Electron Cyclotron Heating at B = 0.5 T in HSX

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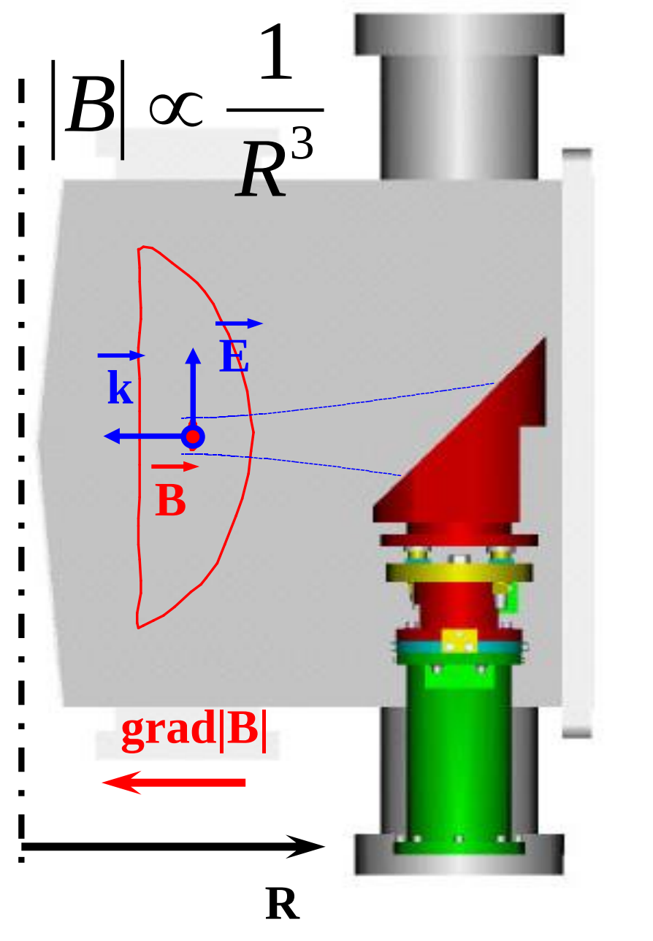
RF Heating in HSX

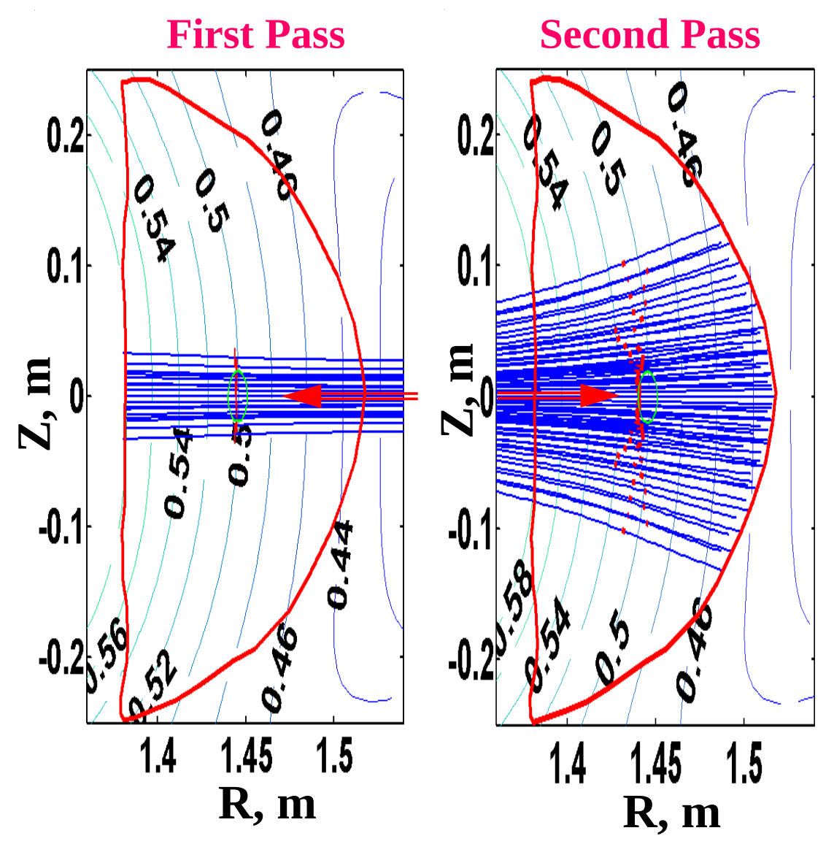
- Microwave power at 28 GHz produces and heats the plasma at the second harmonic of ω_{ce}
- Wave beam is launched from the low magnetic field side and is focused on the magnetic axis with a spot size of 4 cm
- Wave beam propagates almost along grad|B| and grad(n_e) that leads to a small ray refraction
- One can expect a sharp absorbed power profile because modB along the beam axis is inverse to R^3



1. Ray Tracing Calculations

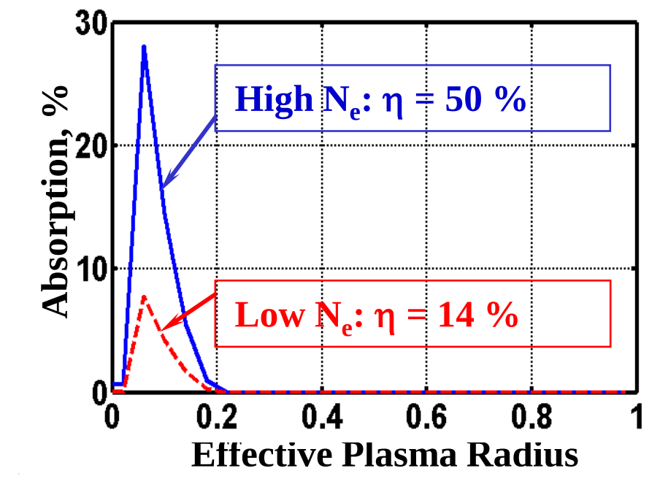
3-D Code is used to estimate absorption in HSX plasma

