Comparison of Electron Cyclotron Heating Results in the Helically Symmetric Experiment with and without quasi-symmetry

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30th EPS conference, St. Petersburg, Russia, July, 7-11, 2003

Outline

Goal: Explore differences in transport between quasi-symmetric and conventional stellarators

- Auxiliary coils provide flexibility

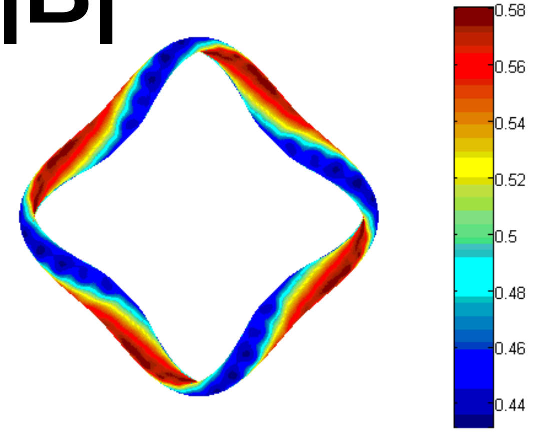
- **Improved single-particle confinement has been observed**
  - **Higher density growth rates**
  - **Higher absorption efficiency at low density**

Outline (cont.)

- At low-field, low-power, differences in stored energy, T_{e0} are minimal
  - Anomalous transport still dominates over neoclassical
- Quasi-symmetry reduces plasma flow damping

The Helically Symmetric Experiment

|B|



- **HSX is a stellarator type of fusion machine**
- **Unlike a conventional stellarator the toroidal curvature term in the HSX magnetic field spectrum is negligibly small and the dominant spectral component is helical (N = 4, m = 1)**

Symmetry in |B| : $B = B_0\left[1-\varepsilon_h \cos\left(N - m\iota\right)\phi\right] \quad , \quad \varepsilon_t \approx 0$

- **Symmetry in |B| leads to a small deviation of trapped particles orbits from a flux surface and, as a result, to improved neoclassical confinement in low collisionality regime**

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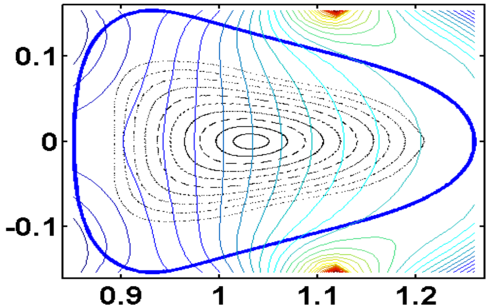
Cross-sections along ½ Field Period

