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INVESTIGATION OF A LINEAR PLASMA BETATRON

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The problem of obtaining intense electron beams in longitudinally uniform or non-uniform plasmas is investigated. Under the conditions of the experiment, limited electron emission from a cold cathode resulted in a redistribution of the electric field applied to the plasma in the region near the cathode. In this case an intense electron beam with an energy corresponding to the applied voltage is produced. The ensuing beam-plasma interaction causes loss of approximately one third of the beam. The remainder leaves the accelerator and can be utilized. The use of a plasma whose concentration decreases in the direction of beam motion results in a sharp decrease of effectiveness of the beam-plasma interaction. The beam losses become smaller and the electron energy spectrum narrower.

1. INTRODUCTION

A number of investigations[1-3] of the acceleration of plasma electrons by an external electric field have shown that the solution of this problem entails considerable difficulties. These are due to the fact that when a beam of accelerated electrons passes through a plasma, instabilities are produced[4-6] and hinder the acceleration. For this reason, the problem of obtaining intense electron beams in a plasma is simultaneously also a problem of finding methods of stopping or weakening the instabilities.

One of the ways of solving this problem is to use a direct discharge or a linear plasma betatron. This makes it possible to increase greatly the electric field in the plasma, and thus prevent the occurrence of a number of instabilities, for example ion-acoustic instability[5,7]. In addition, in the case of the development of drift instabilities (two-stream, Buneman),[4,8,9] the finite dimensions of the system cause the oscillations to be carried outside the system by the beam of accelerated electrons, and their level does not increase to a value that causes the beam to stop.

In experiments with limited electron emission from a cold cathode, the voltage applied to the plasma becomes redistributed in the plasma, producing very high accelerating fields in a small plasma region adjacent to the electrode. An intense beam of electrons is then produced, with an energy equal to the applied voltage, and with a current exceeding 1000 A.

Another way of decreasing the instabilities is to use a plasma whose concentration decreases in the direction of motion of the beam. In this case, as shown in[10,11], the conditions for the development of the instabilities change, and the ensuing beam-plasma interaction leads to results that differ significantly from the results of interaction with a homogeneous plasma. In particular, the level of the high-frequency fields leading to the smearing of the electron-beam velocities, should be much lower in the inhomogeneous plasma. In the presence of a decreasing plasma concentration, the electron velocity spectrum should not contain any electrons with an energy exceeding the applied voltage.

In this paper we analyze the problem of obtaining an intense beam of accelerated electrons in a homogeneous and inhomogeneous plasma. An induction accelerator was used to produce an electric field in the plasma[3].

2. DESCRIPTION OF INSTALLATION AND OF MEASUREMENT PROCEDURE

The experimental setup is illustrated in Fig. 1. A beam of electrons with current 5 A, energy 10 keV, and pulse duration 160 μsec, produced by a source, is injected through an opening in the flange into the accelerating glass chamber 1, of 4 cm diameter and 100 cm length. On passing through the chamber, it ionizes gas at a pressure 10^{-4}–10^{-5} mm Hg, producing a plasma with a high degree of ionization in a magnetic field of intensity up to 5000 Oe.

After the end of the beam injection, a solenoidal electric field of intensity 500–1000 V/cm with pulse duration 0.5 μsec, produced by accelerating windings 2, was applied to the decaying plasma with density 10^{11}–10^{13} cm^{-3}. The current flowing through the chamber was measured with a Rogowski loop 3 mounted on a conductor joining the flanges of the chamber. A considerable fraction of the electrons making up this current was produced by the beam, which passed through the opening in the flange (2 cm diameter), traversed the drift tube 4 (50 cm long) with reduced gas pressure,

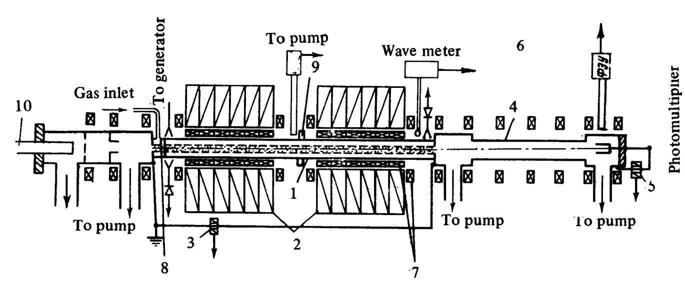

FIG. 1. Diagram of linear plasma betatron: 1—betatron acceleration chamber, 2—accelerating winding of the betatron, 3—Rogowski loop to measure the total betatron current, 4—drift tube, 5—Rogowski loop to measure the current of the beam emerging from the betatron, 6—V_{acc} voltage divider, 7—magnetic-field quartz, 8—capacitive probe, 9—diagmagnetic probe, 10—electron source.

and reached the collector, where it was measured by Rogowski loop 5 and energy-analyzed. The electron energy averaged over the pulse was determined by two methods: with a thermionic probe[12] and from the intensity of the x-rays produced by the beam of accelerated electrons at the collector.

