



# Electron Cyclotron Heating by X-wave in the HSX stellarator

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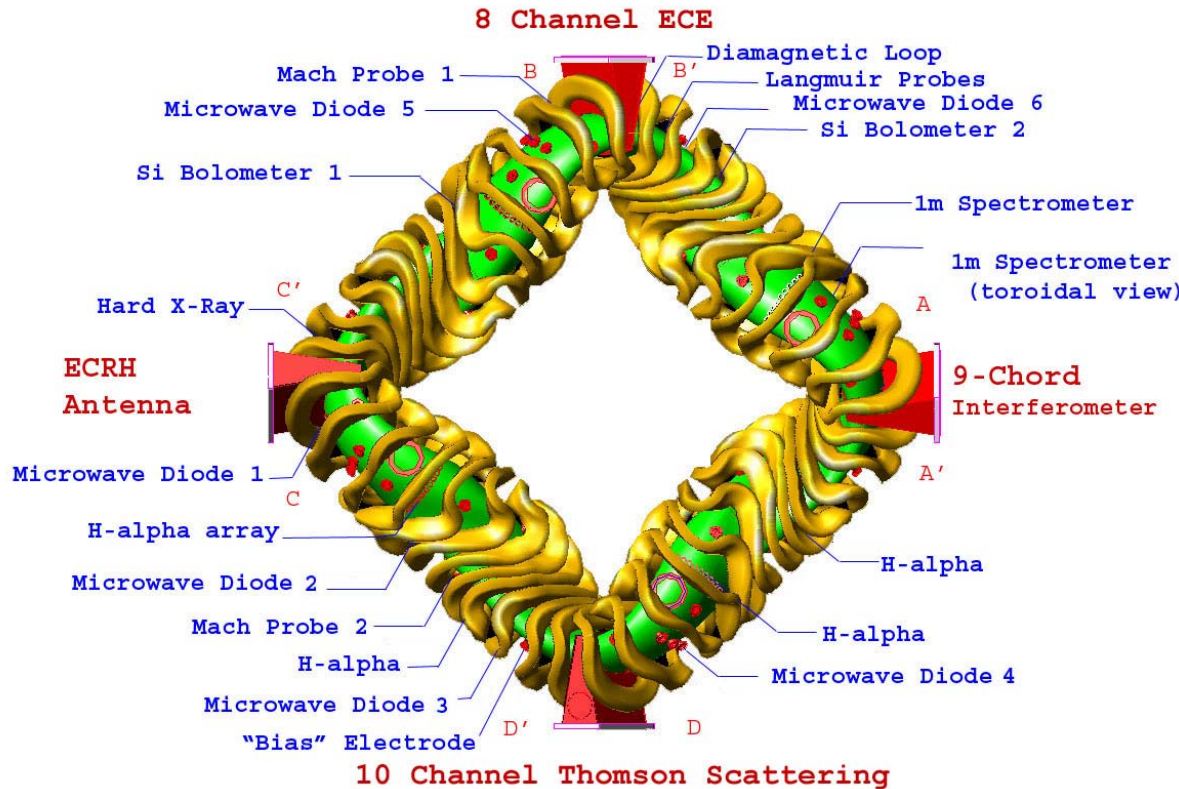


# Outline

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



# The Helicallly Symmetric Experiment



$R, m$	1.2
$a_p, m$	0.15
$B_0, T$	0.5
$n_e, m^{-3}$	$< 5 \cdot 10^{18}$
$T_e, keV$	$\leq 0.6$
$F, GHz$	28
$P_{rf}, kW$	$\leq 130$
$\tau_{rf}, msec$	$\leq 50$

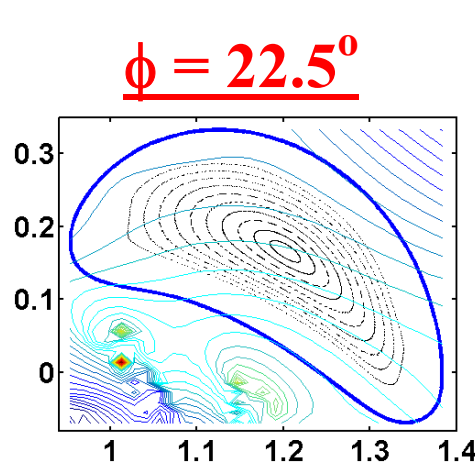
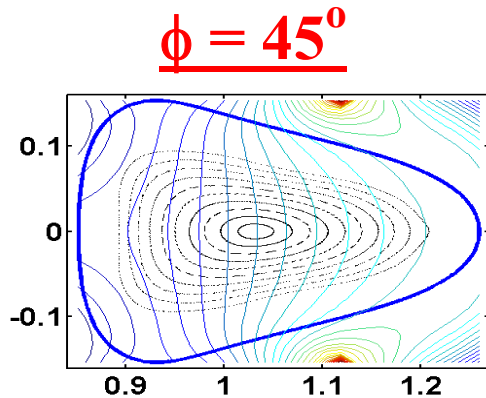
Symmetry in  $|B|$  leads to a small deviation of trapped particles orbits from a flux surface and, as a result, to improved neoclassical confinement in a low collisionality regime



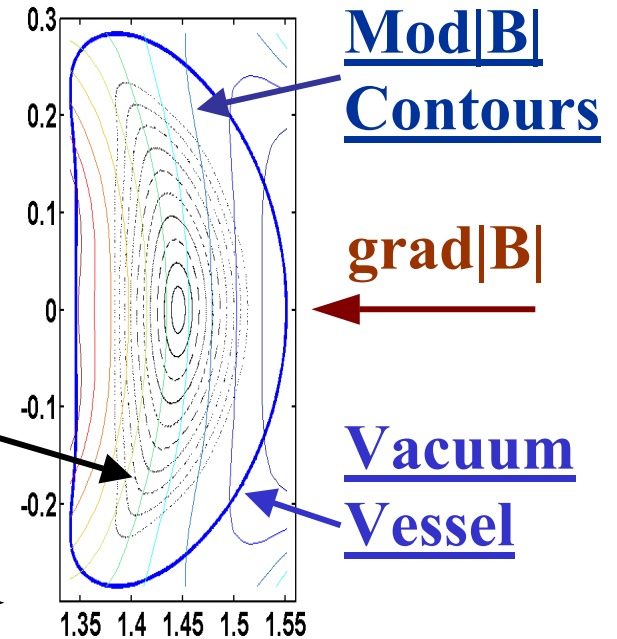
# HSX Cross-sections along $\frac{1}{2}$ Field Period