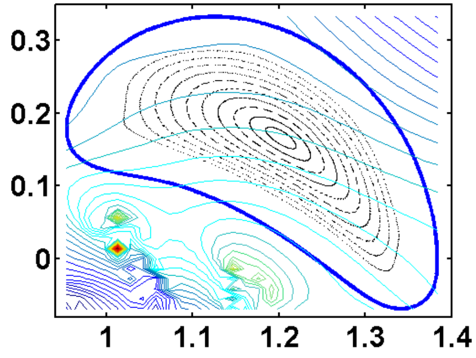
Magnetic axis is wound around R = 1.2 m

$\phi = 45^o$



grad|B|

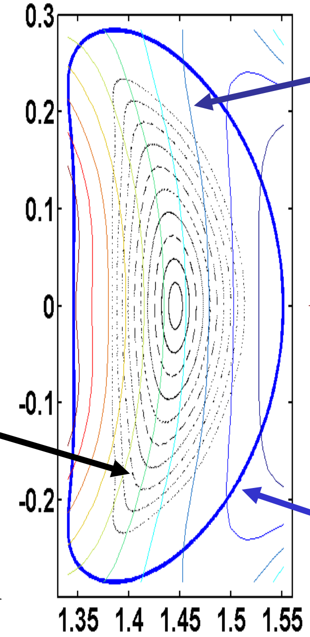
$\phi = 22.5^o$



Nested Flux Surfaces

$\phi = 0^o$

Location of RF antenna



Mod|B| Contours

grad|B|

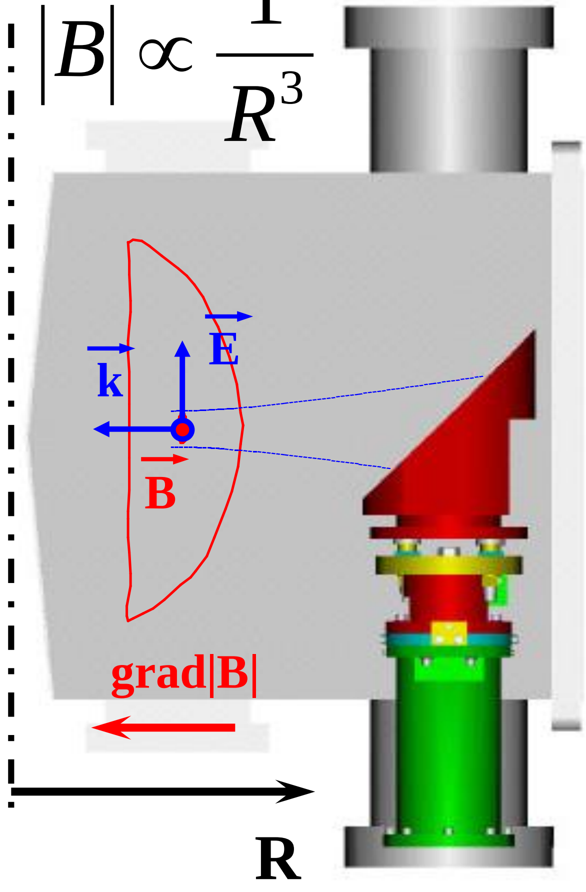
Vacuum Vessel

Major Radius

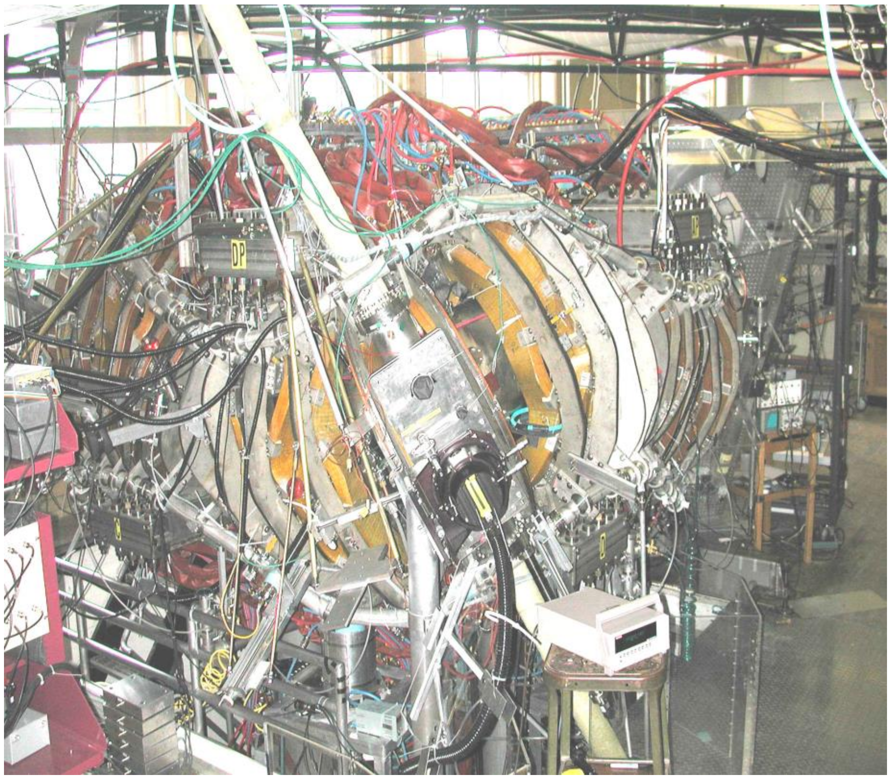
RF Heating in HSX

- Microwave power at 28 GHz breaks down the neutral gas and heats the plasma at the second harmonic of ω_{ce}
- X-wave beam ($E \perp B$) is launched from the low magnetic field side and is focused on the magnetic axis with a spot size of 4 cm

$$|B| \propto \frac{1}{R^3}$$



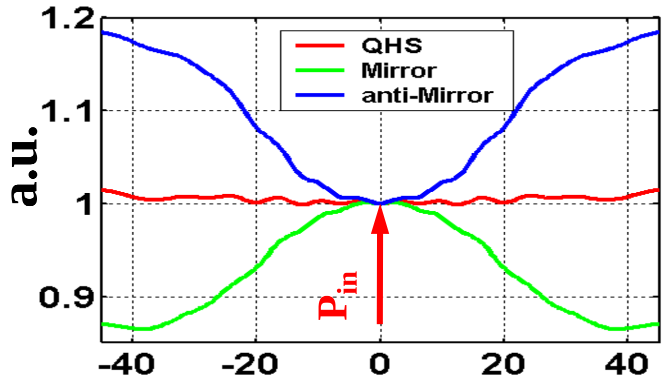
Current Operational Parameters of HSX



Major Radius	1.2 m
Minor Radius	0.15 m
Plasma Volume	0.44 m^3
Magnetic Field	0.5 T
Rot. Transform	1.05→1.12
Periods & Coils	4 with 48
RF Power	≤ 100 kW
RF Pulse length	≤ 50 msec.

Mirror configurations

Normalized mod|B| along axis



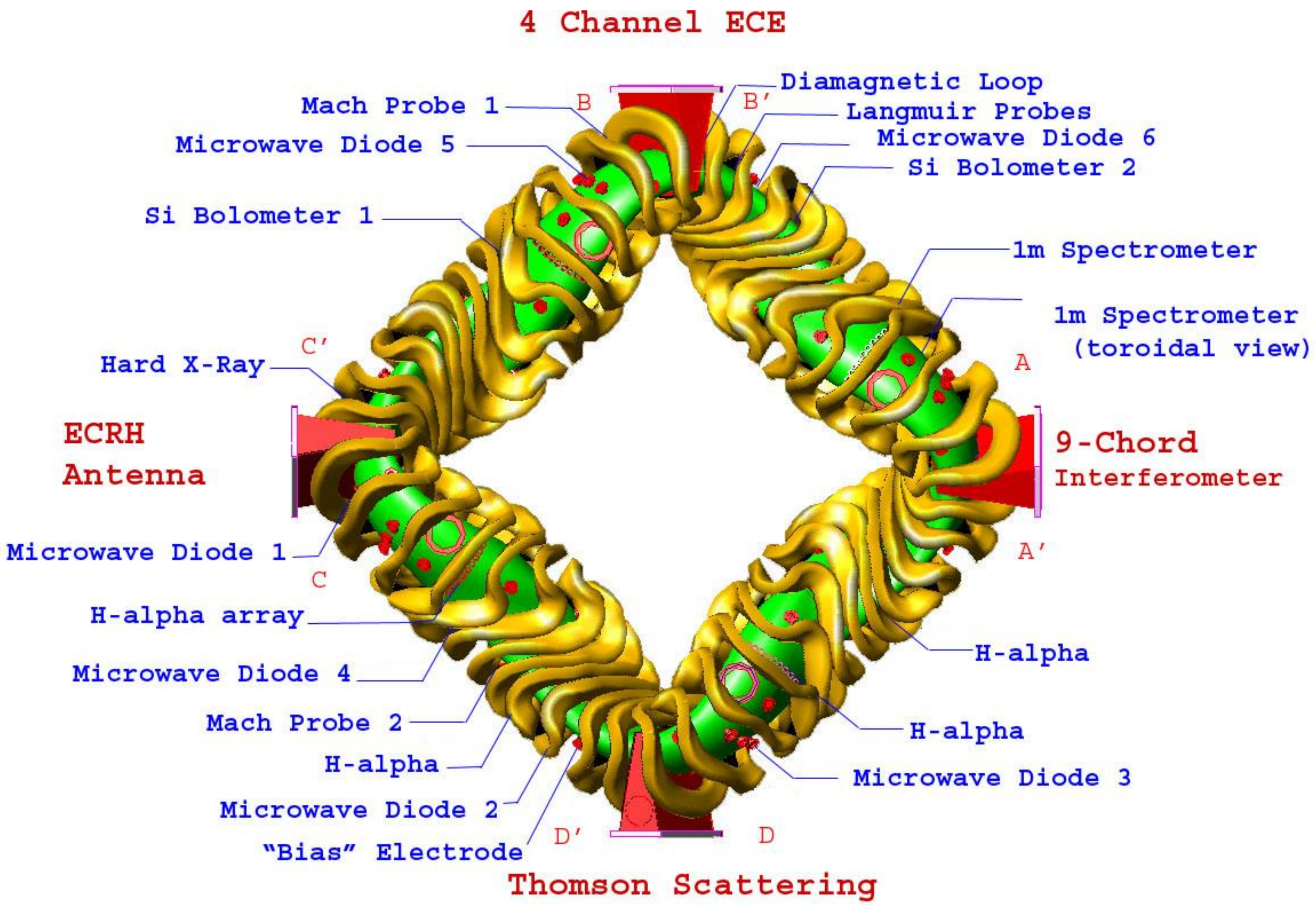
Toroidal angle, degrees

- **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 and <u>In anti-Mirror</u> it is opposite to the main field**

