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

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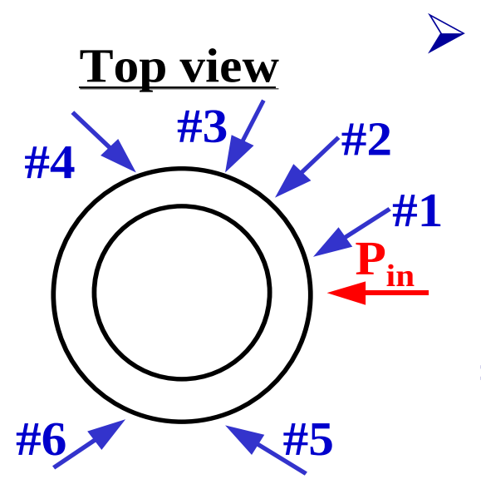
Abstract

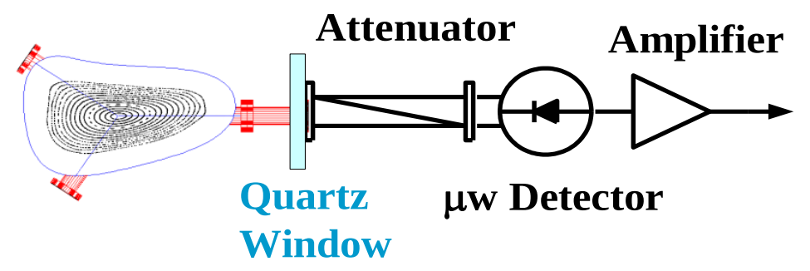
The extraordinary wave at the second harmonic of the electron cyclotron frequency produces and heats the plasma in HSX. Ray tracing calculations predict 40% first pass absorption at a plasma density of $1.5\cdot10^{18}$ m^{-3} and an electron temperature of 400 eV. To measure the wave absorption, a set of absolutely calibrated microwave detectors is installed along the machine. It was found that the absorption efficiency is very high (about 0.9) in the QHS and Mirror configurations and it drops to 0.6 in the Anti-Mirror mode. The confinement of particles in the different configurations is studied in the neutral gas breakdown experiments. With the same gas pressure and heating power, the density for the QHS configuration has a larger growth rate (10^4 sec^{-1}) compared to the Mirror ($5\cdot10^3$ sec^{-1}) and anti-Mirror modes ($2\cdot10^3$ sec^{-1}). A study of the stored energy versus launched power and plasma density shows that it increases linearly (up to 50 J) with power and has a maximum at low plasma density (at about $0.4\cdot10^{18}$ m^{-3}). The central electron temperature measured by Thomson scattering also rises linearly with heating power and reaches 600 eV at 100 kW of launched power.

Measurements of RF Power Absorption

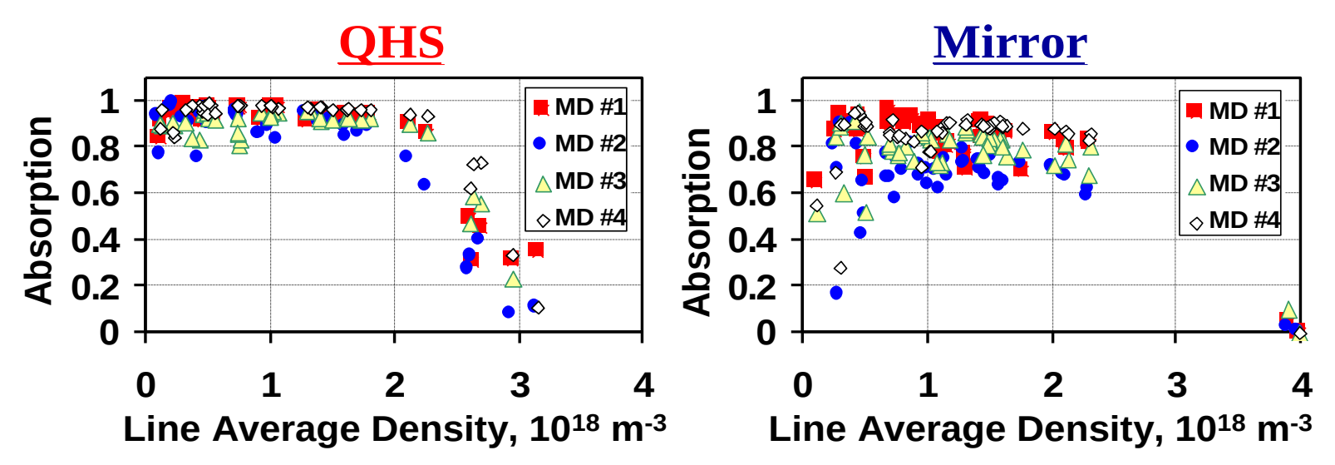


- Six absolutely calibrated microwave detectors are installed around the HSX at 6°, 36°, ±70° and ± 100° (0.2 m, 0.9 m, 1.6 m and 2.6 m away from RF power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the RF launch.

