Electron Cyclotron Heating by X-wave in the HSX stellarator

K.M.Likin[1], ***A.Abdou[1], A.F.Almagri[1], D.T.Anderson[1], F.S.B.Anderson[1], J.Canik[1], C.Deng[2], C.W.Domier[3], S.P.Gerhardt[1], R.W.Harvey[4], H.J.Lu[1], J.Radder[1], J.N.Talmadge[1], K.Zhai[1]***

[1]HSX Plasma Laboratory, Madison, USA
[3]Electrical Engineering Department, UCLA, USA
[2]Department of Applied Science, UC, Davis, USA
[4]CompX, Del Mar, USA

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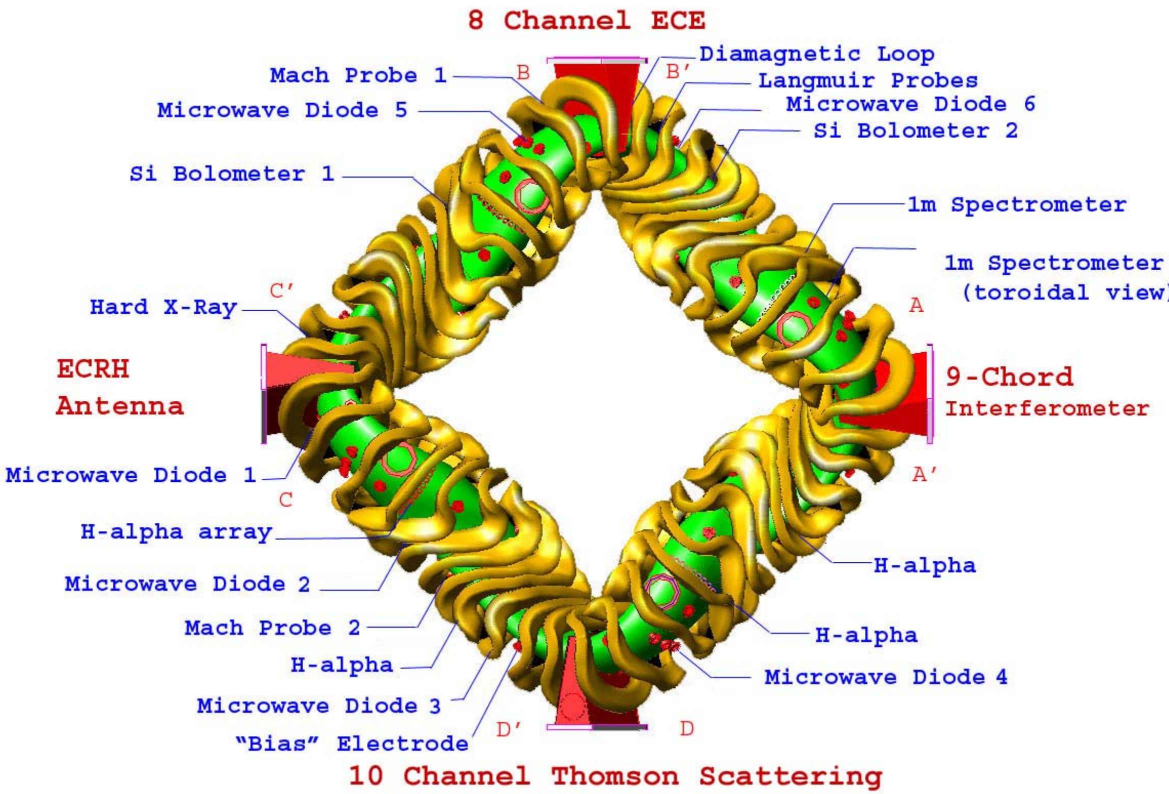
Outline

