LIMITING CURRENTS IN ELECTRON BEAMS WITH COMPENSATED SPACE CHARGE

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The limiting currents have been measured in quasineutral beams with relatively high electron energies (up to 20 keV). It is shown that the experimental data are described by the same laws as for low electron energies (up to 1 keV). These data are consistent with the view that the main cause of current limitation in compensated electron beams moving in a longitudinal magnetic field is drift-type beam instability.

INTRODUCTION

THE problem of the mechanism of current limitation (breakup) in a quasineutral electron beam moving in the direction of an external magnetic field has already been studied by the authors.[1,2] It has been concluded that the current breakup is due to occurrence of the drift-type electron-ion beam instability discussed theoretically by Mikhailovskii[3] and by Bogdankevich et al.[4] The experimentally measured limiting beam current I_l is well described by the relation

$$I_0 < I_l \approx 2I_P \Big/ \left(1 + C_1 \frac{uL}{a\delta\omega_{He}\pi}\right), \qquad (1)$$

where u, L, and a are the electron velocity, length, and radius of the beam, $\omega_{He} = eH/mc$ is the Larmor frequency of the electrons, δ is the characteristic dimension of the transverse (radial) gradient of beam density, H is the intensity of the external longitudinal magnetic field, and C_1 is a numerical coefficient of the order of unity. The quantities I_0 and I_P have the following meanings:

$$I_0 \approx \frac{I_P}{3\sqrt{3}} \approx \frac{12.7 \cdot 10^{-6} W_1^{3/2}}{\ln(R_0/a)} \qquad (2)$$

is the maximum current in the beam without ions, which is limited by the space charge of the beam, and I_P is the so-called Pierce current. Here $W_1 = mu^2/2$ is the electron energy in electron volts, I_0 and I_P are in amperes, and R_0 is the radius of the metallic pipe along whose axis the beam is moving. The value of δ depends substantially on the beam geometry. In the case of a continuous beam with a parabolic density profile,[1,2] $\delta \approx a/2$. In the case of a hollow beam (see below), δ can be a considerably smaller fraction of the radius.

The current-breakup phenomenon being discussed presents interest both from a general physical point of view and because it is controlled by a mechanism related to the mechanism of one of the most important instabilities of a high-temperature plasma—the drift or universal instability.[5] It is also of interest in connection with use of intense relativistic electron beams in new methods of accelerating charged particles.[6] Therefore it was extremely desirable to continue the experiments reported in our earlier articles,[1,2] over the widest possible range of variation of the experimental conditions, i.e., of the basic parameters entering into Eq. (1). With this purpose we undertook the present work, in which the range of variation of the electron energy was extended by about 20 times: the value of W_1 was varied from zero to 20 keV, whereas in refs. 1 and 2 the maximum value of W_1 was only 1 keV. The range of variation of beam diameter was also considerably extended—by variation of the cathode diameter from 1 to 3.5 cm, beam lengths from 5 to 120 cm were obtained. The experimental results turned out to be qualitatively in agreement with the ideas mentioned above.

EXPERIMENTAL APPARATUS AND METHOD OF MEASUREMENT

The experiments were performed in the same experimental apparatus used in refs. 1 and 2. The electron beam moved through an equipotential region along the axis of a metallic cylinder of diameter $2R_0 = 30$ cm and length $L \approx 150$ cm, in the direction of an external uniform magnetic field with a controllable intensity H = 500–7000 gausses. The source of the electron beam (the electron gun) produced single pulses of duration ~2 msec. Space-charge compensation was accomplished by positive ions formed in the residual gas by the beam itself. For a typical residual-gas pressure $p_0 \lesssim 10^{-6}$ mm Hg the beam had a negative potential relative to the surrounding walls of the order of several volts, and the concentration of slow electrons in the beam (from the gas) was negligible. So that the beam could be compensated by ions, the beam current was increased smoothly with time: somewhat more slowly than linearly, with a characteristic time $\tau = 600$ μsec, $\tau > \tau_c$, where $\tau_c = 1/n_0\sigma u$ is the beam compensation time, n_0 is the concentration of residual gas atoms, and σ is the cross section of residual-gas atoms for ionization by beam electrons (the quantity τ is the extrapolated duration of the leading edge of the current pulse). The necessary pulse shape of the accelerated electron current was obtained by means of a circuit similar to that used previously[7,1]—see Fig. 1.[1)]

Figure 2 shows typical oscillograms of the beam current and the accelerating voltage which determined

[1)]The energy of the electrons leaving the gun was determined by the accelerating voltage V_{acc} between the cathode and the third electrode of the gun. The V_{acc} pulse had a rectangular shape with a rise time $\lesssim 1$ μsec. The smoothness of the rise in beam current was determined by the shape of the pulse of extraction voltage between the gun cathode and intermediate electrode 2: the rise time of the beam current pulse τ was determined by the RC time constant for charging the capacitor C from which the extraction voltage was obtained.

