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OPERATIONAL CHARACTERISTICS OF THE ELECTRON ACCELERATOR BASED ON THE PLASMA-FILLED DIODE

E.I. Skibenko, A.N. Ozerov, I.V. Buravilov, V.B. Yuferov

National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine

E-mail: skibenko38@gmail.com, ozerov@kipt.kharkov.ua

The paper is concerned with the plasma-filled diode performance in the intensive mode regulated by means of external gas puffing. The possibility to smoothly vary the plasma parameters in the discharge gap zone, and thus, to optimize the main diode characteristics ($U_{cutoff,}$ I_{cutoff}) by the external gas puffing method has been confirmed by experiment. The introduction of additional quantity of neutral gas into the discharge causes the change in the plasma density balance due to elementary processes in physics of electronic and atomic collisions, such as ionization, dissociation, recombination. The deviation of actual voltage/current values from their maximum values can be attributed to the mismatch in the generator-load feed circuit.

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INTRODUCTION

Many branches of modern physics of plasma and controlled fusion reactions are devoted to consideration, investigation and realization ofpulsed processes and technologies involving the methods and devices that are based on the advances of pulsed power and electronic engineering. These are the generation of microwave radiation pulses, pulsed beams and accelerators, powerful pulsed gas lasers, generators of high-power X-ray pulses. The basis for all this rests on direct-action diodes designed for producing electron beams of various types such as (i) electron beams of large cross-section, (ii) hollow (tubular) electron beams, and also, (iii) dense and focused electron beams. The (i) beams are generally used for technological applications and process solutions, and also, for pumping powerful gas lasers. The (ii) beams – for generation of microwave radiation; and the (iii) beams – for plasma heating and investigation of plasma properties. Of essential practical importance are the diodes for producing high-power pulsed ion beams, and therewith, for developingthe methods of their production. An important place in the development of diode technologies is occupied by plasma-opening and -closing current switches. The last ones are used for creating both the pulse generators (electron accelerators) with nanosecond plasma switches (PCS) and those with microsecond PCS. Considering that during PCS operation, a plasma jumper is formed between two electrodes (anode and cathode), which plays a crucial role in the switch operation, it is of prime importance to know the jumper characteristics (density, temperature, plasma formation profile) and the methods of varying them. The investigators-experimentalists [1-9] have used a variety of techniques for measuring directly the plasma density in the bridge during its filling with plasma. Among them, there were microwave methods and laser circuits of plasma diagnostics using the physical phenomenon of different-frequency electromagnetic wave interferometry. A set of the data is presented in Table 1 and in Fig. 1 in the form of the function $I_{cutoff}=f(n_p)$. Note that the plasma density n_p value is normalized to

$$\sum_{k=8} I^k_{\text{cutoff}} - I^k_{\text{cutoff}},$$

where $\sum_{k=8} I^k_{\text{cutoff}}$is the sum of PCS currents of different installations listed in Table, I^k_{cutoff} is the current of the individual installation. The normalization was carried out to reduce the spread of experimental points, particularly in the region of high $I_{cutoff}$and n_p values. As a result, Fig. 1 shows the function

$$I_{\text{cutoff}} = f\left(\frac{n_p}{\left(\sum_{k=8} I^k_{\text{cutoff}} - I^k_{\text{cutoff}}\right)}\right)$$

The bottom line of Table gives the values of normalization factors (NF) for each individual installation and each value of plasma density.

Normalization factors of different installations

Installation	Proto-1	Proto-1	DI	Gamble-1	Marina	HAWK	DECADE	ACE-4
n_p, cm^{-3}	10^{12}	10^{13}	$\geq 1.7\cdot10^{13}$	$1.5\cdot10^{13}$	10^{14}	10^{15}	10^{15}	10^{15}
NF, A	$11.107\cdot10^6$	$11.107\cdot10^6$	$11.032\cdot10^6$	$10.982\cdot10^6$	$10.902\cdot10^6$	$10.505\cdot10^6$	$9.382\cdot10^6$	$3.182\cdot10^6$

