{11}$ cm^{-3}), and become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

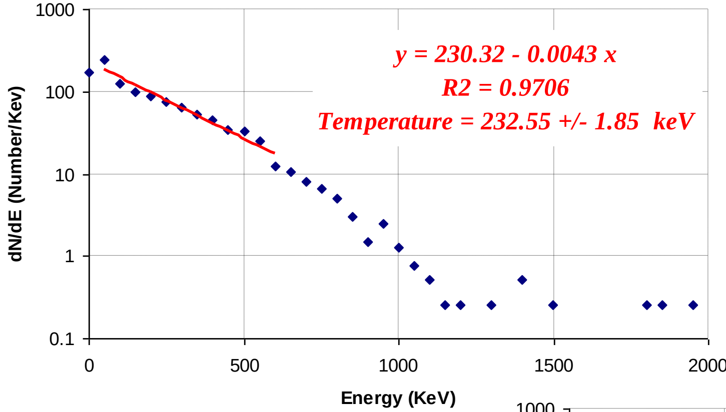
Stored Energy may be Correlated with Hard X-ray



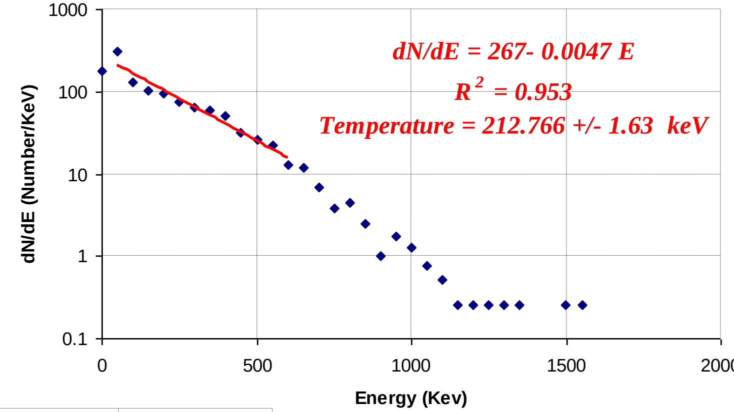


- In Mirror, stored energy increases with density for $n_e < 4.2 \times 10^{11}$ cm^{-3}, and become constant for $n_e > 4.2 \times 10^{12}$ cm^{-3}.
- Hard x-ray and stored energy change their behavior at the same density (i.e. $n_e \sim 4.1 \times 10^{11}$ cm^{-3}).

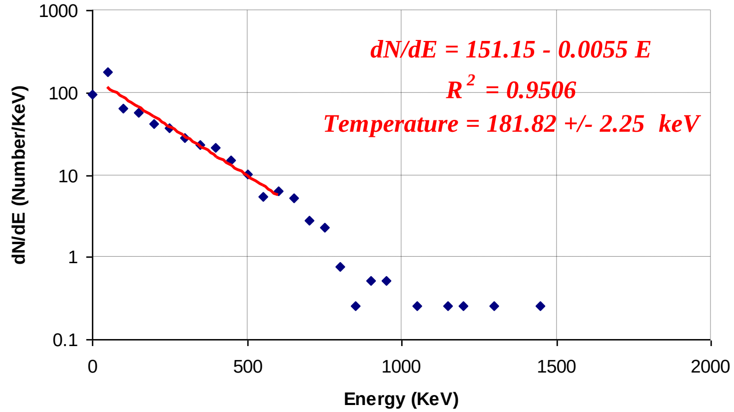
Similar HXR Emission at Different Resonance Locations in QHS



LFS



Central



HFS

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.

Summary of the Initial Results

- At low density, hard x-ray intensity is higher in QHS than in Mirror.
- Higher superthermal electron energy in QHS than in Mirror.
- In QHS, superthermal electrons stays for longer time in the machine compared to Mirror after the ECRH source is turned off.
- Temperature evolution shows good confinement of superthermal electrons in QHS.
- The stored energy may have a nonthermal component.
- Hard x-ray emission does not depend on resonance location for QHS.
- The antiMirror mode has the worst confinement.

Future Work

Future Experiments

- **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.

Future Experiments

- **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.

Why Fokker-Planck Simulation?

- Fokker-Planck calculations permit model of experimental data.
- We will be able to calculate the superthermal electron distribution function in different magnetic configurations.
- Use the calculated distribution function to calculate the HXR emission and compare it with the experimentally measured one.
- Estimate the density and total energy carried by the superthermal electrons.

Fokker-Planck Codes

The CQL3D code

- Multi-species (electrons and ions), toroidal, fully relativistic code
- 3D, two velocity dimensions (v_{γ},$v_{||}$) and one spatial dimension ρ (radial).
- Accepts the measured plasma parameters (T_e and n_e) as simple input variables to calculate the spatial and temporal distribution functions for electrons and ions.
- Ray tracing codes TORAY and/or GENRAY are used to derive the ray tracing of the EC beams
- The diffusion coefficient (velocity space 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 (pulse height analysis system) are computed in CQL3D for direct comparison.

Fokker-Planck Codes

CQL3D has a limited applicability to model the Mirror and antiMirror configurations.

The Marushchenko code

- Bounce-averaged
- 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.

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.

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

    - The slope of the plot of the photon counts versus photon energy at each viewing angle (spectrum at each angle)
  - Bremsstrahlung emission

$$\frac{dN(k',\theta_a)}{dk'dt} \propto \int d^3\vec{P}\, f(\vec{P},\theta_p)\frac{d\sigma(k',\theta_o,P_o,Z_i)}{dk'd\theta_o}v_o$$

  - Bremsstrahlung cross-section
  - Model electron distribution function.

$$f(\vec{p}) = C_N e^{\left(-\frac{P_\perp}{2T_\perp}-\frac{P_{//}}{2T_{//}}\right)}$$

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.