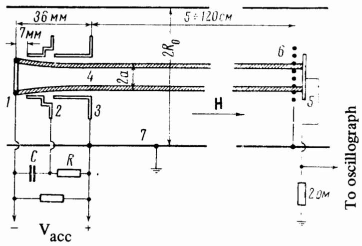

FIG. 1. Experimental apparatus. 1, 2, 3—electron gun: 1—ring cathode, 2—intermediate (extraction) electrode, 3—accelerating electrode; 4—electron beam, 5—beam collector, 6—grid, 7—vacuum chamber. R = 200 ohms, C = 3 μF. The accelerating voltage pulse has a rectangular shape. The time dependence of the beam current leaving the gun is determined by the saw-tooth voltage pulse on capacitor C. The magnetic field strength in the equipotential region is twice that at the cathode, and therefore the beam diameter (25 mm) is correspondingly smaller than the cathode diameter (35 mm).

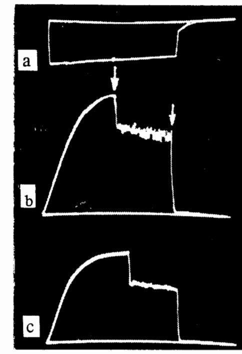

FIG. 2. Oscillograms, a—accelerating voltage, and b, c—beam current: b—for H = 6000G, c—for H = 1000G. The left-hand arrow indicates the moment of current breakup and the right-hand arrow the end of the beam pulse. Sweep length 3 msec, W_1 = 5 keV, p = 10^{-6} mm Hg, L = 100 cm, RC = 0.6 msec.

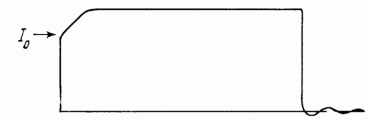

FIG. 3. Shape of beam-current oscillogram for RC = 2 μsec. The arrow indicates the time when the beam current reaches the value I_0. The electron-beam energy W_1 = 4.5 keV, H = 4000G, p = 10^{-6} mm Hg, L = 100 cm. Sweep length 3 msec.

the electron energy. Over the entire investigated range of the parameters (particularly W_1 and H), these oscillograms appeared practically the same (for example, compare Fig. 2 wtih Fig. 4 of ref. 1).[2)] The limiting beam current and accelerating voltage V_{acc} were measured at the moment immediately preceding current breakup. In order to check how well the space-charge compensation condition indicated above was satisfied, the limiting current was measured for different values of RC, which determined the characteristic rise time τ of the beam current, and τ_c, which was controlled by changing the pressure of hydrogen in the region occupied by the beam. The measurements gave the following results: 1) for a typical gas pressure ($p_0 \lesssim 10^{-6}$ mm Hg) the limiting beam current does not depend on τ, if $\tau \geq 600$ μsec; 2) for $\tau = 600$ μsec (the value adopted for subsequent measurements), increase of the gas pressure by even a factor of ten (i.e., decrease by an order of magnitude of the beam-compensation time τ_c) does not lead to a change in the limiting current. These results show that the space-charge compensation of the electron beam was quite complete.

In addition to the limiting current in a compensated beam, we measured the maximum beam current in the absence of ion compensation, I_0, i.e., the limiting beam current for $\tau \ll \tau_c$. For rather small τ (for example, for $\tau = RC \leq 10$ μsec) the current I_0 did not depend on τ. Its value was determined from oscillograms similar to Fig. 3. Until the current of the beam source is less than I_0, the oscillogram of the beam current follows the oscillogram of the accelerating voltage. If the source of the current exceeds the value of I_0, then the beam current I breaks up at $I = I_0$ and then—as a consequence of the accumulation of compensating ions—gradually rises either to a value equal to the source current (as in Fig. 3) or (if the source current is sufficiently large) to a value close to I_l. Current wave forms of this shape for $\tau \ll \tau_c$ have been observed previously by Atkinson[8] and Strelkov.[9] The measurements showed that the value of I_0 does not depend on H (which is quite natural), in contrast to I_l which depends strongly on H (see below and refs. 1 and 2).

