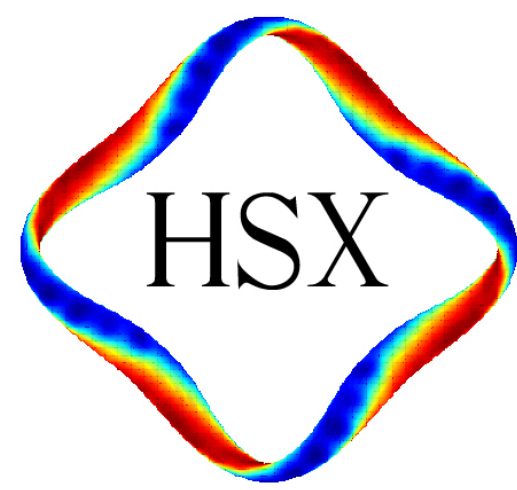




Experimental Plan and Recent Results from HSX

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HSX Project summary

First Electron Temperature profiles in HSX plasmas

- 10 channel Thomson scattering allows a radial profile of T_e – see poster by K. Zhai
- 4-channel ECE allows a sparse radial profile of T_e plus non-thermal contributions – see poster by K.M. Likin
- Thomson and ECE temperatures agree at densities above 1.5×10^{12} where plasmas are thermal.

QHS shows Improved Single Particle Confinement over the symmetry-broken Mirror configuration in Low Density operation

- Rf single-pass power absorption is very good at low densities where the absorption is dominated by the super-thermal tail population of electrons – estimates indicate that at low density up to 75% of the power is deposited into the super-thermal tail
- Hard X-ray signals up to 600 keV for QHS and only for 200 keV in Mirror mode, with at least 4 times the total flux in QHS. All Hard X-ray signals disappear at densities above 1.5×10^{12} cc
- QHS breakdown is $\sim 2\times$ faster than Mirror, with the anti-Mirror growth rate being extremely low.
- ECE effective temperatures Increase as Density Decreases. QHS peaks at 6 keV but only 3keV for Mirror

Plasma Rotation by Biased Electrode

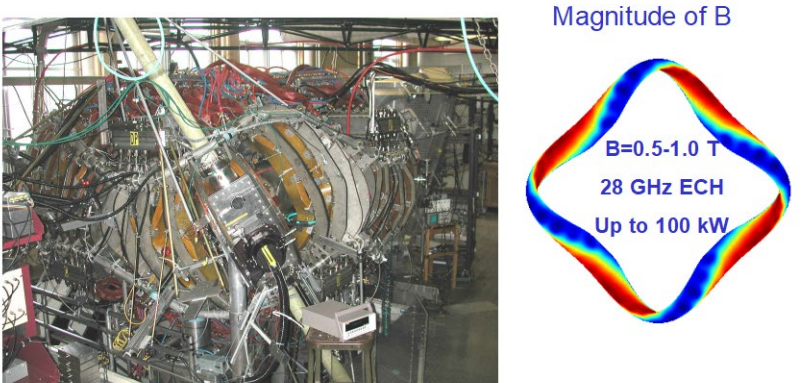
- QHS flow damps more slowly, and rotates faster, for less driving force than the symmetry-broken mirror configuration
- First measurement of Flows with TWO-timescales in a stellarator - the reintroduction of symmetry to a stellarator configuration reduces the viscosity in this direction.

T_e scaling and H_α measurements independently indicate that transport parameters D and C scale as $1/n$

- Experimental results consistent with Alcator-like scaling of anomalous transport (If $\tau \sim n = nT/P$, then: $T \sim P$ (independent of n); $\tau \sim n$; $W \sim nP$) – anomalous transport dominates the HSX plasmas
- Astra model predicts T_e profile well. Assumes $C_{e,anom} \sim 1/n_e$. Experimental G, D, T and τ are all generally consistent with the $C_{e,anom} \sim 1/n_e$ model
- Degas code predicts H and H_2 source rates, and diffusion coefficient, from H_α toroidal and poloidal array – Dan⁶ and D is independent of P.