- **Predicted global neoclassical confinement is poor in both Mirror configurations**

Diagnostics on HSX



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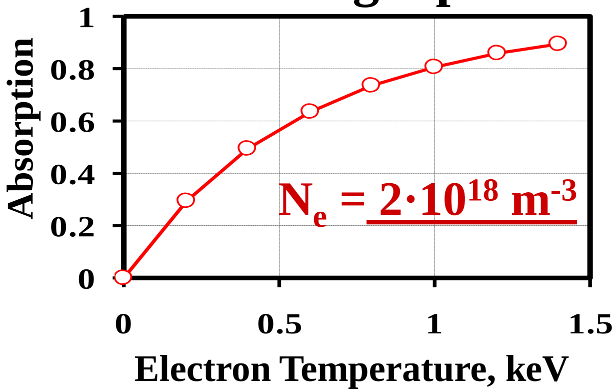
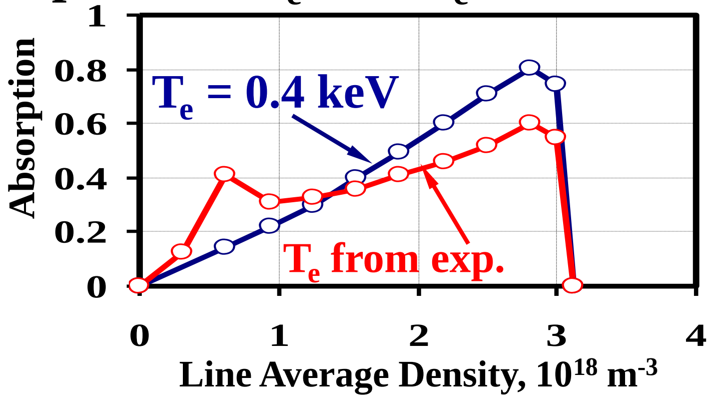
Ray Tracing Calculations

3-D Code is used to estimate absorption in HSX plasma

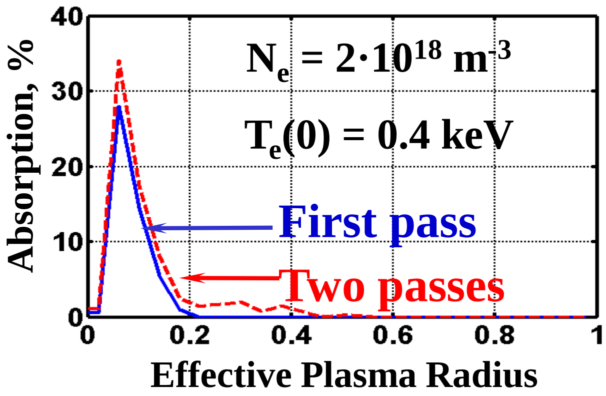
Single-pass absorption vs. T_e and N_e





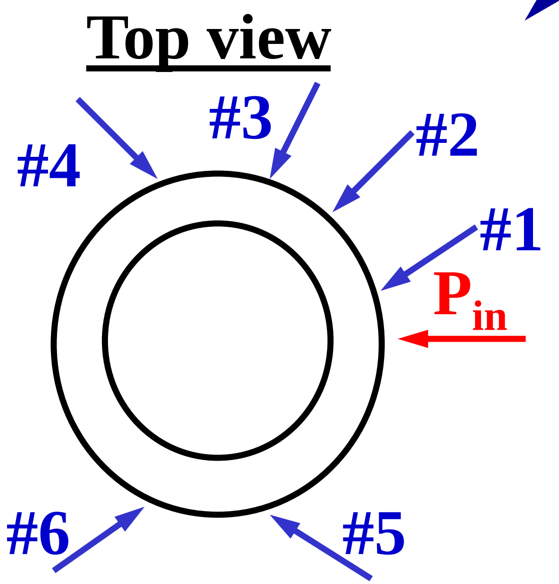
Owing to high temperature at a low plasma density the absorption is high

Absorbed Power Profile



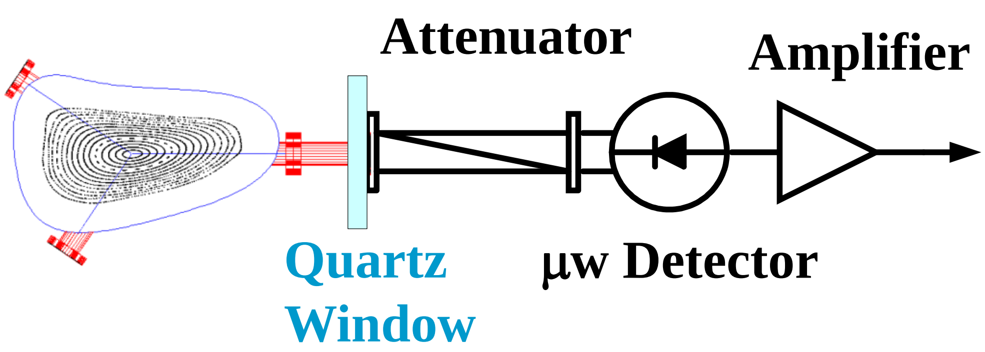
Rays are reflected from the wall and back into the plasma, the absorption is up to 70% while profile does not broaden

Measurements of RF Power Absorption



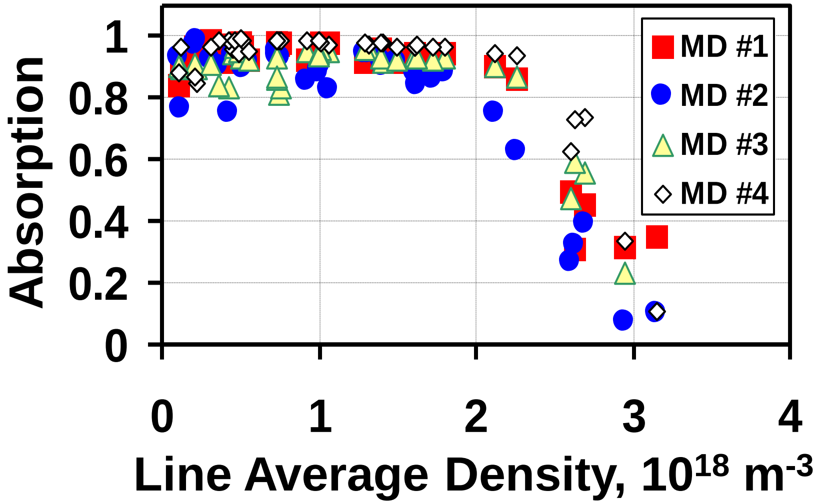
➢ **Six absolutely calibrated microwave detectors are installed around the HSX at 6°, 36°, ±70° and ± 100° (0.2 m, 0.9 m, 1.6 m and 2.6 m away from RF power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the RF launch.**