Several statements can be made about the electron gun. In one part of the experiments a source was used with an indirectly heated flat tungsten cathode (heated by electron bombardment); the cathode diameter was 1 cm. In another part of the experiments the source had a directly heated ring cathode of tungsten or tantalum wire 1.2–1.5 mm in diameter; the cathode diameter was varied from 1 to 3.5 cm. In these experiments the beam was hollow. The results obtained with ring-cathode and continuous-cathode sources of equal diameters agreed within experimental accuracy. The gun had three electrodes (Fig. 1). The second and third electrodes either were covered with grids as in refs. 1 and 2 (when the accelerating voltage did not exceed 3–4 kV) or had open apertures for passage of the beam. The results obtained with sources with grids and without grids turned out to be practically the same.

Before the beginning of systematic measurements, we made a careful check of the possible influence of secondary emission electrons, produced by the beam at the collector, on the measured value of limiting beam current. In refs. 1 and 2 the beam collector was held at a potential of +200 V, and this was quite sufficient to contain the greater part of the secondary electrons. However, as is well known,[10] the secondary-electron energy spectrum has a long, monotonically dropping tail which extends up to the electron-beam energy. In order to contain this tail it is necessary to apply to the collector a positive potential $+V_c$ considerably greater than the beam energy (W_1). This experiment was performed: for W_1 = 3 keV the potential V_c was made as high as 18 kV. Experiments showed that in spite of our misgivings the limiting beam current did not depend on the collector potential for $0 \leq eV_c \leq 6W_1$. Therefore

[2)]Our attention is called to the fact that in the lower oscillogram of Fig. 2 the current breakup occurs appreciably after the moment when the current reaches its greatest value. The question naturally arises as to why the current breakup does not occur sooner. The answer to this question lies in the fact that the limiting current is determined by the electron energy W_1 and, as a result of the gradual discharge of the capacitor bank providing the accelerating voltage, decreases smoothly with time during the beam pulse (see the upper oscillogram of Fig. 2). Current breakup occurs at the moment when the limiting current I_l, decreasing, is the same as the beam current.

in the subsequent measurements we took no measures to remove the secondary-emission tail. Generally the role of secondary electrons, even for $V_c = 0$, was negligible for the beam-collector geometry used in the experiments described below: the collector was mounted at a distance of 1.5 cm from a grounded grid placed in front of it; this grid was made of tungsten wire 0.3 mm in diameter and had a mesh size of 4 mm. With this large collector-grid spacing, the secondary-emission current from the collector, which was limited by space charge, was negligible in comparison with the beam current (the latter was much higher than in refs. 1 and 2 as the result of the substantially increased electron energy, and for the same reason the secondary-emission coefficient was considerably lower).

In order to measure the energy distribution and radial distribution of the density of the electron beam, an opening 1 mm in diameter was made in the collector, beyond which a receiving electrode was placed at a distance of 16 mm. In order to avoid secondary-electron emission from this electrode, a grid with a 2.5-mm mesh was placed between it and the collector; the grid had a potential of −50 V with respect to the receiving electrode, and the beam did not hit it. The energies of the beam electrons (more accurately, their longitudinal components) were determined from the retarding-potential characteristics of the receiving electrode. These characteristics showed that the electron energy W_1 corresponds with an accuracy of ~5–10% to the accelerating voltage V_{acc}.

Before turning to description of the experimental results on electron-beam limiting current, one more important fact must be noted: the limiting current was not limited by any processes in the beam source. This follows from the experiment described below (Fig. 9), which showed that with decrease of the beam length from 100 to 10 cm the limiting current increases substantially (for example, by two or three times) and with further reduction of beam length the source current no longer is sufficient to observe current breakup (i.e., to obtain oscillograms such as Fig. 1). Thus, beam-current breakup is due to processes in the equipotential region in which the beam is moving.

