LOW-PRESSURE GLOW DISCHARGE IN PLASMA LENSES ON PERMANENT MAGNETS

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The results of investigations of the static and dynamic characteristics of self-sustained low-pressure glow discharge (GD) which arises in the crossed E×B field in electrostatic plasma lenses (PL) on permanent magnets are presented. We evaluated parameters of the gas-discharge medium. Instabilities inherent to this kind of the discharge and its influence on the plasma lens focusing properties are discussed.

1. Introduction

Experiments have shown that plasma lenses considerably increase the possibilities to control high-current moderate-energy heavy-ion beams (see, e.g., [1—2]). Such beams are of significant interest for researches in nuclear physics and high-dose ion implantation. During the investigations of wide-aperture plasma lenses PL, a very narrow range of low magnetic fields is found, for which optical properties of PL are significantly improved [3]. This leads to the idea to create a necessary magnetic field configuration using a set of permanent magnets that considerably reduces energy consumption and improves PL processing characteristics. For the first time, such a lens was realized in [4] (we conventionally call this lens as PLc as its magnetic field configuration is similar to those formed by current-driven coils). It is shown that the focusing properties of PLs on permanent magnets are similar to that for the lenses using a pulsed magnetic field created by commonly used current-driven coils. Note that it is much easier to minimize the axial and radial magnetic field gradients using permanent magnets. The last is necessary to reduce spherical aberrations and to suppress the instabilities of the PL working medium [5]. A lens with the modified magnetic field (conventionally called as PLm) was successfully realized in [6—7]. During investigations, it was found that a self-sustained GD in a crossed E×B field can be ignited in the working volume of the plasma lenses using permanent magnets even at a sufficiently low residual gas pressure (10^{-5} Torr). Note that the plasma medium in the lenses using a pulsed magnetic field is created by the ion beam and secondary electrons only. The additional researches of the PLm have shown that the presence of a discharge essentially influences its optical parameters therefore it is necessary to investigate the medium formed by GD in more details. However, the characteristic feature of the PLm is the strong sensitivity of its working medium to the introduction of passive elements even those having size small enough (including capacitive probes, see [6]). Therefore in the work, we use the results of the GD researches in the PLc to explain the difference in the PLm operation at a stationary and pulsed feeding of fixing electrodes.

2. Experimental Devices and Procedure

A simplified scheme of the experimental set-up is represented in Fig. 1. A two-chamber vacuum-arc ion source (MEVVA, see, e.g., [8]) is used to obtain a wide-aperture low-divergent ion beam. In the source, a vacuum arc with a current of up to 200 A is ignited in the vapor of a cathode material (Cu and Pb). A periodically pulsed ion beam with the total current I_b up to 400 mA is extracted from the arc-discharge plasma and formed by a three-electrode accel-decel multiaperture ion optical system (IOS). The IOS contains 84 separate cells ⌀4 mm. The beam initial ⌀ ≈ 5.5 cm, initial current density distribution is practically uniform, accelerating voltage $U_b = 6\div16$ kV, beam duration — 100 μs, pulse repetition rate – 1 Hz, and area of the central collector — 1 cm^2.

Two plasma lenses on permanent magnets having different magnetic field configurations are used in the researches. The PLc lens has a non-uniform magnetic field which is similar to that created by current driven coils (Fig. 2,*a*), and the modified lens (PLm) has a more uniform magnetic field (Fig. 2,*b*). The research of the GD influence on the lens optical parameters is carried out with the PLm while the medium formed by the discharge is investigated with the PLc.