HSX Device

HSX is a Quasi-helically Symmetric Stellarator

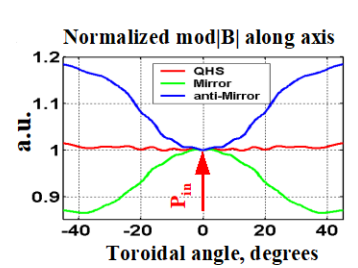


HSX has a helical axis of symmetry in |B| and a resulting very low level of neoclassical transport

Mirror coils add experimental flexibility

MODE	REMARKS: COIL CURRENT DIRECTION											
MIRROR	+	+	+	-	-	-	-	-	-	+	+	+
ANTIMIRROR	-	-	-	+	+	+	+	+	+	-	-	-

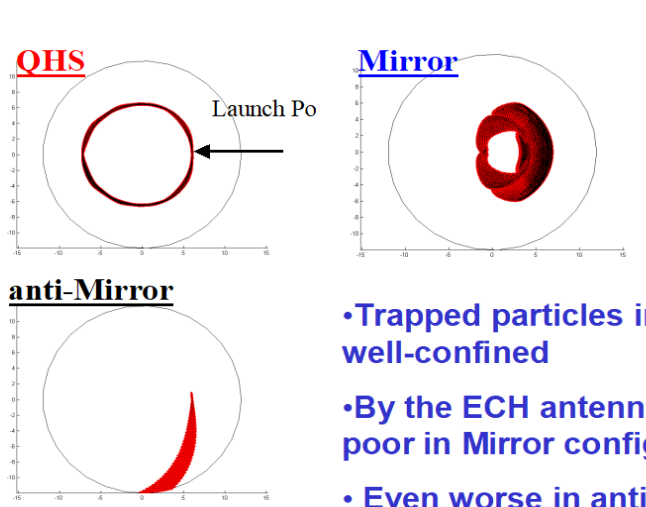
Neoclassical Transport Can Be Increased with Mirror Field