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

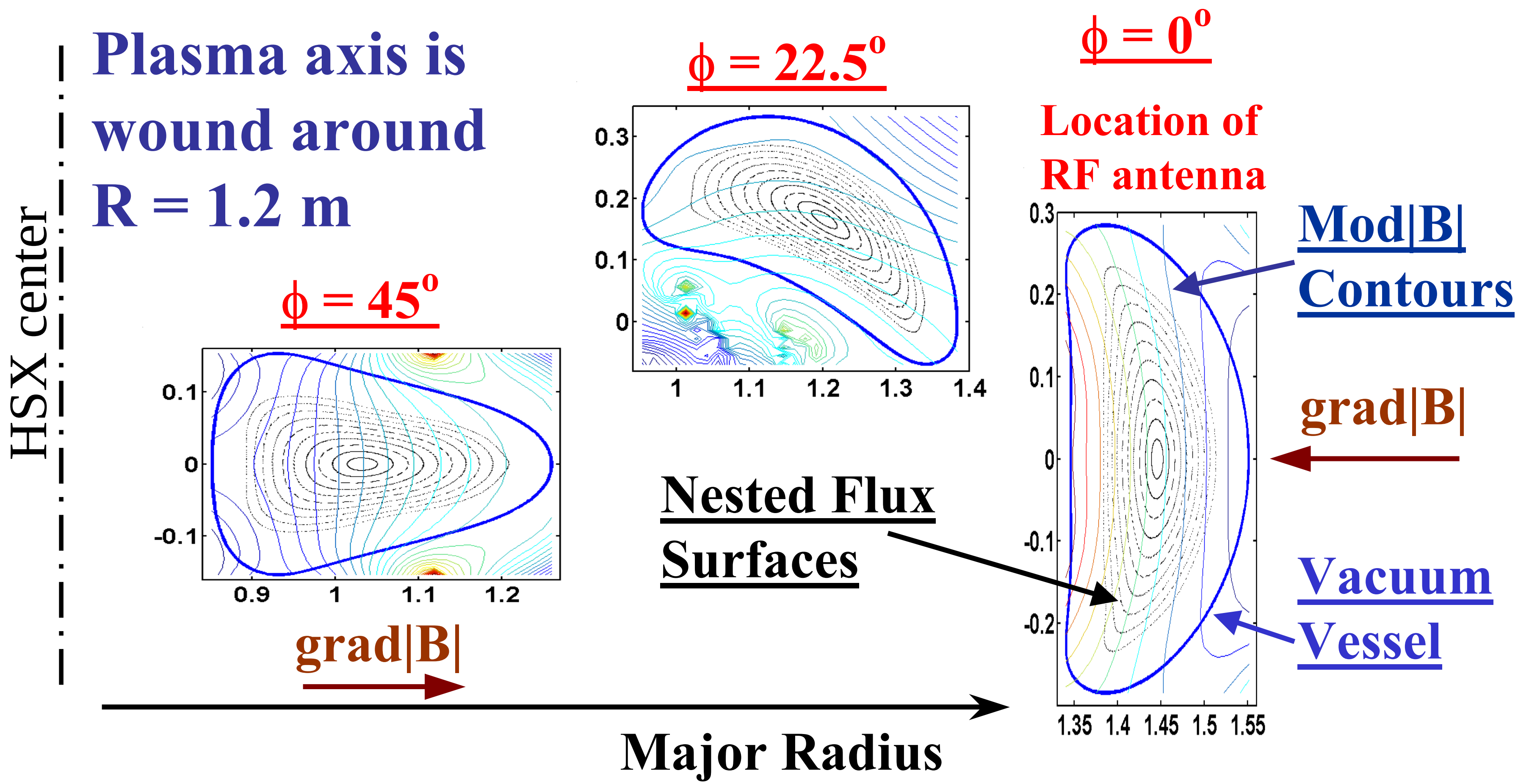
The Helically Symmetric Experiment



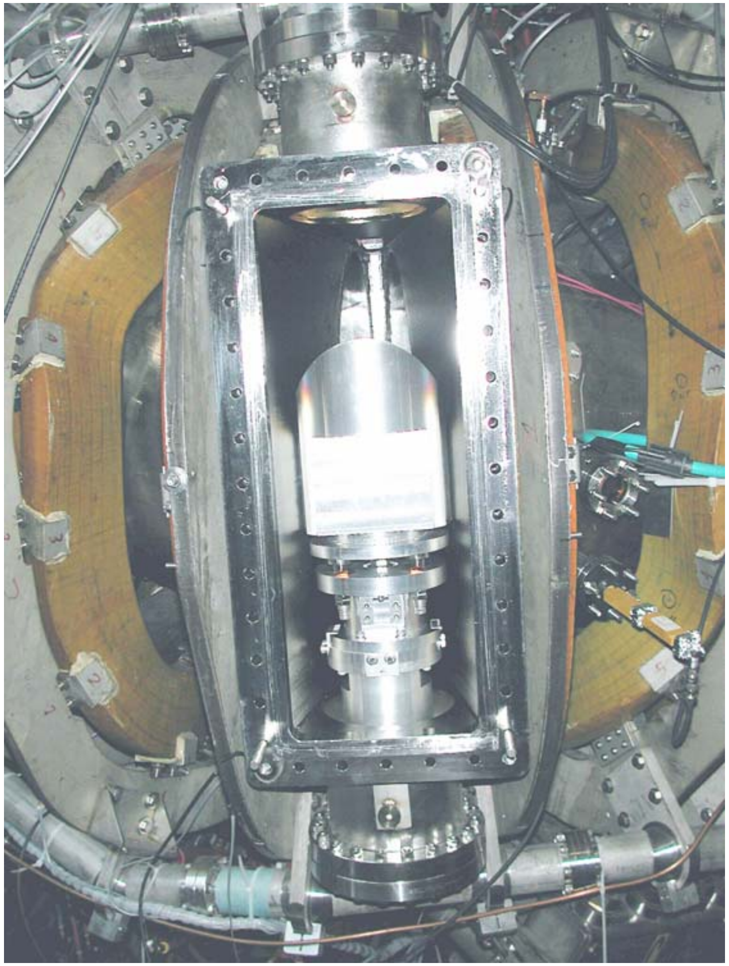
R, m	1.2
a_p, m	0.15
B_o, T	0.5
n_e, m^{-3}	$< 5 \cdot 10^{18}$
T_e, keV	≤ 0.6
F, GHz	28
P_{rf}, kW	≤ 130
τ_{rf}, msec	≤ 50

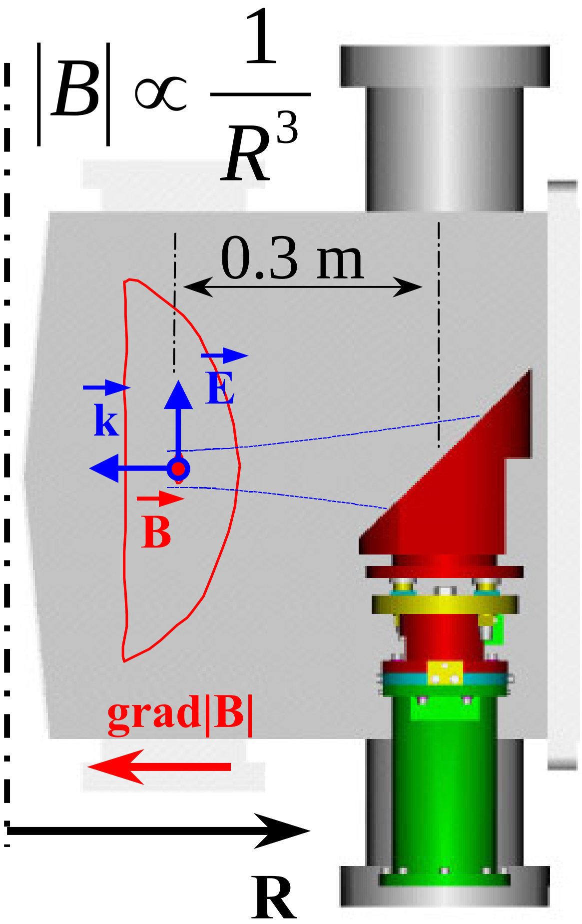
Symmetry in |B| leads to a small deviation of trapped particles orbits from a flux surface and, as a result, to improved neoclassical confinement in a low collisionality regime