EXPERIMENTAL RESULTS AND DISCUSSION

One of the characteristic results of our earlier studies,[1,2] which were carried out for small electron energies ($W_1 \leq 1$ keV), was observation of the fact that the limiting beam current I_l depends substantially on the magnetic field intensity H, the form of this dependence being qualitatively determined by Eq. (1). According to this equation, as W_1 is increased the function $I_l(H)$ should be drawn out in the direction of higher H. For example, if the function $I_l(H)$ exhibits a certain amount of saturation, the field strength $H = H_{sat}$ corresponding to this saturation should increase with increasing W_1. Experiments performed in the present investigation have shown that the expected dependence actually occurs. This is illustrated in Fig. 4, in which we have plotted H_{sat} as a function of W_1, as averaged from the results of five experiments. It is evident that in qualitative agreement with Eq. (1)

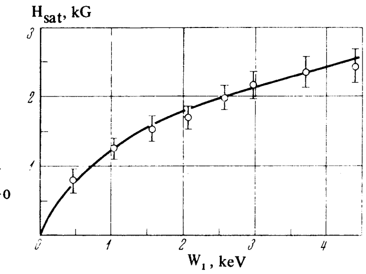

FIG. 4. Magnetic-field intensity corresponding to approximate saturation of the function $I_l(H)$, as a function of electron-beam energy; $p = 0.8 \times 10^{-6}$ mm Hg, L = 120 cm, 2a = 0.7 cm, $2R_0$ = 30 cm.

$H_{sat} \propto \sqrt{W_1}$.[3)] It must be noted that although a saturation in the dependence $I_l(H)$ by no means always occurs (see, for example, curve 3 in Fig. 5), this dependence invariably is drawn out towards higher H with increase of W_1.

Further, according to Eq. (1) the function $I_l(H)$ should be drawn out toward higher H as the beam radius a is decreased. Experiments shows (see Fig. 5) that this relationship is also realized in practice.

To this it must be added that, also in agreement with Eq. (1), as the beam length is decreased (for example, to L = 10–20 cm) the effect of H on I_l becomes extremely weak.

Let ud turn now to description of the dependence $I_l(W_1)$. This dependence is characterized by the experimental data presented in Figs. 6a and b; the two experiments were performed with different magnetic field strengths and utilized hollow electron beams of different diameters.

The effect of electron energy and beam diameter on the value of I_0 is shown in Fig. 7 (the current I_0 naturally does not depend on the field intensity). Here the dashed lines show theoretical curves corresponding to Eq. (2).

From Figs. 6 and 7 the following conclusions may be drawn:

1) The limiting beam current I_l is greater than the current I_0 and less than the Pierce current $I_P = 3\sqrt{3}\, I_0$.

2) At low electron energies the current I_l varies approximately in proportion to $W_1^{3/2}$, and for relatively high electron energies the function $I_l(W_1)$ turns out to be close to linear: $I_l \propto W_1$.

3) A change of the dependence $I_l(W_1)$ to a linear function is observed at higher electron energy if the beam radius is larger (and, generally speaking, if the magnetic-field intensity is greater).

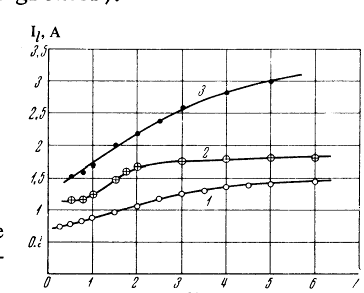

FIG. 5. Limiting current as a function of magnetic-field intensity for two values of beam diameter: curve 1–2a = 0.7 cm, $W_1 \approx 3$ keV, curve 2–2a = 1 cm, $W_1 \approx 3$ keV; L = 100 cm, $p = 0.8 \times 10^{-6}$ mm Hg. Curve 3 (2a = 1 cm, W_1 = 4.7 keV)–illustration of the absence of saturation of the function $I_l(H)$.

[3)]The curve shown in Fig. 4 was taken up to energies W_1 = 4 keV. With further substantial increase of W_1 the saturation of the function $I_l(H)$, while in general it exists, shifts substantially toward higher H and consequently becomes very difficult to define: the existing magnetic field is insufficient.

