ICRF – VOLUME CHARGE – ANTENNA EDGE INTERACTIONS IN THE U-3M AND U-2M TORSATRONS
Part 3. ICRF − VSC INTERACTION

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The brief analysis of the volume-space charge (VCS) influence on the processes of plasma formation and plasma heating with thh use of high-power ion-cyclotron waves in the U-3M and U-2M torsatrons has been carried out. The results of investigations into this problems reached on other facilities were used in this paper.

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INTRODUCTION

In the case of the stationary plasma its state is determined, in main, by the processes running in the confinement volume. In rf discharges the ICRF-space volume charge (VSC) edge interactions play a dominant role. At high rf power levels the ICRF systems can lead to the antenna surface deterioration, increase of heavy impurity emission from the antenna, change of the value and profiles of n_e and T_e in the peripheral plasma, high rf power dissipation. These effects can cause the plasma degradation in the central region [1].

The loss of the rf power P_{RF} may be related with a higher harmonic generation in the VSC layers. Nonlinear interactions between the pump waves and their harmonics lead to the excitation of waves with combination frequencies $(nf_1 \pm mf_2)$ and side frequencies $(f_n - \Omega), f_n, (f_n + \Omega)$], which have been recorded in the U-3M and U-2M torsatrons [2-9].

The results obtained evidence on the strong nonlinear pump wave-VSC interaction accompanied by the parametric decay processes.

The ion-cyclotron range of frequencies (ICRF) was used in experiments for formation and heating of the plasma in the U-3M and U-2M torsatrons. This range includes fast waves (FW), slow ion-cyclotron waves (ICW) and ion Bernstein waves (IBW). For excitation of these waves one needs significant rf field components E_y and E_z and high pump powers P_{RF}, i.e. a strong antenna-plasma coupling is required. This leads to the VSC formation, enhances the ICRF-VSC- antenna nonlinear interactions. Excitation of FW, ICW and IBW waves and their propagation in the plasma, energy transfer to the plasma particles (heating efficiency) and transformation of these modes depend on the edge plasma parameters and their gradients. These parameters, in its turn, depend on the radial motions of the local density plasma as a consequence of formation of convective cells near the antenna and MHD structures at the plasma edge. All these phenomena are interrelated and therefore it is difficult to investigate them. Nevertheless an understanding of these effects is a necessary condition for effective plasma heating in the ICRF range.

1. RECTIFICATION, RF POWER DISSIPATION, HARMONIC GENERATION

In Part 1 of this study the basic physics of space-volume charge (VSC) formation near the antenna surface in the rf discharges are described. As a result of many experimental, theoretical and simulation works a modern concept of a VSC (rf sheath) role in the initiation of many effects has been developed. A basic rf sheath physics is described in [1].

The primary cause for many of the observed phenomena is the rf sheath which exists at the "end-plates" where the field line contacts a conductor. A schematic sketch of the rf sheath is presented in Fig. 1 [1].

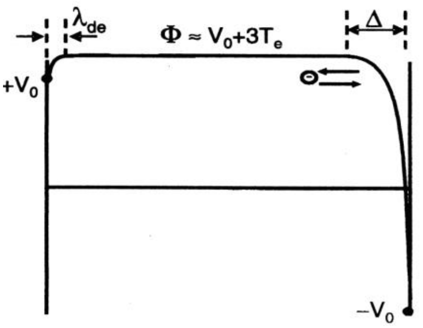

Fig. 1. Basic sheath physics schematic representation. The sheath is formed to equalize electron and ion loss rates. The resulting potential enhances the electron confinement by forming a potential barrier for electrons, i.e. the sheath of a width Δ. The same potential accelerates ions into the plates and causes the sheath power dissipation. For the rf-sheath, the driving voltages ±V_0 at each end oscillate in time and the central potential (≈ 3T_e) remains above the maximum voltage at either ends

Both species, electrons and ions, initially try to leave at their respective thermal velocities. In response to the growing charge inbalance, the plasma develops a potential to confine the electrons and to restore the charge ambipolatity. This potential, which must be higher than the applied voltage at either of the ends, reflects almost all the electrons at the sheath entrance. In addition to the reflecting electrons, this large sheath accelerates ions into the plates, creating a fast ion propagation that enhances physical sputtering. The energy for this acceleration comes from the circuit and appears as lost power to the sheath. The whole process is driven by the need for the charge ambipolarity. This basic sheath physics extends immediately into an ICRF sheath, where an oscillating voltage is applied to each of plates (Fig. 1). Electrons leave alternately out from the one end, then the other, escaping from the end where the applied voltage is the highest. This gives rise to an oscillating parallel electron current. The central voltage oscillates up and down at twice the applied frequency but always remains higher than the applied voltage at either of ends. The net effect is that there is reflection of both the applied voltage and a large second harmonic. Harmonics with the frequencies $\omega = n\omega_0$ (n=1, 2, 3) were recorded in the spectrum of plasma potential oscillations [2] and at the initial stage of rf plasma formation [3] in the U-3 torsatron. In the both papers the rf field harmonic generation is not explained by the rf sheath formation near the antenna. However in [3] it is noted that the excitation of electrostatic plasma oscillations at frequencies $n\omega_0$ (n=2, 3) can be related with parametric instabilities in the electrostatic branch of Alfven waves which exert essential influence on the pumping wave energy dissipation. For the first time the three first harmonics of the rf field in the U-3M torsatron have been obtained from the spectrum of a reflected X-wave of the reflectometer (F=19.1 GHz) [4]. It is noted that the cause might be the formation of a space discharge layers with nonlinear characteristics near the rf antenna. Later we have successfully confirmed this assumption in the simulation study of the interaction between the high-power electromagnetic radiation of ICRF with a nonlinear element (rf sheath) [5]. The ICRF can penetrate into the discharge volume only through the rf sheath layer. Taking this into account the nonlinear character can be presented as a sum

