



# Superthermal Electrons Dynamics in the HSX Stellarator

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## 1. The Helically Symmetric Experiment (HSX)

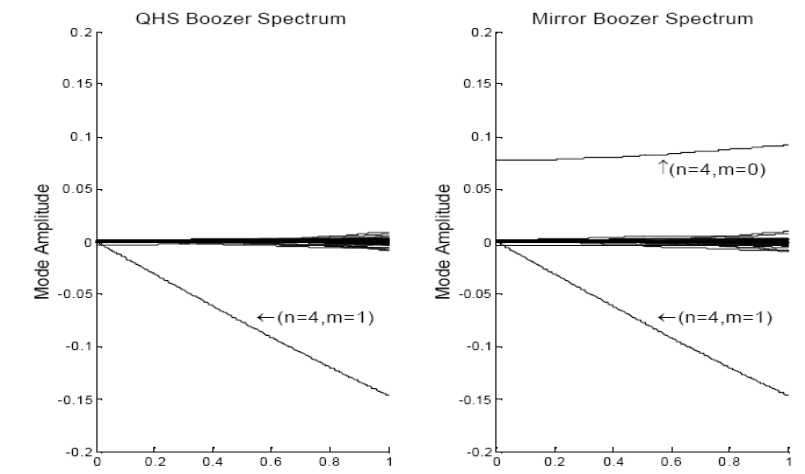
### a. Machine Parameters

|                              |                     |
|------------------------------|---------------------|
| Major Radius                 | 1.2 m               |
| $\langle r \rangle$          | 0.12 m              |
| Volume                       | ~.44 m <sup>3</sup> |
| Field periods                | 4                   |
| $\ell_{axis}$                | 1.05                |
| $\ell_{edge}$                | 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        |

2<sup>nd</sup> harmonic X-mode ECRH is used to produce and heat the plasma  $\Rightarrow$  drives superthermal electron tail at low density

