# BEHAVIOUR OF THE RADIATION OF THE SUPRATHERMAL ELECTRONS AT THE URAGAN-3M TORSATRON AFTER RF HEATING OFF FROM ECE MEASUREMENTS

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The microwave radiometry is a well-known diagnostics to obtain the information on temporal evolution and radial profile of the electron temperature at U-3M torsatron plasma experiments. However, under low plasma density with this diagnostics we report on the large production of runaway electrons after RF heating pulse off. We notice a gradually increasing of the radiometer signal at the frequencies that match the second and third harmonics of electron cyclotron emission of the extraordinary mode. This effect could be explained with the existence of the "runaway" electrons in U-3M discharge. A phenomenological description of this process is presented, where the time evolution of the ECE radiation signal is compared to the electron density evolution.

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## INTRODUCTION

The problem of the suppression of the RE is of the great importance for the present plasma fusion experiments. Now days there are several condition for occurrence of RE generation: (a) low-density regimes in which the normal loop voltage became high enough to enable runaway process; (b) sawtooth crashes, where magnetic reconnection may accelerate runaways; (c) lower hybrid and electron cyclotron current drive, in which large-amplitude microwave radiation accelerates runaways and (d) especially for tokamaks disruptions and rapid shutdowns sometimes accelerate runaways, resulting in damage of the vacuum chamber of the machine.

## 1. URAGAN-3M TORSATRON

### 1.1. EXPERIMENTAL CONDITIONS

Uragan-3M is small size torsatron with $l = 3,\ m = 9$, major radius $R_0 = 1\text{m}$ 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 $70\ \text{m}^3$) vacuum tank, so that an open natural helical divertor is realized. The multimode Alfvén RF resonance heating is used to produce and sustain the hydrogen plasma. The 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 flat top of the magnetic pule the plasma ignites by RF range (8.6 ... 8.8 Mz) antennas and sustained for 50…70 ms. Recently it was shown [1] that RE which are primary originated from magnetic field pulse rise could be successfully suppressed by the applying a constant negative voltage difference (from -50 to -100 V) relative to the torsatron case to one of the RF heating antenna. Those experiments show that for the case of the low pressure of the hydrogen plasma $p_{H_2} = 3.4 \times 10^{-6}\text{Torr}$ signals from ECE, X-ray and Rogowski coils disappear which could be as an evidence of suppressing of the RE multiplication.

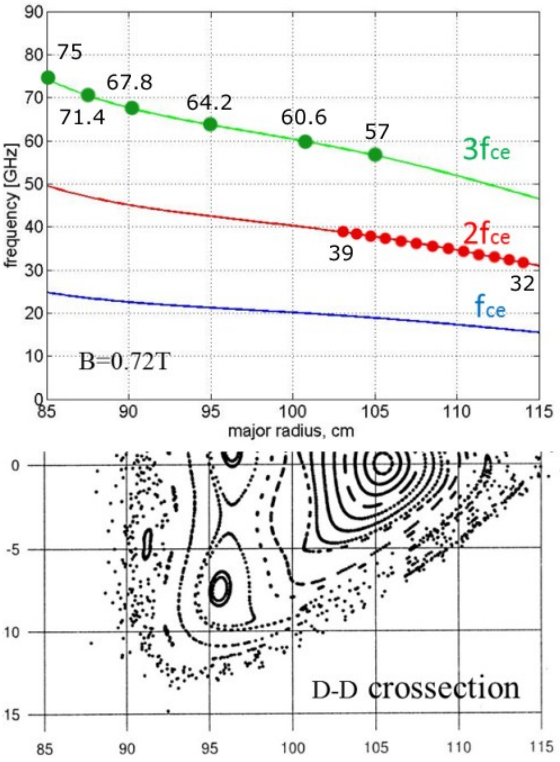

*Fig. 1. Radial distribution of the first three harmonics of the electron cyclotron frequencies for the central magnetic field 0.72 T, operational frequencies for the second and third harmonics depicted as filled circles (upper); and Poincaré plot of the corresponding poloidal cross-section U-3M magnetic fluxes (lower)*

### 1.2. ECE RADIOMETRY SYSTEM

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 super-heterodyne radiometers [2, 3] one of which is operated at the single tunable frequency of the second harmonic for the X-mode in the upper part of the $K_a$-band