Each antenna is an open ended waveguide followed by attenuator



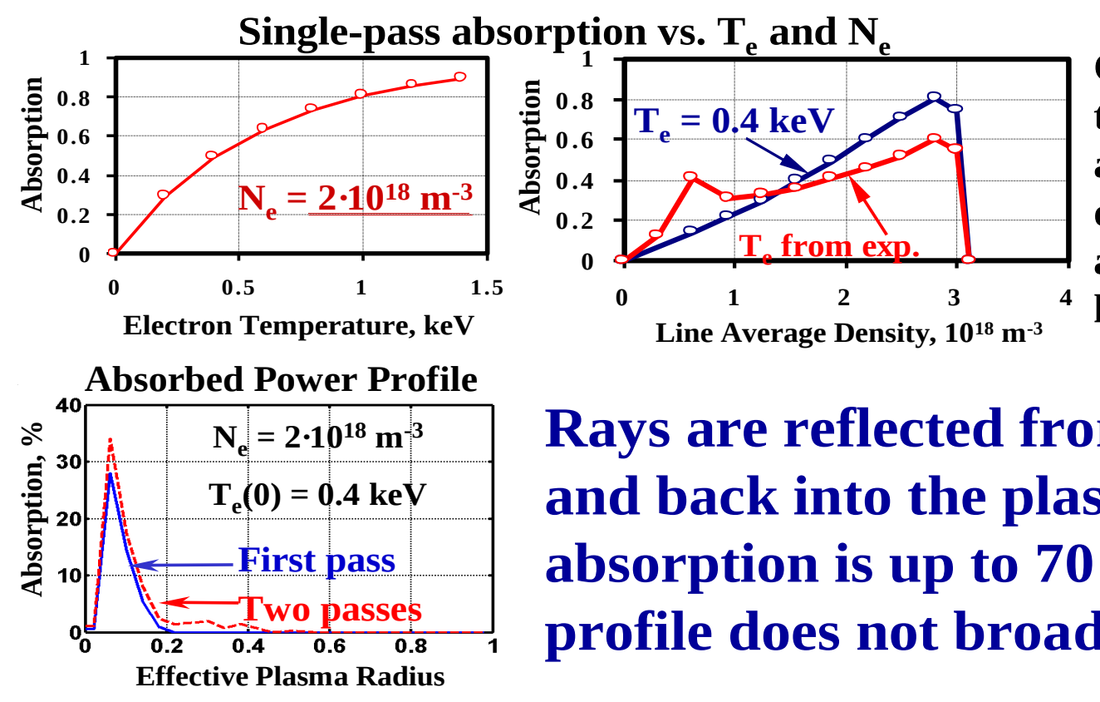
Multi-Pass Absorption



- 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

Ray Tracing Calculations

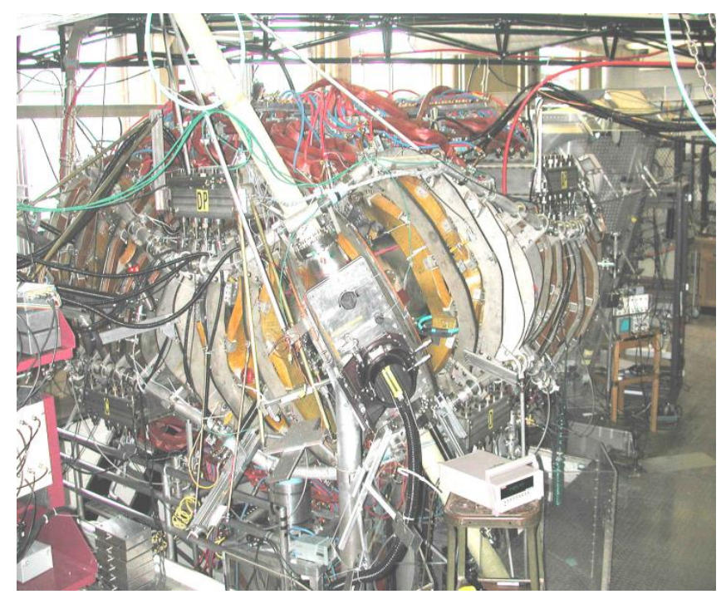
3-D Code is used to estimate absorption in HSX plasma



