Overview of Recent Results from HSX

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The University of Wisconsin-Madison

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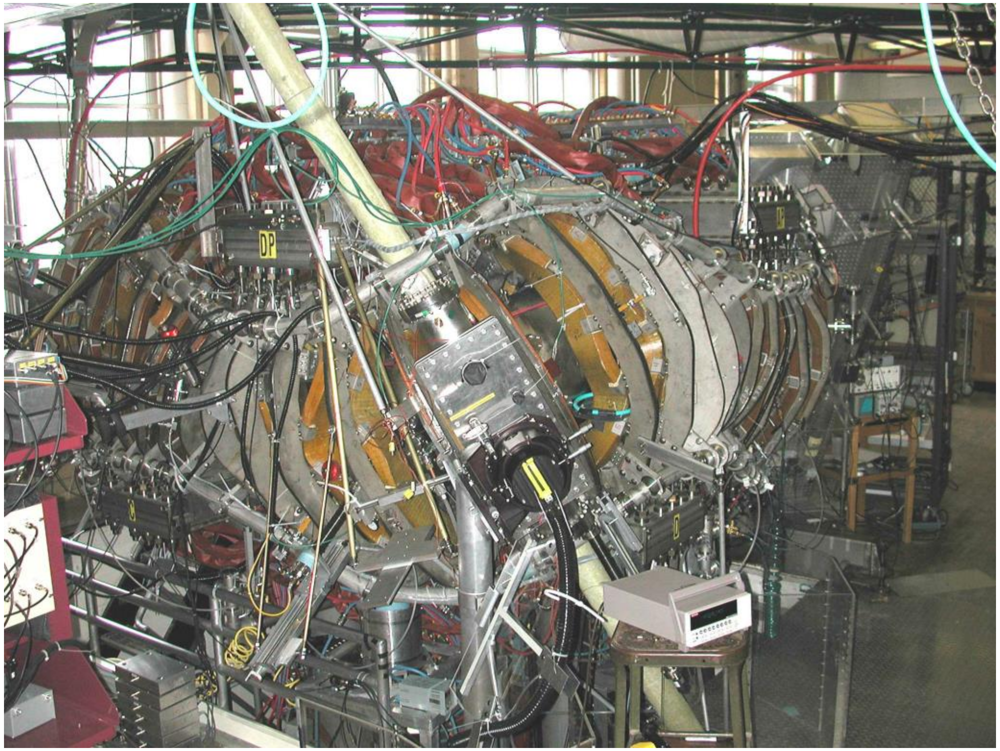
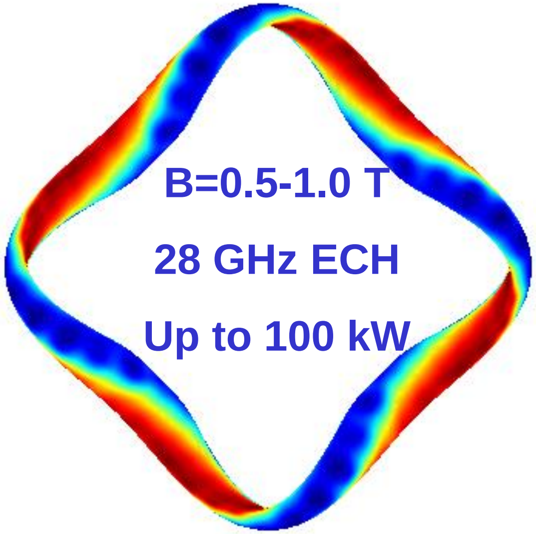
HSX is a Quasihelically Symmetric Stellarator

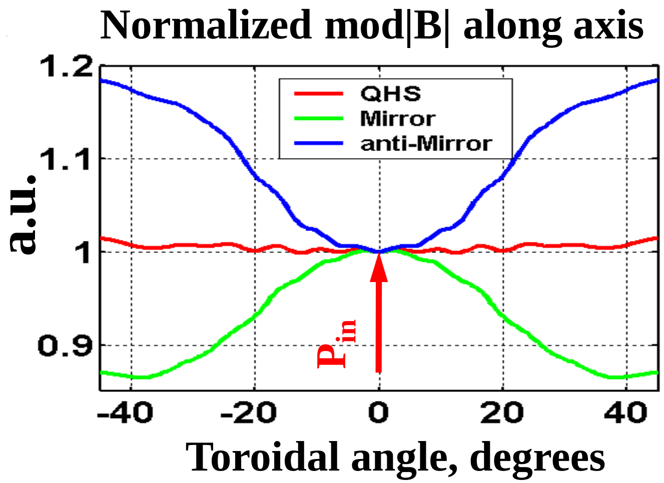


Magnitude of B



HSX has a helical axis of symmetry in |B| and a resulting very low level of neoclassical transport

Neoclassical Transport Can Be Increased with Mirror Field

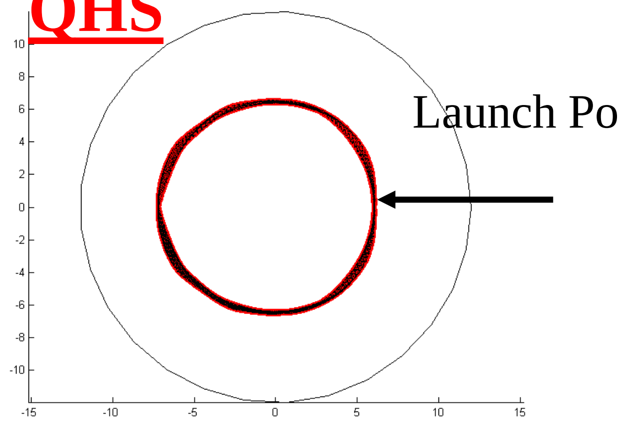


- **Mirror configurations in HSX are produced with auxiliary coils in which an additional toroidal mirror term is added to the magnetic field spectrum**

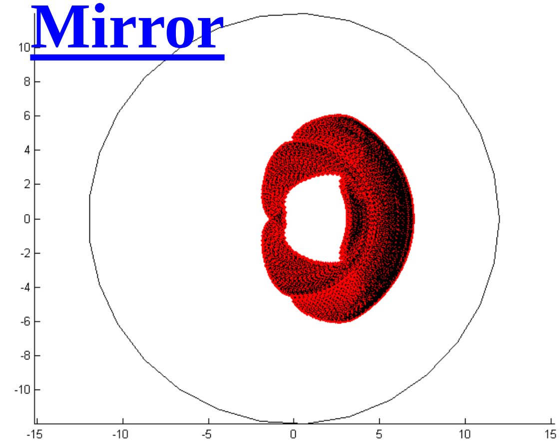
- **<u>In Mirror mode</u> the term is added to the main field at the location of launching antenna**
- **<u>In anti-Mirror</u> it is opposite to the main field**

