



Electron Cyclotron Heating by X-wave in the HSX stellarator

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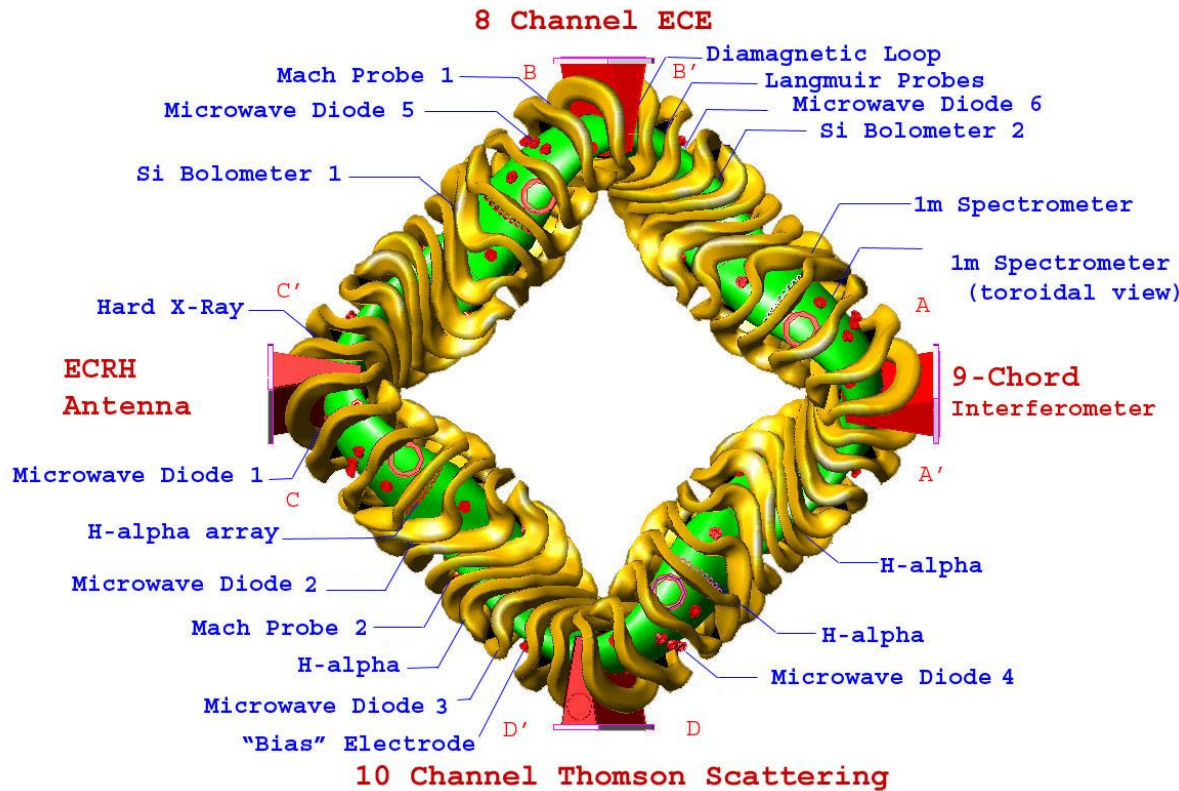


Outline

- Introduction on HSX stellarator
- Gyrotron power into the machine
- Absorption of launched power in HSX plasma
- ECE measurements
- Fokker-Planck code
- Summary



The Helically Symmetric Experiment



$R, \text{ m}$	1.2
$a_p, \text{ m}$	0.15
$B_o, \text{ T}$	0.5
$n_e, \text{ m}^{-3}$	$< 5 \cdot 10^{18}$
$T_e, \text{ keV}$	≤ 0.6
$F, \text{ GHz}$	28
$P_{\text{rf}}, \text{ kW}$	≤ 130
$\tau_{\text{trapped}}, \text{ msec}$	< 50

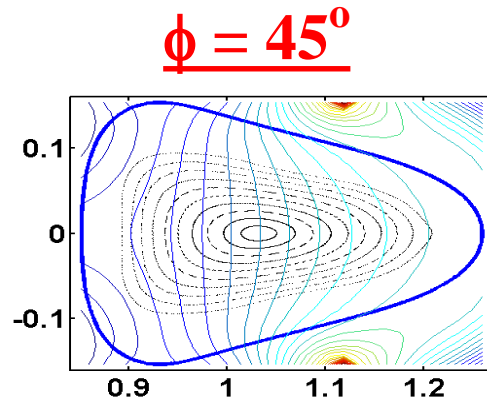
Symmetry in $|B|$ leads to a small deviation of trapped particle orbits from a flux surface and, as a result, to improved neoclassical confinement in a low collisionality regime



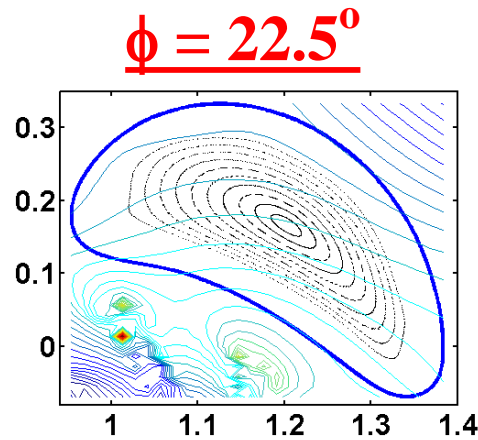
HSX Cross-sections along $\frac{1}{2}$ Field Period

