BEHAVIOR OF SUPRATHERMAL ELECTRONS AT THE URAGAN-3M TORSATRON AFTER RF HEATING OFF

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For the past decades the microwave radiometry is a routinely used diagnostics to obtain the information on temporal evolution and radial profile of the bulk electron temperature at Uragan-3M torsatron plasma experiments. However, in the case of low plasma density operation we observe the high level of electron cyclotron emission at the frequencies that match the second and third harmonics of the extraordinary mode after RF heating pulse off. This effect could be explained with the production of the suprathermal electrons. Study of the behavior suprathermal electrons is of great importance because: (a) suprathermal electrons significantly distort or make it impossible to measure the thermal electron temperature; (b) such electrons influence the ionization process, the excitation of the plasma ions and may lead to the occurrence of several plasma instabilities. The present work describes the results of experimental studies of the behavior of the emission after turning off the RF heat pulse.

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INTRODUCTION

The presence of ECE afterglow which was obtained at the second harmonic $2\omega_{ce}$ under certain operating conditions torsatron Uragan-3M (U-3M) is known for a long time [1]. However, other groups of diagnostics, installed at U-3M, could not observed such phenomena as seen by ECE diagnostics signals, thereby hampering the interpretation of this. Installation of a new radiometer, to receive radiation at frequencies that correspond to the third harmonic $3\omega_{ce}$, helped to confirm the existence of afterglow effect (Fig. 1). The time trace of the received radiation is identical to the standard radiometer signal ($2\omega_{ce}$). It has been proposed the presence of suprathermal electron beam. The question of occurrence of suprathermal electrons in the U-3M and the impact such electrons on the modification of the distribution function, and hence, impact on the definition of "thermal" electrons temperature T_e arose [2-4]. This work includes the first results of a detailed study of the behavior of suprathermal electron radiation.

EXPERIMENTAL CONDITIONS

Uragan-3M is a l=3, m=9 small size torsatron with major radius, R=1 m average plasma radius a_{pl}=0.12 m and toroidal magnetic field B_0=0.72 T. The whole magnetic system is enclosed into large five meters diameter (volume of V=70 m^3) vacuum tank, so that an open natural helical divertor is realized.

Current to the magnetic field coils is supplied in a pulsed mode. Magnetic field pulse duration was about 5s. Wherein, pulse has the following parameters: pulse raise time, pulse fall times are of the order of ~1 s, pulse width ~3s with at least flat top pulse time of ~2 s.

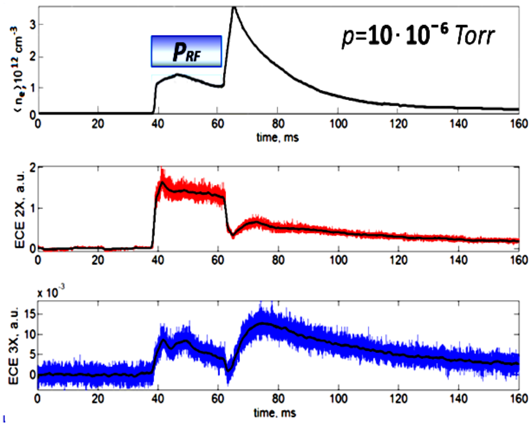

Fig. 1. Electron cyclotron emission at the frequencies that match the second and third harmonics of the extraordinary mode after RF heating pulse off

Producing and plasma heating was carried out by RF method, wherein the power is introduced into the confinement volume at the frequencies (8.6...8.8) MHz, close to the Alfvén resonance frequency $\omega \le \omega_{ci}$ (on a stationary part of the magnetic field pulse). The pulse duration of the RF power was varied in the range (50…70) ms. Input RF power in confinement volume was carried out using two antennas located on the part of a low magnetic field. In the presented experiments, the value of the input power reached 140 kW. The working gas is hydrogen.

ECE RADIOMETRY SYSTEM

Electron cyclotron emission (ECE) diagnostics is a standard tool that routinely used for electron temperature profile measurement of high temperature T_e plasmas at U-3M. The advantage of this method lies in the fact that in inhomogeneous magnetic field, region of emission is close to the resonant surfaces (Fig. 2) and the local temperature can be calculated with good spatial resolution.

