

Electron Cyclotron Heating in the Helically Symmetric Experiment

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HSX Laboratory

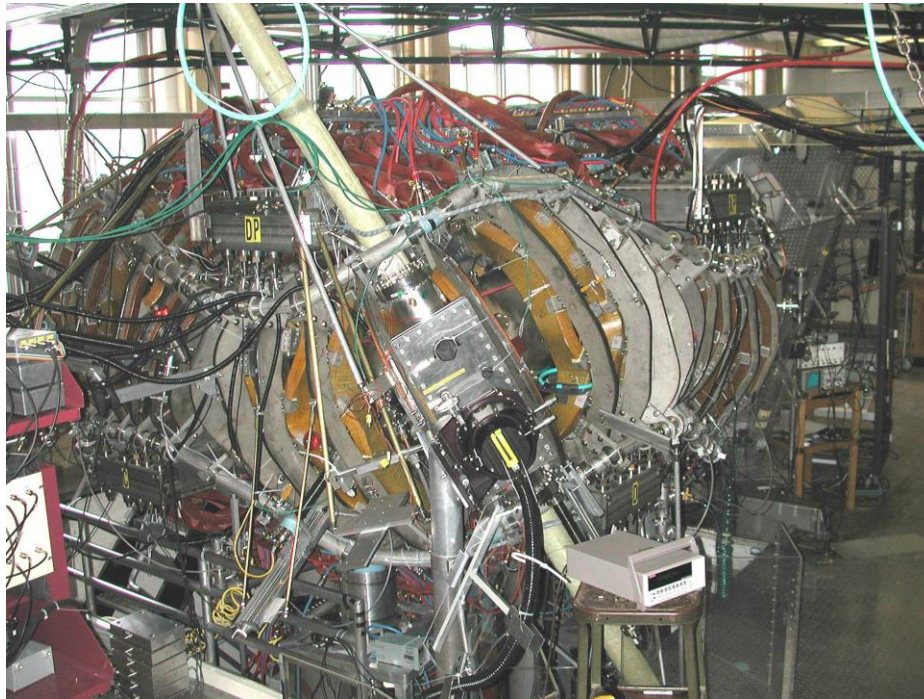
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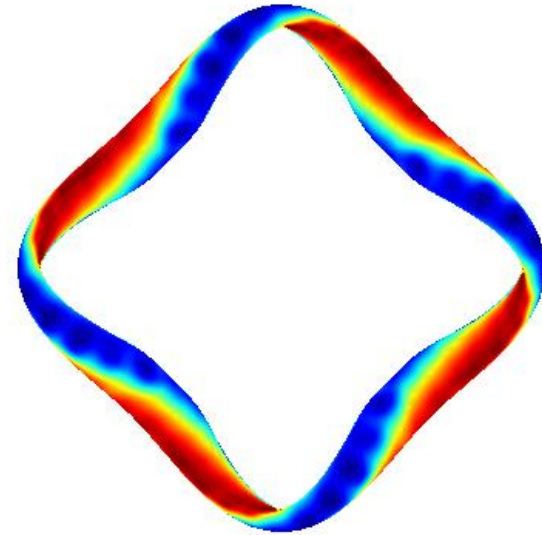
Greifswald, Germany

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HSX is a Quasihelical Stellarator

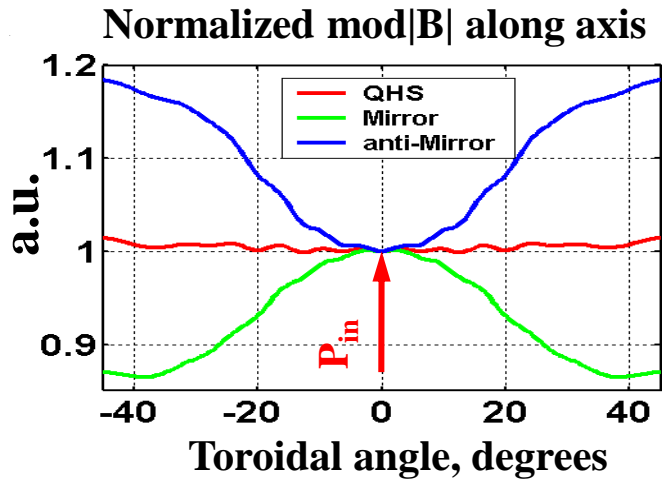


Magnitude of B



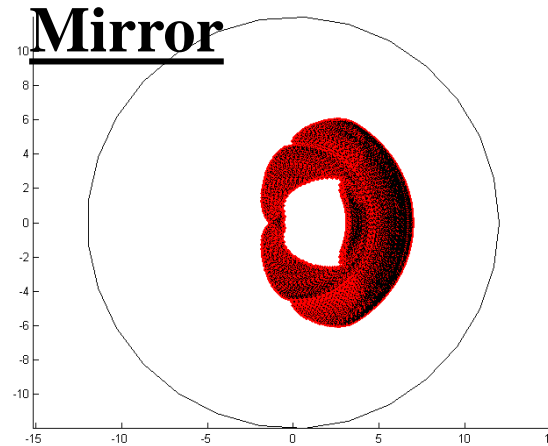
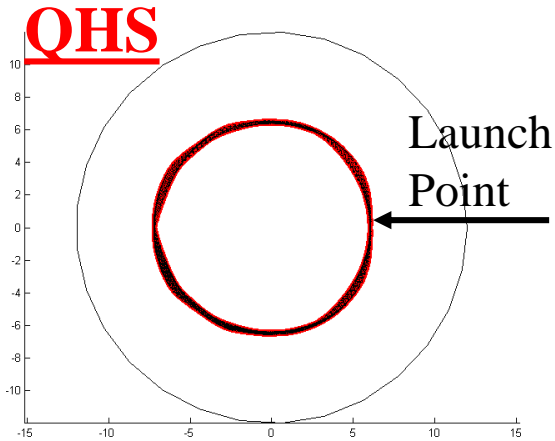
HSX has a helical axis of symmetry and a very low level of neoclassical transport

Neoclassical Transport Can Be Increased with Mirror Field

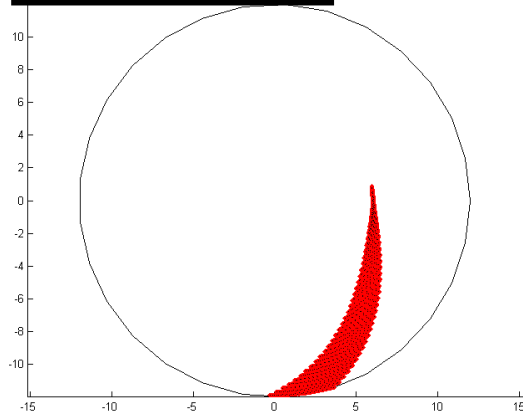


- Mirror configurations in HSX are produced with auxiliary coils in which an additional toroidal mirror term is added to the magnetic field spectrum
- In Mirror mode the term is added to the main field at the location of launching antenna
- In anti-Mirror it is opposite to the main field

Trapped Particle Orbits



anti-Mirror



- Trapped particles in QHS are well-confined
- By the ECH antenna, orbits are poor in Mirror configuration and even worse in anti-Mirror

ASTRA is Used to Model Transport

- The power deposition profile comes from measurements of the radiation pattern from an ellipsoidal mirror and a ray-tracing calculation of the energy deposition profile.
- To model neoclassical transport, a 6-parameter fit to the monoenergetic diffusion coefficient allows for quick solution of the ambipolarity condition to solve for E_r .

