ION FLOWS FROM AREA OF BEAM PLASMA DISCHARGE AT LOW MAGNETIC FIELD – PHYSICS AND APPLICATION

*N.V. Isaev, E.G. Shustin, V.P. Tarakanov**
Institute of Radio Engineering a. Electronics of RAS, Fryazino, Russia
E-mail: shustin@ms.ire.rssi.ru
**Institute of Thermal Physics of Extreme States of UIHT of RAS, Moscow*

For verification of conclusions of the numerical experiment the measurements of a velocity distribution function of electrons escaping area of discharge to its collector, together with energy distribution of ions which are running out from discharge on a normal from an axis are carried out. The effect of essential heating of electrons of plasma in paraxial area is detected in those regimes, when the acceleration of ions is observed. The effect of accumulation of a field of regular oscillations in the region of injection of a beam as well as their stochastisation in process of propagation along the axis of system are detected. The results of physical experiments qualitatively correlate with the data of computer simulation.

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1. INTRODUCTION

In our researches [1] the effect of formation of ion flow in beam plasma discharge (BPD) at low magnetic field was detected. The flow propagates from a discharge axis on normal to periphery. BPD is generated by an electron beam with energy ~2 keV and current density 0,1…1 A/cm^2 in gas medium of low pressure (0,01…0,1 Pa) at low magnetic field (0.2…0.5 mTl). At these conditions electrons of both beam and plasma are magnetized (their Larmour radius is much less than the transversal size of the interaction chamber), while for plasma ions magnetic field is practically imperceptible.

The attempts to determine a mechanism of generation of the ion flow were performed in [2,3], where possibility has been estimated of ion acceleration due to their trapping by low frequency waves excited at beam plasma interaction: helicon [2] or azimuth wave in radially inhomogeneous plasma [3].

The realizability in principle of such mechanisms in conditions, close to conditions of experiments [1], was shown. In these estimations that was supposed, however, that at stage of excitation of low frequency waves the beam saved a narrow enough velocity distribution function (approximation of monokinetic beam).

To test the assumptions on mechanism of acceleration of ions we have conducted computer simulation of interaction in a beam plasma system at parameters of model qualitatively appropriate to conditions of experiments [1]. In this formulation of the task we aimed to reveal main features of interaction in a longitudinally bounded system and their corollary, important for the main problem: definition of a current balance and energy relations for components of plasma in the system.

2. NUMERICAL EXPERIMENT

The simulation was conducted with usage of the "Karat" code [4]. Mathematical model underlying the code is the Maxwell equations with different matter equations, including one in the form of kinetic equation solved by a method of particles (PIC-method), and also ones in the form of different phenomenological models. The Maxwell equations are solved by a plain finite-difference method on shifted grids having the second order of accuracy.

In this work the two-dimensional version was used, in which all components of speed of particles were taken into account.

The axisymmetrical problem is considered. Countable area is a tube of 20 cm in length and 5 cm in radius. Its surface is under a zero potential. From the left end face in a circle of 1 cm radius a beam with energy 2 keV and current 0.5 A is injected. Initially the cylinder is filled with plasma with density n_p=10^{10} cm^{-3}. All countable area is immersed in an external permanent magnetic field 50 Gs.

Numerical and the physical parameters were selected so that the Debye screening distance was more than step of a grid, and the number of macroscopic particles in a Debye orb was much more than unity.

On a surface of the cylinder and end faces limiting plasma the condition of a total absorption of particles was set.

The main results of computer experiment are reduced to following.

The fastest process developing in the system, as well as follows from a theory of interaction in a beam plasma system, is the excitation of oscillations of electrons of a beam and plasma with frequency $\omega\approx\omega_{pe}$ and longitudinal wave number $k_z\approx\omega/V_0$, and appropriate generation of an electrical field. However already in time about 2… 5 t_{trans} (t_{trans} is a transit time of an unperturbed beam) obviously appears essential feature of model: the system under research represents a plasma resonator, the accumulation of energy in which results in constant change of conditions, in which the injected beam falls. It is obvious from phase portraits of electrons in different instants after the injection begins (Fig.1).