Trapped Particle Orbits

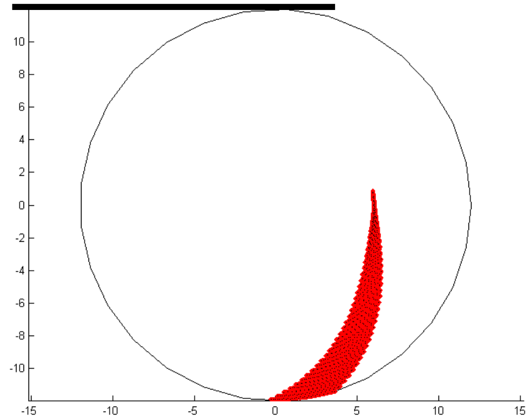
QHS



Mirror



anti-Mirror



- **Trapped particles in QHS are well-confined**
- **By the ECH antenna, orbits are poor in Mirror configuration;**
- **Even worse in anti-Mirror**

Anomalous Transport Should Dominate Thermal Plasmas Under Present Operation

- How does anomalous transport scale in HSX?
  - Evidence that X_e scales like 1/n (vs $T_e^{3/2}$)
- In lower density operation strong evidence for energetic tail population
  - Well-confined in QHS
- What are the benefits of QHS in more thermal plasmas?
  - Good absorption of ECH
  - Reduced rotation damping
  - Eventually, good confinement of thermal plasmas in lmfp regime

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.

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

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

$$\omega_B = C_5 V_d$$

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

$$\tilde{\nu} = \frac{\nu}{C_6}$$

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

Full details on transport modeling and experimental measurements this afternoon in poster by Talmadge

ASDEX L-mode Anomalous Model

- 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:

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

Modeling Anomalous Transport II

- 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}):

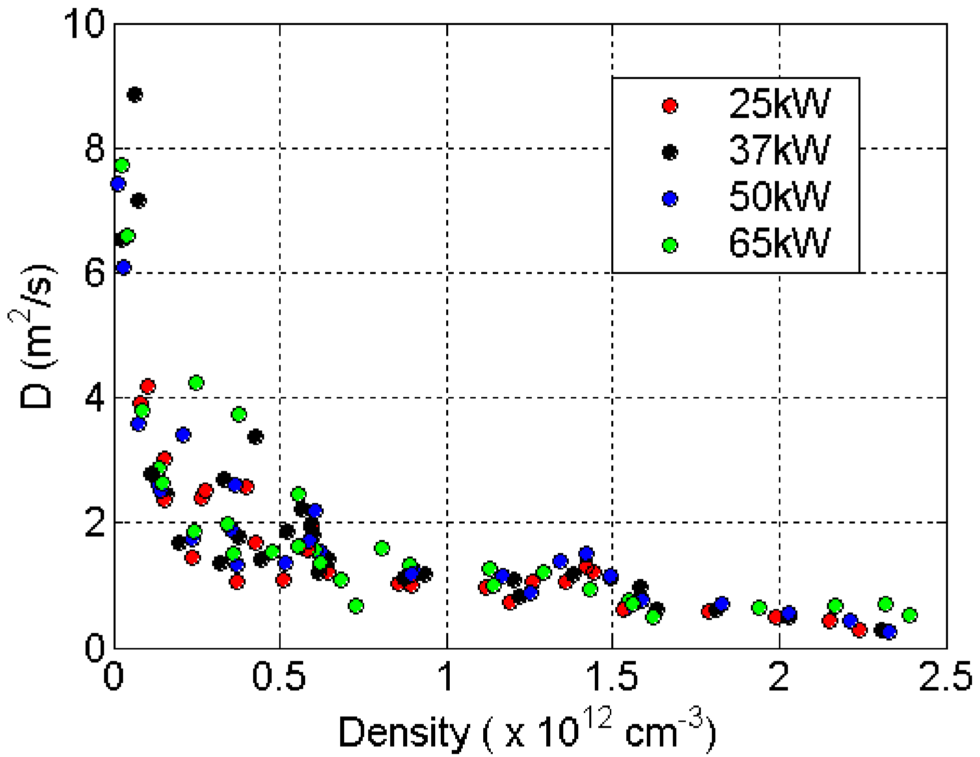
$$\chi_{e,anom} = \frac{10.35}{n_e} \; m^2/s$$

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

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

which is more in agreement with experiment

H_α Measurements Consistent with Model

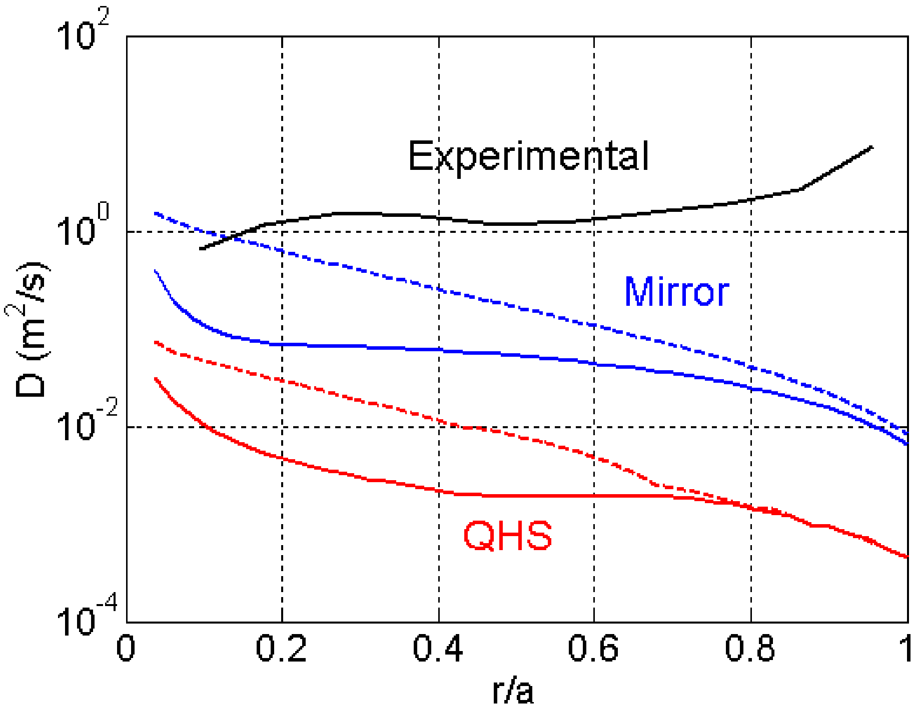


- **See poster by J. Canik**
- H_α toroidal and poloidal data analyzed using DEGAS code for 3 different line average densities and 4 different power levels
- Dependence of diffusion coefficient on n and P:

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

- Negligible dependence on power!