Experiments have shown that the time of 100 μs is not sufficient for the GD to develop, therefore its influence on the PLm focusing properties is investigated

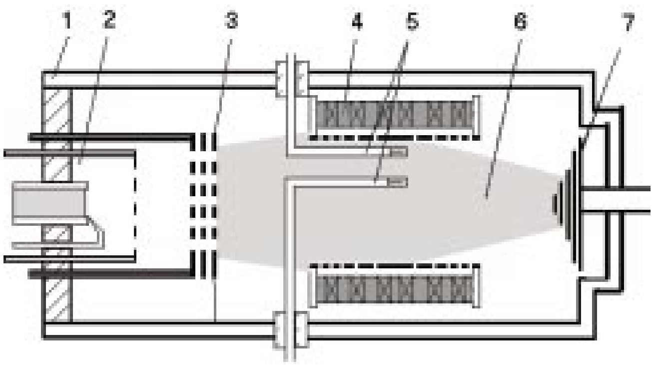

Fig. 1. Experimental set-up. *1* — vacuum chamber, *2* — ion source, *3* — IOS, *4* — PL, *5* — capacitive probes, *6* — ion beam, *7* — collector

by comparison of the lens operation at the stationary and pulsed voltages U_L up to 5 kV on its electrodes. The pulsed source has an impedance of 2.6 kΩ and provides 100-μs voltage pulses. The impedance of the stationary source is 90 kΩ, this source being additionally stabilized with the help of 1-μF capacitors. The form of the voltage supplied to electrodes is permanently checked with the help of oscilloscopes for both cases.

The GD researches are carried out at the pressure $p = (1\div15)\times10^{-5}$ Torr, and the magnetic field induction at the PL center $B_0 = 18\div36$ mT. The researches of the GD influence on the lens optical parameters are carried out at $p = (1\div2)\times10^{-5}$ Torr, $B_0 = 12\div70$ mT.

To research the dynamics of the electric potential in the PLc working medium, two capacitive probes moved in radial and azimuthal directions are used. The probe receiving tips are placed at the central plane of the lens. A Langmuir probe is used also. The experiments have shown that the medium formed by GD is more sensitive to the introduction of such probes compared to capacitive ones. Therefore, the Langmuir probe is used only to estimate the ion density at the PLc axis. The signals taken from probes are recorded via a storage oscilloscope S8-14 (bandwidth — 50 MHz) and a digital oscilloscope device ASK-3151 (bandwidth — 150 MHz).

3. Experimental Results

3.1. PLm lens

The influence of a self-sustained discharge on the PLm parameters in the normal operating mode (where a focused ion beam is passing through the lens) is essential. Due to GD, the ion beam current density increases by a factor of 2 at large magnetic fields (30÷70 mT) (Fig. 3), and also promote a reduction of the time necessary for

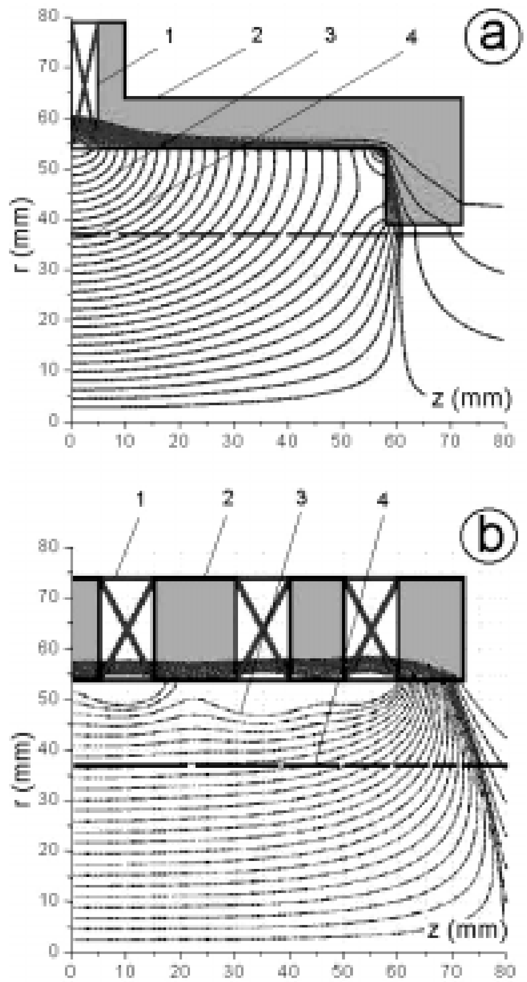

Fig. 2. Plasma lenses. *a* — PLc, *b* — PLm: *1* — permanent magnets, *2* — magnetic conductor, *3* — magnetic field lines, *4* — electrodes

PL to enter the operating mode at small ion beam currents [6]. GD promotes the stabilization of the PLm medium at small magnetic fields (≈10 mT) [7].

