NONLINEAR PHENOMENA IN HELICON PLASMAS

K.P. Shamrai, V.M. Slobodyan, V.F. Virko, Yu.V. Virko, A.A. Gurin, G.S. Kirichenko

Institute for Nuclear Research, National Academy of Sciences,
47 Prospect Nauki, 03680 Kiev, Ukraine; kshamrai@kinr.kiev.ua

Nonlinear phenomena stimulated by enhanced longitudinal electric field arising near the metal surfaces in helicon plasmas are analyzed theoretically. Ponderomotive effect giving rise to nonlinear instability of the edge plasma, and stochastic electron heating that increases the rf power absorption and plasma generation are considered. Experimental evidences for non-equilibrium electron energy distributions including a population of fast particles with mean energies of the order of a few tens electron-volts are presented.

PACS: 52.35.Hr, 52.40.Db, 52.50.Dg

1. INTRODUCTION

Inductively coupled plasmas (ICPs) demonstrate numerous cooperative and nonlinear phenomena at low gas pressures, even without an external magnetic field imposed. Generation of oscillations at the second harmonic of the driving frequency, ponderomotive effects, nonlocal electrodynamic and kinetic processes, including stochastic electron heating, and other cooperative phenomena were found to govern substantially the discharge performance (see, e.g., the review paper [1]).

Much broader variety of nonlinear cooperative phenomena is inherent to the ICPs operating with the magnetic field, so-called the helicon plasmas, which carry various waves. A universal phenomenon for these plasmas is ion-acoustic turbulence that can originate from parametric [2-6] or electron drift current driven [7,8] instabilities. Excitation of ion-acoustic waves can provide an efficient additional channel for the rf power absorption at high levels of input power. Another nonlinear process, generation of super-thermal electrons, was detected in several experiments [9,10]. The underlying nonlinear mechanism was hypothesized to originate from trapping and subsequent acceleration of particles by the longitudinal electric field of traveling helicon waves.

One more potential source for generation of super-thermal electrons and other nonlinear processes is enhanced longitudinal electric field that arises near the boundary of plasma with the metal surfaces transverse to the external magnetic field. Such the field was predicted theoretically and measured experimentally on the helicon discharge [6].

We report on theoretical and experimental study of some nonlinear and stochastic phenomena in helicon plasmas excited by $m = 0$ antennas either across (standard helicon plasma) or along (magnetized ICP) the magnetic field. Enhancement of the longitudinal electric field near the metal plates and related ponderomotive phenomena are discussed in Sec. 2. Stochastic electron heating in the strong edge electric field and its effect on the rf power absorption and plasma production are discussed in Sec. 3. Experimental evidences for non-equilibrium electron distributions are presented in Sec. 4. Section 5 gives conclusions.

2. ENHANCED ELECTRIC FIELD AND PONDEROMOTIVE PHENOMENA IN A NONUNIFORM EDGE PLASMA

Nonuniformity of helicon plasmas influences substantially upon linear and nonlinear processes due to polarization induced by the wave fields. Radial plasma nonuniformity (in particular, a density jump near the plasma boundary with non-conducting confining wall) gives rise to transverse, relative to the magnetic field, polarization resulting in an efficient rf power absorption through the linear mode conversion of helicon waves into quasi-electrostatic waves [11]. Axial plasma nonuniformity is also considerable, especially in the boundary regions near the metal surfaces that are perpendicular to the magnetic field. Owing to plasma polarization in these regions, the longitudinal electric field is enhanced and can give rise to various nonlinear, in particular, ponderomotive phenomena [6].