Until moment $t\approx t_{trans}$=7,6 ns the typical bunching of a beam appropriate to development of instability on fixed frequency is observed. It is important, that the wave is localized in the region of a beam: though the electrons gain considerable transversal oscillation velocity, beam, being dilated, does not fall outside the limits ~$2r_{b0}$. In the same limits energy of an electrical field of a wave is concentrated also.

At the subsequent stages of injection the new portions of a beam fall in a field generated at the previous stage, therefore already after 10 ns the bunching occurs much faster, and at the end of an interaction region the phase bunches practically get mixed up. In time ~100 periods of a principal frequency this is not only full chaotization of motion of the beam that is observed, but also deceleration and even return of a part of the electrons: the electrons of the beam become physically indistinguishable from electrons of plasma.

A temporal structure of a HF field of the excited wave is shown in Fig.2. One can see, that while near to a point of injection the field on the initial stage has regular character appropriate to conception of the theory of hydrodynamic beam instability (an amplitude-modulated wave at Langmuir frequency), further the wave gets stochastic. Amplitude of the field at stage, where it is regular, reaches 1000 V/cm, and then it is reduced up to 200…300 V/cm.

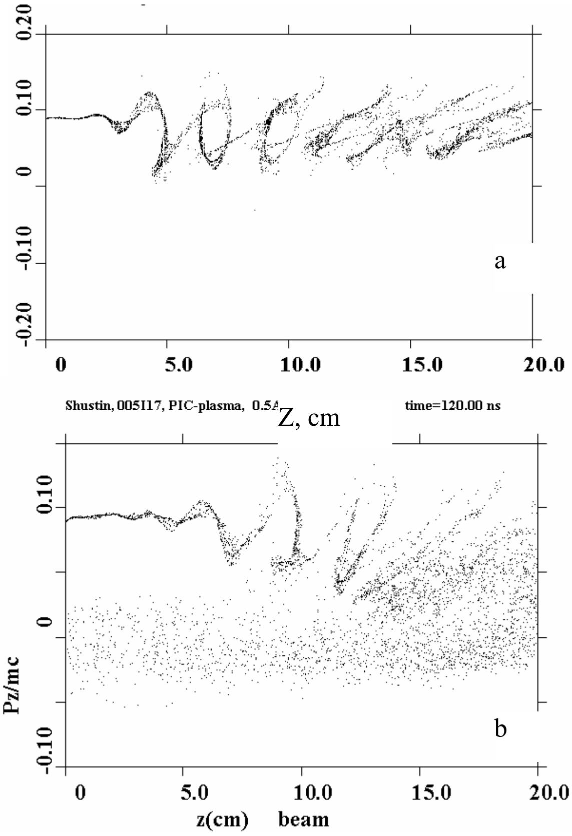

Fig.1. Phase portraits of beam electrons at moments t=8 ns (a); 120 ns (b)