The energy distribution of the electrons was investigated with a sector electrostatic analyzer. The distribution of the electrons over the cross section was determined with a movable aperture of 4 mm diameter in the flange of the accelerating chamber.

The resistance of the discharge was determined by measuring the voltage applied to the plasma and the total current flowing in the accelerator chamber. It was calculated for the instant of time when $dI/dt = 0$, i.e., for the current maximum.

The distribution of the potential along the plasma column was measured by a moving Langmuir probe inserted into the accelerating chamber through a flange that served as the anode during the first half cycle of the voltage. It was grounded during these measurements. The distribution of the potential was also measured with a capacitive probe moving over the glass surface of the accelerating chamber.

The instabilities developing in the plasma in the case of beam-plasma interaction were investigated by measuring the spectra of the frequencies radiated from the plasma and carried out of it by the beam of accelerated electrons. The oscillations radiated by the plasma were received with loop and horn antennas and were fed through wave meters to an oscilloscope. The oscillations carried out from the plasma by the beam were picked off the latter by means of a helical junction or by means of toroidal tunable resonators.

The x-rays emitted when instabilities developed in the plasma were registered at different points along the plasma with the aid of an organic scintillator.

The density of the preliminary plasma was estimated with a microwave interferometer at a wavelength of 8 mm. The working gas was argon or hydrogen.

3. MEASUREMENT RESULTS

A. Uniform Longitudinal Plasma Density

A longitudinally uniform plasma of density 10^{13} cm^{-3} was produced in an accelerating chamber by passing through it a beam of electrons at an initial pressure $p \sim 5 \times 10^{-3}$ mm Hg. The plasma density measurements have shown that application of a strong accelerating field to the plasma and passage of an intense beam of accelerated electrons through the plasma do not lead to an additional increase of the plasma density.

Figure 2a shows oscillograms of the voltage V_{acc} applied to the plasma, of the collector current, and of the total current in the accelerating chamber of the betatron at a plasma density 10^{13} cm^{-3}. We see that the current duration is equal to the voltage duration. The collector receives 2/3 of the current flowing in the betatron. Figure 2b shows the dependence of the collector current I_{col} on the voltage applied to the plasma at three plasma densities. We see that the current of the electrons accelerated in the plasma depends strongly on the plasma density and on the voltage applied to the

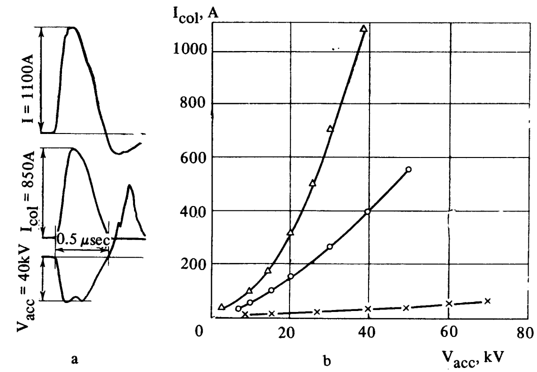

FIG. 2. a) Oscillograms of voltage applied to the plasma ($n = 10^{13}$ cm^{-3}), collector current, and total current on the betatron. b) Collector current at three densities of the homogeneous plasma: $\times$—$n = 3 \times 10^{11}$ cm^{-3}, $\bigcirc$—$n = 5 \times 10^{12}$ cm^{-3}, Δ—$n = 3 \times 10^{13}$ cm^{-3}.

plasma. The plasma density was regulated by delaying the time of application of the high voltage relative to the end of the injection of the beam from the source. When the plasma density drops below 10^{12} cm^{-3}, there is observed not only a decrease of the current, but also a reduction in its duration. Current flows only at the initial stage of the voltage pulse, with duration 0.1 μsec, and there is no current in the plasma during the remaining time of the pulse, in spite of the high voltage.