HSX Cross-sections along ½ Field Period



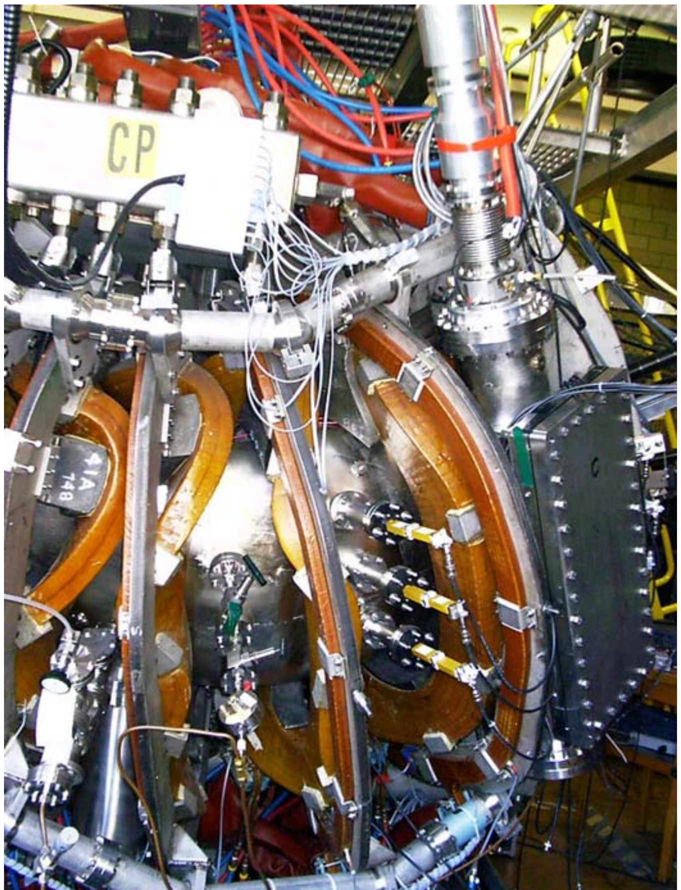
Launching Antenna

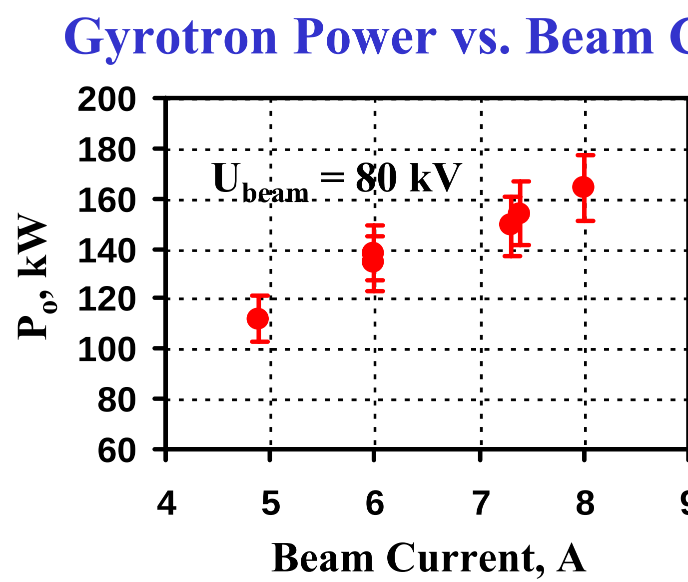




X-wave (E ⊥ B) is launched from the low magnetic field side and is focused at the plasma center with a waist of 2 cm (e^{-2} level)

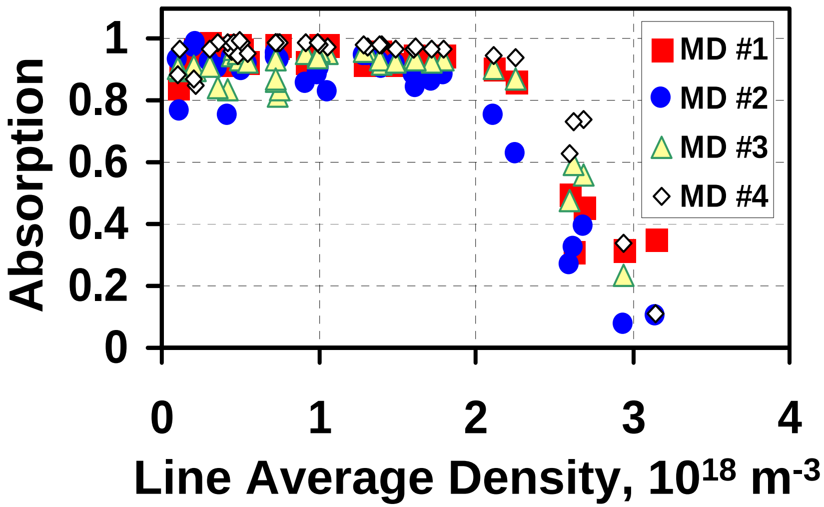
Gyrotron power on HSX window

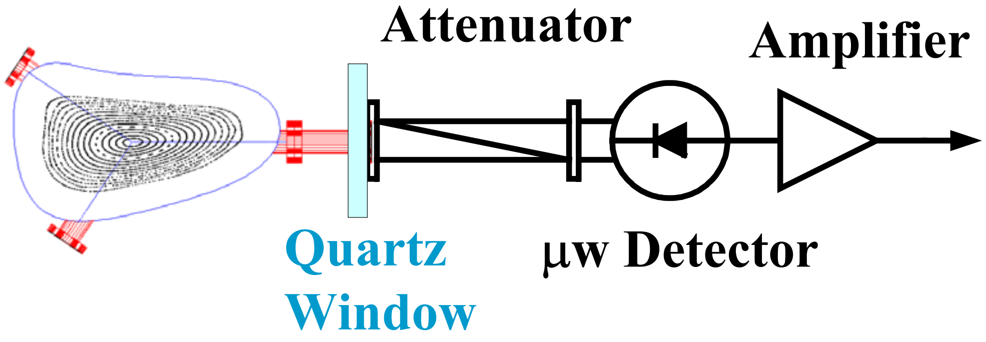


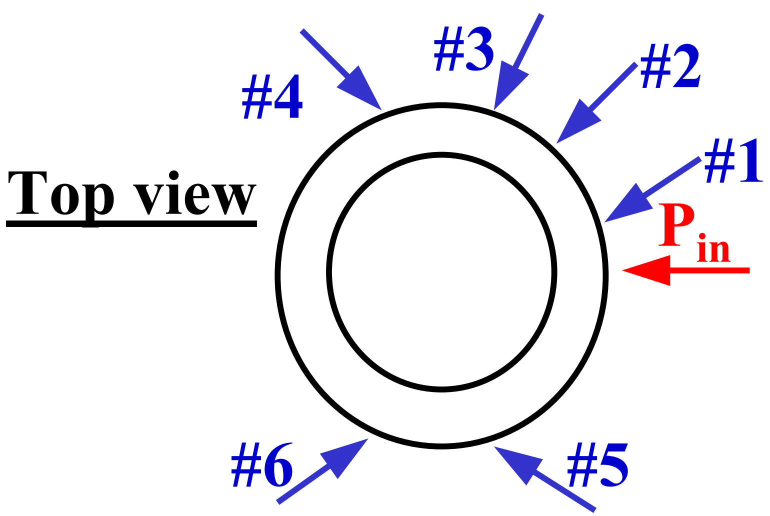


- Calorimetric measurements are made with a compact dummy load just before the barrier window
- In these measurements μ-wave diode on the wg directional coupler is calibrated as well