$$D_{EX} = \frac{\sqrt{\pi}}{2} \varepsilon_t^2 C_6 V_d^2 \frac{\bar{v}}{\omega^2}$$

$$\omega^2 = C_1 \bar{v}^2 + C_2 (\omega_E + \omega_B)^2 + C_3 \omega_B^2 + C_4 |\omega_B| \bar{v}$$

$$\omega_B = C_5 V_d$$

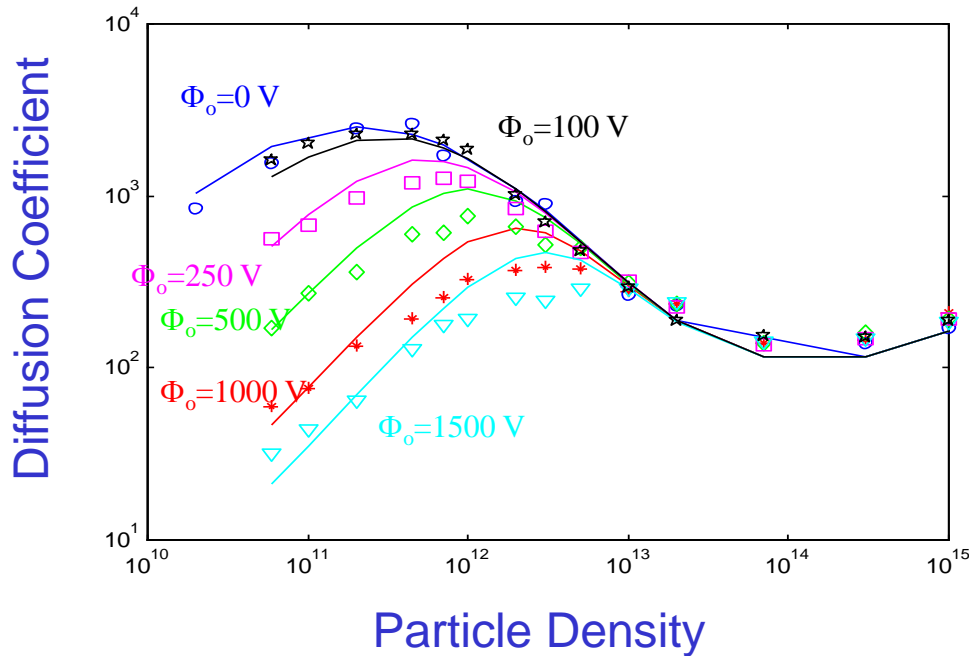
$$V_d = \frac{K}{eBr} \quad \omega_E = \frac{E}{rB}$$

$$\bar{v} = \frac{v}{C_6}$$

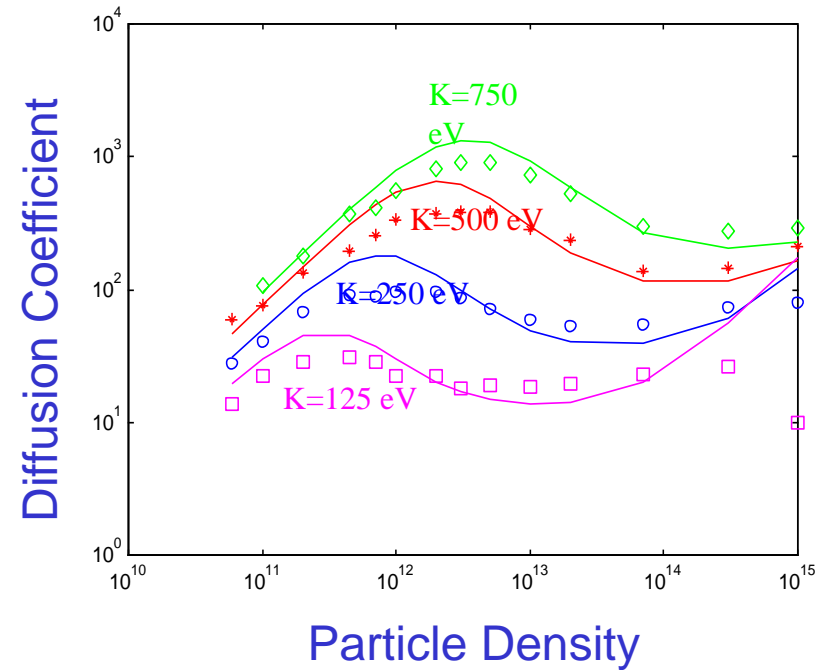
Ref: K.C. Shaing Phys. Fluids 27 1567 (1984).
S.L. Painter and H.J. Gardner,
Nucl. Fusion 33 1107 (1993)

Modeling the Diffusion Coefficient

Electric Field Variation



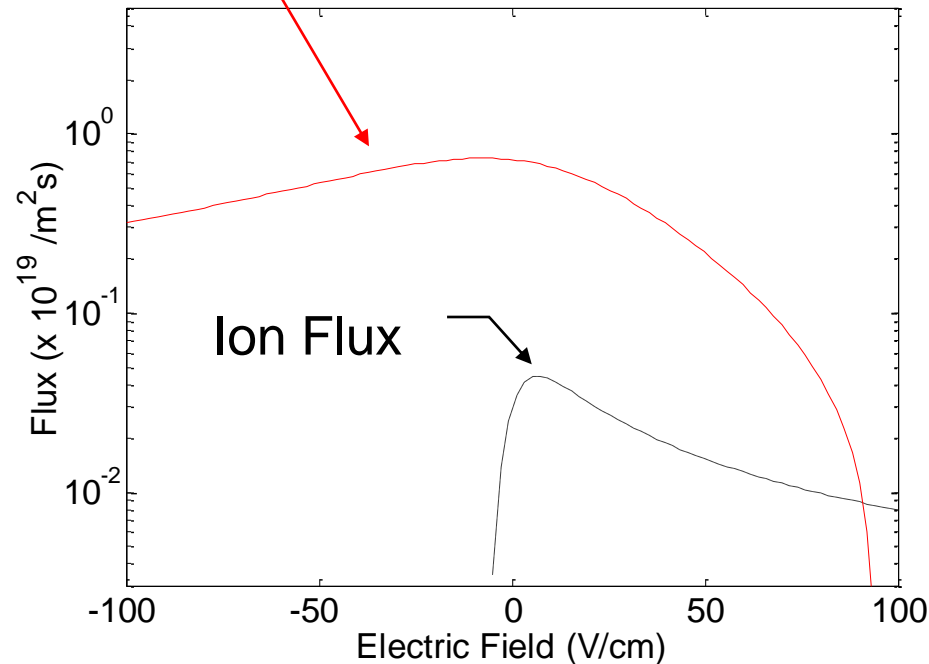
Energy Variation



Six-parameter fit, given by the C_i 's smoothly combines the low collisionality stellarator transport regimes and fits the Monte Carlo data over a broad range of collisionalities, particle energies, magnetic field, electric field and particle mass.

Solving for the Radial Electric Field

Electron Flux



The ambipolarity constraint is solved self-consistently in ASTRA. However it invariably yields an electron root, which probably underestimates the neoclassical contribution.

Modeling Anomalous Transport I

- In addition to the neoclassical transport, we assume that there is an anomalous electron thermal conductivity:

$$\chi_e = \chi_{e,neo} + \chi_{e,anom}$$

- Previously we used an anomalous thermal conductivity based on ASDEX L-mode scaling:

$$\chi_{e,anom} \sim \frac{T_e^{3/2}}{RB^2} \frac{1}{\left[1.1 - (r/a)^2\right]^4}$$

- If $\tau \sim 1/T_e^{3/2} = nT/P$, then:

$$T \sim (P/n)^{0.4}; \quad \tau \sim (n/P)^{0.6}; \quad W \sim n^{0.6}P^{0.4}; \quad \text{ISS95-like}$$

Modeling Anomalous Transport

- ASDEX L-mode model did not agree with scaling dependencies of experimental data.
- A better model of anomalous transport in HSX is an Alcator-like dependency (n_e in units of 10^{18} m^{-3}):