### 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.

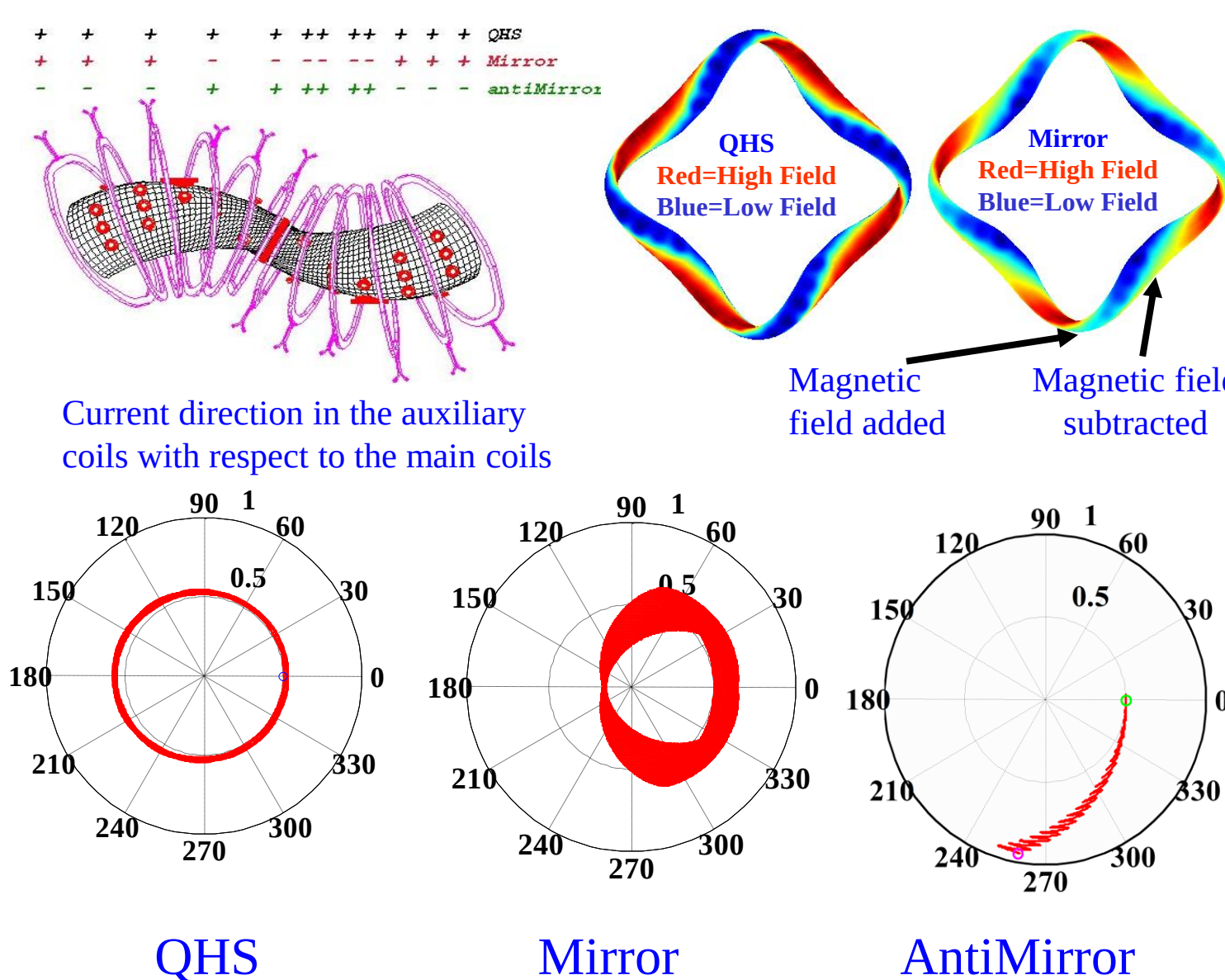


$$B = B_0 [1 - \varepsilon_h \cos(N\phi - m\theta)]$$

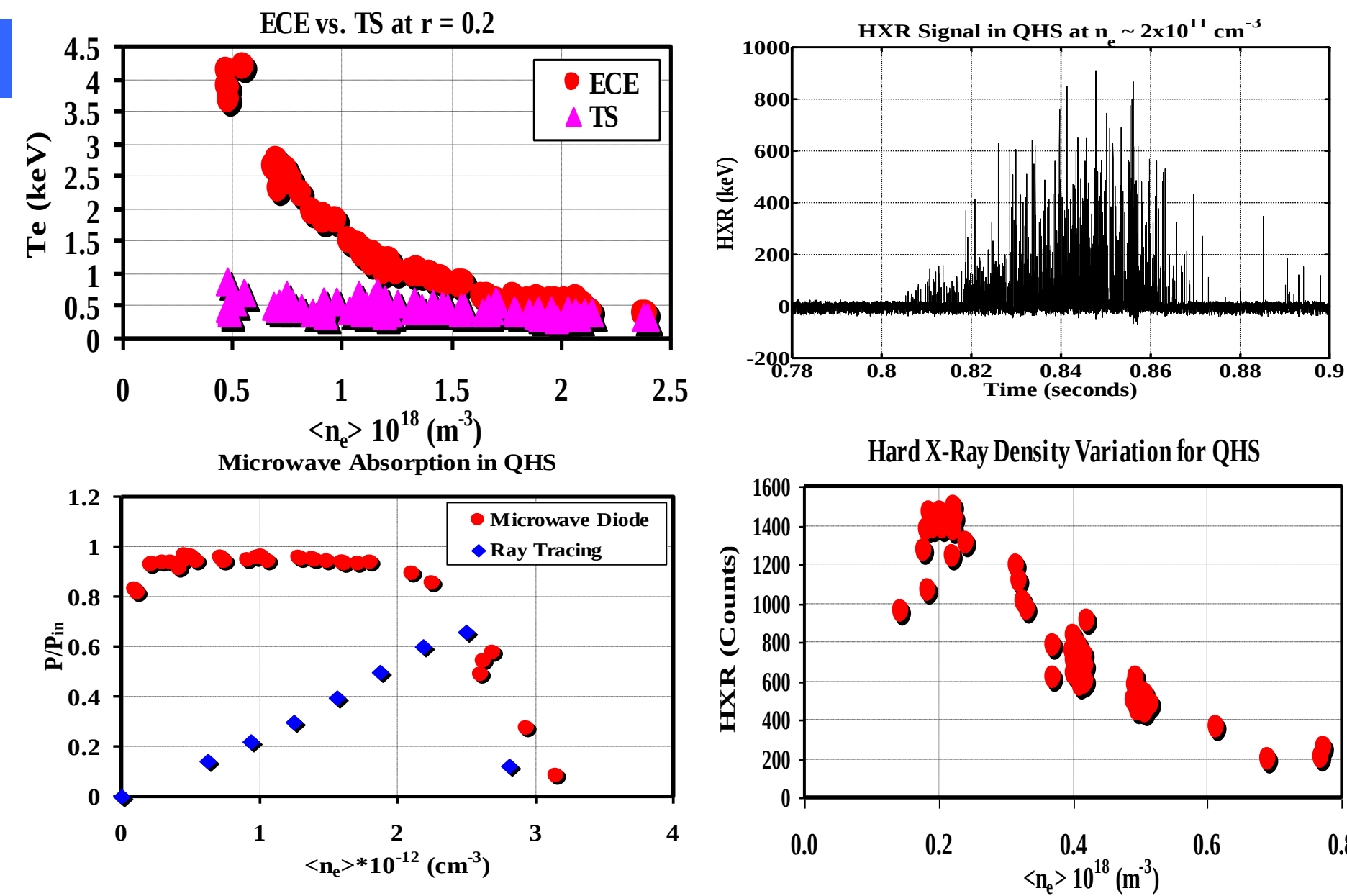
In straight line coordinates  $\theta = t\phi$

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

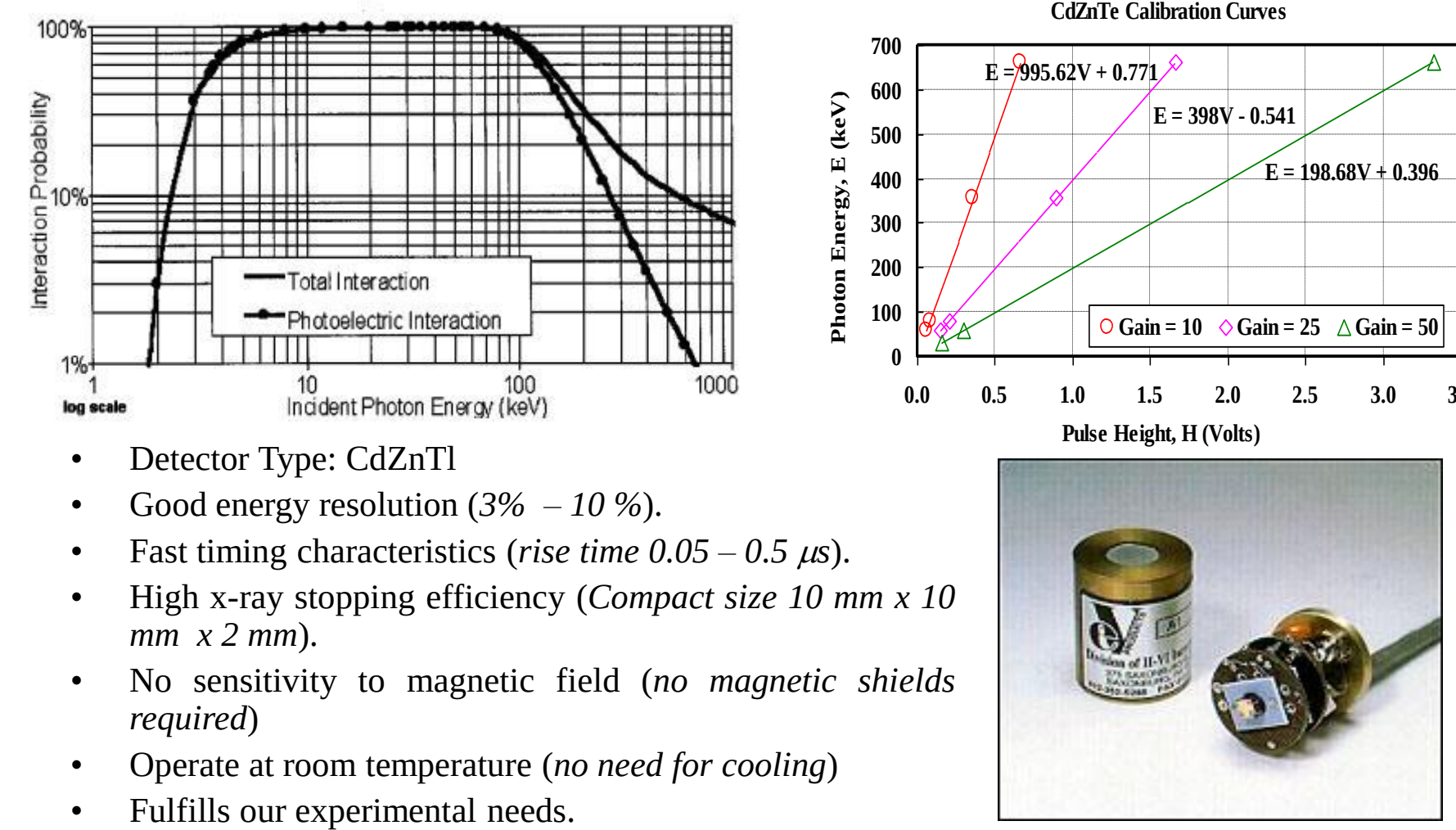
### c. HSX has the Flexibility to Operate with/without Quasi-Helical Symmetry in One Machine