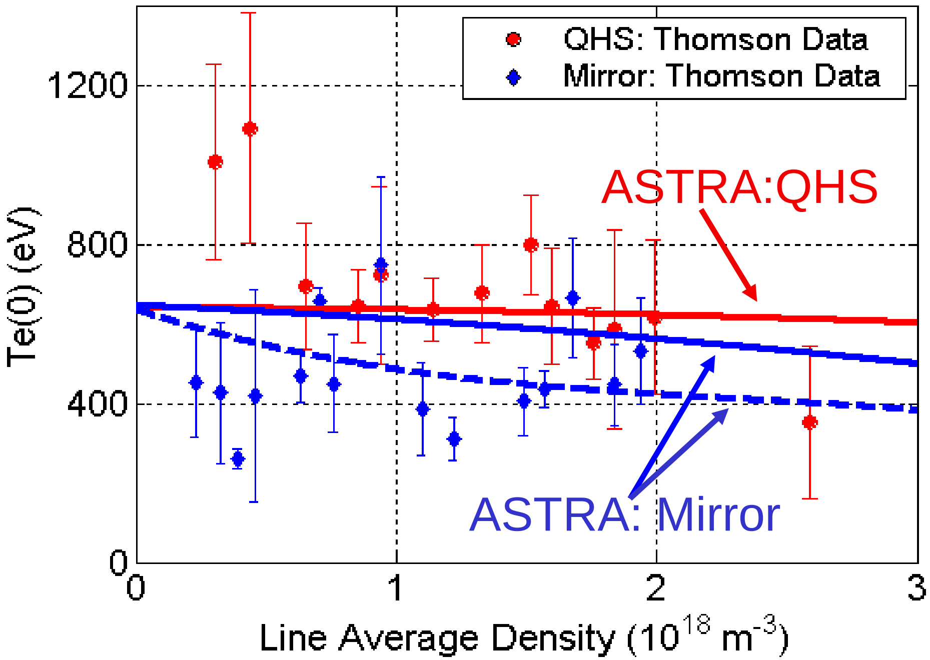
Experimental Diffusion Coefficients Larger than Neoclassical Values



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

D from equilibrium analysis in rough agreement with modulated gas puff

Central Electron Temperature is Independent of Density



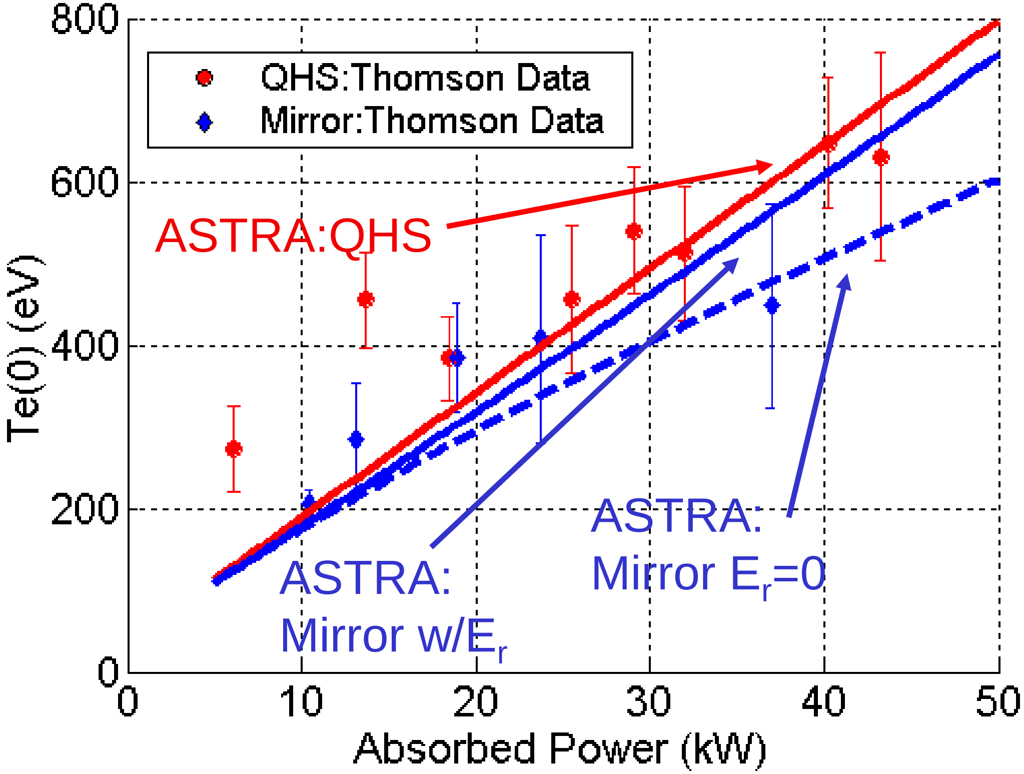
• QHS thermal conductivity is dominated only by anomalous transport

• $T_e(0)$ 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,

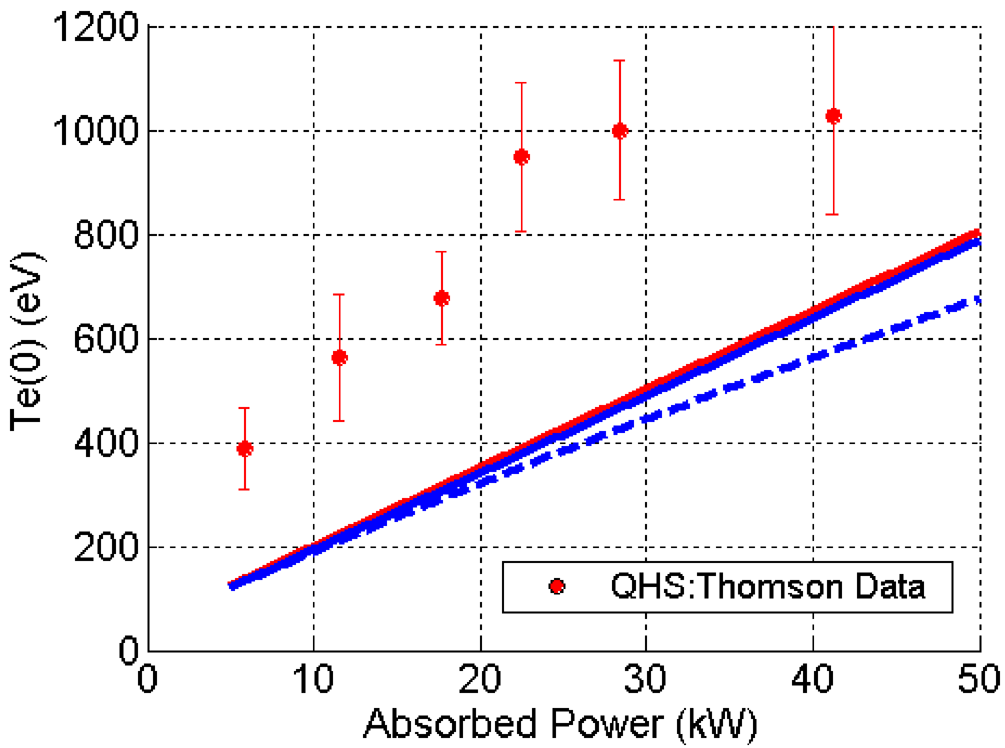
•Consistent with $\chi \sim 1/n$ model.