Each antenna is an open ended waveguide followed by attenuator

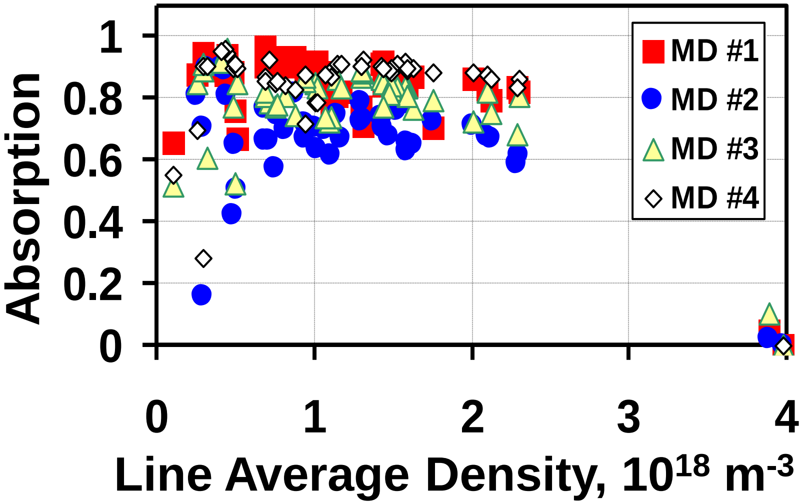


Multi-Pass Absorption

QHS



Mirror

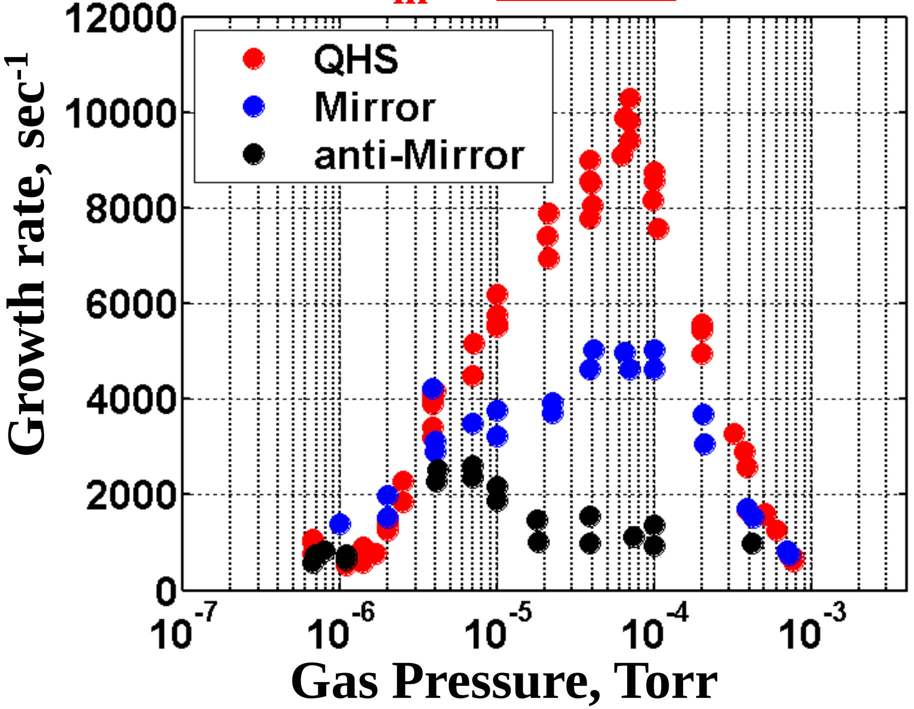


- **RF Power is absorbed with high efficiency**
- **At low plasma density the efficiency remains high due to the absorption on super-thermal electrons, in QHS their population is higher than in Mirror**

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}

P_{in} = 40 kW



- 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

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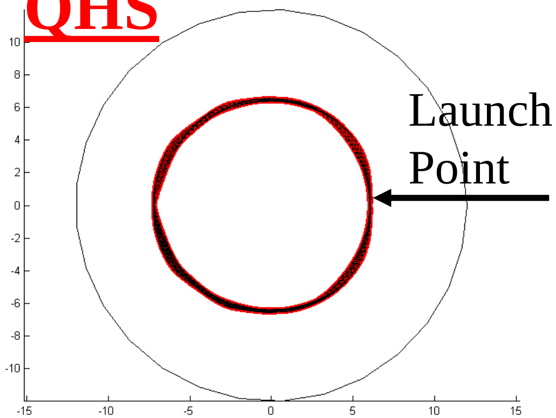
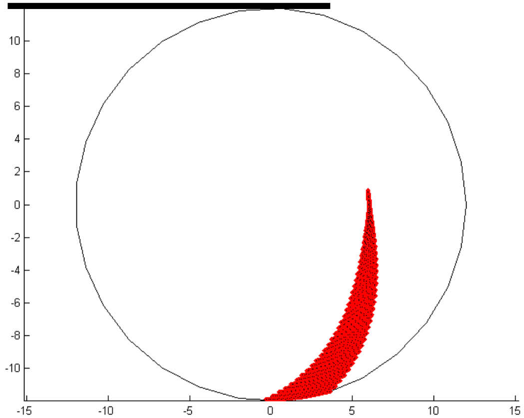
Trapped Particle Orbits

QHS

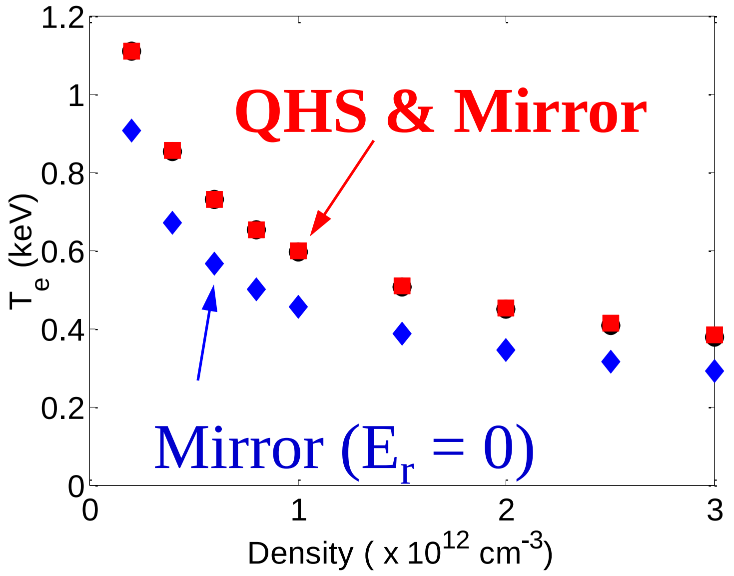


anti-Mirror



- **Trajectories of 25 keV electrons with pitch angle of 80° were calculated**
- **Orbits were followed using the guiding center equations in Boozer coordinates**
- **Launched on the outboard side of the torus at a point of minimum |B|**
- **QHS orbit is a simple helical banana precessing on surface; anti-Mirror orbit quickly leaves the confinement volume**