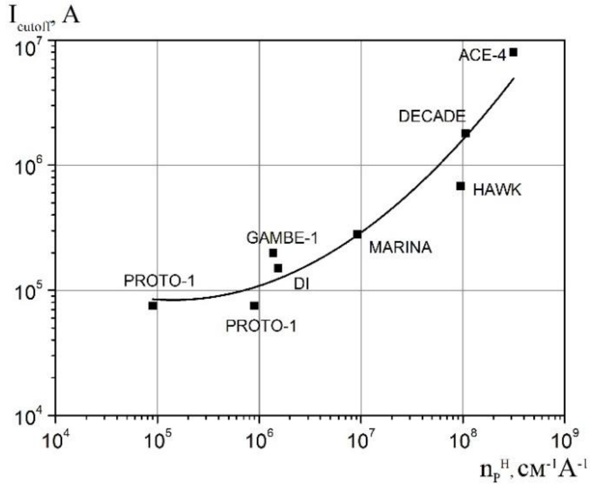

Fig. 1. PCS break current versus the normalized plasma density $n_p^n=n_p/NF$ in the discharge gap for different experimental installations

With energetics of the facilities under consideration [1-9] the PCS electrode surfaces will be exposed to bombardment of rather intense beams of accelerated particles from the interelectrode gap. It is known [10, 11] that at corpuscular and plasma interactions with the solid (metal) surfacea number of processes take place, e.g., electron emission; implantation, reflection and stimulated desorption of particles; the surface layer alteration; change in the charge state of ions; sputtering, blistering, etc.

To protect the PCS electrode system against bombardment, and hence, against sputtering, it is proposed that magnetic fields, special materials and screens should be used. In particular, the case in point is that the electrode surfaces would be made from carbon-carbon material, ~ 7 mm thick. This material shows high resistance to high-power impulse actions [12], a high mechanical strength, optimum conductivity that lets first, the passage of high-density currents (~10 kA/cm^2), and secondly, the avoidance of external magnetic field skinning. The material also has high plasma formation energy (~10 J/cm^2), which reduces the probability of uncontrolled plasma formation from the electrodes as a long pulse is passed. This, in turn, makes it possible to avoid violation of match conditions in the PCS-load circuit.

In some experiments, use is made of multigapplasma guns with a sequential breakdown of ten plasma-forming gaps and a storage volume [13], from which the plasma goes through the cathode orifices to the PCS gap. These guns are sufficiently compact, and the plasma-forming dielectric (plexiglass) is shielded from the bombardment of charged particle flows accelerated in the PCS. The disadvantage of the guns lies in a relatively low plasma yield. Compared to open guns, the current passed through them must be doubled.

Generally, with the use of plasma guns, two modes of their operation are distinguished: 1) high supply voltage of the plasma guns, 2) low supply voltage (Fig. 2).

In the PCS discharge gap, there is the region of optimum plasma density n_{opt} value. Mode 1) features two time intervals, when the current breaking is possible, viz., t_1 at the leading edge (rise in n_p) and t_3 – at the density droop. Within the interval t_2 the oscillatory mode is observed. For mode 2 (see Fig. 2), there exists only one interval t_4, when the current breaking is possible. To increase the pulse length, consideration (with subsequent realization) was given to the variant of programmable filling of the discharge gap with plasma due to a multiple actuation of the guns [14].

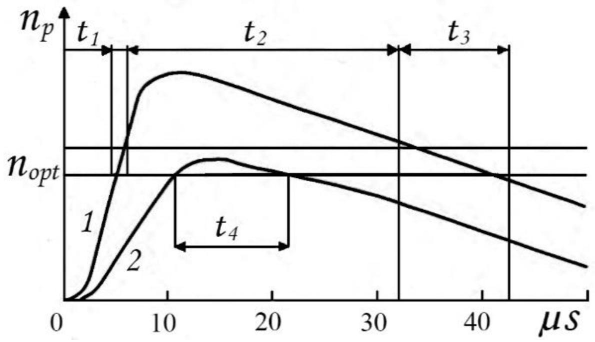

Fig. 2. Illustration of plasma density variation in the PCS discharge gap after gun operation

The dynamics of plasma density setting in the PCS interelectrode gap was traced in Ref. [15]. The multiple switching of guns calls for operation at the minimum possible plasma density (mode 2, see Fig. 2), when there exists one region of delay in energization of the PCS with respect to the guns, when the POS operation (i.e., the current breaking) is possible.

