EFFECTS OF RF FIELD RECTIFICATION AND ACCELERATED ELECTRON BEAM GENERATION IN THE TORSATRON U-3M DURING PLASMA PRODUCTION

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The presented experimental results show that during the interaction between the RF field and a spatial charge of positive ions having the nonlinear volt-ampere characteristic a part of the RF field is rectified into the direct component. This direct electric field accelerates the electrons emitting from the antenna surface.

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THE EFFECT OF THE RF VOLTAGE RECTIFICATION

In a large body of measurements the existence of a high positive spatial potential in the near-electrode space of RF discharges was shown [1,2]. Immediately in the torsatron U-3M this effect has not been studied. However, in the experiments on studying the behavior of impurities during plasma RF-heating the flows of metal impurities into the plasma from the RF-antenna and the helical coil casings were found out, Fig.1 [3]. A main cause for the ingress of impurities Ti and Fe is the sputtering from the surfaces of the antenna and the helical winding casings. It has been suggested that the surface sputtering occurs because of bombarding the surfaces with ions accelerated by a quasi-constant positive potential up to the energies of 100 eV. Such a potential can arise due to the formation of a spatial charge (SC) of positive ions near the electrodes of RF discharges [1,2]. The potential direct component is determined

$$U_0 = 6\pi \cdot e \cdot n_i \frac{\mu_0^2 \cdot U_m^2}{\omega^2 \cdot p^2 \cdot d^2}. \qquad (1)$$

Here $\rho = e \cdot n_i$ – the value of a positive space charge, μ_0 - electron mobility at pressure $p = 1\,Torr$, U_m - peak value of RF voltage, d - the length of RF discharge. As follows from (1) the U_0 amplitude is determined by ρ and the RF field amplitude $A = \mu_0 E_m / p\omega$.

The total Coulomb field of positive ions in the SC usually is 10^6 V/cm [4]. According to the version of [2] the RF discharges possess valvular properties. The direct component of the potential difference U_0 between the plasma and the RF electrode is the result of the rectification of a part of RF voltage: $U_0 = V_{\sim} / \pi$. The rectification of RF voltage occurs similarly to the linear detection mode. In many experiments the value of U_0 reached 400 V [2].

A process of SC formation in U-3M can be represented by the following way. As the RF-generator is brought into operation, the field is localized near the surface of an unscreened frame antenna because its geometrical dimensions ($l \approx 1$ m) are much less than the generated wave length in space ($\lambda \approx 34$ m). Thus, in the initial moment of time the antenna can be represented as a cold cathode. First, the plasma is created in this local RF field near the antenna surface. Therewith, in this plasma layer a spatial charge of positive ions is formed [1,2]. The alternating voltage increasing on the antenna leads to increase of the direct component U_0 [2]. Thus, the energy of the flow of ions bombarding the antenna surface increases, enhancing the effect of antenna sputtering (see Fig. 1).

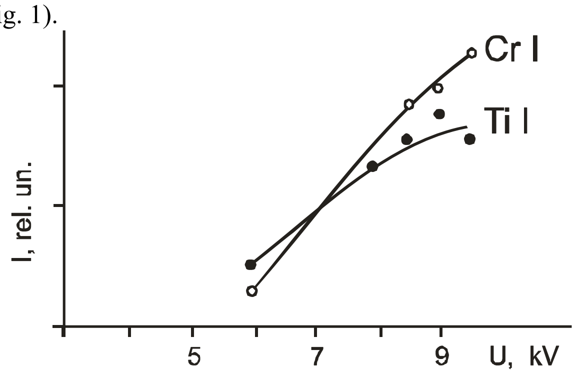

Fig. 1. Intensity of the CrI line near the helical winding casing and TiI line near the RF antenna with TiN coating