$$x_{out}(\mathrm{t})=\mathrm{k}[x_{in}(\mathrm{t})+\varepsilon\, x_{in}^{2}(\mathrm{t})]. \qquad (1)$$

Then, the pump mode $A_1\cos(\omega t)$ at the rf sheath output will be described by the relation

$$x_{out}(\mathrm{t})=\mathrm{A}_1\cos(\omega \mathrm{t})+\varepsilon/2\cdot A_1^2\cos(2\omega t)+\varepsilon/2\cdot A_1^2, \qquad (2)$$

when k=1 is taken for simplification. Thus, at the output of VSC (sheath) not only the main component $\cos(\omega t)$ but also its second harmonic cos $(2\omega t)$ and the time independent term $\varepsilon/2\cdot A_1^2$ appear; the latter indicates that the rectification effect takes place (the net sheath power dissipation). The results of ICRF-sheath interaction are very clearly demonstrated in the plots of Fig. 1 of our paper [5]. The results obtained fully coincide with above mentioned basic rf sheath physics [1]. Besides, our notion about the ICRF-VSC interaction points to their quantitative relation: the second harmonic amplitude and the rectification level are directly proportional to the rf pumping intensity. The latter is in accord with the results of [6]. If it is supposed that not only the first harmonics but the second harmonics too enters at the VSC input (due to the rerefraction from the chamber wall and from the antenna) then according to formulas (1) and (2) there are four harmonics with frequencies nf (n=1, 2, 3, 4) at the output. This process can be extended in the same way. This version is of interest as in the U-3M torsatron in the spectra of different diagnostics the harmonics up to the eleventh harmonic $f_n=nf_0$ (n=2, 3, 4…11) were observed [5]. The amplitudes of the second harmonic and the third harmonic were comparable with the amplitude of the fundamental harmonic [7]. In principle, the second harmonics and the third harmonic can be used for plasma heating. If the discharge conditions do not permit this process then in this case the generation of these harmonics can be considered as one of the rf power loss mechanism. Together with the effect of ICRF part rectification into the constant potential difference [8] the P_{RF} loss will be already appreciable during interaction with VSC. In the U-2M torsatron with the use of the both rf systems K_1 and K_2 the higher harmonics $f_n=nf_1$ (n=1, 2, …6) and $f_m=mf_2$ (m=1, 2, …5), respectively, were observed [9]. For the first time we have observed half-integer harmonics of $\Omega_n = n\cdot(f_0/2)$ (n = 1, 3, 5…13) type, so-called inharmonic obertones. In the case of simultaneous operation of K_1 and K_2 in the U-3M torsatron recorded were the (f_1 - f_2)-type difference frequencies from the spectra of reflected rf signals [10], as well as, the intensities of the line H_α [5]. In the U-2M torsatron the combination frequencies were observed not only between the pumping frequency ($f_1 \pm f_2$) but between their harmonics ($nf_1 \pm mf_2$) too [9]. The frequency upper limits were restricted by the recording capabilities. At the initial stage of the discharge the ($f_n - F$, f_n, $f_n + F$)-type oscillation frequencies were recorded. If $F << f_n$, they are determined as side frequencies [9]. Similar results were obtained using the toroidal facility ACT-1 [11] where the harmonic generation and side frequencies were observed. The harmonic amplitudes have had the intensity sufficient for the parametric decay.

2. EDGE WAVE INTERACTIONS

The ion-cyclotron range of frequencies (ICRF) is widely applicable for plasma heating. It includes fast waves (FW), slow ion-cyclotron waves (ICW) and ion Bernstein waves (IBW) [1].