HSX center

Plasma axis is
wound around
 $R = 1.2$ m

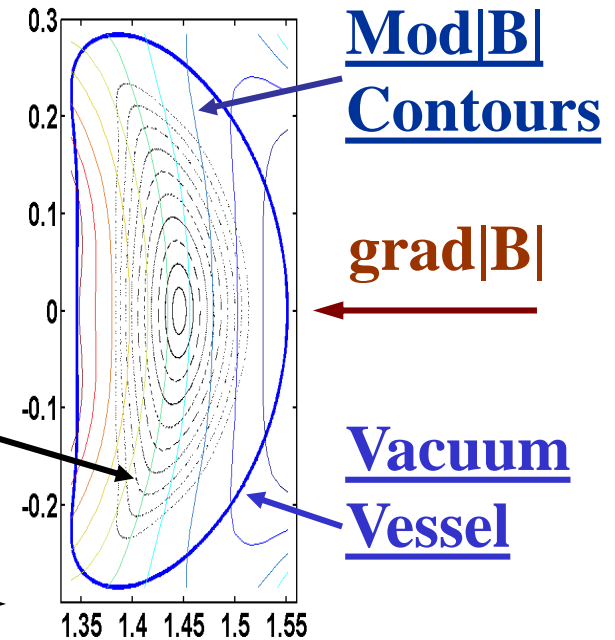


$\text{grad}|B|$



Nested Flux
Surfaces

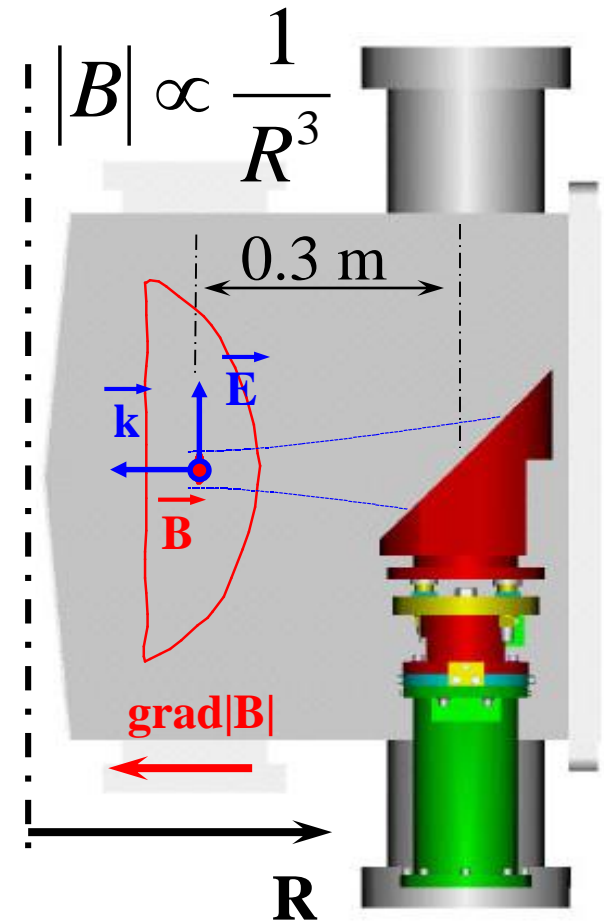
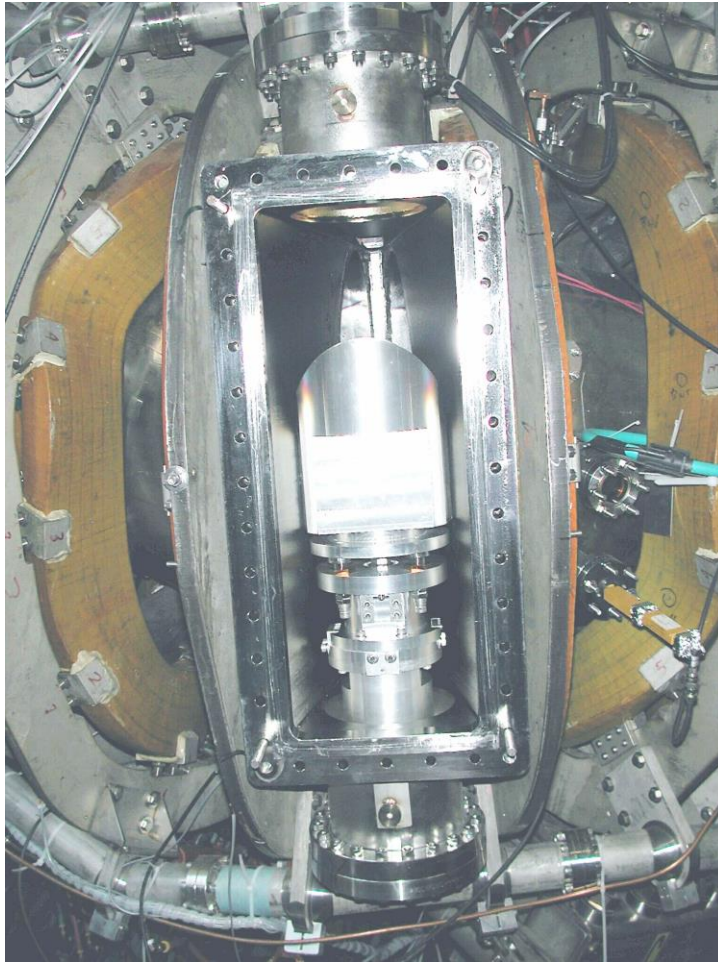
$\phi = 0^\circ$
Location of
RF antenna



Major Radius



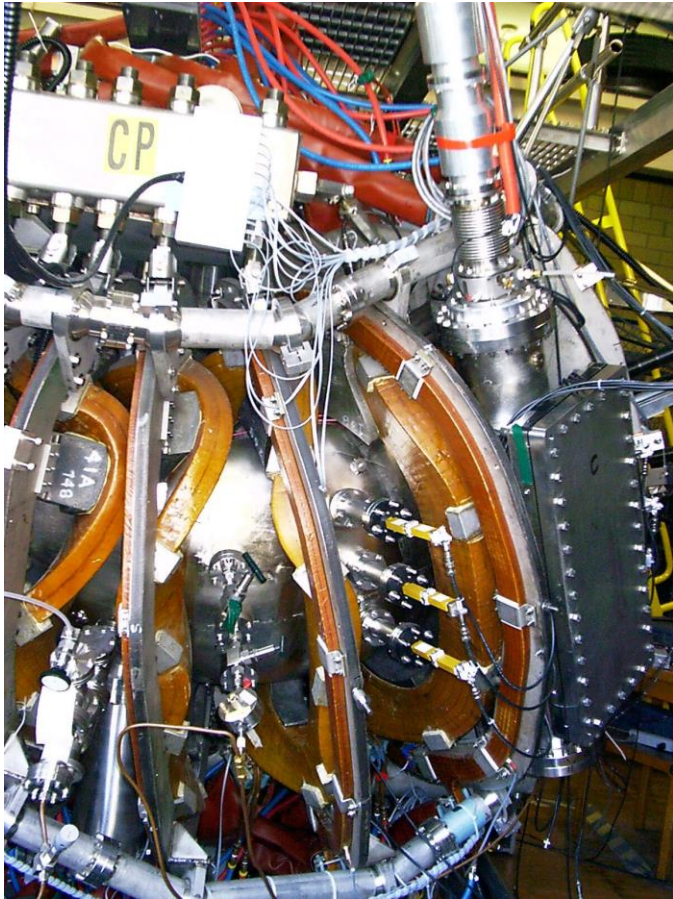
Launching Antenna



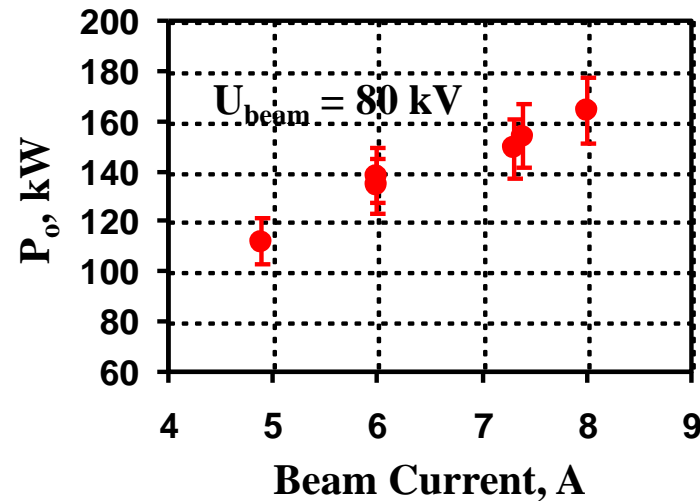
X-wave ($\mathbf{E} \perp \mathbf{B}$) is launched from the low magnetic field side and is focused at the plasma center with a waist of 2 cm (e^{-2} level)