- 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

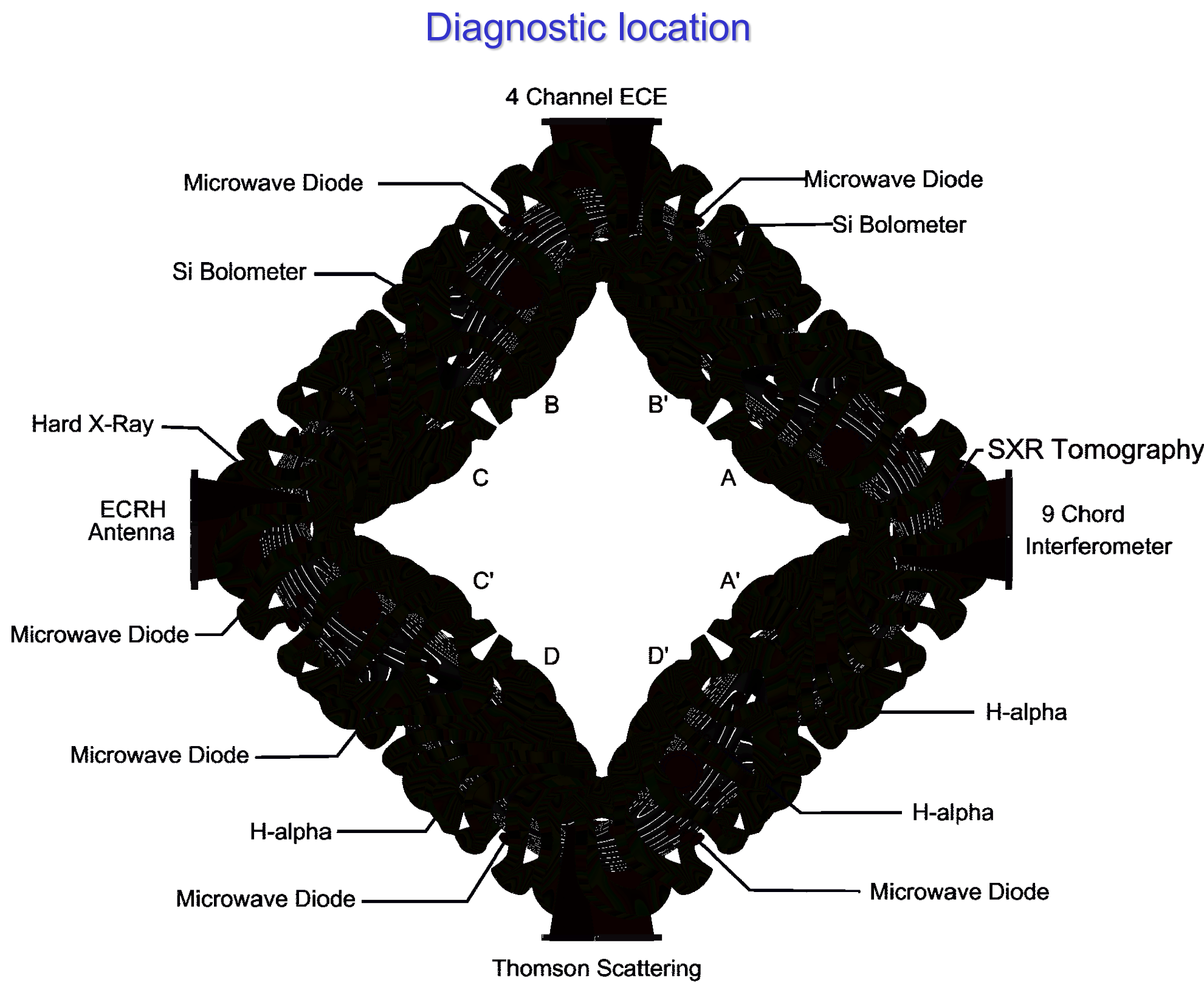


- Trapped particles in QHS are well-confined
- By the ECH antenna, orbits are poor in Mirror configuration;
- Even worse in anti-Mirror

HSX Parameters

Major Radius	1.2 m
Minor Radius	0.15 m
Field periods – Coils/period	4 periods - 12 coils/period
Magnetic Fields	0.5 T
Rotational Transform	$i_0 = 1.05$, $i_{edge} = 1.1$
RF heating source	<100 kW, 28 GHz, up to 100 msec pulses