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

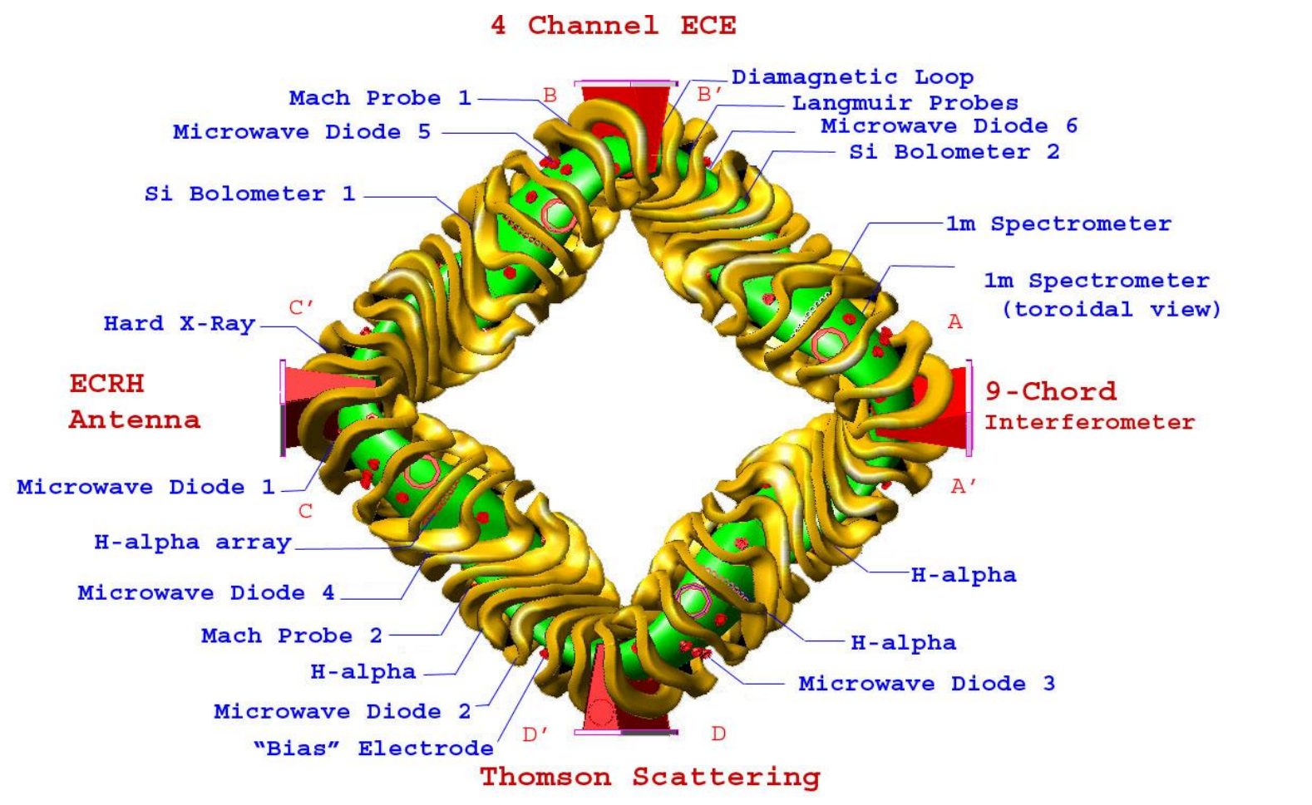
Rays are reflected from the wall and back into the plasma, the absorption is up to 70% while profile does not broaden

Current Operational Parameters of HSX

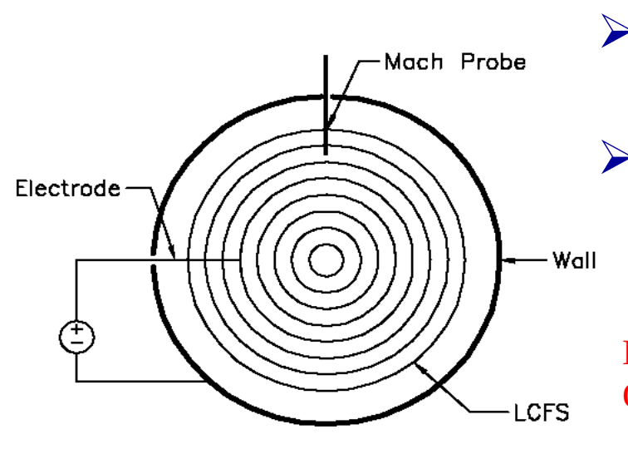


Major Radius	1.2 m
Minor Radius	0.15 m
Plasma Volume	0.44 m^3
Magnetic Field	0.5 T
Rot. Transform	1.05 → 1.12
Periods & Coils	4 with 48
RF Power	≤ 100 kW
RF Pulse length	≤ 50 msec.