The energy of the accelerating electrons was determined by the x-rays emitted by them from the collector, using x-rays films placed at the copper collector outside the drift tube, behind a glass window 1.5 mm thick. The normal film density was produced by one pulse of the beam of accelerated electrons, with a current $I_{col} \sim 800-1000$ A. To calibrate the intensity, another cassette with a film was placed at the window of the x-ray tube (BSVL-T-Cu). The x-ray tube was connected in parallel with the accelerating chamber, i.e., the same voltage V_{acc} was applied to it and to the plasma column in the betatron. By using a large number of pulses ($N \sim 3 \times 10^4$), the total current of the x-ray tube NI_1 was set equal to the current of the beam of accelerated electrons per pulse I_{col} ($NI = I_{col}$). From the ratio of the intensity J of the x-radiation from the beam to the intensity J_1 of the tube x-rays (after N pulses), with allowance for the fact that the materials of the targets were the same, we estimated the average energy of the electrons of the beam in accordance with the relation

$$V^2 = (J_2/J_1)\, V_{acc}^2,$$

where V is the energy of the beam of accelerated electrons, V_{acc} is the energy of the electrons in the x-ray tube (to which a potential V_{acc} was applied). The measurements yielded $J_2/J_1 \approx 1$, and therefore $V \approx V_{acc}$, i.e., the energy of the electrons in the beam emerging from the betatron corresponds to the voltage produced by it.

The measurements of the electron energy by means of the thermal probe yielded identical results.

The time variation of the voltage applied to the plasma (its waveform was close to triangular) created additional difficulties in the determination of the electron energy distribution function. Therefore the energy

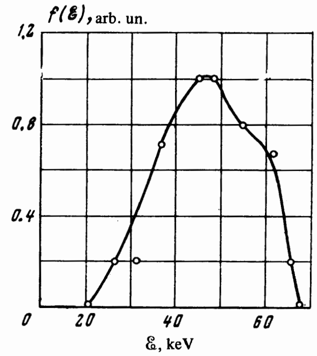

FIG. 3. Energy distribution of the electrons in a homogeneous plasma, $V_{acc} = 50$ kV.

distribution of the electrons accelerated in the plasma was measured for a fixed voltage (for the maximum current) by measuring the current passing through the analyzer at different potentials on the deflecting plates of the analyzer. Oscillograms of the voltage V_{acc} and of the current of the electrons passing through the analyzer were photographed and processed. Figure 3 shows the energy distribution of the electrons for a voltage $V_{acc} = 50$ kV at a plasma density 5×10^{12} cm^{-3}. We see that the maximum of the curve is near the indicated voltage. The electron energy spectrum is quite broad. The beam contains electrons with energies exceeding the applied voltage.

The beam of accelerated electrons covers the entire cross section of the preliminary plasma (of 1.5 cm diameter), with a maximum of 250 A/cm^2 on the axis. The discharge resistance was determined mainly by the effects near the electrodes, since it depended on the material of the cathode (the electrode with a negative potential during the first half-cycle). The discharge resistance is several times larger for a copper cathode than for an aluminum cathode.

Measurement of the potential distribution along the plasma column has shown that the voltage applied to the plasma is concentrated mainly in a plasma layer adjacent to the cathode with thickness smaller than 2 cm.

The oscillations emitted by the plasma interacting with the intense beam of accelerated electrons had a frequency range 30—40,000 MHz. The oscillations had a maximum in the low-frequency part of the spectrum, 100—300 MHz, and in the region of high frequencies, 10,000—20,000 MHz. The high-frequency oscillations shift with decreasing plasma density towards decreasing oscillation frequencies, whereas the oscillations in the frequency range 30—2,000 MHz remain practically unchanged with changing density and type of gas. At both high and low frequencies, the oscillation amplitude has a maximum in the cathode region of the plasma and decreases towards the anode. The oscillation growth time depends on the voltage, decreasing from 2×10^{-7} sec at $V_{acc} = 10$ kV to 2×10^{-8} sec at $V_{acc} = 40$ kV. The oscillations originate in the cathode part of the plasma and propagate along the plasma with a velocity somewhat smaller than the velocity of the beam electrons.

Besides the high-frequency radiation, we have observed in the case of beam-plasma interaction hard x-radiation (in excess of 20 keV) and emission of light. The occurrence times of these radiations correlate with the high frequency radiation. The x-radiation comes from the walls and the flanges of the accelerating chamber.