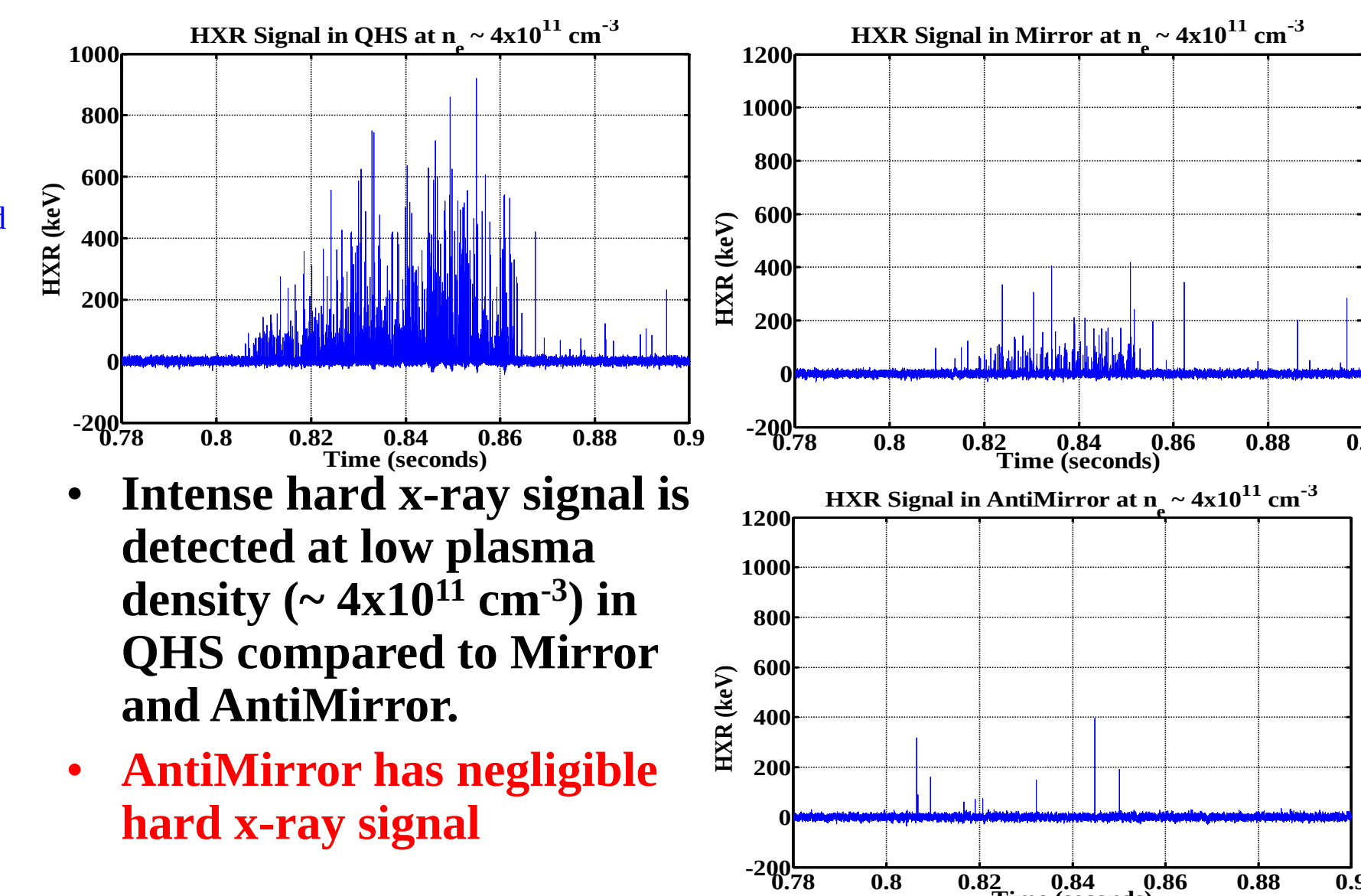
## 2. High Population of Superthermal Electrons is Generated at Low Plasma Density in HSX