Plasma axis is wound around  $R = 1.2$  m

HSX center



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

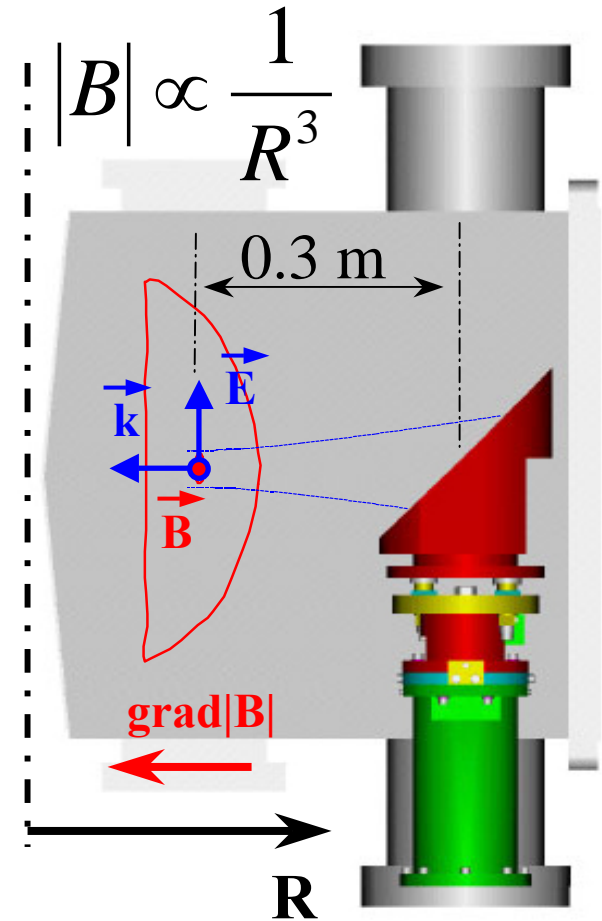
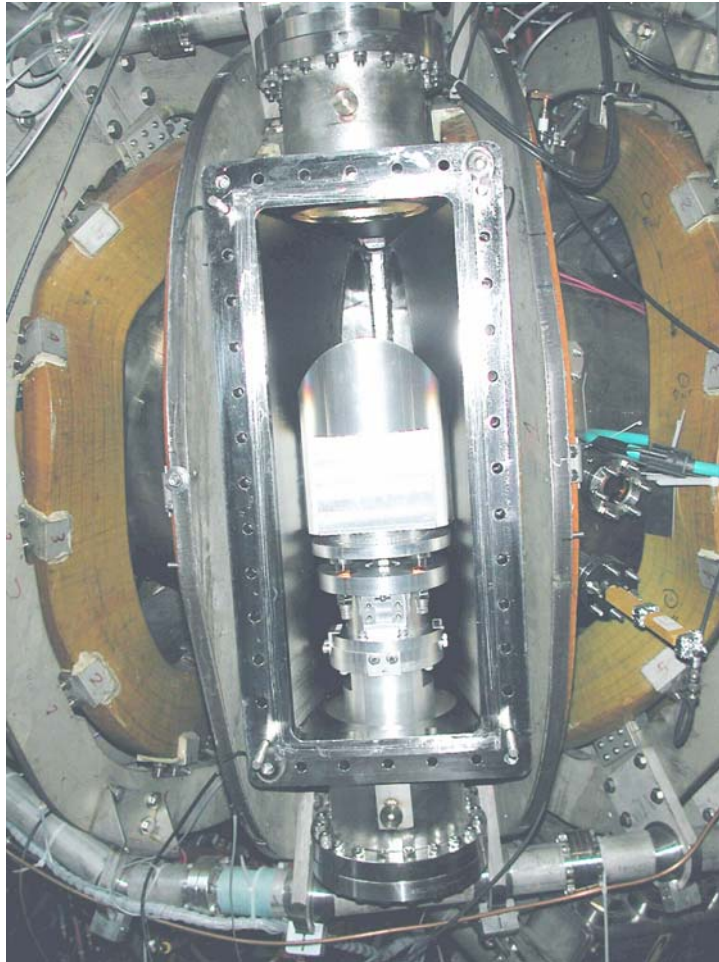


Nested Flux Surfaces

Major Radius



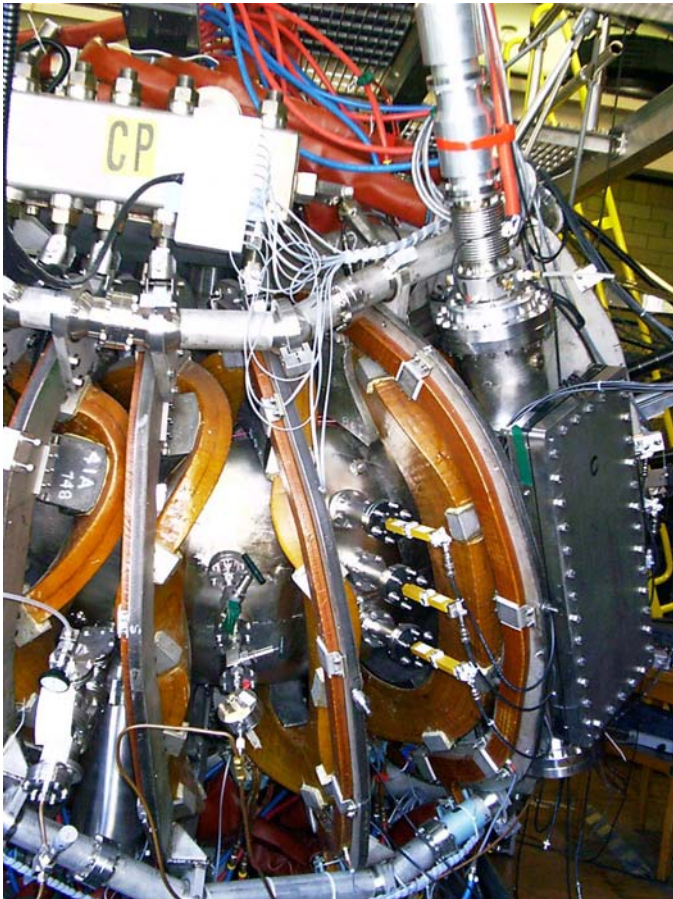
# Launching Antenna



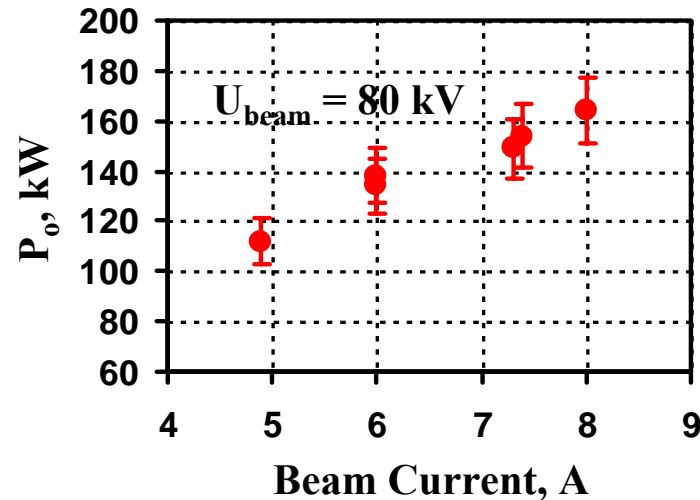
X-wave ( $E \perp B$ ) is launched from the low magnetic field side and is focused at the plasma center with a waist of 2 cm ( $e^{-2}$  level)