Radio-frequency (rf) electric and magnetic fields excited in an axially nonuniform plasma by an azimuthally symmetric ($m = 0$) antenna are represented in a cylindrical geometry as a superposition of various radial harmonics [12]

$$\mathbf{E} = \exp(-\mathrm{i}\omega t)\sum_{i=1}^{\infty}\mathbf{F}_i \cdot \mathbf{J}_i + \mathrm{cc},$$
$$\mathbf{B} = \exp(-\mathrm{i}\omega t)\sum_{i=1}^{\infty}\mathbf{H}_i \cdot \mathbf{J}_i + \mathrm{cc}., \quad (1)$$

where we introduced z-dependent field vectors, $\mathbf{F}_i = \{F_{ri}, F_{\theta i}, F_{zi}\}$ and $\mathbf{H}_i = \{H_{ri}, H_{\theta i}, H_{zi}\}$, and the vector $\mathbf{J}_i = \{J_1(k_{\perp i}r),\, J_1(k_{\perp i}r),\, J_0(k_{\perp i}r)\}$ with $J_{0,1}$ being the Bessel functions. Here, $k_{\perp i} = \gamma_i / R$ is the transverse wave number (γ_i: the i-th root of J_1, R: the plasma radius). As seen from Eq. (1), longitudinal electric field is maximum on the axis. Substituting Eq. (1) into Maxwell equations yields a set of ordinary differential equation with respect to z. Then the amplitudes of the E_z-field radial harmonics take the form

$$F_{zi} = -\mathrm{i}N_{\perp i}(\omega/\omega_{\mathrm{pe}})^2 H_{\theta i}, \quad (2)$$

where $N_{\perp i} = k_{\perp i}c/\omega$ is the transverse refractive index.

If the thickness of the plasma slab neighboring to the metal surface $\delta z < (c/\omega_{\mathrm{pe}})(\omega_{\mathrm{ce}}/\omega)^{1/2}$, the amplitudes of electromagnetic field components, and in particular H_θ, are nearly constant within this slab. As long as the plasma density naturally falls towards the metal surface, equation (2) predicts F_z to grow as n^{-1}. The physical reason for this effect is the following. In a dense helicon plasma

($\omega_{pe}^2 >> \omega_{ce}^2$ where ω_{pe} and ω_{ce} are the plasma and gyro frequencies of electrons), the electron rf conductivity current along z-direction much exceeds the displacement current and, therefore, should be continuous, $j_z \equiv -env_z \approx \text{const}$ ($v_z = -ieF_z / m_e\omega$: the amplitude of electron velocity oscillations), so that the field should grow with decreasing n.

The effect of field enhancement in the edge plasma slab was confirmed experimentally [6]. The $E_z(z)$ profile measured with use of the dipole antenna in a helicon plasma and shown in Fig. 1 clearly demonstrates a tendency to grow towards the metal surface ($z = 0$). Computation results shown in the same figure predict that the maximum field on the surface can amount to 10…20 V·cm^{-1}.

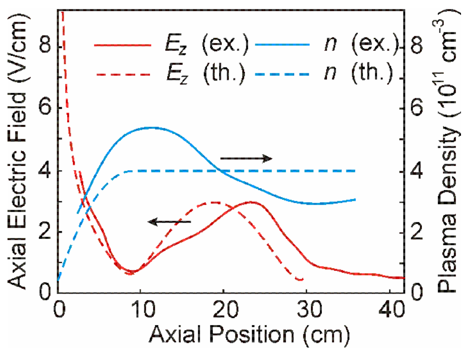

Fig. 1. Measured and computed axial profiles of the longitudinal electric field near the metal flange in the helicon plasma [6]

If the density within the edge slab is quite low, the amplitude of longitudinal electron oscillatory velocity can exceed the transverse one, so that electron motion can be considered in one-dimensional approximation. If, in addition, the amplitude of electron rf excursions is not too high, $eF_z / m_e\omega^2 << \delta z$, the effect of the rf field on slow electron motion is described by an adiabatic ponderomotive force, $F_z = -(m_e/2)\partial|v_z|^2/\partial z$. Then, equation of the average electron motion takes the form

$$m_e \frac{\partial u}{\partial t} = e\frac{\partial \phi}{\partial z} - \frac{1}{n}\frac{\partial p_{\text{eff}}}{\partial z}, \quad (3)$$

where the effective pressure, $p_{\text{eff}} = p_{\text{th}} + p_{\text{pond}}$, is the sum of the thermal and ponderomotive pressures

$$p_{\text{eff}} = nT_e + \frac{m_e c^2}{8\pi^2 e^2}\frac{k_\perp^2 |H_\theta|^2}{n}. \quad (4)$$

One can see from Eq. (4) that if the density is below the critical value, $n_{cr} = (2^{3/2}\pi e)^{-1}(c/v_{te})k_\perp |H_\theta|$, the effective pressure depends anomalously on density, $\partial p_{eff}/\partial n < 0$. This means that any decrease of the density should progress giving rise to the instability like collapse.