Gyrotron power on HSX window



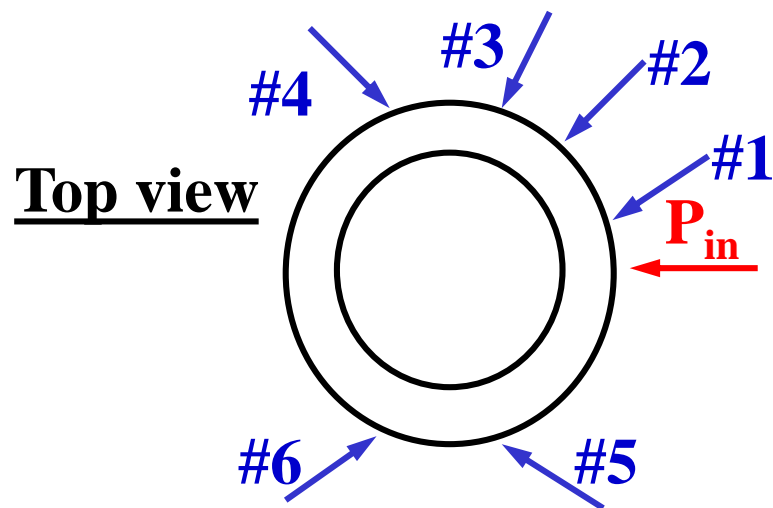
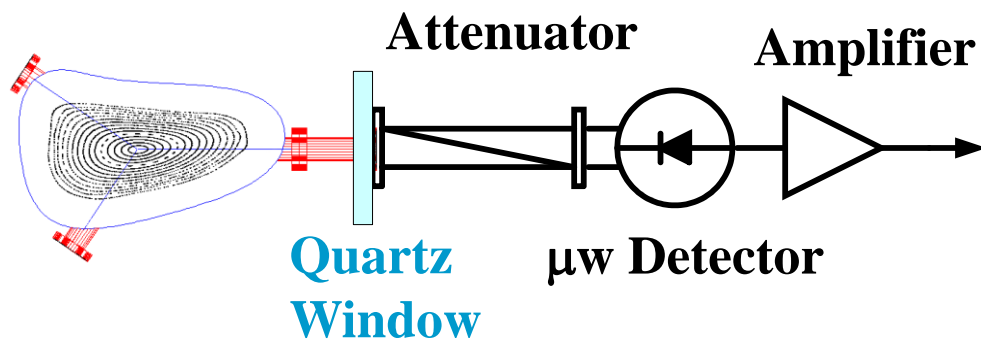
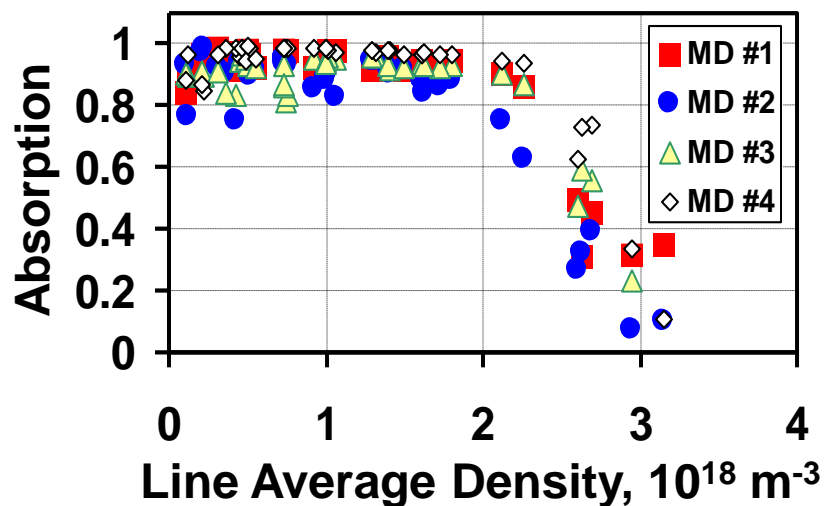
Gyrotron Power vs. Beam Current



- Calorimetric measurements are made with a compact dummy load just before the barrier window
- In these measurements μ -wave diode on the wg directional coupler is calibrated as well



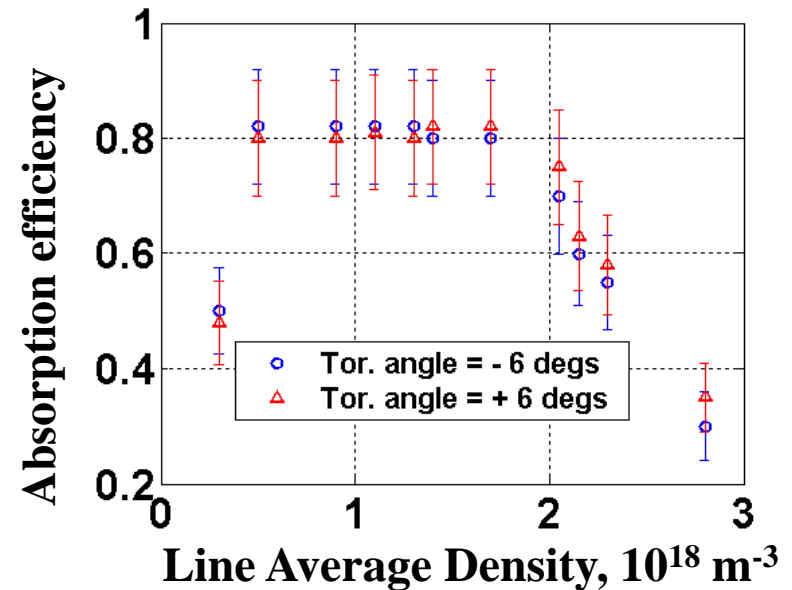
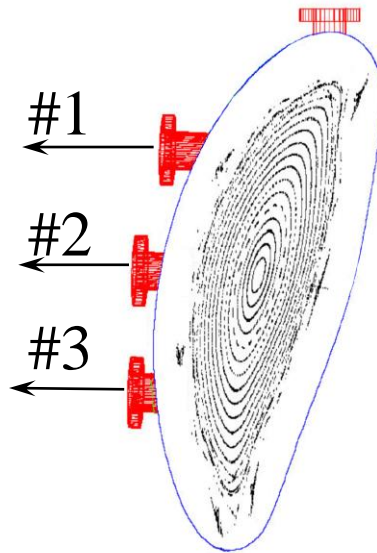
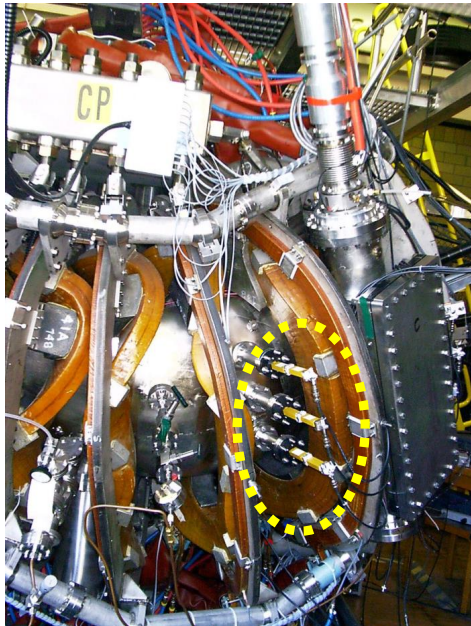
Absorption along the machine



