INTERACTION OF MODULATED REB WITH PLASMA, FORMED AT ITS TRANSIT THROUGH HIGH-DENSITY NEUTRAL GASES

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The theoretical and experimental results of investigations of the relativistic electron beam interactions with plasma, created during its penetration into neutral gas of large pressure, are presented. It is shown that by using of deeply modulated beam it is possible to avoid the depressive influence of dissipation and longitudinal nonuniform plasma density on the beam-plasma interaction efficiency.

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1. INTRODUCTION

The research of processes, arising during injection of relativistic electron beam (REB) in air at atmospheric pressure or other gases of high-density, along with fundamental meaning is of interest for the various applications. In particular, at application of REB in plasma-chemistry it is desirable to fulfil conditions, at which the beam creates plasma, effectively interacts with it, resulting in development of plasma-chemistry processes [1,2]. At the same conditions the microwave radiation in a short-wave range is possible [3]. On the other hand, for radiation processing of various materials, for clearing of sewage and decontamination of medicinal preparations it is desirable to transport REB in atmosphere without essential losses.

In this paper the results of theoretical and experimental researches of interaction of modulated REB with plasma, formed by REB itself in air at atmospheric pressure are presented. In the researches conducted earlier [4-6] insufficient attention to influence of beam modulation on the efficiency of beam-plasma interaction was paid especially in case of nonuniform and dissipative plasma.

2. THEORY

Let's consider a spatial problem of REB injection in plasma half-space $z \geq 0$. The beam with relativistic factor γ_0 and density n_b, previously modulated on density with frequency ω_M, represents a sequence of square pulses of duration T^*, following through the period $T=2\pi/\omega_M$ i.e. REB is modulated with duty factor $S=\lambda/a=6$, where a is the length of a bunch, λ is the wavelength of accelerator HF-power. The plasma is nonhomogeneous $n_p(z)$, therefore at the frequency of an excited wave $\omega \approx \omega_p \approx \omega_M$ the wave vector $k_z(z)$ changes along length of interaction according to a dispersion equation for a plasma wave $\varepsilon(\omega,k_z)=0$. Besides the plasma is supposed dissipative. Damping of the excited wave, determined by pair collisions, stochastic jumps of the wave phase, and processes of decay and radiation etc., will be characterized by an effective collision frequency ν_{eff}.

The self-consistent set of equations in dimensionless variables, describing interaction of modulated REB with collisional nonuniform plasma, has a view:

$$\frac{dC}{d\zeta} = -\kappa G(\zeta)C + \frac{1}{2\pi}G(\zeta)\int_{-\pi}^{\pi} F(\Theta)\Psi(\Theta_0)e^{i\Theta + \int^{\zeta}\Lambda(\zeta')d\zeta'} d\Theta \qquad (1)$$

$$\frac{d\rho}{d\zeta} = -\frac{1}{2}C(\Theta)e^{-i\Theta - i\int^{\zeta}\Lambda(\zeta')d\zeta'} + K.C.; \qquad (2)$$

$$\frac{d\Theta}{d\zeta} = \frac{\gamma_0^2}{\beta}[F(\Theta) - 1]. \qquad (3)$$

The first equation describes excitation of a plasma wave, whose complex amplitude C=E/E$_{tr}$; E$_{tr}$=m$V_0^2\delta k^2\gamma_0^3$/ek$_0$ is the amplitude, at which beam is trapped by a wave; $\delta k = \omega_p^0/\gamma_0 V_o(\omega_b^2 V_0/\omega_p^2 V_g)^{1/3}$ is the spatial coefficient of amplification (gain parameter); $\beta = \delta k\gamma_0^2$; $V_g = d\omega/dk_z$ is the group velocity. Other two equations are self-consistent equations of the beam electron motion of in the field of excited wave; $\rho = (P - P_0)/P_0\beta$ is the dimensionless momentum of the beam electron in a system, bound with the wave. Function Ψ, describing the type of beam modulation, is selected in the form

$$\Psi(\Theta_0) = \begin{cases} 1, & \Theta_0 \le \Theta_*, \\ 0, & \pi \ge \Theta_0 \ge \Theta_* \end{cases} \qquad (4)$$

and corresponds to steep rectangular modulation with duty factor $S=2\pi/\Theta_*$. The relativism of the beam electrons is taken into account by the function

$$F=(\sqrt{(\gamma_0^2 - 1)(1 + \rho\beta) + 1}/\gamma_0(1 + \beta\rho) \qquad (5)$$

The dissipation of the excited wave is characterized by parameter $\mathbf{k} = \nu_{\text{eff}}/2V_0\delta k$. Non-uniformity of the plasma density is described by the function

$$G(\zeta) = k_z/k_0 = 1/(1 - \Lambda\delta k/k_z); \quad \Lambda = (k_z - k_0)/\delta k \qquad (6)$$

Further for the simplicity the linear dependence of the wave number on coordinate is considered. $\Lambda = \alpha\zeta$ corresponds to that.