3. STOCHASTIC HEATING OF ELECTRONS BY ENHANCED EDGE ELECTRIC FIELD

Another nonlinear phenomenon that can be initiated by the enhanced edge field is stochastic heating of electrons. Similar effect was examined in ICPs without the magnetic field, where the enhanced field arises in the skin-layer under the antenna [1,13]. However, there is a difference because in helicon plasmas the enhanced localized field is electrostatic and longitudinal whereas in the ICPs it is electromagnetic and transverse (azimuthal).

To analyze the process of stochastic electron heating occurring in the edge layer of enhanced longitudinal electric field we used the following model. The field profile was chosen as $E_z(z) = E_0 f(z)$ with the shape function $f(z) = (1+\eta z^2/a^2)(1+z^2/a^2)^{-1}$ approximating the measured profile, Fig. 1. Here, E_0 is the maximum value of the field on the metal surface, a is the width of the field slab, and $\eta = n_{edge}/n_0$ is the edge-to-bulk density ratio. The density profile is then $n(z) = n_{edge}/f(z)$.

We computed motion of a set of electrons that start at some initial time moments from some initial positions and with some initial velocities towards the metal surface. Owing to interaction with the edge field slab, which acts as a ponderomotive barrier, the electrons are reflected back. The electrons reaching the metal surface were supposed to be reflected elastically. Distribution of the reflected electrons on longitudinal velocities was computed by averaging over the initial time moments (i.e., in fact, over the initial phase of the rf field) and over the initial co-ordinates and velocities. Initial distribution on longitudinal velocities, as well as the distribution on transverse velocities, was assumed to be maxwellian.

Figure 2 shows the distribution on longitudinal velocities of the incident (Maxwell function with temperature T_e = 4 eV, Fig. 2*a*) and reflected (Fig. 2*b*) electrons computed at E_0 = 15 V·cm^{-1} and a = 1.12 cm.

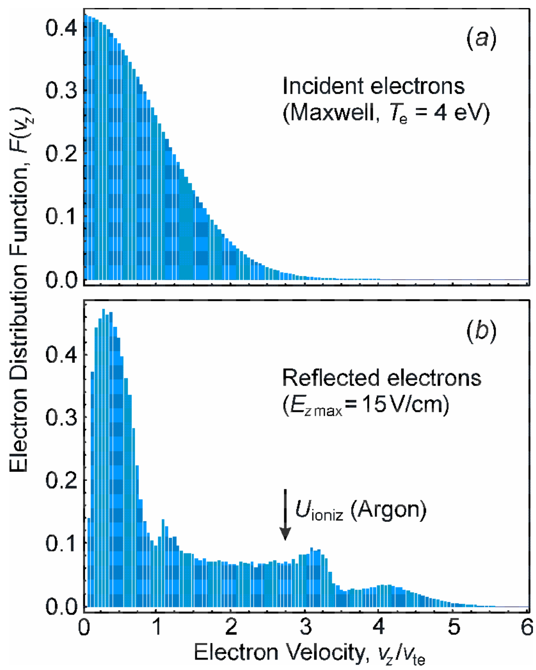

Fig. 2. Velocity distributions of electron flux incident onto (a) and reflected from (b) the edge field layer

As seen, the bulk of reflected electron distribution is being cooled whereas a substantial population of super-thermal, stochastically heated particles appears. A substantial fraction of electrons has energies exceeding the ionization potential for argon, U_{ioniz} = 15.8 eV. These electrons have strong ionization power and can increase substantially the efficiency of plasma generation in the discharge. Peaks on the distribution of reflected electrons, around velocities $v_z/v_{te} \approx 3.2$ and 4.1, arise owing to flight resonances of electrons interacting with the localized field. The most energetic peak corresponds to particles with energies of the order of 35 eV.

