INFLUENCE OF SUPRATHERMAL ELECTRONS ON ECE MEASUREMENTS IN THE URAGAN-3M TORSATRON

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Electron cyclotron emission (ECE) diagnostic (superheterodyne millimeter wave radiometer) is a regular tool to provide the radial distribution and time dependence for a bulk electron population for the Uragan-3M (U-3M) plasmas. Under some plasma conditions when RF heating pulse switched off a substantial increasing of the radiation intensity signal we observed at the frequencies which corresponds to the second and third harmonics of ECE ($2\omega_{ce}$, $3\omega_{ce}$) of the extraordinary mode. The existing phenomena could be attributed with the presence of the suprathermal (ST) and / or "runaway" electrons (RE) in U-3M plasmas. A procedure is described by which the electron temperature profile can be obtained from spectral measurements of the cyclotron emission at optically thin frequencies. No absolute calibration of the detection equipment is needed for this method.

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INTRODUCTION

The presence of the population of the suprathermal electrons caused the additional problems in ECE measurements. Thus, it is of the great importance for the present plasma fusion experiments. Because of their high energy ST could significantly alter the and as a result introduce considerable error in the bulk thermal electrons temperature measurements. It is well known that optically thick second harmonic X-mode is the best candidate to measure electron temperature. However under some condition it is possible to use different approach. A second way may be offered by using an optically thin harmonic. Here $T_e(s)$ can be inferred from the ratio of the spectral distributions of the intensities of the fundamental modes emitted in radial direction within the equatorial plane of a toroidal system. In fact, the intensities of these modes, the ordinary and extraordinary wave, differ, by a factor:

$$\frac{I_{mO}}{I_{mX}} \approx 0.15\left(\frac{k_B T_e}{m_0 c^2}\right)$$

The drawback is that the polarization ratio must be known. It is clear, however, that this method requires that no appreciable change in the polarization occurs during the propagation through the plasma. In this paper we follow [7] with yet another close approach. We will use same polarization (X-mode) but following harmonics $\frac{I_{mX}}{I_{(m+1)X}} \approx A\left(\frac{k_B T_e}{m_0 c^2}\right)$.

1. EXPERIMENTAL CONDITIONS

Uragan-3M is small size torsatron with $l = 3,\ m = 9$, major radius $R_0 = 1$m average plasma radius $a_p = 0.12$ m and toroidal magnetic field $B_0 \leq 1$T . The whole magnetic system is enclosed into large five meters diameter (volume of 70 m^3) vacuum tank, so that an open natural helical divertor is realized. As a heating mechanism, the multimode Alfvén RF resonance heating is realized. To produce and sustain the hydrogen plasma two types of antenna is used. The magnetic field pulse have the following parameters: pulse raise time 1.5 s pulse fall time 1.3 s, pulse width 3.5 s with at least flat top pulse time of 2.0s. At the middle of flattop of the magnetic pulse, the plasma ignites by RF range (8.6 ... 8.8 MHz) antennas and sustained for 50 ... 70 ms. period. Recently it was shown [1, 2] that it is possible to realize two types of plasma discharges. If only frame antenna (FA) with broad spectrum of parallel wavelengths is used than produced plasma have moderate electron temperature of $T_e = 400 \ldots 500$ eV and with low density $\overline{n_e} = 0.8 \ldots 2.5 \times 10^{18}$m^{-3}. During those experiments the plasma is weakly collisional, thus, its investigation could be of some interest for modeling physical processes in large fusion devices. The FA antenna could be used for production of target plasma for the start-up of three-half-turn antenna (THTA) which has shorter wavelengths. Conical horn antenna which is used to receive emitted microwaves from the plasma set for observation at 90° to the toroidal magnetic field and looking inward along a major radius at DD-3 crossection.

