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THE IMPEDANCE OF AN ELECTRODYNAMIC, COAXIAL PLASMA ACCELERATOR

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The properties of the impedance of an electrodynamic plasma accelerator are investigated. Drawing upon an analysis of the generalized Ohm's law, the factors resulting in a decrease in impedance, observed when the "extension currents" of the coaxial gun are blocked, are discussed.

The impedance z of the accelerator system plays an important role in the determination of the macroscopic properties of an electrodynamic plasma accelerator. The impedance consists of two components: ohmic (z_1) and electrodynamic (z_2) [1]. Depending on which of these components prevails, one can judge the character of the occurrence of the plasma-acceleration process [2, 3]. Therefore, it is important to know the laws of variation of these components over the time of operation of the accelerator.

The impedance of a coaxial gun operating in the fractional mode of plasma acceleration was investigated. For this a unipolar current pulse, obtained using an inductive energy accumulator [4, 5], was used for the accelerator supply.

From an examination of typical oscillograms (Fig. 1) of discharge current and voltage obtained, it follows that in the fractional mode of plasma acceleration the total accelerator impedance ($z = z_1 + z_2$) is always kept at a rather high level and its value reaches $z = (1\text{-}1.3)\cdot 10^{-2}\ \Omega$ for a mean discharge current I = 25-30 kA and a voltage U = 300-400 V. It must be assumed that most of the voltage is due to the presence of a back emf, generated as a result of plasma motion through the H_φ field, so that z_2 must be larger than z_1. To confirm this, we estimate the magnitudes of the components z_1 and z_2 on the basis of the energy balance of the accelerator system.

It is known that the energy efficiency of an accelerator depends on z_1 and z_2, which characterize the fractions of input energy expended on ohmic losses in the discharge and on electrodynamic plasma acceleration, respectively. Knowing the accelerator input energy W_{in} and the energy W_{pl} of the plasma jet, one can estimate the mean values of z, z_1, and z_2 from the equations $W_{in} = I^2zt$, $W_{pl} = I^2z_2t$, and $W_{ohm} = I^2z_1t$. On the basis of the experimental data obtained (W_{in} = 3.5 kJ, W_{pl} = 2.8 kJ, W_{ohm} = 700 J, I = 25 kA, $t = 5\cdot 10^{-4}$ sec) we determine the following: $z = 1.1\cdot 10^{-2}\ \Omega$, $z_2 = 0.9\cdot 10^{-2}\ \Omega$, $z_1 = 0.2\cdot 10^{-2}\ \Omega$. It follows from the estimates that z_2 is far larger than z_1. The good agreement between the value of z and the value determined earlier from the volt–ampere characteristic curve indicates the reliability of these estimates.

On the other hand, the total impedance z calculated from the current and voltage oscillograms retains an almost constant value (Fig. 2a) during the entire discharge pulse. During a twofold decrease in current, z does not vary. This means that, in contrast to ordinary high-current (arc) discharges, in the mode under consideration the current is a linear function of the applied voltage. Evidently, the reason for this is the constancy of the component z_2, connected with the plasma motion: $z_2 \sim bV$ (where b is the linear inductance of the accelerator; V is the plasma velocity). From a comparison of the discharge oscillograms (see Fig. 1) and streak-camera pictures (Fig. 3a, b) it follows that as the total current (discharge power) is varied, only the repetition frequency of the plasmoids varies, while their

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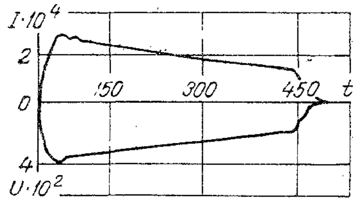

Fig. 1

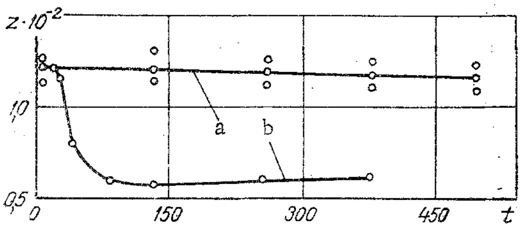

Fig. 2

Fig. 1. Typical oscillogram of the current and voltage of a unipolar discharge. I, A; U, V; t, μsec.

Fig. 2. Curves of time-dependence of the impedance: a) the plasma freely leaves the accelerator; b) the accelerated plasma is blocked inside a quartz cylinder. z, Ω.