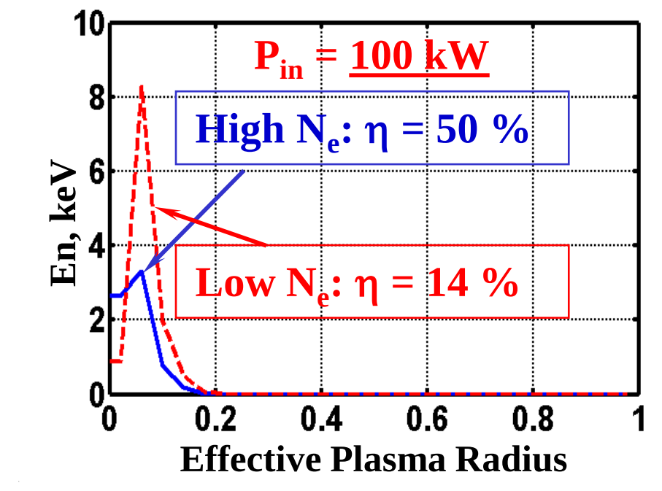
1.1 Ray Trajectories

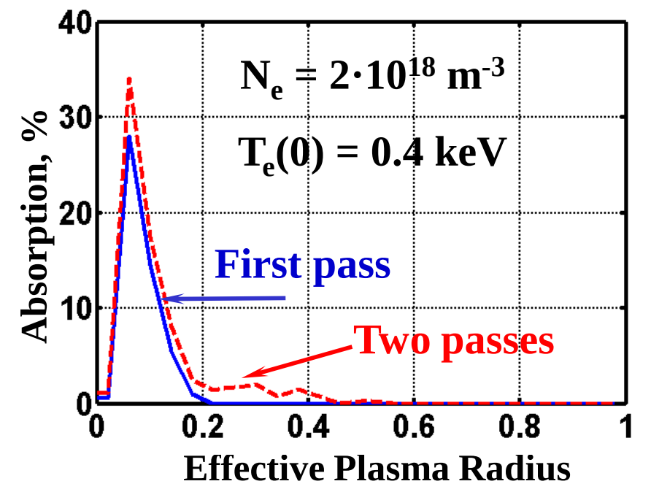


- **First pass:** small refraction because wave vector is almost parallel to grad|n| and grad|B|
- **Second pass:** high ray refraction due to wide beam with 20° divergence

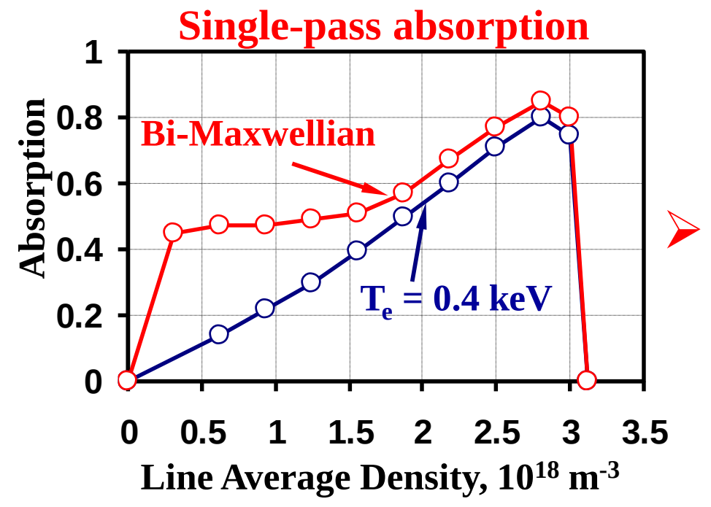
1.2 Absorbed Power Profile







Single-pass absorption



- Single-pass absorbed power profile is pretty narrow (< $0.2a_p$)
- At low plasma density the energy that electrons can gain between collisions is higher than at high plasma density because of high power per particle and longer collision time:

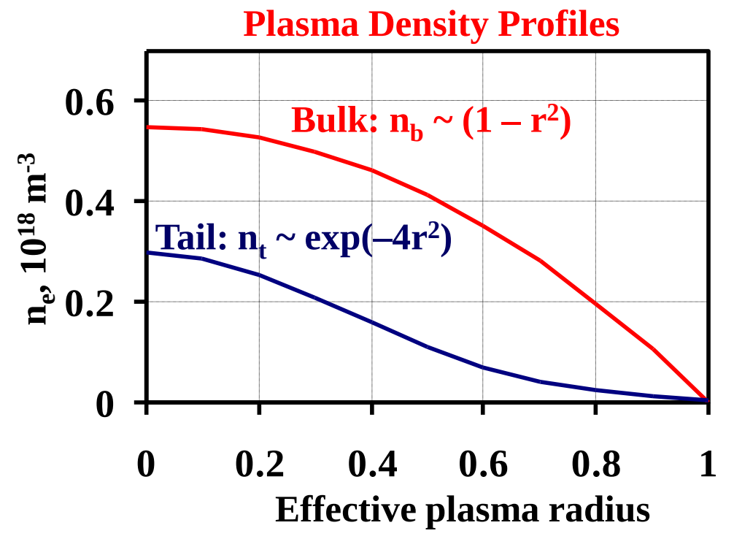
$$En(r) = \frac{p_{abs}(r)}{n_e(r)} \cdot \tau_e(r)$$

where $\tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi}n_e \Lambda e^4}$