A comparison of the oscillograms of the accelerator-electron beam current and of the high-frequency radiation has shown that the development of the instability leads to an interruption of the beam current only at voltages $V_{acc} < 10$ kV. Figure 4 shows oscillograms of the beam current (lower curves) and of the radiation at a wavelength $\lambda = 3$ cm at voltages 8, 15, 25, and 40 kV. At 8 kV, the development of the instability leads to a sharp decrease of the beam current. But with increasing voltage the dip in the beam current decreases with developing instability, although the amplitude of the oscillations increases.

B. Longitudinally Inhomogeneous Plasma Density

When the pressure in the accelerating chamber of the betatron was reduced to 10^{-5} mm Hg, the electron beam injected into the chamber produced a plasma which was very inhomogeneous longitudinally, even at an increased beam power. Thus, at the input diaphragm (cathode) the plasma density reached $n \sim 10^{13}$ cm^{-3} at the end of the beam pulse obviously as a result of desorption of gas from the flange, decreasing to $n \sim 10^{11}$ cm^{-3} at the anode. Application of an electric field to such a plasma also produced an intense beam of accelerated electrons in the plasma; this beam emerged almost as a whole from the accelerating chamber of the betatron. Figure 5a shows the oscillograms of the voltage in the current of the beam of accelerated electrons, while Fig. 5b shows the dependence of the beam current on the voltage on the accelerating chamber.

The energy of the beam electrons, estimated from the intensity of the x-rays produced by the beam at the collector, corresponds to the voltage on the accelerating chamber. Figure 6 shows the electron energy distribu-

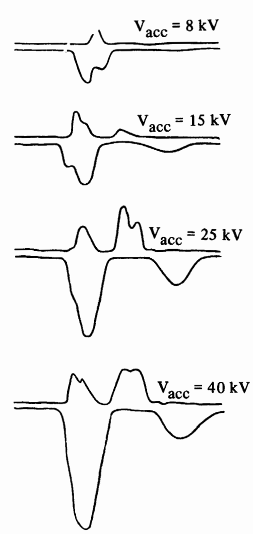

FIG. 4

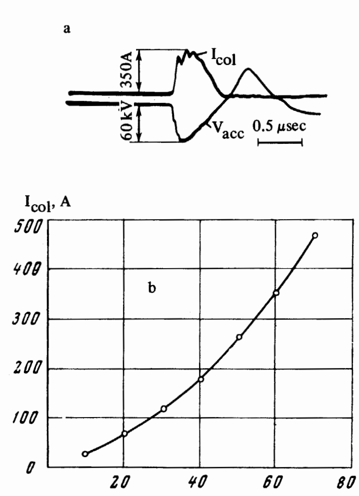

FIG. 5

FIG. 4. Oscillograms of the current of the beam of accelerated electrons and of the high-frequency radiation for four accelerator chamber voltages V_{acc}. Upper curves—A_{HF}, lower curves—I_{col}.

FIG. 5. Oscillograms of voltage V_{acc} and of the current of the beam of accelerated electrons I_{col}, and a plot of I_{col} (V_{acc}) in the case of an inhomogeneous plasma.

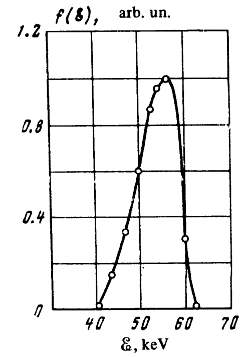

FIG. 6

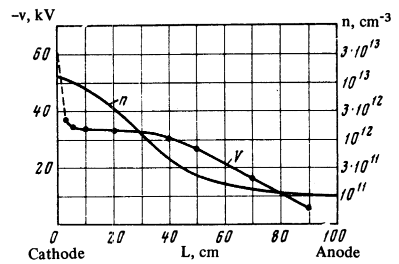

FIG. 7

FIG. 6. Electron energy distribution in the case of an inhomogeneous plasma, V_{acc} = 60 kV.

FIG. 7. Distribution of the potential and of the plasma density along the plasma column.

tion function at the instant of time when the voltage was 60 kV. We see that the electron energy spectrum is much narrower than in the case of a homogeneous plasma. The beam does not contain electrons having an energy exceeding the voltage applied to the plasma.

The distribution of the potential along the chamber also differs somewhat from the case of a uniform plasma. This dependence, and also the approximate longitudinal variation of the plasma density, are shown in Fig. 7. An appreciable fraction of the voltage is distributed along the plasma.