## 3. Hard X-ray Diagnostics

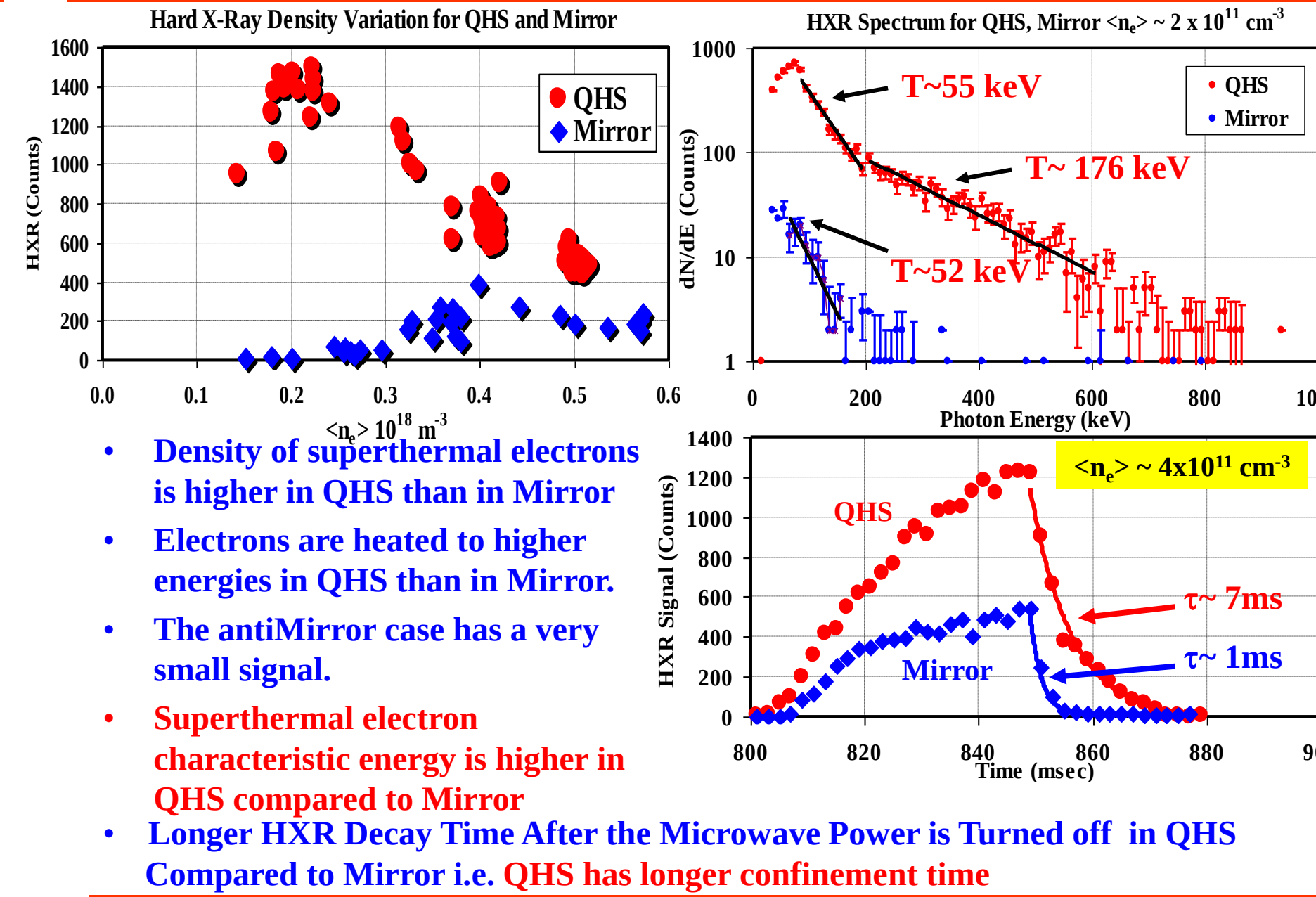


## 4. Different Hard X-ray Emission in Different Magnetic Configurations



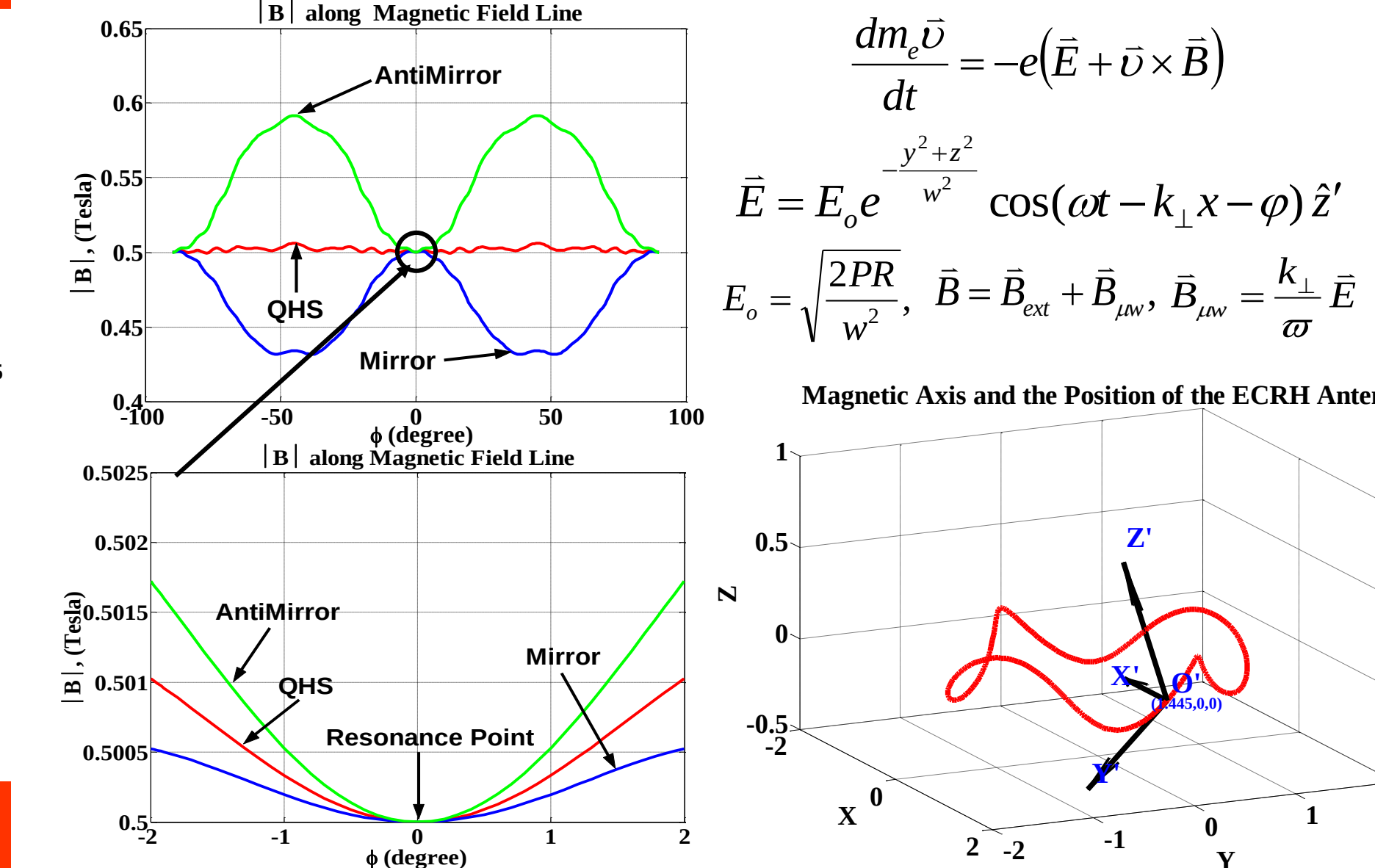
- Intense hard x-ray signal is detected at low plasma density ( $\sim 4 \times 10^{11} \text{ cm}^{-3}$ ) in QHS compared to Mirror and AntiMirror.
- AntiMirror has negligible hard x-ray signal