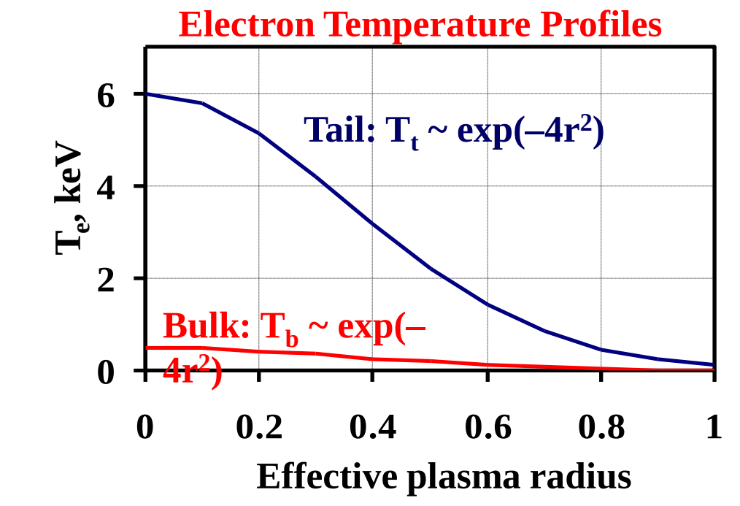
- Second Pass: Rays are reflected from the wall and back into the plasma, the absorption is up to 70% while the profile does not broaden
- Absorption versus plasma density is calculated at constant T_e in Maxwellian plasma and based on the TS and ECE data in bi-Maxwellian plasma
- Owing to high non-thermal electron population at a low plasma density the absorption can be high enough

1.3 Bi-Maxwellian Plasma

Plasma Density Profiles



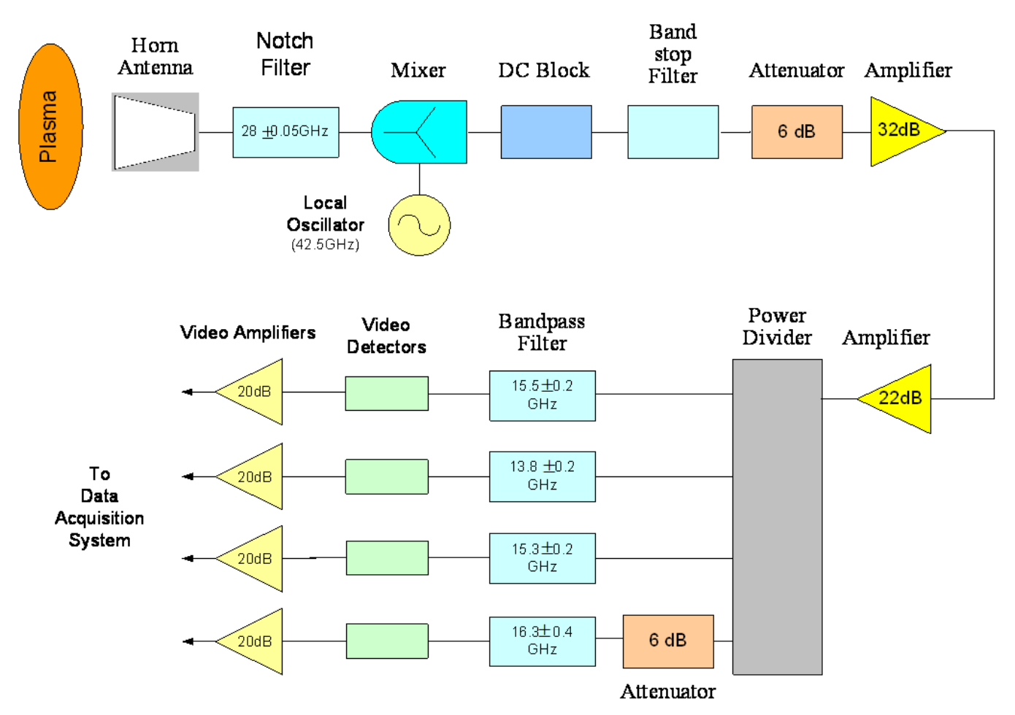
Electron Temperature Profiles



- Model upon bi-Maxwellian distribution function is used to explain the enhanced stored energy and the high absorption efficiency at low plasma density
- The density and temperature profiles are taken from TS, ECE and interferometer measurements
- At $0.5\cdot10^{18}$ m^{-3} the plasma stored energy is 21 J due to super-thermal tail and 5 J due to bulk plasma and the single-pass absorption is about 0.5
- Corresponds to large hard X-ray emission (poster by Abdou)

2. ECE Diagnostic on HSX

2.1 Block diagram

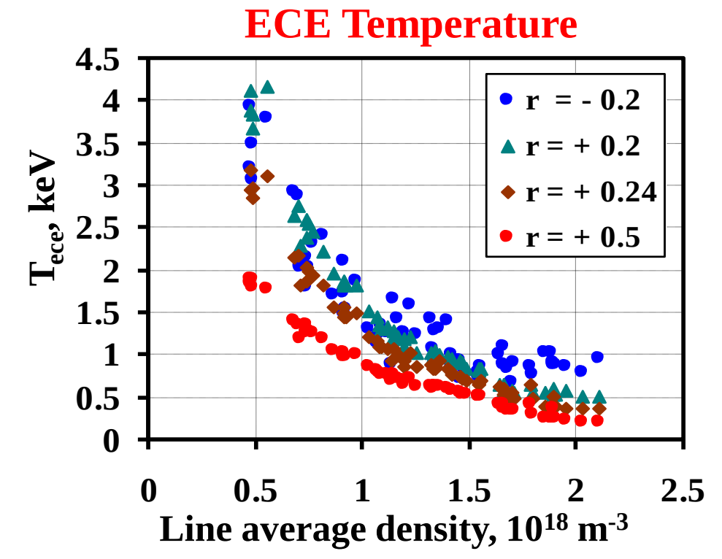


4-channel ECE radiometer is used to measure the electron temperature in HSX plasma: one channel is put on the high field side and 3 others on the low field side. At B=0.5 T (on-axis heating) the effective plasma radii in QHS mode are as follows: -0.2, 0.2, 0.24 and 0.5, respectively