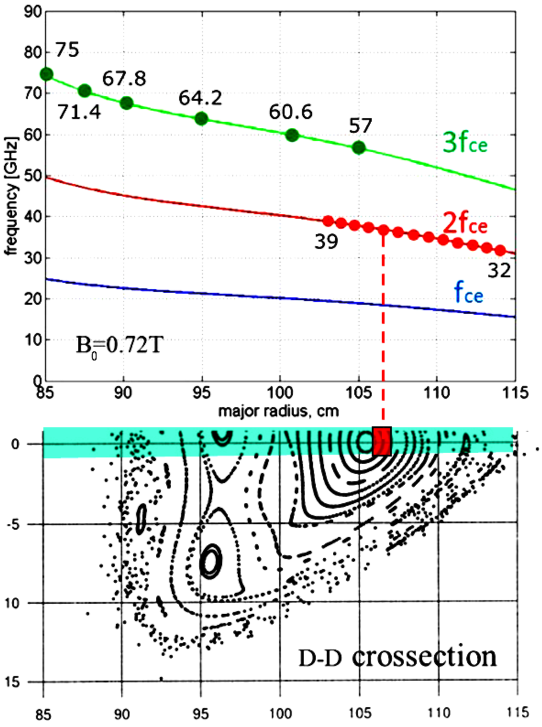

Fig. 2. Radial distribution of the first three harmonics of the electron cyclotron frequencies for the central magnetic field 0.72 T, operational frequencies for the second and third harmonics depicted as filled circles (upper); and Poincaré plot of the corresponding poloidal cross-section U-3M magnetic fluxes (lower)

At the U-3M ECE diagnostics utilize the emission from the plasma at frequencies, which corresponds to the second $2\omega_{ce}$ and the third $3\omega_{ce}$ harmonics X-mode extraordinary wave. Conical horn antenna is oriented perpendicular to the magnetic field lines and is located on the part of a low magnetic field [5].

The frequency range (33…37) GHz for $2\omega_{ce}$ and (57…75) GHz for $3\omega_{ce}$ was chosen according to the value of the toroidal magnetic field of (0.68…0.72) T.

Intensity emission of thermal electron depends on the density, temperature and the average optical depth (τ_{avg}) of the plasma: I(ECE)$\propto n_e$ Te τ_{avg}. Assuming parabolic density profile, with an average plasma density $\overline{n_e}=1.2\cdot10^{18}$ m^{-3}, optical depth of the plasma τ_{avg}~0.4. On this basis, it is possible to estimate value of the electron temperature in the plasma column center: T_{e0}~0.5 keV.

RADIATION OF THE SUPRATHERMAL ELECTRONS AT THE URAGAN-3M TORSATRON AFTER RF HEATING OFF

During previous experiments afterglow effect (see Fig. 1.) suggest that main driver of this phenomena is electric field [6], which produced by time varied magnetic field during plasma discharge. The operational time was extended to full time of the major magnetic pulse (5 *s*).

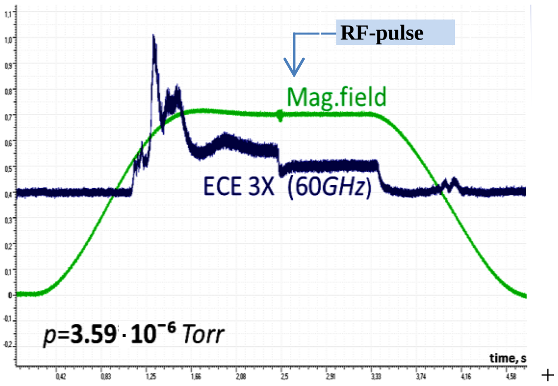

Fig. 3. Maximum intensity of the ECE observed on the rising edge of the magnetic field pulse

It was found that maximum intensity of the ECE observed at the rising edge of the magnetic field pulse (Fig. 3). For this condition electrons go over to a state of continuous acceleration since their dynamic friction force is less than the force exerted by the electric field, arising due to temporal changes of the magnetic field.

In the case of low operating pressure $p_{H2}<3\cdot10^{-6}$ Torr the level of radiation intensity increases and registered during full magnetic field pulse length. With an operating pressure close to $p_{H2}=1.04\cdot10^{-5}$ Torr intensity bursts are observed only at the magnetic field ramp up, ramp down phases, and a short period after the RF-pulse off (supplied at the stationary part of the magnetic field).

