ECE and Reflectometry on the Helically Symmetric Experiment

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For plasma heating in the Helically Symmetric Experiment (HSX) with on-axis magnetic field of 0.5 Tesla, the extraordinary wave at the second harmonic is used, while the ordinary wave at the fundamental resonance is efficient in operation at 1 Tesla. A non-Maxwellian distribution function is detected in HSX plasmas by various diagnostics. The electron cyclotron emission (ECE) spectra are measured with an eight channel radiometer. By switching the narrow band filters, measurements have been made across the plasma column within +/- 0.6 of its effective radius. To model the ECE spectra we use (1) a Bi-Maxwellian distribution function and (2) results from the CQL3D Fokker-Planck code. Results of measurements and modeling are reported in this paper. Plasma fluctuations can be responsible for enhanced heat transport from the plasma. Fourier spectra of ECE signals, as well those from the nine-chord interferometer, Langmuir probes, and magnetic coils show the presence of a coherent mode in the plasma core. To study the density fluctuations, a new reflectometer has been installed and tested on HSX. We present ECE data and the first reflectometer results on density fluctuations in 0.5 Tesla HSX plasmas. As do the other diagnostics, the reflectometer detects the coherent mode in the 50 – 250 kHz frequency range of plasma fluctuations. A wavelet technique is applied to get the time evolution and the radial localization of this mode.

Keywords: Stellarator, plasma heating, electron distribution function, electron cyclotron emission, plasma density fluctuations, reflectometer, wavelet analysis.

1. Inroduction

In plasma heating experiments on fusion machines the particles may have a non-thermal distribution function in momentum space, i.e. there are more particles with high energy as compared to the thermal equilibrium state. Even a small number of high energy particles leads to enhanced emission at the cyclotron harmonics and makes a comparison between experiment and theory, which deals with Maxwellian plasmas, more difficult. Moreover the presence of a non-thermal component obscures a bulk plasma response on small perturbations, such as cold gas injection and/or heating pulse modulation, and as a result in such cases the perturbation method is impractical for measuring the electron thermal conductivity of bulk plasma from ECE signals. Also an excessive number of runaway particles may absorb a significant part of the heating power resulting in uncertainty in determining the power absorbed by the thermal particles based on ECE and/or the diamagnetic loop data.

On the HSX stellarator we use the extraordinary wave at the second harmonic to make plasmas at 0.5 T. HSX also operates at the full designed magnetic field of 1 Tesla, in this case the wave polarization corresponds to the ordinary wave. Available launched power is up to 100 kW and is focused on the plasma axis into a beam spot of 4 cm in diameter. Based on ray tracing calculations [1] the absorbed power density in the HSX plasma is high enough (up to 5 W/cm^3) to produce a tail of high energy electrons, in particularly, in 0.5 T operation when the plasma density is low. For instance, an electron can get up to 10 keV in one pass through the beam at such power density. To make a correct interpretation of measured ECE spectra, we solve the radiative transport equation (1) in bi-Maxwellian plasma [2,3] and (2) with the electron distribution function from the Fokker-Planck code [4].

The ECE radiometer can measure plasma density fluctuations if the plasma isn't simply a black body. It is our case for the plasma parameters at 0.5 T. The calculated optical depth is less than 1. We have found a coherent mode in the frequency spectrum of ECE signals in QHS plasmas. The mode was first detected by the interferometer [5] and then by a set of Mirnov coils. We have estimated the relative amplitude of this mode based on ECE fluctuations.

Recently we installed the reflectometer on HSX. The reflectometer can operate with an extraordinary polarized probing beam in 0.5 T operation and/or the ordinary wave at 1 T. The frequency of the probing beam can (1) be fixed during the plasma discharge and/or (2) be swept to measure a radial profile of fluctuations. We intensively use the wavelet analysis on reflectometer data and make a comparison with Fourier spectra from the Mirnov coils. The wavelet method allows us to see the fast time change

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(on scale of tens of microseconds) in the plasma fluctuation spectrum. Numerical modeling helps us to estimate the amplitude of measured fluctuations.