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



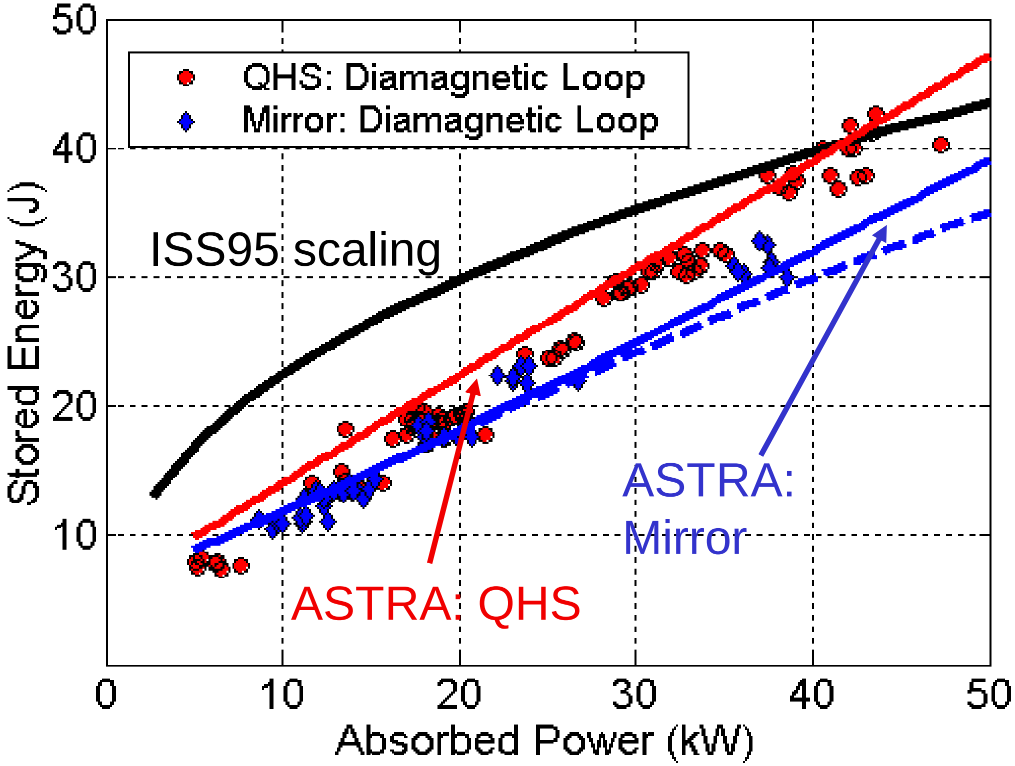
- Fixed density of 1.5 x 10^{18} m^{-3}.
- ASTRA calculation is consistent with Thomson measurements for QHS and Mirror
- T ~ P is supportive of χ ~ 1/n model.

At Lower Density, TS Disagrees with Model



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

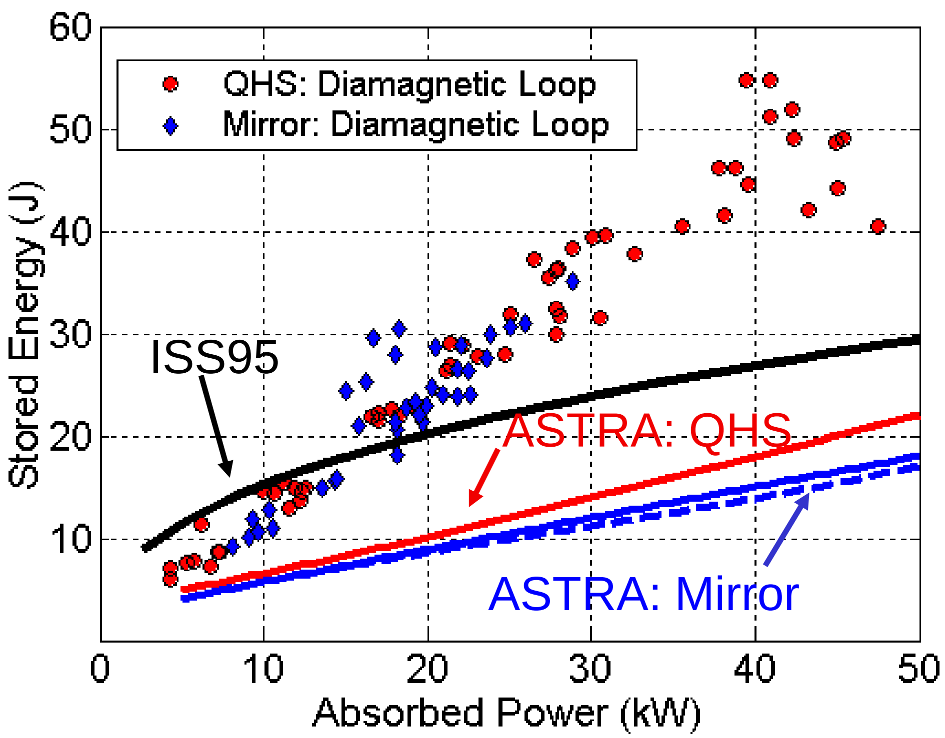
Stored Energy Increases Linearly with Power



- Fixed density of 1.5 x 10^{18} m^{-3}.
- Difference in stored energy between QHS and Mirror reflects 15% difference in volume.
- W ~ P in agreement with χ ~ 1/n model.

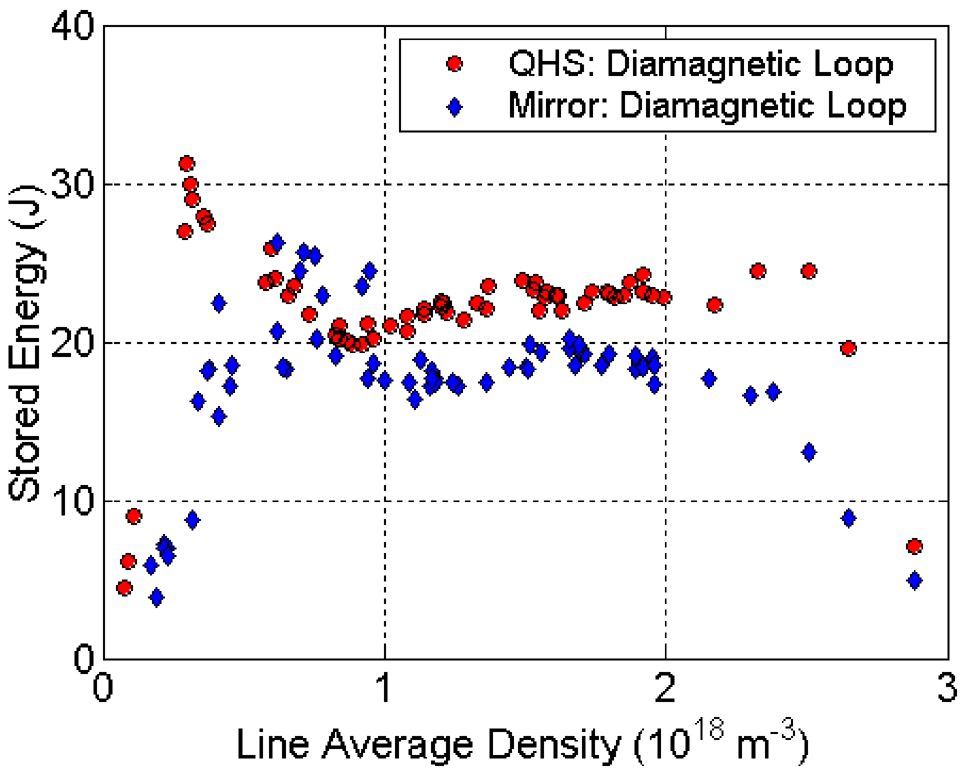
At the "Cross-roads"; higher-power and higher-density operation will be interesting!