(32…39 GHz) other one is the multichannel V-band (57,60.6,64.2,67.8,71.4,75 GHz) radiometer operated at the third harmonic of the X-mode (Fig. 1). The frequency range was chosen according to the value of the toroidal magnetic field of 0.68…0.72 T. For the operational parameters of the standard U-3M plasmas ($\overline{n_e} = 1 - 5 \times 10^{18}\,\mathrm{m}^{-3}$, $T_e = 200 \ldots 700\,\mathrm{eV}$) the detected ECE signals, which are corresponding, to a radiation temperature $T_{\mathrm{rad}}$ is given by equation:

$$T_{\mathrm{rad}} = T_{\mathrm{e}} \frac{1-\exp(-\tau_{\mathrm{avg}})}{1-\Gamma_{\mathrm{wall}}\exp(-\tau_{\mathrm{avg}})}, \qquad (1)$$

where $\tau_{\mathrm{avg}}$ is averaged optical depth through the microwave beam path and $\Gamma_{\mathrm{wall}}$ is the inner wall (inner surface of the helical coils) reflectivity coefficient. A subsequent numerical calculation of the real electron temperature $T_e$ of underdense plasmas (with low optical depth $\tau_{\mathrm{avg}} \leq 0.4$) including the effects of emission and reabsorption of microwave radiation has been conducted.

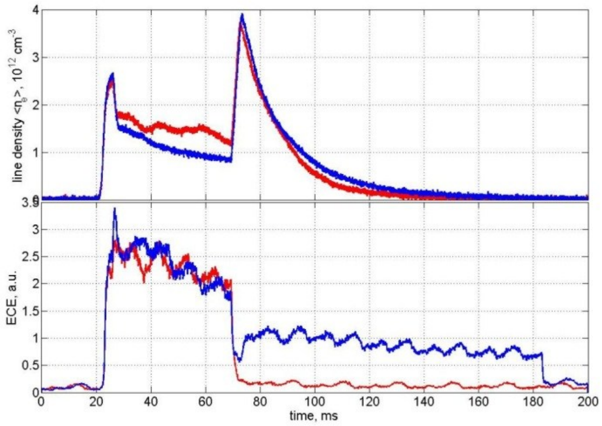

*Fig. 2. Temporal evolution of the line electron density (upper) for the frame RF, central magnetic field B(0)=0.72 T, input RF power 130 kW (RF oscillator voltage U(RF)=9 kV), initial hydrogen pressure* $p_{H_2} = 1.04 \times 10^{-5}\mathrm{Torr}$*; evolution for the radiation intensity of the second harmonic X-mode ECE (lower)*

### 1.3. RUNAWAY ELECTRON GENERATION

Plasma electrons into strong toroidal electric field can be accelerated to form a runaway component if the slowing down process due to interaction with ions is not effective during the acceleration period. For Maxwellian electrons of temperature $T_e$ and density $n_e$ toroidal electric $E_T$ field is given by

$$E_T = (V - L\dot{I}_p)/2\pi R_0\,, \qquad (2)$$

where $V$ is loop voltage, $I_p$ is plasma current induced by electric field, $L$ is plasma inductance. For 'primary' runaway electron generation this electric field must be higher than Dreicer field $E > E_D$[4]. For hydrogen plasma where $Z_{\mathrm{eff}} \cong 1.0$ Dreicer field is given by:

$$E_D = \frac{e^3\, n_e \ln\Lambda}{4\pi\varepsilon_0^2 T_e}, \qquad (3)$$

where $\ln\Lambda \cong 15$ is a Coulomb logarithm, thus, for Uragan-3M plasma ($\overline{n_e} = 1 \times 10^{18}\,\mathrm{m}^{-3}$, $T_e = 700\,\mathrm{eV}$) the Dreicer field is $E_D \cong 0.57\,\mathrm{V/m}$.