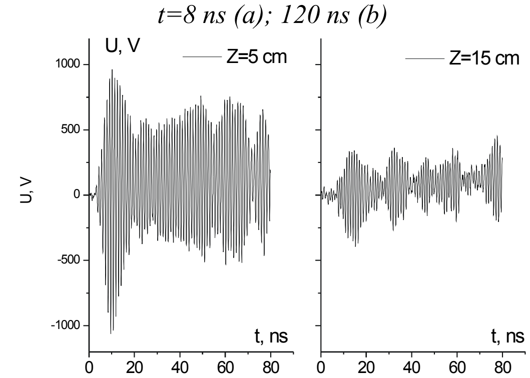

Fig.2. Electric potential at the system axis in time

It is possible to observe energy exchange of the beam with the field and with electrons of plasma in Fig.3. The curves indicate, that up to 15 ns the shape of a distribution function of electrons on velocities (EDF) qualitatively meets to conception of the non-linear theory of hydrodynamic instability. 2 bunches are formed in the beam, in-phase (delayed) and counter-phase (accelerated), more and more dispersing and extending in space of velocities in process of the wave amplitude growth. Thus the distribution function of electrons of plasma practically does not vary. Further chaotization of oscillations results in intermixing bunches and formation of EDF, almost monotonically falling up to speeds ~ 1,5V_0. Since t~30…40 ns there is also heating of electrons of plasma by an intensive HF wave. As a result a group of accelerated electrons of plasma ("a superthermal tail") is created in the beginning, and then heating of all bulk of plasma electrons occurs.

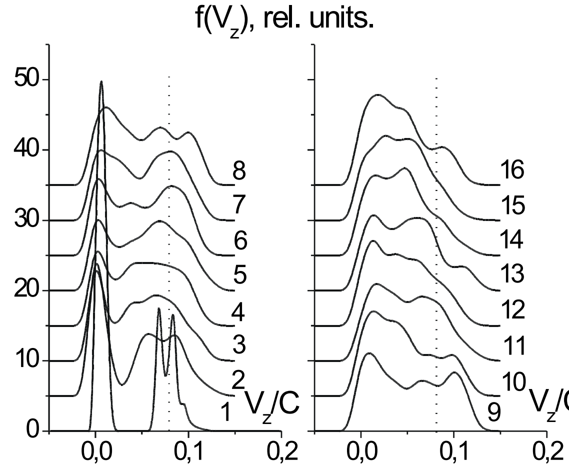

Fig.3. Velocity distribution function of electrons close to back wall of the volume at different time moments: since 10 to 50 ns in 5 ns (curves 1-9) and since 50 to120 ns in 10 ns (curves 9-16). Dotted line is undisturbed beam velocity

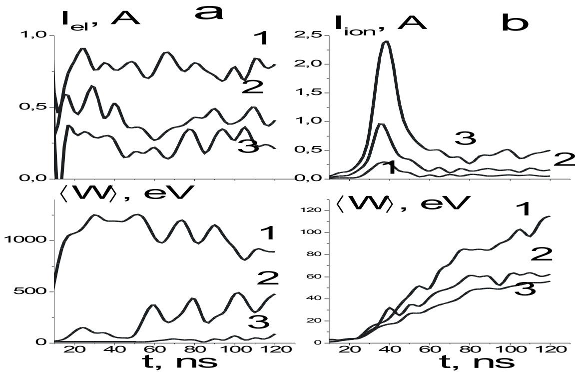

Fig.4. Currents and mean energies of electrons (a) and ions (b) to different parts of plasma volume walls: 1 – to paraxial part of back plate (R<2.5 cm); 2 – to peripheral part of back plate (R>2.5 cm); 3 – to side wall (15 cm<Z<20 cm)

Returning to the analysis of an electrical field, generated in a system, it is necessary to note, that HF oscillations exist on a background of increasing quasi-steady potential: mean value of a potential on a time interval $>>1/\omega_{pe}$ reaches value ~150 V to the moment 120 ns. The growth of a potential is caused by increase of energy of electrons of plasma and appropriate increase of a difference of flows of electrons and ions to interaction region boundaries (Fig.4). As is already pointed above, the generated fields are localized in area occupied by the beam. So the potential gradient on radial boundary of the area accelerating ions to a lateral wall of a volume is created that is obviously seen from a Fig.4.

Thus, it is possible to select two regions in a volume of plasma with different parameters. Inside a beam region the intensive stochastic oscillations in frequency band near to Langmuir frequency are localized. In this area strongly non-equilibrium plasma is formed that is characterized by rather energetic and non-isotropic electron component (the mean energy reaches hundreds eV) and different directions of a drift of electrons and ions. On periphery much more feeble oscillations are excited which don't influence parameters of plasma in this area essentially. The intensive escape of electrons from paraxial area to end plates of the system boosts increase of a potential of this area of plasma and, as a corollary, drift of unmagnetized ions to periphery of this area. Energy of thus accelerated ions can reach several tens eV.