The ingress of high Z impurities into a central plasma volume influences L to H regime transition, development of internal and external transport barriers of RF discharges; even insignificant impurity influx can be problematic for a hot plasma [5]. As was found in [5], impurities were generated due to sputtering of RF antenna surface caused by bombardment with ions accelerated in the field of space charge (other terms used are 'RF sheath', 'plasma sheath' or 'near field sheath'). An attempt was made to suppress the influx of impurities by protection of antenna with Mo tiles or by boronization. In the first case the influx of impurities decreased noticeably but not fully. Much more effective for suppression of impurity influx was boronization of antenna surface; however, the boron-containing film was practically completely eroded during a pulse by plasma impact (with the rate ~20 nm/s) when RF power was P_{RF}=3 MW. Taking into account that RF heating of plasma is planned to be used in ITER, solution of the problem of impurities is very actual. In the review paper [6] more than 100 papers relating different aspects of nonlinear effects in ICRF-plasma are analyzed, including generation of heavy impurities. At the quasi-stationary stage of RF discharge the field frequency is significantly less than the electron plasma frequency $\omega_0 << \omega_{pe}$. Therefore, the condition of RF field localization near the antenna surface is substantially held. Consequently, the RF field, propagating from the antenna, must overcome SC. SC has a nonlinear volt-ampere characteristics [2], therefore, the signal at its output can be represented as $x_{out}(t) = k[x_{in}(t)+\varepsilon x^2_{in}(t)]$. Then the pump wave $A_1\cos(\omega t)$ at the SC output is converted to $x_{out}(t) = A_1\cos(\omega t)+\varepsilon/2\cdot A_1^2\cos(2\omega t) + \varepsilon/2\cdot A_1^2$. Besides the pump wave and its second harmonics, a constant term $\Delta = \varepsilon/2\cdot A_1^2$ appeared. This term corresponds to the shift of the average value of the function $A_1\cos(\omega t)$. It evidences on the presence of the alternating current rectification similar to that shown in [2]. If, e.g., there is simultaneous interaction between the SC and the first harmonic with every next one up to the tenth one, then the shift value appreciably increases [7]:

$$\sum_{n=1}^{10}\Delta_n = \frac{\varepsilon}{2}[A_1^2 + (A_1^2 + A_2^2) + (A_1^2 + A_3^2) + \cdots + (A_1^2 + A_{10}^2)] \quad (2)$$

apparent. In the present paper rectification of some part of RF field become we demonstrate that due to interaction of the pump mode with the nonlinear element, both the effects of higher harmonics generation and

The rectification efficiency is determined by the SC nonlinearity coefficient ε and by the RF harmonic amplitudes participating in the interaction.

GENERATION OF THE ELECTRON BEAM

First works on generation of currents by powerful electromagnetic waves were provided when laser beams interacted with solids. In [8], the current $I = 100\ A$, $W = 10\ kW$ was registered when metallic target was irradiated by the ruby laser beam ($P_0 = 30\ MW$, $\tau = 60\ ns$, $\lambda = 0.7\ \mu m$), with coefficient of efficiency $\cong 3\cdot 10^{-2}\ \%$. In [9] the currents were generated by impact of CO_2 laser radiation ($P_0 = 9.8\ MW$, $\lambda = 10.6\ \mu m$, $\tau = 3 \ldots 4\ \mu s$) with the target (Cu). The current was characterized by $I = 14\ A$, $U = 780\ V$, and coefficient of efficiency $\cong 10^{-1}\ \%$. The direct conversion of energy of microwaves was observed in [10] (metal target). At pulsed rate of flow $q \cong 100\ kW/cm^2$ ($\lambda = 5\ cm$) the current reached $I = 200\ A$, the positive potential $U = 1.5\ kV$, and coefficient of efficiency exceeded $10\ \%$.

Two important conclusions follow from these early results on generation of currents by electromagnetic waves. First, in spite of difference in wavelengths (lasers and RF) and powers, the observed phenomenon of current generation is very similar what indicates that identical physical processes are realized (formation of spatial charge). When high power radiation is focused on a target, some amount of material is vaporized and ionized, thus plasma is created which expands from the target surface. Because of difference in velocities of electrons and ions, the space charge of positive ions forms. Second conclusion: the efficiency of current increases with increasing the wavelength of the power source. For example, in paper [11] the "effective temperature" of fast electrons emitted from plasma target due to strong microwave field ($q_m = 80\ kW/cm^2$; $\lambda = 5\ cm$) was in a good correlation with the scaling law $T_h(keV) = 7.75\cdot 10^{-10}\cdot(q_m\lambda)^{2/3}$, with $q_m\ (W/cm^2)$; λ (μm).

Taking into consideration that RF power in U-3M experiments is close to that used in [11] and the wavelength ($\lambda \cong 34m$) is significantly longer, one can suppose the generation of accelerated electrons in the case of U-3M is also possible.