Distributions of reflected electrons for various values of the maximum field, E_0 = 10, 15, and 20 V·cm^{-1}, are shown in Fig. 3a, for a = 1.12 cm. Location of the peak of most energetic electrons, v_{zmax}, shifts to the larger velocities with increasing E_0, approximately linearly. At E_0 = 20 V·cm^{-1}, the particles are accelerated up to energies 50 eV and above. Distributions for various values of the slab width, a = 0.56, 1.12, and 2.24 cm, are shown in Fig. 3b, for the maximum field E_0 = 15 V·cm^{-1}. One can see that the efficiency of fast electron generation is quite low for the largest a = 2.24 cm. In this case, the field slab width is too large to fulfill the condition of efficient particle acceleration, $a \approx v_{te}/\omega$ [1].

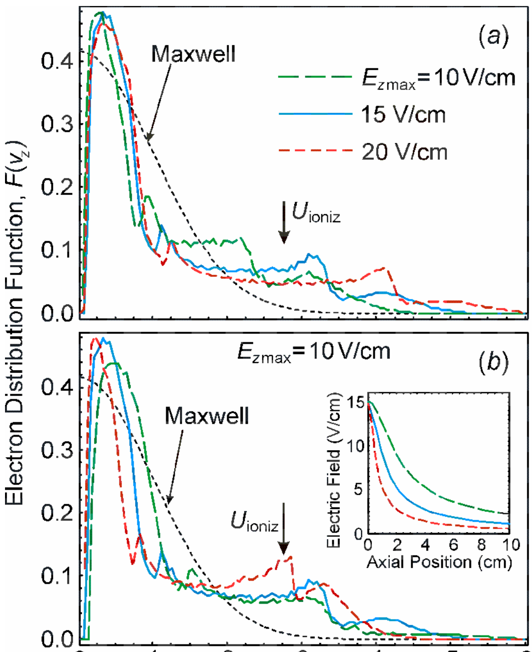

Fig. 3. Distributions of reflected electrons, at various values of (a) the maximum field and (b) the slab width

Stochastic electron heating is expected to contribute substantially to the rf power absorption. To evaluate this effect, we computed the power flux carried by reflected electrons, with distribution on the longitudinal velocities $f_{ref}(v_z)$ and the maxwellian distribution on transverse velocities

$$\Pi_{ref} = (1/2)nT_e v_{te} \int_o^\infty u(u^2+2) f_{ref}(u)du\,, \quad (5)$$

where $u = v_z/v_{te}$. As long as the power flux carried by the incident (maxwellian) electrons is $\Pi_{inc} = (2/\pi)^{1/2} nT_e v_{te}$, a specific (over a 1-cm^2 cross-section) power absorption due to stochastic heating is $\Delta\Pi = \Pi_{ref} - \Pi_{inc}$. One can introduce an effective collision frequency, ν_{eff}, by equating the rate of stochastic heating to the rate of (effective) collisional power absorption [13]: $\Delta\Pi = \int_0^L p_{abs}(z)dz$ where

$$p_{abs} = \nu_{eff} \frac{e^2}{2m_e\omega^2} n(z)E_z^2(z)\,, \quad (6)$$

is a specific (over 1 cm^3) power absorption and L the basic length (chosen to be equal to 15 cm).

The effective-to-binary collision frequency ratio, ν_{eff}/ν_c, is shown in Fig. 4 as function of the maximum electric field. Here, $\nu_c = \nu_{en} + \nu_{ei}$ is the total frequency of electron binary collisions with neutrals and ions. Computations were done for the plasma density $n_0 = 4\times10^{11}$ cm^{-3}, electron temperature T_e = 4 eV, Ar gas pressure p_{Ar} = 3 mTorr, driving frequency f = 13.56 MHz, and the field slab width a = 1.12 cm. As seen, the effective collision frequency exceeds considerably the binary collision frequency, the latter making 1.7×10^7 s^{-1} under these conditions. The effective frequency falls with increasing E_0 due to the fact that the efficiency of stochastic electron heating is approximately proportional to E_0 whereas the collisional power absorption is proportional to E_0^2.