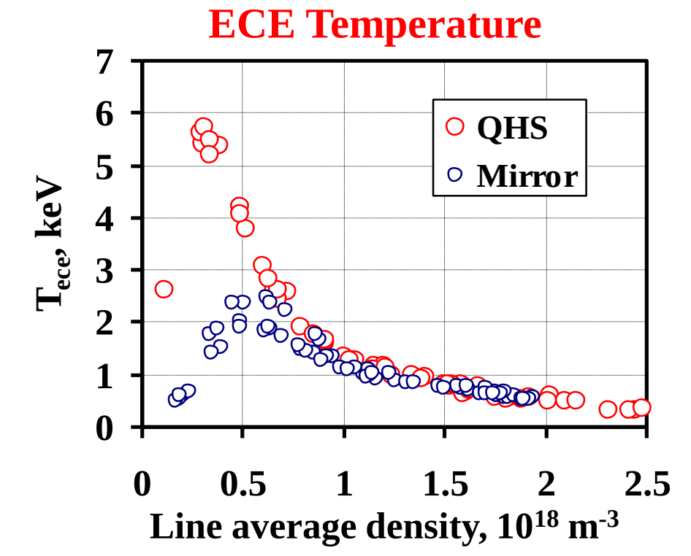
- All channels have been calibrated on a bench. In experiment, the ECE data have been benchmarked with respect to the Thomson Scattering

2.2 Results of Measurements

ECE Temperature

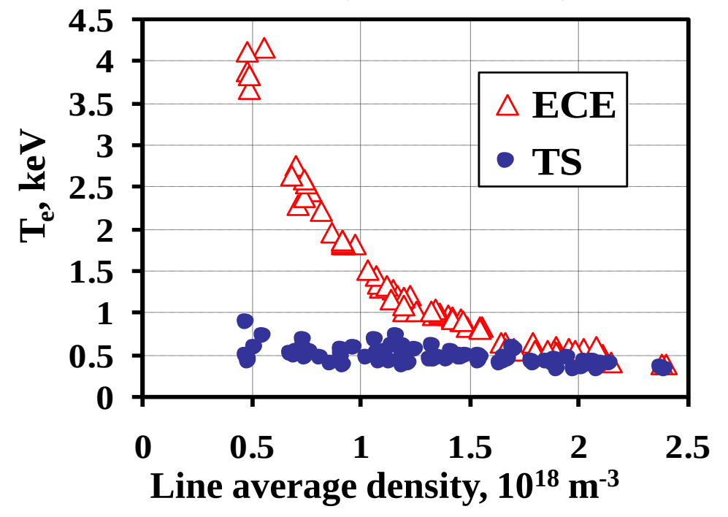


ECE Temperature

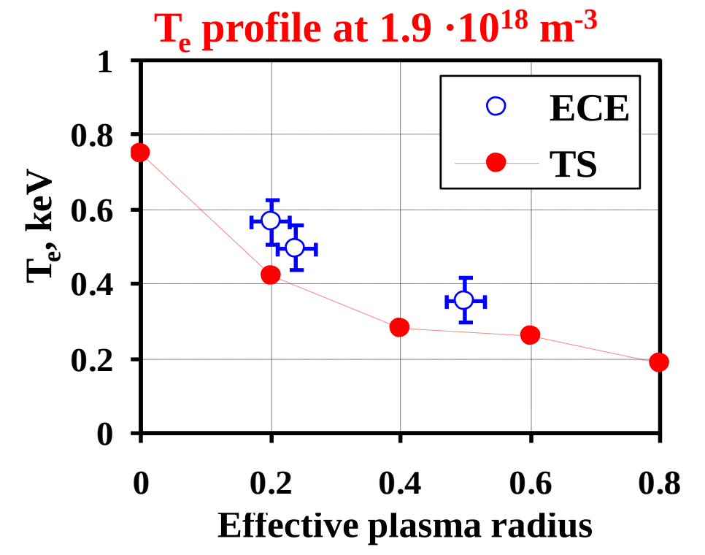


- ECE temperature drops with plasma density. T_{ece} at r = 0.2 at low and high plasma density differs from each other by a factor of 8
- ECE temperature in QHS and Mirror configuration are almost the same except at low plasma density (<$0.6\cdot10^{18}$ m^{-3})

ECE vs. TS at r = 0.2



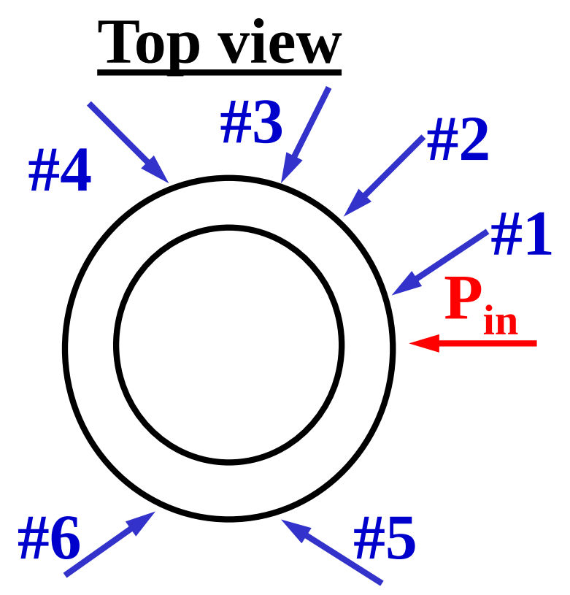
T_e profile at $1.9\cdot10^{18}$ m^{-3}



- Electron temperatures measured by Thomson Scattering and ECE are in a good agreement only at high plasma density
- At low plasma density due to a better confinement of trapped particles the electrons can gain more energy in QHS mode than in Mirror