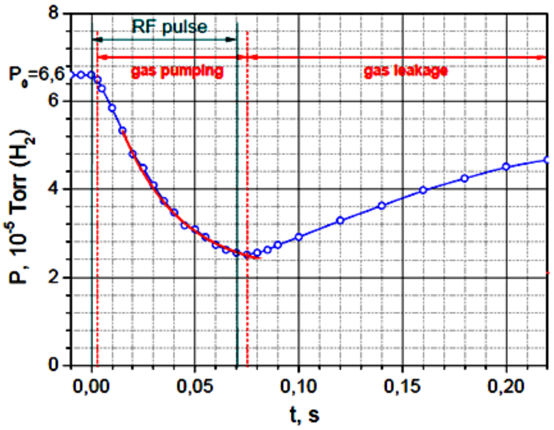

Fig. 4. Time dependences of the hydrogen pressure in the vacuum chamber during and after RF-pulse in the RF heating mode

The temporal behavior of the working gas pressure let us utilize the model which imply that occurrence of the suprathermal electrons, could be described as follows. At the active phase of the plasma discharge (during RF-pulse) the pressure of the working gas are falls and then inertially recovers to the initial level [7] (Fig. 4) The pressure (electron density) cross threshold level which is sufficient for initiation of the electrons to accelerate and its emission is clearly observed.

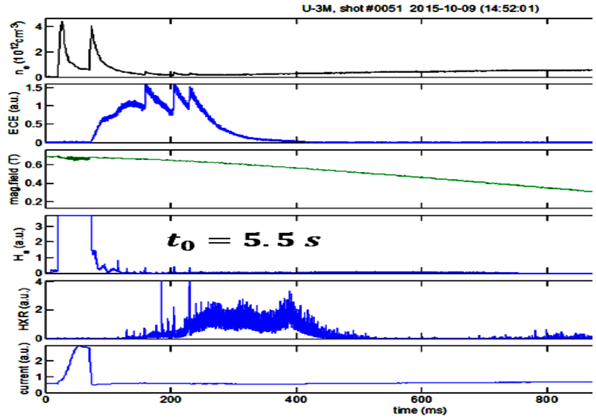

Fig. 5. Experiment of the shift the RF heating pulse to the beginning of decay stage. Here are shown signals of different groups of diagnostics

To investigate of this dependence on varied magnetic field we deliberately shift the RF heating pulse startup time to the beginning of decay stage (Fig. 5).

Thus the parallel electric field will be significantly increased, which led to a stronger flow suprathermal electrons and will finally to significant increasing in the afterglow radiation, observed by ECE diagnostic. Moreover finally it was found a clear correlation in the behavior of signals from ECE detectors (36.5…75) GHz, 140 GHz interferometer (line electron plasma density, $\overline{n_e}$), soft and hard X-ray (SXR+HXR) emission, spectroscopy H_α and plasma current I_{tor} (Rogowski coil).

The temporal traces of the different diagnostics show clear correlated peaks which could attribute as the impact of the suprathermal electrons on construction elements with subsequent ionization ejected impurities. The effect of working gas ionization by the suprathermal electrons has been registered as well (Fig. 6).