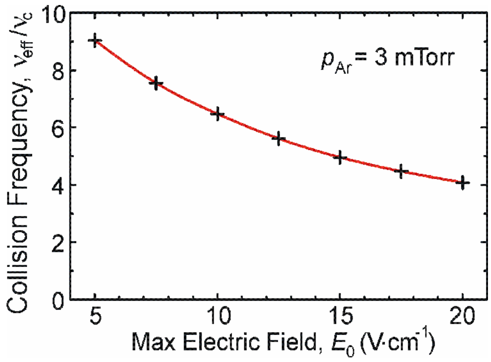

Fig. 4. Effective collision frequency normalized by the binary one, as function of the maximum electric field

Stochastically heated electrons apparently increase the ionization rate and, thus, contribute substantially to plasma production in the discharge. The ionization frequency is defined as $\nu_{iz} = n_a\langle\sigma_{iz}v\rangle$ where n_a is the density of neutrals, σ_{iz} the ionization cross-section, v the electron velocity, and averaging is over the electron distribution. We computed the ionization frequency for argon with the velocity distribution of reflected electrons, at various values of the maximum electric field E_0 and a = 1.12 cm, and compared it with the ionization frequency for maxwellian electrons with temperature

$T_e = 4$ eV. Note the latter to be equal to $\nu_{iz}^{(M)} \approx 1.6{\times}10^4\,s^{-1}$, for a unidirectional along z electron distribution and Ar pressure p_{Ar} = 1 mTorr. Results of computations are shown in Fig. 5. As seen, ν_{iz} rapidly grows with increasing E_0 and exceeds considerably $\nu_{iz}^{(M)}$ in the range of larger fields where the rate of growth is approximately linear.

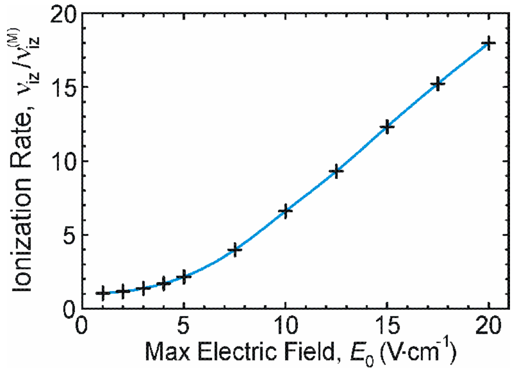

Fig. 5. The ratio of ionization frequencies for stochastically heated and maxwellian electrons, as function of the maximum electric field

4. MEASUREMENTS OF NON-EQUILIBRIUM ELECTRONS IN A HELICON PLASMA EXCITED BY A FLAT ANTENNA

Convincing evidences for super-thermal electrons were found in the magnetized ICP excited by an m = 0 antenna along the magnetic field [12]. First, the probe characteristic shown in Fig. 6 demonstrates two groups of electrons with different temperatures. A noticeable fact is that the graph in Fig. 6 differs cardinally from the probe characteristic available in plasma with a two-temperature electron distribution including a non-maxwellian tail.

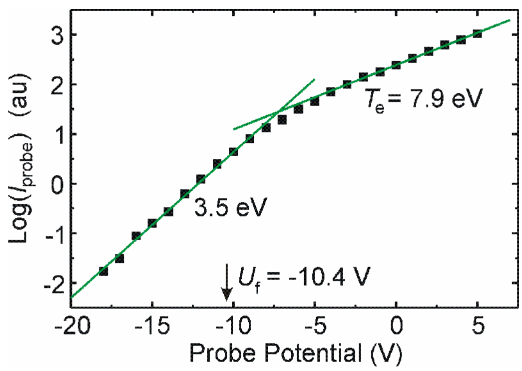

Fig. 6. A semi-logarithmic probe characteristic measured in the helicon plasma with a flat antenna

Indeed, the lower (higher) temperature in Fig. 6 corresponds to more (less) energetic electrons. This fact can be understood by assuming the beam of accelerated electrons in plasma, so that the distribution function has a "bump-on-tail". Then, the lower temperature would relate to the beam whereas the higher temperature to the transitional region, between the beam and the "main body" of electrons, where the distribution function has a small slope corresponding to high "effective" temperature. The beam temperature was measured to be 2.5…4.5 eV in a broad range of conditions, and to depend slightly on radius. As for the temperature of the main body of electrons, it remains uncertain.

