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FIRST RESULTS OF THE UNIVERSITY OF MARYLAND ELECTRON BEAM TRANSPORT EXPERIMENT*

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Abstract. The University of Maryland electron beam transport experiment, in collaboration with the Rutherford Laboratory, is designed to study emittance growth in periodically focused intense beams. For initial studies, the electron gun consists of a 1-cm diam., dispenser-type cathode and an anode covered with a wire mesh. To avoid neutralization, 5 μs, 60 Hz pulses are used and the current is 230 mA at 5 kV. By varying the voltage from 10 kV to 500 volts the space charge depression, ω/ω_o, of the particle oscillation frequencies in the focusing channel can be changed from ~ 0.04 to ~ 0.2. Further increase of ω/ω_o should be possible with modified guns and the use of emittance control grids. Four prototype solenoids have been built, and the results of experiments with the first two are presented in this paper. Beam profile measurements show the nonlinear effects due to the space charge and the magnetic field, and also the effects of the anode mesh on the beam distribution.

Introduction

The electron beam experiment at the University of Maryland[1,2] is designed to study instabilities and emittance growth of intense charged particle beams in long periodic focusing systems. Recent developments in the particle accelerator field, such as the proposed use of heavy ion beams for inertial fusion, led to renewed interest in the problem of high-current beam transport. In detailed studies at the Lawrence Berkeley Laboratory the stability problems were examined for quadrupole (FODO), interrupted solenoid, and long solenoid channels.[3] Results of the analytical theory are in good agreement with numerical simulations.[4,5] All of this theoretical work so far is based on the K-V distribution[6], the only known phase-space distribution that leads to linear force equations for the equilibrium beam. More recent studies[7] indicate that some of these instabilities may be artifacts of the K-V distribution or may not result in rms emittance growth.

The objective of our experiment is to obtain an understanding of what is happening in the actual particle distribution of laboratory beams and to make comparisons with theory. Even in the absence of instabilities, it is of interest to study the emittance growth associated with nonlinearities arising from the nonuniform charge density distribution in the beam, and to compare measurements with the results of computer simulations.

According to the theory, the stability behavior of the beam depends on the ratio of the space charge force to the applied focusing force, or the ratio of the particle oscillation frequency with space charge to the frequency without space charge, ω/ω_o. A measure for this tune depression is the dimensionless parameter u which for a long solenoid is given by $u = K/2\sqrt{\kappa}\,\varepsilon_r$ where $K = 1.5 \times 10^4\ I/V^{3/2}$ is the generalized perveance, $\kappa = (qB/2mv)^2$ is the magnetic focusing strength, and $\pi\varepsilon_r$ is the transverse emittance. For periodic focusing channels, the particle oscillations with and without space charge forces are described by the phase shifts μ and μ_o, respectively, of the oscillation in one period. The parameter u in this case is defined by

$$u = KS/(2\mu_o\varepsilon), \qquad (1)$$

where S is the length of one channel period. According to the smooth-approximation theory[8], the tune depression due to space charge forces is given by

$$\omega/\omega_o = \mu/\mu_o = \sqrt{1+u^2} - u. \qquad (2)$$

Furthermore, if α is the channel acceptance, we have the relation $\mu/\mu_o = \varepsilon/\alpha$.

An important goal of our experiment is to vary the space charge parameter u over a wide range of values to cover the most important regions examined by theory. Such variation can be achieved by changing either the perveance or emittance of the beam. The perveance is determined by the given geometry according to the Child-Langmuir law,

$$I = \text{const}\ V^{3/2}/d^2, \qquad (3)$$

where V is the gun voltage and d is the cathode-anode spacing. The rms emittance for a thermal beam, on the other hand, depends on the cathode temperature T, the gun voltage V, and the cathode radius r_c:

$$\varepsilon = \bar{\varepsilon}_x = \sqrt{2}\ r_c(kT/eV)^{1/2}. \qquad (4)$$

In electron beams $\bar{\varepsilon}_x$ is very small; however, we can achieve some variation by operating at different gun voltages (between 500 V and 5000 V) and by using guns with different cathode radius. We expect to cover a range of μ/μ_o from about 0.04 to 0.2. Further increase of the emittance should be possible by use of special grids that introduce transverse scattering; this problem will be studied at the Rutherford Laboratory.

Plans and conceptual design parameters for the experiment were described at the San Francisco Accel. Conf. in March 1979[1]. An electron gun designed by W. Herrmannsfeldt at Stanford is being built at Hughes Electron Dynamics Division. In our experiments so far, we have used a home-built planar Pierce gun with a cathode diameter of 1 cm and a fine mesh at the anode.

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The purpose of this paper is to describe the status of the experiment with our gun and two focusing magnets.

Experimental Apparatus

A schematic diagram of the experimental setup is shown in Figure 1. The electron gun consists of a planar cathode of 1 cm diameter and an anode hole covered with a fine tungsten mesh. The cathode-anode spacing is 1.7 cm. The cathode temperature is about 1400 ^{o}K for space charge limited operation with 230 mA and 5 kV. To avoid neutralization, the gun voltage is pulsed with typically 5 μs pulse length and a 60 Hz repetition rate.