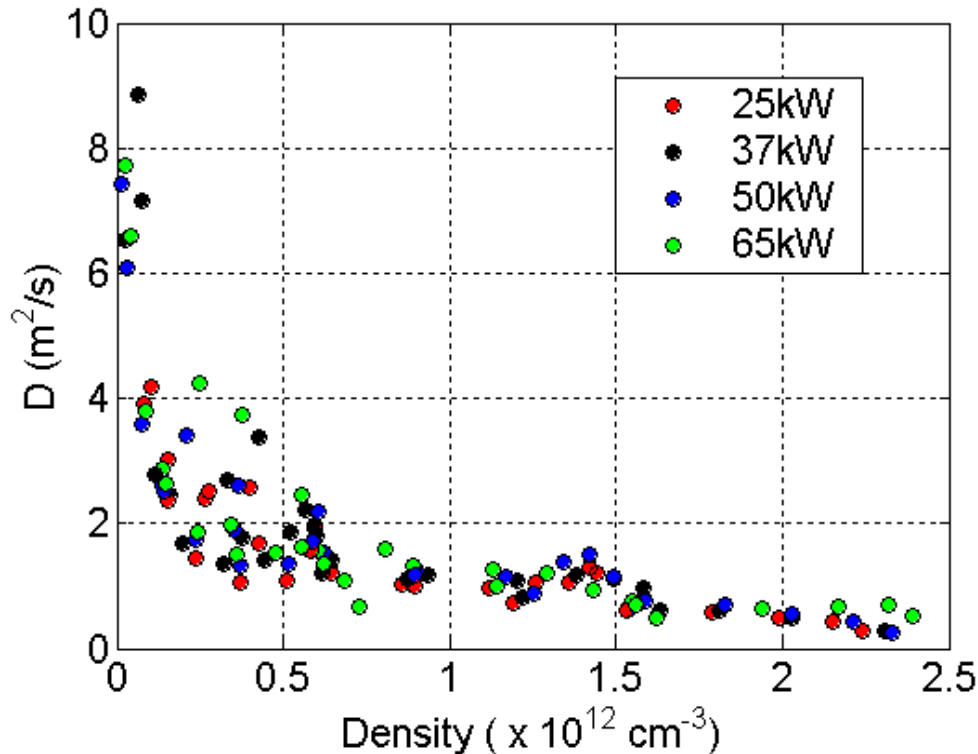
$$\chi_{e,anom} = \frac{10.35}{n_e} \text{ m}^2 / \text{s}$$

- If $\tau \sim n = nT/P$, then:

$T \sim P$ (independent of n) ; $\tau \sim n$; $W \sim nP$;

which is more in agreement with experiment

H_α Measurements Consistent with Model

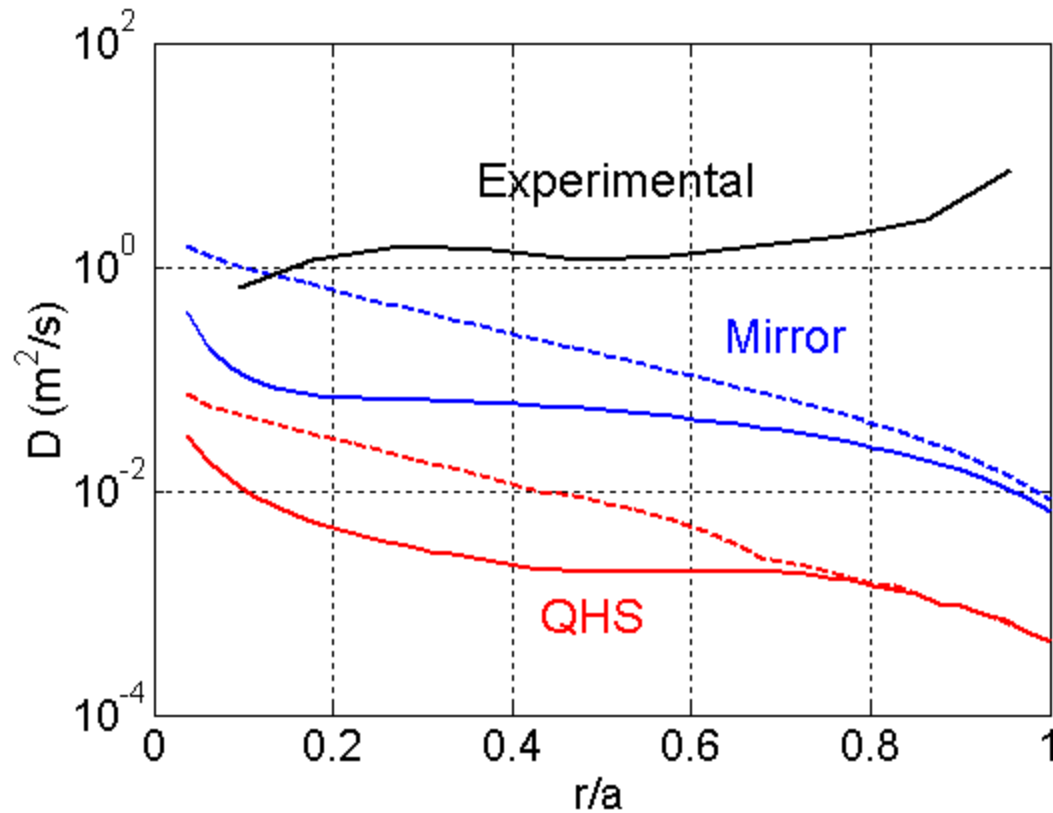


- See poster by J. Canik
- H_α toroidal and poloidal data analyzed using DEGAS code for 3 different line average densities and 4 different power levels
- Dependence of diffusion coefficient on n and P :

- Negligible dependence on power!

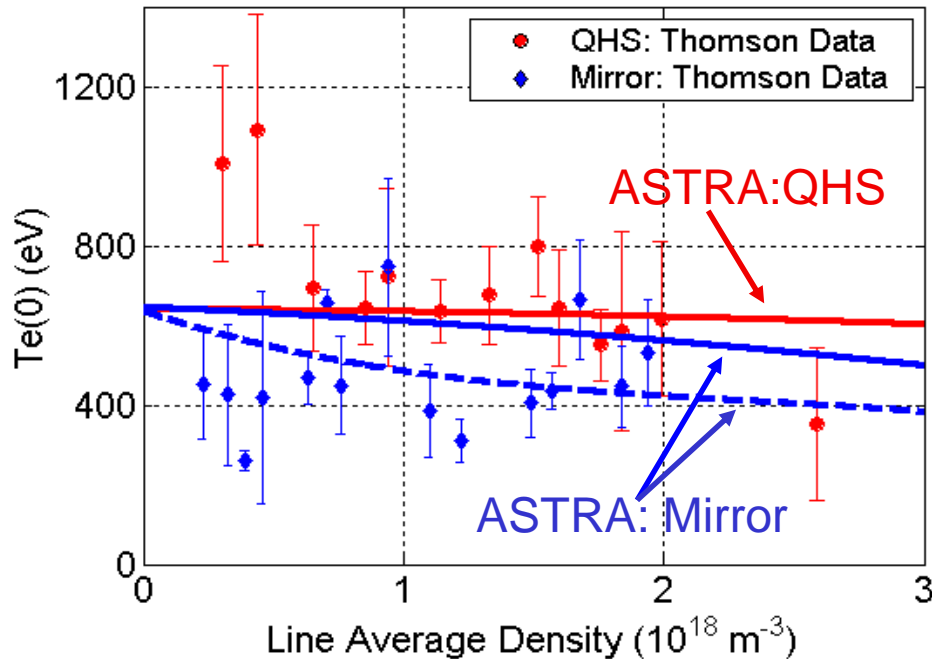
$$D_{anom} \sim \frac{P^{0.09}}{n^{0.6}}$$

Experimental Diffusion Coefficients Larger than Neoclassical Values



ASTRA calculations of neoclassical diffusion coefficients with ambipolar E_r (solid) and $E_r = 0$ (dashed)