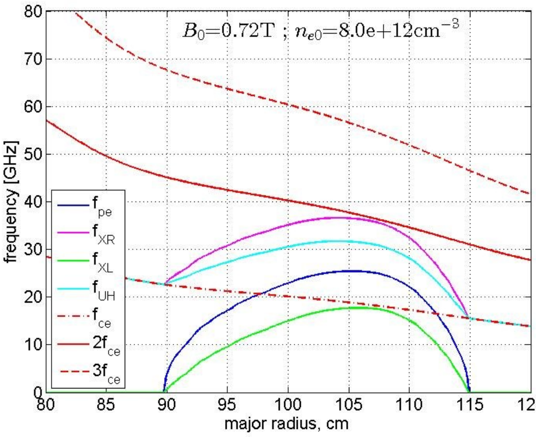

Fig. 1. Radial distribution of the characteristic frequencies for the central magnetic field 0.72T and central electron density $n_{e,0} = 8 \times 10^{18} m^{-3}$ in the equatorial plane for the U-3M plasma

2. ECE RADIOMETRY

Electron cyclotron emission diagnostics is a standard tool that routinely used for electron temperature profile measurement of high temperature plasmas at U-3M. The diagnostic utilize a conventional single antenna superheterodyne radiometers [3-5] one of which is operated at the single tunable frequency of the second harmonic for the X-mode (X2) in the upper part of the K_a-band (32…39 GHz) other one is the multichannel V-band (57; 60.6; 64.2; 67.8; 71.4; 75GHz) radiometer which is operated at the third harmonic of the X-mode (X3) (Fig. 1). The frequency range was chosen according to the value of the toroidal magnetic field of B_0 =0.68…0.72 T. For the standard operational regime of the torsatron plasma parameters was in the range ($\overline{n_e} = 1 - 8 \times 10^{18}\mathrm{m}^{-3}$, $T_e = 100 \ldots 700$ eV). In this case the detected ECE signals, which are corresponding, to a so-called 'radiation temperature' $I_{\mathrm{ECE},\,l}$ of the given polarization and harmonic number l. According to [6] measured ECE intensity from a thermal plasma (with Maxwellian distribution function) is given by equation:

$$I_{\mathrm{ECE},\,l} = I_{\mathrm{BB}} \left\{ \frac{1-\exp(-\tau_l)}{1-\Gamma_{\mathrm{w,\,eff}}\exp(-\tau_l)} \right\}, \qquad (1)$$

where

$$I_{\mathrm{BB}} = \frac{\omega^2 T_e}{8\pi^3 c^2}, \qquad (2)$$

is emission level of the blackbody at a temperature T_e and τ_l is averaged optical depth through the microwave beam path from the plasma to the X-band conical horn antenna. There is no 'classical' toroidal inner wall inside U-3M tank. To include reflection from helical winding components an effective reflectivity coefficient $\Gamma_{\mathrm{w,\,eff}}$ has to be introduced (see denominator in Eq. 1). Following procedures described in [6] for the perpendicular propagation case the numerical calculation of the optical depth for the X2, X3 harmonics was done according to formula:

$$\tau_{\mathrm{X},l} = \frac{\pi^2 l^{2(l-1)}}{2^{(l-1)}(l-1)!} Z_l(q) \left(\frac{k_B T_e}{m_0 c^2}\right)^{l-1} \frac{f_{ce}}{c} R\,, \qquad (3)$$

where

$$Z_l(q) = q\left(1 - \frac{(q/l^2)(l^2-q)}{l^2-q-1}\right)^{l-\frac{3}{2}} \left(1 + \frac{q/l}{l^2-q-1}\right)^2, \qquad (4)$$

and $q = \left(\omega_{pe}/\omega_{ce}\right)^2$ is square of electron / plasma gyrofrequency ratio.

A numerical calculation of the optical depth for the given electron temperature $T_e(R)$ and electron density $n_e(R)$ profiles is shown in the Fig. 2. According to calculation for the X2 case with maximum electron density $n_e(0) = 7.5 \times 10^{18}\mathrm{m}^{-3}$ only central part of the plasma column (R=102…107 cm, where optical depth τ_l~2) ECE radiation is almost proportional to the electron temperature T_e. For the rest of the plasma ECE signal mast be corrected. X3 mode remains optically thin for entire plasma radius. For this plasma $\tau_l \leq 1$ an $I_{\mathrm{ECE},\,l} \propto \tau_l T_e \,/\left(1 - \Gamma_{\mathrm{w,\,eff}}\{1 - \exp(-\tau_l)\}\right)$.

