SOME FEATURES OF THE DYNAMICS OF SUPRATHERMAL ELECTRONS AFTER RF HEATING OFF AT THE URAGAN-3M STELLARATOR PLASMAS

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For the past decades the microwave radiometry is a routinely used as diagnostic tool to obtain the information on temporal evolution and radial profile of the electrons temperature at Uragan-3M torsatron plasma experiments. However, in the case of low plasma density operation we observe the high level of emission at the frequencies that match the second and third harmonics of the extraordinary mode of electron cyclotron emission (ECE), after RF heating pulse off. This effect could be explained with the production of the suprathermal electrons. The present work describes the suprathermal electrons (SE) dynamics after turning off the RF heat pulse at the Uragan-3M torsatron (n_e=2·10^{12} cm^{-3}, Te=300 eV, P_{RF}=115 kW, B_0=0.69 T). In the absence of the well-known suppressive techniques (resonant magnetic perturbations and massive gas injection) an attempt was made to describe the factors, which contribute to the generation of the suprathermal electrons for the Uragan-3M plasmas. The temporal evolution of the ECE emission intensity and it dependence on the working gas pressure in the torsatron vacuum chamber is presented. The level of the ECE emission shows strong correlation with other diagnostics (plasma density, plasma current, HXR and H_α emission intensity). The gradual increase of the pressure (after RF off) could be is one of the reasons that temporarily sustain the process of electron acceleration. The dependence of the time ECE emission on the rate in magnetic field change (δB) is also given.

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INTRODUCTION

The presence of ECE afterglow which was obtained at the second harmonic $2\omega_{ce}$ under certain Uragan-3M (U-3M) operating conditions torsatron is published previously [1]. However, for those experiments other groups of diagnostics could not observe such phenomena as seen on ECE diagnostic signals, thereby impede the interpretation of this phenomenon. Installation of a new radiometer, which operated at the third harmonic $3\omega_{ce}$, helped to confirm the existence of afterglow effect (Fig. 1). In a paper published earlier [2], the results on time shift of RF power input on the plasma at the decay stage of the magnetic field pulse were presented. As a result, radiation from the plasma was detected at both frequencies corresponding to the cyclotron harmonics of $2\omega_{ce}$ and $3\omega_{ce}$ after turning off the RF heating pulse. This effect can be explained by the fulfillment of the conditions for the existence of suprathermal electrons in the torsatron confinement region. This paper presents some extended results of this phenomenon: (a) the influence of the working pressure in the vacuum chamber; (b) the influence of the induction electric field arising due to the non-monotonic decrease of the magnetic field.

1. 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 [3]. 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.

Total magnetic field pulse duration time was about 6 s, with the following parameters: pulse raise time, pulse fall times are of the order of ~ 1 s, pulse width ~ 3 s with at least flat top pulse time of ~ 2 s.

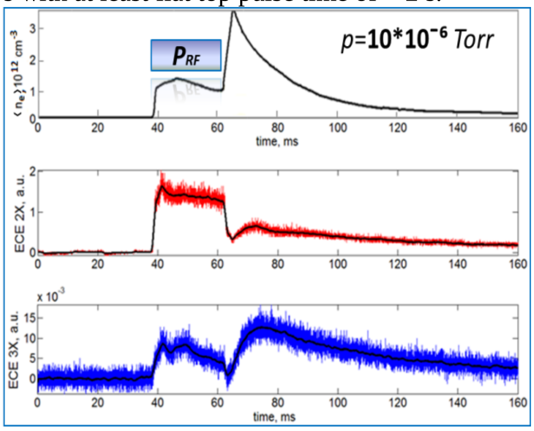

Fig. 1. Electron cyclotron emission at the frequencies that match the second and third harmonics ($2\omega_{ce}$, $3\omega_{ce}$) of the extraordinary mode after RF heating pulse off

Plasma production and heating was carried out by RF method. The RF power is introduced into the confinement volume at the frequencies 8.6...8.8 MHz, which are close to the Alfvén resonance frequency $\omega \leq \omega_{ci}$ (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 injected by two antennas located on the low magnetic field side ports. In the presented experiments, the value of the input power reached 140 kW. The working gas is hydrogen.

2. 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.