So, various research teams and study groups practically continuously work at optimizing the operation of PCS and other devices (pulse generators and electron accelerators). This is why the present work has been aimed to optimize the operation of the “DI” facility (accelerator) versus pressure of the volume-neutral POS, and therefore, to optimize the modes of its operation in the “standard” [6, 7] and “intensive” (present experiment) formats.

1. DISTINCTVE FEATURES OF THE “DI” FACILITY DESIGN

The description and schematic diagrams of the “DI” facility, and also, the methods and means for plasma diagnostics and other associated physical processes are presented in sufficient detail in Refs. [6, 7]. It will be recalled thatthe “DI” facility represents a compact direct-action electron accelerator having an effective plasma current commutator (PCS-PCI) operating in the nanosecond range. As regards the level of the generated electric power, the facility is related, according to the world rating, to the medium-power setups of a similar nature (see Fig. 1). The main distinctive features of the “DI” design are as follows:

- low inductance values of certain diode elements and sections, and also, the total inductance value (see [7]) are designed to attain the enhanced plasma density values in the discharge gap and, eventually, the switching current value;
- actually, the volume occupied by the externally injected plasma is considerably smaller than the vacuum chamber volume, this being due to the design feature of the anode and its holder (see Fig. 1 in Ref. [7]). The

holder has grooves (slots) in amount equal to the number of plasma guns. This favors the uniform plasma filling of the discharge (anode-cathode) gap, and also, improves the gas exchange during neutral gas injection (inlet) up to the operating pressure value, and then, its pumping outafter the current switching event;

- the choice of the cathode/anode orifice diameters close to each other in size facilitates the formation and propagation of anelectron beam of finite dimensions;

- the chosen plasma-gun design [7] and additional injection (inlet) of working gas (Ar) make it possible to maintain both the fixed gaseous atmosphere composition inside the diode vacuum chamber and the elemental composition of the plasma, except for electrode sputtering products (Cr, Ni, Ti, Fe);

- the possibility of contactless microwave sounding (probing) of plasma, externally injected into the interelectrode gap, at a frequency of 35 GHz;

- the capability of measuring vacuum characteristics of the current switch under study and of the diode as a whole, including the absolute value of pressure and its dynamics, the gain in pressure and gas evolution per pulse;

- the operating conditions with lower gun voltages were used for reducing the erosion of gun and diode electrodes, vacuum chamber walls, and also, of insulator surfaces. This has resulted in the reduction of energy input in the plasma guns by more than an order of magnitude in comparison with the literature data.

Thus, the main design criteria of the diode, viz., the minimum of inductive power loss and the maximum of gas-kinetic conductivity in the interelectrode gap region, have found their solution in the chosen variant of project realization.

2. MEASURING MEANS FOR DIODE VOLT-AMPERE CHARACTERISTICS

The main means for measuring volt-ampere characteristics of switching circuits and impulse devices include the Rogowski loops and various types of voltage dividers (capacitive and resistive). Our case is no exception. Below we give the characteristics of the devices used in the studies.

2.1. ROGOWSKI LOOPS

In the "DI" experiments, the Rogowski loops, structurally similar in terms of design, were used to measure both the pulse voltage generator current (Fig. 3 in [7]) and the load current. Their parameters were as follows:

- mean winding radius 245 mm;
- sensitivity 5 kA/V (experiment);
- decay constant at a frequency of 10^6 Hz = $5.5\cdot10^{-6}$ s;
- the rise time 17 ns.

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2.2. CAPACITIVE-RESISTIVE VOLTAGE DIVIDER PERFORMANCE

- voltage division ratio $3\cdot10^4$;
- matter constant $3\cdot10^{-6}$ s.

3. EXPERIMENTAL RESULTS

Experimentally, the following parametric dependences were investigated:

- the load switching voltage $U_{cutoff}=f(p_{in.})$ as a function of the initial pressure of gas let in from the outside (see Fig. 3);
- the diode switched current $I_{cutoff}=f(p_{in})$ as a function of the initial pressure of the gas injected (Fig. 4);
- the pulsed power realizable in the diode during the unit act of current switching $W_g= f(p_{in.})$ versus initial pressure of the gas injected (see Fig. 5);
- pressure gain in the vacuum chamber of the accelerator during the switching act versus the switched current value (Fig. 6).