The set of equations (1) - (3) was solved numerically on the computer (method of particulate computer simulation [7] for area of parameters, close to experiment: $\gamma_0=5$; $S=6$; $\kappa = 0 - 5, \Delta = 0 - 2$.

The results of the computer simulation show, that for unmodulated beam both dissipation and longitudinal nonuniformity of plasma density result in failure of instability (Fig. 1).

If at these conditions ($\kappa=2$, $\Delta=-0.2$) the modulated beam is used with $S=6$, the instability develops in spite of taken non-uniformity and dissipation, i. e. the same values of maximum amplitude of a field, as well as in uniform nondissipative case for the unmodulated beam are reached.

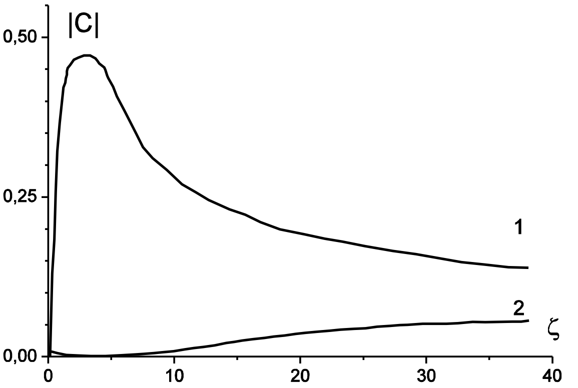

Fig. 1. Dependence of amplitude of the excited wave on coordinate: 1 - modulated beam; 2 - unmodulated beam (κ =2; Λ =-0,2)

Thus excitation of HF-fields and beam-plasma breakdown can be most effective, when the frequency of modulation of the beam ω_M is close or is multiple to a plasma frequency $\omega_M \approx \omega_p = \left(4\pi n_p e^2 / m\right)^{1/2}$. If plasma density increases above than this level, resonance is baffled, intensity of HF-fields, in which the discharge is developed, decreases and plasma density drops. It can result in relaxational oscillations of plasma density near its resonant value $n_p^* = \omega_M^2 m / 4\pi e^2$. It is possible to receive an estimation of a necessary current density of the beam for creation of resonant conditions, at pressure close to atmospheric, using expression for plasma density, formed by REB at its transporting in gas [8].

$$\frac{\partial n_e(z)}{\partial t} = \frac{I_b}{e A_p(z) E_{ei}} \frac{dE}{dz} - \alpha n_e n_i - k_{np} n_{e_0}^2 \qquad (7)$$

here I_b is the beam current, $A_p(z)$ is the area of a plasma channel, formed by the beam, $\frac{dE}{dz}$ is the ionization losses of the beam on a unit of length of a path, E_{ei} is the energy of derivation of ion - electron pair.

The first term in a right member (7) yields number of electrons, produced by the beam. The second and third terms determine losses of plasma electrons, which are determined by a dissipative recombination with a constant α and three-dimensional trapping of plasma electrons by oxygen molecular with constant k_{np}. n_i is the ion density, which equals in our case to electron density n_e. Using value $\frac{dE}{dz}$ and E_{ei} and from [9], α and k_{np} from [10], we obtain, that the minimum current density, at which the resonant plasma with density $n_p \approx 10^{11}$cm^{-3} can be obtained, equals $J_{cr} \approx 0.2$ *A/cm²*.