Diagnostics on HSX

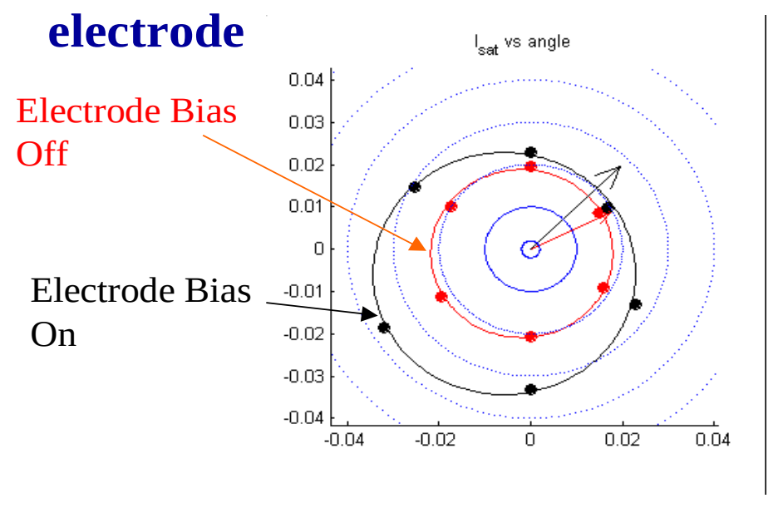


Ion Flows Induced with Biased Electrode

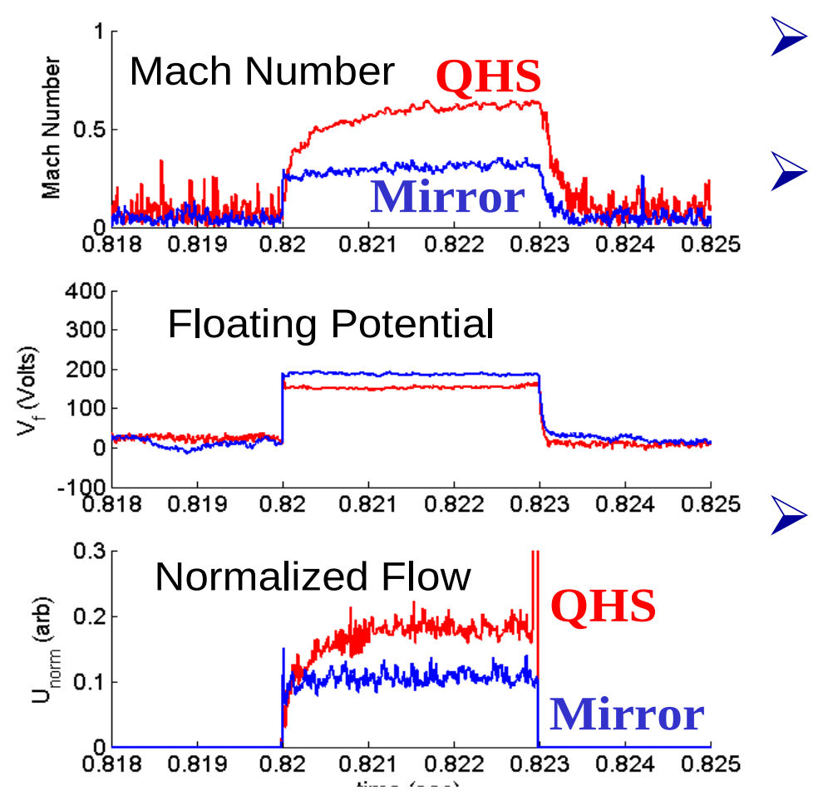


- Measure the flow with 6-tip Mach probes
- Flow is measured in the region between the LCFS and the electrode

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



Reduced Damping with Quasi-Symmetry

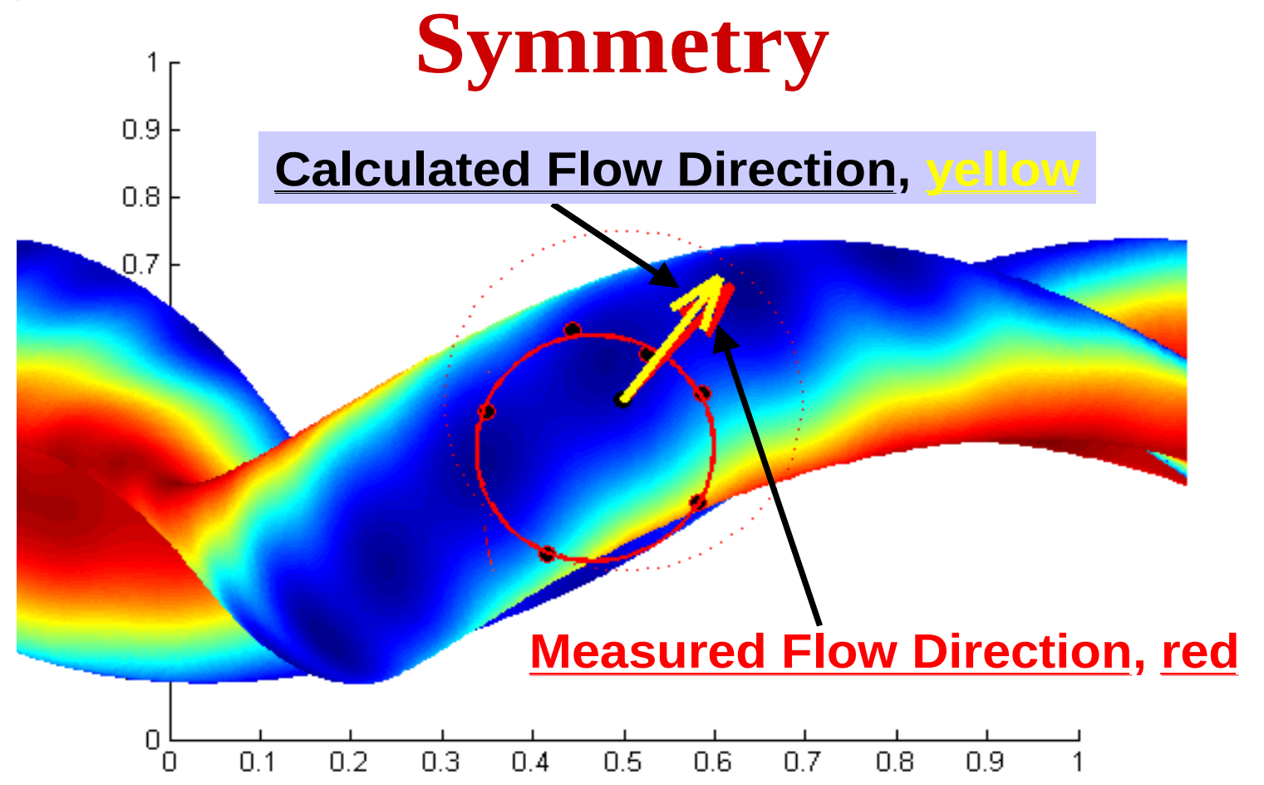


- QHS flow rises more slowly to a larger value
- Normalized flow velocity indicates reduced damping

