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SPACE-CHARGE LIMITED CURRENT OF AN UNCOMPENSATED RELATIVISTIC ELECTRON BEAM

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An experimental study has been made of the space-charge limited current of an electron beam in the absence of compensating ions, passing through an evacuated drift tube, for an electron energy of 600 keV and for various ratios of tube radius to beam radius. It is established that in the presence of an external magnetic field $H_0 \leq 2000$ Oe the measured values of space-charge limited currents are in good agreement with the theoretical values.

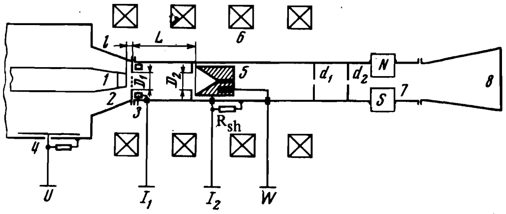
In connection with progress with development of high-current electron accelerators, the problem of space-charge limited currents is of great interest. The limiting currents of nonrelativistic electron beams in an evacuated drift tube and in the presence of an ionic background which compensates the space charge have been discussed repeatedly in the literature.[1,2] The limiting currents of relativistic compensated electron beams also have been studied both theoretically[3] and experimentally.[4] The limiting current of a relativistic electron beam in an evacuated drift tube has been discussed only theoretically[5] and, as far as we know, has not been studied experimentally. Under static conditions the limiting current of an electron beam in a drift tube whose longitudinal dimension is considerably greater than the transverse dimension is determined by the interpolation formula[5]

$$I_L = \frac{mc^3}{e}\frac{(\gamma^{2/3}-1)^{3/2}}{1+2\ln(R/r)}, \tag{1}$$

where m and e are the mass and charge of the electron, c is the velocity of light, γ is the relativistic factor, R is the drift tube radius, and r is the beam radius. This expression is valid if a sufficiently strong magnetic field H_0 is applied to the system to prevent spatial spreading of the beam; the energy of the field must be appreciably greater than the kinetic energy of the electron beam, i.e.,

$$H_0^2/8\pi \gg n_e mc^2(\gamma-1), \tag{2}$$

where n_e is the electron density in the beam. In the present article we report the results of an experimental study of the limiting current transmitted by an evacuated drift tube for a constant electron energy as a function of the ratio R/r and the value of H_0.



The electron source used was a pulsed electron gun whose parameters are given in an earlier article.[6] The basic diagram of the experiment is shown in the figure. Electrons are emitted from the field-emission cathode 1 through an accelerating grid and pass through an evacuated drift tube of radius 3.0 cm and length L = 100 cm. The cathode diameter is D_C = 25 mm and the distance from the cathode to the accelerating grid is l = 10 mm. Directly beyond the accelerating grid is placed a diaphragm D_1 of adjustable diameter (D_1 = 25, 20, 15, 10 mm) which determined the beam radius and limited the electron emission current. At the other end of the pipe is placed diaphragm D_2 of adjustable diameter (D_2 = 20, 15, 10 mm) for determination of the current-density distribution in the electron beam. The coils 6 produce a quasistationary uniform longitudinal magnetic field H_0 of intensity up to 8000 Oe. The cathode 1 is in the uniform magnetic field. The voltage on the cathode was monitored by a capacity divider 4. The electron currents (I_1 and I_2) were measured by a Rogowski loop 3 and by a shunt resistance R_{sh} in a coaxial arrangement. The electron flux energy W was measured by a calorimeter 5. The electron beam diameter was determined from the darkening of the surface of a glass plate placed in the path of the beam.[7] The electron energy was determined by a magnetic analyzer 7 ($d_1 = d_2$ = 0.2 mm) with detection by a photographic plate 8.

Previously[6] we described in detail the operating conditions of the pulsed electron beam and the beam parameters. In carrying out the present experiment the maximal cathode emission current measured directly after the accelerating grid was $I_1 \approx 7.5$ kA, and the electron flux energy W ≈ 90 J. The current pulse width at half-height was $\tau_4 \approx 20$ nsec. The electron energy was $\epsilon \approx 600$ keV ($\gamma = 2.2$), and the spectrum with $\Delta\epsilon \approx \pm 60$ keV. In the cathode chamber 2 and the drift tube a pressure of $\sim 10^{-5}$ mm Hg was maintained. At this pressure for a current pulse duration $\tau_4 \approx 20$ nsec the degree of compensation of the beam was $n_i\gamma^2/n_e \leqslant 10^{-2}$.

Measured values of the emission current I_1 for $H_0 \geq 2000$ Oe in the plane of diaphragm D_1 in the absence of the drift tube (L ≈ 2 cm) are given in the table. Also shown are the limiting currents I_L calculated from Eq. (1) for various ratios R/r. It can be seen from the table that for R/r = 2.4, 3, and 4 the cathode emission current exceeds the limiting current. This permits the maximal current transmitted by the drift tube for vari-

R/r	I_1, kA	I_L, kA $\gamma = 2{,}2$	I_2, kA	W, J
2,4	7,5	4.0	4,5	53
3	5,0	3.2	3,6	42
4	2,8	2,6	2,0	22
6	1.0	2.2	1,0	9.5

ous ratios R/r to be determined for a given emission current. It should be noted that the spread in the measured values of I_1 and I_2 (and W) from pulse to pulse is ±15%, which exceeds the experimental errors. Therefore the values of I_1, I_2, and W given in the table are averaged over the results of a series of measurements from 15 pulses.

For $H_0 \geq 2000$ Oe the electron beam diameter is equal to the cathode diameter, and when H_0 is increased to 8000 Oe the beam diameter, current I_1, and the current-density distribution over the beam cross section remain constant.

Measurements at the end of the drift tube (L = 100 cm) showed that for $H_0 \geq 2000$ Oe the electron-beam diameter is equal to the diameter of the entrance diaphragm D_1. When H_0 is increased to 8000 Oe the beam diameter, current I_2, and current-density distribution over the cross section remain constant, the current-density distribution over the beam cross section being uniform within 25%. In the table we have given the absolute values of the currents I_2 (and electron flux energy W) transmitted by the drift tube.

It is evident from the table that the experimentally determined currents I_2 are in good agreement with the space-charge limited current values calculated from the interpolation formula (1).

Under the experimental conditions the value of external magnetic field H_0 necessary to conduct the limiting current through the drift tube was ~2000 Oe. For the values of the current I_2 and the beam diameter shown in the table this corresponds to the condition

$$H_0^2 \gtrsim 8\pi n_e mc^2(\gamma - 1), \qquad (3)$$

i.e., the more severe condition (2) is not necessary. It should be noted that under these conditions the value of H_0 is several times larger than the intrinsic magnetic field of the current $H_\varphi = 2I_2/cr$.

It was pointed out above that Eq. (1) is valid for stationary current flow. The time of flight of the electron beam through the drift tube of length 100 cm is 3.3 nsec. The rise time of the current pulse is ≤ 10 nsec. During the transition process of establishing the current an energy ϵ_M is expended in producing the intrinsic magnetic field of the current. This energy is related to the kinetic energy of the electron flux ϵ_K by the following equation:

$$\frac{\varepsilon_M}{\varepsilon_K} \approx \frac{(\gamma^{2/3} - 1)^{3/2}}{4(\gamma - 1)} \frac{1 + 4\ln(R/r)}{[1 + 2\ln(R/r)]}. \qquad (4)$$

It follows from the experimental data that the transition stage of the process of establishing the current apparently does not affect the space-charge limited current value for R/r = 2.4 or 3, where $\epsilon_M/\epsilon_K \approx 30\%$.

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