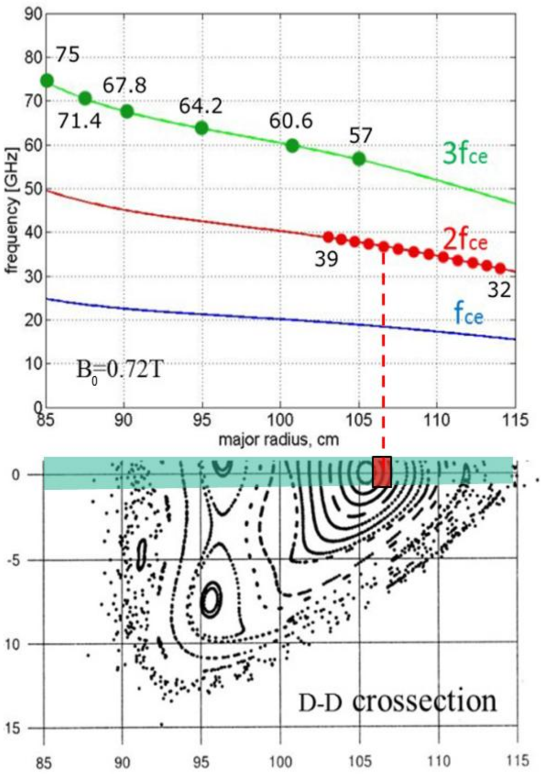

Fig. 2. Radial distribution of the first three harmonics of the electron cyclotron frequencies for the central magnetic field 0.72 T ($f_{ce}=2\pi\omega_{ce}$, $2f_{ce}=4\pi\omega_{ce}$, $3f_{ce} = 6\pi\omega_{ce}$), operational frequencies for the second and third harmonics depicted as filled circles (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 $2f_{ce}$ and the third $3f_{ce}$ 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 [4].

The frequency range $33 \le 2f_{ce} \le 37$ GHz and $57 \le 3f_{ce} \le 75$ GHz was chosen according to the value of the central magnetic field of $0.68 \le B_0 \le 0.72$ T.

Intensity emission of thermal electron depends on the density, temperature and the average optical depth (τ_{avg}) of the plasma: $I(ECE) \propto n_e Te\, \tau_{avg}$. Assuming parabolic density profile, with an average plasma density $\overline{n_e}=1.2 \cdot 10^{18}$ m^{-3}, averaged optical depth of the plasma $\tau_{avg} \sim 0.4$. On this basis, it is possible to estimate value of the electron temperature in the plasma column center: T_{e0}~0.5 keV.

3. RADIATION OF THE SUPRATHERMAL ELECTRONS AT THE URAGAN-3M TORSATRON AFTER RF HEATING OFF. IMPACT OF WORKING GAS PRESSURE

It was found that, in the case of low operating pressure p_{H_2}<$3 \cdot 10^{-6}$ Torr the level of radiation intensity increases and registered during full magnetic field pulse length. With an operating pressure close to $p_{H_2}=1.04 \cdot 10^{-5}$ Torr intensity bursts are observed only at the magnetic field ramp up, ramp down phases, and a short period after the RF-pulse off (at the stationary part of the magnetic field). For this condition electrons go over to a state of their 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 [5, 6].

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. 3) The pressure (electron density for almost constant temperature) cross threshold level which is sufficient for initiation of the electrons to accelerate and, thus, its emission is clearly observed.

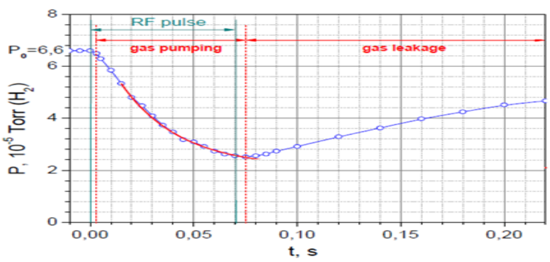

Fig. 3. Time dependences of the hydrogen pressure in the vacuum chamber during and after RF pulse in the RF heating mode (reproduced with permission of the authors [7])