HSX Diagnostics

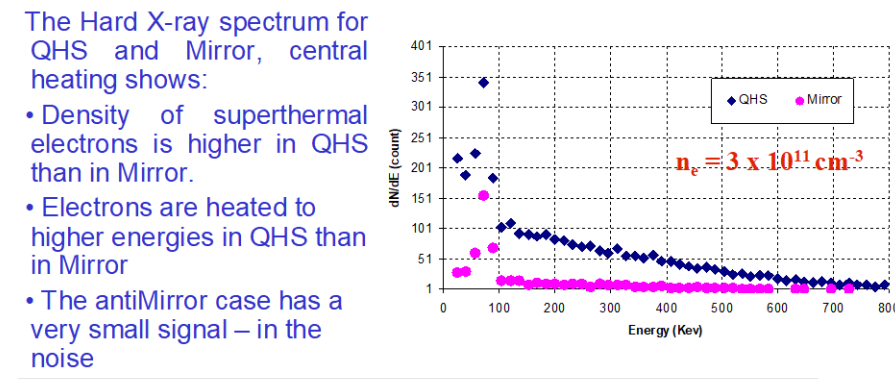


- **10 channel Thomson** scattering system for T_e up to 3keV – based on the DIII-D divertor Thomson system – see K. Zhai poster
 - Currently providing radial profiles at one time during a plasma shot - Designed for 50 hz double-pulse operation
- **9 chord m-wave interferometer** provides full time evolution of plasma density profiles
- **4-channel ECE** system provides T_e for thermal plasmas, and a guide to non-thermal emissions by Thomson Scattering comparison
- **Diamagnetic loop** for stored plasma energy.
- **H_α poloidal and toroidal array** for source rate distribution and, from DEGAS, a diffusion coefficient – see J. Canik poster
 - 7 detectors in toroidal array and 9 detectors in the poloidal array
- **20 silicon photodiodes** form a multichord array of **Soft X-ray detectors** – see V. Sakaguchi poster
 - 7 currently used for initial testing – will be expanded to using all 20 diodes in the array, and 3 or 4 arrays for tomographic reconstruction
 - 5 micron Be filter gives 400 eV lower energy limit, and the photodiodes limit the upper energy to <6 keV
- **A Hard X-ray** pulse height analysis detector provides X-ray energy data from 20 to 900 keV - see A.Abdou
- 6 absolutely calibrated **microwave detectors** are toroidally arrayed to provide rf absorption measurements
- 4 calibrated diode **bolometers** provide toroidal resolution of radiated power
- **Edge probes** provide basic edge parameters (n , T , f), and allow examination of fluctuation induced transport
 - A multi-probe ‘Gundesrup’ probe is used for plasma flow analysis – see S.P Gerhardt
 - Biased electrodes provide plasma rotation and edge bias
 - Poloidal and radial probe arrays provide plasma and floating potential and density information, and correlated fluctuation measurements – see W. Guttenfelder
 - Unique HSX magnetics allow outside access to both low-field or high-field magnetics

Major Results

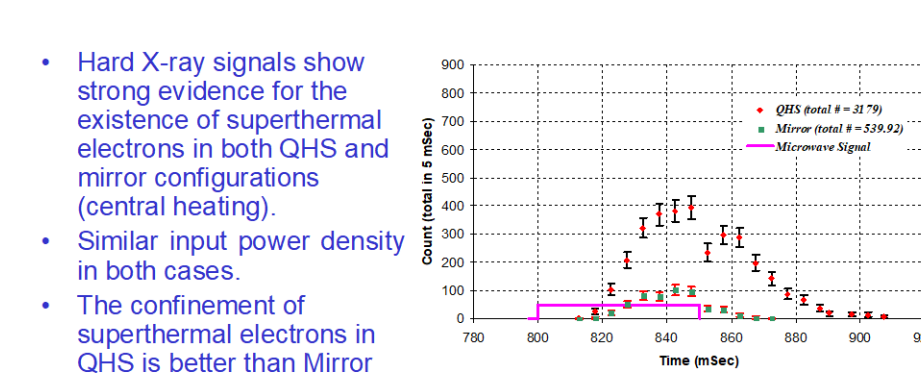
Low density shows a strong non-thermal electron population , and improved single-particle confinement of QHS over Mirror