ASTRA Code



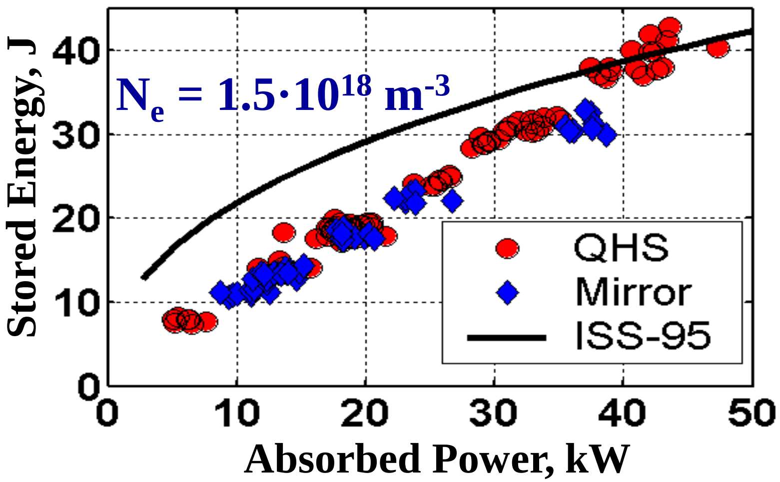
$$\chi_e = \chi_e^{neo} + \chi_e^{anom}$$

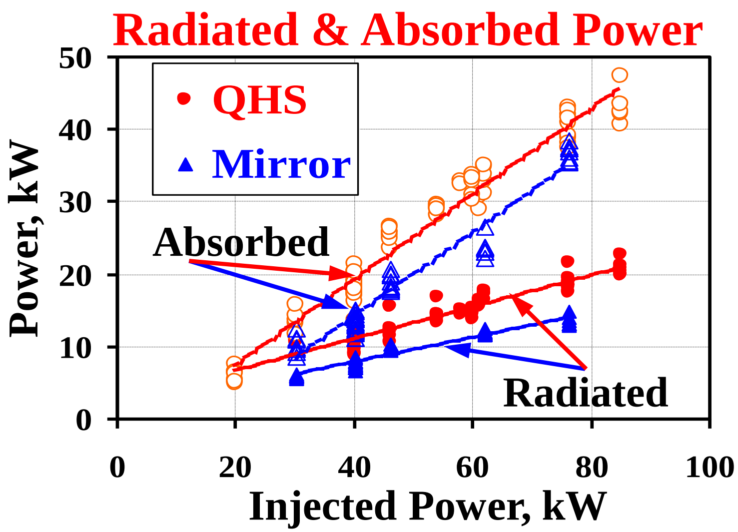
ASDEX L-mode scaling:

$$\chi_e^{anom} \propto \frac{T_e^{3/2}}{RB^2} \cdot \frac{1}{(1-(r/a)^2)^4}$$

- **At 1 T and 100 kW absorbed power ASTRA predicts 200-300 eV central temperature difference**
- **Both neoclassical and anomalous contributions to the transport are included**
- **At 40 kW of launched power and 0.5 T of magnetic field we expect little difference between QHS and Mirror**

Injected Power Scan

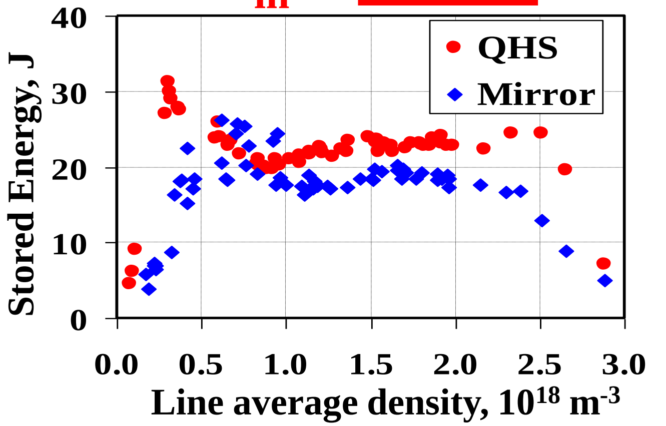




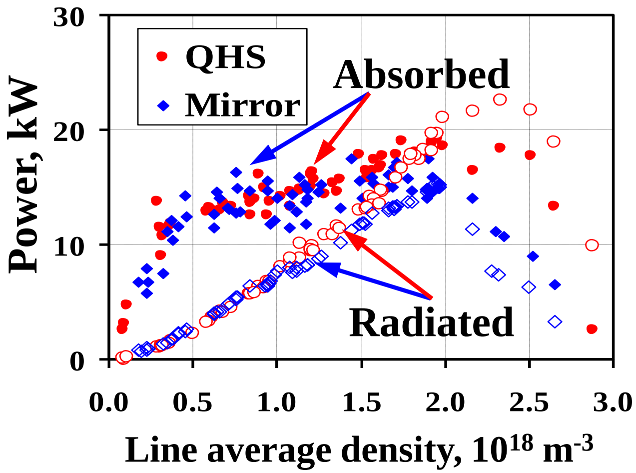
- No degradation observed in the plasma stored energy in heating power scan
- At 45 kW the HSX plasma meets ISS-95 scaling
- Radiated power is roughly 50% of absorbed power estimated from the change of diamagnetic loop slope