At Lower Density, Stored Energy is Greater than Predicted



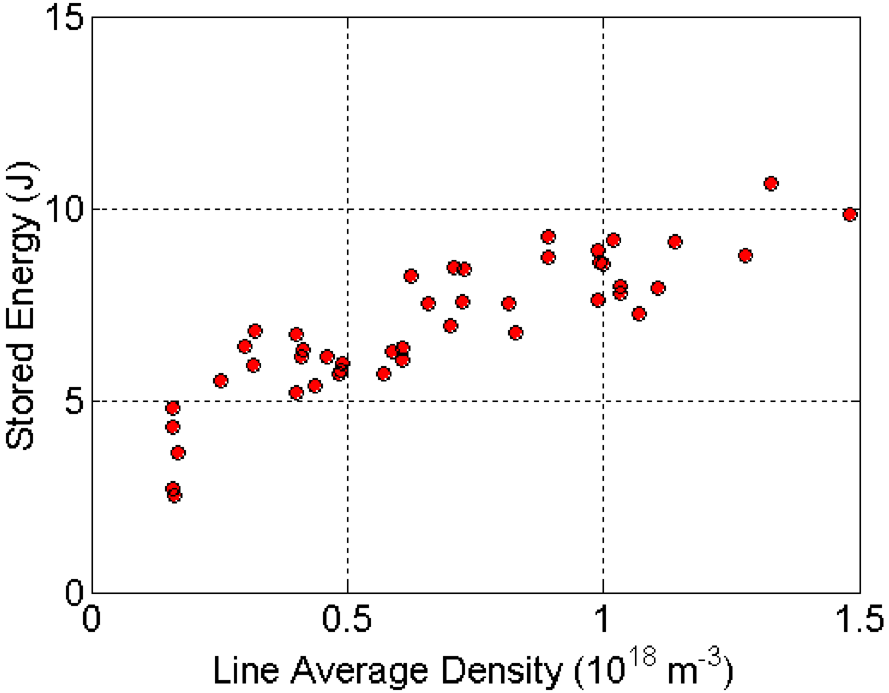
- Fixed density of 0.7 x 10^{18} m^{-3}.
- Data shows stored energy even greater than ISS95 scaling
- However, still W ~ P in agreement with $\chi \sim 1/n$ model.
- Are nonthermal electrons responsible for large stored energy?

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?

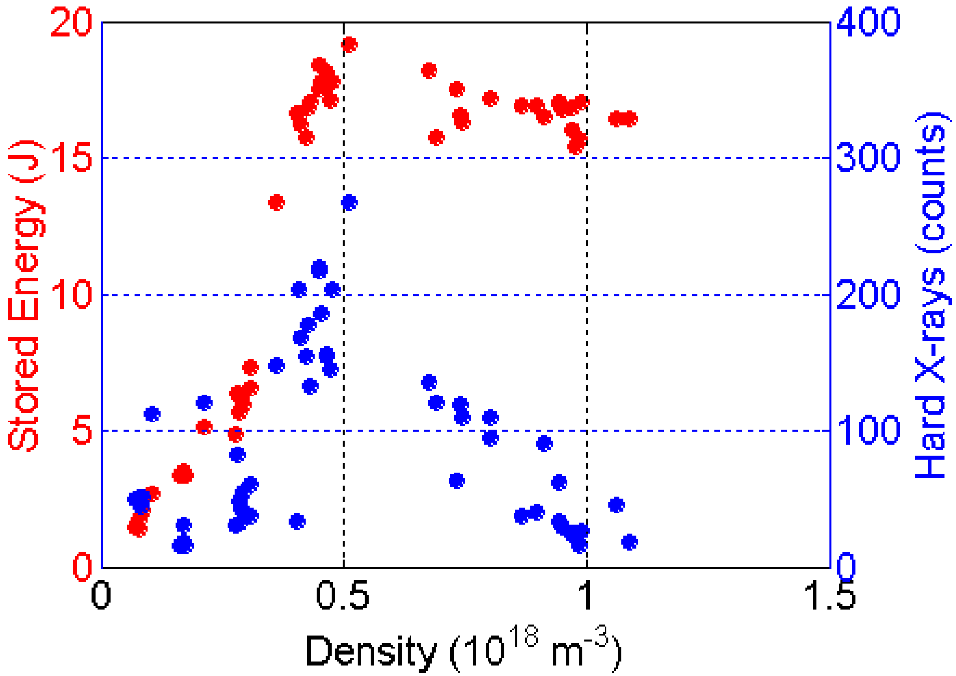
Stored Energy Goes Up Linearly with Density when Confinement is Poor



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

•Stored energy of 7 J at n= 0.7 x 10^{18} m^{-3} now in agreement with ASTRA prediction

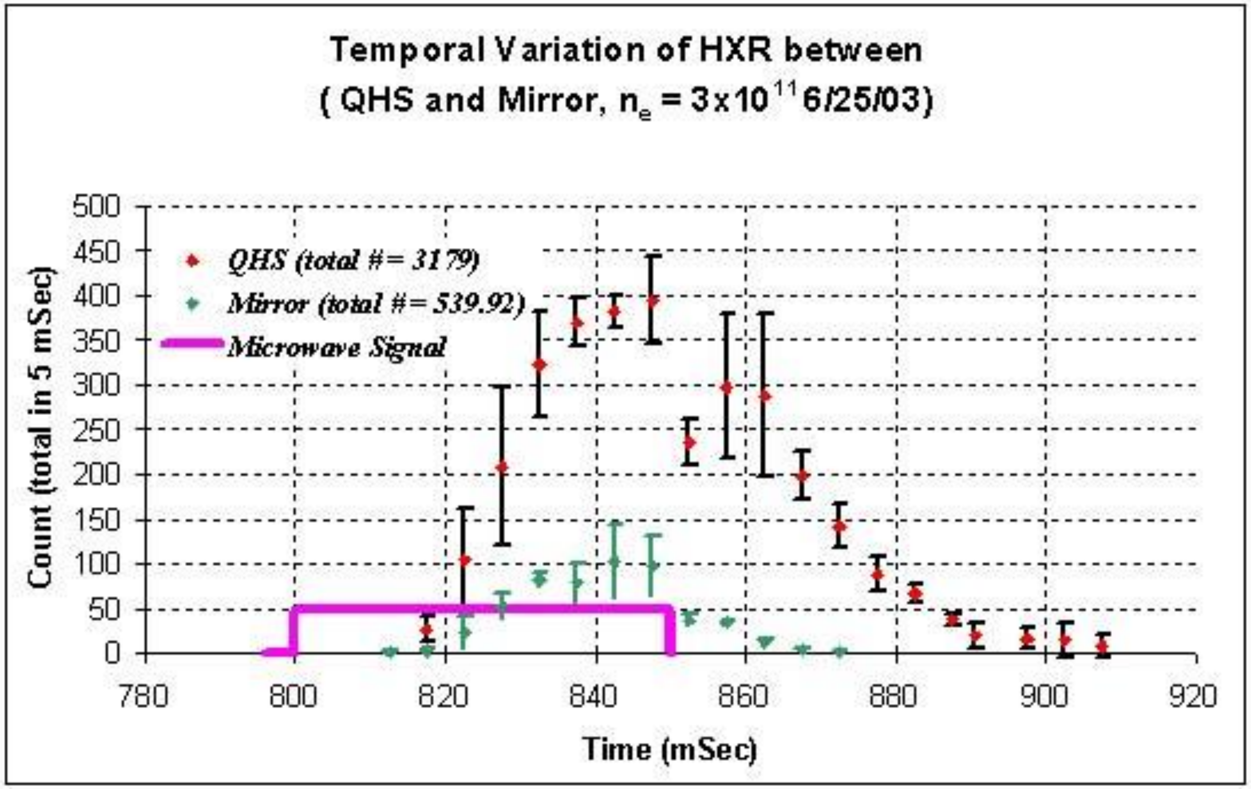
Hard X-rays Have Similar Dependence on Density as Stored Energy for n < 1 x 10^{18} m^{-3}