The next evidence for non-equilibrium electrons is seen from radial profiles of the floating potential (V_f) measured with the Langmuir probe and profiles of the plasma potential (V_s) measured with a thermo-emissive probe (Fig. 7). By comparing these profiles, one can see that the difference between the plasma and floating potentials can be as large as 70 V on the axis. Thus, the relation $V_s \approx V_f + 5T_e$, which is valid for equilibrium (maxwellian) electrons, is not satisfied at any reasonable assumption regarding the electron temperature.

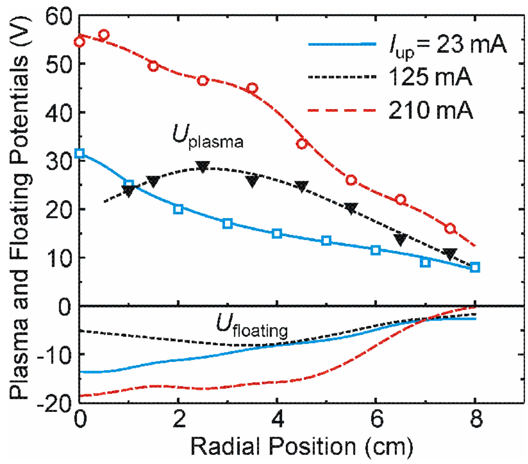

Fig. 7. Radial profiles of plasma and floating potentials, for various magnetic field strengths

Electron energy distribution function was measured with use of so called the second-derivative method. With modulation of the probe bias potential at a low frequency, of the order of 1 kHz, the signal at the second harmonic, which is proportional to the electron distribution function, was received. Results of measurements shown in Fig. 8 corroborate clearly the existence in plasma of the population of fast electrons whose mean energy increases towards the source center and amounts to 40 eV on the axis. This accords with theoretical prediction (Sec. 3) that electrons are accelerated by the axial electric field having the on-axis maximum. The distribution of fast electrons was measured to be almost isotropic in velocities.

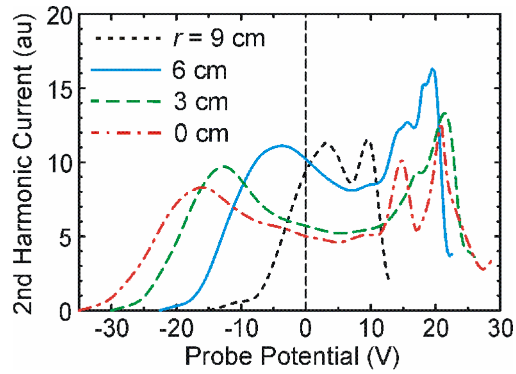

Fig. 8. Electron energy distributions measured at various radial positions

5. CONCLUSIONS

Enhanced longitudinal electric field near the metal surfaces in helicon plasmas was shown to be a potential source for various nonlinear and stochastic processes. Nonlinear instability like the collapse of Langmuir waves can arise in this region, if the edge density is below the critical value. The edge field can also drive efficient stochastic acceleration of electrons, up to energies of a few tens of eV, giving rise to substantial enhancement of the rf power absorption and the ionization rate in the discharge. Experiments reveal non-equilibrium electrons, in particular, the population of fast particles whose energies agree with theoretical prediction was detected.

ACKNOWLEDGEMENT

This work was partly supported by the Science and Technology Center in Ukraine under contract # 3068.

