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Drift velocity measurements in relativistic electron beams

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A novel experimental method to measure the average drift velocity of relativistic electron beams is presented. The method is based on simultaneous measurements of the beam current and the radial electrostatic potential induced by the space charge of the beam. The method was applied to analyze the beam at different diode voltages and guide fields. The average drift velocity was found to be always considerably less than that corresponding to the diode voltage.

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Knowledge of the relativistic electron beam in free-electron laser experiments is of major importance. Ideally, one would like to obtain a monoenergetic cold beam in which all electrons have only momenta parallel to the guide field. This is obviously impossible, particularly if the beam is generated by a field emission diode. In order to obtain some knowledge of the beam, computer simulations are used[1] which indeed show that the stringent requirement for free-electron lasers is not easily obtained. Shefer and Bekefi[2] showed that the undesirable transverse energy in the beam can be removed, at the expense of beam current, by a series of diaphragms. There are no direct experimental measurements which correlate the parallel drift velocity of the beam, the diode voltage, and the guide magnetic field.

In this letter we describe an experimental method by which one can measure, on line, the average drift velocity of the electron beam. As will be shown below, the drift velocity in our system is always considerably less than one would expect from the accelerating voltage of the diode.

The experimental system (Fig. 1) comprised a Febetron (Model 706/2670) electron gun, which provided 80–100-ns pulses with up to 500 kV. The beam was shot through a 4-mm-diam hole in the anode into a drift tube, 80 cm long and 3.6 cm in diameter. The dc magnetic guide field B_z could be raised up to 3 kG. A series of diaphragms were used to obtain a narrow (<3 mm diameter) electron beam.

The beam current was collected on a 12-mm-diam aluminum disc and measured with a low inductance resistor ($R = 1\,\Omega$). The radial electrostatic potential V_c, induced due to space charge of the beam, was measured by means of a coaxial cylindrical capacitor. The capacitor is basically a quartz tube, 45 mm long, with an inner diameter of 32 mm. This tube is inserted snugly into a brass tube (i.d. 36 mm) which is grounded. The inner side of the quartz tube is wrapped along 40 mm with a thin copper foil. A 10-$\kappa\Omega$ low inductance resistor connects the copper foil to terminated (50 Ω) transmission line. In order to minimize the noise, all the components—the transmission line, the resistor, etc.—were carefully screened.

The beam current is

$$I(t) = e\lambda(t)v_z(t), \tag{1}$$

where e is the electron charge, λ the linear charge density, and v_z the beam drift velocity averaged across the beam. The voltage V_c induced by the beam on the cylindrical capacitor is given by

$$V_c(t) = \frac{e\lambda(t)l}{C}, \tag{2}$$

where l and C are the length and the capacitance of the capacitor, respectively. Thus, the beam drift velocity is

$$v_z(t) = k\frac{I(t)}{V_c(t)}, \tag{3}$$

where

$$k = \frac{2\pi r\epsilon_0\epsilon_r}{\Delta r}, \tag{4}$$

and r, Δr, and ϵ_r are the radius, the distance between the plates, and the dielectric constant of the capacitor, respectively. The assumption made in deriving Eq. (4) is that the

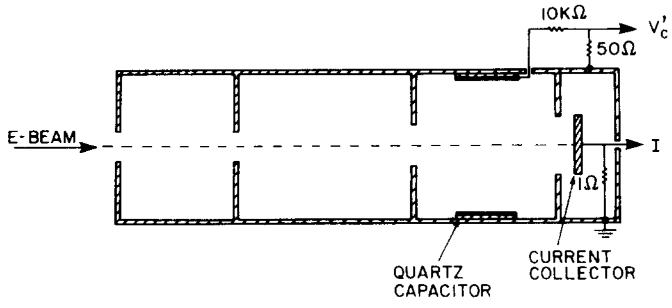

FIG. 1. Schematic of the average drift velocity analyzer.