For excitation of FW a high electron density ($n_e>5\cdot10^{13}$ cm^{-3}) and a poloidal component E_y of the pumping wave are required. Usually FW vanishes in the low-density edge plasma as a consequence of the right-handed screw cutoff. Therefore a good antenna-plasma coupling is necessary, i.e. the antenna should be closer to the plasma. Thus during the VSC-antenna interaction the nonlinear effects are enhanced that is noted in Part 2 of this study. In the peripheral transforming layers FW can be transformed into other waves with nonlinear properties (ICW and IBW). In the U-3M and U-2M torsatrons commonly ICW (Alfven waves) are used for plasma formation and heating [12]. Because of low group velocity ICW and IBW require higher electric field E_0 of pumping waves for excitation and maintenance of a considerable power flux. It leads to the same result, namely to the increase of P_{RF} and, as a consequence, to the enhancement of nonlinear interactions with plasma. In U-3M the excitation of IBW was recorded under conditions when the relative electron and ion velocity $U = |\vec{V}_e - \vec{V}_i|$ became comparable with the thermal ion velocity V_{Ti} [13]. In [14] the excitation of

IBW in U-3M was interpreted as a consequence of the parametric instability. In [13] IBW and its harmonics with n=1, 2, 3 were recorded in the spectra of capacitor probes. In the both cases the IBW harmonics were observed near the ion cyclotron frequency harmonics. However, the excitation and propagation of these waves in the edge plasma, as well as, the energy transfer to the plasma particles (heating efficiency) are strongly dependent on the local plasma parameters (n_e and T_e) and their gradients due to the ICRF-VSC interaction. The local density depletion n_e at the antenna is consistent with density pump-out by strong $\vec{E}$ X $\vec{B}$ convection [15]. The peripheral conditions undergo the influence of periodic MHD instabilities at the plasma edge (or ELM). They arise on the side of a lower value of B_0 and are filamentary-like structures with increased n_e and T_e. In the course of time they elongate along the B_0 lines with a characteristic size (5-10 cm) and then they accelerate outwards into SOL [16]. These radial plasma motions change the antenna-plasma coupling that leads to the change of the P_{RF} dissipation in VSC and changes the value of E_0 with corresponding consequences. The size and frequency of ELM's depend on the plasma form, in particular, on its triangularity: the higher the plasma triangularity the less is the recurrence rate and the larger are the ELM sizes. The plasma geometry influence on the ICRF-antenna connection was observed on many facilities [16]. The plasma heating conception in U-3M and U-2M with the use of ICRF is presented in [3, 12, 17].

As noted above the VSC formation begins with electron escape from the plasma to the antenna. Some of the authors have proposed a mechanism of energetic electron augmentation in the plasma [18, 19, 20]. The mechanism is based on the principle of stochastic Fermi acceleration that is experienced by the particle which comes occasionally in time into the layer with rf field. Just VSC's are such layers in the rf discharges, as is indicated earlier. The particles are reflected from the oscillating layers and gain an additional energy as solid particles from the vibrating wall. Probably this mechanism can lead to the two-temperature state of electrons in U-3M. At least, the two-temperature state of ions in U-3M was observed experimentally [21].

CONCLUSIONS

To use successfully the ion-cyclotron waves for plasma heating a complete understanding of ICRF-plasma interaction is necessary. A key feature of rf discharges is the presence of near-surface volume ion charges (VSC, rf sheath), Their linear and nonlinear numerous effects substantially change the structure and dynamics of rf discharges, determine the rf plasma heating efficiency. In many tokamaks ICRF is applied as an additional method of plasma heating and can be used for the current excitation.

Taking everything into account, ICRF is expected to be used in the thermonuclear facility ITER that stimulates a wide investigation of linear and nonlinear effects (not all of them) mentioned in this paper. To study these effects is a matter of some difficulty because most of them are interrelated and, moreover, the possibilities of diagnostics are limited. The design features of U-3M and U-2M torsatrons consist in the fact that in experiments on these facilities neither the preliminary ionization (plasma formation), nor the plasma heating by other methods, unless ICRF, are not applied. Thus, there is a good chance for the program investigations of the volume charge-antenna edge interactions in pure relic form. This certainly requires upgrading rf systems, introducing advanced diagnostics, providing many manipulations (periodic boronization, changing and varying of diagnostics, antenna displacement etc.) without vacuum condition deterioration.

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КРАЕВЫЕ ВЗАИМОДЕЙСТВИЯ ICRF – ОБЪЁМНЫЙ ЗАРЯД – АНТЕННА В ТОРСАТРОНАХ У-3М И У-2М
ЧАСТЬ 3. ВЗАИМОДЕЙСТВИЕ ICRF – ОБЪЁМНЫЙ ЗАРЯД

В.Л. Бережный

Проведен краткий обобщённый анализ влияния объёмного пространственного заряда (VSC) на процессы создания плазмы и эффективности её нагрева мощными ионно-циклотронными волнами в торсатронах У-3М и У-2М. Использовались также достижения исследований по этой проблеме на других установках.

КРАЙОВІ ВЗАЄМОДІЇ ICRF – ОБ'ЄМНИЙ ЗАРЯД – АНТЕНА У ТОРСАТРОНАХ У-3М ТА У-2М
ЧАСТИНА 3. ВЗАЄМОДІЯ ICRF – ОБ'ЄМНИЙ ЗАРЯД

В.Л. Бережний

Проведено короткий узагальнюючий аналіз впливу об'ємного просторового заряду (VSC) на процеси створення плазми та ефективності її нагріву потужними іонно-циклотронними хвилями в торсатронах У-3М і У-2М. Використовувались також досягнення досліджень з цієї проблеми на інших установках.