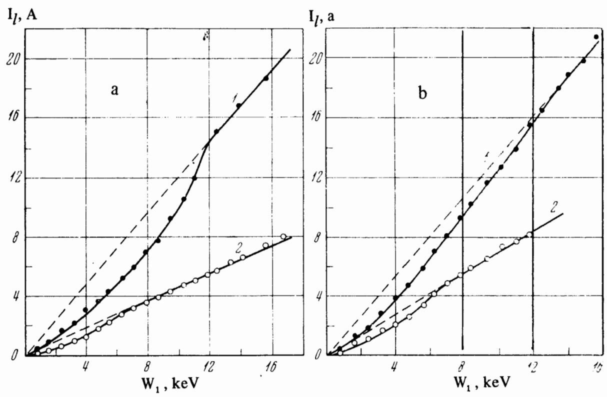

FIG. 6. Limiting current as a function of electron-beam energy: a—for H = 1500G, b—for H = 5000G; p = 1.8 × 10⁻⁶ mm Hg (nitrogen), L = 120 cm. Curves 1—2a - 2.5 cm, curves 2—2a = 0.7 cm.

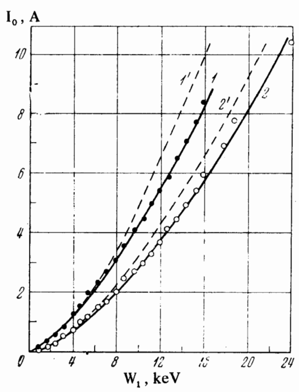

FIG. 7. Maximum current I_0 in a beam without ions, as a function of electron-beam energy. Curves 1, 1′—2a = 2.5 cm, curves 2, 2′—2a = 0.7 cm. The pressure is p = 1.4 × 10⁻⁶ mm Hg, L = 120 cm, $2R_0$ = 30 cm, H = 1500G. The dashed curves were calculated with Eq. (2).

4) With increasing beam radius the limiting current I_l increases appreciably faster than the maximum current I_0; in other words, the limiting current I_l differs more from I_0, the greater the beam radius, and also the lower the electron energy W_1 and the stronger the magnetic field.

5) The bending of the function $I_l(W_1)$ appears more distinctly, the lower the magnetic-field intensity.

6) The value of I_0 measured experimentally is extremely close to the theoretical value calculated (with idealized assumptions) from Eq. (2).

7) The limiting current I_l decreases with decrease of H, while the maximum current I_0 does not depend on H.

It is easy to see that all these patterns correspond qualitatively to Eqs. (1) and (2).

In Fig. 8 we have shown typical curves of the limiting current I_l as a function of the beam length L for various electron energies and magnetic-field intensities. It is evident that with increasing L the current I_l decreases the more strongly, the smaller the field H and the larger W_1. For a sufficiently small beam length ($L \le 10$ cm), as we have already noted, the current supplied by the source is not sufficient for suppression of the beam (current breakup). Here the greater the ratio W_1/H, the smaller the minimum beam length beginning with which current breakup is observed.

These facts are also in good qualitative agreement with Eq. (1). From Fig. 8 it is easy to see that the greatest current supplied by the source and measured for $L \le 10-30$ cm varies in proportion to $W_1^{3/2}$, which is quite natural.

In Fig. 9 we have shown the lateral (radial) distribution of the beam electrons. It is apparent that the characteristic dimension of the radial gradient of beam density δ is ~ 3 mm. On the basis of this result we can attempt a quantitative comparison of the experimental data with Eq. (1). (We should recall the origin of the coefficient 2 in the numerator of Eq. (1): the square of the total wave number in the case of axially asymmetric oscillations of the first azimuthal mode is roughly a factor of two larger than in the case of axially symmetric oscillations—see ref. 2.) Setting the coefficient $C_1 = 1$ in Eq. (1), we see that for electron energies $W_1 \gtrsim 5$ keV the second term in the denominator of (1) is considerably greater than unity. (The value of C_1 may differ somewhat from unity (for example, by a factor of two) in either direction, depending on the nature of the falloff in current density in the beam cross section.) Here, if the magnetic field is rather strong (for example, H = 5000 G), the value of I_l determined from Eq. (1) is practically the same as that measured experimentally. For relatively weak fields (for example, H ≈ 1500 G) Eq. (1) gives a value of I_l less than the measured value by two or three times.

Thus, the entire set of experimental data obtained is qualitatively well described by (1).