## 5. X-ray Diagnostics Show Higher Superthermal Electron Tail in QHS Compared to Mirror

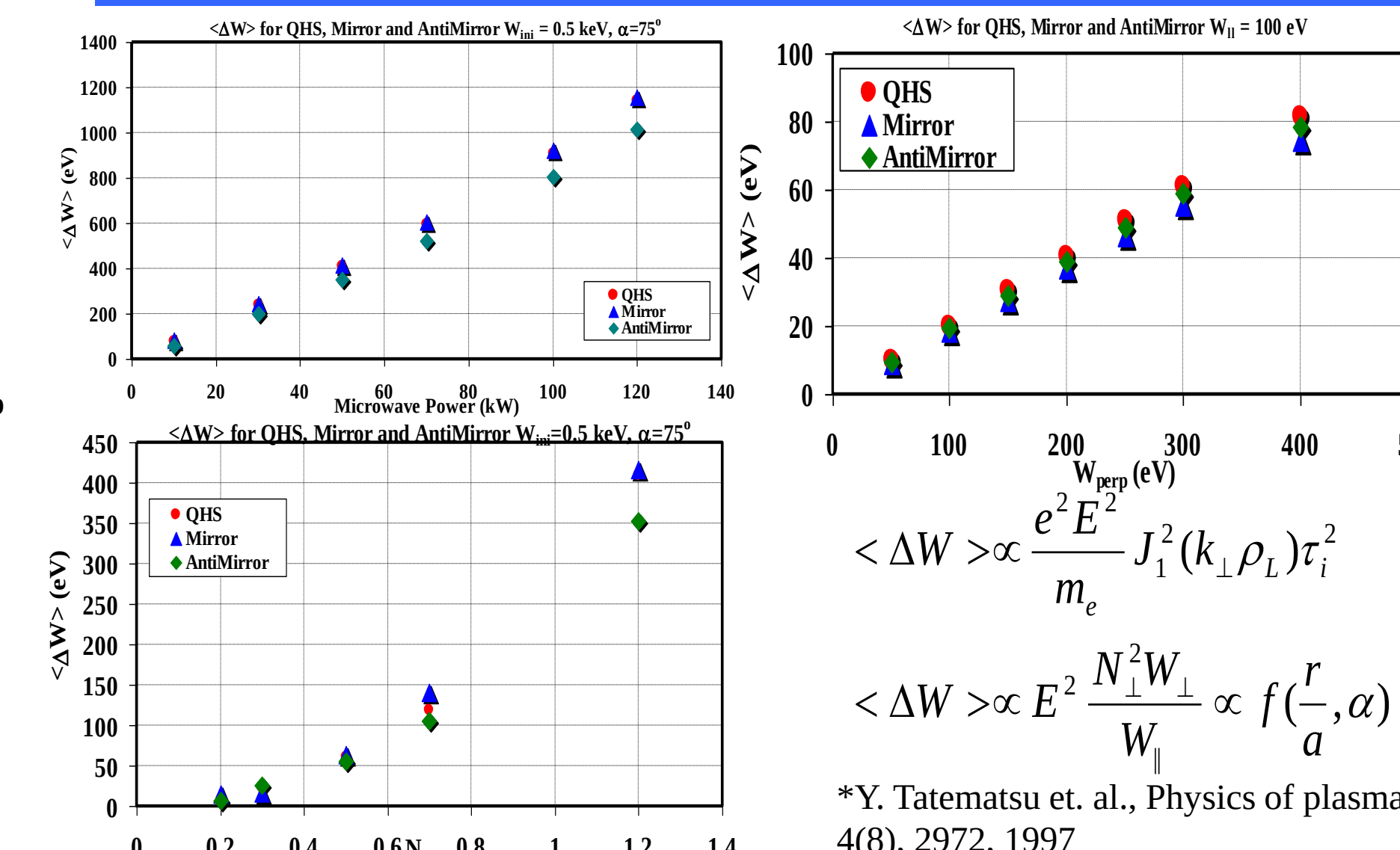


- Density of superthermal electrons is higher in QHS than in Mirror
- Electrons are heated to higher energies in QHS than in Mirror.
- The antiMirror case has a very small signal.
- Superthermal electron characteristic energy is higher in QHS compared to Mirror
- Longer HXR Decay Time After the Microwave Power is Turned off in QHS Compared to Mirror i.e. QHS has longer confinement time

## 6. The Equation of Motion with a Lorentz Force is Solved to Study Single Transit Energy Gain $\langle \Delta W \rangle$



### a. No Difference in $\langle \Delta W \rangle$ between Magnetic Configurations



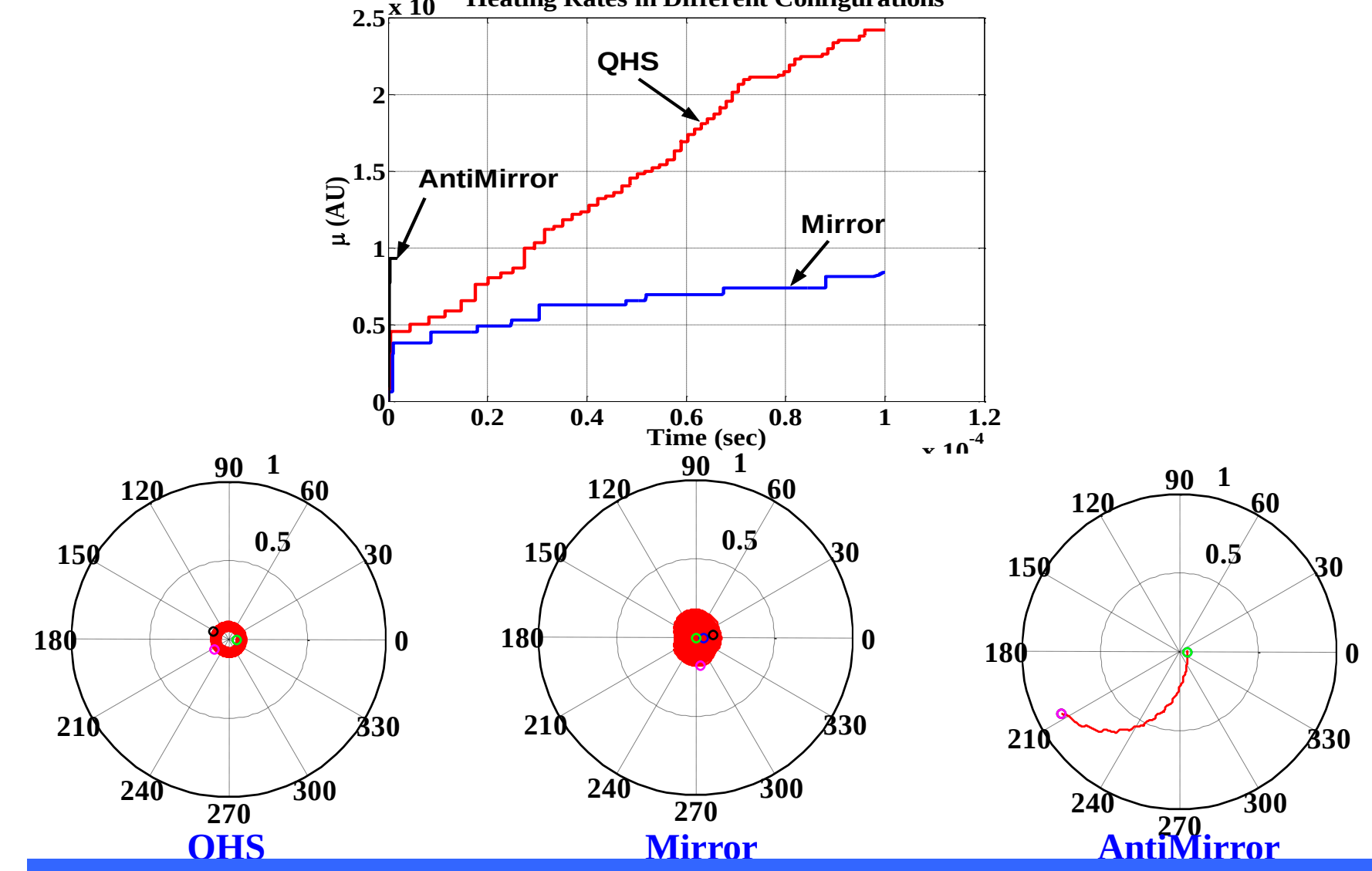
$$\frac{dm_e \bar{v}}{dt} = -e(\bar{E} + \bar{v} \times \bar{B})$$