3. PHYSICAL EXPERIMENT

Results of computer experiments boosted measurements of a spatial distribution of high frequency fields excited in the system and analysis of distribution function of electrons (EDF) at an exit from the interaction region. The installation diagram is shown in a Fig.5.

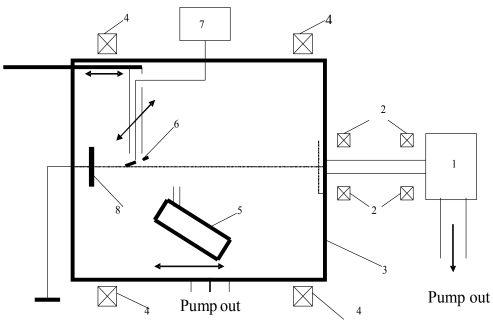

Fig.5. Diagram of experiment. 1 – Pierce type electron gun; 2 – beam focusing coils; 3 – plasma chamber; 4 – Helmholtz coils; 5 – ion energy analyzer; 6 – HF dipole probe; 7 – HF spectrum analyzer; 8 – collector

At an opposite wall of the plasma chamber the collector of electrons combined with an energy analyzer of electrons (an electrostatic grid analyzer with decelerating field) is placed. For diagnostics of oscillations in plasma the symmetrical dipole probe loaded with an input of a spectrum analyzer through a resistance transformer is used. The probe is movable along an axis and on radius of the chamber.

As a receiver of an ion flow the electrostatic analyzer with a flat deflecting mirror movable along a side of theplasma chamber is used. A collimator of ions is oriented on normal to axis of the chamber. Parameters of an analyzer are: range of energies 0…100 eV, sensitivity ~$0{,}5\cdot10^{-9}$ A/cm^2, resolution on energy $\Delta W/W_0=0.12$.

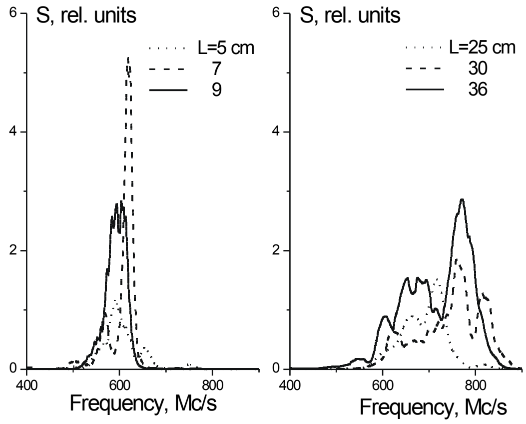

Fig.6.The power spectra of E_z component

In a Fig.6 the power spectra of E_z component in band $\omega\approx\omega_{pe}$, registered by the probe on different distances L from a collector are shown.

One can see that in the beginning of an interaction region a spectrum is rather narrow-band, then the spectrum widens to more high frequencies. In Fig.7 the longitudinal distributions of the oscillation intensity in frequency band appropriate to peak of the spectrum in the beginning of area (an integral of a spectral curve on a band 610±10 Mc/s – curve 1), and in the whole of band of generated oscillations (curve 2) are shown. Effect of accumulation of regular (near monochromatic) oscillations near to a point of beam injection is evident here, after which goes more or less smooth growth of intensity of stochastic oscillations. The analysis of transversal distribution of a field strength displays, that the oscillations in range of Langmuir frequencies are obviously localized on radius in limits R_{beam}.