### 1.4. ECE RADIATION AFTER RF OFF

Temporal evolution of line electron density measured by 140 GHz microwave single chord interferometer and intensity radiation of ECE second harmonic X-mode (Fig. 2) are shown for the two discharges with small difference in density evolution. RF heating pulse with input RF power of 130 kW (RF oscillator voltage of 9kV) was applied from 20 to 70 ms for both cases, the hydrogen pressure was $p_{H_2} = 1.04 \times 10^{-5}\mathrm{Torr}$ and the central magnetic field was $B_0$=0.72 T. For 'red' discharge average density do not drop to the level of $\overline{n_e} = 1.3 \times 10^{18}\,\mathrm{m}^{-3}$. There is no ECE intensity signal after RF was off. However, when during RF pulse average density crosses 'threshold' critical level of $n_e^{cr} = 1.0 \times 10^{18}\,\mathrm{m}^{-3}$ 'ECE afterglow' is clearly visible. In fact, the critical electron density $n_e^{cr}$ at which generation of runaway electrons occurs could be deducted from Dreicer field expression. Those values could be order smaller, because there is no information on the plasma density profile. From divertor density measurements via several sets of Langmuir probes we can estimate the edge (inside LCFS) density as $n_e^{\mathrm{LCFS}} \sim 0.3 \ldots 0.5 \times 10^{18}\,\mathrm{m}^{-3}$. This implies that at the plasma edge the Dreicer field could be two or three times lower $E_D^{\mathrm{LCFS}} \cong 0.2\,\mathrm{V/m}$. It was shown before in [5] that for close U-3M plasma parameters electrical field attain value of $E_T \cong 0.4\,\mathrm{V/m}$ measured at the moment current decay just after RF field was switched off.

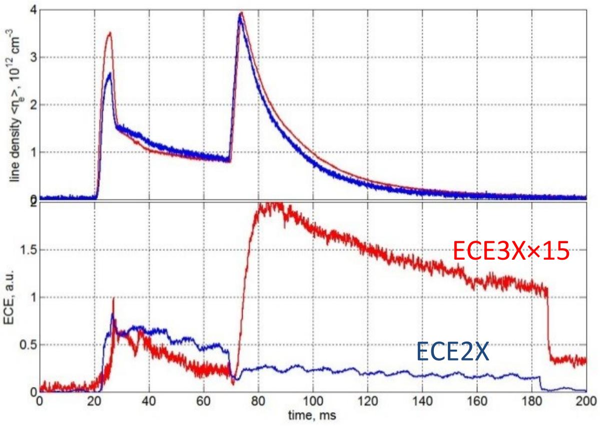

*Fig. 3. Temporal evolution of the line electron density (upper) for the frame RF, central magnetic field B(0)=0.72 T, input RF power 130 kW(RF oscillator voltage U(RF)=9 kV), initial hydrogen pressure* $p_{H_2} = 1.04 \times 10^{-5}\mathrm{Torr}$*; evolution for the radiation intensity of the 37 GHz second (blue) and 60GHz third harmonics (red) X-mode ECE (lower)*

The ECE 'afterglow' spectrum is wide because all radiometer channels (second and third harmonics) from 32 to 75 GHz shows substantial intensity signal after RF power off (Fig. 3). Here we present only the phenomenological description of some RE dependencies. As was mentioned above we observed that for the density below some ‘threshold’ or critical density $n_e^{cr} = 1.0 \times 10^{18}\ \mathrm{m}^{-3}$ there is an appearance of ECE radiation that could be attributed to the presence of RE.

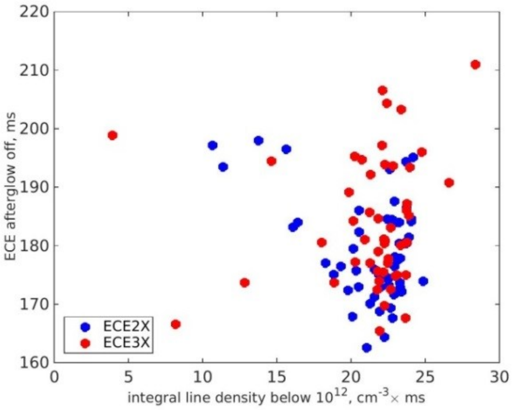

*Fig. 4. Dependence of second and third harmonics ECE ‘afterglow’ radiation drop time on $S_{nl}^*$ parameter*