The magnets for the focusing system are identical short solenoids with iron shields. The solenoids have an axial width of 6.8 cm, a bore radius of 2.54 cm, and a pole gap of 3.2 cm. The magnetic field profile on the axis is 4.4 cm FWHM. The first two solenoids are controlled by independent power supplies and used to match the beam at the entrance of the focusing channel. A special solenoid at the end of the focusing channel, also controlled by a separate power supply, will be used to focus the beam in the diagnostic chamber.

The vacuum is obtained by a 400 ℓ/ sec turbo-molecular pump in the diagnostic chamber and by two 8 ℓ/ sec ion pumps in the gun chamber. The base pressure of the system is $0.6 - 1.0 \times 10^{-7}$ Torr. A gate valve is used to maintain vacuum in the gun chamber and to avoid the reactivation of the electron gun during vacuum breaks of the system. When this valve is closed the pressure in the gun chamber is maintained at 6×10^{-9} Torr by the ion pumps.

The beam density profiles are measured with a Faraday cup. A 0.5 mm diameter pinhole is at the center of a thin tantalum foil covering the Faraday cup The inner cup has a small opening to reduce secondary electron effects. The Faraday cup is mounted on a rod which is movable in the axial direction and rotatable to scan the beam cross section. A precision XYZ-manipulator controlled by a CAMAC system will be used to measure beam emittances.

The fluorescent screen is a very useful diagnostic tool since it allows viewing of the beam cross section at beam voltages higher than 3 kV. It is made with P-31 phosphor and potassium silicate deposited on a glass plate. The fluorescent layer is coated with aluminum thin film using vacuum evaporation technique. A wire mesh with 5 mm squares is attached to the screen assembly to measure the beam size. In order to clear the sight of view for a camera, the screen assembly is mounted at the end of a long pipe which can be inserted into the beam drift tube.

Experimental Results

The electron beam from the gun has been investigated by a Faraday cup with a pinhole and a fluorescent screen. To avoid neutralization of ions, 5 μs, 60 Hz pulses are used; the beam current is 230 mA at 5 kV. The beam envelopes for various cases are shown in Figure 2. The $B_o = 0$ curve represents the free-space expansion of the beam. It is in good agreement with computer calculations using the K-V envelope equation.

The beam emittance is proportional to $V^{-1/2}$ at constant cathode temperature and beam perveance. Figure 3 shows the current profiles at Z = 6 cm for 500 volt and 5000 volt beams in the free expansion case. The envelope of the 500 volt beam is slightly larger than that of the 5000 volt beam due to the increased emittance. The 5000 volt beam shows the nonuniform density profile due to the anode mesh.

The beam envelopes with a single magnetic lens located at Z = 8.6 cm are shown in Figure 2(a). As the strength of the lens is increased, the beam waist is decreased. The envelope curves for B_o = 88, 117, and 147 G are in good agreement with computer calculations. However, when the magnetic field is further increased to values higher than B_o = 147 G, the beam envelope "explodes" near its waist and the beam size is no longer well defined. This effect is characterized by a dense core and a halo with distorted images of the anode structure. Further increase of the lens strength to about B_o = 380 G produces a well defined circular beam with a clear anode mesh image in the further downstream region. In B_o = 380 G, for example, the beam is first focused to a radius of about 1 mm at 9.2 cm, then it "explodes" between Z = 9.2 - 12 cm (the dotted line in Figure 2(a), and further downstream beyond Z = 12 cm it forms well defined envelopes with clear anode mesh images. This sequence of beam envelope changes is shown in Figure 4 for Z = 9, 10, 11, and 13 cm. The same pattern of beam envelope behavior along the axial direction with a fixed lens strength, is also observed at a fixed position when changing the lens strength. Figure 5 shows the beam cross sections at Z = 16.5 cm with B_o = 60, 176, 350, and 380 G.

The observed beam spot size of about 1 mm in the B_o = 380 G case is considerably larger than the value calculated with the K-V envelope equation. We believe that the difference is caused by the combination of the extra emittance from the anode mesh and nonlinear effects due to nonuniform density profile and lens aberrations that are not included in the computer program. The image formation may provide very useful information in identifying nonlinear effects; for example, it is easily noted from Figures 4 and 5 that there is anisotropic distortion of mesh wires and that images near the center are not as clear as in the rest of the beam cross section. The beam "explosion" occurs only when the beam waist is so small that the envelope is mainly determined by emittance rather than space charge forces. The distorted mesh images are caused by electrons with large transverse velocities due to the scattering at the anode mesh.