# Gyrotron power on HSX window



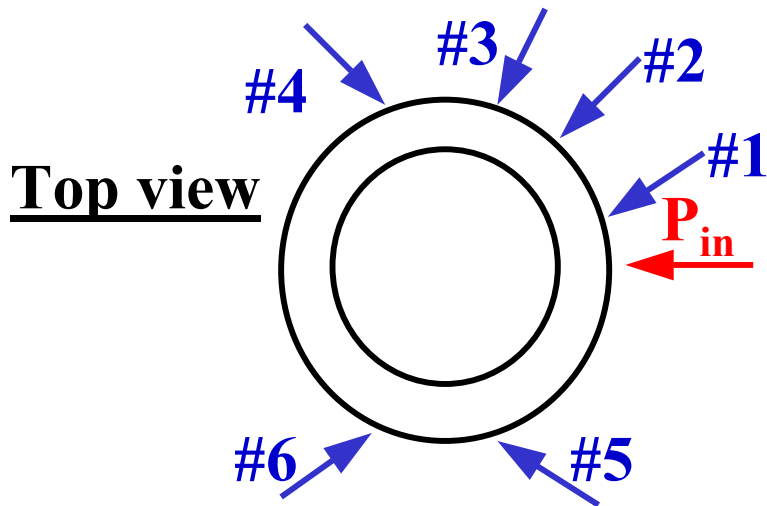
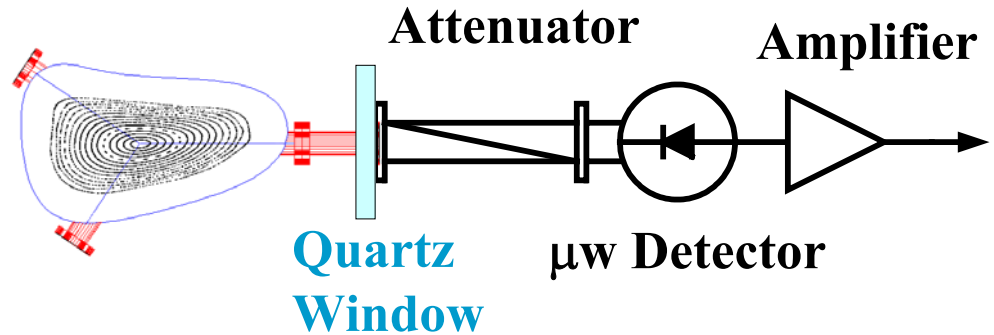
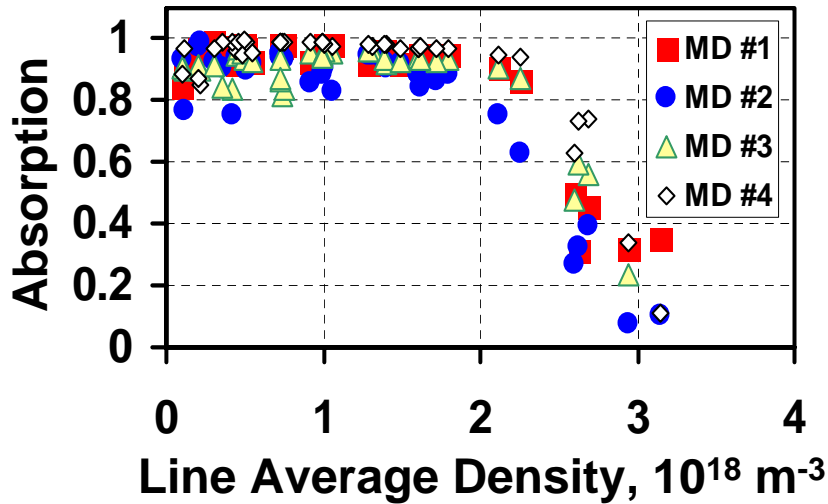
Gyrotron Power vs. Beam Current



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



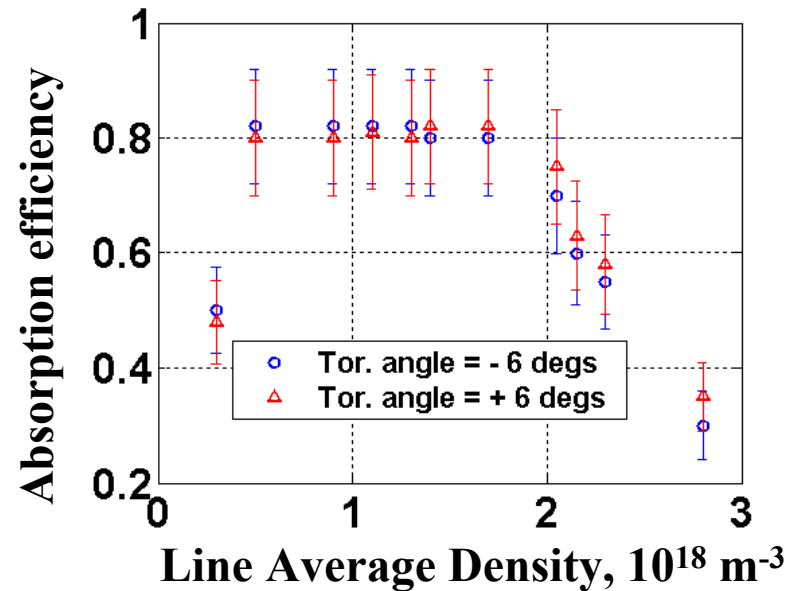
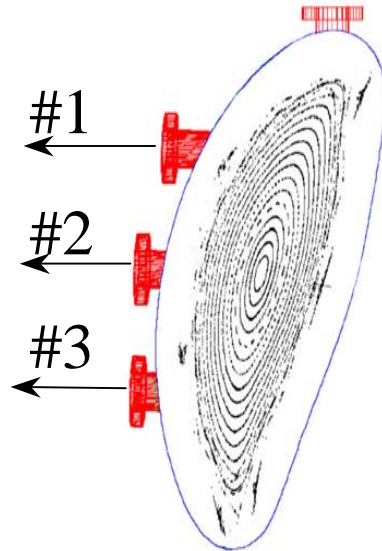
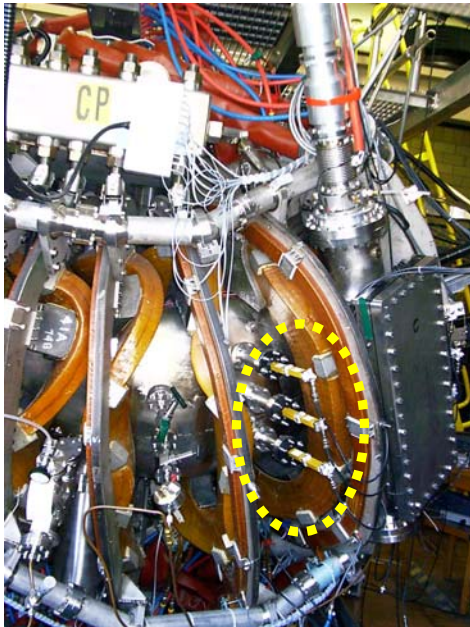
# Absorption along the machine