Six absolutely calibrated μ -wave detectors are installed around the HSX at 6° , 36° , $\pm 70^\circ$ and $\pm 100^\circ$ (0.2 m, 0.9 m, 1.6 m and 2.6 m away from μ -wave power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the ECRH antenna



Absorption in vicinity of ECRH antenna



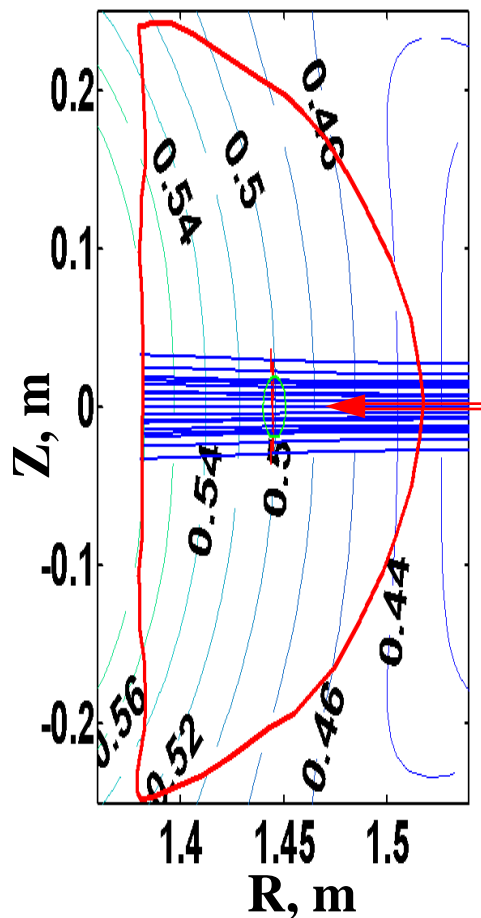
- The same μ -wave probes have been installed on the ports next to the ECRH antenna
- ECRH power is mostly absorbed in first passes through the plasma column
- Absorption is symmetric with respect to the ECRH antenna



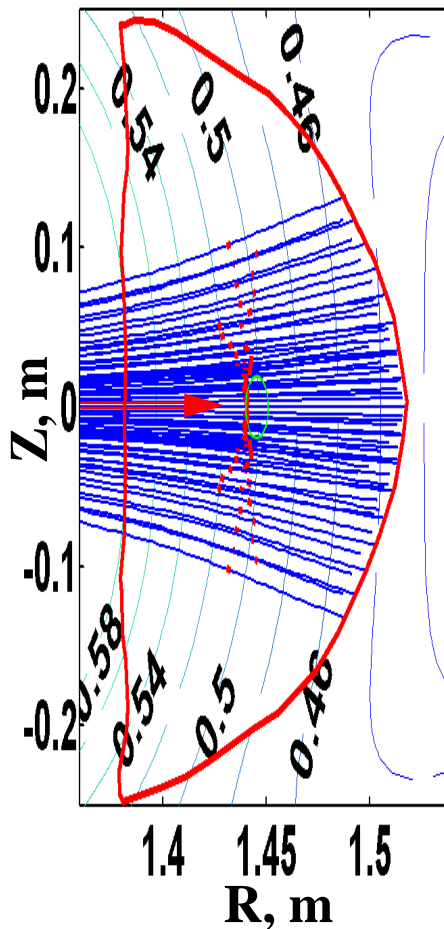
Ray tracing calculations

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

First Pass



Second Pass

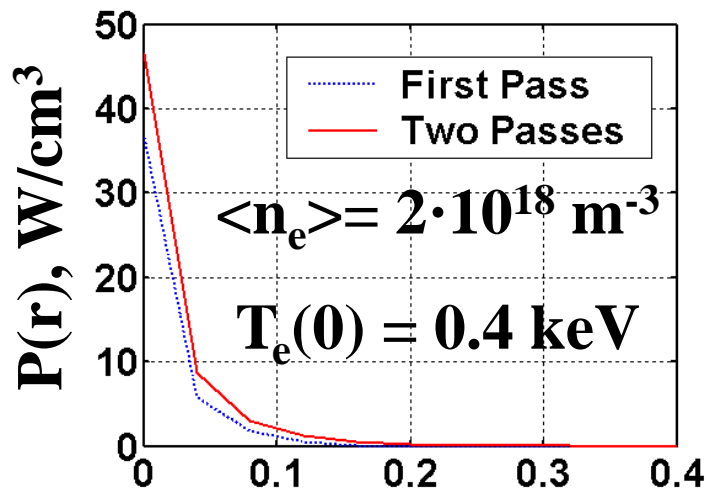


- The code runs on a parallel computer with OpenMP and MPI constructs
- The code returns an absorbed power profile and integrated efficiency
- An optical depth and ECE spectrum can be calculated as well
- Bi-Maxwellian plasma is applied if necessary



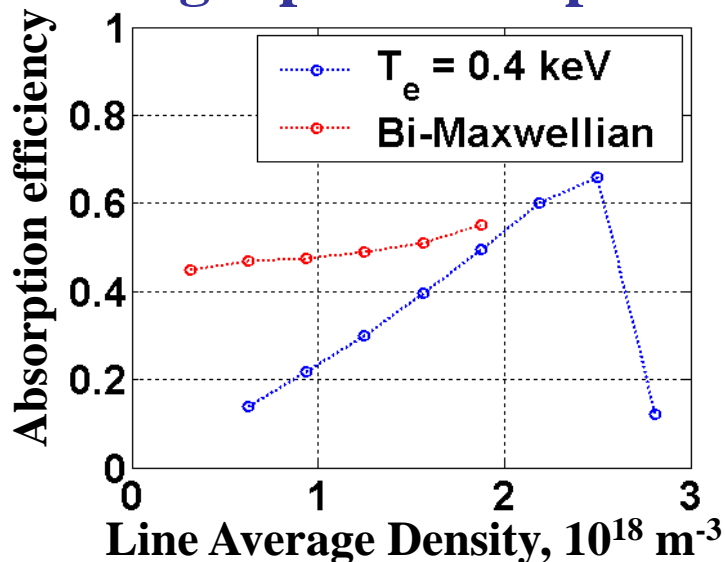
Profile and Efficiency

Absorbed Power Profile



- Single-pass absorbed power profile is quite narrow ($< 0.1a_p$)
- 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