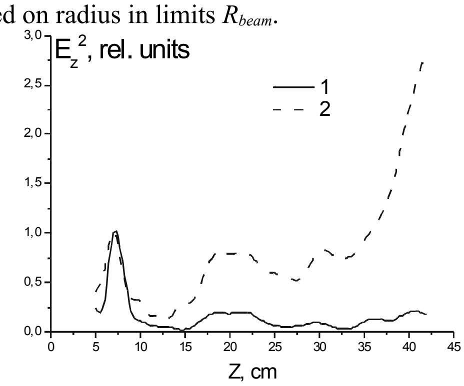

Fig.7. The longitudinal distributions of the oscillation intensity

In Fig.8 the curves of distribution function of electrons on longitudinal velocities (EDF) of electrons reaching a collector are represented at different chamber pressures (so, at different relations n_b/n_p). (For visualization curves in Figs.3,8 and 9 sequentially are biased on a vertical). The EDF on a collector in pre-discharge regime (p=0,05 mTorr) represents peak of electrons of the beam, spreading to smaller velocities due to twist of the beam in a non-uniform magnetic field at input to the plasma chamber. At a pressure buildup there is an avalanche ignition of beam plasma discharge. The EDF of beam is jump-like spread to smaller velocities, running up to a shape of a plateau at this interaction length. In process of gas pressure growth plasma density increases (accordingly, the relation n_b/n_p decreases), and the diffusion of EDF of the beam decreases. Simultaneously with diffusion of the beam on velocities the part of EDF appropriate to electrons of plasma is obviously dilated also: the mean energy of a longitudinal motion of plasma electrons in the area occupied by the beam reaches 100…120 eV.

The measurements with an energy analyzer moving on radius have shown, that both heating of main bulk of electrons of plasma and group of electrons with intermediate energies are observed only in a central part of a plasma column, where the beam is present.

At approach of the collector with the energy analyzer to a gun, both parameters of the beam and pressure of gas being constant, there is a discontinuation of discharge on length of an interaction area $L\approx15$ cm: density of plasma diminishes by order, both the intensity and shape of glow, intensity and spectrum of UHF of radiation from plasma vary essentially. At increase of length, followed by ignition of the discharge, EEDF sequentially is dilated, reaching a plateau, and then becomes monotonically falling curve.

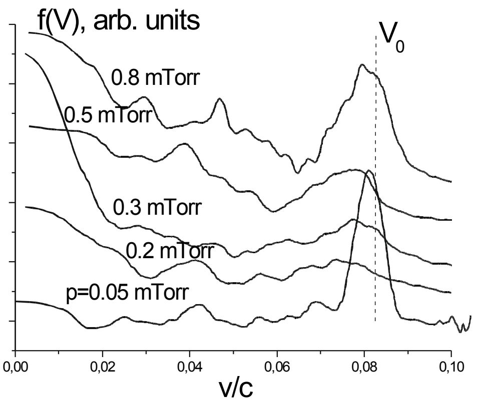

Fig.8. A distribution function of electrons on longitudinal velocities of electrons

The distribution function on energies (IEDF) of ions which escape from area of discharge on a normal to an axis, in different points on length of the chamber together with power distribution of electrons on a collector are shown in a Fig.9. The flow of ions varies on intensity and on value of mean energy along length of area of discharge, reaching a maximum of both these values in an region, where the maximum value of intensity of excited HF oscillations is registered. This is characteristic, that the flow of accelerated ions is detected only when the obvious heating of electrons of plasma is observed. At large pressure of gas (small n_b/n_p) the energy of a longitudinal electron motion does not exceed 10 eV; simultaneously flow of ions to periphery decreases by the order and has mean energy no more than 10…15 eV.

The results represented here qualitatively meet to conclusions of section 2. The accumulation of energy of coherent oscillations in the beginning of an interaction region with the subsequent development of stochastic oscillations is observed. The diffusion of EDF of beam electrons at stage of excitation of stochastic oscillations is accompanied by essential heating of electrons of plasma.