REFERENCES

1. V. Godyak. Plasma phenomena in inductive discharges // *Plasma Phys. Control. Fusion*. 2003, v. 45, p. A399-424.
2. A.I. Akhiezer, V.S. Mikhailenko and K.N. Stepanov. Ion-sound parametric turbulence and anomalous electron heating with application to helicon plasma sources // *Phys. Lett*. A. 1998, v. 245, p. 117-122.
3. N.M. Kaganskaya, M. Krämer and V.L. Selenin. Enhanced-scattering experiments on a helicon discharge // *Phys. Plasmas.* 2001, v. 8, p. 4694-4697.
4. J.L. Kline, E.E. Scime, R.F. Boivin, A.M. Keesee, X. Sun and V.S. Mikhailenko. Rf absorption and ion heating in helicon sources // *Phys. Rev. Lett.* 2002, v. 88, p.195002-1-4.
5. V.F. Virko, G.S. Kirichenko and K.P. Shamrai. Parametric ion-acoustic turbulence in a helicon discharge // *Plasma Sources Sci. Technol*. 2003, v. 12, p. 217-224.
6. K.P. Shamrai, S. Shinohara, V.F. Virko, V.M. Slobodyan, Yu.V. Virko and G.S. Kirichenko. Wave stimulated phenomena in inductively coupled magnetized plasmas // *Plasma Phys. Control. Fusion*. 2005, v. 47, p. A307-315.
7. C.S. Corr, N. Plihon, P. Chabert, O. Sutherland and R.W. Boswell. Spatially limited ion acoustic wave activity in low-pressure helicon discharges // *Phys. Plasmas*. 2004, v. 11, p. 4596-4602.
8. K.P. Shamrai, V.F. Virko, V.M. Slobodyan, Yu.V. Virko and G.S. Kirichenko. Ion acoustic wave activity in $m = 0$ helicon plasmas // *Problems of Atomic Sci. Technol. Ser. "Plasma Electronics and New Acceleration Methods" (5)*. 2006, N 5, p. 48-53.
9. A.W. Molvik, A.R. Ellingboe and T.D. Rognlien. Hot electron production and wave structure in a helicon plasma source // *Phys. Rev. Lett*. 1997, v. 79, p. 233-236.
10. S.M. Tysk, C.M. Denning, J.E. Scharer and K. Akhtar. Optical, wave measurements, and modeling of helicon plasmas for a wide range of magnetic fields // *Phys. Plasmas.* 2004, v. 11, p. 878-887.
11. K.P. Shamrai and V.B. Taranov. Volume and surface rf power absorption in a helicon plasma source // *Plasma Sources Sci. Technol.* 1996, v. 5, p. 474-491.
12. V.M. Slobodyan, V.F. Virko, G.S. Kirichenko and K.P. Shamrai. Helicon discharge excited by a flat antenna along the magnetic field // *Problems of Atomic Sci. Technol. Ser. "Plasma Electronics and New Acceleration Methods" (3).* 2003, N 4, p. 235-240 (in Russian).
13. M.A. Lieberman and A.J. Lichtenberg. *Principles of plasma discharges and materials processing*. New York: Wiley, 1994, p. 555.

НЕЛИНЕЙНЫЕ ЯВЛЕНИЯ В ГЕЛИКОННОЙ ПЛАЗМЕ

К.П. Шамрай, В.М. Слободян, В.Ф. Вирко, Ю.В. Вирко, А.А. Гурин, Г.С. Кириченко

Теоретически проанализированы нелинейные явления, стимулированные повышенным продольным электрическим полем, возникающим вблизи металлических поверхностей в геликонной плазме. Рассмотрен пондеромоторный эффект, приводящий к нелинейной неустойчивости краевой плазмы, и стохастическое ускорение электронов, увеличивающее поглощение ВЧ-мощности и генерацию плазмы. Представлены экспериментальные подтверждения неравновесности распределений электронов по энергиям, содержащих популяцию быстрых частиц со средними энергиями порядка нескольких десятков электрон-вольт.

НЕЛІНІЙНІ ЯВИЩА В ГЕЛІКОННІЙ ПЛАЗМІ

К.П. Шамрай, В.М. Слободян, В.Ф. Вірко, Ю.В. Вірко, А.А. Гурін, Г.С. Кириченко

Теоретично проаналізовано нелінійні явища, стимульовані підвищеним поздовжнім електричним полем, що виникає поблизу металевих поверхонь в геліконній плазмі. Розглянуто пондеромоторний ефект, що призводить до нелінійної нестійкості крайового шару плазми, і стохастичне прискорення електронів, що підвищує поглинання ВЧ-потужності та генерацію плазми. Представлено експериментальні підтвердження нерівноважності розподілів електронів за енергіями, які містять популяцію швидких частинок з середніми енергіями порядка декількох десятків електрон-вольт.