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



# Absorption in vicinity of ECRH antenna



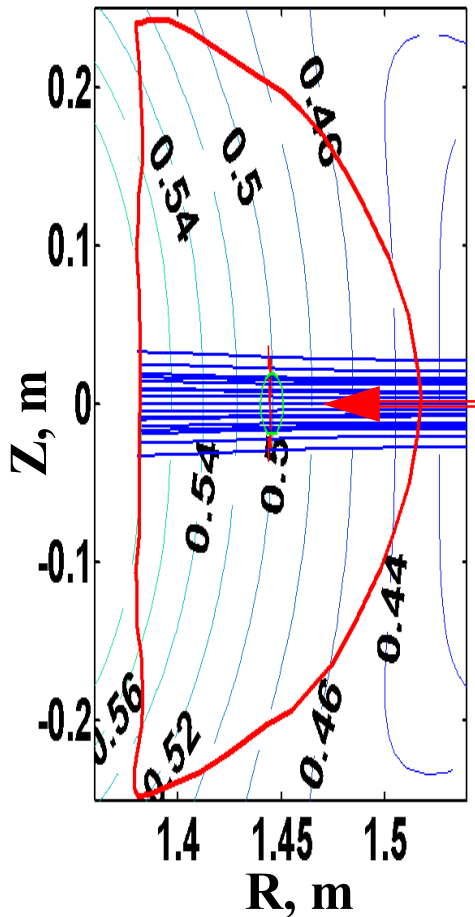
- The same  $\mu$ -wave probes have been installed on the ports next to the ECRH antenna
- ECRH power is mostly absorbed in first passes through the plasma column
- Absorption is symmetric with respect to the ECRH antenna



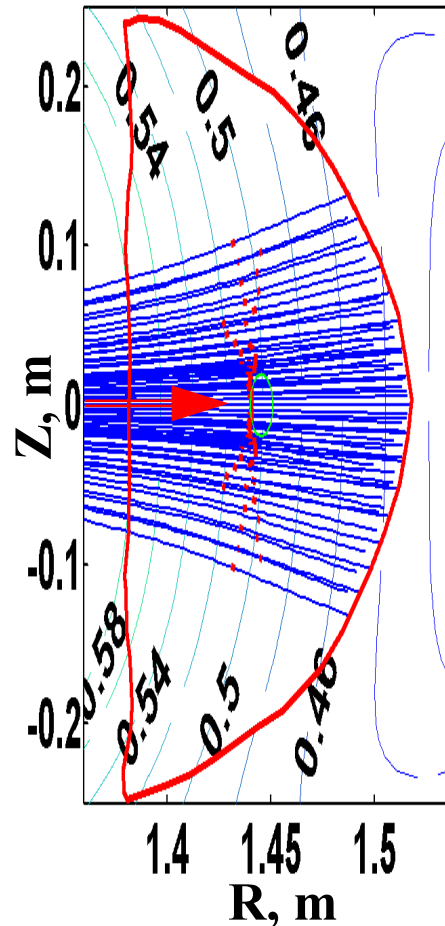
# Ray tracing calculations

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

First Pass



Second Pass



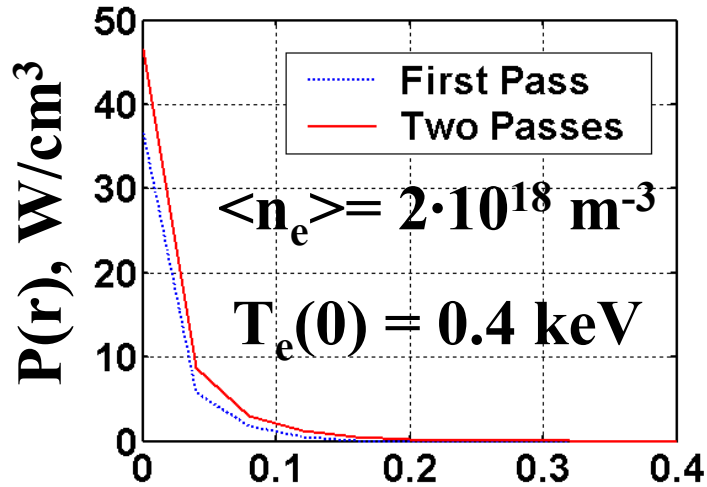
- The code runs on a parallel computer with OpenMP and MPI constructs
- The code returns an absorbed power profile and integrated efficiency
- An optical depth and ECE spectrum can be calculated as well
- Bi-Maxwellian plasma is applied if necessary



