WAVE NONLINEAR INTERACTION EFFECT ON BEAM-PLASMA RECIPROCAL INFLUENCE

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The authors have examined the oscillation excitation by an extensive nonrelativistic beam of electrons in the beam-plasma discharge in the magnetic field when the beam power is about hundreds of kilowatts. It is demonstrated that low-frequency (LF) ion waves from the range of the low hybrid (LH) resonance play the determinative role in maintaining the beam-plasma discharge. Excitation of such waves is stimulated by the nonlinear interaction between electron plasma oscillation modes of the decay type. The electromagnetic radiation emission from the discharge of pulses is stimulated by the above-mentioned nonlinear interaction, which also causes the wave stochasticity and stabilizes the beam instability.

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INTRODUCTION

For understanding the physical nature of the collective beam-plasma (BP) interaction it is important to study the process of transition of the continuous regime of generation of plasma potential oscillations (further denoted as microwaves) to the discontinuous radiation emission (EMR) interaction under the condition of augmenting the beam power (current) [1]. Being of the analytical interest, these investigations also have the practical value for the elaboration of beam-plasma generators of microwaves. In the given report, we submit the results of the experimental investigations of this phenomenon. We will demonstrate that the basic processes that stimulate this transition are conditioned by the plasma no linearity during the excitation of microwaves, characterized by the electric field strength of large amplitudes. The tests are based on the correlation between the plasma parameters, oscillation amplitude and the function of beam electron distribution in energy during time intervals of EMR emission.

TEST BENCH AND RESULTS OF INVESTIGATIONS

The researches were conducted in terms $\omega_{pe}.> \omega_{He}$ (ω_{pe} ω_{He}-electron plasma end cyclotron frequency). The pulse beam parameters are the following: the duration is 250µs, the energy is~40keV, the current is (1-15) A and the beam diameter is 20 mm. The interaction occurs in a glass tube of the diameter 200 mm and the length 1.5m. Zones of the tube and gun differ in pressure: in the gun it makes $2*10^{-4}$ Pa, whereas the pressure in the interaction area is (10^{-2}-10^{-1}) Pa. Hydrogen, helium and argon are used as the plasma-generating gases. The gun and interaction area are placed into the magnetic field ($8*10^{4}$-$1.6*10^{5}$) A/M. The plasma density spatial distribution (n_e) and the electron temperature (T_e) distribution over the beam-plasma discharge (BPD) radius are determined by the optical method, elaborated in [2]. The beam energy spectrum is investigated with the electrostatic analyzer of the resolution 0.1% and the temporal resolution smaller than 0.1µs. The EMR is received with an antenna, registering the magnetic component. The signal is analyzed with the help of a set of filters and a tunable resonator. The time of the plasma formation in BPD is (5-50) µs (n_e~(1-5)×10^{12} cm^{-3}; T_e = (30-100) eV). The plasma is characterized by the spatial anisotropy of ion energy. The ions of the energy about several keV are detected along the discharge, whereas in the radial direction the ions of the energy up to (30-50) eV are registered. All the investigations have been carried out after 50µs since the current pulse initiation.

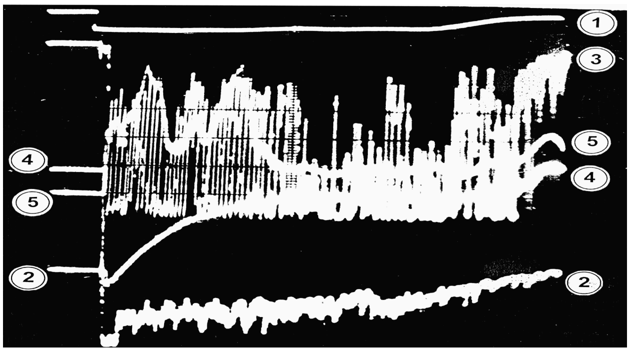

Fig. 1

In Fig.1, one can see the following oscillograms: the beam energy (1); the beam current pulse (2); EMR pulses (3); the light integral radiation emitted by the plasma (4); the lines 5015 Å (5). The oscillograms (4) and (5) indicate that the plasma average density is maintained constant during the pulse duration. At the same time, EMR is registered in the form of pulses ~1µs, the repetition period being (1-1.5) µs. The frequencies less than the electron-plasma frequency are registered in the EMR spectrum. As it is found out, the EMR pulse duration depends on the beam power. If the beam power makes several kW, the EMR emission duration can reach 1µs. If the beam power is about several hundreds of kW, the pulse duration makes tenths parts of µs, and the pulse repetition period is chaotic.

It is also discovered that notwithstanding a high level of LF ion oscillations that provide Bohm coefficient of the plasma diffusion (3×10^{5}cm^{2}/s), the radial gradients of n_e do not change their values during the time~1µs. That is, the BPD geometry is preserved.