Absorption along the machine

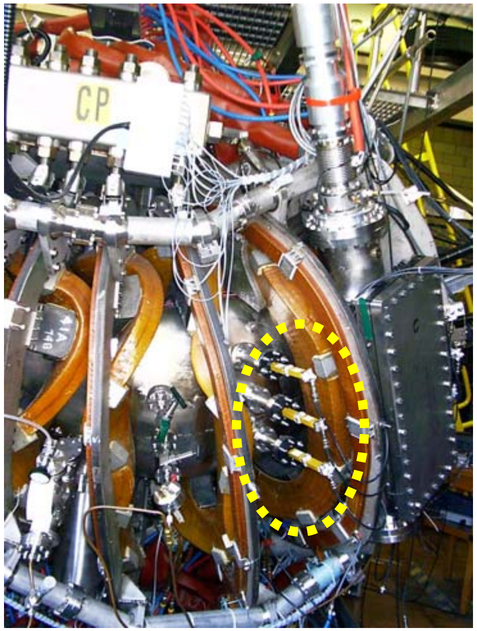


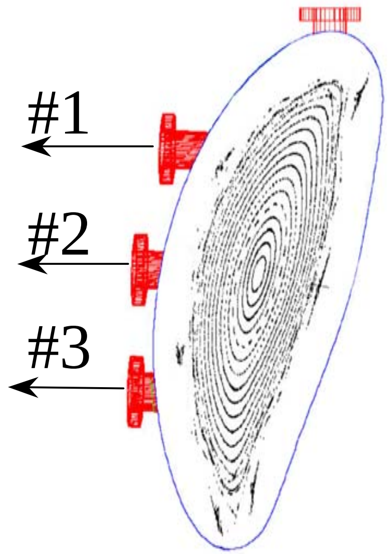


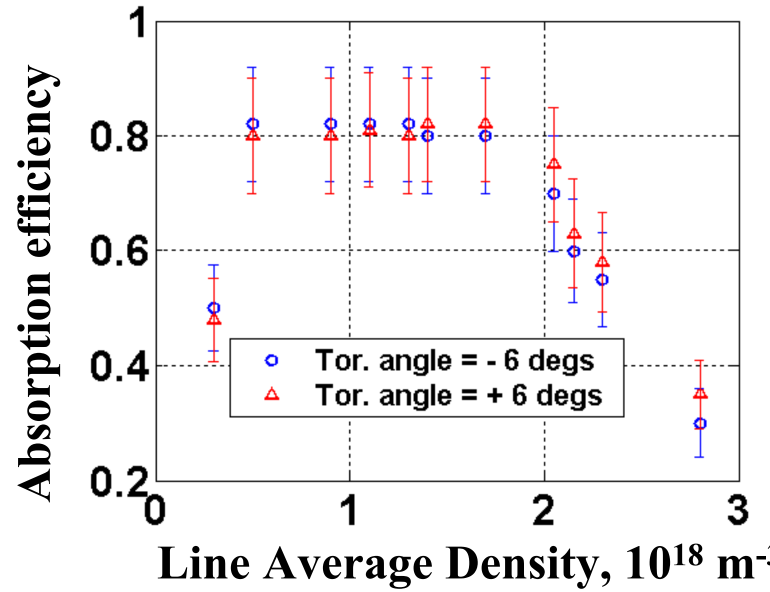


Six absolutely calibrated µ-wave detectors are installed around the HSX at 6°, 36°, ±70° and ± 100° (0.2 m, 0.9 m, 1.6 m and 2.6 m away from µ-wave power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the ECRH antenna

Absorption in vicinity of ECRH antenna



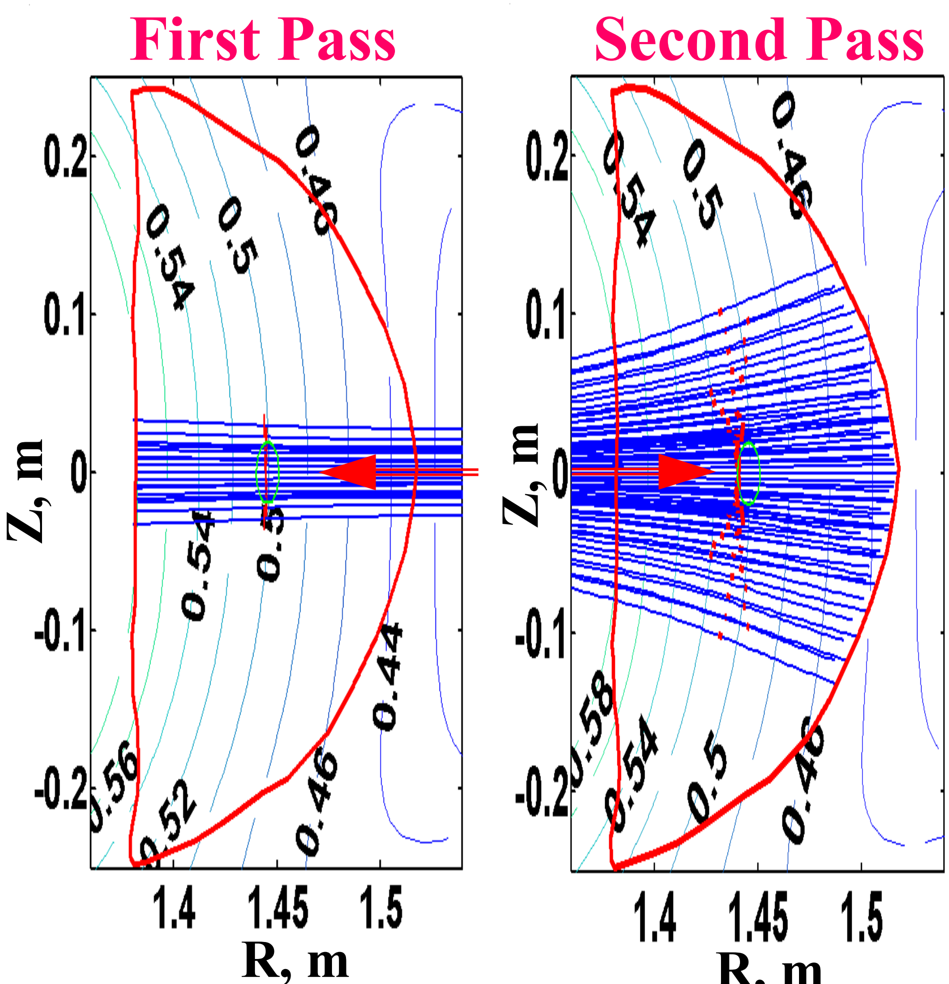




- The same μ-wave probes have been installed on the ports next to the ECRH antenna
- ECRH power is mostly absorbed in first passes through the plasma column
- Absorption is symmetric with respect to the ECRH antenna

Ray tracing calculations

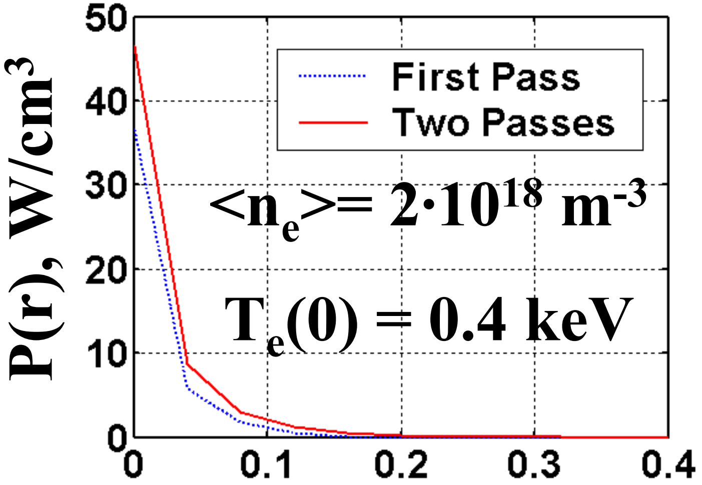
3-D Code is used to estimate absorption in HSX plasma



