ECH and ECE on HSX Stellarator

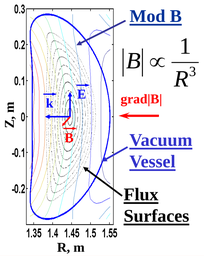
K.M.Likin, A.F.Almagri, D.T.Anderson, F.S.B.Anderson, C.Deng[1], C.W.Domier[2], R.W.Harvey[3], H.J.Lu, J.Radder, J.N.Talmadge, K.Zhai

HSX Plasma Laboratory, University of Wisconsin, Madison, WI, USA; [1]UCLA, CA, USA; [2]UC, Davis, CA, USA; [3]CompX, Del Mar, CA, USA

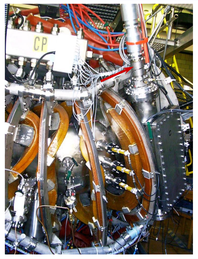
1. Plasma Geometry and Launched Power

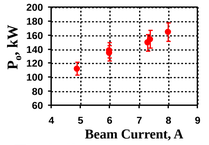
1.1 HSX Vertical Cut

- X-wave (E ⊥ B) 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) which results in small wave refraction



1.2 Gyrotron Power on HSX window



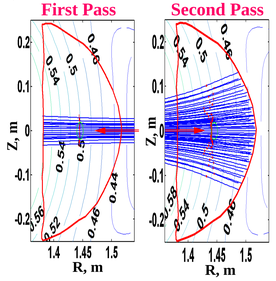


- The bellows are replaced by a compact dummy load
- μ-wave diode on the wg directional coupler is calibrated as well

2. Ray Tracing Calculations

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

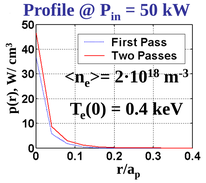
2.1 Ray Trajectories

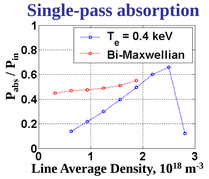


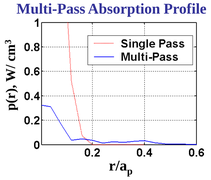
- The code runs on a parallel computer with OpenMP and MPI constructs
- The code returns an absorbed power profile and integrated efficiency

➢ An optical depth and ECE spectrum can be calculated as well

2.2 Efficiency & Power Profile

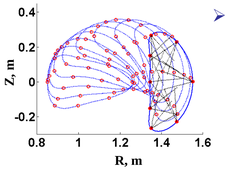






- Single-pass absorbed power profile is quite narrow (< 0.1a_p)
- Second Pass: Rays are reflected from the wall and back into the plasma, the absorption is up to 70% while the profile does not broaden
- Absorption versus plasma density is calculated at constant T_e and also based on the TS, ECE and diamagnetic loop data in bi-Maxwellian plasma
- Owing to a high non-thermal electron population the absorption can be very high at a low plasma density
- Multi-pass absorption adds (4 – 7)% to the total efficiency

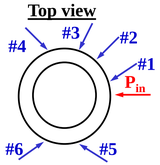
2.3 Model for Multi-Pass Absorption



- 240 rays are launched into the plasma from 80 points distributed uniformly across and along the machine at random angles

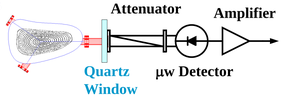
3. Multi-Pass Absorption

3.1 Experimental Lay-out

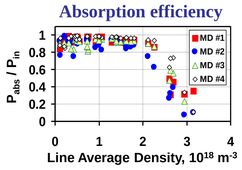


Six absolutely calibrated μ-wave detectors are installed around the HSX at 6°, 36°, ±70° and ± 100° (0.2 m, 0.9 m, 1.6 m and 2.6 m away from μ-wave power launch port, respectively). #3 and #5, #4 and #6 are located symmetrically to the ECRH antenna

Each antenna is an open ended waveguide followed by attenuator



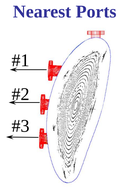
3.2 Results of Measurements

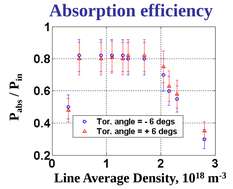


- Power is absorbed into the plasma with a high efficiency in a wide range of plasma densities
- At low plasma density the efficiency remains high due to absorption on supra-thermal electrons

3.3 Absorption around ECRH Antenna

The same μ-wave probes have been installed on the ports next to the ECRH antenna





- Launched power is mostly absorbed in first passes through the plasma column
- Absorption is symmetric with respect to the ECRH antenna