The standard magnetic configuration in our stellarator is quasi-helical symmetric (QHS) when the symmetric spectral component dominates along the field line. In the configuration with broken symmetry the mirror term is added to the magnetic field spectrum and we name this configuration Mirror. The gross magnetic properties are the same in both configurations but they differ in amplitude of magnetic field ripples (QHS has less ε_{eff} at $r/a_p = 2/3$ by an order of magnitude). In this paper we present the results. obtained at 0.5 T with 50 kW of launched power at (1.4 - 1.6)$\cdot 10^{12}$ cm^{-3} of the line averaged plasma density (Fig. 1).

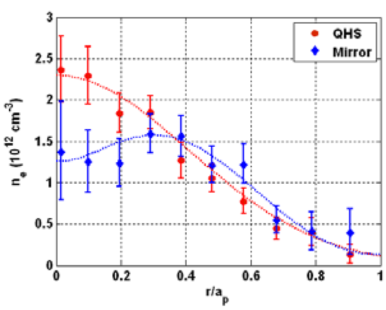

Fig.1 Plasma density profile in QHS and 10% Mirror

2. ECE Measurements and Modeling

The HSX radiometer has eight narrow band filters. By switching the filters we can get the ECE spectrum over the entire plasma. In this paper we report the results obtained with two sets of intermediate frequency (IF) filters. One set allows us to measure the emission from the high magnetic field (HF) side while the other one from the low magnetic field (LF). As we use the extraordinary wave at the second harmonic for heating and ECE measurements the emission cannot be detected from the heating resonance layer. At the plasma periphery the plasma optical depth is too low ($\tau <$ 0.1) to get a decent emission. Thus, we configure the ECE channels between 0.2 and 0.7 of the effective plasma radius.

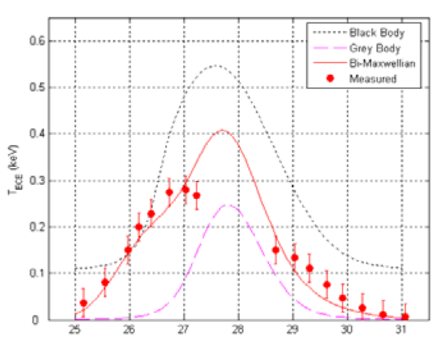

Fig.2 Measured ECE spectrum and the fit based on Bi-Maxwellian plasma model

The ECE radiometer has been calibrated against the Thomson scattering (TS) in plasmas with off-axis heating when the plasma stored energy measured by the diamagnetic loop and integrated from TS profiles is in agreement. For the HF set of IF filters the resonance is shifted outboard at $r=+0.3\cdot a_p$ and for the LF set we use inboard resonance at $r=-0.2\cdot a_p$, in both cases the TS profiles are identical. Then we took data in on-axis resonance with the two sets of filters. The measured ECE spectrum is shown in Fig. 2. It is clearly seen that the spectrum is non-symmetric (28 GHz corresponds to the plasma axis) due to the presence of supra-thermal electrons.

To find the population and the temperature of the high energy electrons the Bi-Maxwellian plasma model is applied. We use TS profiles ($T_e(0)$ = 0.6 keV, $n_e(0)$ = $2.6\cdot 10^{12}$ cm^{-3}) to calculate the optical depth of the bulk plasma. The results of modeling are shown in Fig. 2. The higher emission at the HF side compared to the level of

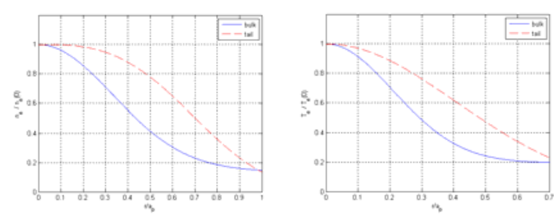

Fig.3 Normalized N_e and T_e profiles for bulk and tail plasmas

grey plasma is mostly due to the broad population of supra-thermal electrons, and the tail temperature is responsible for enhanced signals at the LF side (Fig. 3). The best fit to the measured spectrum is for T_{tail} = 4.5 keV, n_{tail} = $0.6\cdot 10^{11}$ cm^{-3}. The calculations made with the CQL3D Fokker-Planck code support the simple Bi-Maxwellian model (Figs. 4,5). In Fig. 5 the results at 1 T are also shown. At 50 kW of launched power the plasma stays thermal at a high density ($> 6\cdot 10^{12}$ cm^{-3}). The central

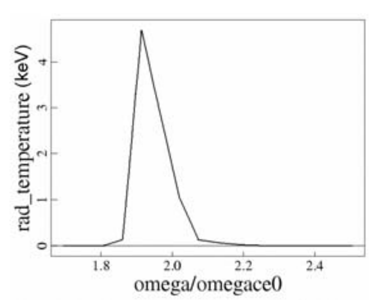

Fig.4 Black body spectrum from CQL3D code

electron temperature is 1.2 keV at 50 kW and 2 keV at 100 kW corresponding to the experimental data.