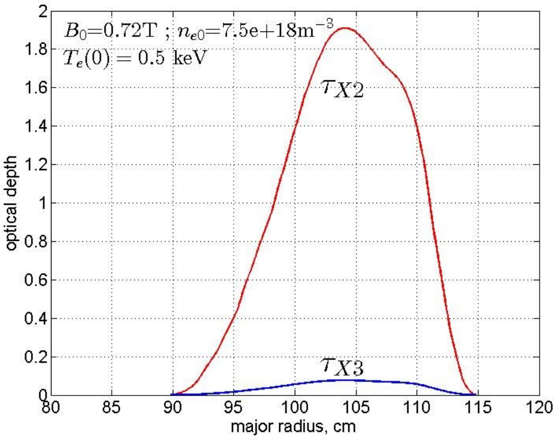

Fig. 2. Radial distribution of the optical depth for the second and third harmonics for the extraordinary mode; B(0)=0.72 T, Te(0)=0.5 keV, ne(0)=7.5e+018 m^{-3}

Now, let us consider the discharge with significantly lower density $\overline{n_e} = 1.5 \times 10^{18}\mathrm{m}^{-3}$. In this case $f_{pe}/f_{ce} \leq 0.35$ and optical depth drop up to 0.4. The corresponding calculation of the optical depth for the same as at the Fig. 2 electron temperature $T_e(R) = 0.5 keV$. Calculated profiles are shown in the Fig. 3.

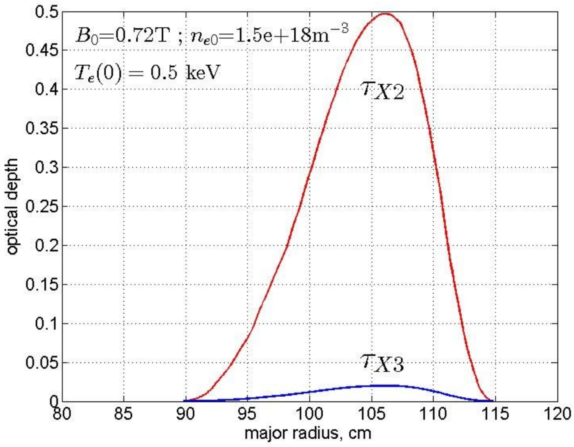

Fig. 3. Radial distribution of the optical depth for the second and third harmonics for the extraordinary mode; B(0)=0.72 T, Te(0)=0.5 keV, ne(0)=1.5e+018 m^{-3}

In this case, both X-mode harmonics are optically thin. Thus, entire electron temperature profile data have to be corrected with the optical depth factor.

3. FAST ELECTRONS 'AFTERGLOW'

The emission for the extraordinary mode is measured for a wide range of plasma parameters, $100 \leq T_e \leq 500$ eV, $0.4 \leq f_{pe}/f_{ce} \leq 1.3$ where the effect of energetic electrons according to [6] is relatively small. As long as we measure ECE intensity at θ =90° to the magnetic field, we can neglect the Doppler broadening of the emission line for a Maxwellian distribution.

$$\Delta\omega_{\mathrm{D}} \approx \sqrt{2\pi}\, l\omega_{ce} \left(\frac{k_B T_e}{m_0 c^2}\right)^{0.5} \cos\theta. \qquad (5)$$

The line width due to relativistic broadening is approximately:

$$\Delta\omega_{\mathrm{R}} \approx \sqrt{2\pi l}\, l\omega_{ce}\left(\frac{k_B T_e}{m_0 c^2}\right). \quad (6)$$

For the bulk electrons with Te of 500 eV numerically $\Delta f_{\mathrm{R}}(X2) \approx 25\,MHz$ and $\Delta f_{\mathrm{R}}(X3) \approx 45\,MHz$. Only electrons which have temperature of 5…10 thermal can significantly deform distribution function.

