EFFECT OF THE EXTERNAL MAGNETIC FIELD ON THE DYNAMICS AND POWER OF THE SELF-SUSTAINED PLASMA-BEAM DISCHARGE

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The paper is related to the studying the effect of the external constant magnetic field on the dynamics and power of the self-sustained plasma-beam discharge. It is shown that a relatively small (up to 1 kG) magnetic field of a specific configuration allows to increase the power inputted into the discharge at several times. The distinctive features of the discharge in the presence of the external constant magnetic field are noted.

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INTRODUCTION

The energy input with a high power density (at the level of 10^9 W/cm^2 and higher) into the plasma opens new possibilities both for fundamental research in plasma physics and gas discharge, and in various fields of engineering and technology. Such power densities make it possible to obtain plasma with Debye sphere which contains one ion, i.e. as it were a quasi-crystalline plasma structure. In the technical field, such power densities are used for generation of powerful (megawatt and higher for one wavelength) directional radiation in the extreme ultraviolet range from plasma of multiply ionized atoms [1]. Here, due to volumetric radiation-stimulated effects, the radiation intensity in the longitudinal direction can be one or two orders of magnitude greater than the radiation intensity in the transverse direction. In the technology field – pulse impact on solids at such power levels allows to significantly modify their surface layer, giving unique properties. This is achieved through intensive thermal and deformation processes, when the structure and phase composition radically change. As a result, strength, wear resistance and corrosion resistance increase [2].

A self-sustained plasma-beam discharge (SPBD) gives a unique opportunity for energy input with a high power density into the local plasma region [3]. Its feature is that the acceleration of powerful electron beam occurs on the space charge double layer in the local area inside its gas discharge plasma [4]. This electron beam immediately begins to give its energy behind the acceleration zone. By controlling the double layer location it is possible to form an electron beam directly in front of the object where the energy input is supposed (plasma, solid, other objects). And here there is a fundamental difference from the case of external injection of the electron beam, which was formed by any accelerator. At high power levels, when charge compensation is required to transport the beam, the beam gives off a significant energy share in the plasma of transport space, even if it is very short. (As a rule, the beam penetration depth is determined by powerful collective effects [5]).

The power level in SPBD can reach hundreds of gigawatts. At discharge voltages $U_d \sim 10^2…10^6$ V, the electron beam current can be $I_b \sim 10^2…10^6$ A. Even in case of a system with a relatively low power ($U_d \sim 20$ kV and $I_b \sim 10$ kA), the power density can reach ~ 2…3 GW/cm^2 by reducing the current channel cross-section to $S \sim 2...3$ mm^2. Here the search for new acceptable control methods both double layer parameters (hence, the electron beam energy and current) and its location is important.

The aim of this work was to study the effect of the external constant magnetic field on the SPBD dynamics and the possibility of increasing the level of active power inputted into the discharge.

1. EXPERIMENTAL SETUP

To implement the SPBD mode, a high-current pulsed plasma diode of low-pressure was chosen. The schematic representation of the discharge cell is shown in Fig. 1.

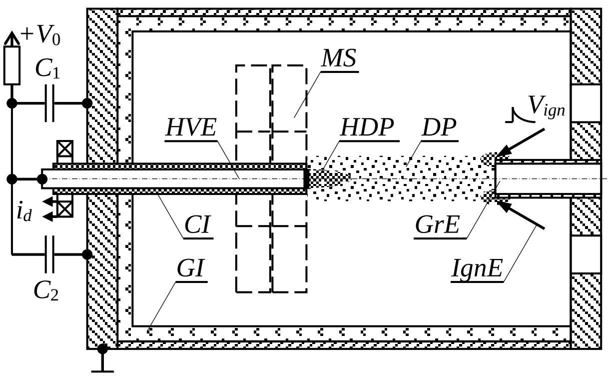

Fig. 1. Schematic representation of the discharge cell of high-current pulsed plasma diode

The diode was placed in a vacuum chamber and included a rod high-voltage electrode *HVE* (at the initial moment of time it was under positive potential) and a tubular grounded electrode *GrE*. The diameter and length of the tubular electrode were 1 and 3 cm, respectively, and the diameter of the rod electrode was 0.5 cm. The distance between the electrodes was 5 cm.

To excite the SPBD at plasma concentrations above 10^{15} cm^{-3} with double layer formation near the rod electrode, the working surface of the rod electrode did not exceed 0.2 cm^2 and was two orders of magnitude smaller than the working surface of the tubular electrode. For this purpose the rod electrode was tightly insulated by means of ceramics *CI*, so that only its end remained open. To exclude the discharge excitation from the walls, they were also insulated with a glass insulator *GI*.