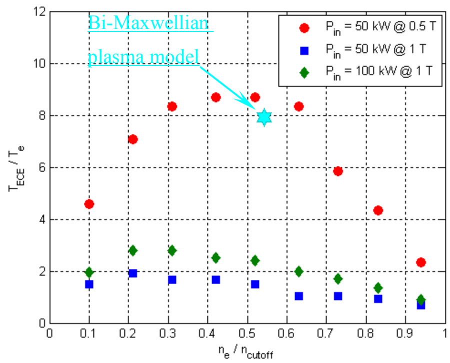

Fig.5 Normalized T_{ECE} calculated by CQL3D

In the QHS configuration the ECE radiometer is able to detect the coherent plasma density fluctuations in the narrow frequency band (38 - 44 kHz). The amplitude of the mode is defined as follows.

$$rms \equiv \sqrt{\int_{\Delta f} pdf} \Big/ A_{DC} \qquad (1)$$

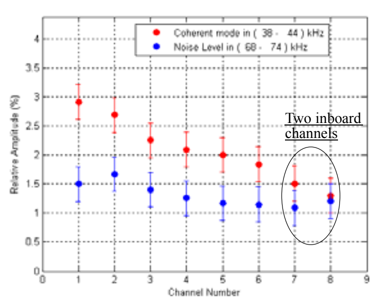

Fig.6 Amplitude of plasma density fluctuations measured by ECE radiometer

The channels (1 – 6) correspond to the LF side and channels 7 and 8 are on the HF side. For the thermal plasma channel #1 receives emission at r = 0.2·a_p, channel #6 – at r = 0.6·a_p, #7 and #8 – at -0.5·a_p and -0.6·a_p, respectively (Fig.6). The mode is well pronounced in the plasma core (r < 0.7·a_p) in the QHS configuration. According to Dr. C.Deng, the mode is driven by high energy electrons. The frequency of the mode is equal to the precision frequency of trapped particles circulating around the machine.

3. Reflectometer on HSX

Reflectometry is a well known method for measuring the plasma density [6]. We use a heterodyne detection with double frequency conversion so that the output signal frequency band is broad enough to detect plasma density fluctuations up to 10 MHz. To get reflections from low and high density plasmas two overlapping microwave sources are used. A fast pin switch (switch time ~ 10 nsec) is used to connect the appropriate source to the output channel. An extraordinary wave is used in 0.5 T operation. The polarization can be easily changed for 1 T plasmas by rotating the horn antenna. The probing beam is focused inside the vacuum vessel into a small spot (~ 10 cm in diameter). To protect the sources and the mixer diodes narrow band-stop filters at 28 GHz are used.

In this paper we present the first results on plasma density fluctuations measured with the new reflectometer on HSX. The frequency spectra are measured in QHS and Mirror configurations. In Fig. 7 the spectra at fixed probing beam frequency (f_o = 19 GHz), which corresponds to the plasma density gradient region, are shown. The Mirror spectrum is much broader than the QHS one. To estimate

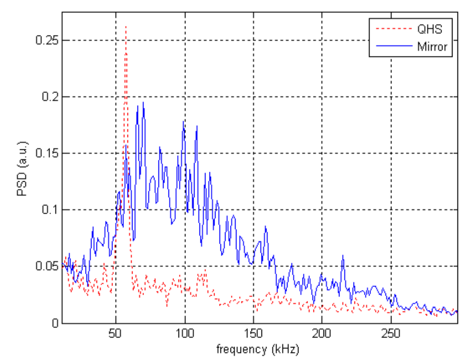

Fig.7 FFT of the reflectometer signals in QHS and 10% Mirror

the amplitude of fluctuations we need to apply 2-D modeling for the wave propagation in the HSX plasma.