3.2. Lens PLc

The researches have shown that the so-called VSPD potential distribution over electrodes is optimal for the GD ignition. At VSPD, a positive potential is supplied to the central electrode, all others being grounded. The discharge current makes up from several tens of μA to one mA. The lowest GD ignition threshold (U_L = 0.5 kV) is observed at a magnetic field of 36 mT and the VSPD distribution, and the threshold practically does not depend on the pressure. It proportionally grows to

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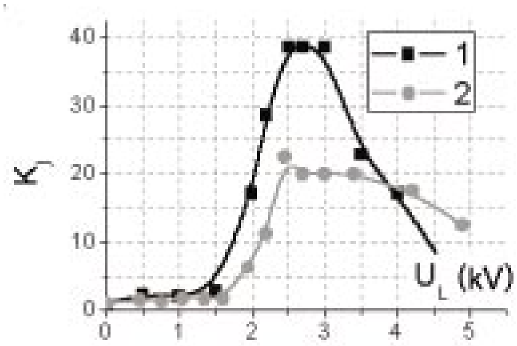

Fig. 3. Dependence of the ion beam compression factor on the maximum voltage U_L supplied to the PLm electrodes. The electrostatic potential distribution over electrodes: 1, 0.9, 0.8, 0.6, 0.45, 0.25, 0; $U_b =$ 16 kV, $B_0 = 70$ mT, $p = 1 \times 10^{-5}$ Torr, Pb, $I_b = 40$ mA; $K_j = 1$ corresponds to the current density $j_1 =$ 0.35 mA/cm^2 on the central collector. *1* — stationary U_L, *2* — pulsed U_L

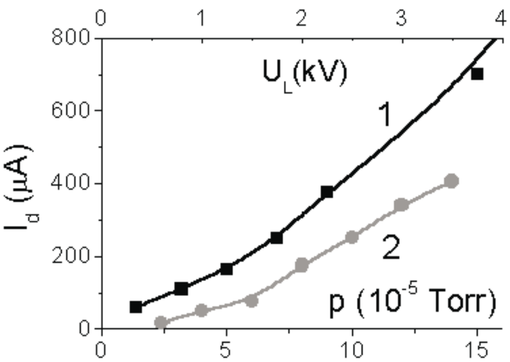

Fig. 4. Dependence of the GD current in PLc: *1* — on the pressure p, $U_L =$ 1 kV; *2* — on U_L, $p = 1 \times 10^{-5}$ Torr. VSPD, $B_0 = 36$ mT

1 kV and the discharge current is doubled, the PL magnetic field being decreased by a factor of 2. GD ignites at $U_L \geq 4$ kV, a potential being simultaneously supplied to the central and several adjacent PL electrodes. The dependence of the GD current on the residual gas pressure and voltage U_L is represented in Fig. 4. As have been observed, the GD is subjected to low-frequency (LF) (3—200 kHz) and high-frequency (HF) (2— 30 MHz) oscillations. Note that these instabilities are of importance for the GD medium diagnostics.

HF oscillations steadily arise under all conditions, GD being observed. These oscillations are the waves of electric potential. Their phase velocities have an azimuth component only, the wave number for the basic frequency remains constant ($m_\theta = 1$) for all conditions of observation; the direction of wave motion coincides with the $E \times B$ drift one; the amplitude and frequency of HF waves increase proportionally to U_L and are practically independent of pressure. The amplitude of oscillations steadily increases from the PL axis up to $r = 26$ mm. The amplitude of waves decreases with the magnetic field induction, while their frequency proportionally increases. Under certain conditions, the amplitude of HF oscillations can be modulated by the frequency of LF waves.