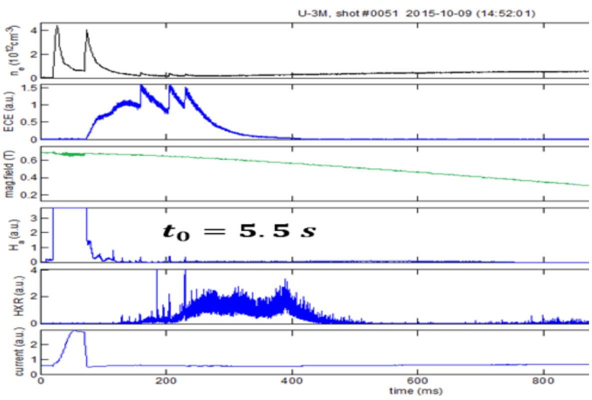

Fig. 4. Experiment of the shift the RF heating pulse to the beginning of decay stage. Here are shown signals of different groups of diagnostics

Thus, having shifted the start time of RF power input into the plasma from the stationary part of the magnetic field pulse at the time of its fall (Fig. 4), it becomes possible to combine these factors of influence on the suprathermal radiation from the plasma. In fact, such a transfer stimulates the acceleration of suprathermal

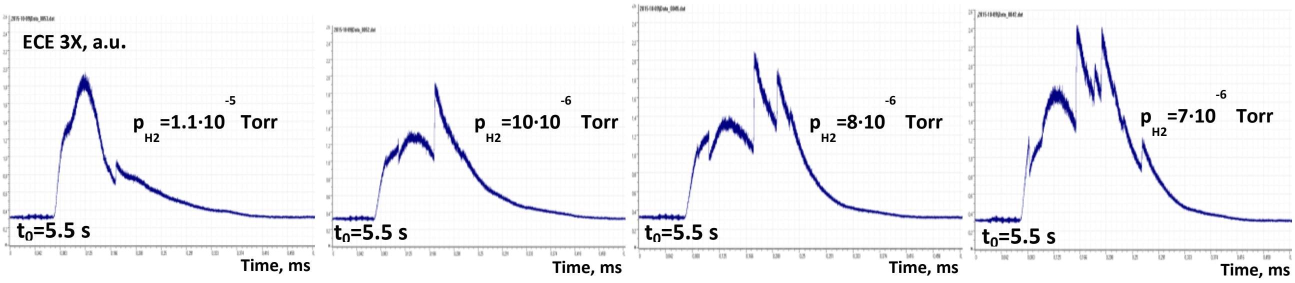

Fig. 5. Dependence of working gas pressure p_{H_2} on the level of the radiation of suprathermal electrons for the identical δB/δt values (detected by ECE diagnostic)

electrons. The amount of radiation increases by one order. This allows us to study in detail the temporal behavior of this phenomenon.

The series of experiments were conducted for the different pressure values: from $p_{H_2} = 1\cdot10^{-5}$ Torr to $p_{H_2} = 7\cdot10^{-5}$ Torr (Fig. 5). It was found that with an increase in the working pressure in the vacuum chamber, the electron acceleration mechanism during the decay of the magnetic field of the same magnitude also is leveled.

4. THE EFFECT OF δB/δt ON THE ACCELERATION/DECELERATION OF SUPRATHERMAL ELECTRONS

However, the detected radiation of suprathermal electrons is not observed all the time of the decay phase of the magnetic field pulse. For a possible explanation of the temporal behavior of the signal, it was assumed that the magnetic field does not fall at a constant speed. After numerical smoothing the signal (δB/δt) from the magnetic sensor, the derivative signal was analyzed. The calculation showed that at a certain time the rate of change of the magnetic field ceases to increase and slows down, with an obvious point of extremum t_{ex} (Fig. 6). The signal detected by the radiometer also terminates at this point. This result is well correlated (see Fig. 6) with the results of other diagnostic groups that observe the effect of the presence of suprathermal electrons (hard and soft X-rays).

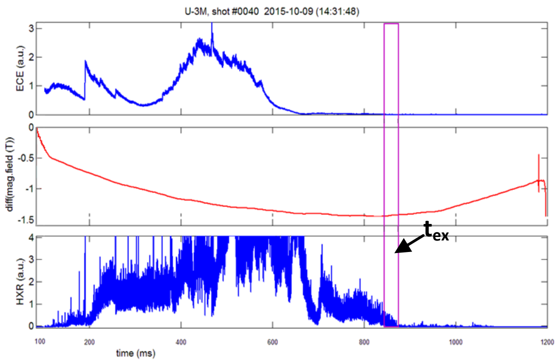

Fig. 6. The rate of change of the signal δB/δt (red line). Temporary behavior of ECE radiation and HXR received from plasma (blue lines)

CONCLUSIONS

Extended experimental evidence of suprathermal electrons mechanism was obtained for the series of the plasma discharges after turn-off the heating RF-pulse in torsatron Uragan-3M. 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, the results show clear and simultaneous response of the main plasma parameters.