$$\bar{E} = E_0 e^{-\frac{y^2 + z^2}{w^2}} \cos(\omega t - k_{\perp} x - \phi) \hat{z}$$

$$E_0 = \sqrt{\frac{2PR}{w^2}}, \quad \bar{B} = \bar{B}_{ext} + \bar{B}_{\perp w}, \quad \bar{B}_{\perp w} = \frac{k_{\perp}}{\omega} \bar{E}$$

Magnetic Axis and the Position of the ECRH Antenna

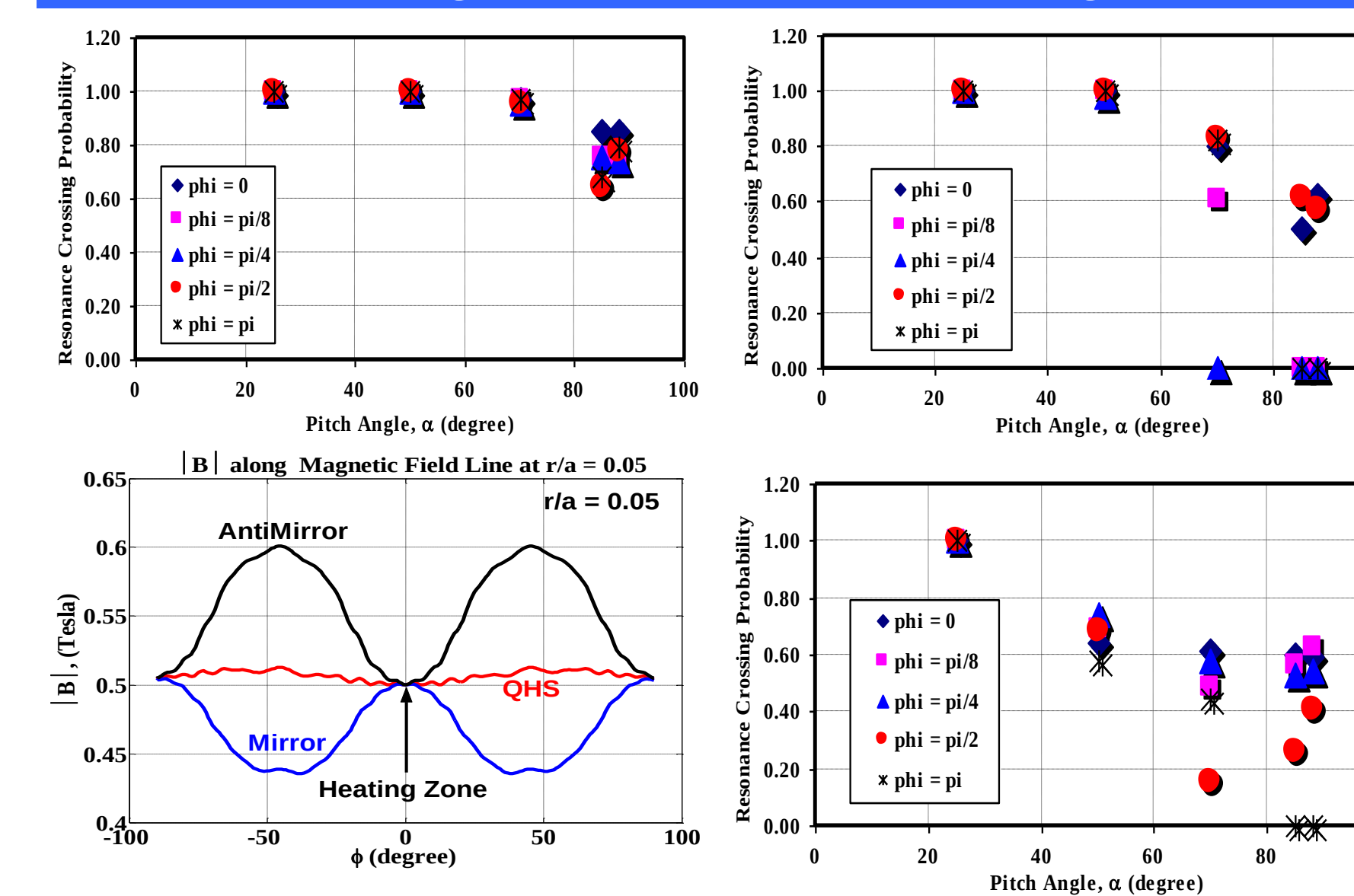
## 7. Higher Heating Rate in QHS Compared to Mirror