Passage of a beam of accelerated electrons through the inhomogeneous plasma also gives rise to a beam-plasma interaction, revealed by the occurrence of high-frequency and optical radiation. The oscillations measured in the near-cathode part of the plasma are emitted by the plasma in the same frequency range as from a homogeneous plasma, but the level of the oscillations is lower by one order of magnitude than in the case of a homogeneous plasma.

There was no x-radiation from the walls of the accelerating chamber.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

As shown by the measurements, a limited emission of electrons from the cold cathode takes place under the experimental conditions. This is evidenced by the strong dependence of the beam current on the cathode material and the plasma density. At a plasma concentration less than 10^{12} cm^{-3}, practically no electrons are emitted from the cathode and, in spite of the presence of high voltage, there is no current through the plasma.

The limited electron emission causes the voltage across the plasma to be concentrated on a narrow layer of plasma near the cathode, where electric fields exceeding 30 kV/cm are produced. Such strong accelerating fields produce in the near-cathode layer of the plasma an intense beam of electrons with energy equal to the applied voltage.

From the values of the accelerated-electron beam current, from its cross section, and from the electron energies it is possible to estimate the density of the beam particles. It equals $n_1 \sim 10^{11}$ cm^{-3}, which amounts to $\sim 1\%$ of the plasma electron density, both for a longitudinally uniform and a longitudinally non-uniform plasma, if one considers its density in the near-cathode region.

We note that the acceleration of electrons by a longitudinally uniform electric field was considered in[13,14] In this case, the fraction of accelerated electrons of energy comparable with the applied voltage is small ($n_1/n \sim 10^{-4}$). It can therefore be concluded that the redistribution of the applied voltage, whereby the voltage drop is concentrated in the near-cathode region and the electric field intensity increases strongly, leads to a sharp increase in the number of accelerated electrons.

The redistribution of the electric field in a thin layer of plasma was observed also in[15,16].

Let us examine the possible instabilities that can develop in our case.

We consider first the conditions for the occurrence of ion-acoustic instability. As shown in[5], ion-acoustic instability occurs in a plasma at electric fields $E_{cr}^{I} \ll E \ll E_{cr}^{II}$, where $E_{cr}^{II} \equiv N_D E_{cr}^{I}(m/M)^{1/2}$. Here E_{cr}^{I} is the critical Dreicer field, and N_D is the number of particles in a sphere having the Debye radius. In our case, at n = 10^{13} cm^{-3} and $T_e \sim 10$ eV, we get $E_{cr}^{II} \sim 350$ V/cm, which is much lower than the E ~ 30,000 V/cm prevailing in the near-cathode section. We can therefore conclude that no ion-acoustic instability can develop in the near-cathode section of the plasma. This instability can occur in the remaining part of the plasma, which has the anode potential, and where there are no strong electric fields. However, the fact that the observed low-frequency oscillations do not depend on the kind of gas indicates that there is apparently no ion-acoustic instability in this plasma region.

In order for Buneman instability to occur[4] it is necessary to have $n_1 \sim n$. The frequency spectrum of the excited oscillations lies in the frequency region $\omega \sim \omega_{pe}(m/M)^{1/3}$. In our case the density of particles with velocity $v_e \gg v_{Te}$ is much smaller than the plasma density, $n_1/n \sim 10^{-2}$, and the observed low-frequency oscillations do not depend on the type of gas and on the plasma density. It can therefore be assumed that the Buneman instability likewise does not occur under the experimental conditions.

In our case, the conditions are closest to those needed for the development of two-stream instability[8]. First, $n_1/n \sim 10^{-2}$. Second, the electrons move through the plasma with velocity $v_e \gg v_{Te}$. The spectrum of the high-frequency oscillations excited in such an instability is determined by the Cerenkov-radiation condition $\omega = kv_0$, and lies in the frequency region $\omega \approx \omega_{pe}$. In the experiment one observes oscillations at the plasma frequencies, and their occurrence can obviously be attributed to the development of two-stream instability.

The growth increment of the instability is $\delta_0 \sim \omega_{pe}(n_1/n)^{1/3}$, for the case of a monoenergetic beam or $\delta \sim [(n_1/n)^{1/3} v/\Delta v]^2 \delta_0$ for a beam with a spread $\Delta v/v \gg (n_1/n)^{1/3}$. Substituting the experimentally obtained values, we get $\delta_0 \sim 10^{10}$ and $\delta \sim 5 \times 10^8$. The experimentally observed growth increment $\delta_{exp} \sim 10^8$ is closest to the growth increment for a beam with an electron velocity spread.