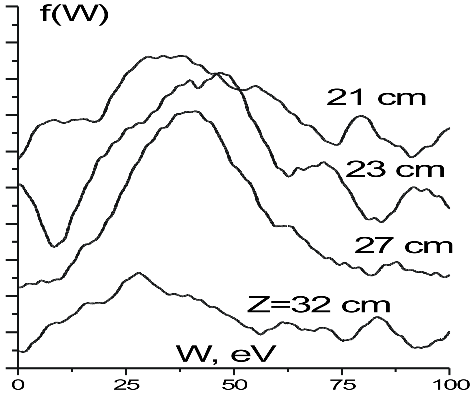

Fig.9. A distribution function on energies of ions

The power characteristics of a flow of accelerated ions on periphery of discharge are obviously related to intensity of excited oscillations and with heating of plasma electrons. Thus, it is possible to approve, that offered above explanation of the mechanism of ions acceleration in BPD in a low magnetic field has experimental confirmation.

4. DISCUSSION

In [5, 6] attention have been drawn first to the fact of a relaxation distance reduction for a monochromatic beam in semi-bounded plasma. This is owing to effect of accumulation of oscillations in plasma near to a plane of injection of a beam because of a smallness of their group velocity in comparison with speed of the beam. Value of a maximum field is rated there: for conditions of our experiment ($n_p=10^{10}$ cm^{-3}, $n_b=10^8$ cm^{-3}, $W_b=2*10^3$ eV, $T_e=10$ eV) in absence of collisions of electrons with heavy particles $E^2/4\pi\approx 4n_bW_b$~3…5 kV/cm, that meets well enough to the data of a Fig.2.

It is necessary to remind, that at stochastic oscillations one should account inverse of correlation interval as an effective collision frequency [7]. Both in numerical and in physical experiments the effect of stochastization of excited oscillations is obviously observed, thus width of a spectrum (i.e. the reciprocal interval of a correlation) reaches or even exceeds $0,1\omega_0$. According to [6], the accumulation of energy in this case is essentially reduced (compare to a Fig.2,a,б).

Stochastization of excited oscillations is rather essential feature detected in numerical experiment. Let's remind, that in physical experiments the generation noise-like oscillations was observed regularly, including [1], and the attempts were done to explain this effect by interaction of excited high-frequency waves with other types of oscillations. From results shown above it is evident, that stochastization comes already then, when any other instabilities in the system are not manifested yet.

As is shown in [8], longitudinal limitation of the realistic plasma beam system results in feedback obviously influential in dynamics of development of instability and time-space structure of generated fields. In that paper the analogy of the system to the generator of stochastic microwave oscillations executed as a traveling-wave tube with the delayed feedback was offered.

It is necessary to note, that the stochastic character of excited oscillations appears for the broad class of the determinate dynamic systems [9,10]. The particular mechanism of stochastization in our case still should be researched.

Although our numerical experiment describes development of process on the initial stage, the corollaries of observed processes have become apparent at studies of a stationary system as well, including at beam plasma discharge, as is shown at section 2. Let's also remind of measurements of dissipation of a beam on angles and energies in BPD without a magnetic field [11], where were detected both superthermal electrons and monotonically falling EDF of a beam simultaneously with generation of a broadband spectrum of RF radiation from plasma. Paper [8] was already mentioned above as well, containing the proofs of a chaotization of generated oscillations due to feedback in a beam - plasma system. In [12] the formation of a peak in distribution of HF fields in the beginning of a system with amplitude, sufficient for essential strengthening of ionization in this area is shown.