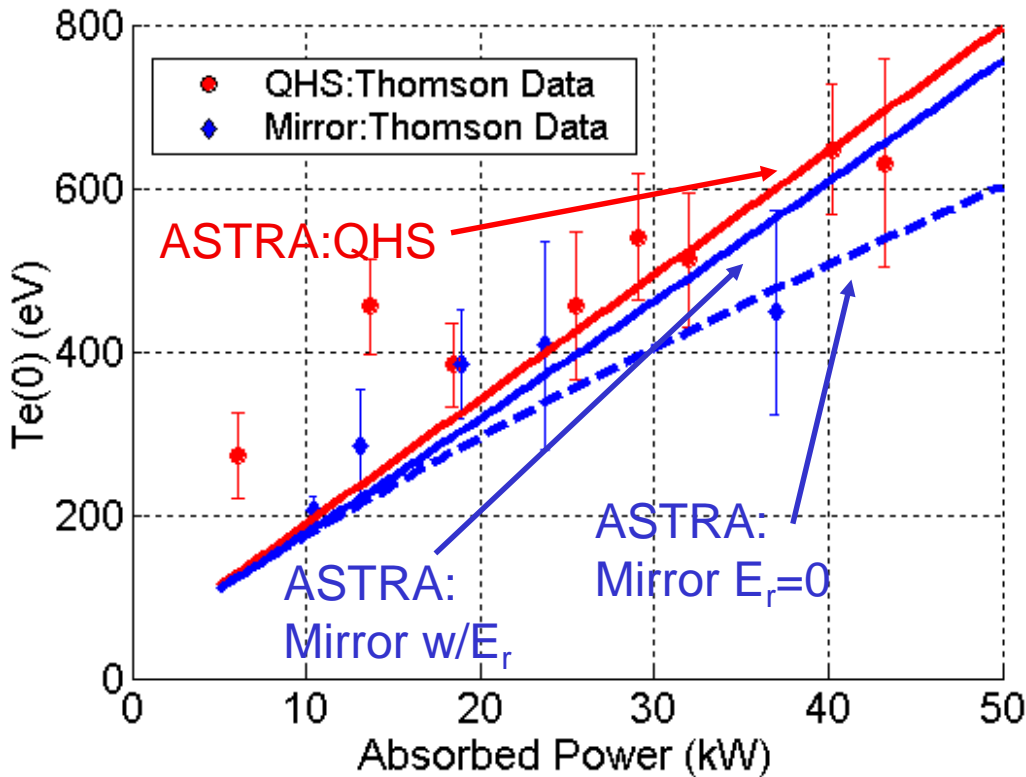
Central Electron Temperature is Independent of Density



- QHS thermal conductivity is dominated only by anomalous transport
- $T_e(0)$ in Mirror is calculated with self-consistent E_r (solid line) and $E_r = 0$ (dashed).

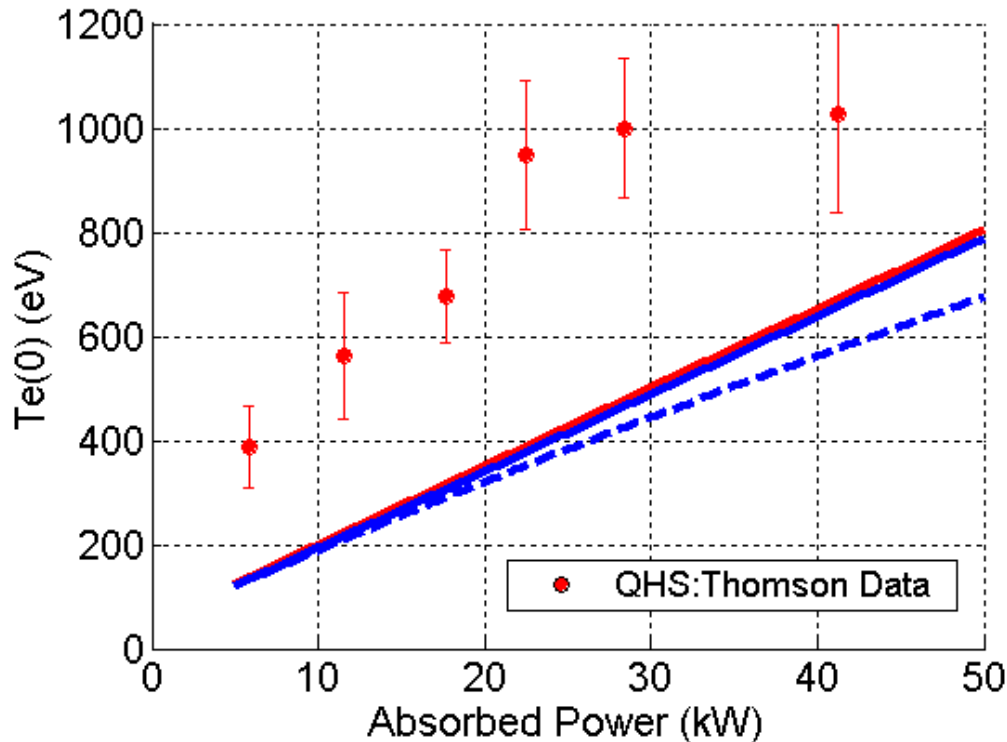
- Except for lowest densities, $T_e(0)$ from Thomson scattering is roughly independent of density,
- Consistent with $\chi \sim 1/n$ model.

Thomson Data shows $T_e(0)$ Increases Linearly with Power



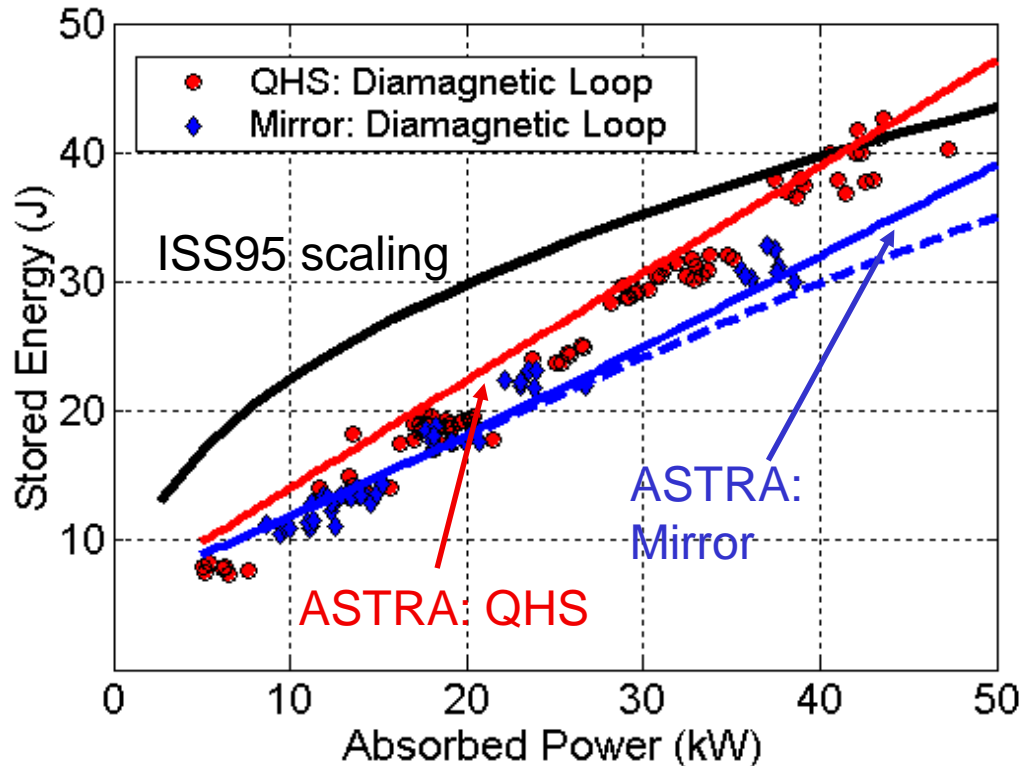
- Fixed density of $1.5 \times 10^{18} \text{ m}^{-3}$.
- ASTRA calculation is consistent with Thomson measurements for QHS and Mirror
- $T \sim P$ is supportive of $\chi \sim 1/n$ model.