The presence in the beam of electrons with energy higher than the applied voltage, observed in experiments with a uniform plasma, can be qualitatively explained on the basis of the results of Ryutov[10], who investigated the problem of quasilinear relaxation of an electron beam in a plasma with small concentration inhomogeneities. He has shown that in the presence of small concentration inhomogeneities in the beam-motion direction, the process of quasilinear relaxation leads to the appearance of electrons whose velocity greatly exceeds the initial beam velocity, and its relaxation proceeds both in the $v < v_0$ and in the $v > v_0$ direction.

In the case of a strong magnetic field, the influence of the density inhomogeneity $\epsilon = \Delta n/n$ on the phase velocity of the oscillations becomes appreciable if the change of the frequency due to the plasma inhomogeneity $\Delta\omega \sim \omega_{pe}(k_z/k)\Delta n/2n$ exceeds the change of the oscillation frequency due to the dispersion $\Delta\omega \sim \omega_{pe}(k_\perp^2/k^3)\Delta k_z$. From this we get the condition for the concentration inhomogeneity:

$$\varepsilon \gtrsim \frac{k_\perp^2 \Delta k_z}{k^2 k_z} \sim \frac{\pi^2}{R^2}\frac{\Delta v_z}{v_0}\left(\frac{\omega^2}{v_0^2}+\frac{\pi^2}{R^2}\right)^{-1},$$

where R is the beam radius. In the case of a weak magnetic field, the limitations on the dimension of the inhomogeneity a and on ϵ will be

$$\frac{a}{\sqrt{\varepsilon}} \gg \frac{v_0}{\omega_{pe}}\frac{v_0}{v_{Te}}, \qquad \frac{v_{Te}^2}{v_0^2} \ll \varepsilon \ll 10^{-1}.$$

In our case $\omega \sim 10^{11}$, $v_0 \sim 10^{10}$, $v_{Te} \approx 2\times10^8$, $R \sim 1$ cm, and $\Delta v_z \sim 5\times10^9$. We therefore have $\epsilon \gtrsim 5\times10^{-2}$ and $a \gg 0.4$ cm, which can fully occur in the experiment.

The experimentally obtained concentration drop along the chamber, amounting to two orders of magnitude, has led to an appreciable change of the character of beam-plasma interaction. First, whereas in a longitudinally homogeneous plasma the beam of accelerated electrons lost approximately one-third of the electrons as a result of scattering by the oscillations, in the case of a decreasing plasma concentration the beam emerged from the accelerator almost intact. Second, the level of the high-frequency radiation in a plasma with a decreasing concentration is smaller by one order of magnitude than the radiation level in a uniform plasma, and no x-rays are produced. Third, the electrons with energy exceeding the applied voltage have disappeared from the beam electron energy distribution spectrum, and the spectrum itself has become much narrower.

All this indicates that the use of a plasma in which the density decreases in the direction of the beam motion leads to an appreciable attenuation of the two-stream instability.

Our results agree qualitatively with those of[10,11]. Thus, according to[11], the level of the high frequency fields, leading to a smearing of the beam in the case of beam-plasma interaction in a plasma with non-uniform concentration, should be much lower than for a uniform plasma. Ryutov[10] has shown that if the plasma density in the direction of the beam motion decreases monotonically, then the beam relaxation is only in the $v < v_0$ direction, and no electrons with velocity $v > v_0$ are produced, as was indeed observed in our experiment.

Thus, our results lead to the following conclusions:

1. The redistribution of the electric field in the near-cathode part of the plasma creates conditions favoring the occurrence of an intense beam of accelerated electrons.

2. The resultant beam-plasma interaction leads to scattering by oscillations and to loss of only one third of the beam. The remaining part of the beam emerges from the betatron and can be used.

3. The current of the beam emerging from the betatron reaches 1000 A, and its energy is ~40 keV. The character of the dependence of the current on the voltage indicates that it is possible to obtain much higher beam powers when the betatron power is increased.

4. The use of a plasma with decreasing density leads to a sharp decrease of the effectiveness of the beam-plasma interaction. The losses of the beam decrease and the electron energy spectrum becomes narrower.

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