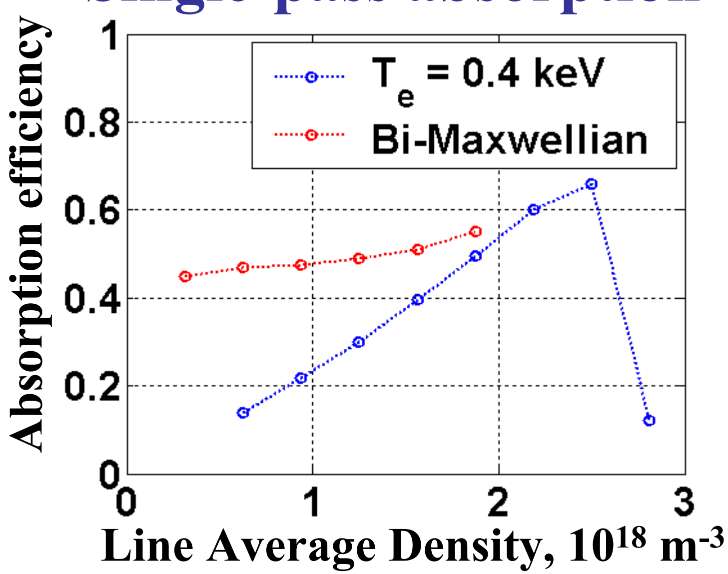
- The code runs on a parallel computer with OpenMP and MPI constructs
- The code returns an absorbed power profile and integrated efficiency
- An optical depth and ECE spectrum can be calculated as well
- Bi-Maxwellian plasma is applied if necessary

Profile and Efficiency

Absorbed Power Profile



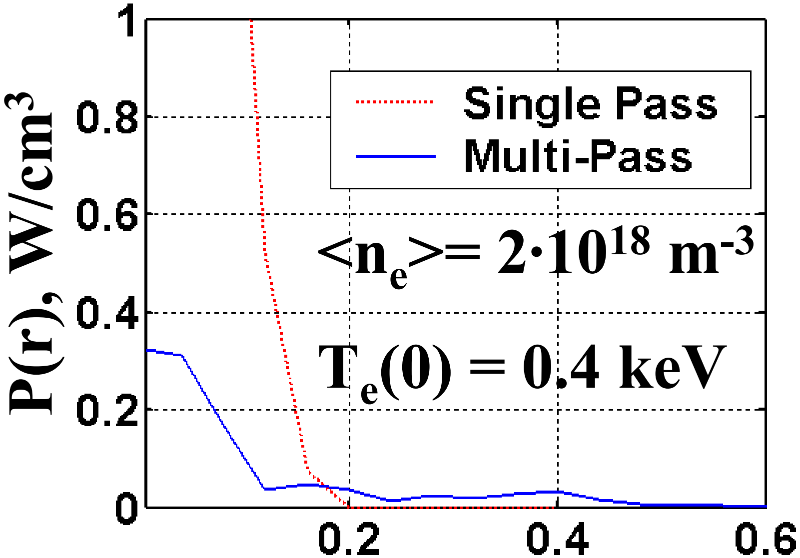
Single-pass absorption

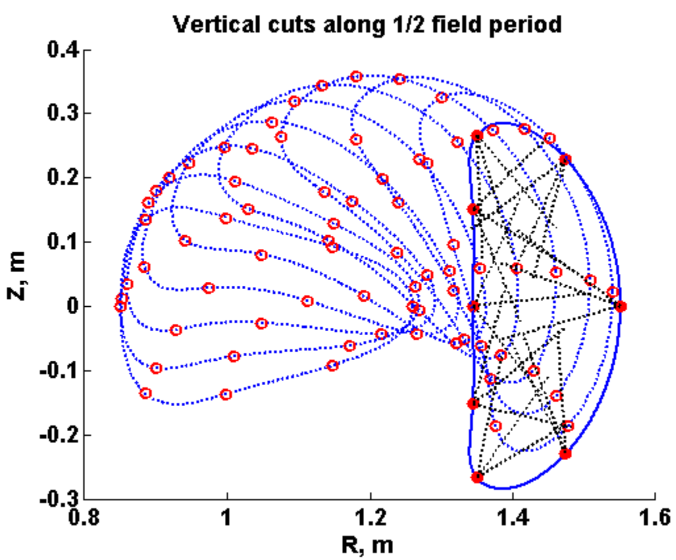


- Single-pass absorbed power profile is quite narrow ($< 0.1a_p$)
- Second Pass: Rays are reflected from the wall and back into the plasma, the absorption is up to 70% while the profile does not broaden
- Absorption versus plasma density is calculated (1) at constant T_e and (2) based on the TS, ECE 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

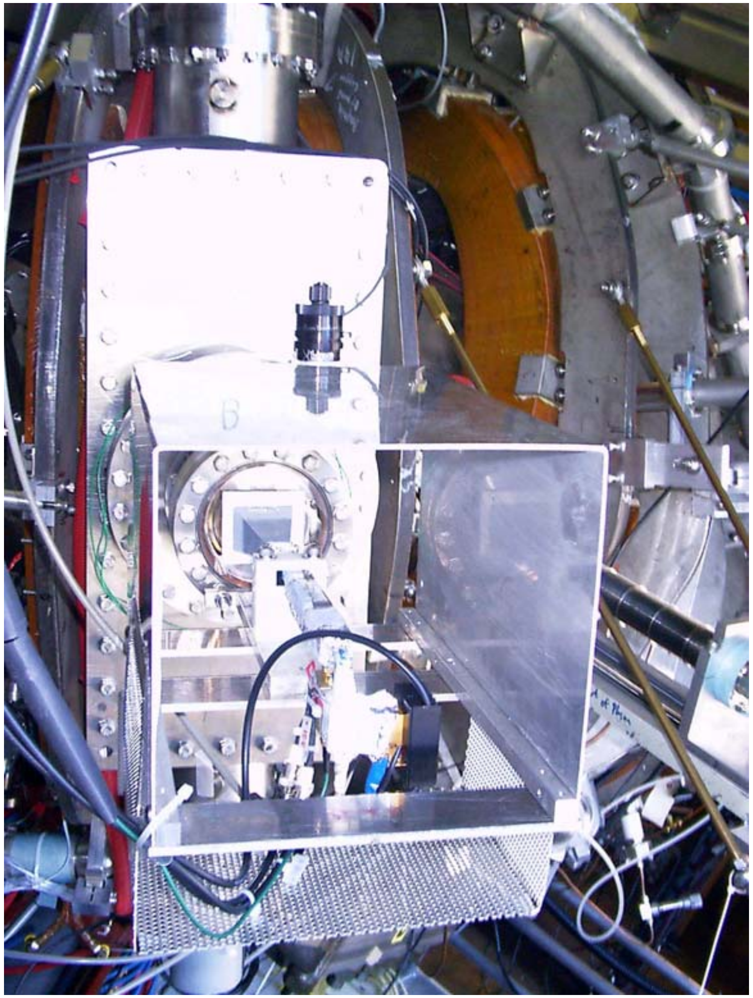
Absorbed Power Profile





- 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 $(0.5 – 2)\cdot 10^{18}$ m^{-3}
- This multi-pass absorption is low due to (1) low power density in the plasma core and (2) high ray refraction