Plasma Density Scan

P_{in} = 40 kW



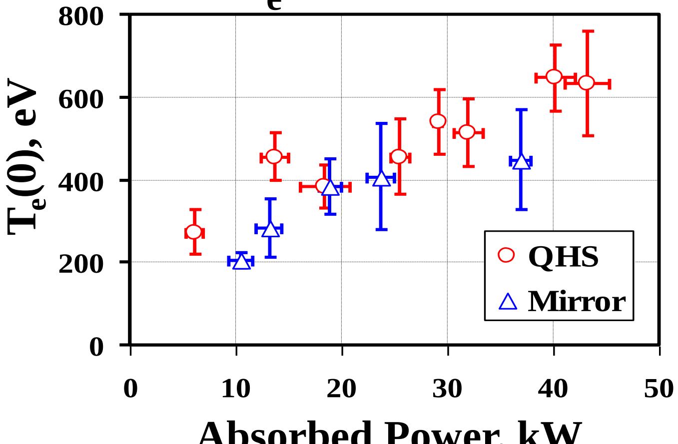
Radiated and Absorbed Power



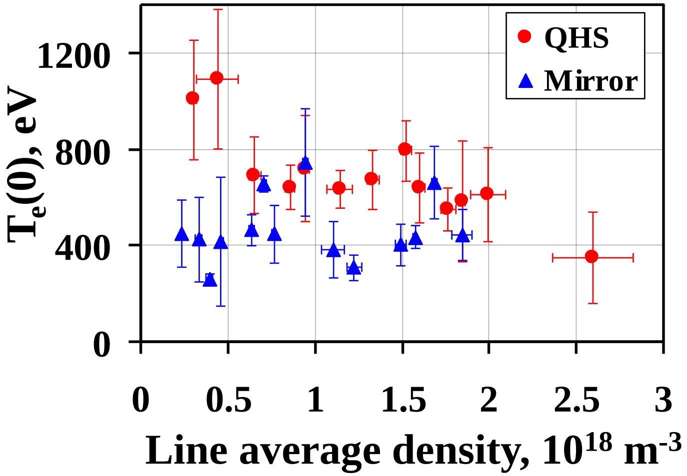
- In both QHS and Mirror modes the stored energy is about 20 J at high plasma density (> 10^{18} m^{-3})
- At low plasma density the stored energy has a peak due to super-thermal electrons
- Absorbed power is almost independent of plasma density
- Radiated power rises with plasma density

Electron Temperature

$N_e = 1.5 \cdot 10^{18}$ m^{-3}

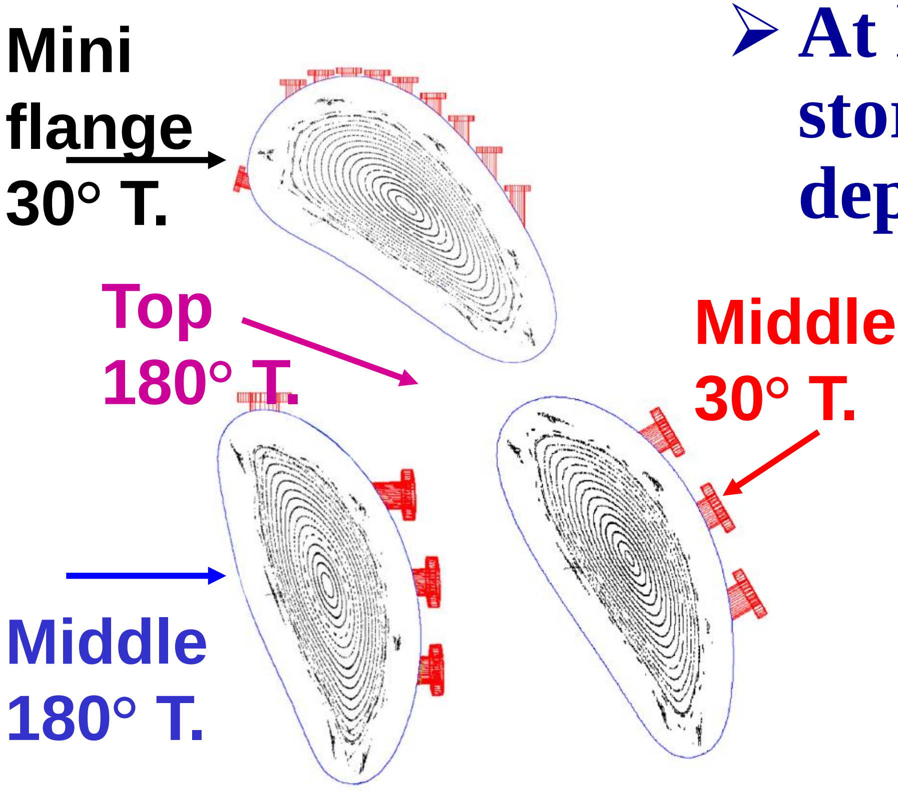


P_{in} = 40 kW

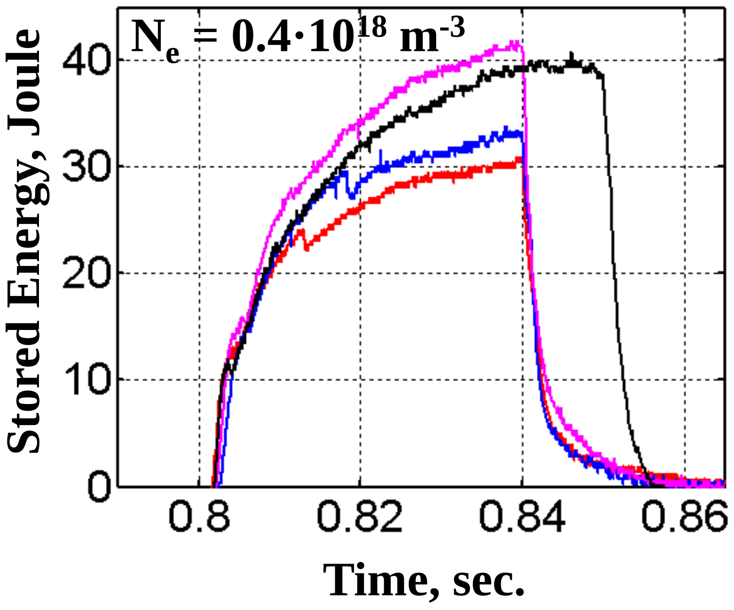


- **Central electron temperature measured by TS linearly increases with heating power**
- **Minimal difference in T_{e0} between QHS and Mirror except perhaps at low density ($< 0.5 \cdot 10^{18}$) m^{-3}**
- **To make a complete power balance we need to measure the temperature profiles**