Different Hard X-ray Characteristics in QHS and Mirror



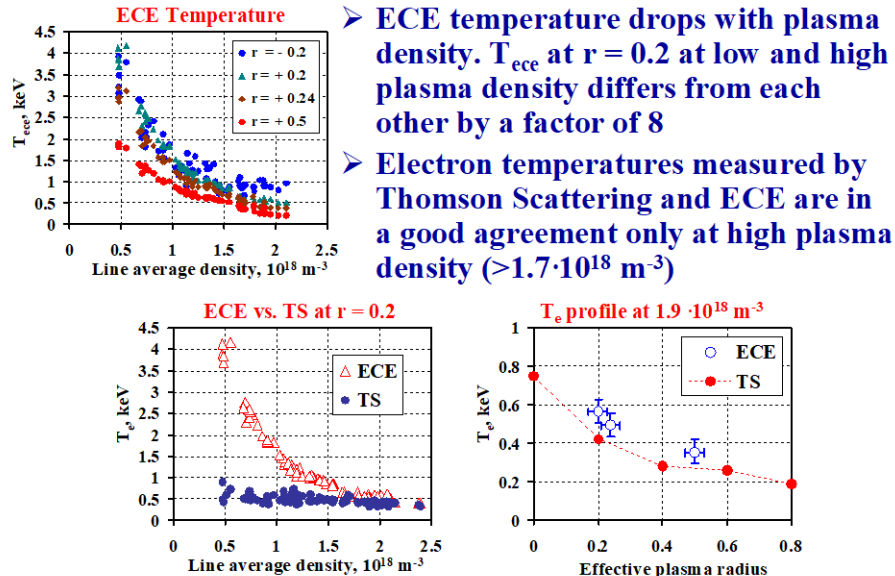
Property	QHS	Mirror
Max. Intensity (number)	~351	~151
Max. Energy (keV)	~600	~100

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



Property	QHS	Mirror
Max. Intensity (number)	~351	~151
Decay Time (nsec)	13.0	5.3

Electron Temperature in QHS



Neutral Gas Breakdown

- Motivation:** (1) to study the particle confinement (2) to study the physics of plasma breakdown by X-wave at the second harmonic of ω_{ce}
- Growth rate is determined from exponential fit to the interferometer central chord signal
- In QHS mode the growth rate is twice as that in Mirror
- In anti-Mirror mode the gas breakdown occurs with a very low growth rate

Plasma flows

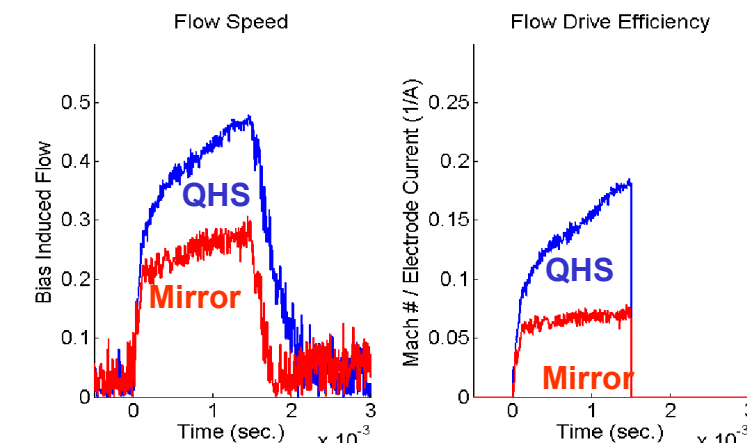
See poster by S.P. Gerhardt

Flow spin-up and damping exhibit 2 time-scale characteristics, indicative of two directions of flows

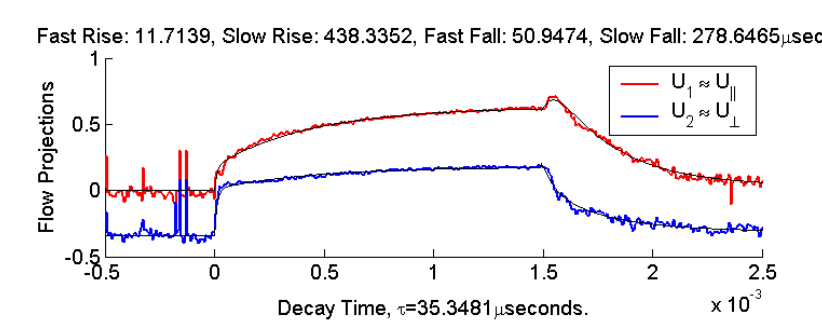
- Slower, low-viscosity in the symmetry direction
- Faster timescale for flows perpendicular to the symmetry direction

QHS Flow Damps Slower, Goes Faster For Less Drive.