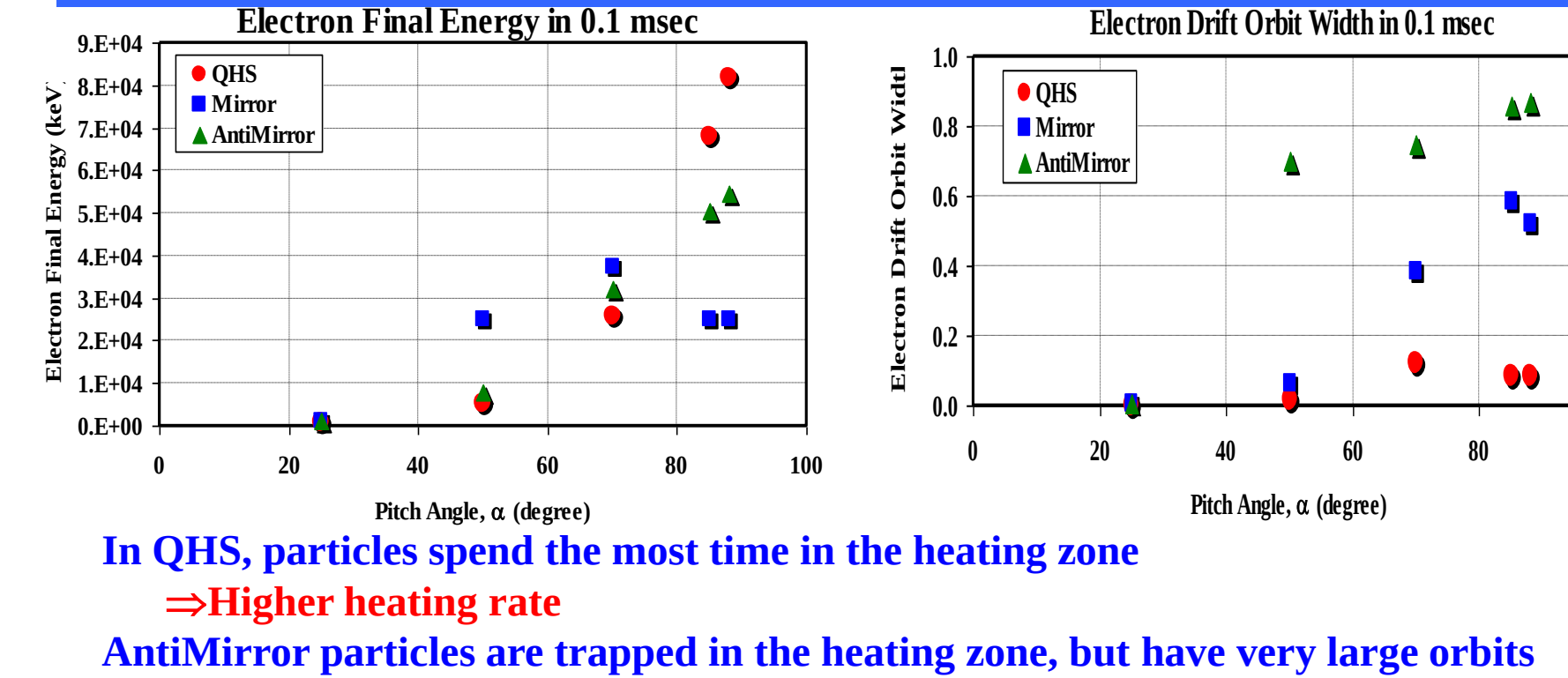
### a. Figures of Merit to Quantify Orbit Topology

- Resonance zone crossing probability (small circle area/large circle area)
- Resonance zone crossing time fraction (time fraction particle spend in resonance)
- Final electron energy (heating rate)
- Electron drift orbit width ( $r_{max} - r_{min}$ )