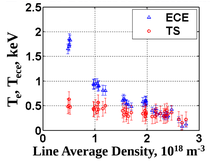
4. ECE Diagnostic Results

4.1 Description of Radiometer

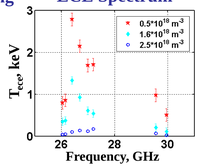
- Conventional 8 channel radiometer implemented: 6 channels receive ECE power emitted by plasma at the low magnetic field side and 2 frequency channels – at the high field side
- 60 dB band-stop filter is used to reject the gyrotron power at (28 ± 0.3) GHz
- Low-pass filter (insertion loss > 40 dB) cuts the gyrotron second harmonic
- Fast pin switch protects the mixer diode from the spurious modes on the leading edge of gyrotron pulse

4.2 ECE vs. Plasma Density

ECE & Thomson Scattering

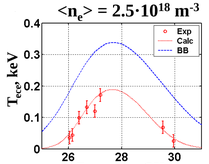


ECE Spectrum

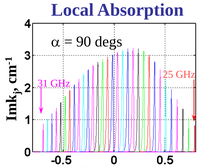


- ECE temperature drops with plasma density while the electron temperature from Thomson scattering diagnostic is almost independent of plasma density
- In a density scan the non-thermal feature from the low magnetic field side increases first and then the high frequency emission starts increasing

4.3 High Plasma Density

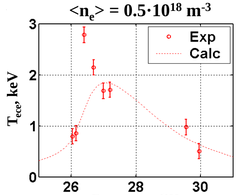


Local Absorption

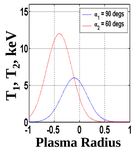


- Emission at high plasma density is thermal
- Optical depth should be taken into account to estimate the electron temperature: $T_{ece} = T_e \cdot (1 - e^{-\tau})$
- Thomson scattering and interferometer data are used to calculate the optical depth

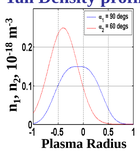
4.4 Low Plasma Density



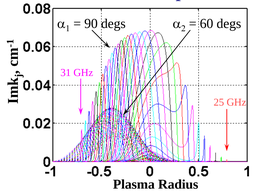
Tail T_e profiles



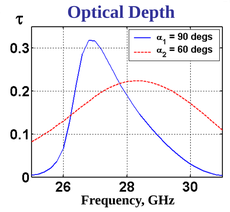
Tail Density profiles



Local Absorption



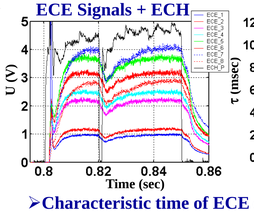
Optical Depth



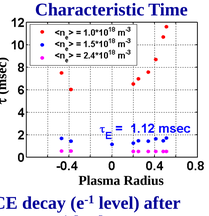
- Two propagation angles are chosen. Along each direction we assume "Maxwellian tail" with different T_e and n_e
- ECE temperature is defined as $T_{ece} = T_1 \cdot (1 - e^{-\tau_1}) + T_2 \cdot (1 - e^{-\tau_2})$

4.5 ECE Decay Time

ECE Signals + ECH



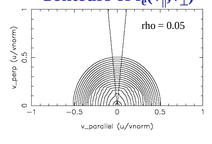
Characteristic Time



- Characteristic time of ECE decay (e^{-1} level) after the gyrotron turn-off decreases with plasma density --- at $1 \cdot 10^{18}$ m^{-3} the decay is slower than energy confinement time from the diamagnetic loop ($\tau_E \approx 1$ msec) and faster at $2.4 \cdot 10^{18}$ m^{-3}

5. CQL3D code

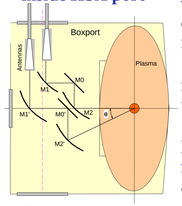
Contours of $f_e(v_{||}, v_\perp)$



- QHS configuration in HSX has a helical axis of symmetry and its mod-B is tokamak-like
- CQL3D code 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. In the plasma core a distortion of distribution function occurs in the energy range of (5 – 15) keV

6. ECE Imaging

Antenna Lay-out inside HSX port



- Temperature fluctuations with a level higher than 4% can be detected by the actual radiometer
- Smaller fluctuations can be measured with a correlation technique
- New system is supposed to have two sightlines with 8 frequency channels each with a spatial resolution about 3 cm
- Estimated fluctuation level which the new system will be capable to resolve is 0.6%

Summary

- Measured multi-pass absorption efficiency in HSX plasma stays high in a wide range of plasma densities
- ECE measurements show a presence of supra-thermal electrons in HSX plasmas at a density up to $2.2 \cdot 10^{18}$ m^{-3}
- Bi-Maxwellian plasma model partly explains the high absorption and enhanced electron emission
- CQL3D code predicts 5 – 15 keV electrons in the HSX plasma core at 100 kW

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