Single-pass absorption

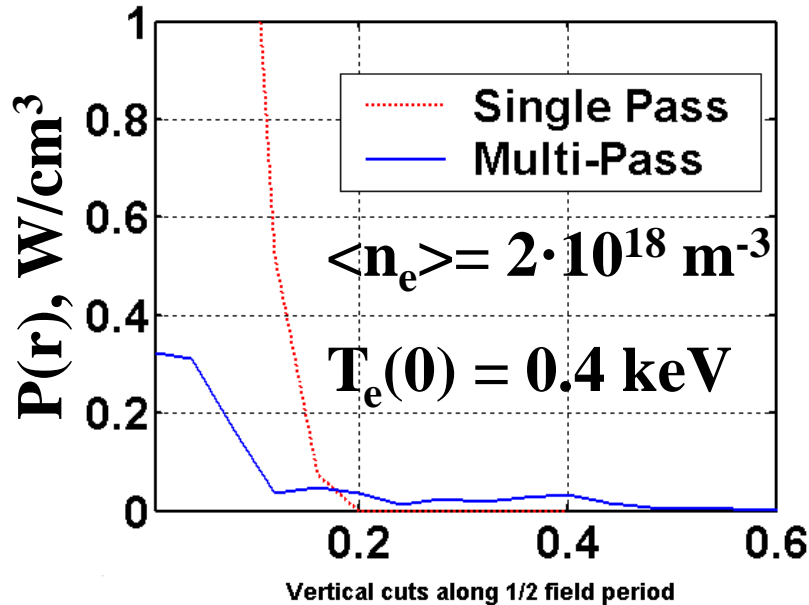


- Absorption versus plasma density is calculated (1) at constant T_e and (2) based on the TS, ECE and diamagnetic loop data in bi-Maxwellian plasma
- Owing to a high non-thermal electron population the absorption can be high enough at a low plasma density

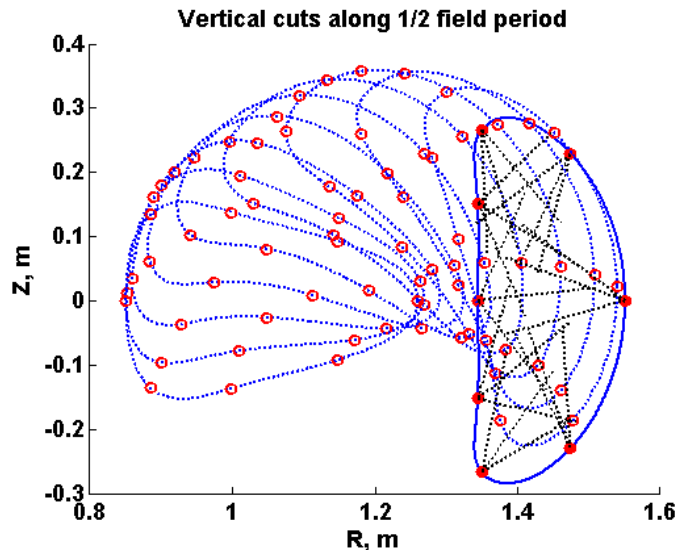


Multi-pass absorption

Absorbed Power Profile

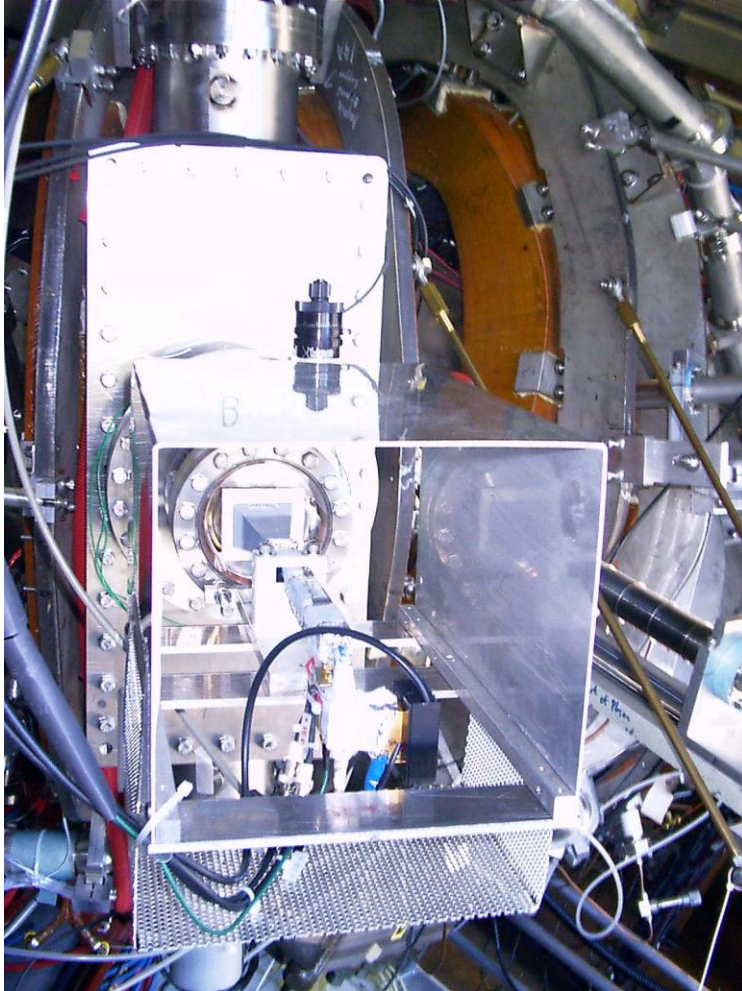


- 240 rays are launched into the plasma from 80 points distributed uniformly across and along the machine at a random angle
- Multi-pass absorption adds (4 – 7)% to the total efficiency in a wide range of plasma density $(0.5 - 2) \cdot 10^{18} \text{ m}^{-3}$
- This multi-pass absorption is low due to (1) low power density in the plasma core and (2) high ray refraction