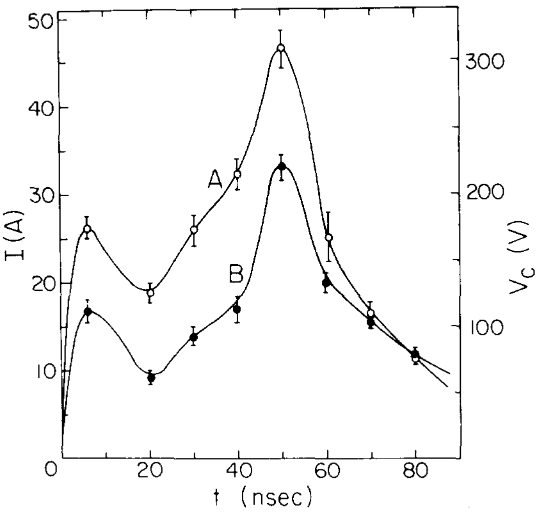

FIG. 2. Beam current (curve A) and the voltage on the cylindrical capacitor (curve B) vs time. The guide field is $B_z = 1.6$ kG and the peak diode voltage is 380 kV.

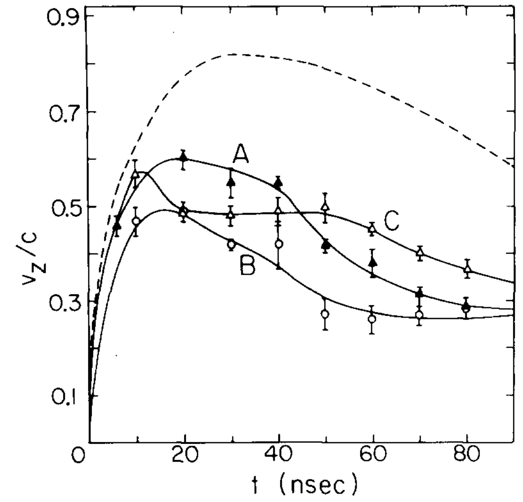

FIG. 3. Average drift velocity v_z/c (solid lines) vs time. A: $B_z = 1.6$ kG; B: $B_z = 2.2$ kG; C: $B_z = 2.7$ kG. The peak diode voltage is 380 kV. The dashed curve represents the average drift velocity which could be expected from the diode voltage if all the electrons had acquired only parallel velocity.

charge of that part of the beam, which is inside C, equals the charge induced on the capacitor itself. The constant k in Eq. (4) contains only known factors and thus can be either calculated or found by calibration of the experimental setup. This was done and the difference between the experimental k and the calculated one is about 10%.

Figure 2 shows the current $I(t)$ and the voltage $V(t)$ for a given value of the guide magnetic field. Figure 3 shows $v_z(t)/c$ (the solid lines) as obtained from Eq. (3) for different values of B_z. Each curve is an average for 10 successive shots and the error bars are standard deviations. In the same figure the dashed line shows the beam velocity, one would expect if all the voltage on the diode would be transferred into parallel velocity.

One sees in Fig. 3 that v_z/c is much lower than that expected from the accelerating voltage. This result is in fair agreement with the theoretical predictions[3,4] which expect the parallel relativistic factor γ_z of the beam on the axis to be equal to $\gamma_{in}^{1/3}$ (with γ_{in} being the relativistic factor corresponding to the diode voltage) in simplified diode geometries, high currents and strong guide fields.

Finally, Fig. 3 also shows that the average drift velocity of the beam is very complicated function of the diode characteristics and the guide field, a result which should be accounted for in application. By using a Rogowski coil instead of the collector for the current measurement, the system described here can be used, on line, to monitor the average beam drift velocity without disturbing the beam in free-electron lasers. The method is applicable up to average drift velocities which approach the velocity of light. The upper limit of this diagnostic depends upon the accuracy by which the current I and the capacitor voltage V_c are determined.

This work in which the average drift velocity of the electron beam was measured directly, for the first time, comprises only a part of a wider program to diagnose the quality of relativistic electron beams.

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