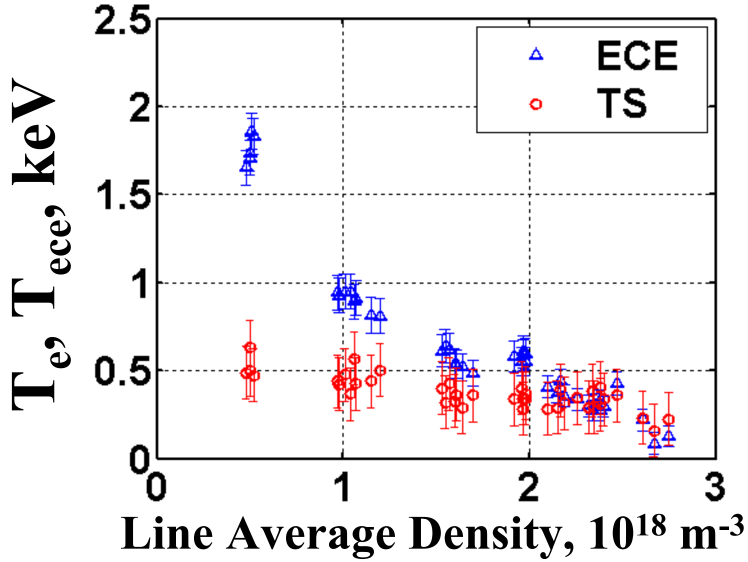
ECE Radiometer



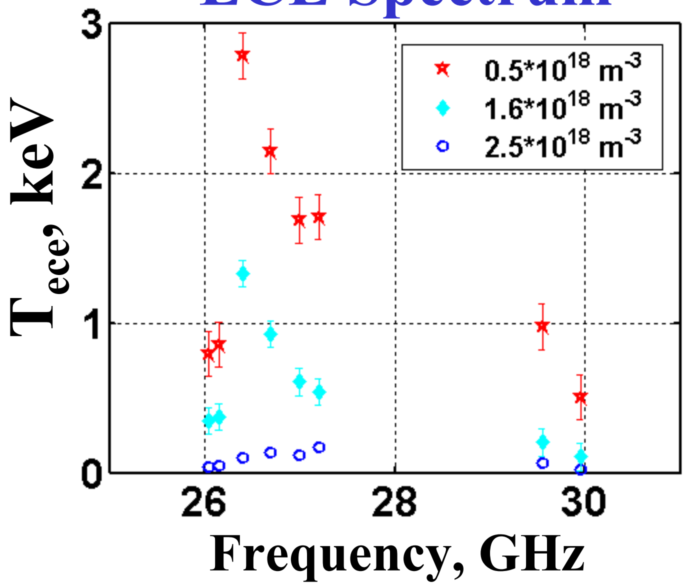
- Conventional 8 channel radiometer implemented: 6 channels receive ECE power emitted by plasma at a low magnetic field side and 2 frequency channels – at a high field side
- 60 dB BS filter is used to reject the gyrotron power at (28 ± 0.3) GHz and 40 dB fast pin diode protects the mixer from the spurious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

ECE Temperature vs. Plasma Density

ECE vs. Thomson Scattering



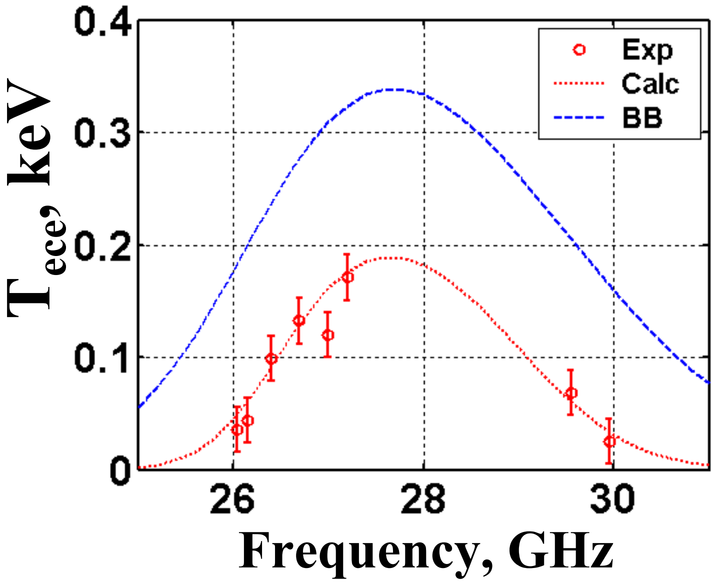
ECE Spectrum

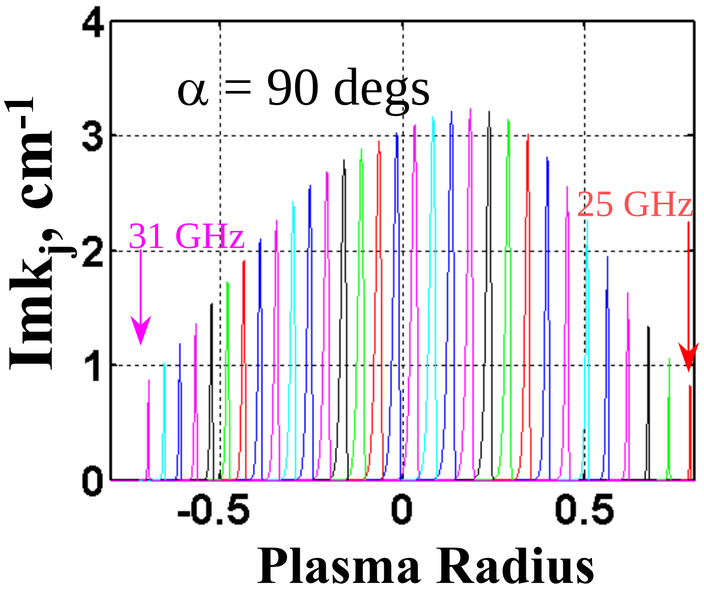


- ECE temperature drops with plasma density while the electron temperature from Thomson scattering diagnostic is almost independent of plasma density
- In plasma density scan the non-thermal feature at a low magnetic field side increases first and then the high frequency emission gets risen