$$U_{nom} = \mathcal{M}\cdot n_e / I_{bias}$$

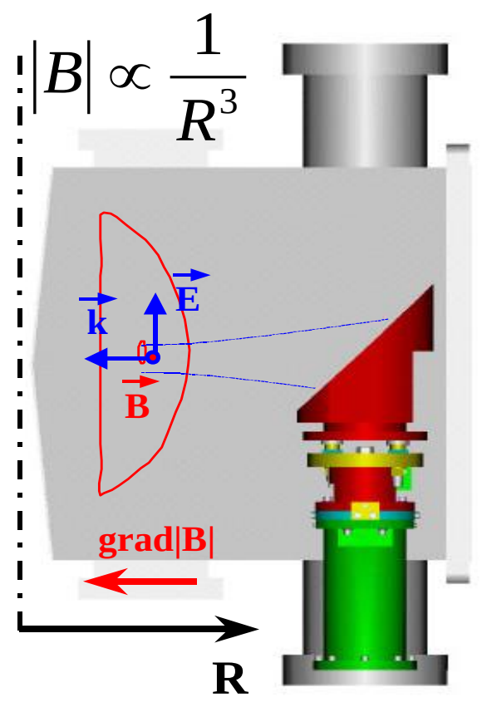
- Factor of 2 difference consistent with modeling including neutrals and parallel viscosity

Flow is in Direction of Symmetry

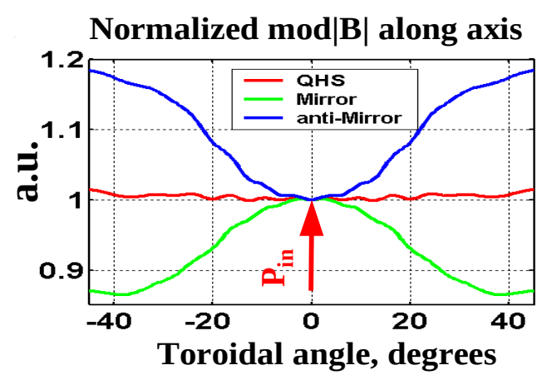


RF Heating in HSX

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

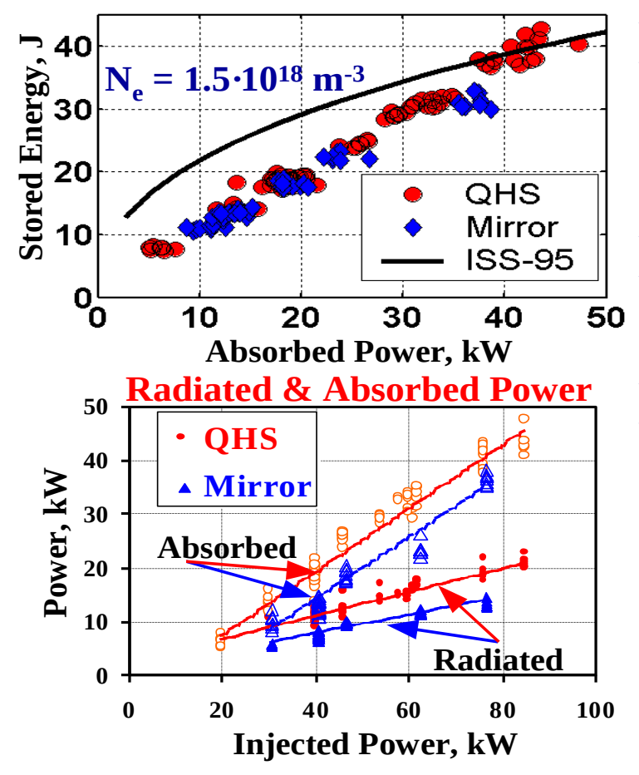


Mirror configurations



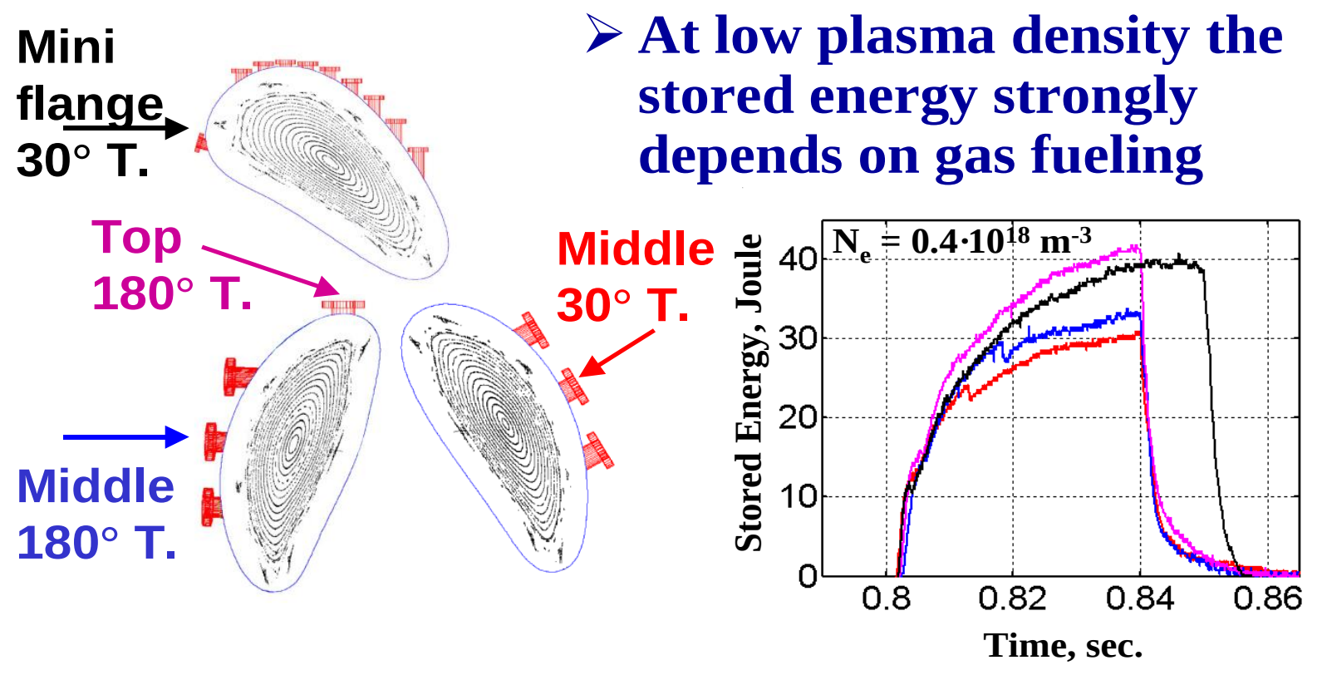
- Mirror configurations in HSX are produced with auxiliary coils in which an additional toroidal mirror term is added to the magnetic field spectrum
- In Mirror mode the term is added to the main field at the location of launching antenna and In anti-Mirror it is opposite to the main field
- Predicted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