At Lower Density, TS Disagrees with Model



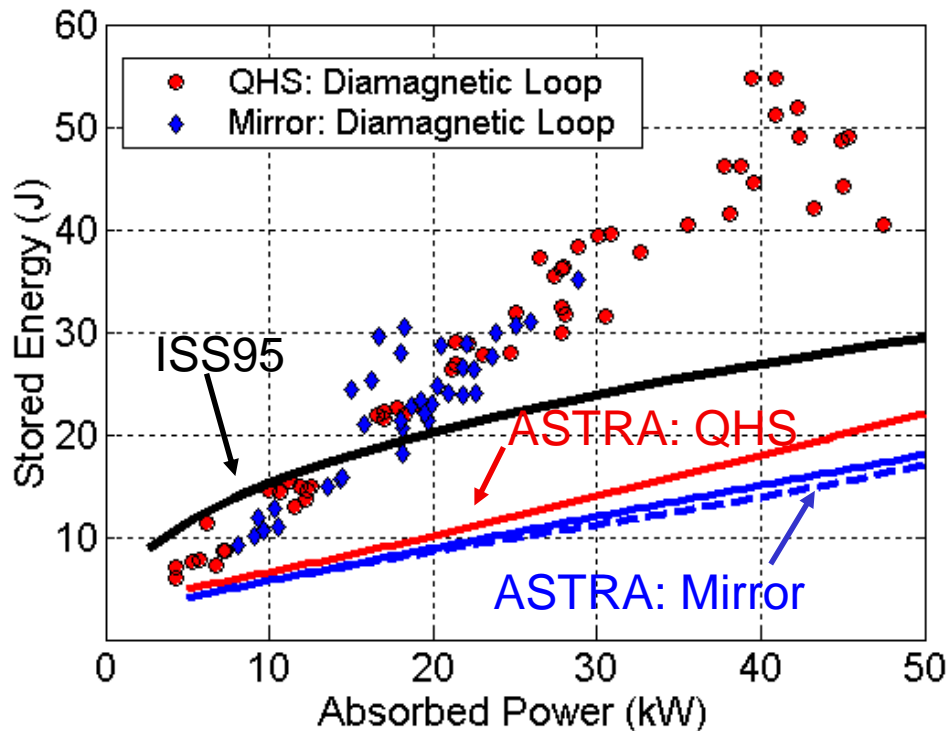
- Fixed density of $0.7 \times 10^{18} \text{ m}^{-3}$.
- Does Thomson data overestimate $T_e(0)$ compared to model because of poor statistics at low density or because of nonthermal electron distribution?

Stored Energy Increases Linearly with Power



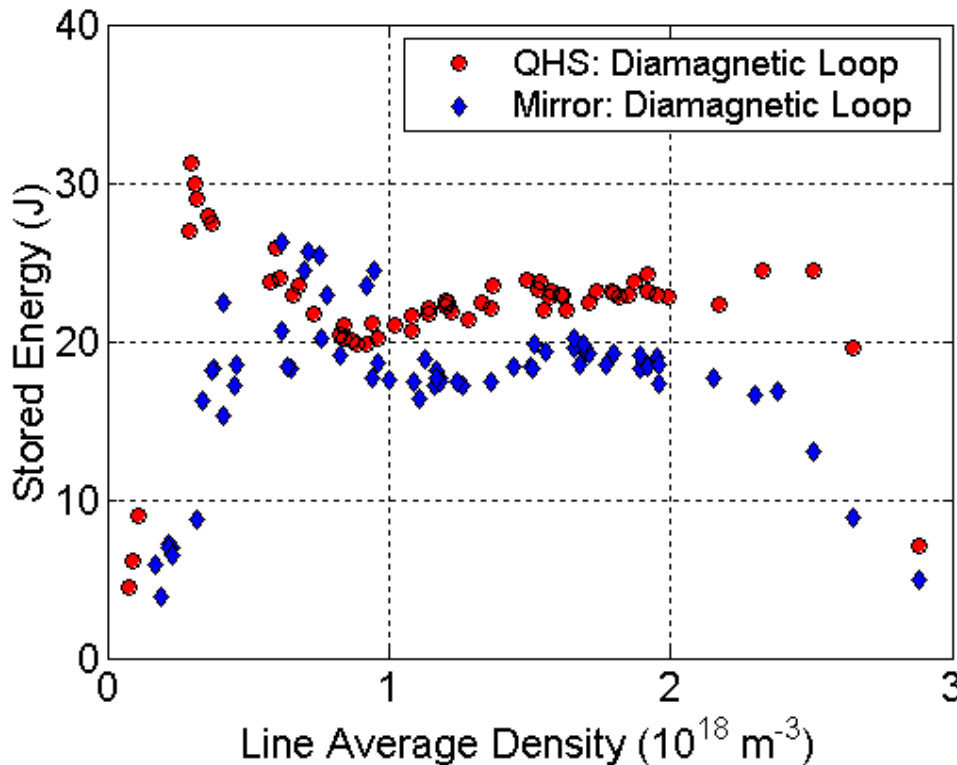
- Fixed density of $1.5 \times 10^{18} \text{ m}^{-3}$.
- Difference in stored energy between QHS and Mirror reflects 15% difference in volume.
- $W \sim P$ in agreement with $\chi \sim 1/n$ model.

At Lower Density, Stored Energy is Greater than Predicted



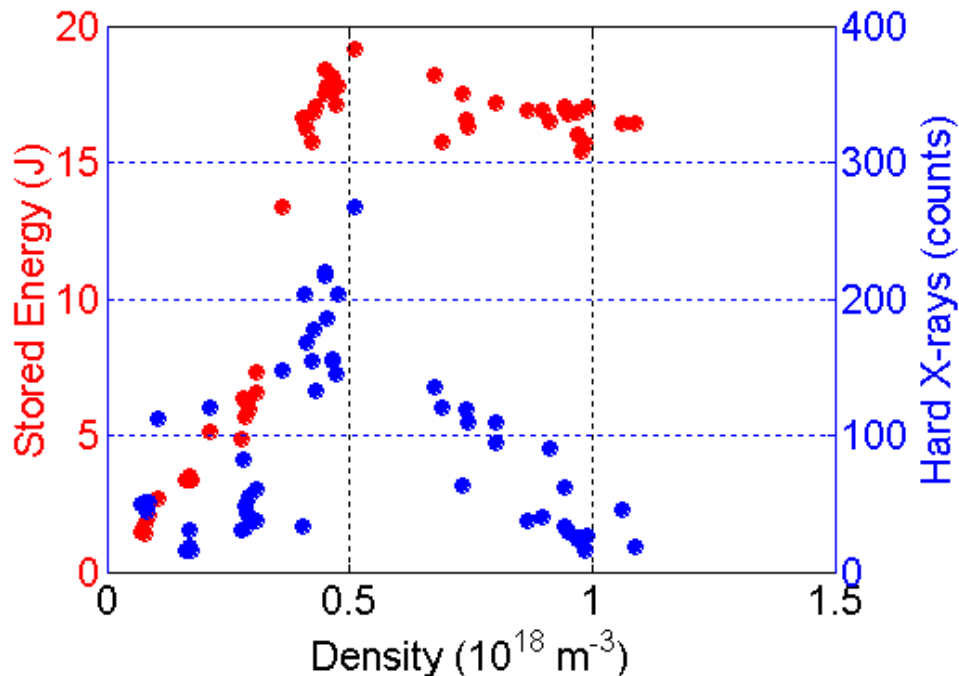
- Fixed density of $0.7 \times 10^{18} \text{ m}^{-3}$.
- Data shows stored energy even greater than ISS95 scaling
- However, still $W \sim P$ in agreement with $\chi \sim 1/n$ model.
- Are nonthermal electrons responsible for large stored energy?

Stored Energy Does Not Have Linear Dependence on Density



- Fixed input power, 40 kW.
- For $\chi \sim 1/n$ model, $W \sim n$ for fixed power. Data clearly does not show this.
- Are nonthermal electrons causing stored energy to peak quickly at low density?