The diode pulsed power supply was carried out from a low-inductance capacitor bank with a capacity of $C_0 = 1.914\ \mu F$, which was charged to a voltage of $V_0 = 4...14$ kV and directly, without a switch, was connected to the diode electrodes. The switch was the discharge gap. The discharge was excited at a pressure $p \sim 10^{-6}$ Torr after filling the gap with a primary low-density plasma due to a surface breakdown between the tubular and ignition electrodes *IgnE*. The inductance of the whole discharge circuit didn't exceed 160 nH, which provided a current up to 40 kA. The share of the discharge gap inductance was at the level of 10 %, so its minor changes had little effect on the discharge current.

The discharge included two stages: the initial high-voltage stage after 1…10 μs was replaced by a high-current stage with the current oscillations period of ~ 3.5 μs. The high-voltage stage duration depended on the charging voltage and the ignition power. The formation of a dense ~ $10^{16}...10^{17}$ cm^{-3} discharge plasma occurred during the transition from the high-voltage to the high-current stage under intense evaporation conditions of the rod electrode working surface and high-power ionization of vapour. The energy for these processes was supplied by an electron beam accelerated in the double layer, which throughout the whole high-voltage stage was located near the rod electrode. With the beginning of the high-current stage, this double layer disappeared, but other double layers periodically appeared and disappeared, changing their localization and the potential drop magnitude. The appearance of the next double layer was clearly seen as a surge in the discharge active voltage.

To control the double layers location at the high-current discharge stage and to increase the power inputted into the discharge, an external magnetic field, which was created by ring permanent magnets, was used in the work. It is necessary to immediately make a reservation that the external magnetic field was two orders of magnitude less than the intrinsic magnetic field of the current-carrying plasma cord. And this field was by no means intended to be used to hold a plasma cord. His goal was to form such a topology of the primary plasma, which would later set a certain scenario for the development of a high-current discharge with a given place of double layers formation and parameters.

The permanent ring magnets with external and internal diameters of 6 and 2.5 cm, respectively, had a thickness of 0.9 cm. The magnetic field magnitude varied due to the number of magnets in the magnetic system *MS*. Optimal results were obtained for the magnetic system with two ring magnets. A feature of ring magnets is the presence of a magnetic field inversion point, which arises from the bifurcation of field fluxes. Part of the magnetic flux is closed through the central hole, and a part – through the outer space (Fig. 2). Such distribution of magnetic fluxes creates a magnetic trap and magnetic barriers for the plasma. Due to diamagnetism, the primary low-temperature plasma is concentrated in the region near the field inversion point and hardly overcomes the humps of the intensities B_{min} and B_{max}.

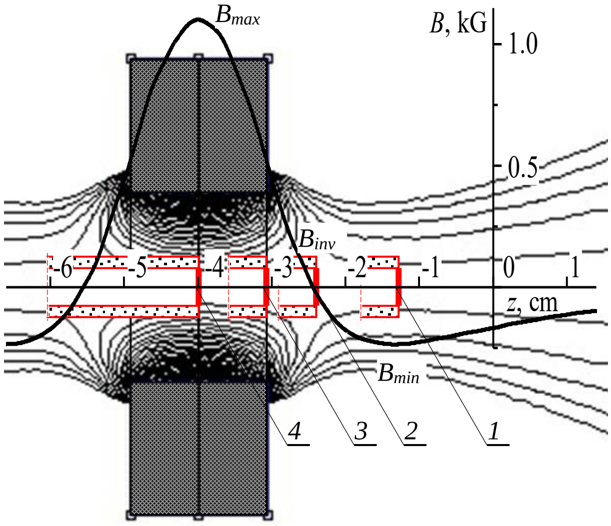

Fig. 2. Magnetic field topology and the induction distribution on the discharge axis for magnetic system with two ring permanent magnets

The experiments were carried out for four positions of the magnetic system regarding the high-voltage electrode. In the first case, the electrode end was in the region of minimal magnetic field $|B_{min}|$ = 0.235 kG, in the second case – in the region of the magnetic field inversion point $B_{inv} = 0$, in the third case – at the intermediate point with magnetic field induction ~ 0.64 kG (the electrode end coincided with the magnetic system end), in the fourth case – in the region of the maximum magnetic field B_{max} = 1.1 kG (in the center of the magnetic system). The magnetic field topology and the field induction distribution on the discharge cell axis, corresponding to the four listed cases, for magnetic system with two magnets are shown in Fig. 2.