Injected Power Scan



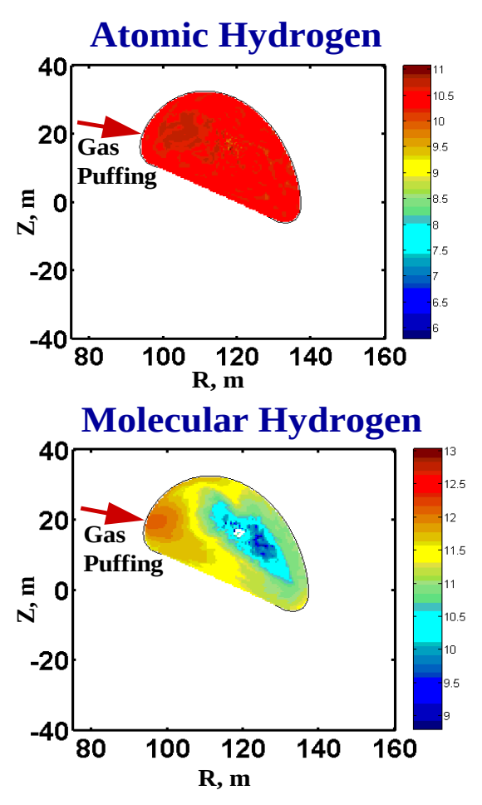
- No degradation observed in the plasma stored energy in heating power scan
- At 45 kW the HSX plasma meets ISS-95 scaling
- Radiated power is roughly 50% of absorbed power estimated from the change of diamagnetic loop slope

Stored Energy vs. Gas Puffing Location

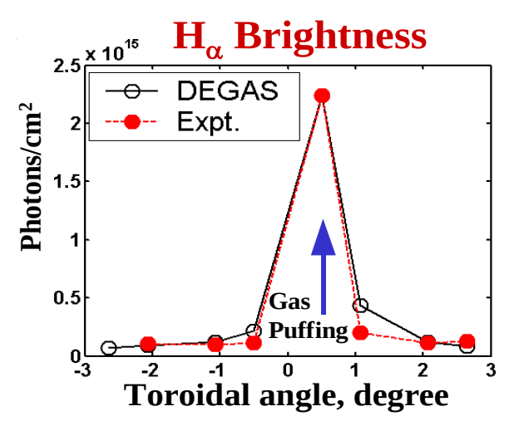


- At low plasma density the stored energy strongly depends on gas fueling

Neutrals Modeled by 3-D DEGAS

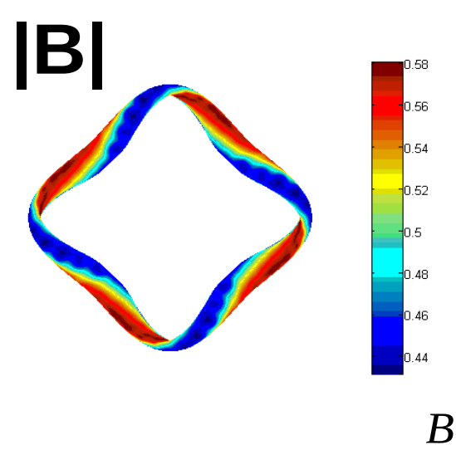


- Higher stored energies associated with reduced molecular penetration to core
- In experiment, 16 H_α detectors are used to measure the light



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

The Helically Symmetric Experiment

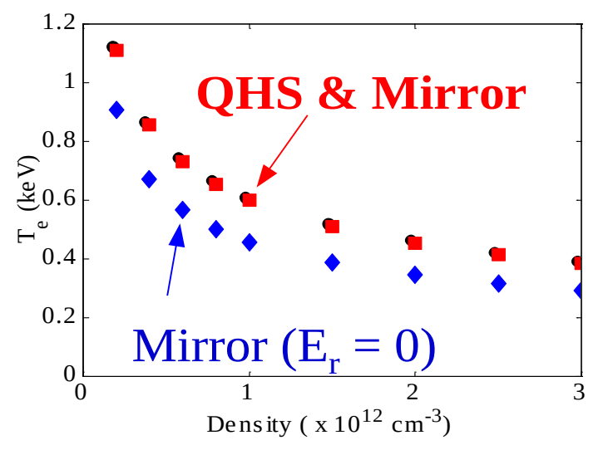


- HSX is a stellarator type of fusion machine
- Unlike a conventional stellarator the toroidal curvature term in the HSX magnetic field spectrum is negligibly small and the dominant spectral component is helical (N = 4, m = 1)