The formation of a near-cathode SC layer is a necessary condition for the electron emission from the cold cathode [12,13]. In general, the field emission occurs in the direct electric field due to bombardment of cathode by positive ions and by tunneling electrons due to positive ion fields arising as a result of excited atom ionization at the antenna surface. The electron beam moves perpendicularly to the antenna surface against the beam of ions which bombard it. By their way electrons ionize gas atoms thus maintaining the concentration of positive ions in the SC, and go on into the main plasma. In the direct electric field some electrons pass into the fast electron regime. In the acceleration process the electrons appeared near the antenna surface as a result of gas ionization are also involved. If the intensity of the direct electric field exceeds the Dreicer field $E_- > E_D = 2\pi n_e \ln\Lambda / T_e = 10^{-12}\frac{n_0\ (cm^{-3})}{T_e\ (eV)}$, then in the acceleration process a significant part of antenna-emitting electrons and plasma electrons are participating [14]. For the mode of U-3M operation with $n_e = 2\cdot 10^{12}$ cm^{-3} and T_e of several hundreds of electrons this condition is well-fulfilled. The presence of an accelerated electron beam is qualitatively confirmed by the experimental fact of a H_β line intensity increasing up to the initial level, 9 μs after fall down to zero since the RF pulse finish in U-3M, Fig.2 [15]. The $\cong 9\ ms$ time delay can characterize the time for relaxation of the beam energy in collisions with hydrogen molecules, with start to come freely into the confinement volume after the density of periphery plasma (mantle) decreased and its screening effect disappeared. The second rise of the divertor plasma density cam also be explained by this reason.

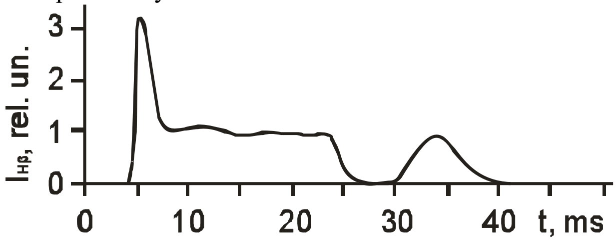

Fig. 2. Time behavior of H_β line intensity

CONCLUSIONS

1. So, the processes of RF field harmonic generation, RF field rectification and electron acceleration occur as a result of SC formation and SC-RF field interaction. These nonlinear processes are the main sources of RF power

loss on the fundamental harmonic, the frequency of which is selected to the condition of plasma heating in U-3M $\omega = (0.8...1)\times\omega_{\beta i}$. As an example, let P_0 = 150 kW. One third of this power is rectified into the direct component of the potential difference U_0. The rest 100 kW we should roughly distribute between the first four harmonics and thus obtain $P(\omega_0) \approx 25$ kW. This figure roughly coincides with estimations of the plasma energy density <nT>.

2. Effect of rectification $U_{\sim}\to U_0$ represents in [2] as $U_0 = V_{\sim}/\pi$ and in [5] as $U_0 = \sqrt{P_{Rf}}$. We showed that the efficiency of rectification is determined by the sum of squares of amplitudes of all harmonics which interact with a RF-sheath.

3. Formation of RF-sheath results in bombardment of RF antenna with accelerated ions, provoking flux of heavy particles into plasma.

4. Existence of RF-sheath is a necessary condition for the beam of accelerated electrons to be formed. This effect is used in investigations on the direct transformation of electromagnetic energy into the energy of current. Recently with the laser beam energy 10…15 J, laser wavelength λ = 810 nm, pulse duration τ_u = 40…50 fs the accelerating voltage reached ≈ 1 GV/cm and the energy of accelerated electrons up to 200 MeV [16]. For the conditions of U-3M experiments some estimations give the electron energy ≈ 170 keV. The accelerated electrons can be strongly weakened because of anomaly resistance due to excitation of current instabilities [17]. Also high energy electrons in U-3M can provide additional ionization of gas that comes into the confinement volume from the vacuum tank.

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ЭФФЕКТЫ ВЫПРЯМЛЕНИЯ ВЧ-ПОЛЯ И ГЕНЕРАЦИИ ПУЧКА УСКОРЕННЫХ ЭЛЕКТРОНОВ В ТОРСАТРОНЕ У-3М

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Показано, что при взаимодействии ВЧ-поля с объемным пространственным зарядом положительных ионов с нелинейной вольт-амперной характеристикой часть его выпрямляется в постоянную составляющую. Кулоновское поле положительных ионов ускоряет эмиттирующие из поверхности антенны электроны.

ЕФЕКТИ ВИПРЯМЛЕННЯ ВЧ- ПОЛЯ ТА ГЕНЕРАЦІЇ ПУЧКА ПРИСКОРЕНИХ ЕЛЕКТРОНІВ У ТОРСАТРОНІ У-3М

В.Л. Бережний, І.В. Бережна, В.С. Войценя, І.Б. Пінос, В.В. Філіппов

Показано, що при взаємодії ВЧ-поля з об'ємним просторовим зарядом позитивних іонів з нелінійною вольт-амперною характеристикою частина його випрямляється у постійну складову. Кулонівське поле позитивних іонів прискорює електрони, що емітуються з поверхні антени.