5. APPLICATION

In order to optimize the treatment of materials in plasma processing reactors operating at low gas pressures, it is very important to control the parameters of ions bombarding the processed material. Thus, in devices for the ion etching of semiconductor materials in RF discharge plasma, the ion energy distribution function (IEDF) and the angular distribution of the ions bombarding the material's surface critically affect the rate of etching and the degree of its anisotropy. It has been shown that the shape of the IEDF can be controlled, e.g., by applying an RF bias voltage directly to the substrate or by using an auxiliary electron source (either an additional discharge or a thermal-cathode gun) to inject electrons into the discharge. It was shown in [1] that a beam plasma discharge (BPD) in a low-pressure gas can be used as a source of an ion flow escaping the discharge region on normal to its axis. We have shown that, by changing the external parameters of a beam plasma discharge in the equipotential interaction chamber and by using electron beams premodulated in velocity, the energy of the ions bombarding the surface of a sample placed near the side wall of the chamber can be varied within a range of 10…100 eV. Note that it is precisely this ion energy range that is required for surface treatment (such as deposition of thin films and etching) of materials for semiconductor electronics and acoustoelectronics.

The approbation of the technology of soft etching by ion flows of Ar^+ with mean energy 60…70 eV of pseudomorphic semiconducting heterostructures AlGaAs/InGaAs/GaAs (P-HEMT), brought up on substrates of GaAs and applied for manufacturing of microwave field effect transistors has been carried out. The influence of such processing to concentration and mobility of electrons of 2DEG, sensing to radiation defects imported during etching was researched.

The researches that have been carried out on test samples of p-HEMT structures with Hall contacts have shown, that at conditions mentioned above there is no accumulation of radiation defects aggravating parameters of two-dimensional electron gas.

The version of technological process of manufacturing gate grooves of p-HEMT devices through a slot in dielectric is tested also. With the help of an electron beam lithography narrow (0.1…0.5 microns) slots in resist were made, through which the selective etching of dielectric coating Si_3N_4 by width 80 nm up to a layer of the semiconductor GaAs, where the process of etching is stopped, was made. After resist removal the sizes of etched grooves were measured with the help of an atomic microscope. The depth of etching at the designated above time of exposure has made 35 nm. There are no detected signs of a non-uniformity of etching on a plate of 60 mm diameter. The presence of effect of etching without an essential degradation of parameters of heterostructures (mobility of electrons) testifies to small density of radiation disturbance and possibility of using BPD in the technology of manufacturing of heterostructure microwave HEMT devices.

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ИОННЫЕ ПОТОКИ ИЗ ОБЛАСТИ ПУЧКОВО-ПЛАЗМЕННОГО РАЗРЯДА В СЛАБОМ МАГНИТНОМ ПОЛЕ – ФИЗИКА И ПРИЛОЖЕНИЯ

Н.В. Исаев, Е.Г. Шустин, В.П. Тараканов

Для проверки выводов численного эксперимента были проведены измерения функции распределения по скоростям электронов, выходящих из области разряда на коллектор, совместно с распределением по энергии ионов, которые выходят из разряда по нормали к оси. В режимах, когда наблюдаются ускоренные ионы, детектирован эффект существенного нагрева электронов плазмы. Детектирован эффект аккумуляции поля регулярных осцилляций в области инжекции пучка и их стохастизации в процессе распространения вдоль оси системы. Результаты физических экспериментов качественно коррелируют с данными компьютерного моделирования.

ІОННІ ПОТОКИ З ОБЛАСТІ ПУЧКОВО-ПЛАЗМОВОГО РОЗРЯДУ У СЛАБКОМУ МАГНІТНОМУ ПОЛІ – ФІЗИКА І ЗАСТОСУВАННЯ

Н.В. Ісаєв, Е.Г. Шустін, В.П. Тараканов

Для перевірки висновків чисельного експерименту були проведені вимірювання функції розподілу за швидкостями електронів, що виходять з області розряду на колектор, разом з розподілом за енергіями іонів, які виходять з розряду по нормалі до осі. В режимах, коли спостерігаються прискорені іони, детектовано ефект суттєвого нагріву електронів плазми. Детектовано ефект акумуляції поля регулярних осциляцій в області інжекції пучка та їх стохастизації у процесі поширення вздовж осі системи. Результати фізичних експериментів якісно корелюють з даними комп’ютерного моделювання.