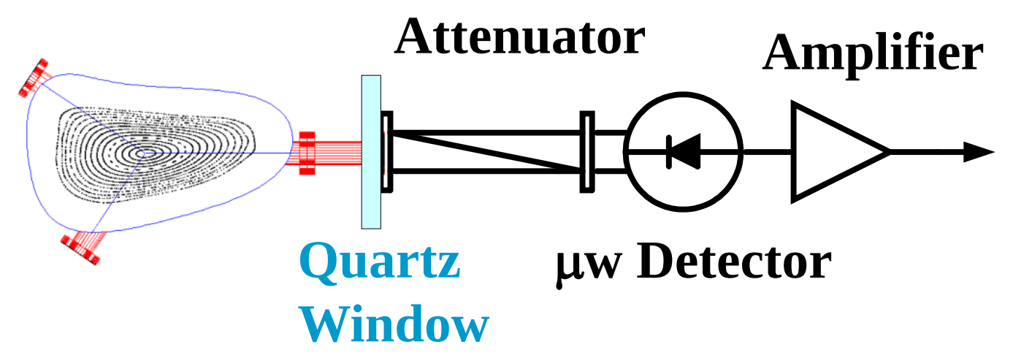
3. Multi-Pass Absorption

3.1 Experimental Lay-out



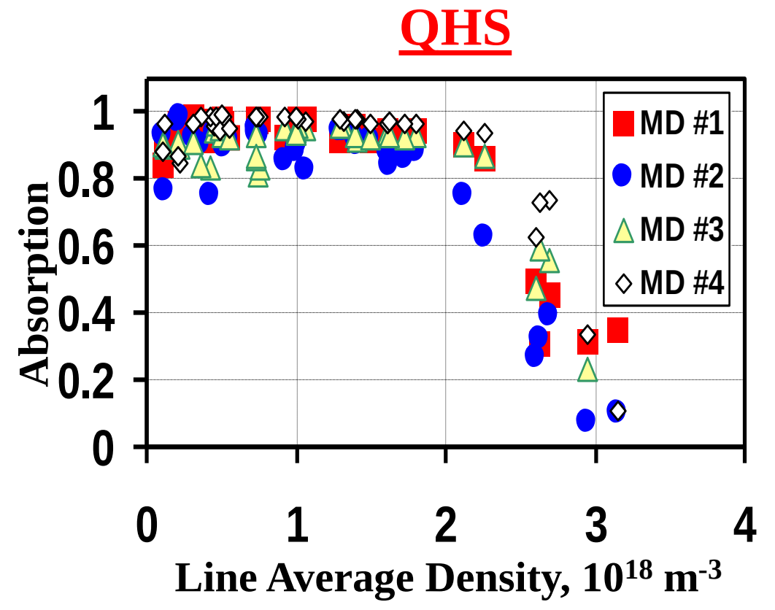
Six absolutely calibrated microwave detectors are installed around the HSX at 6°, 36°, ±70° and ± 100° (0.2 m, 0.9 m, 1.6 m and 2.6 m away from RF power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the RF launch

Each antenna is an open ended waveguide followed by attenuator

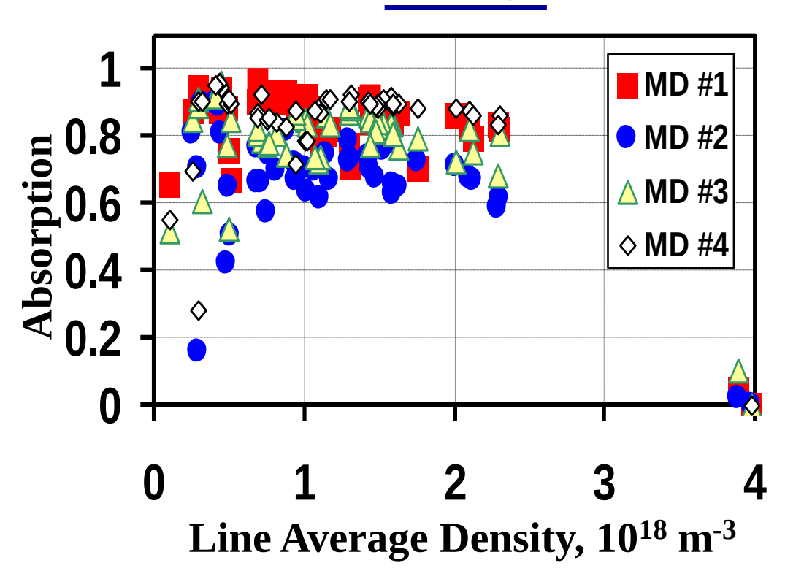


3.2 Results of Measurements

QHS



Mirror

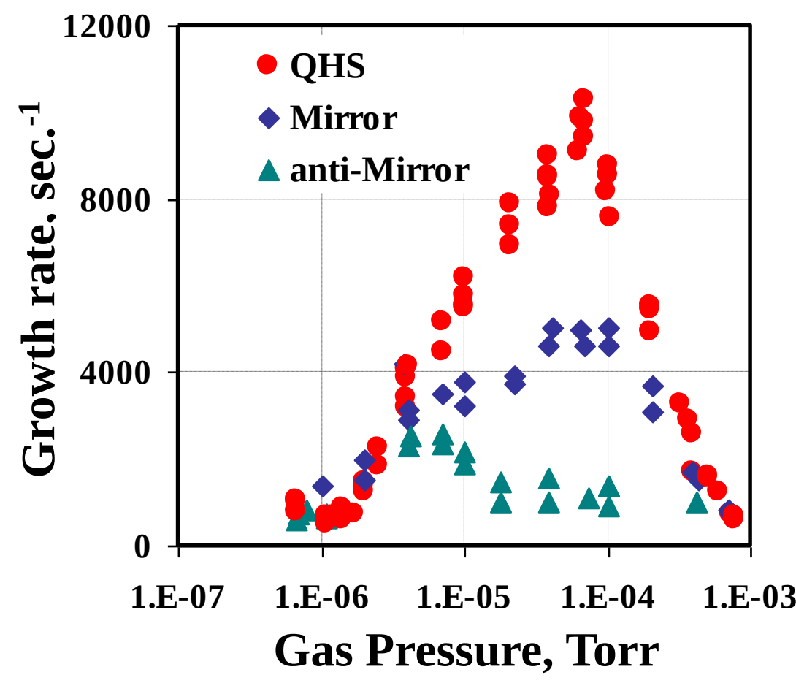


- RF Power is absorbed with high efficiency in a few passes through the plasma column for a wide range of plasma densities
- At low plasma density the efficiency remains high due to the absorption on super-thermal electrons, in QHS their population is higher than in Mirror