# Profile and Efficiency

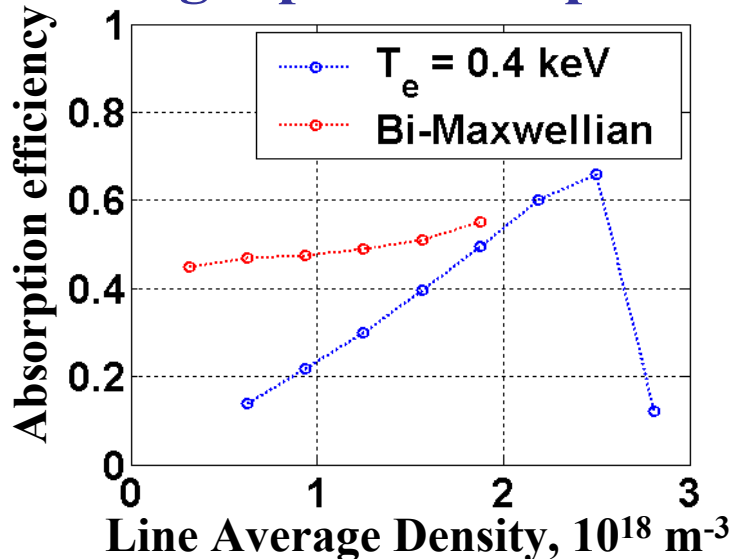


## Absorbed Power Profile



- 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

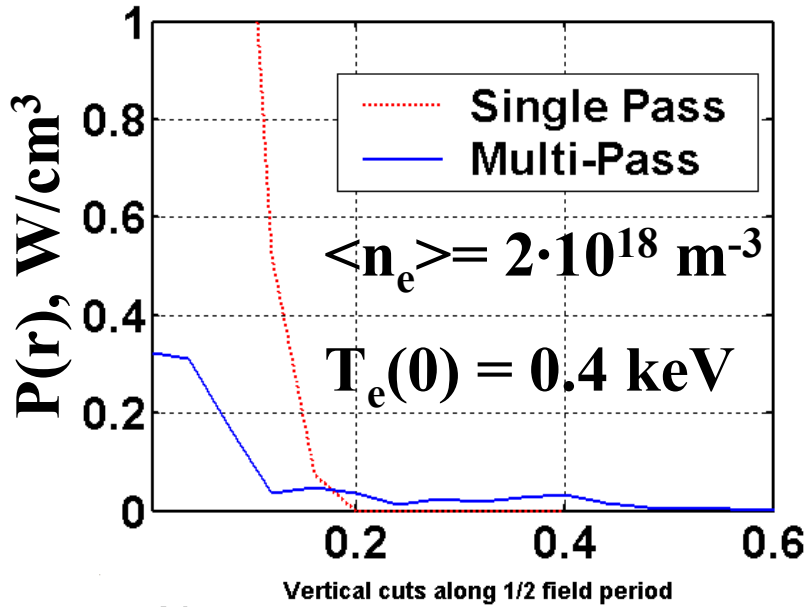


- Absorption versus plasma density is calculated (1) at constant  $T_e$  and (2) based on the TS, ECE and diamagnetic loop data in bi-Maxwellian plasma
- Owing to a high non-thermal electron population the absorption can be high enough at a low plasma density

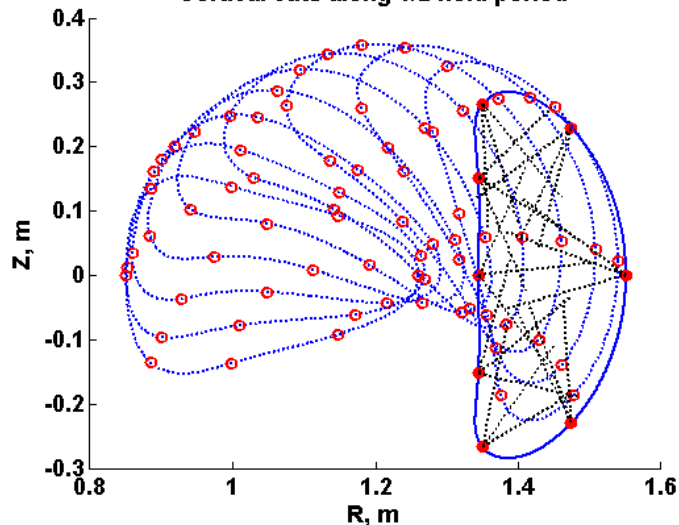


# Multi-pass absorption

## Absorbed Power Profile

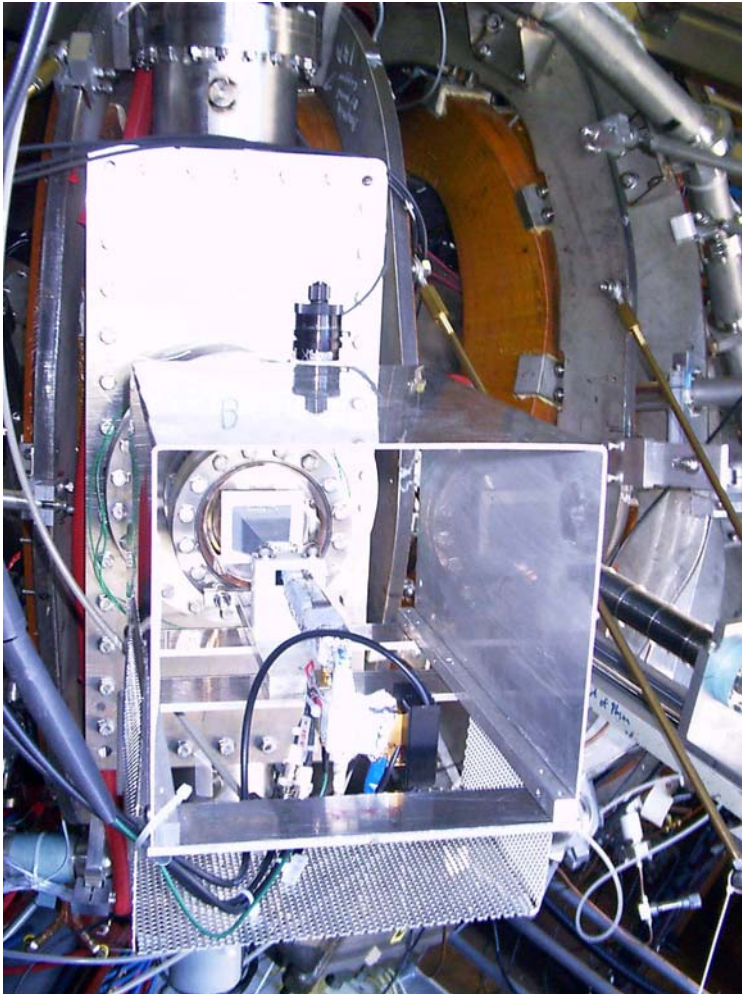


- 240 rays are launched into the plasma from 80 points distributed uniformly across and along the machine at a random angle
- Multi-pass absorption adds (4 – 7)% to the total efficiency in a wide range of plasma density  $(0.5 - 2) \cdot 10^{18} \text{ m}^{-3}$
- This multi-pass absorption is low due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