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

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

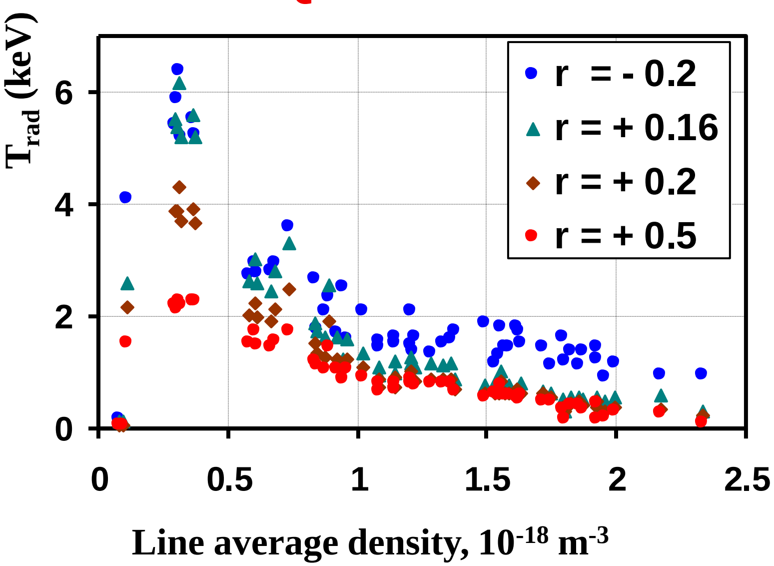
Hard X-rays Greater in QHS than Mirror



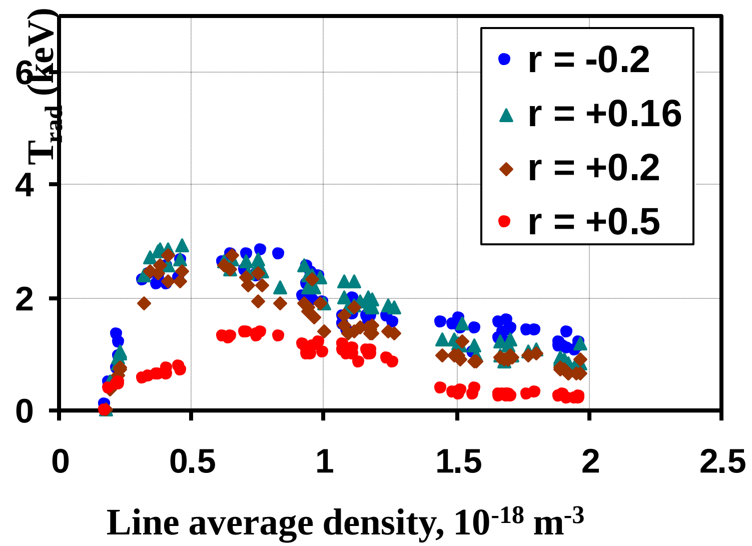
• Intensity increases till gyrotron turn-off, then decreases with 13 ms time constant for QHS, 5 ms for Mirror; virtually no hard x-ray counts for anti-Mirror