- QHS Flow Rises and Damps More Slowly
- Flow Goes Faster For Per Unit Drive



Flow exhibits TWO timescales



Note: Floating Potential Rises Much Faster Than the Flows.

Moderate density plasmas exhibit thermal plasma properties and Alcator-like anomalous transport

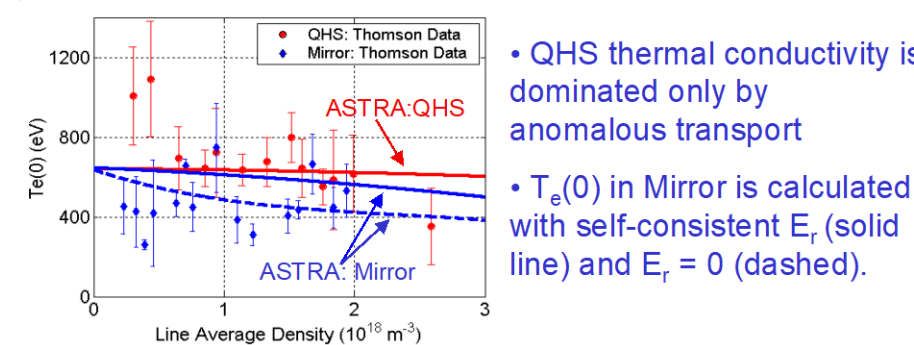
Modeling Anomalous Transport

- 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

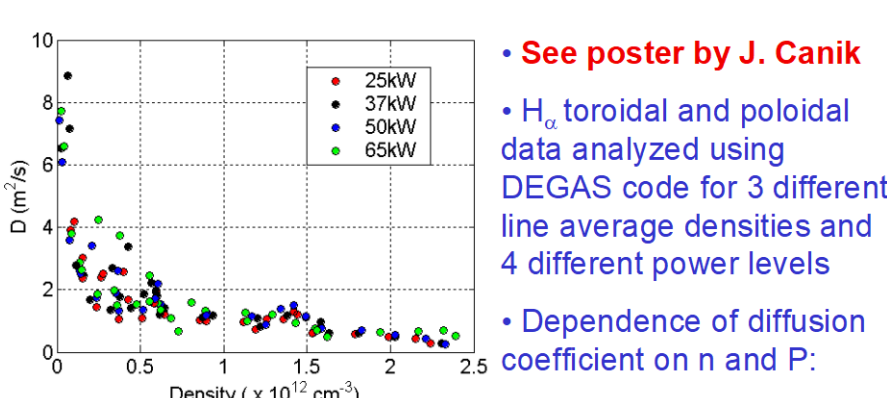
Central Electron Temperature is Independent of Density



- 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.

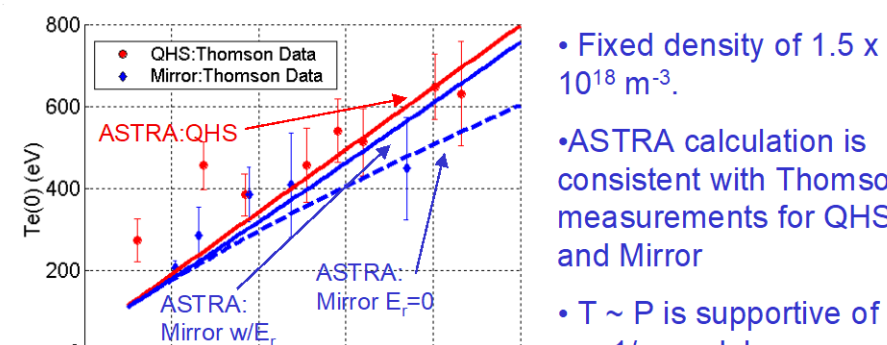
H_α Measurements Consistent with Model



- 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 :