Stored Energy vs. Gas Puffing Location

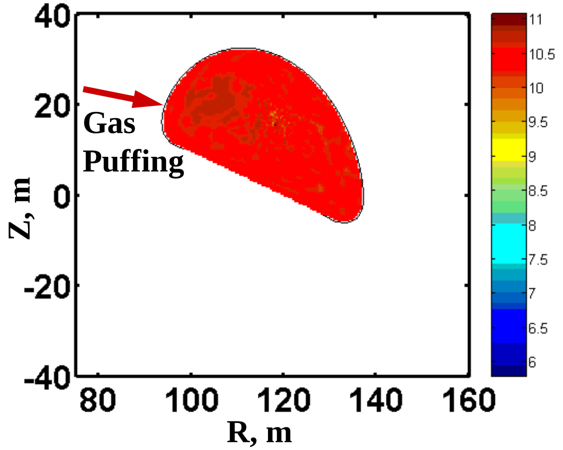


- At low plasma density the stored energy strongly depends on gas fueling

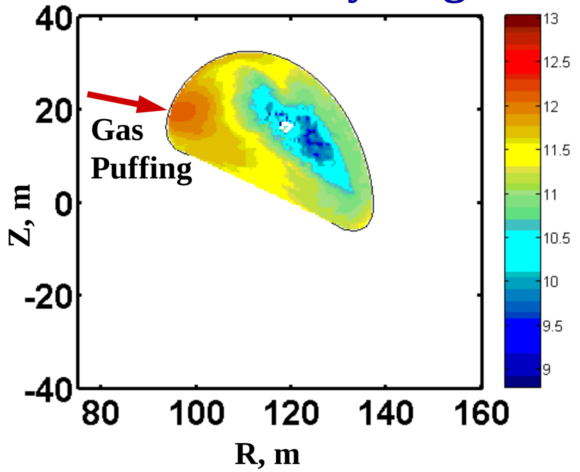


Neutrals Modeled by 3-D DEGAS

Atomic Hydrogen

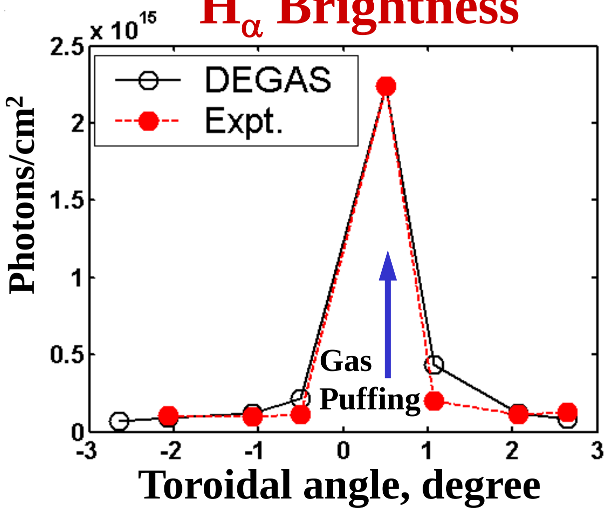


Molecular Hydrogen



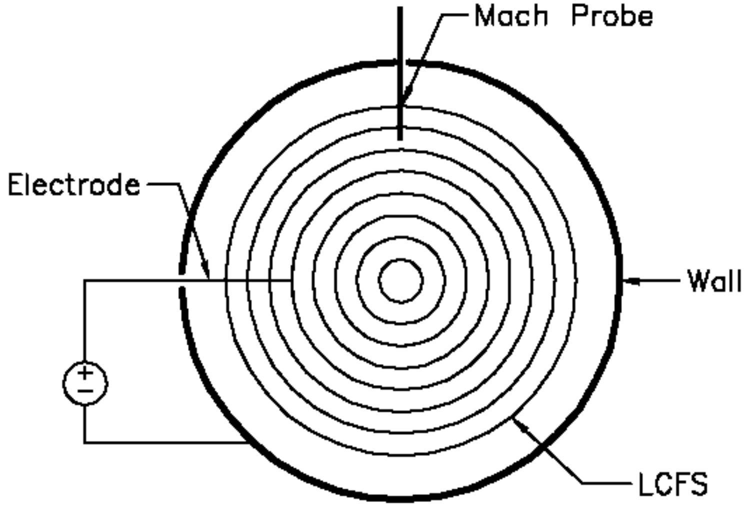
- Higher stored energies associated with reduced molecular penetration to core
- In experiment, 16 H_α detectors are used to measure the light

H_α Brightness

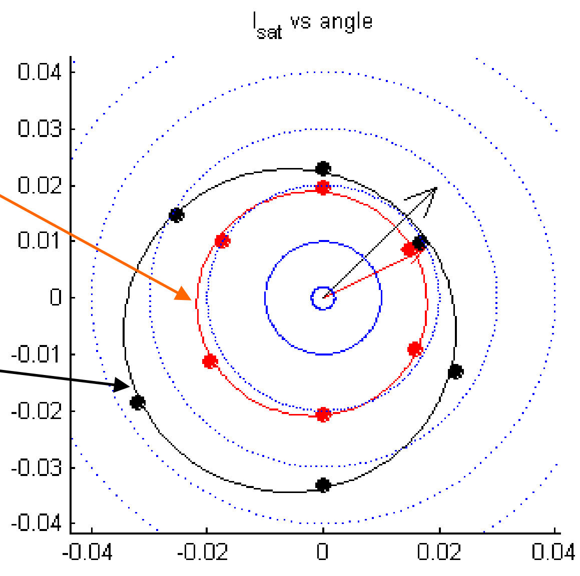


- Calculations are in a good agreement with measured H_α brightness both toroidally and poloidally