T_{rad} by ECE Shows Large Non-Thermal Component at Low Densities

QHS

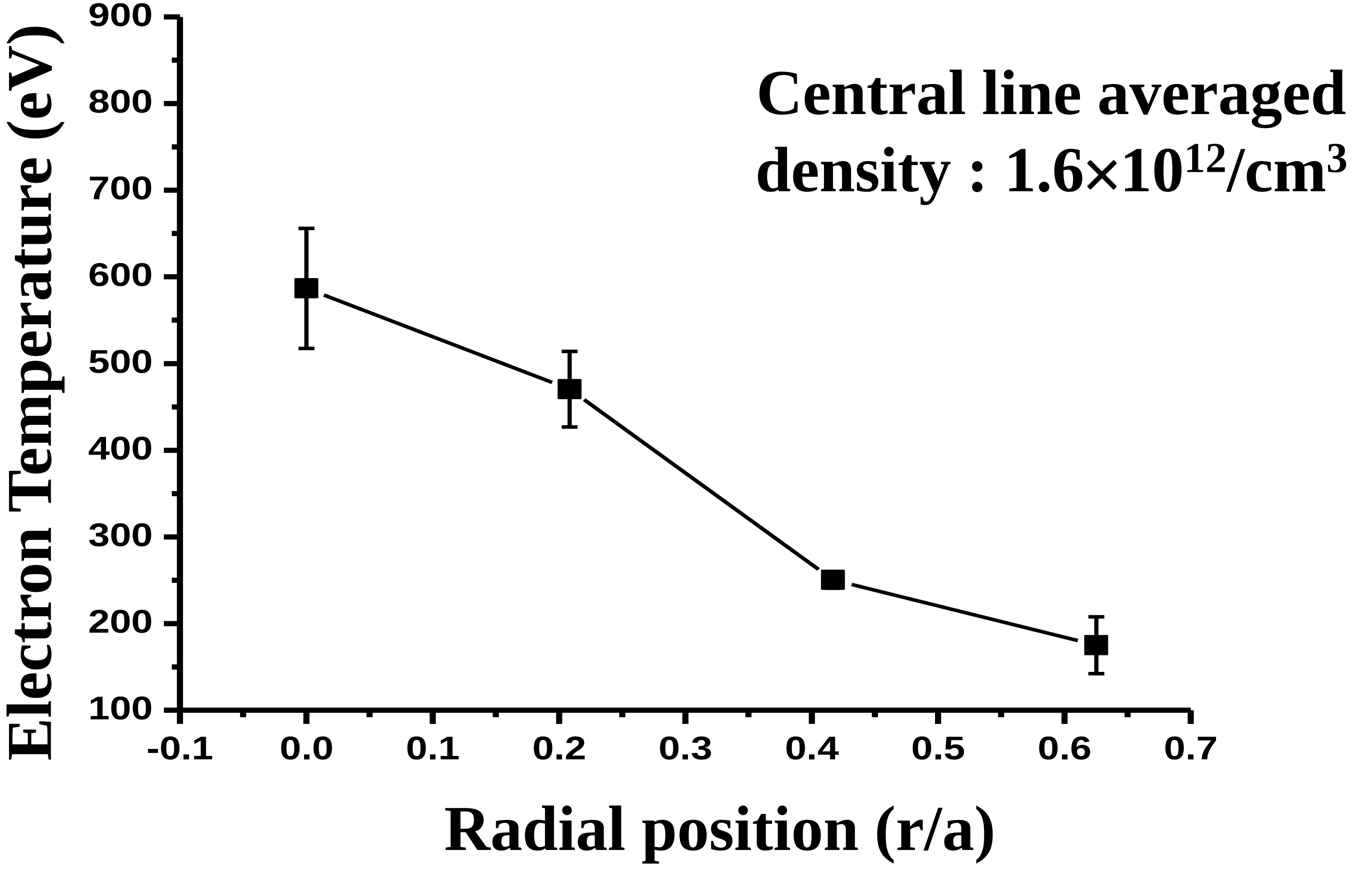


Mirror



- T_{rad} as high as 6 keV in QHS; less than 3 keV in Mirror
- At densities of 1.5 x 10^{18} m^{-3} emission is thermal in both QHS and Mirror plasmas

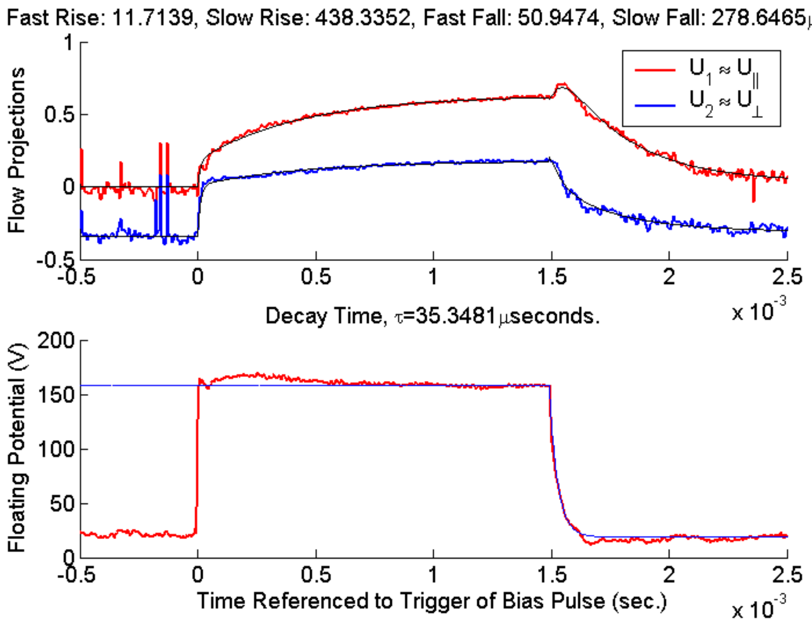
QHS Central Resonance
Thomson Scattering Profile

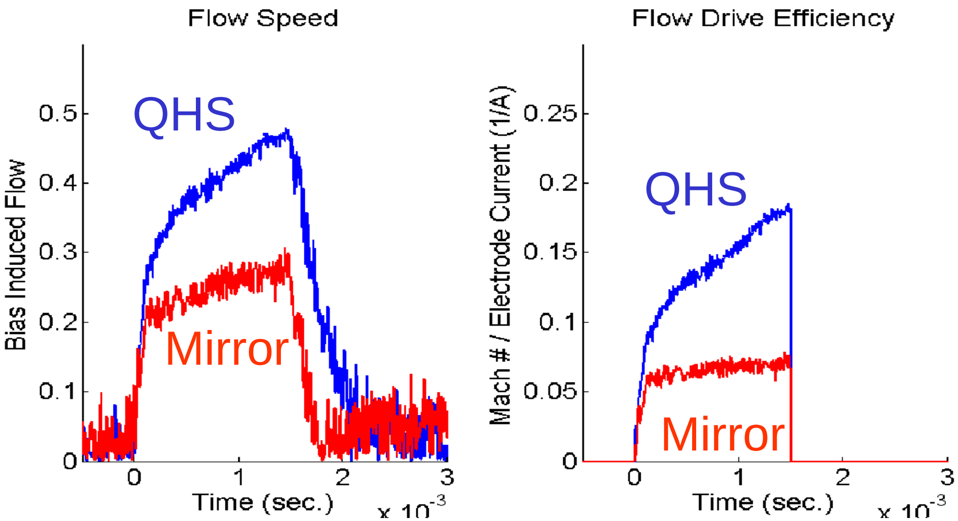


Thomson scattering and ECE in agreement for densities where non-thermals not playing a significant role