In Fig.2, the radial distributions of n_e and T_e over the BPD central cross-section are presented. depicts that the BPD geometry is close to the form of a tube. The distribution of n_e in radius is obtained by averaging the measurements over a large number of the pulses. The experimental data indicate that the detected phenomena have to be determined by a specificity of the beam interaction with the annular waveguide.

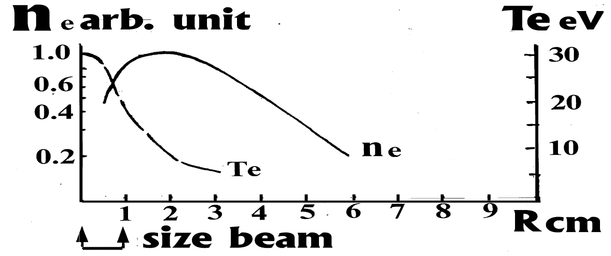

Fig. 2

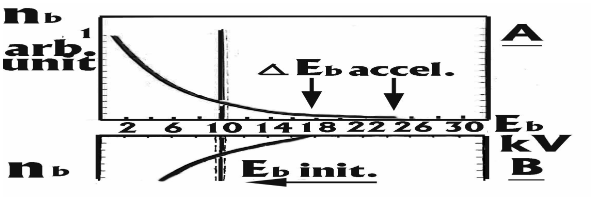

Fig.3

In Fig.3, we have plotted the functions of the beam electron distribution in energy, registered in the time intervals of the EMR emission (B) and its absence (A). As one can clearly see, the beam is substantially scattered in energy. The beam energy losses during EMR emission (B) are heavier than during its absence. The accelerated electrons of energies much higher than the average beam energy are registered. The estimations indicate that the beam energy expenditure on the electron acceleration is commensurable with the EMR energy about 30% of the beam energy content. The derivative of the distribution function of electrons in energy, taken with respect to their velocity, is negative. Dynamics of changes in the beam spectra permits supposing the following: (1). Either in BPD start periodic nonlinear processes that alter the wave polarization, or (2) the beam stimulates the excitation of microwave potential oscillations that periodically transfer into EMR. However, a high coefficient of the microwave transformation into EMR is inexplicable with the help of linear mechanisms for the BP interaction. Besides, according to [3-4], the inclined microwave excitation effectiveness is not high under the experimental conditions. It is more probably that EMR emission is stimulated by the wave nonlinear transformation with the participation of oscillations from the range of low hybrid (LH) resonance at the frequency $\omega_h=(\omega_{He}\omega_{Hi})^{1/2}$ (here ω_{Hi} are the ion cyclotron frequencies). This supposition is confirmed by the existence of EMR amplitude modulation at LH frequency. Besides, the LF oscillation spectrum enrichment with small-scale longitudinal ion oscillations from the LH resonance range, which occurs during the beam power increase, also serves as a characteristic feature of the LH oscillation participation in the wave nonlinear interaction.

The analysis given to the beam interaction with a tubular plasma waveguide indicates that the waveguide electrodynamic characteristics favor the wave nonlinear interaction development.

According to [5-7], in a tubular waveguide can exist axially-symmetric potential microwaves of the three types: spatial waves and surface waves with the normal and abnormal dispersion, emitted at the frequencies lower than the electron-plasma one ω_{pe}. Approaching this frequency, the wave phase velocities become low and close to one another. This means that at certain moments the beam, losing its energy, can interact with a pair of waves, exciting them simultaneously, which favors the establishment of nonlinear coupling between these waves. In particular, the coupling is strengthened when the difference in the microwave mode frequencies is equal to the wave frequency. In this case, microwaves transfer their energy to this wave $\omega_h=(\omega_{He}\omega_{Hi})^{1/2}$ However, before the realization of the given condition, the microwave excited by the beam can be decomposed into the electromagnetic and LH waves. An important aspect of the wave nonlinear interaction is that the initial value of LF wave amplitude is large. The presence of an initial disturbance in plasma diminishes the threshold values of the microwave electric field strength, after the excess of which the decay-type nonlinear interaction begins [8]. If the beam excites microwaves in an annular waveguide, the electric field strength threshold values, required for the decay nonlinear process realization, can be diminished due to the phenomenon of the double resonance. The beam excites two microwave modes at close frequencies and LF mode at the difference frequency. At the same time, at the kinetic stage in the instability development, when the beam distribution function in velocity $f(v_e)$ becomes spatially inhomogeneous (in addition, $d\ (v_e)/dv_{ez}$), the beam can directly excite LF wave at the same difference frequency [9]. The analysis indicates that the beam characterized by the distribution function presented in Fig.3 can excite oscillations from the LH resonance range, the increment of growth of which is equal to the ion-plasma frequency period.