3.EXPERIMENTAL INSTALLATION

In our experiments REB was used, obtained with the help of a linear electron accelerator. Parameters of the beam: energy *W*=2 *MeV*, current in a pulse $I_b = 1A$, pulse duration $t = 2\mu s$, frequency of the beam modulation $f_0 = 2850$ *MHz*. Each pulse has $N = 6 \times 10^3$ bunches of electrons with duration $\tau_o = 1{,}5 \times 10^{-11} s$. Mean density of electrons in the beam $n_b = 5 \times 10^8 cm^{-3}$. At realization of experiments there was the possibility to change width of the electron distribution function of the beam on energy in limits from *8 %* up to 50 % by changing the modulation frequency over the range *0,15 %.*

The beam was injected directly in atmosphere or in the chamber of interaction, representing glass tube of length *50cm* and diameter *10cm*, through a titanium foil by depth *50µm*. The chamber of interaction was filled with different gases, which pressure varied in limits from *1* up to *760Torr*.

The current of the beam electrons was measured by Faraday cylinder and mobile Rogovsky belt of diameter *30 cm* . The plasma density, formed by the beam, was determined on its conductivity σ by the special microwave - probe [11]. At high pressure of neutral gas and frequency of the applied field $\omega = 10^4 - 10^7 s^{-1}$ this conductivity $\sigma = e n_p \mu_e$. The electron motility μ_e at given density and temperature of neutral gas was determined under the tables [12]. The measurement accuracy of plasma density by such method is within the limits of 20 %.

The duration of plasma glow was determined with the help of FEU-29, whose maximum sensitivity is in the region of the visible spectrum. For protection of FEU from X-radiation, arising at injection of the beam from an accelerator, it was placed outside of a zone of X-radiation, and light on FEU was transmitted by the optical waveguide of length 2*m*.

The X-radiation from interaction zone registered by the semiconducting x-ray sensor and obscure chamber.

4.EXPERIMENTAL RESULTS

The experiments have shown, that at injection of REB in atmosphere, the plasma with intensive glow in visible range of a spectrum is produced. Thus the duration of plasma glow ($t \approx 5\mu s$) considerably surpasses pulse duration of the beam current ($\tau = 2\mu s$) (Fig. 2a, b). The beginning of the plasma glow is not synchronized with beam current pulse (glow starts *0.3–0.4 µs* after beginning of a current pulse). The maximum amplitude of glow is on the second half of current pulse. At small pulse duration of the current ($\tau < 0.5\mu s$) the glow is not observed. The most intensive glow is observed from area, arranged apart 5 – 10cm from exit foil of the accelerator.

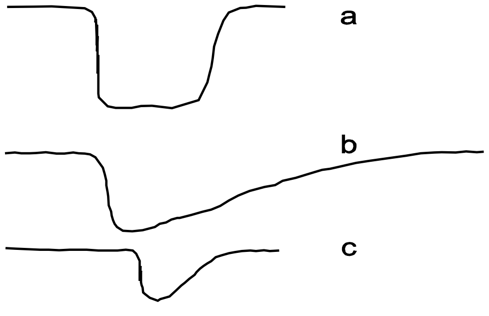

Fig. 2. The oscillograms: a - current pulse of a beam; b - signal of plasma glow; c - signal of X-radiation

The results of measurement of plasma density have shown, that in the region of intensive glow ($0 < l < 10cm$) the plasma is uniform (Fig. 3), and its density $n_p \approx 5 \times 10^{11} cm^{-3}$, so the plasma frequency is close to frequency of the beam modulation ($\omega_M \approx \omega_p$). On large distances ($l > 10$ *cm*) plasma density decreases, that is explained as decreasing of the current density of the beam in connection with its angular divergence, and with dissipation of the beam electrons at its interaction with plasma in a resonance region. The measurements by the x-ray sensor and chamber - obscurer have shown presence of region of soft X-radiation generating, which coincides with region of maximum plasma glow. The pulse of X-radiation is shorter than a current pulse of the beam and corresponds to the second half of this pulse (Fig.2, c).