2. RESULTS AND DISCUSSIONS

The efficiency of energy input into the discharge using an external magnetic field was determined by the level of active power generated in the discharge. The active power calculation was made on the basis of the discharge current dynamics using the original method. A full description of this method is presented in [6].

Fig. 3 shows the characteristic time dependence of the discharge current, the discharge active voltage, and the active power inputted into the discharge, at the charging voltage V_0 = 12 kV. The solid line corresponds to the case when the high-voltage electrode end is located at the magnetic field inversion point, the dashed line – to the case without the external magnetic field. One can see that the presence of the external magnetic field leads to discharge current level decrease. This is due to the primary plasma concentration in the axial region and a decrease its current-carrying ability. The studies of the high-voltage electrode diameter effect on the discharge dynamics are indirect confirmation of this [7]. Against the background of discharge current decrease, the level of active power inputted into the discharge increases, which is directly related to the discharge active voltage increase. In the given case, in the presence of external magnetic field, the level of power inputted into the discharge at the current maximum, increases from 30 to 55 MW, while the current decreases slightly from 34 to 30 kA. The active voltage magnitude at this moment is several times greater than without the external magnetic field.

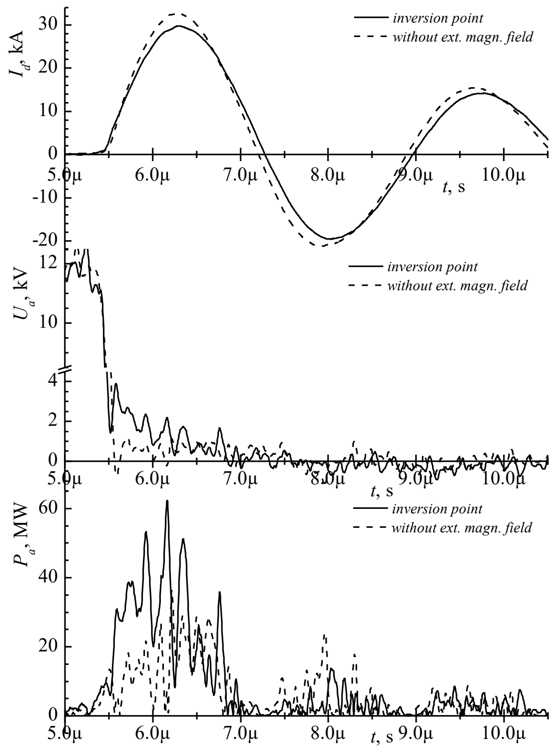

Fig. 3. Dynamics of discharge current, discharge active voltage and active power inputted into the discharge at the charging voltage V_0 = 12 kV

Fig. 4 demonstrates the comparative time dependence of the active power inputted into the discharge in the 1st half-period, in the presence of an external magnetic field P_a and its absence P_a^*. These time dependences correspond to the charging voltage V_0 = 12 kV. The solid line corresponds to the case when the high-voltage electrode end is located at the magnetic field inversion point, the dashed line – at the magnetic field minimum, the dotted line – at the point with the magnetic field induction of about 0.64 kG. The comparative dependence is presented only for the 1st half-period, since the most of energy is released in this half-period and accordingly, the highest power levels are generated. The figure shows that in the presence of the external magnetic field, the level of active power inputted into the discharge increases. In this case, the largest power increase is observed for the case when the high-voltage electrode end is located at the magnetic field inversion point. On average, for the 1st half-period, the power level increases by 2 times.

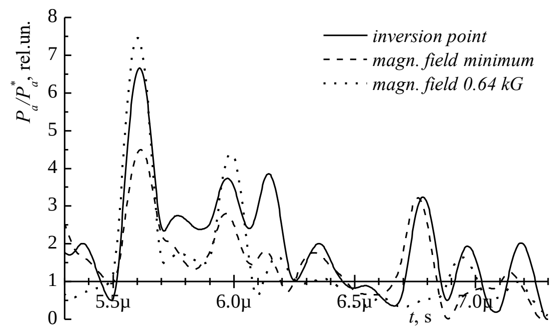

Fig. 4. Comparative time dependence of the active power inputted into the discharge in the 1st half-period in case of presence P_a and absence P_a^* of the external magnetic field

Fig. 5 shows the ratio of the energies released in the discharge in the 1st half-period, with external magnetic field W_a and without it W_a^* depending on the initial stored energy. One can see that the energy share, released in the discharge in the 1st half period, in the presence of the external magnetic field, exceeds the case without the magnetic field. At the initial stored energy up to 80 J, the largest increase of the energy, released in the discharge, is observed for the case when the high-voltage electrode end is located at the magnetic field minimum, over 80 J – at the magnetic field inversion point.