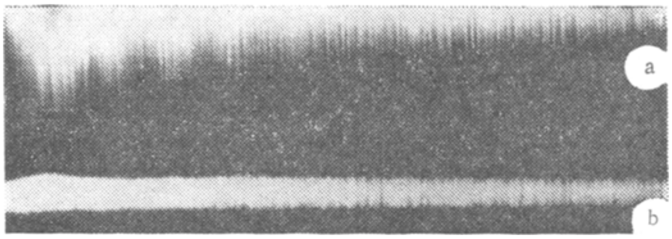

Fig. 3. Streak-camera picture of plasmoid motion beyond the accelerator cut with the slit oriented along (a) and perpendicular to (b) its axis.

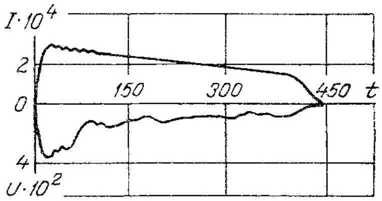

Fig. 4. Current and voltage oscillogram of the discharge when a quartz cylinder is present.

velocities remain constant, and in the majority of cases the plasmoids retain the configuration of flat disks oriented perpendicular to the direction of motion, which indicates the independence of the profile of the cluster front from the radius. A comparative analysis of these results confirms the assumption made earlier that z_2 retains a constant value during an entire discharge pulse.

To complete the physical picture, we ran tests allowing us to estimate the fraction of z connected with plasma motion directly from the current and voltage oscillograms. In these tests the acclerated plasma was blocked inside a quartz cylinder with a sufficiently strong bottom, which fitted onto the outer acclerator electrode. The volume of the cylinder was chosen such that it was filled well in advance. The corresponding current and voltage oscillograms are presented in Fig. 4. As one would expect, the voltage undergoes a jump at the instant the cylinder is filled with plasma, whereas the current remains unchanged. The voltage jump indicates a rapid decrease in z. A curve of the time dependence of z constructed from the data of these oscillograms is presented in Fig. 2b. It qualitatively confirms the presence of two z components. So long as the plasma freely leaves the accelerator, both components z_1 and z_2 differ from zero and z retains a high value.

From the instant the cylinder is filled with plasma, the discharge takes place in a slowly moving plasma, so that the total impedance z is determined mainly by the ohmic component z_1

($z \approx z_1$), which indicates the presence of a less efficient (ohmic) means of plasma acceleration. The reason for this is the following: From the instant the volume is filled with plasma, the current extensions of the accelerator electrodes ("extension currents") prove to be blocked inside the quartz cylinder, which results in disruption of the self-regulated process of emergence of plasmoids from the crossed $\mathbf{E}_r$ and $\mathbf{H}_\varphi$ fields of the accelerator [5]. It should also be noted that as the plasma jet decelerates, the plasma density grows with its simultaneous cooling as a result of heat emission to the cool walls of the quartz cylinder and through radiation. Thanks to this, in the volume occupied by the decelerating plasma there appears a neutral component, which also penetrates into the interelectrode space. The presence of a neutral component and the increase in plasma density between the accelerator electrodes result in the disappearance of plasma magnetization and Hall currents and prevent the generation of self-consistent fields in the moving plasma, which promotes the recovery of the ordinary plasma conductivity and the burning of a high-current arc within the accelerator volume.

In confirmation of the experimental facts presented, we conduct an additional analysis of the generalized Ohm's law in application to the experiment described above. Under these conditions the breakup of the plasma into individual plasmoids initially disappears, which makes the process stationary, i.e., the term which contained the expression $\partial \mathbf{j}/\partial t$ in the generalized Ohm's law becomes insignificant compared with the ratio containing the conduction currents. Therefore, the generalized law takes the form

$$\mathbf{j} + \omega_e\tau_e (\mathbf{j}\times\mathbf{B})_B = \sigma\left(\mathbf{E} + \mathbf{V}_c\times\mathbf{B} + \operatorname{grad} P_e - \frac{m_e}{m_i}\operatorname{grad} P_i\right) + \beta(\mathbf{V}_c - \mathbf{V}_n). \tag{1}$$

Let us also estimate the other terms of Eq. (1). Under the experimental conditions, when there is a cool and dense plasma, the expressions containing grad P_e and grad P_i can be neglected owing to their smallness. In the presence of a neutral component the last term on the right side of Eq. (1) plays an important role, since it corresponds to friction and describes an additional loss mechanism operating simultaneously with ordinary ohmic heating [6].