4. Breakdown Studies

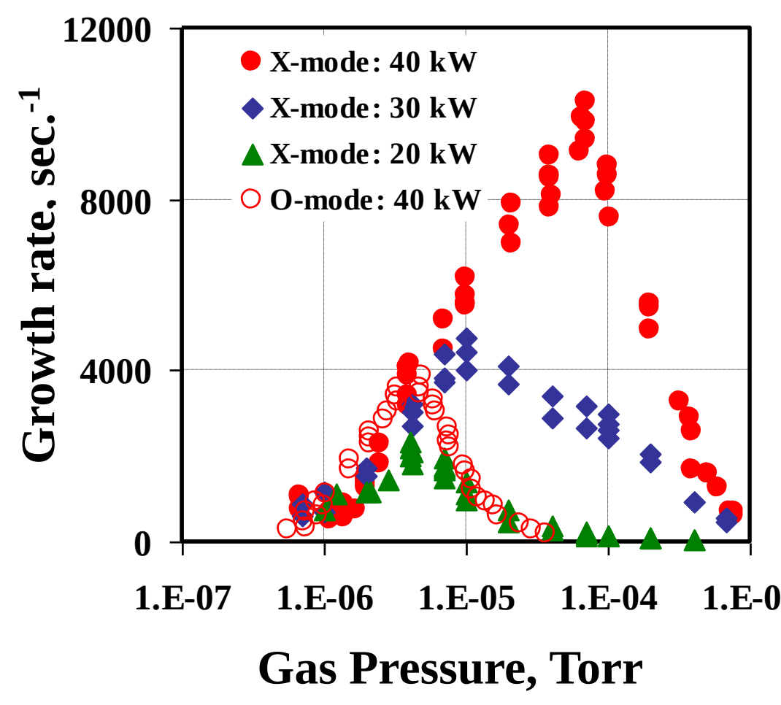
Motivation: (1) to study the particle confinement
(2) to study the physics of plasma breakdown by X-wave at the second harmonic of ω_{ce}

4.1 Growth Rate vs. Mode of Operation



- Growth rate is determined from exponential fit to the interferometer central chord signal
- In QHS mode the growth rate is twice that in Mirror
- In anti-Mirror mode the gas breakdown occurs with a very low growth rate

4.2 Growth rate vs. RF Electric Field

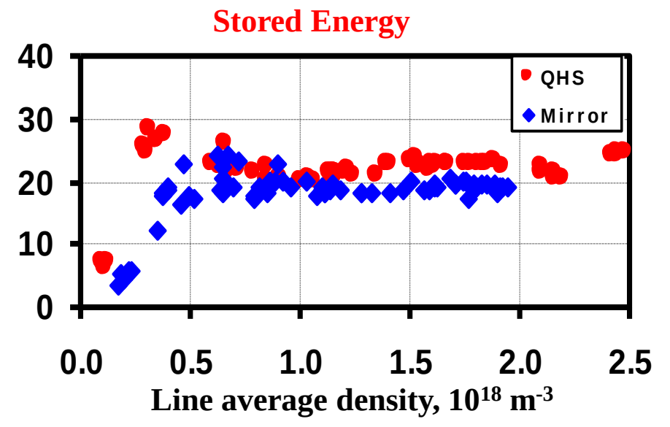


- In QHS mode the growth rate has been measured at different launched power levels. The growth rate drops with decreasing of RF power and its maximum is shifted towards lower gas pressure
- With ordinary mode the growth rate is similar to that with X-mode at a low power level
- *High electric field in front of the launching antenna causes the gas to break down at a higher rate*