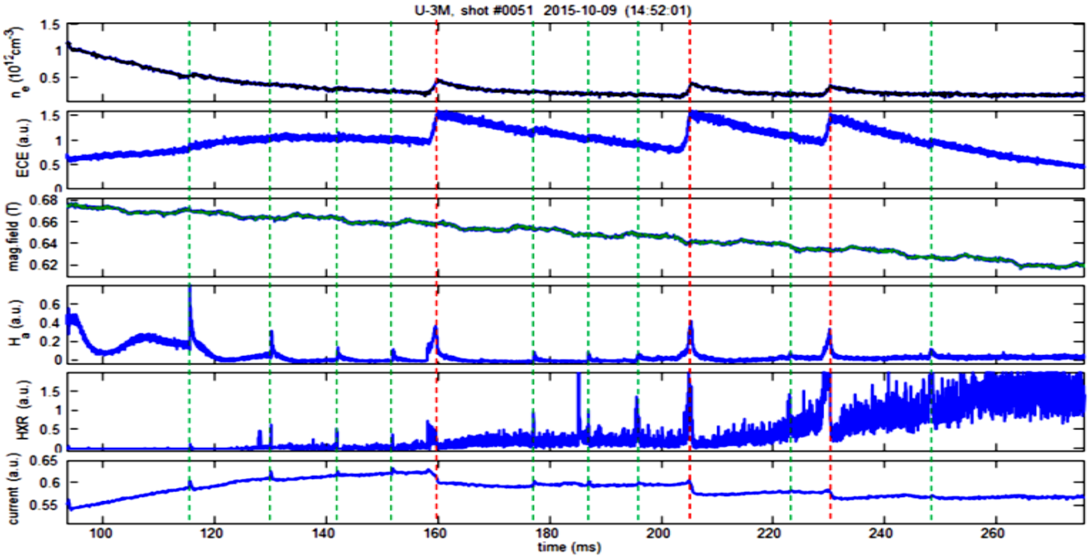

Fig. 6. Detailed analysis of the data leads to the conclusion about the interaction of the suprathermal electron beam with elements of construction (red dot); and of the ionization of the working gas (green dot)

CONCLUSIONS

In torsatron U-3M continued detailed experimental study of driving of the suprathermal electrons after turn-off RF-pulse, for the low plasma density case $\overline{n_e}$ =(0.5…1.2)·10^{18} m^{-3} and different initial pressure values p_{H_2}=(0.85…1)·10^{-5} Torr, shows clear and simultaneous response at the main plasma parameters.

The main driver for the suprathermal electrons appearing is the time variation of the local magnetic field, which led to increasing of the accelerating electric field.

This phenomenon indicates that the suprathermal electrons in torsatron U-3M can play an active role in the breakdown of the working gas in the containment region (inside the helical coils).

It shown that the presence of suprathermal electrons may lead to their interaction with the elements of construction torsatron and additional ionization. Finally we have to point out about the drawback of such operational scenario. It is almost impossible to avoid that undesirable high level HXR radiation which is attributed with interaction of the high energetic particles with inner vessel mechanical components.

To assess the value of ECE depending on the prehistory of the rise of the magnetic field, further detailed studies of suprathermal electrons will be held in torsatron U-3M on the magnetic field phase of growth.

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ПОВЕДЕНИЕ ИЗЛУЧЕНИЯ НАДТЕПЛОВЫХ ЭЛЕКТРОНОВ В ТОРСАТРОНЕ УРАГАН-3М ПОСЛЕ ВЫКЛЮЧЕНИЯ НАГРЕВА

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В течение последних десятилетий микроволновая радиометрия – обычно используемая диагностика для получения информации о временной эволюции и радиальном профиле температуры электронов во время плазменных экспериментов на торсатроне Ураган-3М. Тем не менее, в случае низкоплотной плазмы при помощи этой диагностики наблюдается появление излучения после отключения импульса высокочастотного нагрева. Этот эффект можно объяснить существованием надтепловых электронов. Изучение поведения надтепловых электронов важно, поскольку: (а) надтепловые электроны существенно искажают или делают невозможным измерения электронной температуры; (б) такие электроны влияют на процессы ионизации, возбуждения ионов плазмы и могут приводить к возникновению целого ряда неустойчивостей. Описываются результаты экспериментальных исследований поведения излучения после выключения импульса ВЧ-нагрева.

ПОВЕДІНКА ВИПРОМІНЮВАННЯ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ У ТОРСАТРОНІ УРАГАН-3М ПІСЛЯ ВИМКНЕННЯ НАГРІВУ

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Протягом останніх десятиліть мікрохвильова радіометрія є діагностикою, що зазвичай використовується для отримання інформації про часову еволюцію та радіальний профіль температури електронів під час плазмових експериментів на торсатроні Ураган-3М. Тим не менш, у випадку низькощільної плазми за допомогою цієї діагностики спостерігається поява випромінювання після відключення імпульсу високочастотного нагріву. Цей ефект можна пояснити існуванням надтеплових електронів. Вивчення поведінки надтеплових електронів важливо, оскільки: (а) надтеплові електрони істотно спотворюють або унеможливлюють вимірювання електронної температури; (б) такі електрони впливають на процеси іонізації, збудження іонів плазми і можуть призводити до виникнення цілого ряду нестійкостей. Описуються результати експериментальних досліджень поведінки випромінювання після вимкнення імпульсу ВЧ-нагріву.