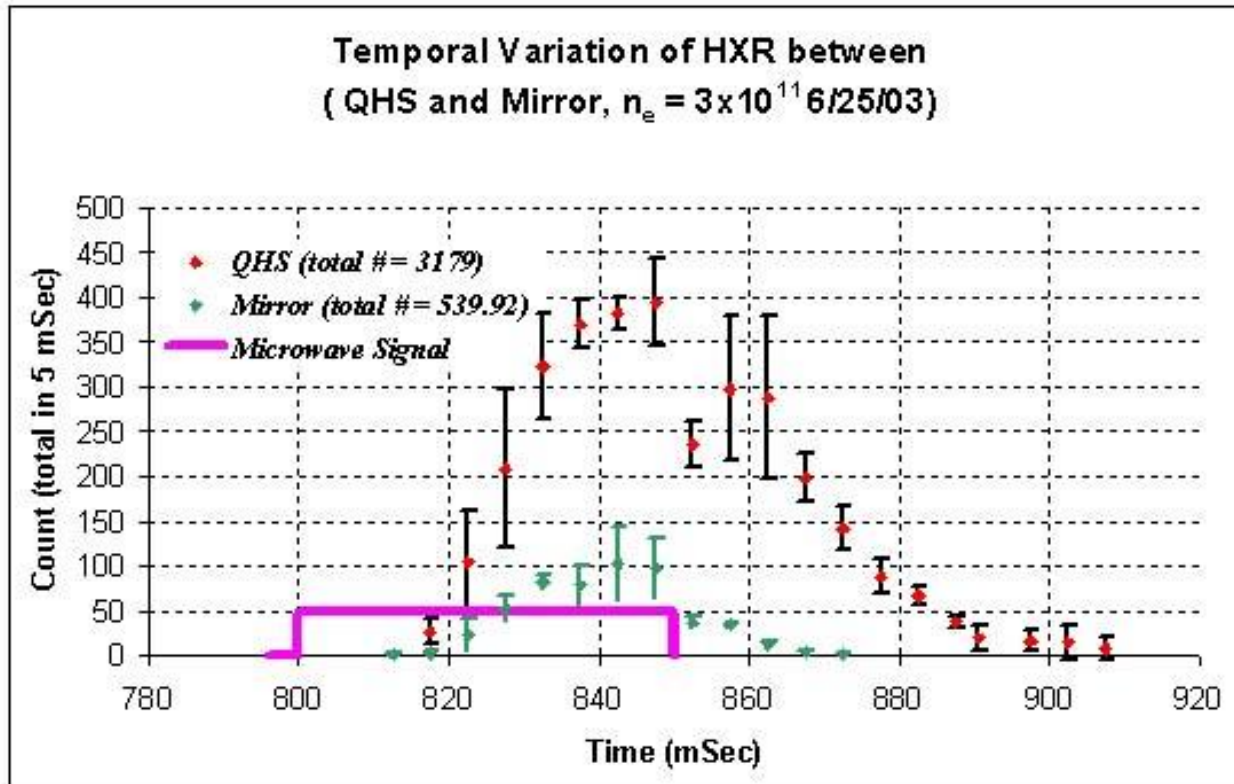
Hard X-rays Have Similar Dependence on Density as Stored Energy



- Shielded and collimated CdZnTe detector with 200 μm stainless steel filter.
- Fixed input power: 40 kW.
- Hard X-ray intensity peaks at $0.5 \times 10^{18} \text{ m}^{-3}$, as does stored energy.

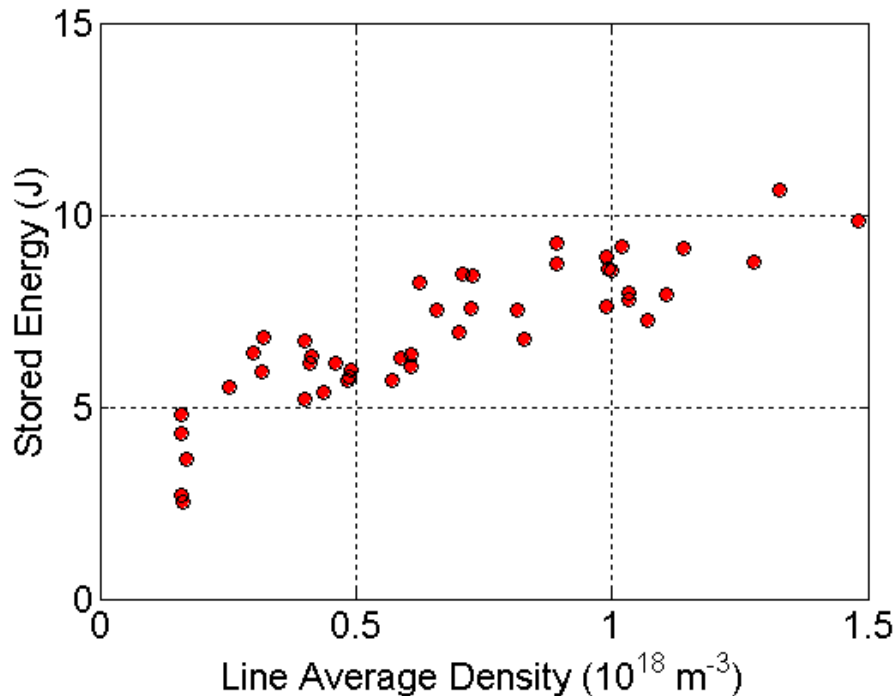
- Hard X-ray intensity falls off sharply beyond $1 \times 10^{18} \text{ m}^{-3}$, while stored energy remains roughly constant.

Hard X-rays Greater in QHS than Mirror



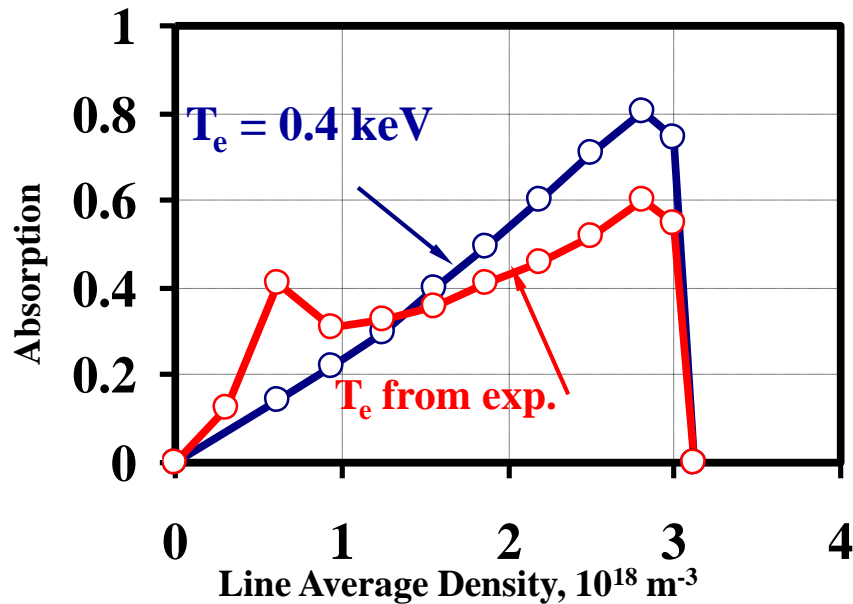
- Intensity increases till gyrotron turn-off, then decreases with 13 ms time constant for QHS, 5 ms for Mirror.