In contrast to HF waves, the phase of LF waves is independent of the azimuth coordinate; the frequency increases proportionally to the pressure and U_L. The research of the distribution of LF waves over the PL volume has shown that the largest amplitude is at the lens center. As a rule, the amplitude of these oscillations quickly falls down, the distance from the maximum in the radial and axial directions being increased (note that the amplitude decreases in the axial direction more slowly). The maximum amplitude of these waves increases with the pressure and U_L.

4. Discussion of the Results of Experiments

4.1. Static characteristics of the discharge

In the first approximation, the PL radial potential distribution in vacuum may be considered as parabolic. Thus, the highest electric field strength is realized near the surface of central electrode (anode). As a result, the ionization processes are most intensive in the near-electrode region. Therefore, a tubular distribution of the electron density can be created in the lens (see, e.g., [9]).

Next we estimate the electron density within the layer. The researches have shown that the probes influence the GD parameters at distances from the lens axis exceeding $R_1 = 26$ mm. Therefore, we assume that R_1 corresponds to the inner border of the layer. The maximum distance between points of magnetic field lines and the central electrode surface for those lines which cross this electrode equals 1 mm. Electrons which approach the anode up to a distance less than 1 mm are no longer magnetized. Thus, $R_2 = 36$ mm may be considered as the outer border of the layer. We use the following model: the electron density, vacuum potential of the anode, and magnetic induction are constant within the layer, all electrons have the energy which is calculated as the average between the energy of electrons at the outer and inner surfaces of the layer, electrons acquire energy due to their azimuthal drift in the electric and magnetic fields, the influence of ions is neglected. In the calculations, we use the dependence $I_d = Q\nu_i$, which actually is a balance equation corresponding to the equal generation rate of electrons due to collisional ionization and their losses on the anode. Here, I_d is the discharge current, $Q = en_eV_1$ is the layer total charge, n_e is the electron density, e is the electron charge, V_l is the layer volume, $\nu_i = n_aV_e\sigma_i$ is the ionization frequency, n_a is the density of residual gas molecules (nitrogen), σ_i is the cross-section of their ionization by electrons, V_e is the electron velocity. The dependence of σ_i on the energy [10] is approximated by two linear ones corresponding to the cross-section growth with increase in the energy from 15 eV up to 100 eV and its decrease at higher energies. The electric field, which is necessary to calculate the velocity of electrons, is determined as the sum of the anode field in vacuum and that created by electrons of the layer. The anode vacuum field is determined using the Poisson's equation $\Delta\phi = 0$ with the help of numerical techniques, boundary conditions being taken into account. The self-consisted value of the layer electron density is calculated by the method of iterations using the value of the total GD current obtained experimentally.

At $B_0 = 36$ mT, $p = 10^{-5}$ Torr, the discharge current approximately equals 50 μA. Using the above model, it is possible to calculate the electron density in the layer, $n \approx 7 \times 10^8$ cm^{-3}, and their total charge $Q \approx 1.6 \times 10^{-9}$ C.

To make the obtained results more clear, we use the maximum density $n_{\max}$ and maximum charge $Q_{\max}$ of the uniform uncompensated column of electrons which are defined by the longitudinal confinement of electrons in the lens volume: $Q_{\max} = 4\pi\varepsilon_0 L_a U_L$, $n_{\max} = 4\varepsilon_0 U_L/R_L^2$, where $L_a = 1.5$ cm is the anode width, ε_0 is the permittivity. For the PLc geometry, $Q_{\max} \approx 1.6\times10^{-9}$ C, $n_{\max} \approx 1.6\times10^8$ cm^{-3} at $U_L = 1$ kV. Thus, $n \approx 4 \times n_{\max}$ and $Q \approx Q_{\max}$. The calculations at $B_0 = 18$ mT give the values which are less approximately by a factor of 1.5. The result depends rather weakly on the methods of averaging and the layer thickness, being changed within a reasonable range. It means that, under supplying stationary potentials to the PL fixing electrodes, there are electrons in the lens even before the ion beam entry. This fact explains the accelerated formation of the plasma medium in the PLm volume in a constant crossed $E \times B$ field.