In the QHS configuration the reflectometer detects the coherent mode as well. The frequency of the probing beam can be swept. We use a step function for a single sweep in order to localize the mode. The single sweep (Fig. 8) is chosen to be 10 msec so that there are up to 5 full sweeps in the 50 msec plasma discharge. The X-wave

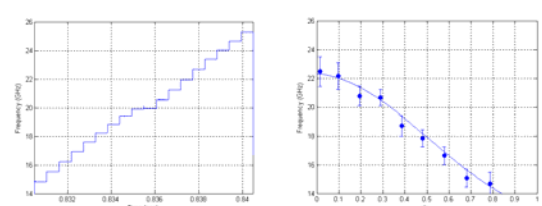

Fig.8 Probing beam frequency sweep and X-wave cut-off frequency in HSX plasma

cut-off frequency is calculated based on TS profile (see Fig.1) and Biot-Savart code (Fig. 8). We use wavelet analysis to get good temporal resolution. The Mironov coil is monitoring the presence of the mode in the time window of this full sweep. Based on time evolution of the wavelet

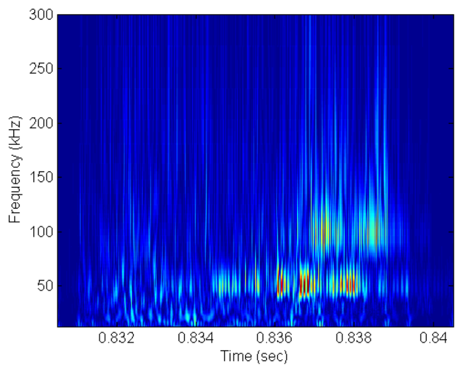

Fig.9 Wavelet coefficients in QHS (one full sweep of the reflectometer)

coefficients (Fig. 9) and the calculated cut-off frequency we easily see that the mode is localized within the plasma core ($r < 0.4 \cdot a_p$).

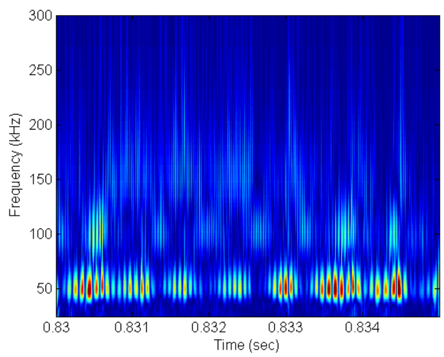

Fig.10 Time evolution of the coherent mode (5 msec time window)

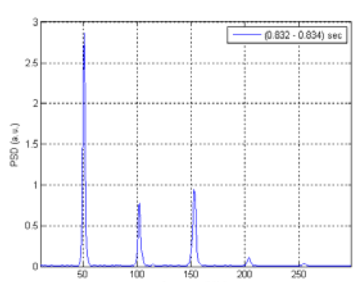

Fig.11 FFT of reflectometer signal in time interval of (0.832 – 0.834) sec

We looked at the evolution of the mode in a short time interval at fixed frequencies. Deep in the plasma core, at the probing beam frequency greater than 23 GHz, the harmonics of the main mode (50 kHz) are found (Fig. 10). At this moment we do not know why the mode has harmonics. Another feature of the mode is its bursty character. The fast changes are on the order of the electron-electron collision time (100 μsec). The FFT technique has a better frequency resolution than the wavelet analysis. The Fourier spectrum in a 2 msec time window shows a very narrow frequency band where the mode exists (Fig. 11).

4. Summary

ECE spectra in HSX plasma have been measured at 0.5 T. The Bi-Maxwellian model and CQL3D Fokker-Planck code show the presence of 5 keV tail of electrons in the distribution function. The ECE radiometer detects the coherent mode in QHS plasma as do the interferometer, Mirnov coils and Langmuir probes. This mode is thought to be driven by high energy trapped particles circulating around the machine.

First results on plasma density fluctuations have been obtained with the new reflectometer. The frequency spectrum in 10% Mirror configuration is much broader than in QHS. The reflectometer data show that the coherent mode in QHS plasmas is localized in plasma core and its amplitude gradually reduces with the mirror percentage (at 8% of mirror term the mode vanishes). The wavelet analysis helps us to see the bursty behavior of the coherent mode and its harmonics. The fast changes are on the order of electron-electron collision time.

Acknowledgments

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