### b. QHS has the Highest Resonance Zone Crossing Probabilities

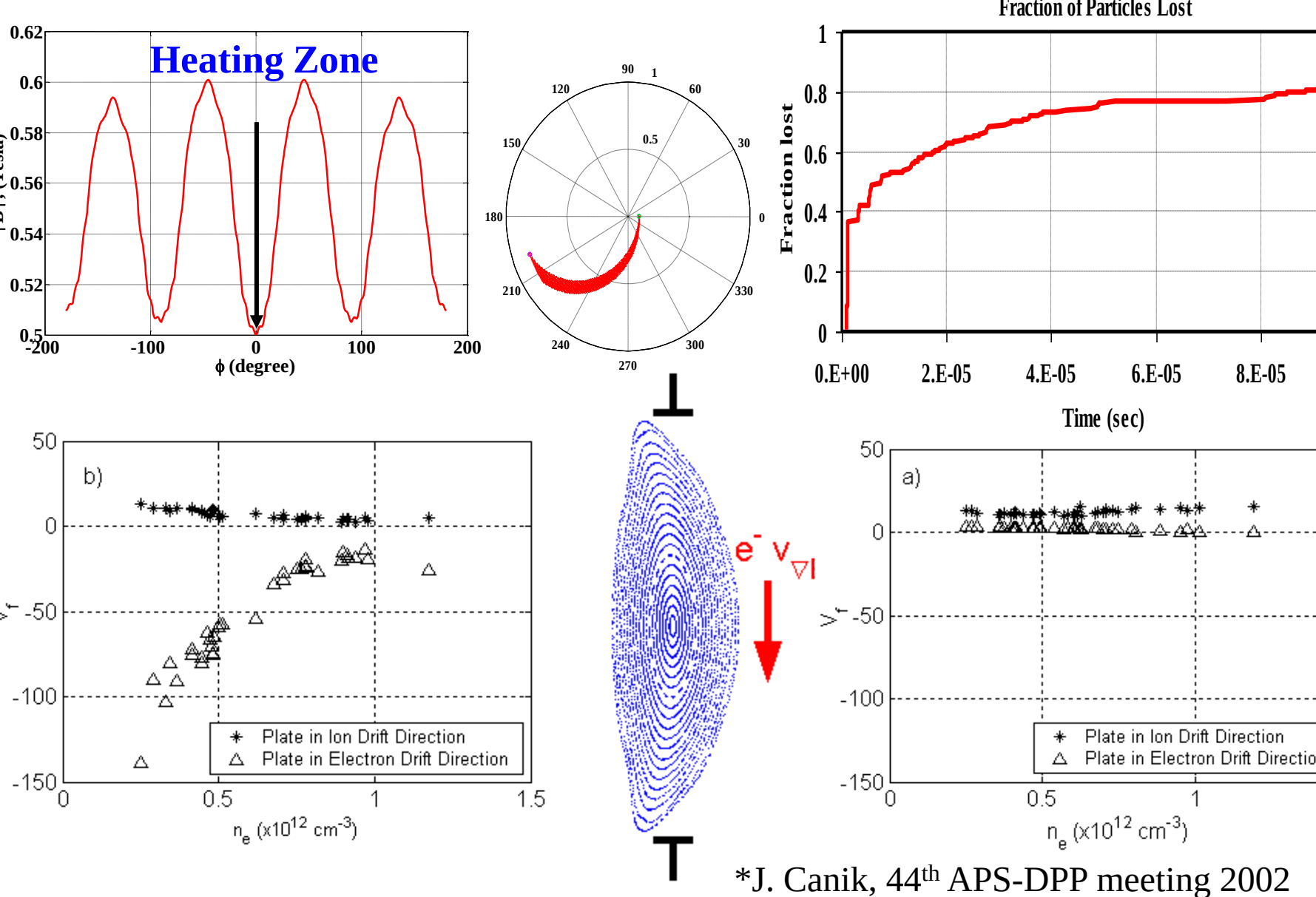


### c. Net Heating Rate is Largest in QHS



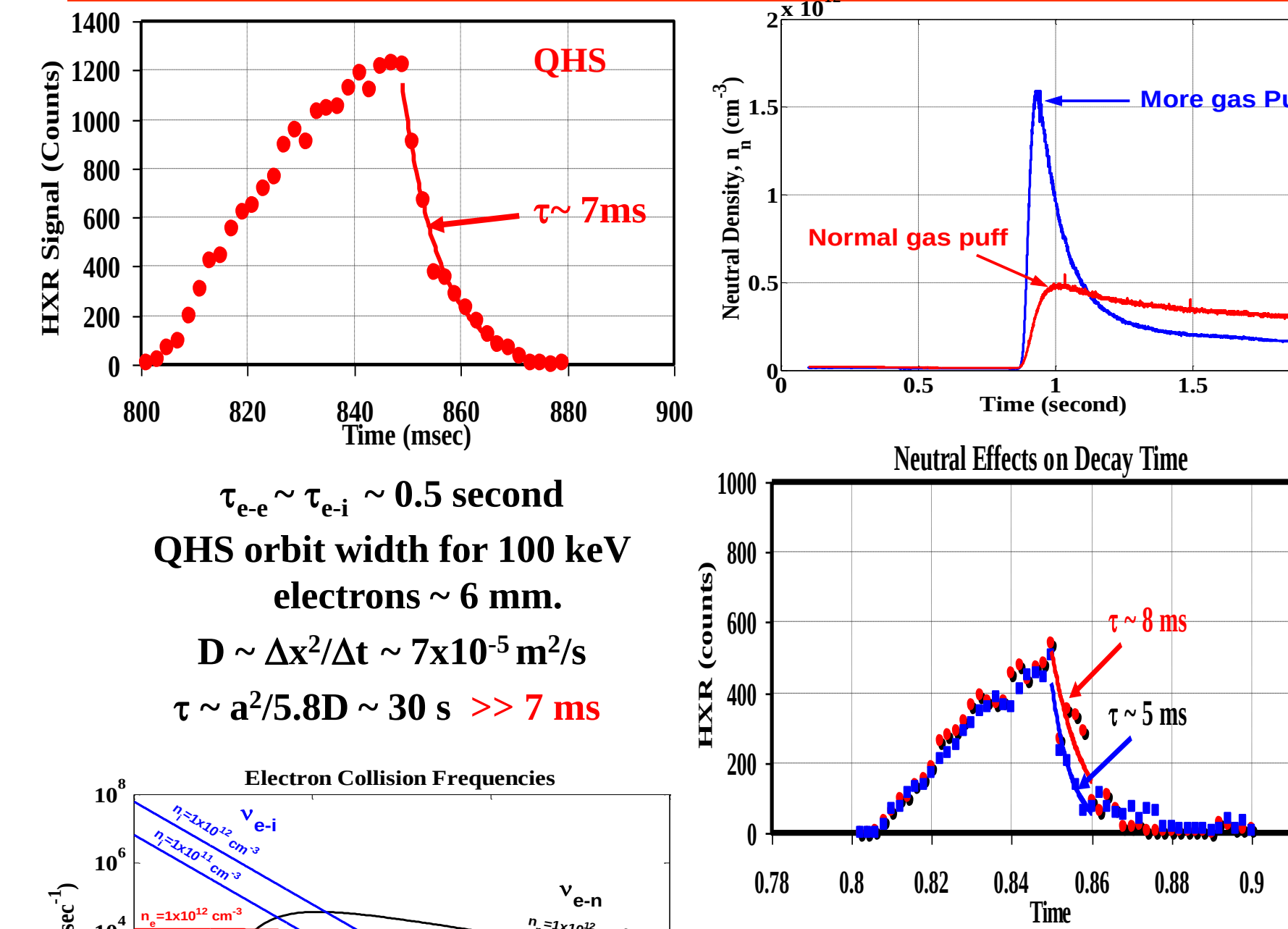
In QHS, particles spend the most time in the heating zone  $\Rightarrow$  Higher heating rate  
AntiMirror particles are trapped in the heating zone, but have very large orbits

## d. Direct Loss Orbits at Heating Zone in AntiMirror

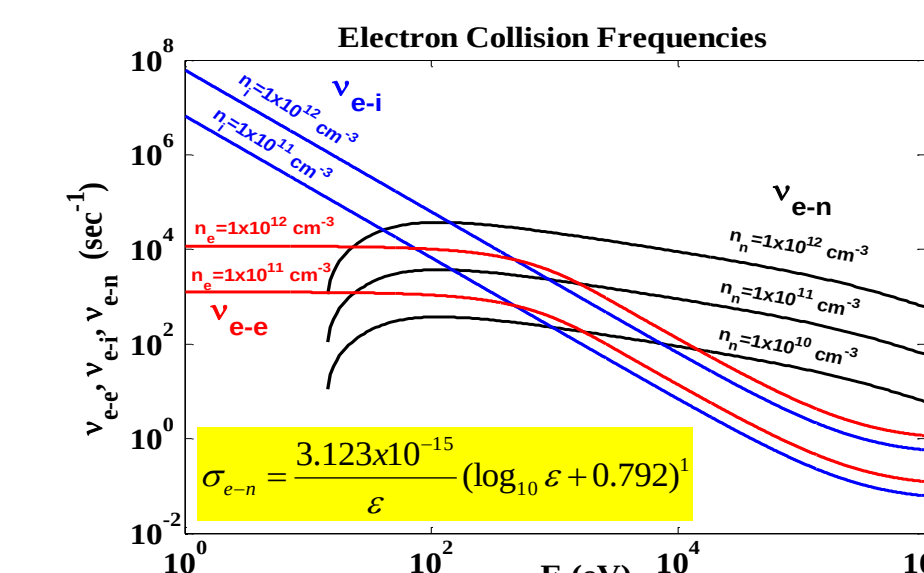


\*J. Canik, 44<sup>th</sup> APS-DPP meeting 2002

## 8. Neutrals Affect Superthermal Confinement



$\tau_{e-e} \sim \tau_{e-i} \sim 0.5$  second  
QHS orbit width for 100 keV electrons  $\sim 6$  mm.  
 $D \sim \Delta x^2 / \Delta t \sim 7 \times 10^{-5} \text{ m}^2/\text{s}$   
 $\tau \sim a^2 / 5.8D \sim 30 \text{ s} \gg 7 \text{ ms}$



Increased neutral density after ECRH turn off reduces hard x-ray decay time  
For 100 keV electrons and  $n_n \sim 10^{12} \text{ cm}^{-3}$ , the e-n collision time is,  $\Delta t_{e-n} \sim 0.1 \text{ ms}$ .  
 $\Delta x \sim 6 \text{ mm}$ ,  $\tau_{QHS} \sim 7 \text{ ms}$

<sup>1</sup>R. K. Janev et al., "Elementary Processes in Hydrogen Helium Plasmas", Springer-Verlag, (1987)

## 9. Conclusions

- Single particle heating calculations shows:  
 $\Rightarrow$  No difference in single transit heating between configurations
- Guiding center drift orbit model shows effects of orbit topology:  
 $\Rightarrow$  QHS has higher multiple-transit heating rate, smaller orbit width
- Neutral collisions determine superthermal electron confinement time
- Experiment verifies improved orbit topology in QHS  
 $\Rightarrow$  Higher hard x-ray intensity and energy  
 $\Rightarrow$  Longer confinement time of superthermal electrons