For the EMR emission, the waveguide proper waves must participate in the decay process. However, for the beam of the energy examined in the experiment, this scheme is unrealizable. Under the experimental conditions, the wave can be decomposed just into an improper electromagnetic wave and a LH one. The correlation between the amplitude and shape of the oscillations from the LH resonance range and the amplitude of EMR testifies that in the experiments can exist the given sequence of decays. The examination of the oscillations from the LH resonance range in the probe current has indicated that their pulse duration is by (30-40)% longer than the duration of EMR pulse.

If the LF oscillation amplitude is longer than one third of the maximum value, there happens the amplitude modulation, which results in the formation of short LF pulse trains. The emergence of modulation and LF oscillation trains is accompanied by the EMR emission. At the front of LF oscillation amplitude decay, the oscillations do not restore their regular shape. When the oscillations of the LH resonance range vanish, the EMR emission is not detected. That is, if LF oscillations are correlated with the phenomenon of decay of the waves excited by the beam, this process goes in the two stages. At the first stage, the excitation of LF oscillations is not accompanied by EMR emission. At the second stage, simultaneously there exist LF oscillations and EMR emission.

We have checked experimentally the existence of the decays, in which simultaneously participate potential microwaves excited by the beam and EMR emission. The beam is modulated by two microwave signals at frequencies lower than ω_{He}, and their difference is equal to the LH frequency. As it found out, if one of the microwave modulating signals is augmented in power, there takes place an increase in the amplitude of the oscillations at the frequency of LH resonance range and they change their shape. Simultaneously, there starts the EMR emission. An increase in the microwave signal amplitude reduces the time of intensification of the oscillations at the frequency $\omega_h=(\omega_{He}\omega_{Hi})^{1/2}$ and there occurs the transition to their pulse excitation. There arise trains of LF oscillations and EMR emission with the same periodicity. The existence of the decay process detected in the experiment is confirmed by the coincidence of the measured LH wave phase velocity ($(10^7$-$2\times10^8)$ cm/s) with the calculated value, where the velocities of the microwave excited by the beam and EM waves are taken into account.

According to [10], the decay process must cause stochasticity of microwaves and diminish the effectiveness of their coupling with the mono-energetic beam injected into plasma. Besides, there takes place an intensive absorption of LH waves in plasma, to which microwaves excited by the beam transfer their energy, along with the microwave absorption itself. All these circumstances have to cause the BPD derangement. The experimental trials have confirmed this supposition. There exists a threshold value of the LH oscillation field strength, the exceeding of which is accompanied by the BPD extinction. When LF power is injected, at first the suppression of drift oscillations in BPD is observed, and further there takes place the discharge derangement. The discharge extinction is detected under the LH oscillation electric field strength equal to 500 V/cm.

CONCLUSIONS

On the basis of the above-presented scheme of the beam-plasma interaction in BPD, formed by the no relativistic electron beam, one can state that the generation of pulses of EMR is stimulated by the following factors:

1. Formation of BPD by several proper modes of microwaves;
2. The cascade-like nature of the decay processes that occur in microwaves excited by the beam;
3. The beam instability stabilization due to stochasticity of the waves, conditioned by the process of their decay and by a high effectiveness of their attenuation.

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ВЛИЯНИЕ НЕЛИНЕЙНОГО ВЗАИМОДЕЙСТВИЯ ВОЛН НА ПУЧКОВО-ПЛАЗМЕННОЕ ВЗАИМОДЕЙСТВИЕ

В.А. Буц, О.Ф. Ковпик, Е.А. Корнилов

Проведены результаты исследований возбуждения колебаний протяженным нерелятивистским электронным пучком при мощности сотни киловатт в пучково-плазменном разряде в магнитном поле. Показано, что в поддержании пучково-плазменного разряда определяющую роль играют низкочастотные ионные волны из области нижнегибридного резонанса. Их возбуждение обусловлено нелинейным взаимодействием электронных плазменных мод колебаний типа распада. Электромагнитное излучение из разряда импульсов обусловлено выше указанным нелинейным взаимодействием. Оно же приводит к стохастизации волн и стабилизации пучковой неустойчивости.

ВПЛИВ НЕЛІНІЙНОЇ ВЗАЄМОДІЇ ХВИЛЬ НА ПУЧКОВО-ПЛАЗМОВУ ВЗАЄМОДІЮ

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Приведені результати досліджень збудження коливань довгим нерелятивістським електронним пучком при потужності сотні кіловат в пучково-плазмовому розряді в магнітному полі. Показано, що в підтримці пучково-плазмового розряду визначаючу роль відіграють низькочастотні іонні хвилі із області нижчегібридного резонансу. Їх збудження зумовлено нелінійною взаємодією електронних плазмових мод коливань типу розпаду. Електромагнітне випромінювання з розряду імпульсів обумовлене вище вказаною нелінійною взаємодією. Вона і приводить до стохастизації та стабілізації пучкової нестійкості.