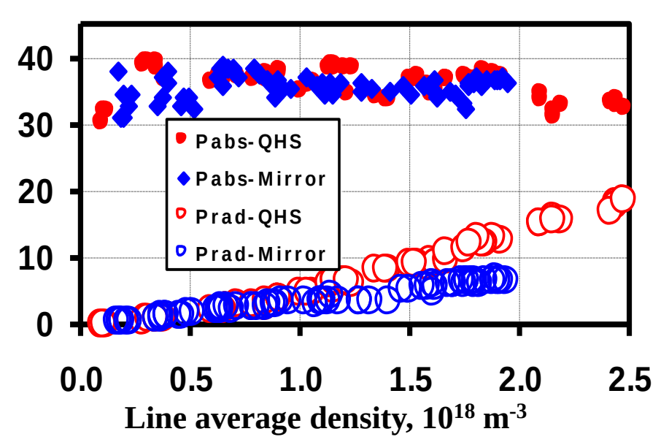
5. Stored Energy Studies

5.1 Plasma Density Scan

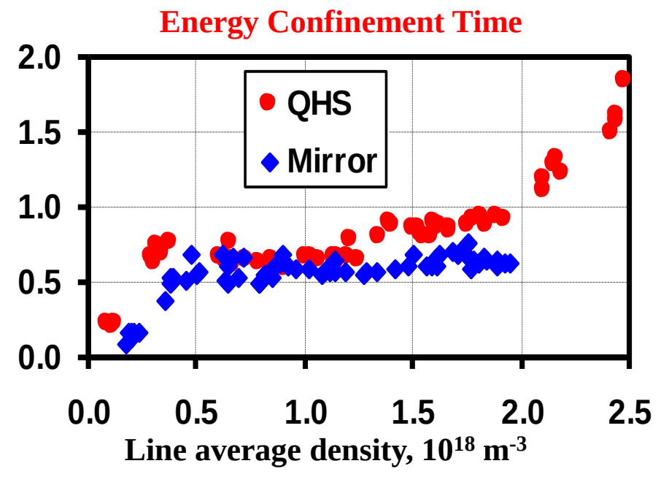
Stored Energy



Absorbed and Radiated Power



Energy Confinement Time

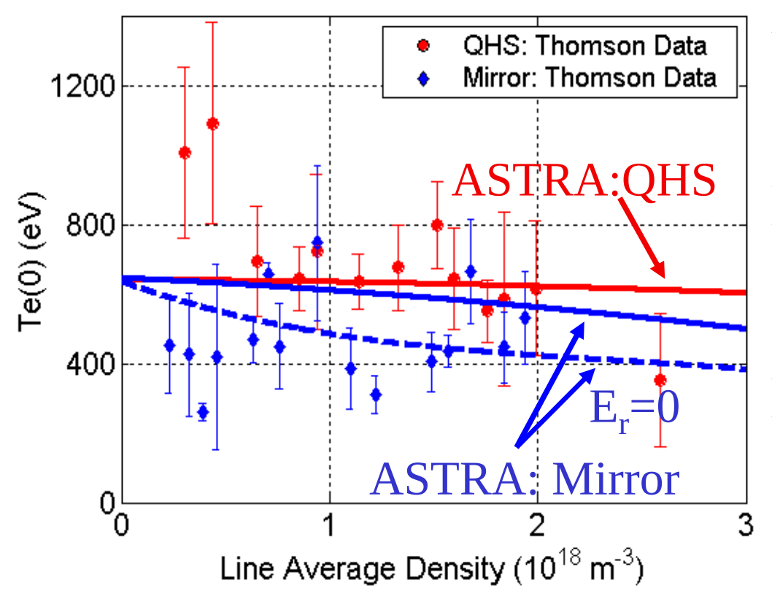


- In both QHS and Mirror modes the stored energy is about 20 J at high plasma density (> 10^{18} m^{-3})
- Absorbed power is almost independent of plasma density
- Radiated power rises with plasma density
- Energy confinement time is defined from the experimental data:

$$\tau_E = \frac{W_E}{P_{abs} - P_{rad}}$$

- At $1.9\cdot10^{18}$ m^{-3} the energy confinement time is by a factor of 1.5 higher in QHS as compared to Mirror

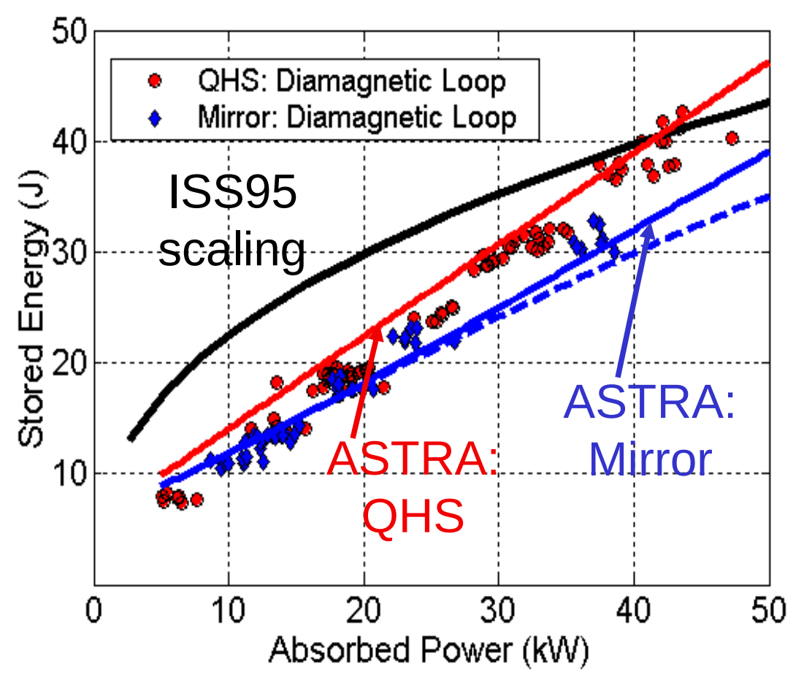
5.2 ASTRA Code



- QHS thermal conductivity is dominated only by anomalous transport
- Data is consistent with Alcator-like scaling where $\tau_E \sim n$
- $T_e(0)$ from Thomson scattering is roughly independent of density. Consistent with $\chi \sim 1/n$ model.