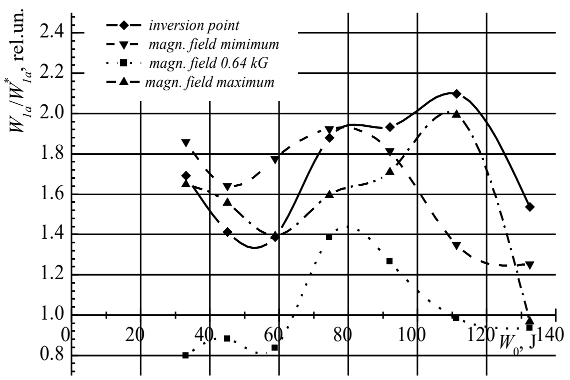

Fig. 5. Ratio of the energy released in the 1st half-period in case of presence W_a and absence W_a^* of the external magnetic field from the initial stored energy

It should be noted a distinctive feature of the discharge in the presence of the external magnetic field. When the high-voltage electrode end is located at the magnetic field minimum, the primary plasma, when filling the discharge gap, overcomes the magnetic barrier with the magnetic field induction $|B_{\min}|$. In case when the electrode end is located at the magnetic field inversion point, the plasma, having overcome the first magnetic barrier, is forced into the region of reduced magnetic field and concentrated near the inversion point. In the third and fourth case, when the electrode end is located beyond the inversion point, the plasma must pass two magnetic barriers, the first – with magnetic field induction $|B_{\min}|$ and the second – with induction of ~ 0.64 kG for the third case, and induction B_{max} for the case of the maximum magnetic field. In the last case, a higher density of the primary plasma is required. In case when the electrode end was located at the magnetic field maximum, the minimum discharge ignition voltage was 2 kV, and a stable discharge excitation was observed at the ignition voltage of 3…4 kV. Also it should be noted that in other cases, the application of the external magnetic field contributed to decrease of the minimum ignition voltage, which implies the creation of the primary plasma with reduced density.

CONCLUSIONS

Thus, it has been shown that the presence of the external magnetic field, which was created by the magnetic system on permanent ring magnets, effects on the dynamic of the self-sustained plasma-beam discharge and allows to increase the level of active power inputted into the discharge. In spite of the fact that the external magnetic field was two orders of magnitude less than the intrinsic magnetic field of the discharge, this made it possible to form such a topology of the primary plasma, which subsequently set a certain scenario for the development of a high-current discharge with a given place of double layer formation and parameters. It has been noted that the presence of the external magnetic field, with configuration that given in this paper, makes it possible to reduce the primary plasma density, but at the magnetic field maximum a higher density is required to excite a high-current discharge.

The greatest increase of the active power inputted into the discharge has been observed in the case when the high-voltage electrode end is located in the magnetic field inversion point, which is a distinctive feature of the ring magnet. Due to diamagnetism, the primary plasma was displaced into a region with a low magnetic field and concentrated near the magnetic field inversion point. It has been shown that the power increase is observed against the background of the discharge current decrease and the discharge active voltage increase.

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ВЛИЯНИЕ ВНЕШНЕГО МАГНИТНОГО ПОЛЯ НА ДИНАМИКУ И МОЩНОСТЬ САМОСТОЯТЕЛЬНОГО ПЛАЗМЕННО-ПУЧКОВОГО РАЗРЯДА

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Работа связана с исследованием влияния внешнего постоянного магнитного поля на динамику и мощность самостоятельного плазменно-пучкового разряда. Показано, что относительно небольшое (до 1 кГс) магнитное поле специфической конфигурации позволяет в несколько раз увеличить вводимую в разряд мощность. Отмечены отличительные особенности протекания разряда при наличии внешнего постоянного магнитного поля.

ВПЛИВ ЗОВНІШНЬОГО МАГНІТНОГО ПОЛЯ НА ДИНАМІКУ ТА ПОТУЖНІСТЬ САМОСТІЙНОГО ПЛАЗМОВО-ПУЧКОВОГО РОЗРЯДУ

Я.О. Гречко, М.О. Азарєнков, Є.В. Бабенко, Д.Л. Рябчіков, І.М. Середа, Д.О. Болото, О.Ф. Целуйко

Робота пов'язана з дослідженням впливу зовнішнього постійного магнітного поля на динаміку і потужність самостійного плазмово-пучкового розряду. Показано, що відносно невелике (до 1 кГс) магнітне поле специфічної конфігурації дозволяє в декілька разів збільшити потужність, що вводиться в розряд. Відзначено відмінні особливості протікання розряду при наявності зовнішнього постійного магнітного поля.