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

- 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

ASTRA Code



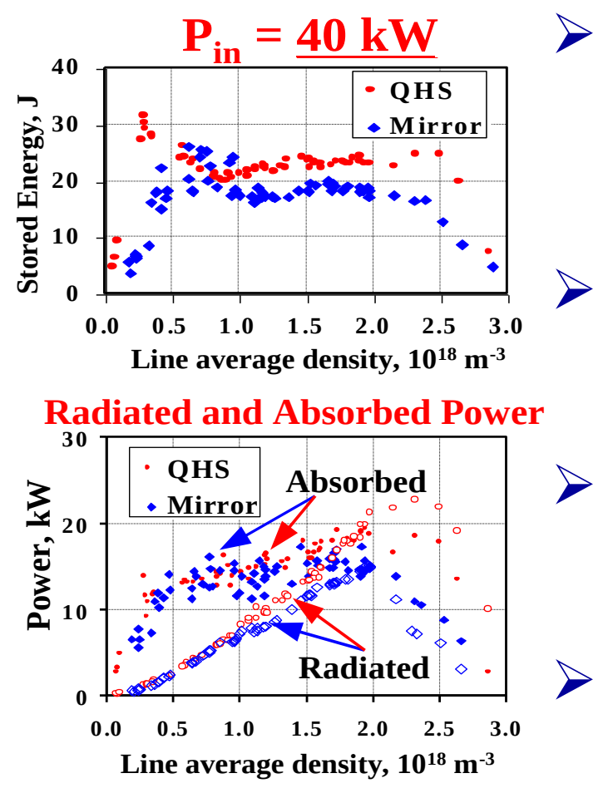
$$\chi_e = \chi_e^{neo} + \chi_e^{anom}$$

ASDEX L-mode scaling:

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

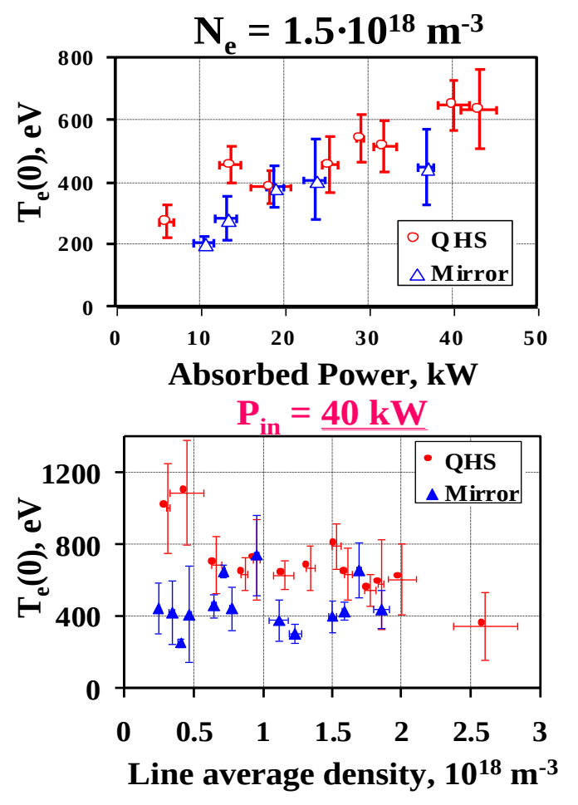
- At 1 T and 100 kW absorbed power ASTRA predicts 200-300 eV central temperature difference
- Both neoclassical and anomalous contributions to the transport are included
- At 40 kW of launched power and 0.5 T of magnetic field we expect little difference between QHS and Mirror