ECE Radiometer

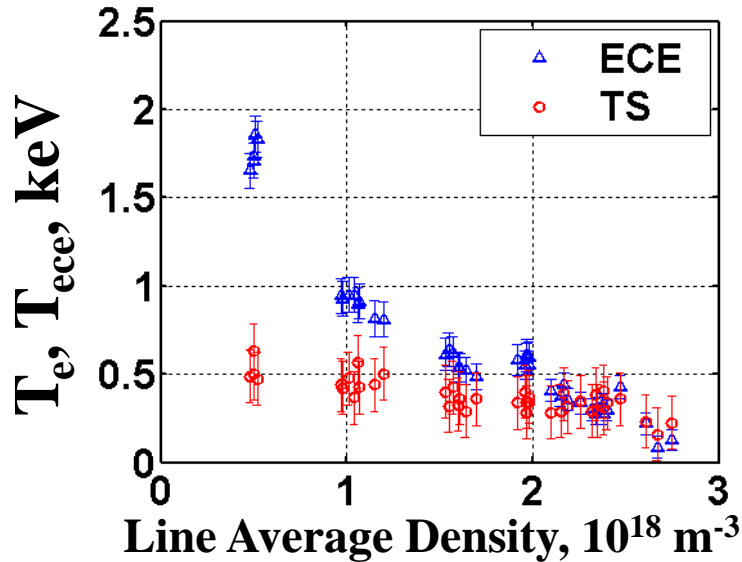


- Conventional 8 channel radiometer implemented:
6 channels receive ECE power emitted by plasma at a low magnetic field side and 2 frequency channels – at a high field side
- 60 dB BS filter is used to reject the gyrotron power at (28 ± 0.3) GHz and 40 dB fast pin diode protects the mixer from the spurious modes on a leading edge of gyrotron pulse

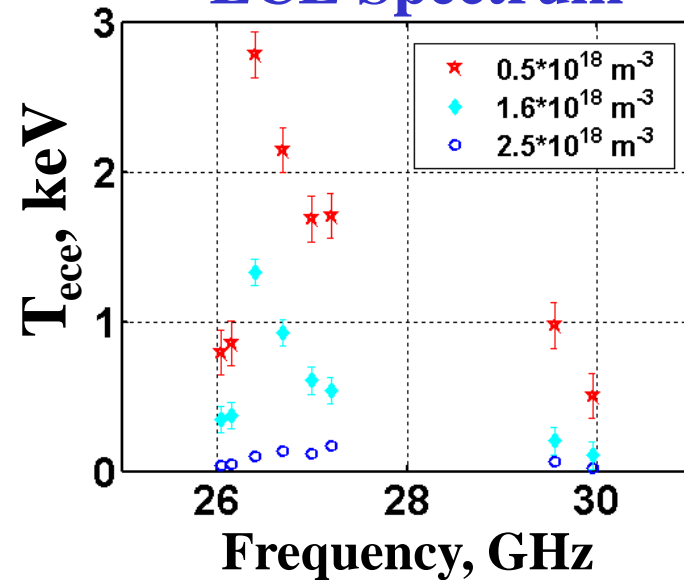


ECE Temperature vs. Plasma Density

ECE vs. Thomson Scattering



ECE Spectrum



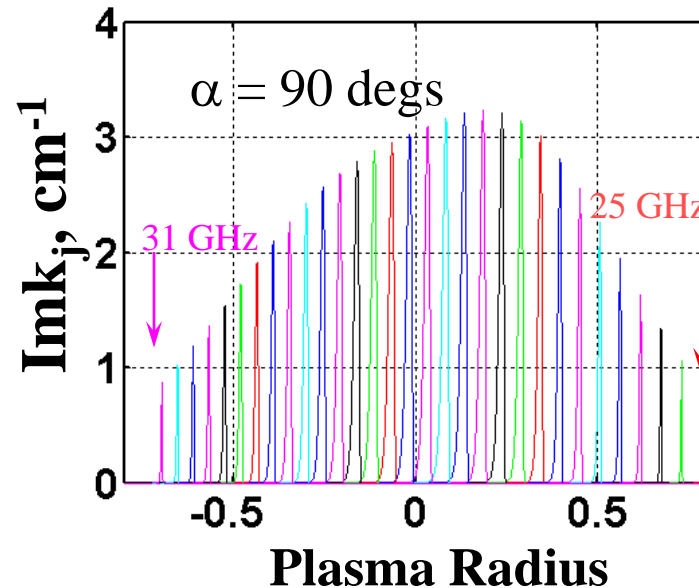
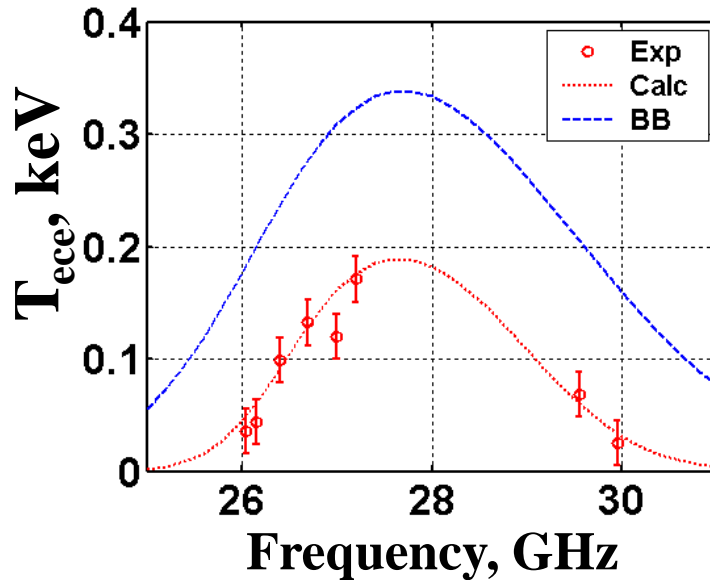
- ECE temperature drops with plasma density while the electron temperature from Thomson scattering diagnostic is almost independent of plasma density
- In plasma density scan the non-thermal feature at a low magnetic field side increases first and then the high frequency emission gets risen