It was found that after some time the ‘afterglow’ ECE signals intensity during 100…300 μs abruptly drops. To describe the dependence on threshold average density we use some parameter, which is a product of line density below $n_e^{cr} = 1.0 \times 10^{18}\ \mathrm{m}^{-3}$ and the time from crossing this critical value $t_{\mathrm{n12}}^{\mathrm{cr}}$ to the time $t_{\mathrm{off}}^{\mathrm{RF}}$ when RF heating pulse off. This parameter could be given by the following expression:

$$S_{nl}^* = \int_{t_{\mathrm{n12}}^{\mathrm{cr}}}^{t_{\mathrm{off}}^{\mathrm{RF}}} \overline{n_e}(t)\, dt. \qquad (4)$$

Obtained results for wide (32…75 GHz) ECE spectrum are presented in the Fig. 4. For the almost identical plasma discharge parameters which is shown in the Fig. 3 integration time $\tau^* = t_{\mathrm{off}}^{\mathrm{RF}} - t_{\mathrm{n12}}^{\mathrm{cr}}$ was close to 20…25 ms. There is no substantial difference between second and third ECE harmonics data.

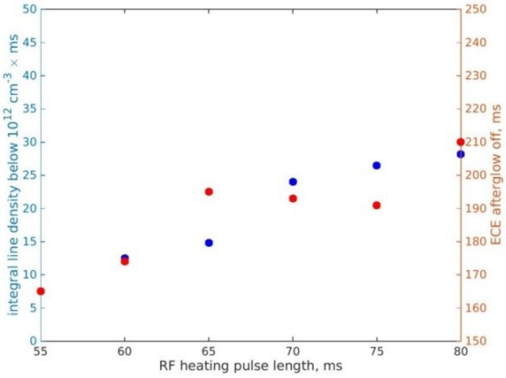

*Fig. 5. Dependence of $S_{nl}^*$ parameter and ECE ‘afterglow’ radiation drop time on the RF heating pulse length*

Spreading of ECE ‘afterglow’ end time could be attributed to the deviation of the density profile (edge density, peaking factor) which are not clearly distinguishable in line density variations measured by single channel interferometer.

For several consecutive plasma discharges, there was gradually increasing of the RF heating pulse length. This leads to simultaneous increase of the $\tau^*$ parameter and to the reduction of instantaneous average density. The corresponding dependence is shown in the Fig. 5. As expected, both data presented clear quasi-linear trend.

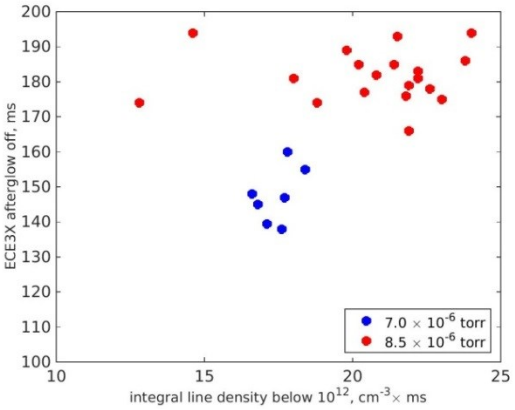

*Fig. 6. Dependence of third harmonics ECE ‘afterglow’ radiation drop time on $S_{nl}^*$ parameter for different initial pressure*

Final set of experiments conducted for two different ‘start-up’ pressures in the vacuum chamber volume $p_{H_2}(I) = 7 \times 10^{-6}$ Torr and $p_{H_2}(II) = 8.5 \times 10^{-6}$ Torr. Variation of the initial gas pressure $p_{H_2}(t = 0)$ in the U-3M vacuum chamber directly affects the value of the average density. From other hand it govern the level of the drag force $F(v) \propto v^{-2}$, which balances the electric acceleration of electrons. We can state that ECE ‘afterglow’ radiation drop time have scattered dependence on $S_{nl}^*$ parameter for above mentioned initial plasma pressure. However, those experimental results (Fig. 6) fill the general rule: lower pressure cause vanishing of ‘short-range’ collisions drag force balance term and leads to higher level of EC emission radiation after RF heating pulse off.

## CONCLUSIONS

Fusion research requires understanding of runaway electrons phenomenon in toroidal devices. It is well documented both theoretically and experimentally fact that RE are likely to appear in either a low density, high temperature plasma under rather moderate electric field or during very rapid and drastic changes in the plasma current. The former may be case in the edge region of a plasma to be driven by externally applied power, while the latter will usually be associated with the current disruption phenomena.