It is evident from Figs. 3 to 5 that the maximum voltage values ranging from 450 to 510 kV are attained at injected gas (Ar) pressures between $8\cdot10^{-5}$ and $1.5\cdot10^{-3}$ Torr; the maximum switched current values ranging from 110 to 150 кA – at p_{in}~$2\cdot10^{-4}$...$6\cdot10^{-3}$ Torr; the maximum diode power from 4 to $6\cdot10^{10}$ W – at $p_{in.}$~$2\cdot10^{-4}$...$3\cdot10^{-3}$ Torr. The maximum final pressure values in the diode chamber after the unit act of switching are realizable by varying the switched current in the range from 45 to 150 kA.

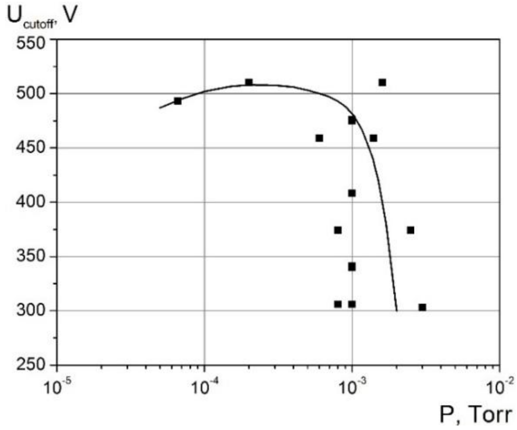

Fig. 3. Load switching voltage as a function of the initial pressure of gas let in from the outside

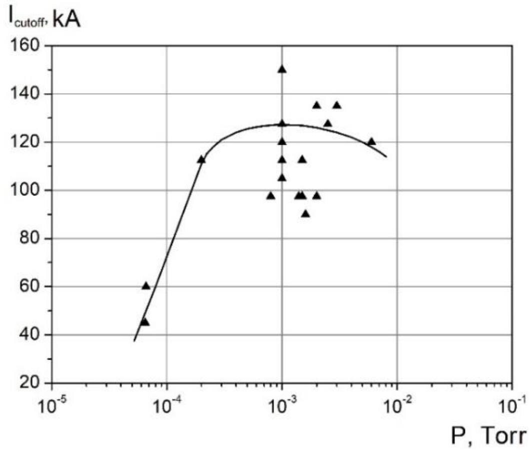

Fig. 4. Diode switched current as a function of the initial pressure of the gas injected

The concept of direct charging of the inductive energy storage unit from Marx generators, with subsequent energy extraction to the load by means of a microsecond plasma–opening switch (PCS), has been realized in one of the world's largest pulse generators – MJ complex PVG-12.

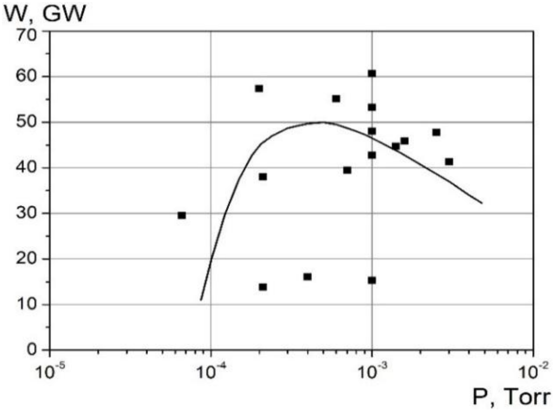

Fig. 5. Pulsed power realizable in the diode during the unit act of current switching versus initial pressure of the gas injected

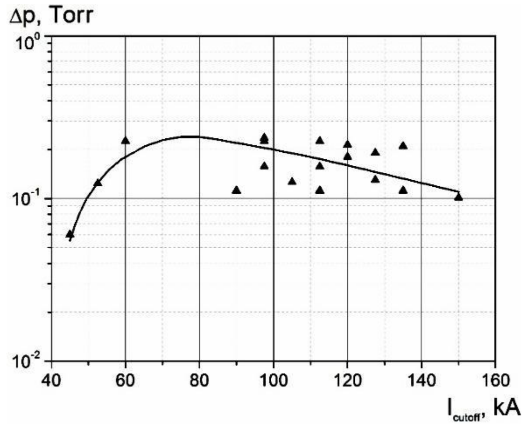

Fig. 6. Pressure gain in the vacuum chamber of the accelerator during the switching act versus the switched current value

In describing its performance [16], it has been indicated that if the plasma concentration in the switch zone is too high, then a part of the plasma is transferred to the loaded region, and that violates the generator-load matching conditions. The generator-load mismatch (because of excess or lack of plasma) may possibly account for the deviation of the actual U_{cutoff} and I_{cutoff} values from their predicted maximum values (see Figs. 3 and 4) beyond the range of optimum injected-gas pressure values. Really, the puffing of additional amount of neutral gas to the discharge may cause the change inthe plasma density balance due to the occurring elementary processes of ionization, dissociation, recombination of particles, and the electrode material sputtering.