ECE at high plasma density



$$\langle n_e \rangle = 2.5 \cdot 10^{18} \text{ m}^{-3}$$



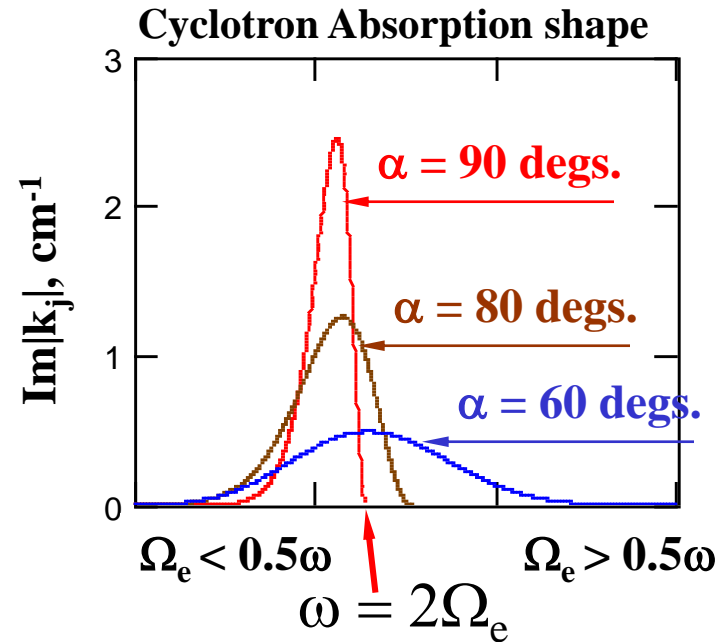
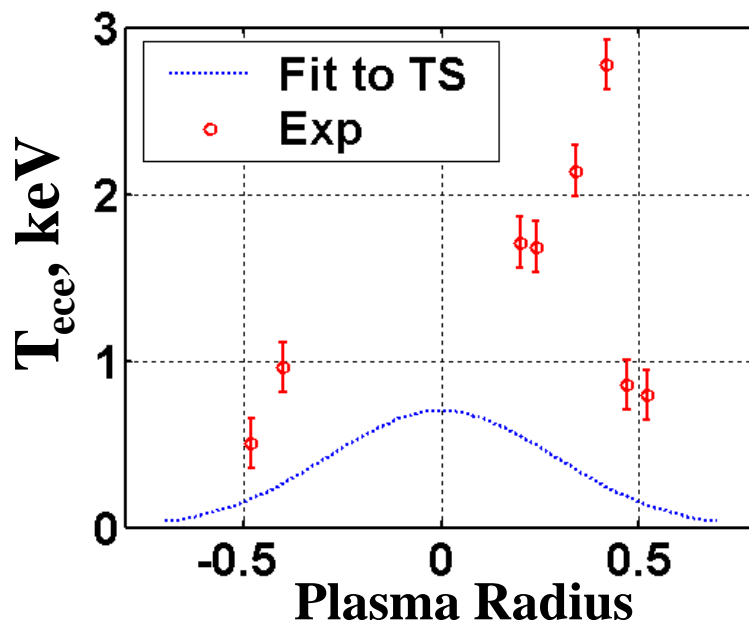
- Emission at the high plasma density is thermal
- HSX plasma is not a black body: an optical depth should be taken into account to estimate the electron temperature:

$$T_{ece} = T_e \cdot (1 - e^{-\tau})$$

- Thomson scattering and interferometer data are used to calculate the optical depth



ECE at low plasma density



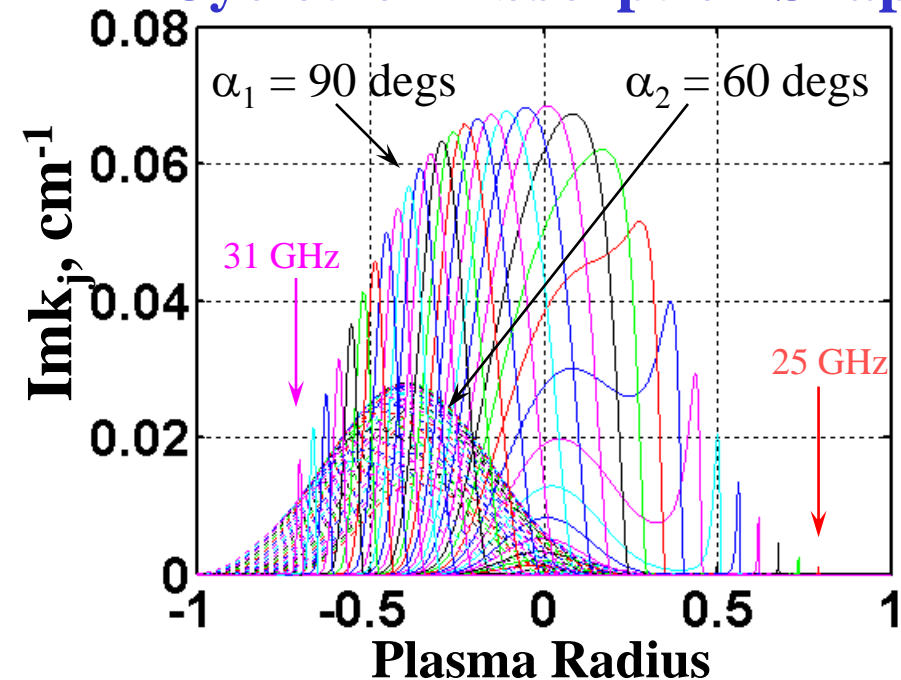
- ECE signal is high at both low and high field sides
- High signal from outboard side is due to emission from central resonance region where a population of supra-thermal particles is supposed to be high at a central heating
- Oblique emission from central regions can contribute to the signal detected at higher frequencies (> 28 GHz, inboard side)



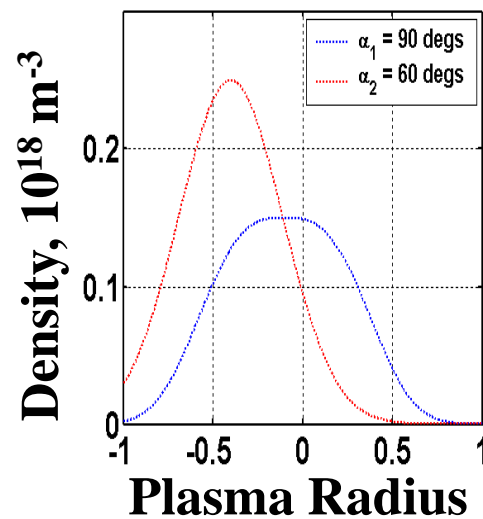
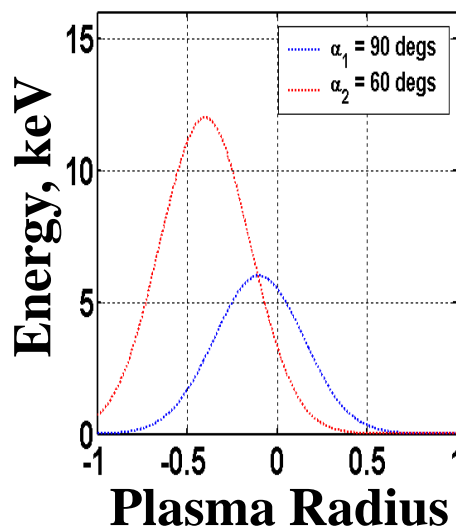
Perpendicular and Oblique sight view

Cyclotron Absorption Shape

- Two propagation angles are chosen. Along each direction we assume “Maxwellian tail” with different T_e and n_e
- The following profiles are assumed for tail electrons:

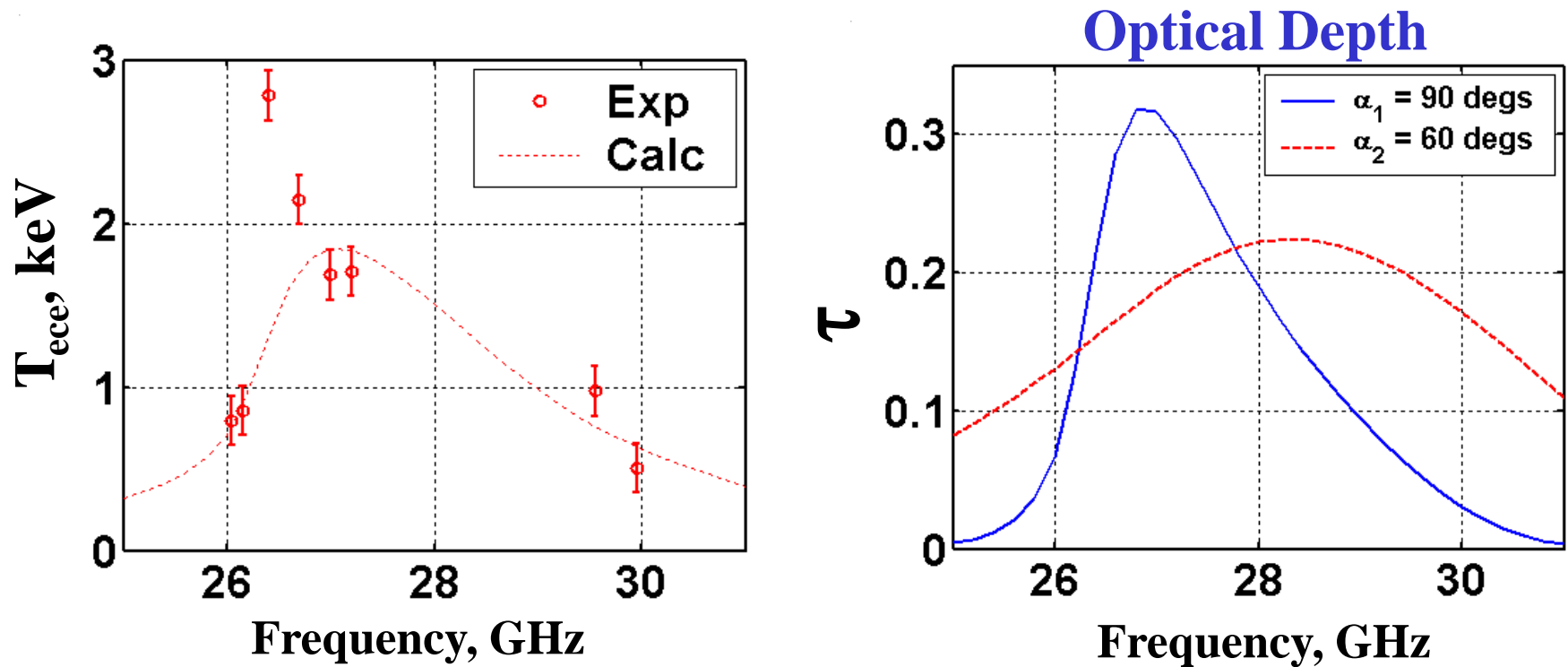


Solid lines represent the local absorption at perpendicular propagation and dash lines – at oblique propagation





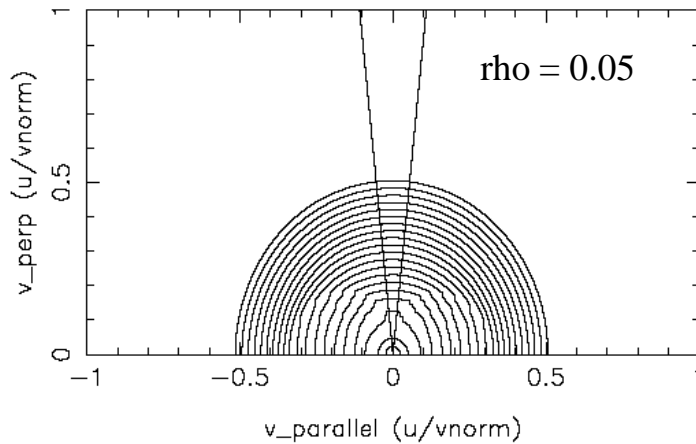
ECE Spectrum at $0.5 \cdot 10^{18} \text{ m}^{-3}$



- ECE temperature is defined as $T_{\text{ece}} = T_1 \cdot (1 - e^{-\tau_1}) + T_2 \cdot (1 - e^{-\tau_2})$
- This estimate shows that about 30% of electron density belongs to the tail with $T_{1\text{max}} = 6 \text{ keV}$ and $T_{2\text{max}} = 12 \text{ keV}$, $n_{1\text{max}} = 0.15 \cdot 10^{18} \text{ m}^{-3}$ and $n_{2\text{max}} = 0.25 \cdot 10^{18} \text{ m}^{-3}$

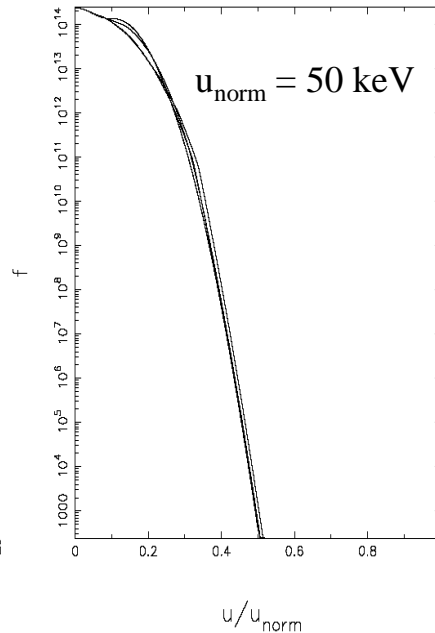
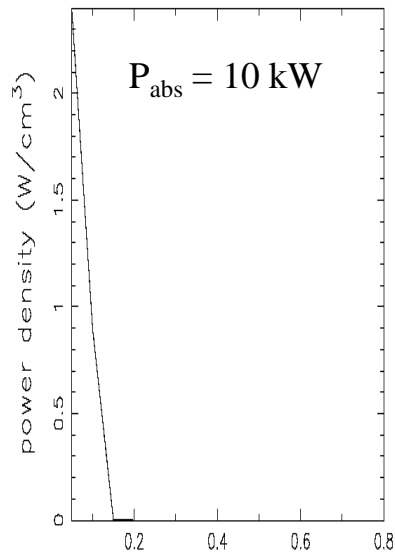


CQL3D code for HSX



➤ QHS configuration in HSX has a helical axis of symmetry and its mod-B is tokamak-like. So with CQL3D code we can simulate the distribution function in HSX flux coordinates

Absorbed Power Profile Cuts at some pitch angles



➤ First runs of CQL3D have been made for HSX plasma at $3 \cdot 10^{18} \text{ m}^{-3}$ of central density and 100 kW of launched power. At plasma center a distortion of distribution function occurs in the energy range of (5 – 15) keV



Summary

- Measured multi-pass absorption efficiency in HSX plasma is high in a wide range of plasma densities
- ECE measurements in HSX exhibit a non-thermal feature at a low plasma density
- Bi-Maxwellian plasma model partly explains the high absorption and enhanced emission
- CQL3D code predicts 5 – 15 keV electrons in the HSX plasma core at 100 kW of launched power