However, as reported in [4] for low density discharge the effect of the ECE 'afterglow' signal with wide spectrum was observed. Cyclotron emission radiation signals at all channels (X2, X3; 32…75 GHz) raised and sustained at almost constant level more than 100…120 ms after RF pulse off (Fig. 4). One of the possible explanation is that when average plasma density crosses the 'threshold value' equal to $n_e^{cr} = 1.0 \times 10^{18}\mathrm{m}^{-3}$ during RF heating phase. Appearance of the ECE signal that could attribute with suprathermal electrons is possible due to the Dreicer, hot-tail, gamma-ray Compton scattering, avalanche generation mechanisms, and due to radial diffusion caused by magnetic field fluctuations. At the moment we do not have the definitive opinion on this.

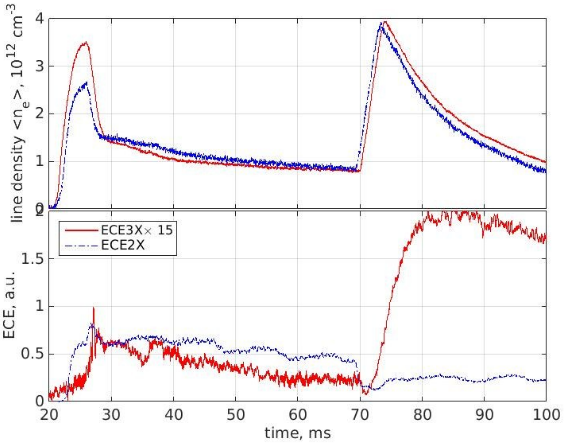

Fig. 4. Time evolution of the line electron density (upper) for the FA, magnetic field B(0)=0.72 T, RF power 130 kW; evolution for the ECE intensity X2, X3 harmonics (lower)

In order to obtain local information more accurately, the intensity ratio of the second- to the third-harmonic emission is investigated similar to Boyd [7]. To confirm that ST have considerable influence not only after RF off but at the heating phase as well intensity ratio of the neighboring harmonics must have slow variation. Otherwise, the content of distribution function during RF heating and after will be different. The specific intensity ratio

$$R_{23} = I_{2X}/I_{3X}$$

of the second and third harmonics of ECE is given in the plane-parallel- model by:

$$I_{lX} = l^2\,(1 - \exp(-\tau_l))/\big(1 - \Gamma_{\mathrm{w,\,eff}}\exp(-\tau_l)\big). \quad (7)$$

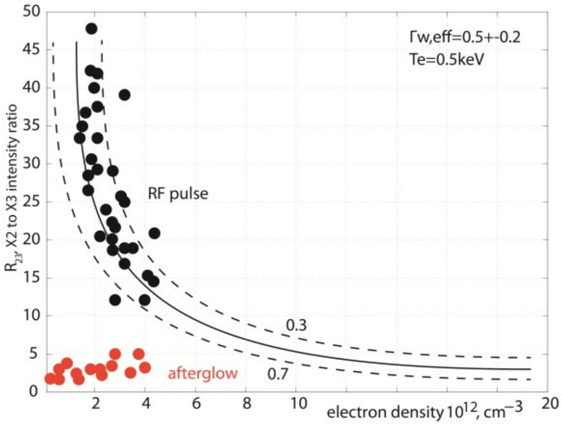

Fig. 5. Intensity ratio vs electron density. Curves represents calculation according the Eq. 7 for different wall reflection coefficient 0.3; 0.5; 0.7

The magnetic configuration allows deduction of the intensity ratio without harmonics overlapping inside the confinement region (see Fig.1). In fact, overlapping will be if:

$$\frac{l}{l+1} \geq \frac{1-\epsilon}{1+\epsilon}, \quad (8)$$

where $\epsilon = a_p/R_0$ is inverse aspect ratio. For U-3M case $\epsilon = 0.11$. Overlapping zones are very small. They are near helical coils and have width 1…2 cm. One can see that for a given inverse aspect ratio the higher harmonics are more strongly affected by overlapping. Another complication that can arise is that on reflection the radiation can suffer a polarization change. At the moment this effect is not included in the scope of the paper.