Stored Energy Goes Up Linearly with Density when Confinement is Poor



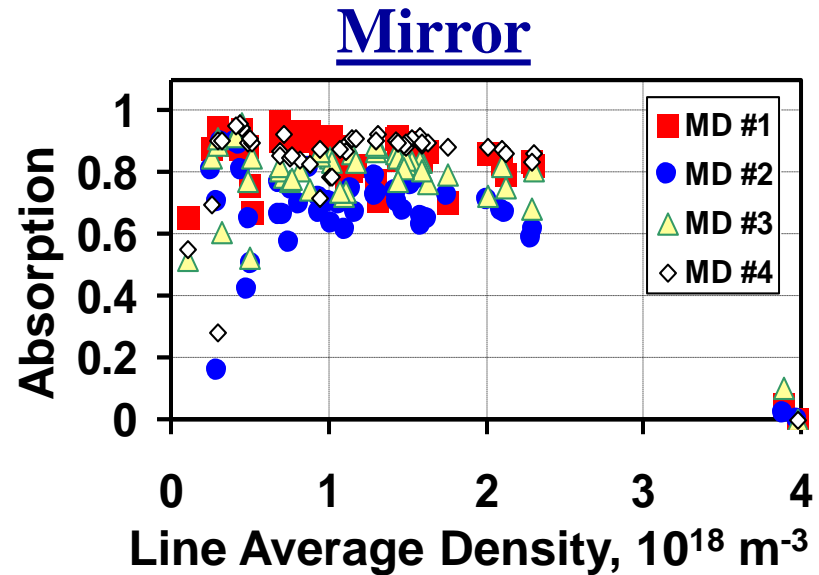
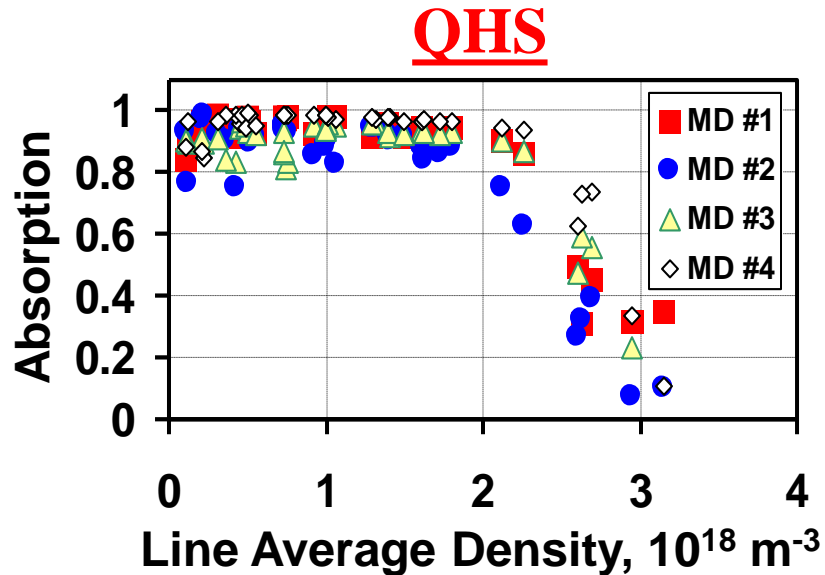
- Resonance is on low-field side of Mirror configuration where confinement of trapped particles is degraded
- $W \sim n$ in this configuration is now consistent with $\chi \sim 1/n$ model.

Ray Tracing Predicts Absorption Increases with Density



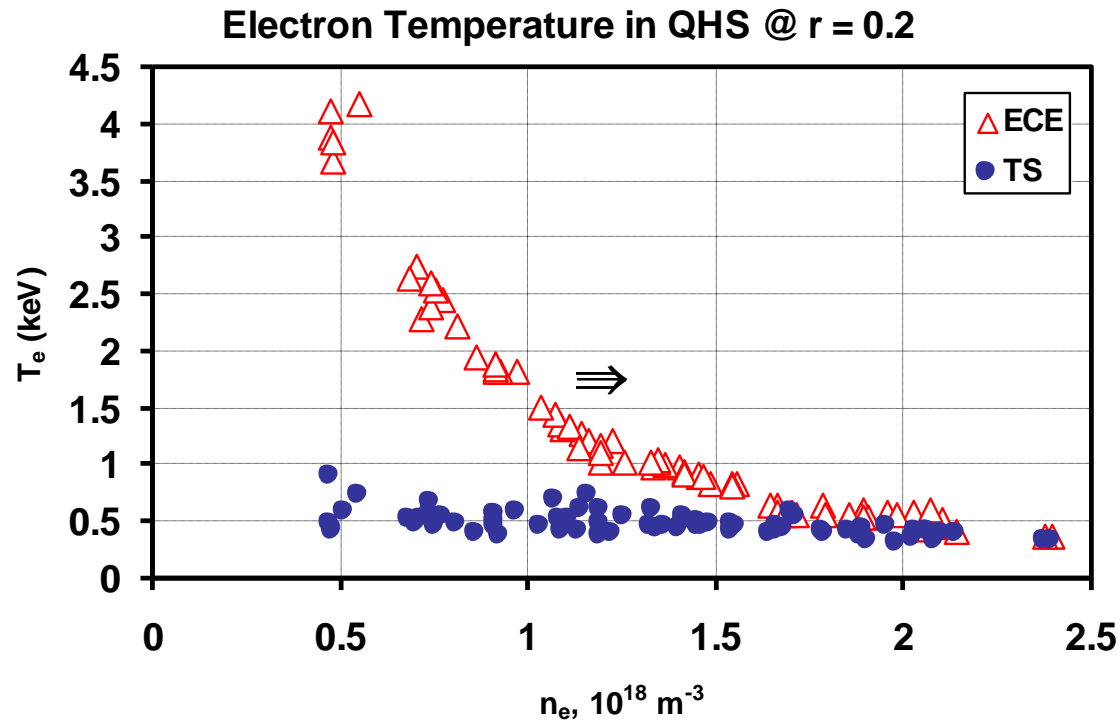
- Gaussian profile for electron temperature and parabolic profile for density
- Single-pass absorption calculations are done for fixed central temperature $T_e = 0.4 \text{ keV}$ as well as experimental Thomson data.
- Experimental measurement shows high absorption even at lower densities.

Absorption Efficiency is Very High for both Configurations



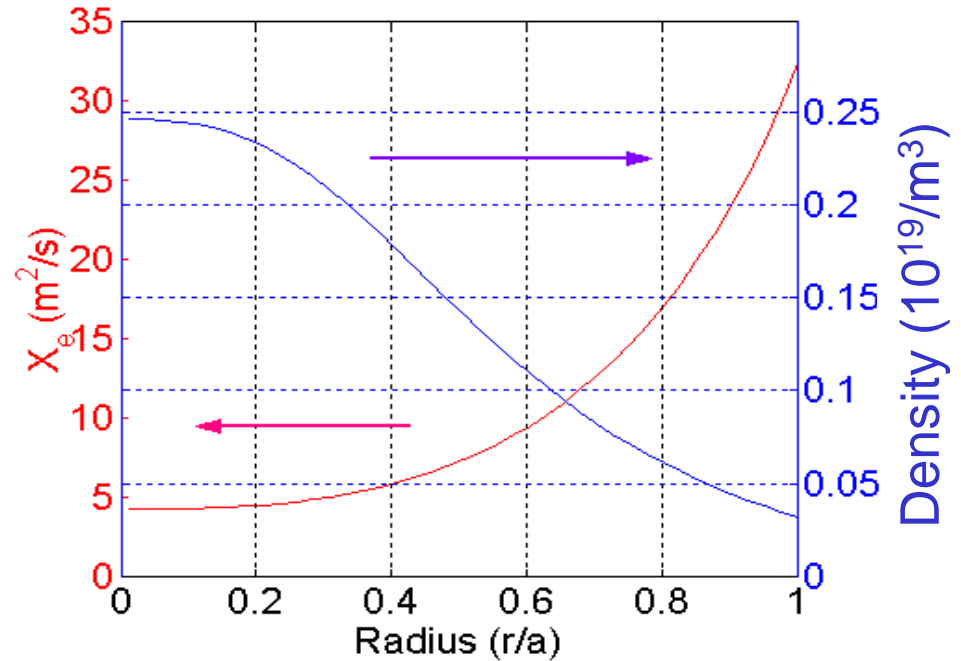
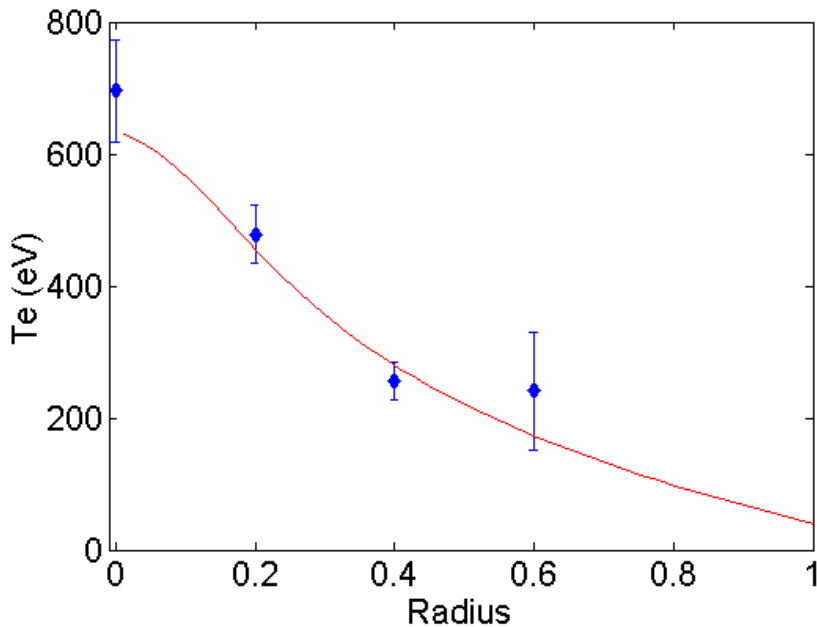
- Calibrated microwave detectors show rf power is absorbed with high efficiency, but degrades at $n > 2 \times 10^{18} \text{ m}^{-3}$.
- At low density, absorption efficiency in QHS is higher than for Mirror, due to absorption on superthermal electrons.