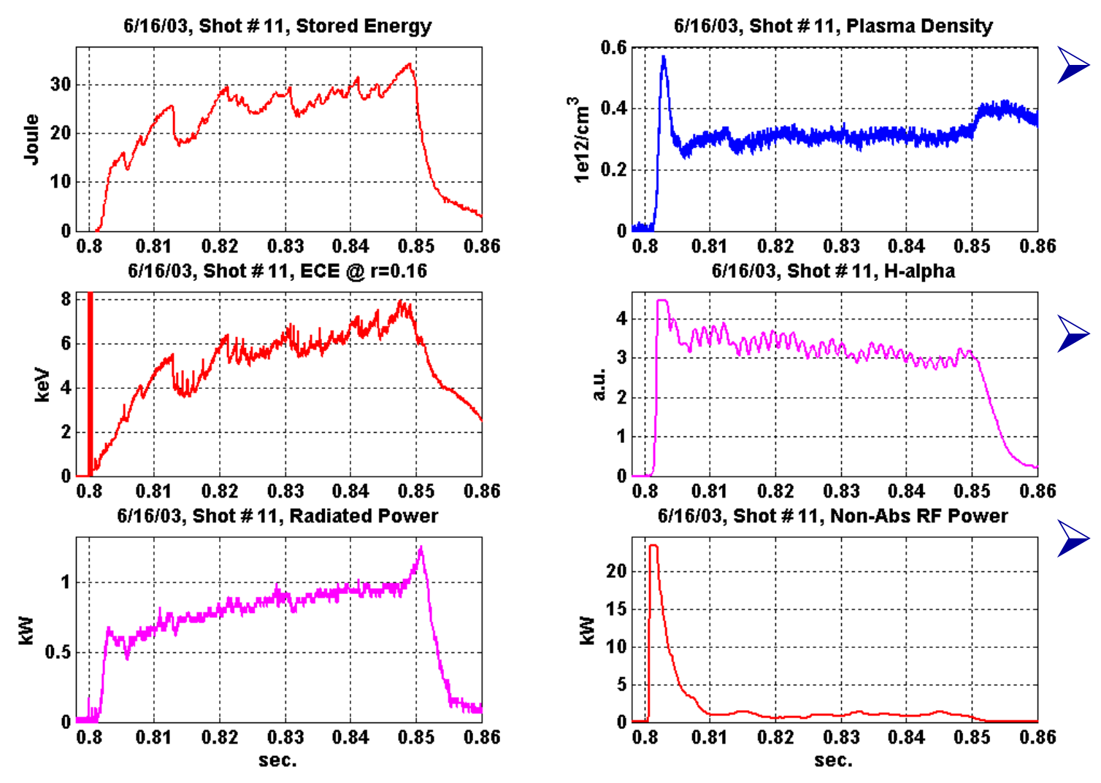
Stored energy should have linear dependence on density but data clearly does not show this (see above).

5.3 RF Power Scan



- Fixed density of $1.5\cdot10^{18}$ m^{-3}
- Difference in stored energy between QHS and Mirror reflects 15% difference in volume
- W ~ P in agreement with $\chi \sim 1/n$ model
- *At lower density, stored energy is greater than predicted by ASTRA code and TS disagrees with the model*

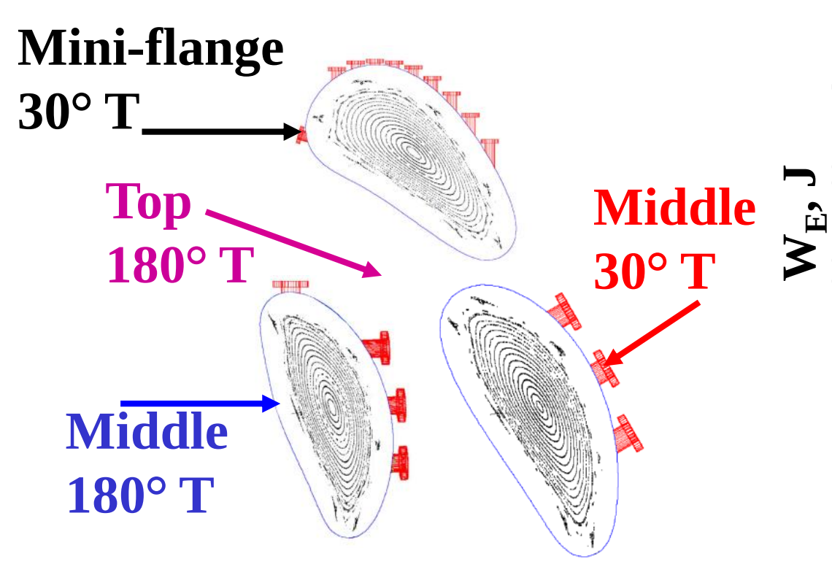
5.4 Stored Energy Crashes



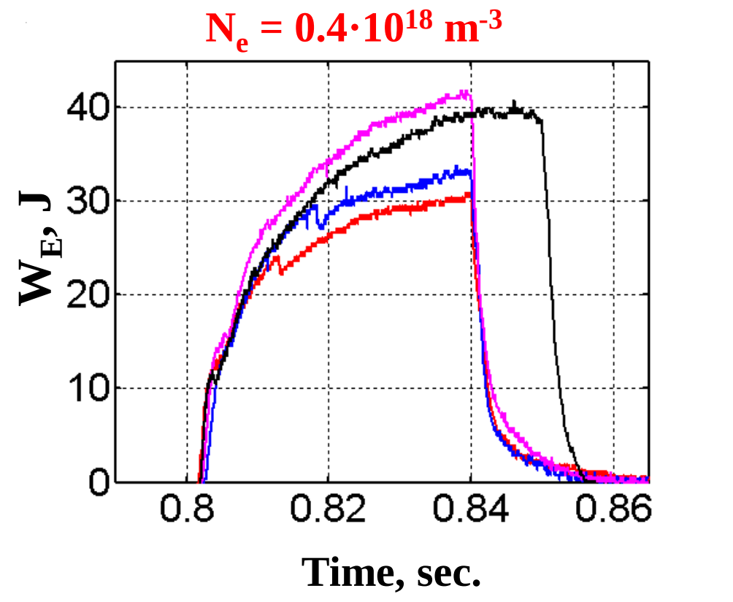
- Diamagnetic loop shows the plasma energy crashes at low plasma density
- ECE signals are in phase with the energy crashes
- Also observed on soft X-ray emission (see poster by Sakaguchi)

5.5 Stored Energy vs. Neutrals

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



$N_e = 0.4\cdot10^{18}$ m^{-3}



When the puffing valve is moved further away from the plasma axis, the neutral density drops in the plasma center where the resonant RF-electron interactions take place. Electrons then gain more energy between collisions because they suffer less scattering on neutrals

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
- ECE and TS data are in a good agreement at high plasma density
- At low plasma density the ECE radiometer measures a high non-thermal electron population in QHS and Mirror configurations; higher signal for QHS
- ASTRA modeling shows the need for higher-power, higher-density to observe differences in central electron temperature between Mirror and QHS

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