# ECE Radiometer



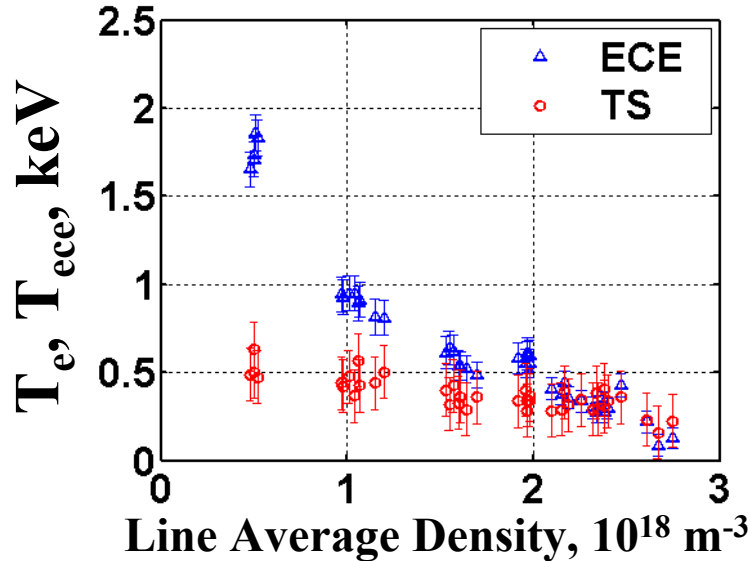
- Conventional 8 channel radiometer implemented:  
6 channels receive ECE power emitted by plasma at a low magnetic field side and 2 frequency channels – at a high field side
- 60 dB BS filter is used to reject the gyrotron power at  $(28 \pm 0.3)$  GHz and 40 dB fast pin diode protects the mixer from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



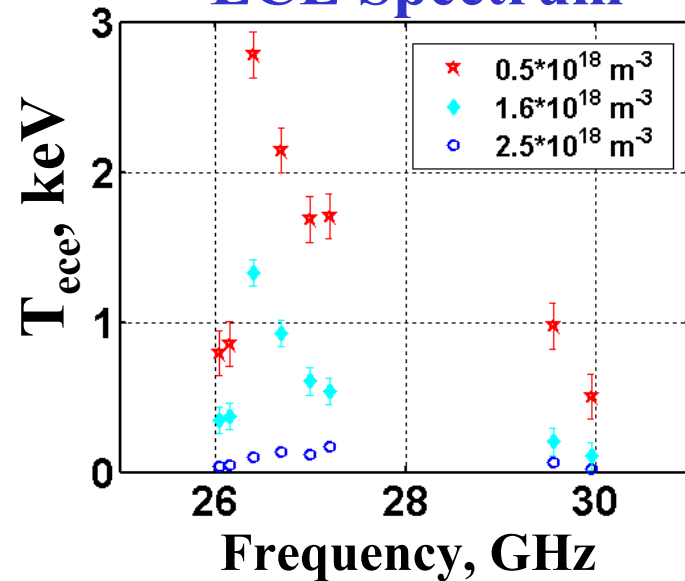
# ECE Temperature vs. Plasma Density



## ECE vs. Thomson Scattering



## ECE Spectrum



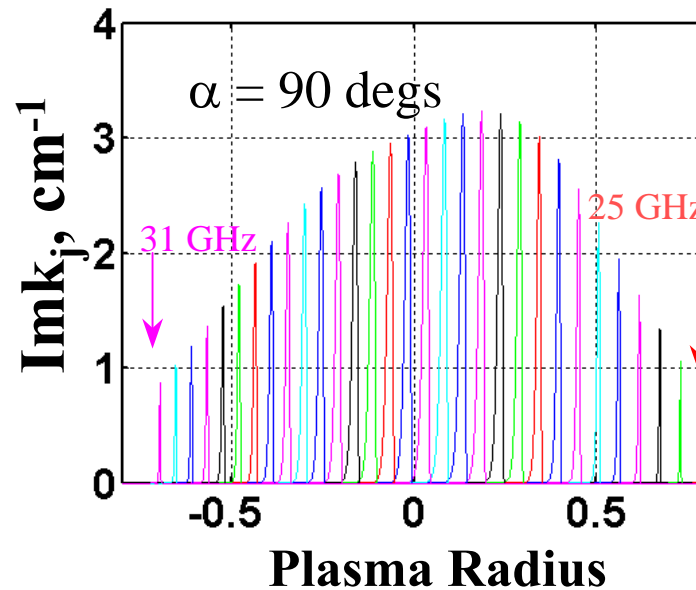
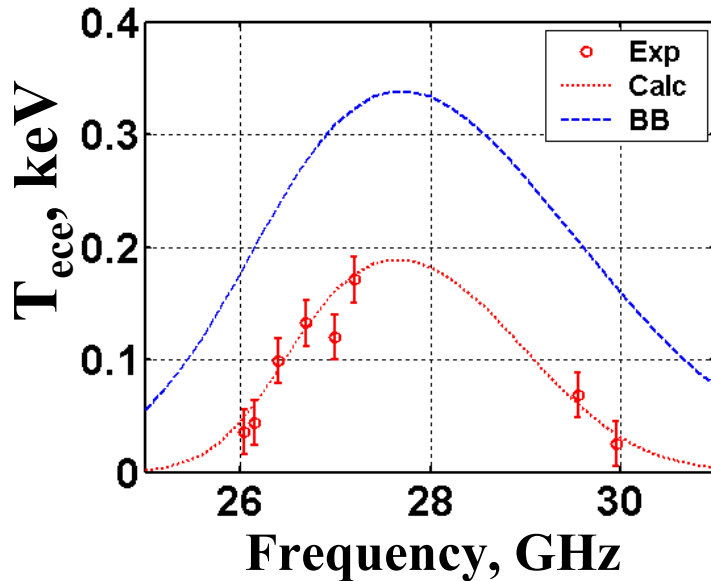
- ECE temperature drops with plasma density while the electron temperature from Thomson scattering diagnostic is almost independent of plasma density
- In plasma density scan the non-thermal feature at a low magnetic field side increases first and then the high frequency emission gets risen