Comparison of TS and ECE



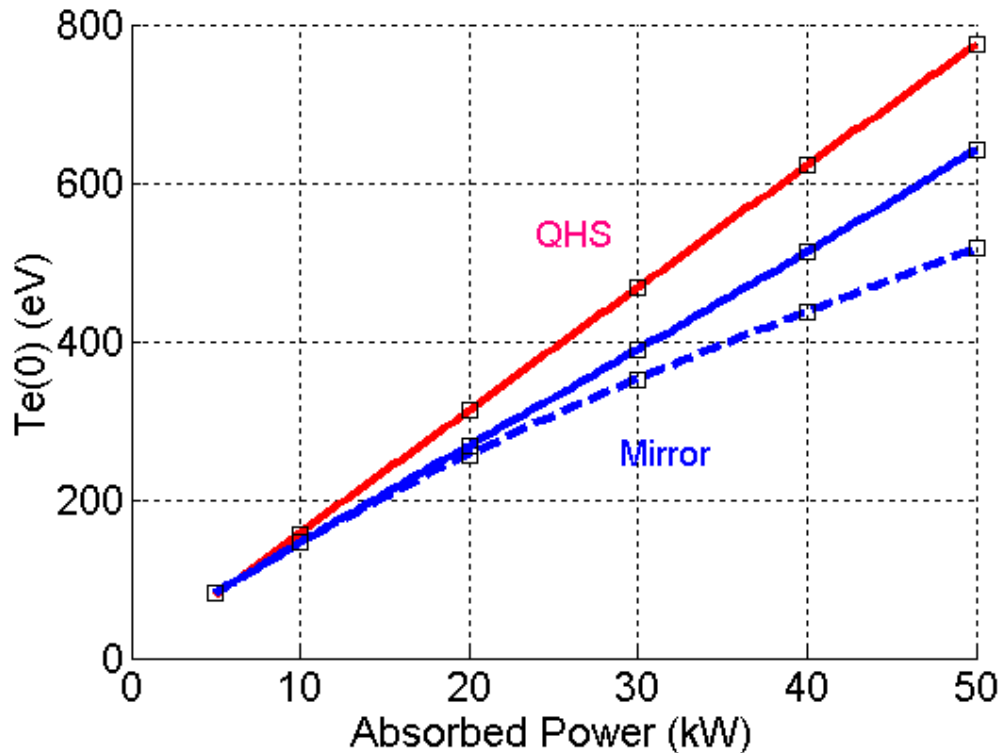
- At low densities, ECE signal shows much higher T_e than Thomson data BUT good agreement at higher densities
- As before, T_e is independent of density.

Comparison of ASTRA and Te Profiles



- Using the exact same dependence as before, $X_e = 10.35/n_e$ m²/s, ASTRA gave good prediction of T_e profile!

Higher Density and More Power Might Make QHS/Mirror Differences Stand Out



- Density of 3×10^{12} reduces anomalous thermal conductivity so neoclassical differences between QHS and Mirror might stand out.
- Higher power accentuates those differences.

Some Ideas

- The $X_{\text{anom}} \sim 1/n$ model seems to reproduce some of the major experimental features. Independently verified (more or less) by John's H_α measurements and calculations of D.
- The major disagreement of the X_{anom} model from the experiment is in the stored energy as a function of density.
- However, this appears to be explained by a large nonthermal population at the lower densities. This is the ECE, H-X measurements and discrepancy between ray-tracing calculation and absorbed power measurements.

Some Ideas

- When we predict that we are going to have poor confinement of trapped particles (anti-Mirror or low field side Mirror), then stored energy goes up linearly with density.
 - ⇒ It would be good to redo these measurements and see if there is any H-X, S-X flux or nonthermal ECE radiation temperature in the poor confinement regimes. Also check absorbed power from diodes.
- We need to do the thermal conductivity problem in reverse --- specify the absorbed power profile and the measured temperature gradient.
 - ⇒ A good understanding of the error bars in the temperature profiles is required

Some Ideas

- If the transport is dominated by anomalous particle and thermal transport, shouldn't we see some correspondence in the turbulence?

⇒ Which direction is the turbulent driven transport?

Where does it reverse sign?

Does it scale with density?

How do the turbulent fluxes compare to John's particle fluxes?

What are single-frequency modes that are seen in the QHS configuration, but not the mirror?

What mechanism is driving the turbulent transport?

Some Ideas

- Can we detect differences in the T_e profile of QHS and Mirror?

⇒ Need to be careful to compare central T_e in QHS and Mirror because Mirror axis is shifted in. How do we account for that? (Don't want to think there is a temperature difference when there is not.)

Higher density, more power is better, but we are limited in how high a density we can go by the cut-off.

Higher density is better if we want to reduce the nonthermal population – also better statistics for TS

At what point do we consider 1.0 T operation to get higher density?

Some Ideas

- At what point do we no longer see scaling that goes inversely with density? At what point do we reach or exceed ISS-95 scaling?
- Need to measure E_r to see what effect it has on T_e in the mirror mode. Is it possible to get an electron root in HSX plasmas?
⇒ What is the best mechanism to measure E_r , Φ or V ?

Conclusions I

- Central T_e and stored energy increase linearly with power, in agreement with $\chi \sim 1/n$ model.
- For constant power, T_e is roughly independent of density, also in accord with $\chi \sim 1/n$ model.
- Model is consistent with H_{α} measurements that show D is roughly independent of power, but depends on $1/n^{0.6}$
- At low density, stored energy W does not increase linearly with n . However, hard X-ray flux shows similar density dependence as W ; disappears at $n > 1 \times 10^{18} \text{ m}^{-3}$.
- QHS shows higher absorption efficiency and higher X-ray flux than Mirror at low density. At high density, absorbed power falls off at $n > 2 \times 10^{18} \text{ m}^{-3}$.

Conclusions II

- When confinement of trapped electrons is poor, stored energy does show linear increase with density.
- Hence, superthermal electrons at low density and degraded absorption at high density account for discrepancy of stored energy with $\chi \sim 1/n$ model.

ABSTRACT

Up to 100 kW second harmonic extraordinary mode ECH with a frequency of 28 GHz is injected into the Helically Symmetric Experiment at a magnetic field of 0.5 T. We use the ASTRA code to investigate neoclassical and anomalous thermal conductivity in HSX. Thomson scattering and diamagnetic loop measurements indicate that the central electron temperature and stored energy increase linearly with power. Experimentally it is found that the central electron temperature is roughly independent of density. These findings are consistent with a thermal conductivity that scales inversely with the density. Typically in good confinement configurations, the stored energy shows a peak at low density and is constant at the higher densities, in contradiction to the model. On the other hand, in configurations that poorly confine trapped particles, the stored energy increases linearly with density, as expected. From measurements of X-ray emission and absorbed power, as well as calculations of the absorption efficiency from ray tracing, it is concluded that at low densities a nonthermal electron population accounts for a significant fraction of the stored energy for the good confinement configurations.