During recent experiments at U-3M torsatron it was found an ‘afterglow’ radiation measured via microwave electron cyclotron emission diagnostic appears just after heating RF pulse off. It was established that EC emission with wide spectrum (32…75 GHz) of both second and third harmonics of the X-mode 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 only phenomenological explanations on the experimental data are presented. To minimize scattering of the experimental data it is also possible that the signal received by the radiometer, which is characterized runaway electrons. Thus, it is necessary to interpret the not by the cut-off time, but by the same integral characteristic as the $S^*_{nl}$ parameter.

Finally, it must be emphasized that during future experiments a more systematic survey of RE phenomena, which are related to the enhancement of the operation condition, is quite necessary. Additional data that are describes torsatron operation such as hydrogen pressure, loop voltage, magnetic field components and their fluctuations have to be included in next RE experiments.

## REFERENCES

1. V.E. Moiseenko et al. The effect of an electrostatic field on runaway electrons in the Uragan-3M stellarator. // *Technical Physics Letters*. 2014, v. 40, № 8, p. 669-672.
2. R.O. Pavlichenko et al. Peculiarities of the radiometric measurements on Uragan-3M torsatron for RF heated plasma // *Problems of Atomic Science and Technology. Series "Plasma Physics" (17)*. 2011, № 1, p. 191-193.
3. V.S. Voitsenya et al. Progress in stellarator research in Kharkov IPP // *Physica Scripta*. 2014, v. T161, p. 014009.
4. H. Dreicer. Electron and ion runaways in fully ionized gases. I // *Phys. Rev.* 1959, v. 115, № 2, p. 238.
5. V.K. Pashnev, E.D. Sorokovoy. Appearance of neoclassical effects in plasma behavior in torsatron URAGAN-3M // *Problems of Atomic Science and Technology. Series "Plasma Physics" (14)*. 2008, № 6, p. 31-33.

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## ПОВЕДЕНИЕ ИЗЛУЧЕНИЯ СВЕРХТЕПЛОВЫХ ЭЛЕКТРОНОВ НА ТОРСАТРОНЕ УРАГАН-3М ПОСЛЕ ВЫКЛЮЧЕНИЯ НАГРЕВА ПО ДАННЫМ ЭЛЕКТРОННОГО ЦИКЛОТРОННОГО ИЗЛУЧЕНИЯ

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Микроволновая радиометрия является хорошо известной диагностикой для получения информации о временной эволюции и виде радиального профиля температуры электронов во время плазменных экспериментов на торсатроне У-3М. Тем не менее, в случае низкоплотной плазмы при помощи этой диагностики наблюдается появление значительного числа «убегающих» электронов после отключения импульса высокочастотного нагрева. Замечено постепенное увеличение сигнала радиометра на частотах, которые соответствуют второй и третьей гармоникам электронной циклотронной эмиссии необыкновенной волны. Этот эффект можно объяснить существованием «убегающих» электронов в разряде У-3М. Представлено феноменологическое описание этого процесса, где временная эволюция сигнала излучения ECE сравнивается с эволюцией плотности электронов.

## ПОВЕДІНКА ВИПРОМІНЮВАННЯ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ НА ТОРСАТРОНІ УРАГАН-3М ПІСЛЯ ВИМКНЕННЯ НАГРІВУ ЗА ДАНИМИ ЕЛЕКТРОННОГО ЦИКЛОТРОННОГО ВИПРОМІНЮВАННЯ

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Мікрохвильова радіометрія є добре відомою діагностикою, для отримання інформації про тимчасову еволюцію та вигляд радіального профілю температури електронів під час плазмових експериментів на торсатроні У-3М. Тим не менш, у випадку низькощільної плазми за допомогою цієї діагностики спостерігається поява значного числа «тікаючих» електронів після відключення імпульсу високочастотного нагріву. Помічено поступове збільшення сигналу радіометра на частотах, які відповідають другій і третій гармонікам електронної циклотронної емісії незвичайної хвилі. Цей ефект можна пояснити існуванням «тікаючих» електронів у розряді У-3М. Представлено феноменологічний опис цього процесу, де тимчасова еволюція сигналу випромінювання ECE порівнюється з еволюцією щільності електронів.