As pointed out above, the operation of the "DI" accelerator was investigated in the two modes:
i) standard and ii) intensive. In the first case, the discharge gap was filled with plasma be means of plasma guns in number of four to twelve. In the second case, in addition to the above, Ar was let in into the accelerator chamber just before the act of current switching with the PCS. Fig. 7 shows the current-voltage characteristics of the "DI" diode for the two operating modes under study. It is obvious that the gas puffing has considerably improved the diode parameters; in particular, the voltage (see Fig. 7) and power (see Fig. 5). We mention in passing that the gas puffing technique employed at the "DI" facility was used independently at the "HAWK" setup [5].

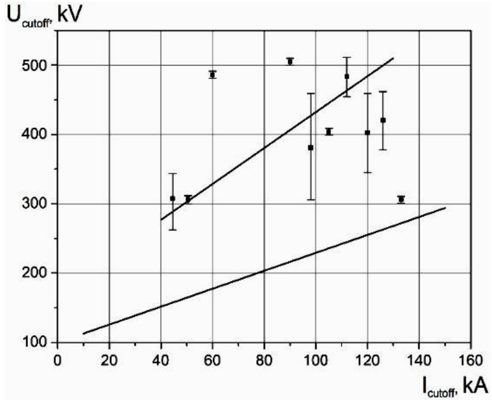

Fig. 7. Comparison of current-voltage characteristics of the "DI" accelerator at two modes of its operation: standard [7] and intensive (present experiment)

4. DISCUSSION OF RESULTS. CONCLUSIONS

In experiments and devices with relativistic electron beams, in diodes, it is important to prevent a monotonic decrease in the diode impedance z(t). The initial conditions of the diode operation are as follows.Consideration is given to a planar diode fully filled with plasma. The cathode is at negative potential. The double layer (DL) [17, 18] is formed in the proximity of the cathode. At this time, the plasma diode undergoes several stages of evolution. The first is the so-called "seed" stage. The duration of its formation is $t_0 \sim \omega_{pi}^{-1}$. Here, the thermal pressure of plasma and the inertia of the charges of both signs are of importance. During this period the electric field pressure in the DL overruns the thermal pressure of plasma, and then, under the action of the field, the DL starts expanding at $t > t_0$. In this case, we have $n_i \sim n_p$, $\nu_{e,i} \sim \nu_{Te}$, $\varphi \sim T_e/e$, $d_{layer} \sim r_{Debye}$. The second stage represents the process of DL growth. Here, only the ion inertia and the quasistationary electron flow are of importance. Fig. 8 shows the general view of the diode configuration under study (a), and the distribution of the acting force potential (b). In the C-A system, three regions are distinguished: 1) the undisturbed (equilibrium) plasma region, 2) the region filled only with particle flows (DL), 3) the transition layer (TL). The TL is the field penetration zone characterized by the transition from the directional charge motion in the DL region to the thermal motion in the plasma. During the second stage the ions from the near-anode plasma layer leave for the cathode, the fast electrons e_f (see Fig. 8) move from the cathode to the anode, and the thermal electrons e_s (see Fig. 8) in the TL region reciprocate from the plasma-TL boundary to the TL-DL boundary. The third stage is characterized by a gradual decrease in the DL growth, and with that the current is quasi-stationary. The 2nd and 3rd stages of diode evolution are typified by the presence of the process of plasma decay (erosion) ahead of the DL in the unsteady motion.