Differences Appear Between QHS and Mirror Modes for Thermal Plasmas

Biased electrode used to spin plasma





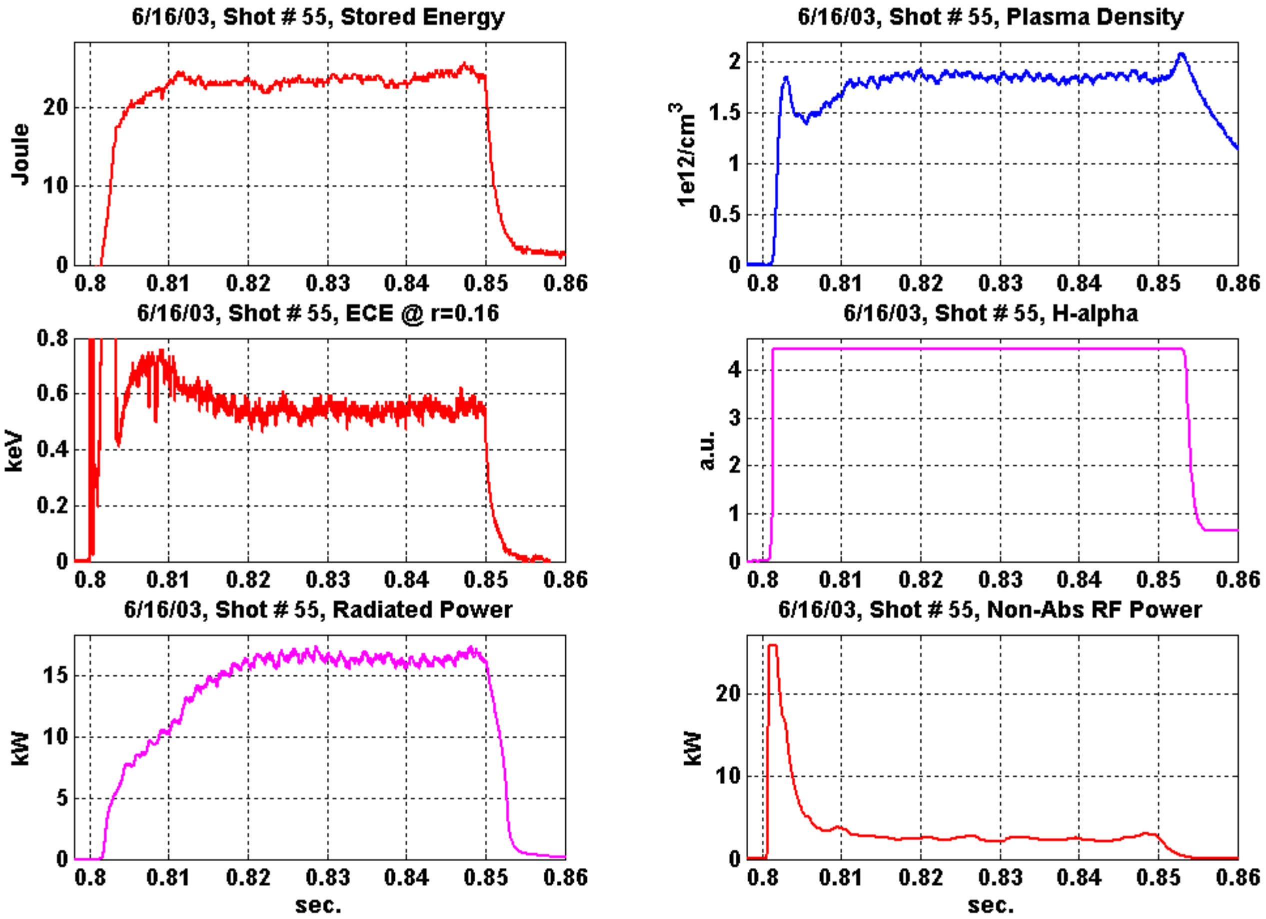
Two time scales for flow rise

(This is QHS case)

QHS flow damps slower, goes faster, for less drive

Talk by Gerhardt this session

Stable, Thermal Discharges Are Achieved with QHS at Higher Density



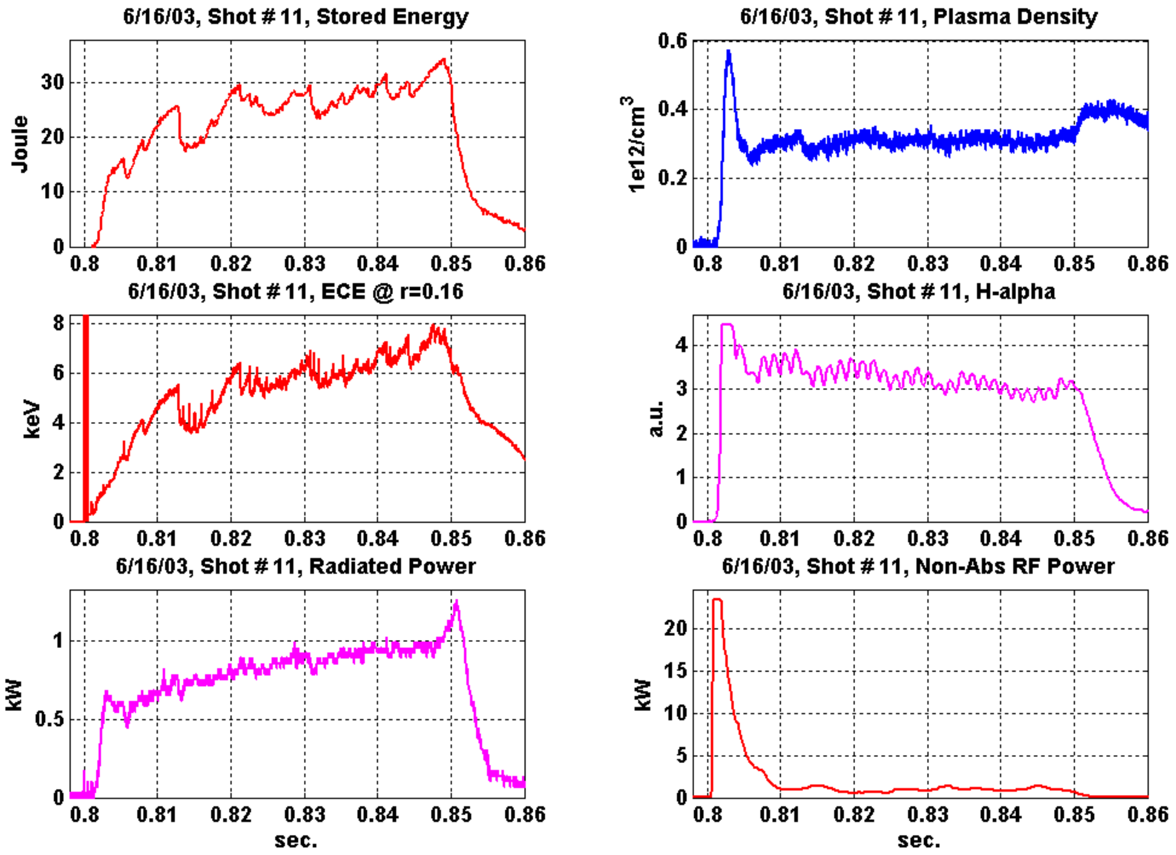
$T_e(0)$ ~ 600 eV, line averaged density ~ 1.8 x 10^{12} m^{-3}

W ~25 J, P_{rad} ~ 17 kW (50 kW injected)

In Low Density QHS Discharges, 'Crashes' Are Observed in Stored Energy and T_{rad}

Stored Energy

T_{rad}



Trapped electron modes; electron velocity anisotropy?

Concluding Remarks

- 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_{alpha} measurements that show D is roughly independent of power, but depends on $1/n^{0.6}$
- At low density, increases in stored energy are commensurate with energetic trapped population
  - Hard x-ray data
  - Non-thermal ECE emission
  - Outboard resonance mirror returns to proper scaling
- QHS shows higher absorption efficiency and higher X-ray flux than Mirror at low density. At high density, absorbed power falls off at $n > 2 \times 10^{18}\ m^{-3}$.
- Hence, superthermal electrons at low density and degraded absorption at high density account for discrepancy of stored energy with $\chi \sim 1/n$ model.

- For thermal plasmas, ECE and Thomson scattering are in good agreement with central electron temperature of ~600 eV at a line averaged density of ~1.5×10^{18} m^{-3}
  - Centrally peaked electron temperature profile (QHS)
- Differences in flows and damping have been observed for thermal plasmas between QHS and Mirror; two timescales
  - QHS slower damping, faster flow, for less drive than mirror
- Superthermal electrons may be drive in stored energy energy drops observed in low density QHS operation

Differences are observed between QHS and Mirror Modes for both thermal and non-thermal plasmas

Near term goals are increasing heating power and plasma density to further understanding of the role and modeling of anomalous transport in quasi-symmetric configurations