ECE at high plasma density

$<n_e> = 2.5 \cdot 10^{18}\ m^{-3}$



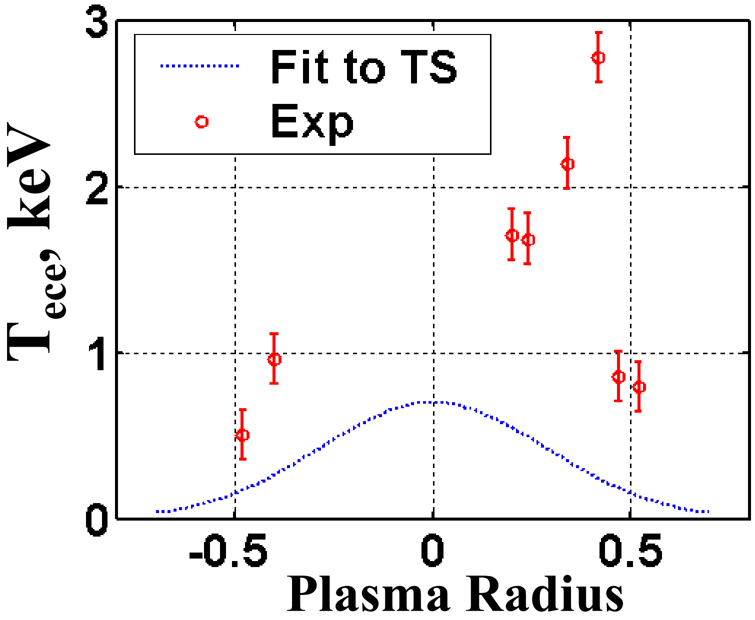


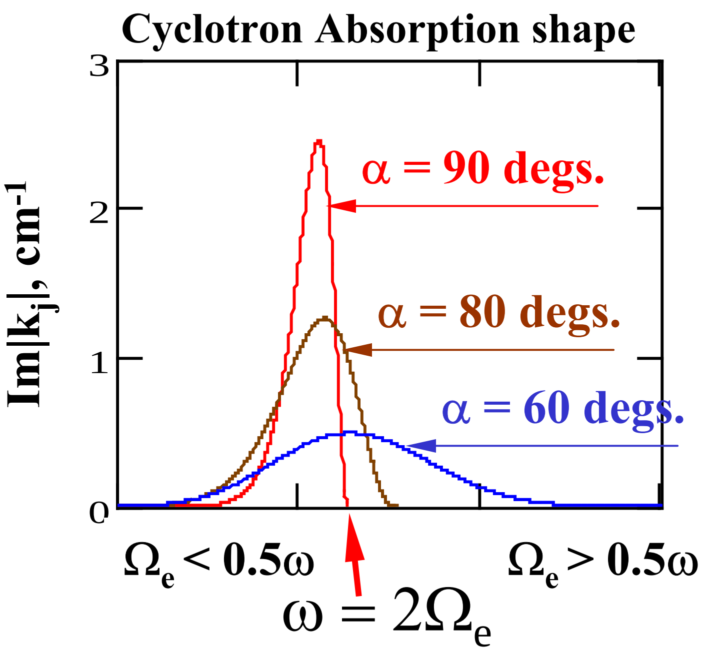
- Emission at the high plasma density is thermal
- HSX plasma is not a black body: an optical depth should be taken into account to estimate the electron temperature:

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

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

ECE at low plasma density

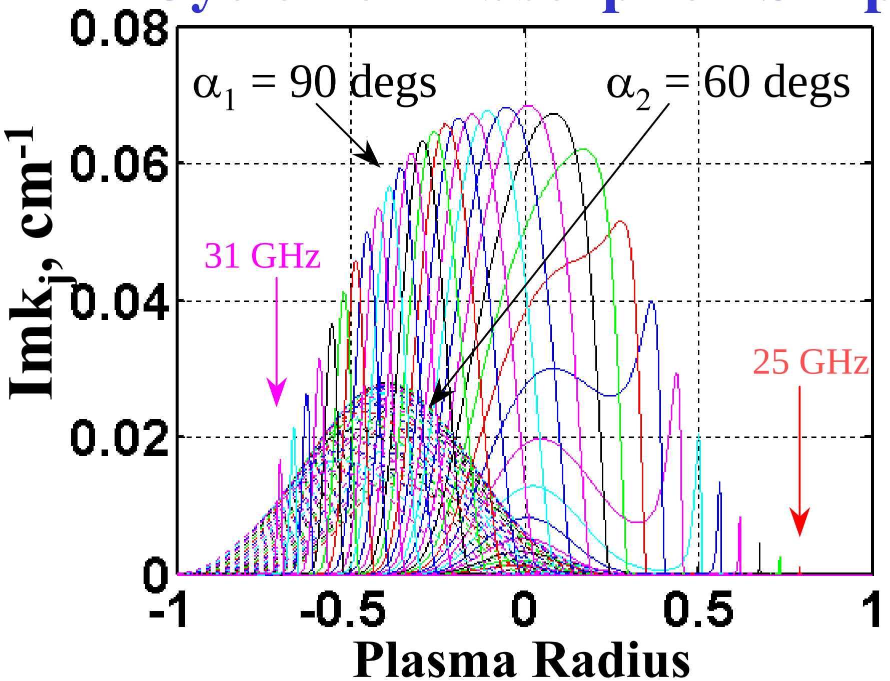




- ECE signal is high at both low and high field sides
- High signal from outboard side is due to emission from central resonance region where a population of supra-thermal particles is supposed to be high at a central heating
- Oblique emission from central regions can contribute to the signal detected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