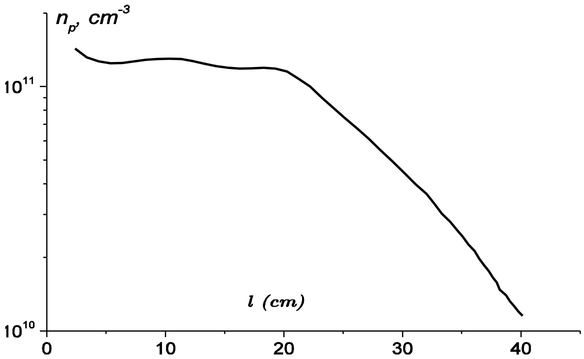

Fig. 3. Distribution of plasma density along the axis of the beam propagation

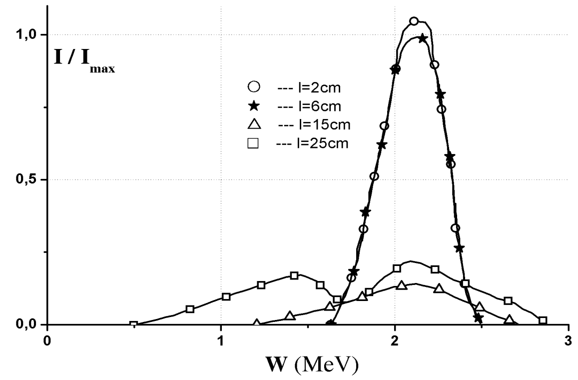

Fig. 4. Energy distributions of beam electrons on different distances from an exit foil

The energy distributions of the beam electrons, past through the plasma, formed in atmosphere by beam, apart 2, 6, 15 and 25 *cm* from an exit foil of an accelerator are shown in Fig. 4. It is visible, that if near to the foil the energy distribution is close to a distribution in vacuum, after transit of a resonance region the considerable change of the energy distribution with formation of an electron bunch lost up to 25 % of the energy is observed. On large distances from an exit foil (*l >25cm*) the change of the energy distribution in comparison with vacuum are less sizeable, as the electrons, lost energy as a result of collective interaction with plasma, do not fall in an analyzer, because of considerable angular dissipation.

At increase of width of the beam electron energy distribution up to 50 % the power loss of electrons equals *100-120 keV*, that coincides value of ionization and radiation power losses of a relativistic electron at its transit in air of atmospheric pressure of distance *25cm*, at absence of collective interaction.

At decreasing of the beam current $I_b \leq 200$ *mA*, it was revealed, that all effects, bound with collective interaction of the beam, disappear. This current value is critical and is well agreed with minimum current, which is necessary for creation of resonant plasma density, determined by expression (7).

5.CONCLUSIONS

Thus, the results of the experiments show, that at transporting of modulated REB with current 1A and width of an energy distribution of the beam electrons $\Delta W/W \leq 10\%$ in neutral gas with pressure *20-760 Torr* the localized equilibrium and resonant plasma is produced, with which REB effectively interacts.

The large beam energy losses, found in experiment, presence of X-ray and microwave - radiation from an interaction region, and also the dependence of these effects on width of an energy distribution of the beam electrons, evidences the collective interaction of this beam with plasma.

Computer simulation has shown that for the modulated beam the restrictions on dissipation of the beam and spatial non-uniformity of the plasma density are considerably softened in comparison with a non-modulated beam. The results of experiment coincide with theoretical calculations.

The experiments with the hydrodynamic beam and beam with a wide distribution function of the beam electrons on energies show that the efficiency of the relaxation of the beam essentially depends on a degree of mono-energy distribution of the beam pursuant to [13].

It is necessary to mark, that REB interacts most effectively with plasma, formed at its transit through molecular gases with many electrons in atom (air, oxygen). Through the hydrogen and helium REB passes with much smaller energy losses of electrons and all other physical effects are expressed much more weakly.

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ВЗАЄМОДІЯ МОДУЛЬОВАНОГО РЕП З ПЛАЗМОЮ, ЩО ВИНИКАЄ ПРИ ЙОГО ПРОХОДЖЕННІ ЧЕРЕЗ НЕЙТРАЛЬНИЙ ГАЗ ВЕЛИКОЇ ГУСТИНИ

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Представлені теоретичні та експериментальні результати досліджень взаємодії релятивістського електронного пучка з плазмою. Показано, що при використанні глибоко промодульованих пучків можливо уникнути пригнічення пучково-плазмової нестійкості дисипацією і поздовжньою неоднорідністю плазми

ВЗАИМОДЕЙСТВИЕ МОДУЛИРОВАННОГО РЭП С ПЛАЗМОЙ, ОБРАЗОВАННОЙ ПРИ ЕГО ПРОХОЖДЕНИИ ЧЕРЕЗ НЕЙТРАЛЬНЫЙ ГАЗ БОЛЬШОЙ ПЛОТНОСТИ

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Представлены теоретические и экспериментальные результаты исследований взаимодействия релятивистского электронного пучка с плазмой. Показано, что при использовании глубоко промодулированных пучков возможно избежать подавления пучково-плазменной неустойчивости диссипацией и продольной неоднородностью плазмы.