Along with the formation of a near-anode layer, ions can be accumulated in the lens near-axis region. The measurements with the help of a Langmuir probe have shown that the ion density at the PLc center is $\sim 10^8$ cm^{-2} at $U_L = 1$ kV and $p = 1.5 \times 10^{-5}$ Torr. Thus, the influence of ions on focusing can be significant even at a very low pressure (their density is comparable to that for focusing electrons).

4.2. Dynamic properties of the discharge

The frequency of HF waves obtained experimentally corresponds to the formula

$$f = \frac{E(R_1)}{2\pi R_1 B},$$

where R_1 is the distance from the PLc axis to the inner border of the layer, $E(R_1)$ is the electric field calculated accordingly to the above-described static model, and B is the magnetic field induction. This is the evidence for that the observed oscillation is a diocotron instability. Similar oscillations having a frequency close to that for the drift rotation of an electron layer in an $E \times B$ crossed field were observed and discussed in many papers (see, e.g., [11—13]), where the low-pressure discharge in Penning cells was studied. The peculiarities of the PLc magnetic field configuration enable us to investigate, for the first time, this type of discharge with the help of capacitive probes. Due to this opportunity one can investigate the peculiarities of instabilities which develop in a discharge (in particular, the diocotron instability) in more details. The dynamics of a potential in the PLc volume give the evidence for that we observe the excitation of an unstable diocotron wave similar to that described in [13]. In Fig. 5, the oscillograms of potential oscillations obtained with the use of two capacitive probes located near the PLc axis and the electron layer are represented. One can easily see a decrease of the potential in the near-axis region after the excitation of the diocotron instability, while the plasma potential near the layer is increased: the LF oscillations near the axis and the electron layer are in antiphase practically in all the range of investigations. Due to the intense ionization near the anode, the processes of near-anode layer formation and destruction can occur periodically, which gives rise to LF waves. The calculations show that the frequency of LF oscillations is close to the ionization frequency ν_i, i.e. the pulsation frequency of the electron layer.

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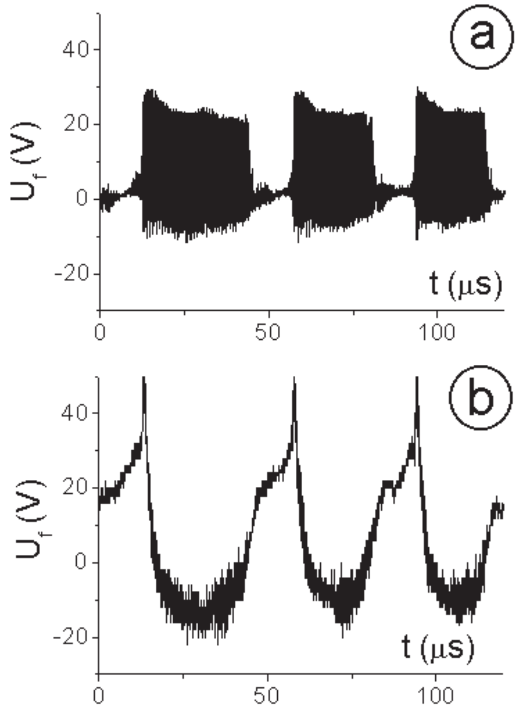

Fig. 5. Oscillograms of floating potential (U_f) oscillations at the PLc central cross-section, zero level of the potential is relative; VSPD, $B_0 = 36$ mT, $U_L = 1$ kV, $p = 1.6 \times 10^{-5}$ Torr; *a*) $r = 25$ mm; *b*) $r = 0$