Plasma Density Scan



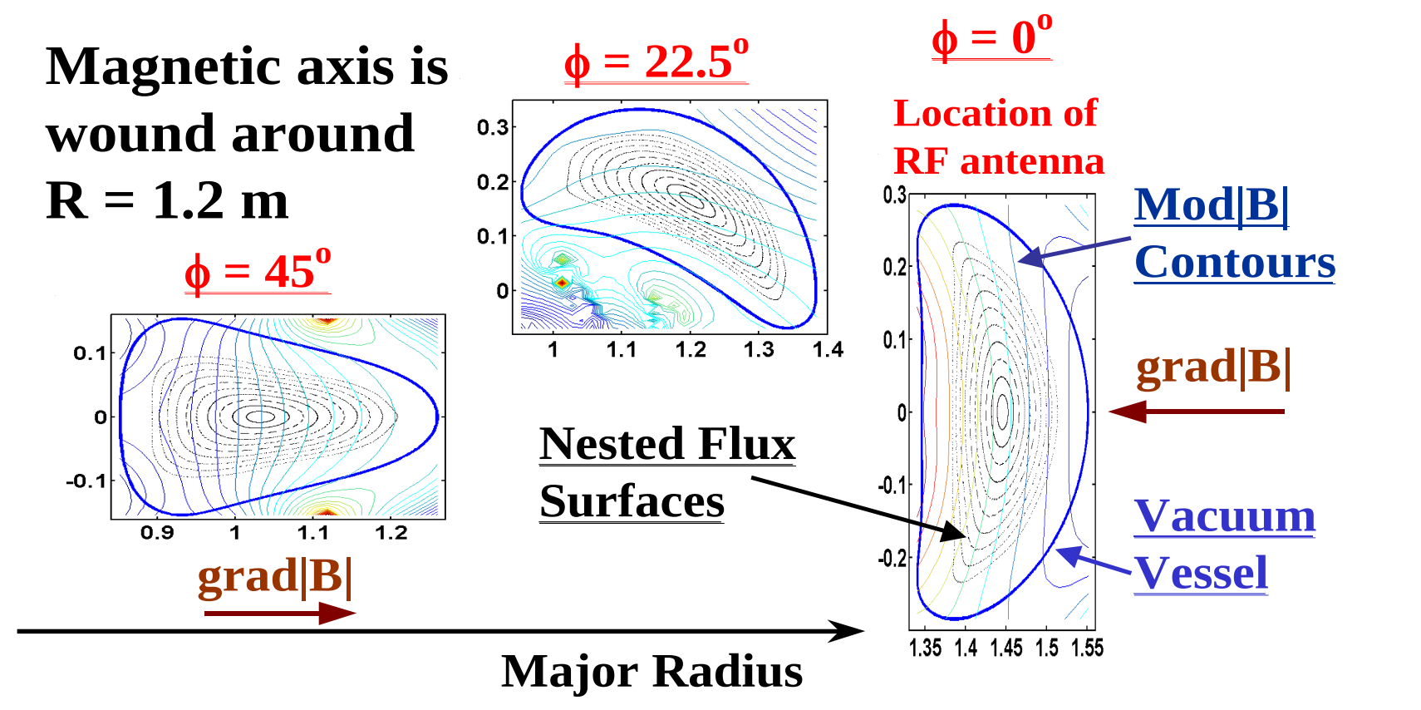
- In both QHS and Mirror modes the stored energy is about 20 J at high plasma density (> 10^{18} m^{-3})
- At low plasma density the stored energy has a peak due to super-thermal electrons
- Absorbed power is almost independent of plasma density
- Radiated power rises with plasma density

Electron Temperature



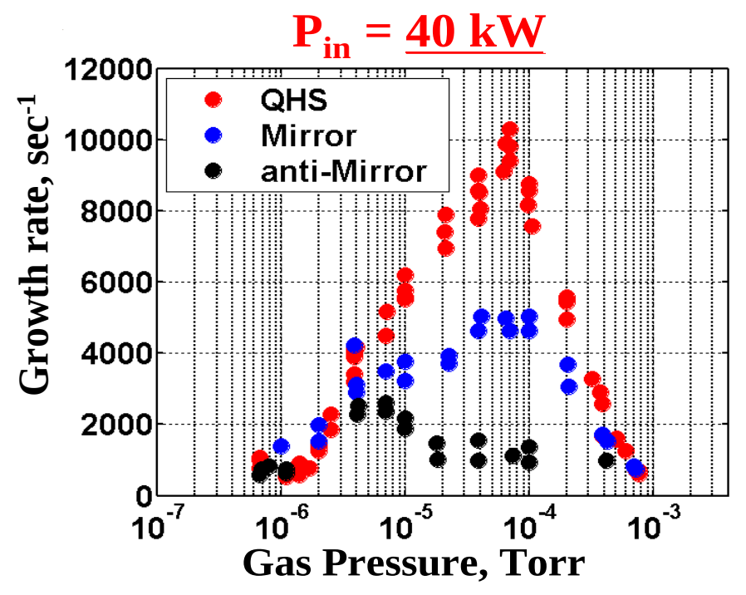
- Central electron temperature measured by TS linearly increases with heating power
- Minimal difference in T_{e0} between QHS and Mirror except perhaps at low density (< 0.5 $\cdot10^{18}$) m^{-3}
- To make a complete power balance we need to measure the temperature profiles

Cross-sections along ½ Field Period



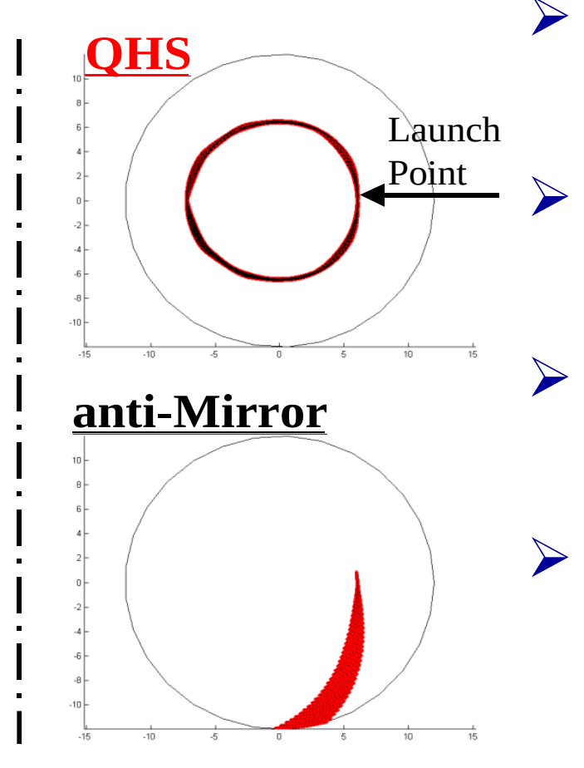
Neutral Gas Breakdown

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

Trapped Particle Orbits



- 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

Summary I

- 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

Summary II

- Electron temperature increases linearly with absorbed power up to at least 600 eV
- 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

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