Figure 2(b) shows envelopes measured when a second lens is added at Z = 22 cm and the magnetic fields in both lenses are maintained at the same value. The three curves are for magnetic fields of B_o = 88, 103, and 117 G. The beam envelopes vary smoothly and the anode mesh image is not observed in this range of lens sgrength. This operating regime will be used in the focusing channel in the next phase of the experiment. It should be noted, however, that anode mesh images may also be found with the two lenses. If the first lens strength is in the range of B_o = 88 - 117 G, images are obtained beyond the second lens when the strength of the second lens is between 180 and 240 G. From these experimental results, it is assured that matched beams for the periodic focusing channel can be obtained by independently controlling the first two solenoids which serve as matching lenses.

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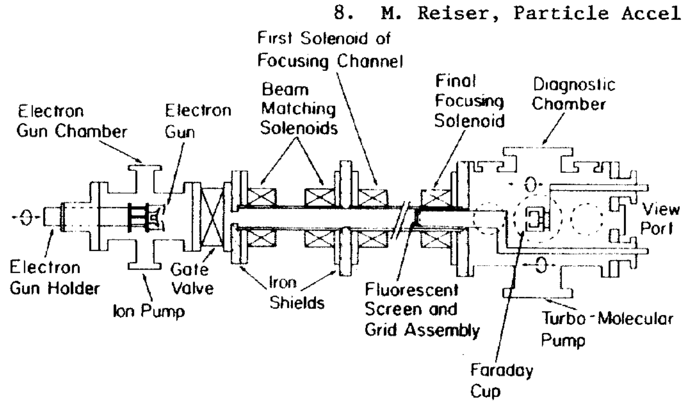

Figure 1. Schematic diagram of the electron beam transport experiment.

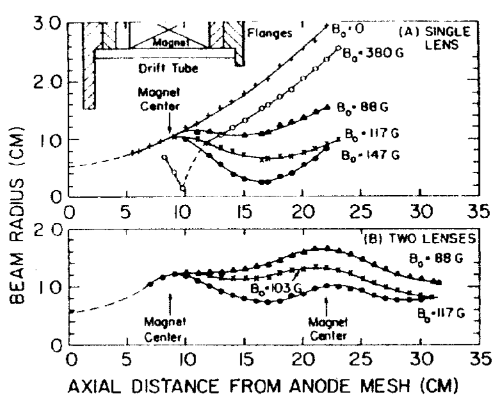

Figure 2. The beam envelope curves along the axial direction; (a) with a single magnetic lens at z=8.6 cm from the anode, and (b) with two magnetic lenses at z=8.6 cm and z=2Z cm.

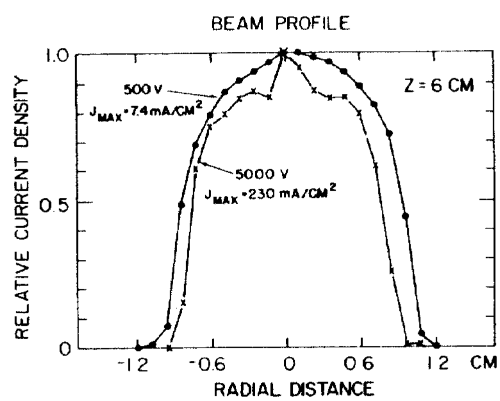

Figure 3. The current profiles for 500 volt and 5000 volt beams at z=6 cm in the free-space expansion.

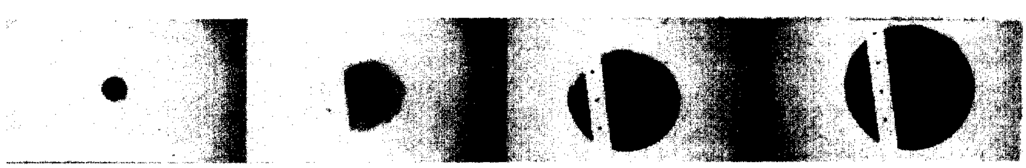

Figure 4. The beam cross sections at the locations, z=9, 10, 12, 13 cm for the magnetic strength B_o=380 G with one lens. (ↄ mm between dots)

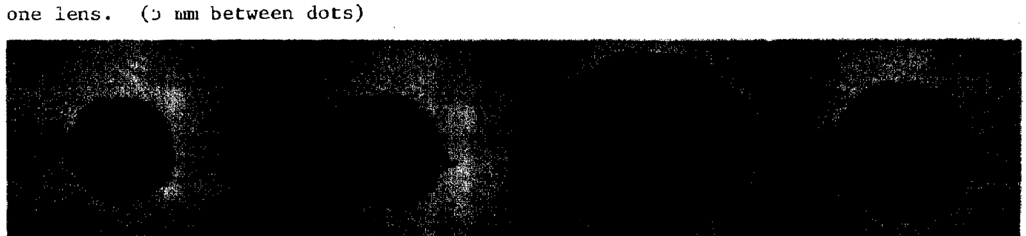

Figure 5. The beam cross sections at z=16.5 cm for the magnetic strengths for one lens B_o=60, 176, 350, and 3ȣ0 G. (5 mm square mesh)