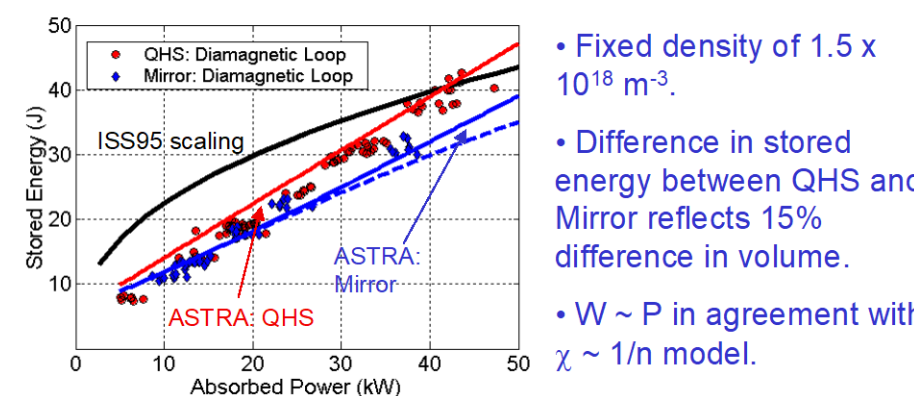
$$D_{anom} \sim \frac{P^{0.09}}{n^{0.6}}$$

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



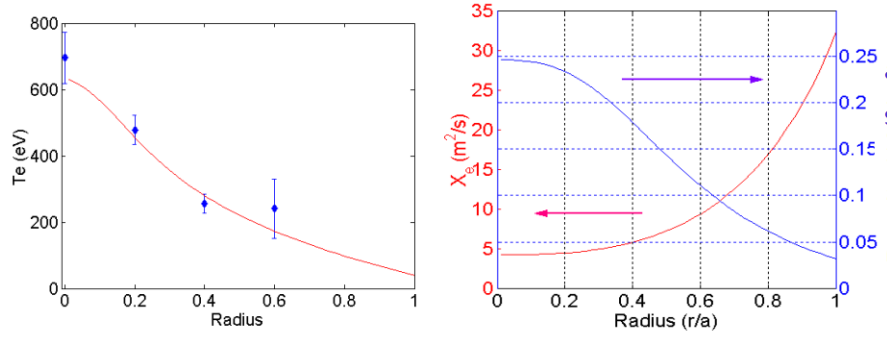
- Fixed density of $1.5 \times 10^{18} \text{ m}^{-3}$.
- ASTRA calculation is consistent with Thomson measurements for QHS and Mirror
- $T \sim P$ is supportive of $\chi \sim 1/n$ model.

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.

Comparison of ASTRA and Te Profiles



- Using the exact same dependence as before, $X_e = 10.35/n_e \text{ m}^2/\text{s}$, ASTRA gave good prediction of T_e profile

- At higher densities, the probe-measured fluctuation induced transport is in reasonable agreement with the flux calculated from DEGAS based on H_α source rates – see poster by W. Guttenfelder

- Density modulation experiments also show D decreasing with density – consistent with the H_α measurements – see poster by C. Deng

Future directions

- The $X_{anom} \sim 1/n$ model seems to reproduce some of the major experimental features, especially for the moderate density, more thermal, plasmas. This scaling is independently supported by H_α measurements and modeling, determination of D from gas-puff modulation experiments, and fluctuation induced transport measurements. At what absorbed powers and densities does this model no longer hold? When do we reach or exceed ISS-95 scaling for thermal plasmas?
- We need to confirm whether the Electron Thermal Conductivity is really smaller in QHS as compared to Mirror. Data indicates QHS has higher T_e than Mirror, but measurements are still somewhat uncertain. Modeling shows that we need more POWER and more DENSITY to clearly show the QHS : Mirror difference.
- We need to measure the radial electric field, E_r , for anomalous transport studies, especially as this strongly impacts the modeling.
- Boronization to reduce P-radiated as density is increased, since radiated power now scales with density.