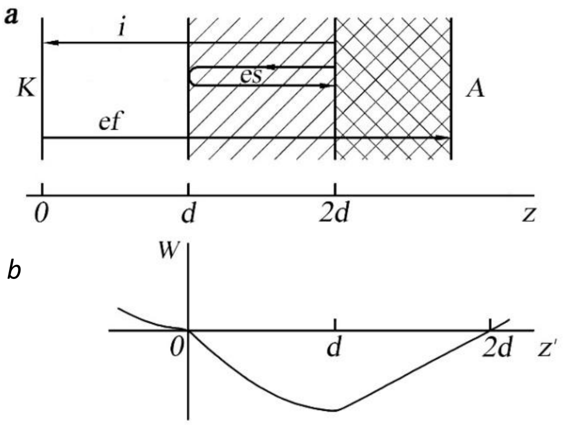

Fig. 8. Plasma diode configuration.
a – general view, b – force potential distribution acting on the slow electrons in the transition layer

In experiments [1, 2] the Debye radius in a quiet (nonturbulent) plasma is r_D~ 10^{-3}cm, the free path of ions is λ_i~10^{-2} cm. The time between collisions of ions is $\tau_i=(\lambda_i/v_{Ti})$~$10^{-8}$ s = 10 ns, which allows one to consider the plasma collisionless at the voltage front. However, the field penetration into the plasma from the DL ($t>t_0$ and $d>r_d$) is due to the directional motion of electrons rather than to the thermal motion. In this case, as mentioned above, two groups of electrons are distinguished:

i) fast electrons e_f coming from the DL and being emitted by the cathode;

ii) slow electrons e_s that are accelerated by the penetrating field and are favorable to the plasma erosion. The flow of fast electrons is quasistationary, and is described by the equations $en_{ef}v_{ef}=j_{ef}$, and $mv_{ef}^2/2 -e\varphi=0.$ At the same time, the quasistationary motion of slow electrons is connected with the displacementof the DL boundary. In this case, the slow electrons appear to be in the potential well (see Fig. 8). The DL boundary serves as a turning point (turn back place) for the slow electrons, and the leading edge of the field penetration zone is coincident with the potential well bottom. The slow electrons pass through the TL twice: in forward and backward directions. In the fixed frame of reference, the "backward" current is matched by the acceleration of slow electrons from the state of rest in the quiet (nonturbulent) plasma up to the DL velocity at the moment when the DL comes up to these electrons. The subsequent acceleration corresponds to the "forward" current, and it continues until the electrons reach the leading front (edge) of the TL.

Thus, in the plasma ($n_p\geq10^{12}$ cm^{-3}, T_p~1 eV), which fills the high-current diode, at the leading edge of the external voltage pulse the near-cathode DL is formed. Its further growth is characterized by the accelerated (the so-called "supersonic") motion of the boundary. The ions are supplied to the DL through the field penetration into the plasma. This occurs due to acceleration of the plasma electrons that provide the penetration at a depth equal to the DL width. As a result, intensive plasma decay (erosion) occurs, thereby promoting the DL propagation.The duration of the phase lasts a few nanoseconds at n_p ~ 10^{12} cm^{-3}. It decreases quickly with a density increase, and as early as at n_p~ 10^{14}cm^{-3} it turns out to be <1 ns. The subsequent quasistationary phase is characterized by the transition from the so-called "supersonic" to "sub-sonic" boundary motion. The stage permits the constancyof the diode impedance, which is of importance for matching the diode with the generator. This points to the fact that the plasma diode can be operated in both the mode of the current switch and the mode matched with the generator operation.

1. One of the major conclusions of the present studies is the confirmed feasibility of regulating the plasma parameters in the discharge gap zone, and hence, the main characteristics of the diode (U_{cutoff}, I_{cutoff}), by the external gas puffing method.

2. The introduction of additional quantity of neutral gas into the discharge causes the change in the plasma density balance due to elementary processes in physics of electronic and atomic collisions, such as ionization, dissociation, and recombination.

3. The deviation of the actual U_{cutoff} and I_{cutoff} values from their predicted maximum values (see Figs. 3, 4) beyond the range of optimum injected-gas pressure values may be due to mismatch in the generator-load (diode) circuit, andthis may be responsible forthe mentioned parameters degradation.

4. With due regard to the characteristics of the plasma sources employed (T_p ~ 1 eV), the threshold plasma density n_p ~ 10^{12} $A^2\cdot$cm^{-3}($A = m_i/m_p$) has been established, at which the DL formation takes place. Below the threshold value, the DL does not occur, and the diode is operating like a vacuum one in the beam mode. Above the threshold, the Bohm criterion ($v_0>v_{Te}$), required for the DL formation, is fulfilled. Among the plasma sources used, preference is given to those with A=1, as their parameters are readily determined.