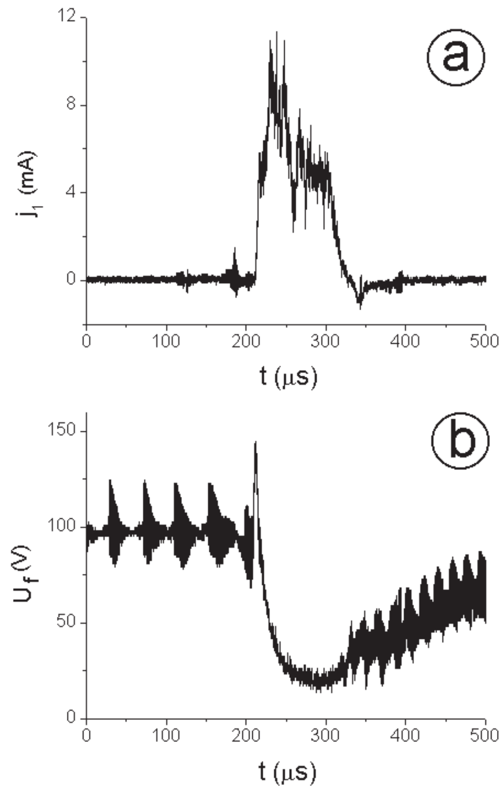

Fig. 6. Oscillograms (PLc): *a*) ion beam current onto the central collector; *b*) floating potential at the PLc central cross-section, $r =$ 25 mm, zero level of the potential is relative. VSPD, $B_0 = 36$ mT, $p = 1.5 \times 10^{-5}$ Torr, $U_L = 1$ kV, $U_b = 6$ kV, $I_b = 130$ mA, Cu

5. Influence of the Discharge on Focusing

In the normal operating mode of PL, the total current of electrons of the secondary ion-electron emission (due to the bombardment of electrodes by the ion beam) approximately equals the current of the focused ion beam. Therefore, it exceeds the GD current by some orders of magnitude. Due to the dominating emission from electrodes, the radial distribution of the electron density is smoothed somewhat. This is confirmed by the disappearance of HF oscillations, which are arisen due to the presence of the electron density gradient (Fig. 6). The calculations by the offered model show that the radial electric field decreases due to a more uniform distribution of electrons in the lens. Therefore, the ionization rate of residual gas molecules by electrons decreases by some factor. Thus, the generation of electrons in the PL working volume occurs mainly due to the secondary emission from electrodes, and the generation of slow ions practically ceases. Note that those ions, which have been accumulated previously in the discharge, leave the working volume during the time which is approximately equal to $L_2/\sqrt{2eU_L/m_a} \approx 1$ μs, where L_2 is the half-length of the lens and m_a is the mass of a nitrogen ionized molecule, because the main part of them is generated in the region, where the plasma potential approximately equals the potential of central electrode. Thus, it is possible to consider that nothing but the near-anode electron layer remains from the medium generated by GD when the ion beam enters the lens. The difference in the PLm operation at the dc and pulsed feedings of the electrode system indicates that this layer promotes a faster accumulation of focusing electrons and makes their distribution to be more uniform, which stabilizes, probably, the PLm medium.

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ЖЕВРІЮЧИЙ РОЗРЯД НИЗЬКОГО ТИСКУ У ПЛАЗМОВИХ ЛІНЗАХ НА ПОСТІЙНИХ МАГНІТАХ

О.А. Гончаров, І.М. Проценко, Ю.М. Чех

Р е з ю м е

Наведено результати досліджень статичних і динамічних характеристик самостійного жевріючого розряду (ЖР) низького тиску, що виникає в конфігурації схрещених ($E \times B$)-полів в електростатичних плазмових лінзах (ПЛ) на постійних магнітах. Зроблено оцінки параметрів плазмового середовища, сформованого розрядом. Обговорюються нестійкості, характерні для даного типу розряду. Розглянуто вплив розряду на фокусуючі властивості лінз.