To simplify the problem of estimating the terms of the equation, we assume that:

1) The neutral components of the plasma are at rest: 2) friction between ions and neutral particles is large; 3) the inequality

$$\omega_i\tau_i \ll 1 \tag{2}$$

holds (even if $\omega_e\tau_e \gg 1$). In the case under consideration the condition (2) is satisfied because of the high density of the cool plasma, and τ_i is determined mainly by collisions between ions and neutral atoms. On the basis of the mean free path and the drift of ions in the electric field, we can determine the order of magnitude of the ion velocity [6],

$$|\mathbf{V}_i| \simeq \frac{|e|\,\tau_{in}}{2m_i}|\mathbf{E}|.$$

Since $|\mathbf{V}_n| = 0$ and $|\mathbf{V}_i| = |\mathbf{V}_c|$, the term corresponding to friction in Eq. (1) has the order of magnitude

$$|\beta(\mathbf{V}_c - \mathbf{V}_n)| \simeq \frac{m_e}{|e|}\left(\frac{1}{\tau_{en}} - \frac{1}{\tau_{in}}\right)\frac{|e|\,\tau_{in}}{2m_i} \approx \frac{m_e}{m_i}|\mathbf{E}| \ll |\mathbf{E}|.$$

It is easy to show that the expression ($\mathbf{V}_c \times \mathbf{B}$) in Eq. (1) is also less than $|\mathbf{E}|$.

Thus, under the experimental conditions under consideration the friction between ions and the neutral plasma component is high enough to assure the smallness of the term ($\mathbf{V}_c \times \mathbf{B}$), and at the same time the expression $\beta(\mathbf{V}_c - \mathbf{V}_n)$ corresponding to the friction remains insignificant compared with $\sigma\mathbf{E}$. Then Eq. (1) takes the form

$$\mathbf{j} + \omega_e\tau_e(\mathbf{j}\times\mathbf{B})/B = \sigma\mathbf{E}. \tag{3}$$

A further increase in the plasma density n results in the fact that $\omega_e\tau_e$ becomes less than unity ($\omega_e\tau_e < 1$), thanks to which the second term drops out of Eq. (3) and we obtain the usual expression for Ohm's law, $\mathbf{j} = \sigma\mathbf{E}$, as in the case of the absence of macroscopic velocity and magnetization of the plasma.

NOTATION

j, conduction current density vector; **B**, induction vector of magnetic field produced by the conduction current; **E**, electric field strength vector; P_e and P_i, partial pressures of electrons and ions; V_c, macroscopic velocity of plasma motion; V_n, velocity of the neutral component; β, coefficient of friction; $\beta = \frac{m_e}{|e|} \times \left(\frac{1}{\tau_{en}} - \frac{1}{\tau_{in}}\right)$; σ, conductivity: $\sigma = \frac{e^2 n \tau_e}{m_e}$;

$\frac{1}{\tau_e} = \frac{1}{\tau_{ei}} + \frac{1}{\tau_{en}} + \frac{m_e}{m_i} \frac{1}{\tau_{in}}$; e, m_e, electron charge and mass; m_i, ion mass; n, electron density, cm^{-3}; $1/\tau_{ei}$, frequency of collisions of electrons with ions; $1/\tau_{en}$ and $1/\tau_{in}$, frequencies of collisions of electrons and ions, respectively, with neutral particles.

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AUTOMATED DESIGN OF A COOLING SYSTEM FOR SEMICONDUCTING MODULES

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Thermal and mathematical models of semiconducting modules are proposed and a block scheme for automated design of cooling systems is proposed.

Semiconducting electrical energy transducers (gating devices, rectifiers, semiconducting transistor switches, etc.) are currently widely used in different areas of technology. In addition, as energy use increases, the requirements for efficiency, reliability, and convenience in use of these devices increase. These requirements can be satisfied and development time can be decreased only with the use of automated design systems (ADS). One of the subsystems in ADS is the design of transducers and their cooling systems. In this paper, we describe a technique for automated design of a power semiconducting switch with natural and forced air cooling.

The technical job of designing power semiconducting devices usually includes the following:

type of transistors or other elements used to construct the switch, as well as the auxiliary parts (diodes, thyristors, etc.), the admissible temperature of their p–n junctions, internal thermal resistance between the housing of the device and the crystal or the allowable temperature of the housing with a definite heat load;

operational regime of the device: currents, voltages, time diagram, which permit calculating the intensity of heat losses;

temperature of the surrounding medium;

size requirements for the transducer;

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