Equation (1) has the following relation to the theory cited above.[3,4] This theory is linear. It predicts only that for a beam current I which exceeds a certain

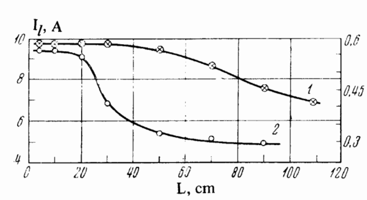

FIG. 8

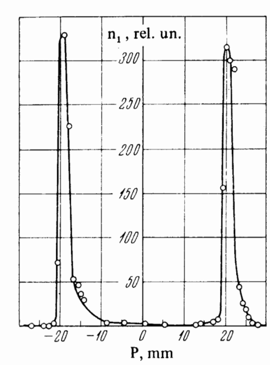

FIG. 9

FIG. 8. Limiting current as a function of beam length for different electron-beam energies and magnetic field intensities; p = 10⁻⁶ mm Hg, 2a = 2.5 cm. Curve 1—H = 500 G, W_1 = 1 keV, curve 2—h = 500G, W_1 = 6 keV. The left-hand ordinate scale refers to curve 2, and the right-hand scale to curve 1. For insufficiently large beam length (L < 30 cm in the case of curve 1 and L < 15 cm in the case of curve 2), current breakup does not occur: the limiting beam current I_l exceeds the maximum current emitted from the electron gun. The experimental points on the indicated portions of curves 1 and 2 give values of the maximum gun current.

FIG. 9. Radial distribution of electron density at the beam collector for 2a = 2.5 cm. In the region of the (movable) collector the magnetic-field intensity is 2.5 times smaller than in the main portion of the beam trajectory, and therefore the measured beam diameter (4 cm) turns out to be correspondingly greater. The pressure is p = 10⁻⁶ mm Hg, L = 120 cm, H = 3000G, W_1 = 7.8 keV.

threshold or critical current I_c, instability can arise in a quasineutral electron beam with respect to buildup of axially asymmetric electron-ion oscillations of the drift type. The instability threshold I_c (in the theory just I_c, but not I_l!) is determined by Eq. (1). The theory given by Mikhaĭlovskiĭ[3] and Bogdankevich et al.[4], being linear, cannot predict the macroscopic consequences which will result from development of instability. In particular, it cannot predict such a phenomenon, to a high degree nonlinear, as breakup of the beam current.

However, the experiments performed by us previously[1,2] (in the range $W_1 \leq 1$ keV) show that under the conditions when $I_c > I_0$, the threshold I_c determined by Eq. (1) differs relatively little (on the low side) from the limiting current I_l at which current breakup occurs in the beam. On the basis of this experimental fact, we use Eq. (1) to describe the behavior of the limiting current I_l, although in the theory it is written for the critical current I_c.

It is necessary, however, to keep in mind that a quantitative difference between I_l and I_c nevertheless exists (even for $I_c > I_0$). Therefore, as in ref. 1, speaking of the comparison between experiment and theory,[3,4] we first of all have in mind a qualitative comparison of the measured values of I_l with theoretical values of I_c as a function of the main parameters of the system investigated, and also a quantitative comparison in order of magnitude. Such an analysis, which has been made above, shows that over the entire region of electron-beam energy studied—up to 20 keV—experiment is in good agreement with theory.

In conclusion we make one observation of a historical nature. Before the theoretical work of Pierce[11] the opinion existed that the current limitation in an electron beam (occurring in the absence of ions at $I = I_0$) could be removed by compensation of the space charge of the beam by positive ions. However, Pierce showed theoretically[11] (see also ref. 12) that in an electron beam whose space charge was compensated by ions, beam instability should arise at a current $I = I_P \approx 3\sqrt{3}\, I_0$. A nonlinear analysis of this instability[13] led to the conclusion that the current I_P should be the limiting current of a compensated electron beam. The experiments performed in the present work, and also in refs. 1 and 2, have shown that the limiting beam current is actually even less than I_P and under certain conditions (high electron-beam energy and not too strong magnetic field) is not very different from I_0. There is no great basis for assuming that this situation changes with further increase of electron energy. Nevertheless, it would be of considerable interest to extend the experiments described here to the near relativistic ($W_1 \gtrsim 100$ keV) and relativistic ($W_1 \approx 1-5$ MeV) regions of electron-beam energy.

Finally, we will recall that in the present work, as in work of Pierce,[11] we have been dealing with a two-component system: the electron beam and the compensating ions. If we introduce into this system, while leaving it electrically neutral, an "excess" plasma, then, as we have shown experimentally,[2,14] the limiting beam current increases considerably and can be an order of magnitude greater than the Pierce current I_P. For a sufficiently high plasma density the instabilities discussed here in general disappear.[2,14] The review article written by one of us[15] discusses in detail the instabilities of quasineutral electron beams in vacuum and in a plasma.

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