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

With increasing pressure of the working gas inside the vacuum vessel, the mechanism of acceleration of suprathermal electrons during the decay of the magnetic field is leveled.

It was found that the rate of decay of the magnetic field is not constant.

The signal of ECE and hard x-rays (especially) almost always terminates when the rate of change of the magnetic field decreases.

The experimental results obtained require more rigorous consideration and further analysis. For an accurate explanation of the mechanism of the appearance of accelerated particles, it is necessary to detect the pressure value as a function of time after the RF pulse throughout the entire magnetic field pulse. It is necessary to take into account the assumption that the pressure in the chamber after the RF pulse should be restored at a constant speed for the entire time of the experimental company. And also the fact that the time which is needed to reach the working pressure level after the RF pulse is approximately one order longer than the characteristic time of the suprathermal electron radiation detection.

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НЕКОТОРЫЕ ОСОБЕННОСТИ ДИНАМИКИ НАДТЕПЛОВЫХ ЭЛЕКТРОНОВ ПОСЛЕ ВЧ-НАГРЕВА ПЛАЗМЫ НА СТЕЛЛАРАТОРЕ УРАГАН-3М

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В последние десятилетия микроволновая радиометрия регулярно используется в качестве диагностического инструмента для получения информации о временной эволюции и радиальном профиле температуры электронов в экспериментах на торсатроне Ураган-3М. Тем не менее, в случае низкоплотной плазмы при помощи этой диагностики наблюдается появление излучения на частотах, соответствующих второй и третьей гармоникам необыкновенной волны циклотронного излучения (ЭЦИ), после отключения импульса высокочастотного нагрева. Этот эффект можно объяснить существованием надтепловых электронов. Описана динамика надтепловых электронов (НЭ) после выключения ВЧ-импульса на торсатроне Ураган-3М (n_e=2·10^{12} см$^{-3}$, Te=300 эВ, P_{RF}=115 кВт, B_0=0,69 Тл). В отсутствие известных методов подавления (резонансные магнитные возмущения и массивная инжекция газа) была предпринята попытка описать факторы, способствующие генерации надтепловых электронов в плазме Ураган-3М. Представлена временная динамика интенсивности эмиссии ЭЦИ и ее зависимость от давления рабочего газа в вакуумной камере торсатрона. Уровень эмиссии ЭЦИ демонстрирует строгую корреляцию с результатами других методов диагностики (плотность плазмы, ток плазмы, интенсивность HXR и H_α). Постепенное повышение давления (после отключения ВЧ-мощности) может быть одной из причин, которые поддерживают процесс ускорения электронов. Также приведена временная зависимость излучения ЭЦИ от скорости изменения магнитного поля (δB/δt).

ДЕЯКІ ОСОБЛИВОСТІ ДИНАМІКИ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ ПІСЛЯ ВЧ-НАГРІВУ ПЛАЗМИ НА СТЕЛАРАТОРІ УРАГАН-3М

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Протягом останніх десятиліть мікрохвильова радіометрія регулярно 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 на частотах, відповідних другій і третій гармонікам незвичайної хвилі циклотронного випромінювання (ЕЦВ), після відключення імпульсу високочастотного нагріву. Цей ефект можна пояснити існуванням надтеплових електронів. Описані динаміка надтеплових електронів (НЕ) після виключення ВЧ-імпульсу на торсатроні Ураган-3М (n_e=2·10^{12} см$^{-3}$, Te=300 еВ, P_{RF}=115 кВт, B_0=0,69 Тл). За відсутності відомих методів придушення (резонансні магнітні збурення і масивна інжекція газу) була зроблена спроба описати фактори, що сприяють генерації надтеплових електронів у плазмі Ураган-3М. Представлена тимчасова динаміка інтенсивності емісії ЕЦВ і її залежність від тиску робочого газу у вакуумній камері торсатрона. Рівень емісії ЕЦВ демонструє чітку кореляцію з результатами інших методів діагностики (щільність плазми, струм плазми, HXR і H_α). Поступове підвищення тиску (після відключення ВЧ-потужності) може бути однією з причин, які підтримують процес прискорення електронів. Також наведена часова залежність випромінювання ЕЦВ від швидкості зміни магнітного поля (δB/δt).