# ECE at high plasma density



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



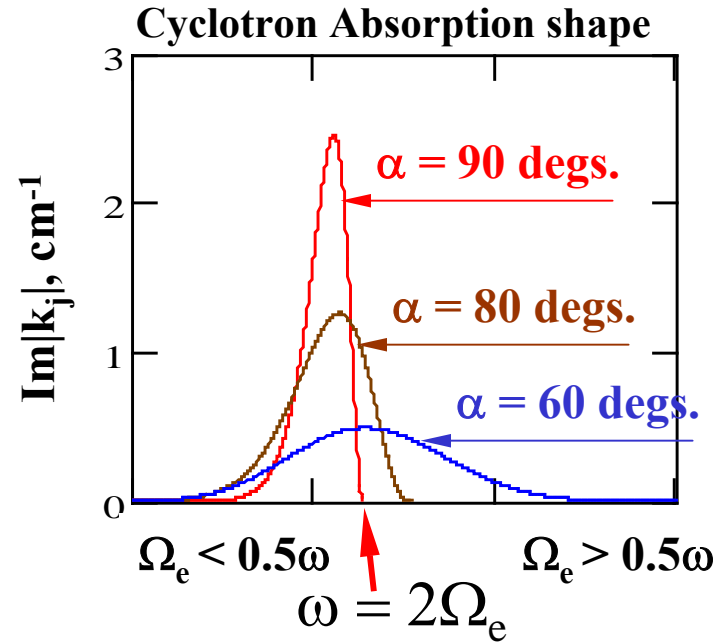
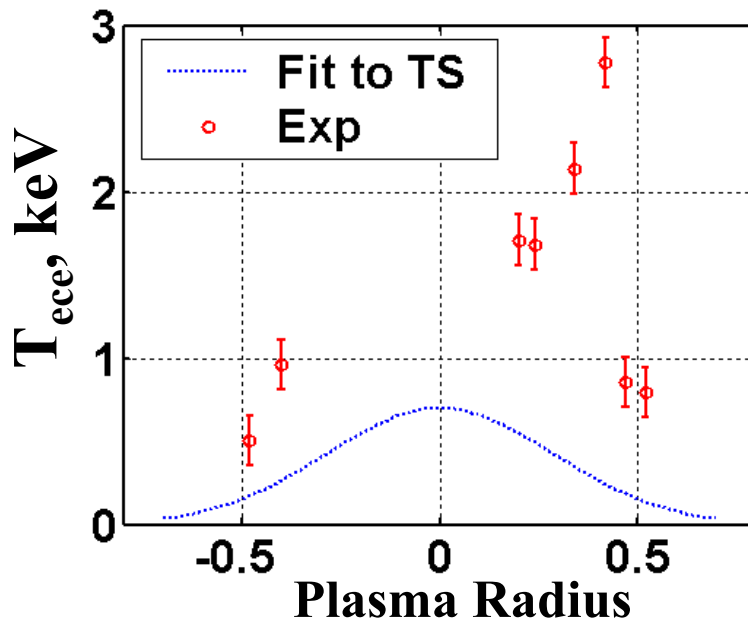
- Emission at the high plasma density is thermal
- HSX plasma is not a black body: an optical depth should be taken into account to estimate the electron temperature:

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

- 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)

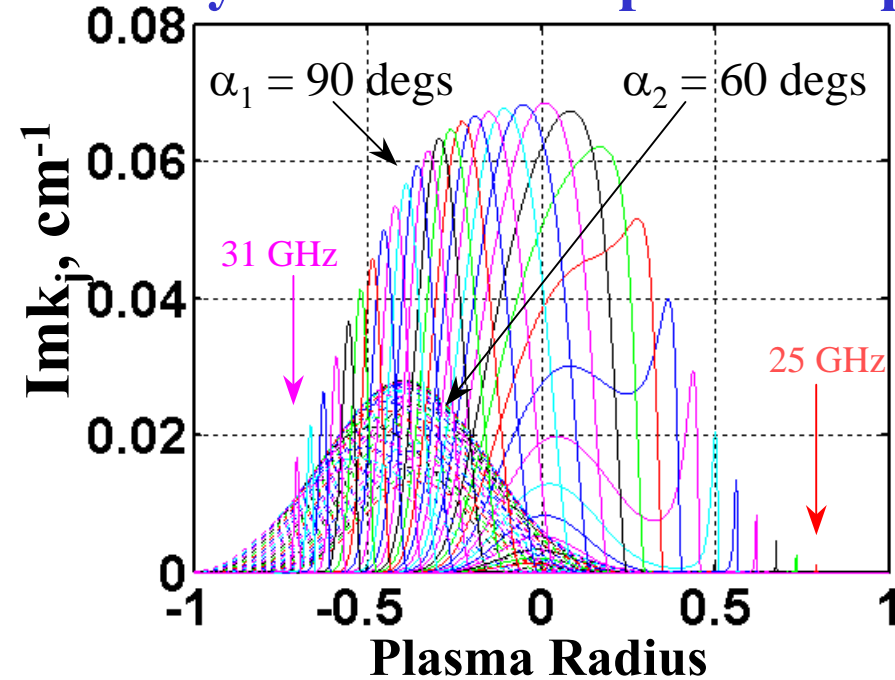


# Perpendicular and Oblique sight view

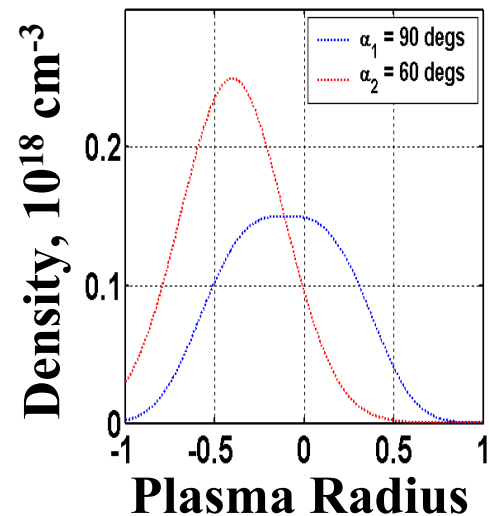
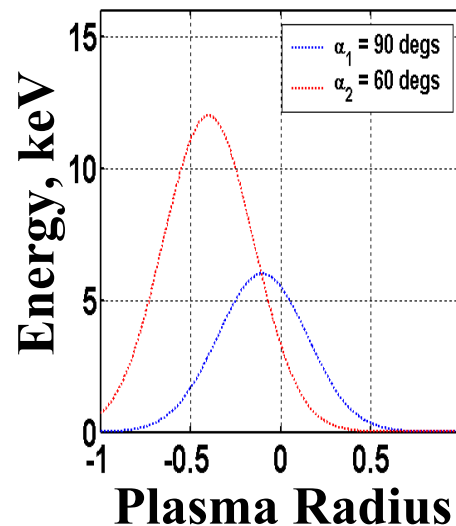


## Cyclotron Absorption Shape

- 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:

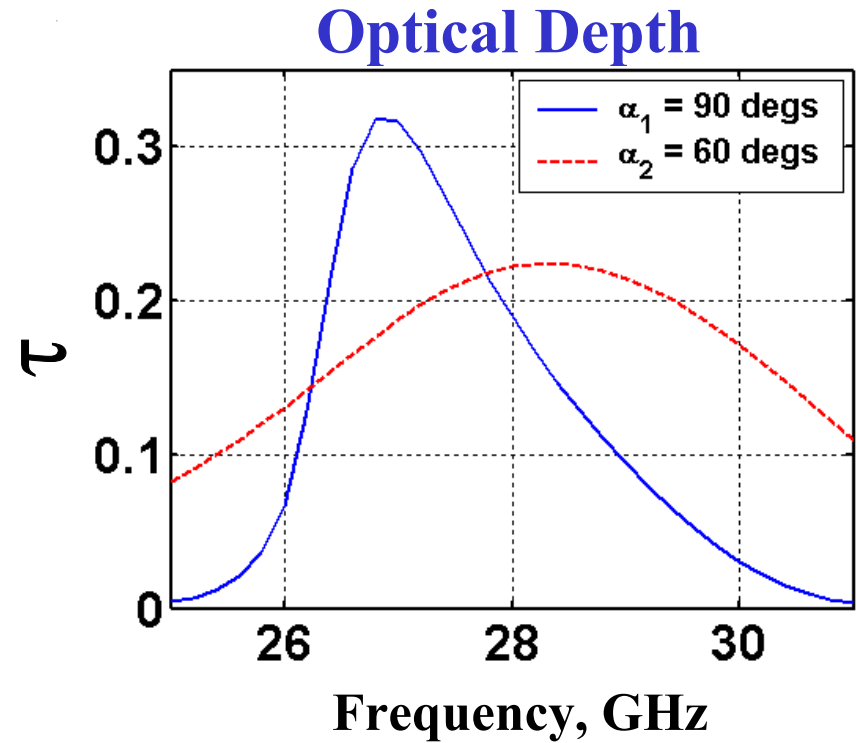
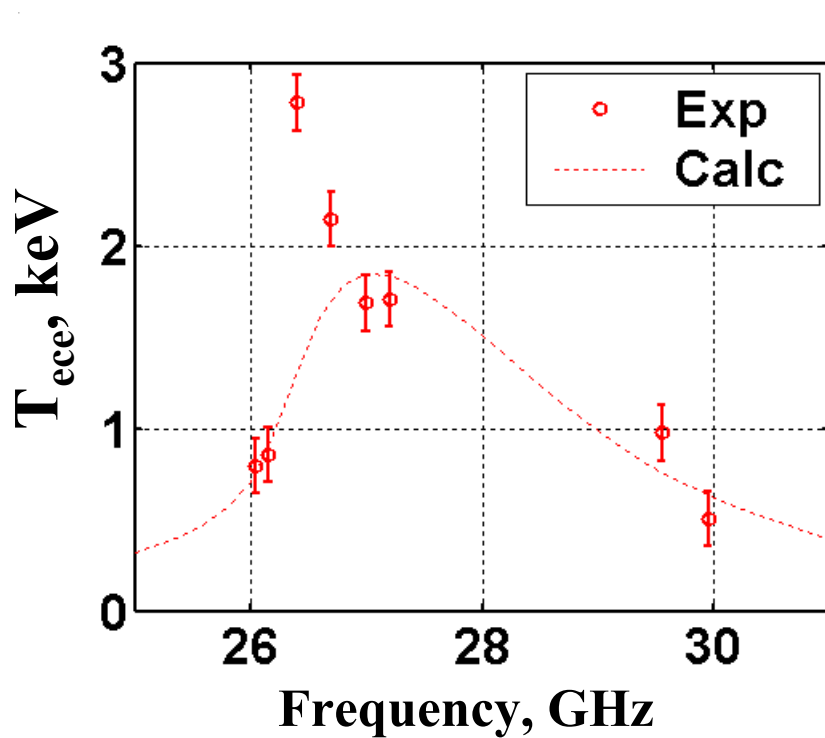


Solid lines represent the local absorption at perpendicular propagation and dash lines – at oblique propagation





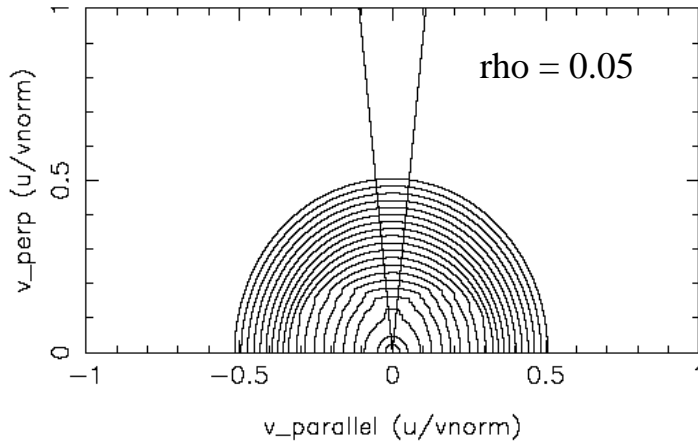
# ECE Spectrum at $0.5 \cdot 10^{18} \text{ m}^{-3}$



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

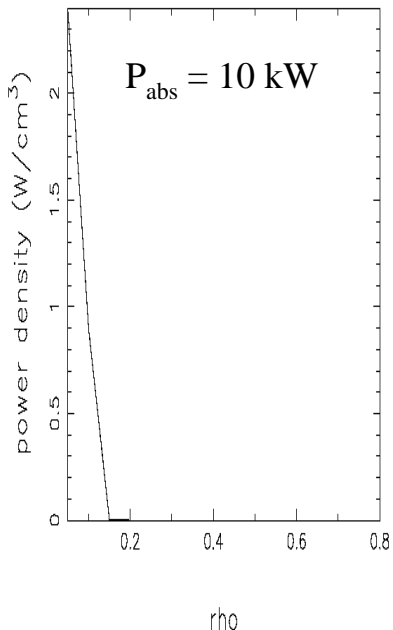


# CQL3D code for HSX

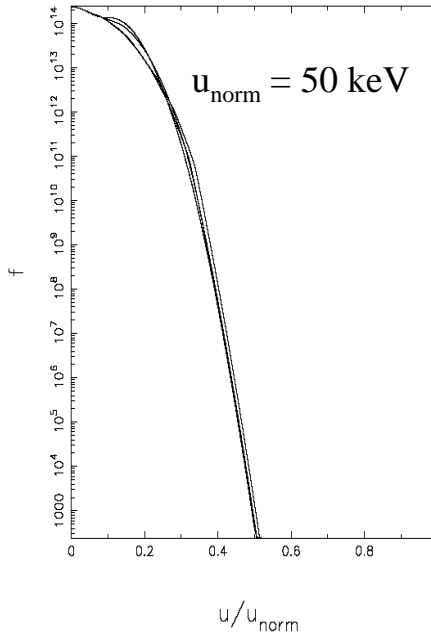


- QHS configuration in HSX has a helical axis of symmetry and its mod-B is tokamak-like. So with CQL3D code we can simulate the distribution function in HSX flux coordinates

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**