5. The rate of DL growth $\dot{d}$, the field potential $e\varphi_p$, and the diode impedance *z* have been estimated for the condition that $\nu_{e,i}$ ~ ν_{Te} [18]. The obtained data are in agreement with the results obtained in ref. [2] for the DL growth for the time < 10 ns up to the DL size *d* ~ 10 cm, the DL growth rate being ~100 cm/μs. As this takes place, the impedance increases from 10^{-5}...10^{-4} to 1...10 Ω for the time ≤10 ns, this being in agreement with a value of 50 Ω measured in [2]. In the case of a higher-density plasma (10^{13}…10^{14} cm^{-3}) and at t_0~0.1 ns, the operational mode similar to that of ref. [19] can be observed, i.e., when only the quasistationary stage of DL evolution is realized, without observation of thesecond stage, namely, the supersonic ($\dot{d}>v_{Ti}$), accelerated (d>0) DL expansion. Note also that at $n_p=10^{14}$ cm^{-3}, $r_d=10^{-3}$ cm, $\omega_{pe}=5.64\cdot10^{11}$ s^{-1}, S=1 cm^2, $\omega_{pi}=1.32\cdot10^{10}$ s^{-1}, $t_0=0.76\cdot10^{-2}$ ns, the DL grows rather quickly for a few nanoseconds 1...2 ns from a few tenths of cm (0.294) up to about 10 cm (9.6), and the impedance increases up to 142.5 Ω for 5 ns.

Relying on the experimental data of work [15], computations have been performed to estimate the duration of the process of plasma decay (erosion) in the Gamble-1 diode, and also, the rate of plasma density decrease (loss) in the discharge gap, which occurs in consequence of the mentioned process. It has appeared that the process time takes about 500 ns, and the density decrease is $8\cdot10^{12}$ particle/(cm$^3\cdot$ns). The decrease in the density value reaches ~ 50 %.

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ОПРЕДЕЛЕНИЕ РАБОЧИХ ПАРАМЕТРОВ ЭЛЕКТРОННОГО УСКОРИТЕЛЯ НА ОСНОВЕ ПЛАЗМОНАПОЛНЕННОГО ДИОДА

Е.И. Скибенко, А.Н. Озеров, И.В. Буравилов, В.Б. Юферов

Проведено исследование характеристик плазменного диода в режиме "intensive", который регулировался путем внешнего газонапуска. Экспериментально подтверждена возможность плавного изменения плазменных параметров в зоне разрядного промежутка и соответственно оптимизации основных характеристик диода ($U_{ППТ}$, $I_{ППТ}$) методом внешнего газонапуска. Введение в разряд дополнительного количества нейтрального газа приводит к изменению баланса плотности плазмы за счет элементарных процессов физики атомных и электронных столкновений – ионизации, диссоциации, рекомбинации. Отклонение текущих значений от максимальных значений напряжения и тока может быть связано с рассогласованием в цепи "питающий генератор-нагрузка".

ВИЗНАЧЕННЯ РОБОЧИХ ПАРАМЕТРІВ ЕЛЕКТРОННОГО ПРИСКОРЮВАЧА НА ОСНОВІ ПЛАЗМОНАПОВНЕННОГО ДІОДА

Є.І. Скібенко, О.М. Озеров, І.В. Буравілов, В.Б. Юферов

Проведено дослідження характеристик плазмового діода в режимі "intensive", який регулювався шляхом зовнішнього газонапуску. Експериментально підтверджена можливість плавноїзміни плазмових параметрів у зоні розрядного проміжку і, відповідно, оптимізації основних характеристик діода ($U_{ППТ}$, $I_{ППТ}$) методом зовнішнього напуску газу. Введення в розряд додаткової кількості нейтрального газу призводить до зміни балансу щільності плазми за рахунок елементарних процесів фізики атомних і електронних зіткнень – іонізації, дисоціації, рекомбінації. Відхилення поточних значень від максимальних значень напруги і струму може бути пов'язане з розгалуженістю у ланцюзі "генератора живлення і навантаження".