Ion Flows Induced with Biased Electrode

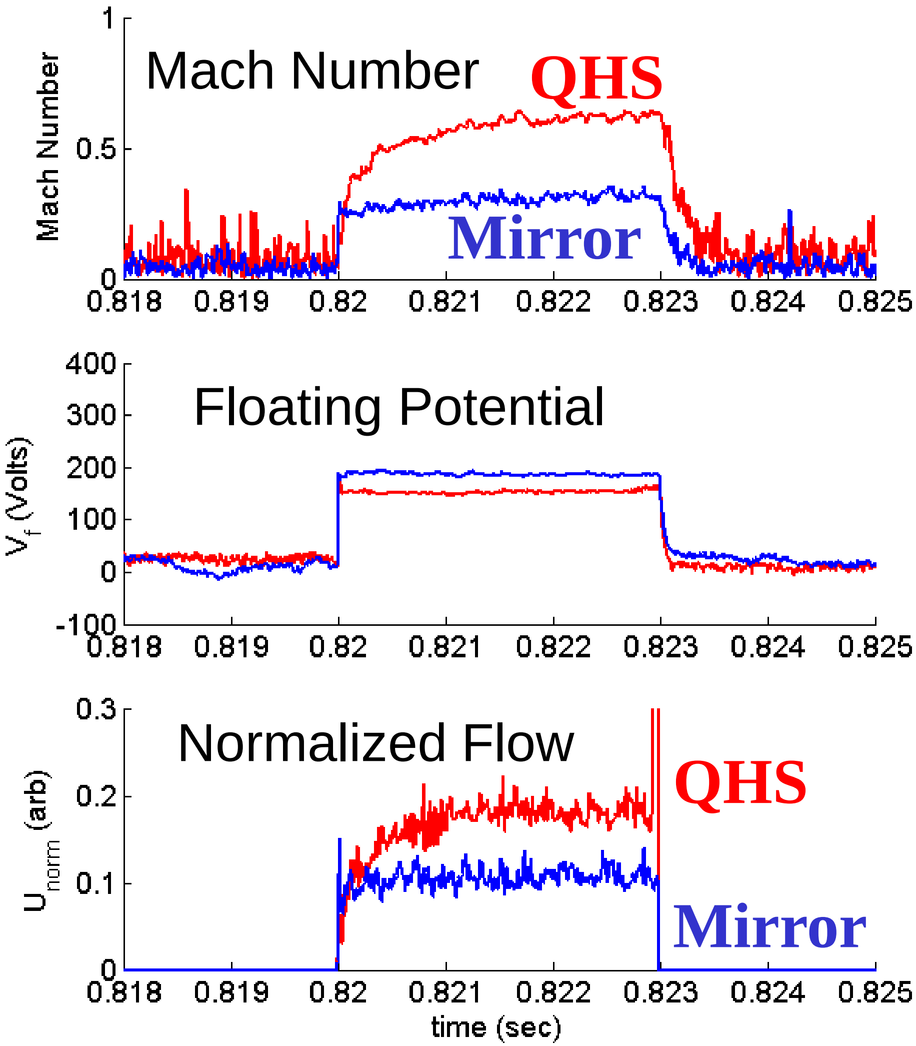


- Measure the flow with 6-tip Mach probes
- Flow is measured in the region between the LCFS and the electrode



PS: 600 V, 200 A, turn-on time - 20 μsec

Reduced Damping with Quasi-Symmetry

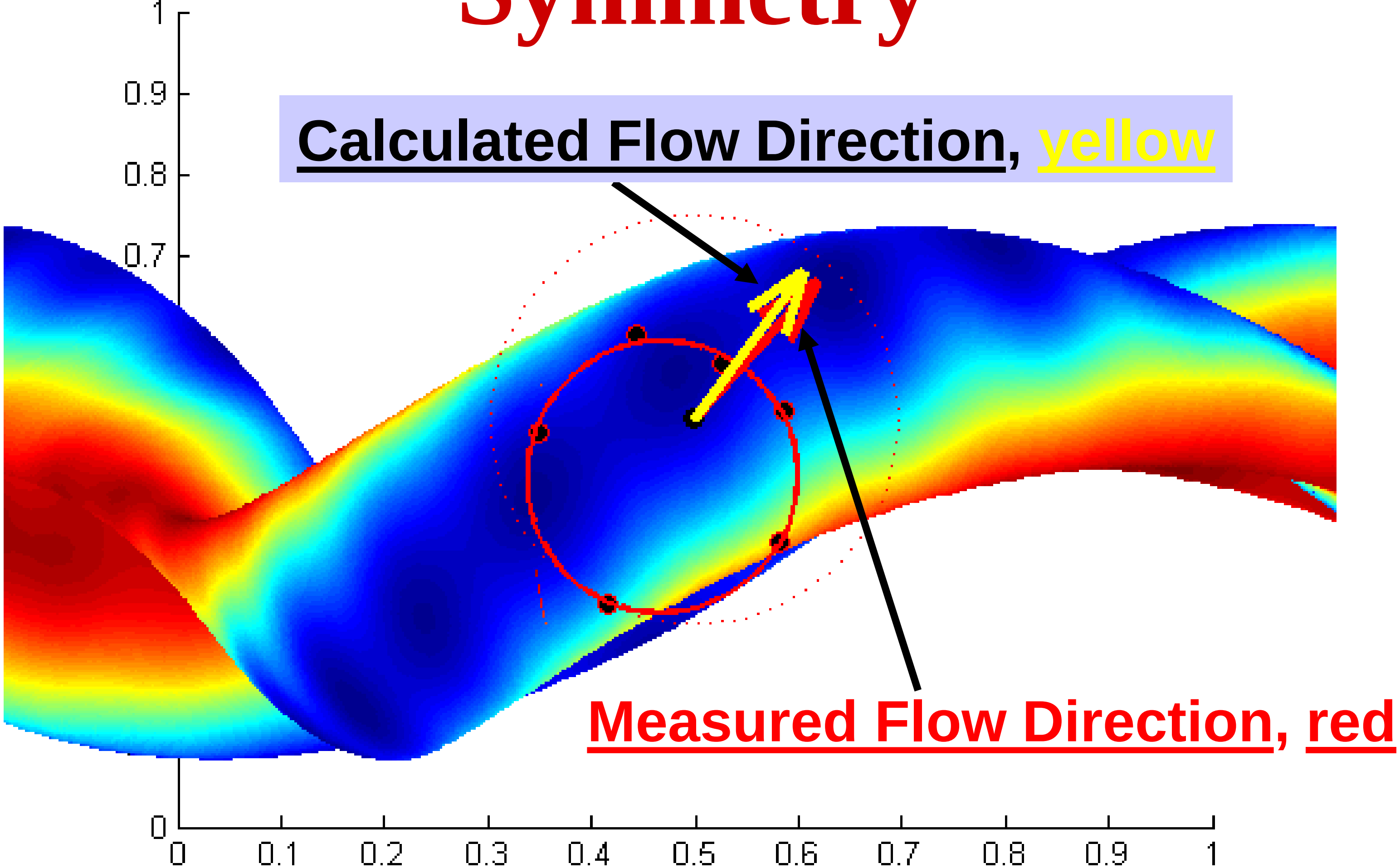


- **QHS flow rises more slowly to a larger value**
- **Normalized flow velocity indicates reduced damping**

$$U_{norm} = M \cdot u_e / I_{bias}$$

- **Factor of 2 difference consistent with modeling including neutrals and parallel viscosity**

Flow is in Direction of Symmetry



Summary

- The microwave multi-pass absorption efficiency is higher in QHS and Mirror (0.8-0.9) than in anti-Mirror (0.6)
- Density growth rates at breakdown clearly indicate the difference in particle confinement in different magnetic configurations
- Electron temperature increases linearly with absorbed power up to at least 600 eV

Summary (cont.)

- Neutrals play a significant role in HSX plasma performance
- Viscous damping is less in the symmetric configuration => Plasma flow damps faster with broken symmetry
- ASTRA modeling shows the need for higher-power, higher-field to observe differences in central electron temperature between Mirror and QHS