CONCLUSIONS

In summary, it has been shown that the intensity ratio of the second- to the third-harmonic emission is in good agreement with calculated results using the plane-parallel-walls model having a low effective reflectivity of the vacuum vessel wall. This makes it possible to obtain the electron temperature from ECE measurement without an absolute intensity calibration of the radiometer if density is known and the reflectivity is less than 0.5. The low reflectivity may be made by placing a radiation dump in the vacuum vessel opposite to a receiving antenna of high angular resolution. Moreover, this method is useful to obtain the time behavior of the local electron density in the absence of overlapping of the harmonics. Plasma physics research requires understanding of runaway population influence on bulk electrons in toroidal plasma.

During recent experiments at U-3M torsatron it was found an 'afterglow' radiation measured via radiometry diagnostic. It appears just after heating RF pulse off. We confirm that EC 'afterglow' emission has wide spectrum (32…75 GHz) for both second and third harmonics of the X-mode. This emission appears when average plasma density crosses the threshold value equal to $n_e^{cr} = 1.0 \times 10^{18}\mathrm{m}^{-3}$ during RF heating phase. At the moment we have only phenomenological explanations on the experimental.

The main result of the specific intensity ratio measurement is that to sets of data exists. First one is represents 'afterglow' radiation and it has low, almost constant 2-5 ratio. Other one that is very close to the modeled curve (for bulk temperature of $T_e = 500$ eV). The data points are between zones, which correspond to effective wall reflection index 0.3…0.5. Thus, it can be stated with some degree of confidence that ECE radiation during RF heating time is mostly from bulk, thermal electrons. The influence of the ST is negligible

To minimize scattering of the experimental data it is also possible to tune X2 frequency for more precise to identity in both radial positions.

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ВЛИЯНИЕ СВЕРХТЕПЛОВЫХ ЭЛЕКТРОНОВ НА РАДИОМЕТРИЧЕСКИЕ ИЗМЕРЕНИЯ В ТОРСАТРОНЕ УРАГАН-3М

Р.О. Павличенко

Диагностика электронного циклотронного излучения (ЭЦИ) является штатным инструментом для обеспечения информации о временной эволюции и радиальном распределении электронной температуры во время экспериментов на торсатроне Ураган-3М (У-3М). Было обнаружено, что после окончания импульса ВЧ-нагрева наблюдается значительное увеличение сигнала интенсивности излучения на частотах, что соответствует второй и третьей гармоникам ЭЦИ ($2\omega_{ce}$, $3\omega_{ce}$) необыкновенной волны. Существующие явления можно объяснить присутствием сверхтепловых или «убегающих» электронов (УЭ) в плазме торсатрона У-3М. Описана процедура, в которой профиль температуры электронов может быть получен из спектральных измерений циклотронного излучения для оптически тонких гармоник. Обнаружено, что для этого метода не требуется абсолютной калибровки оборудования.

ВПЛИВ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ НА РАДІОМЕТРИЧНІ ВИМІРЮВАННЯ В ТОРСАТРОНІ УРАГАН-3М

Р.О. Павліченко

Діагностика електронного циклотронного випромінювання (ЕЦВ) є штатним інструментом для забезпечення інформації про тимчасову еволюцію і радіальний розподіл електронної температури під час експериментів на торсатроні Ураган-3М (У-3М). Було виявлено, що після закінчення імпульсу ВЧ-нагріву спостерігається значне збільшення сигналу інтенсивності випромінювання на частотах, що відповідає другій і третій гармонікам ЕЦВ ($2\omega_{ce}$, $3\omega_{ce}$) незвичайної хвилі. Існуючі явища можна пояснити присутністю надтеплових або «тікаючих» електронів (ТЕ) у плазмі торсатрона У-3М. Описана процедура, в якій профіль температури електронів може бути отриманий із спектральних вимірювань циклотронного випромінювання для оптично тонких гармонік. Виявлено, що для цього методу не потрібно абсолютного калібрування обладнання.