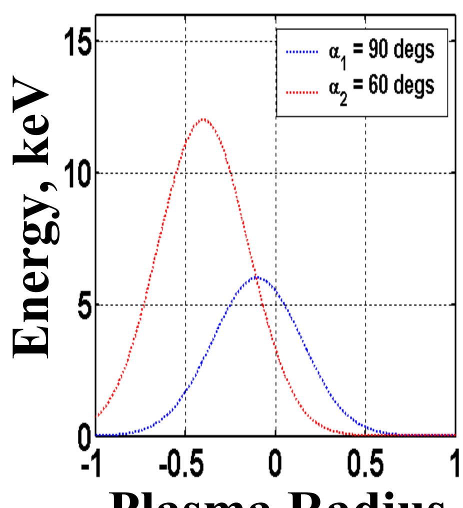
Perpendicular and Oblique sight view

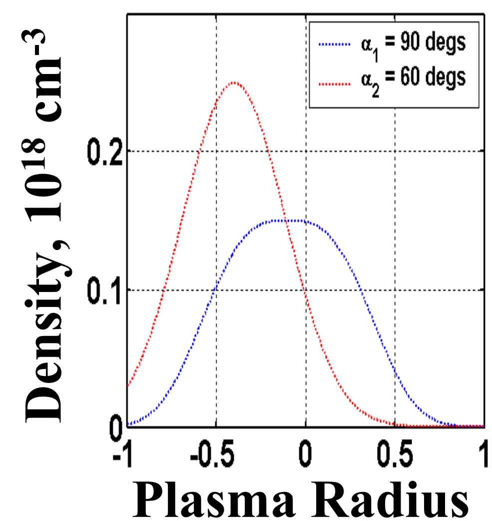
Cyclotron Absorption Shape



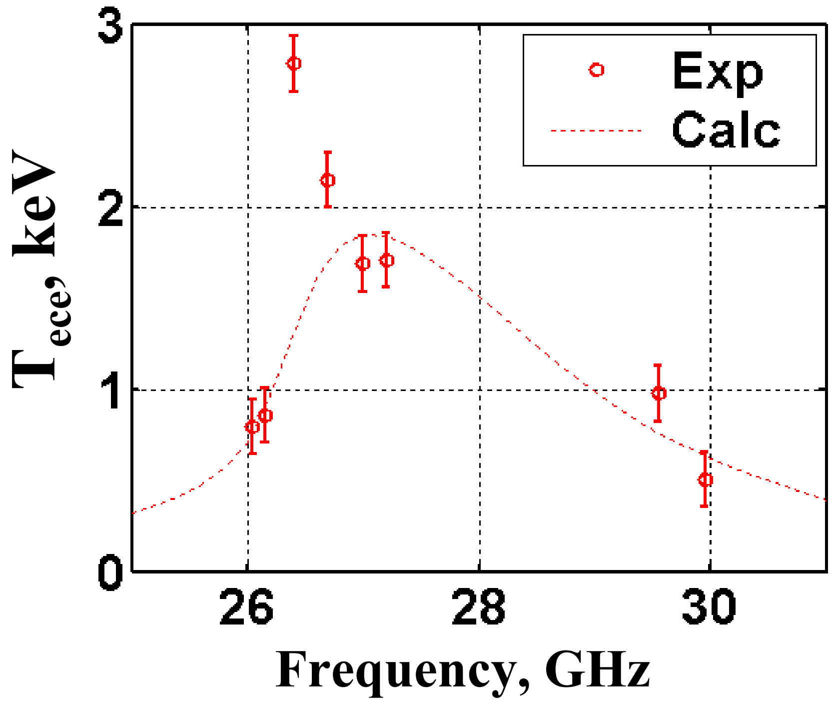
Solid lines represent the local absorption at perpendicular propagation and dash lines – at oblique propagation

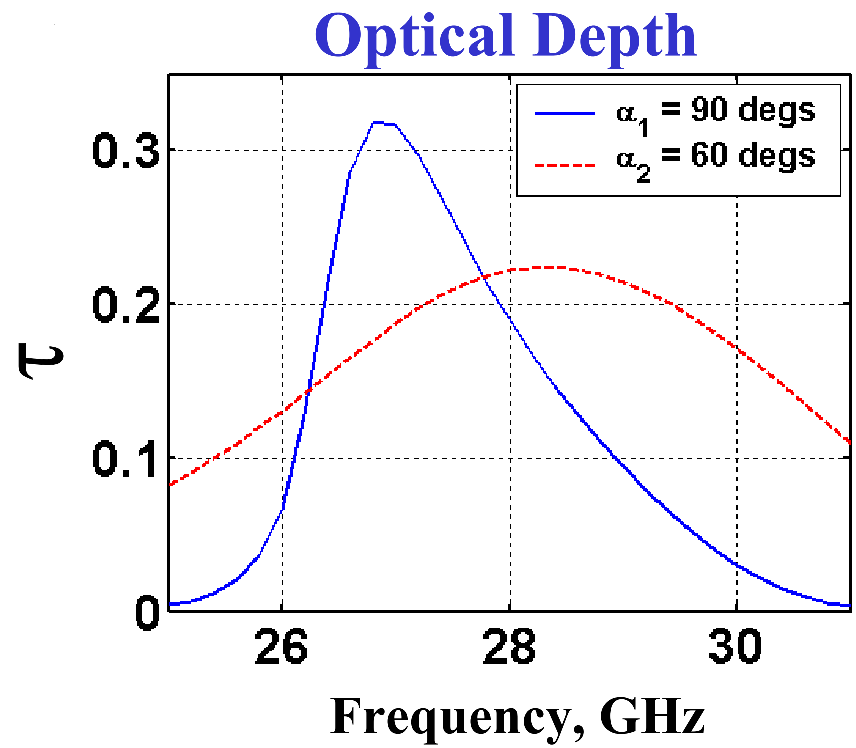
- Two propagation angles are chosen. Along each direction we assume "Maxwellian tail" with different T_e and n_e
- The following profiles are assumed for tail electrons:





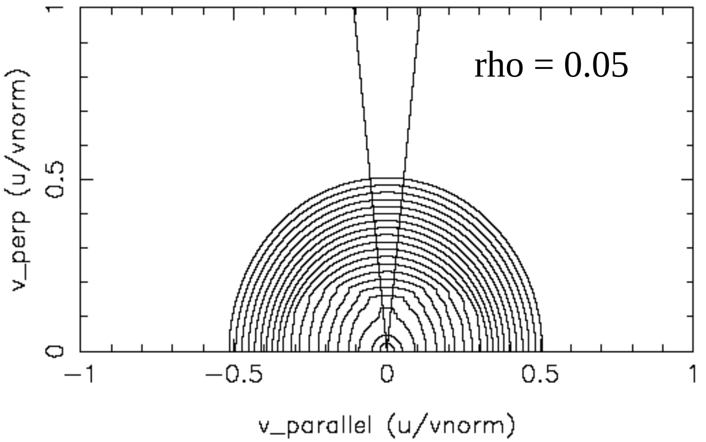
ECE Spectrum at $0.5 \cdot 10^{18}$ m^{-3}



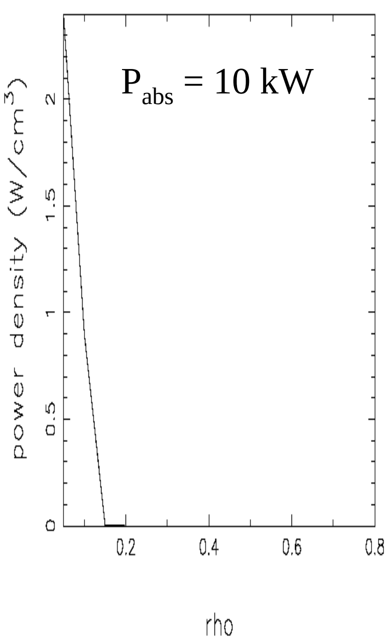


- ECE temperature is defined as $T_{ece} = T_1 \cdot (1 - e^{-\tau_1}) + T_2 \cdot (1 - e^{-\tau_2})$
- This estimate shows that about 30% of electron density belongs to the tail with T_{1max} = 6 keV and T_{2max} = 12 keV, $n_{1max} = 0.15 \cdot 10^{18}$ m^{-3} and $n_{2max} = 0.25 \cdot 10^{18}$ m^{-3}

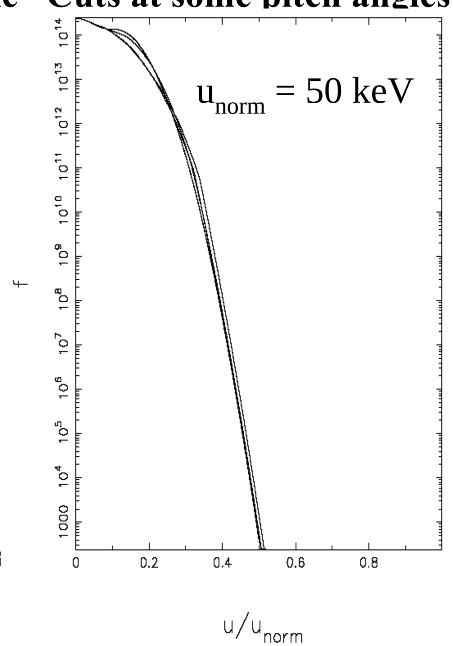
CQL3D code for HSX



Absorbed Power Profile



Cuts at some pitch angles



- **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**
- **First runs of CQL3D have been made for HSX plasma at $3 \cdot 10^{18}$ 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