CYLINDRICAL BEAM STUDIES FOR THE MARYLAND ERA*

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Abstract

A hollow cylindrical beam of 1.4 MeV electrons 5cm in diameter produced by a pulsed field-emission diode has been studied. The number of particles in r-r´ phase space within an emittance of 0.09cm rad and within an energy interval at the maximum of 0.1% (corresponding time interval $\sim$0.5ns) was estimated to be 9×10^{12}. Beam dynamic studies are reported of the variation of the major radius of the beam with changing field along the axis and of the beam width as a function of the axial magnetic field near the anode.

I. Introduction

In this paper, a preliminary study is reported of the characteristics of a high-current hollow cylindrical beam. This beam was produced by a field-emission diode having a ring cathode with a Marx-generator-type voltage source. A similar beam is to be used to form an electron-rich ring of small minor radius in the static magnetic field of an electron-ring accelerator. Such a system is being designed and constructed at the University of Maryland[1]. The results reported here refer to a 1.4 MeV electron beam, however the injector for the Maryland electron-ring accelerator will operate at 5 MeV.

II. Description of Diode and General Beam Characteristics

A Febetron Model 705 was used as a voltage source in the studies reported here. The normal output voltage pulse has a peak amplitude of $\sim$2 MeV across a 400 ohm load and a pulse duration of 50-100 ns. In this study the diode supplied by the manufacturer was replaced by a special diode assembly. This is shown in Fig. 1. The principal advantages of this arrangement over the standard diode are that no material windows are required and that the diode may be readily disassembled for alteration and maintenance. (The previously reported study[2] on the beam produced by a 6.35 mm diameter emitter also used the same supporting configuration shown in Fig. 1.)

The glass vacuum envelope shown in Fig. 1 supports the cathode structure. It was chosen (after some analog voltage studies) principally for convenience of construction and has proven to be satisfactory, at least for these initial tests[3]. The Al. cathode has rounded edges and has a 25μ thick Tantalum ribbon[4] forming a circle of 5cm diameter which protrudes a distance of $\sim$2 mm from the lower surface. Several other cathodes were tried, one was identical to the one shown except that a triangular protrusion of 2 mm with a sharp edge (30° angle) was used for the emitting surface, but no observable change in characteristics of the beam was found. In some preliminary studies, a cylinder 5cm in diameter ending in a 25μ tantalum emitting surface, was used but required a 7.5 cm cathode-anode gap for a roughly equivalent diode impedance.

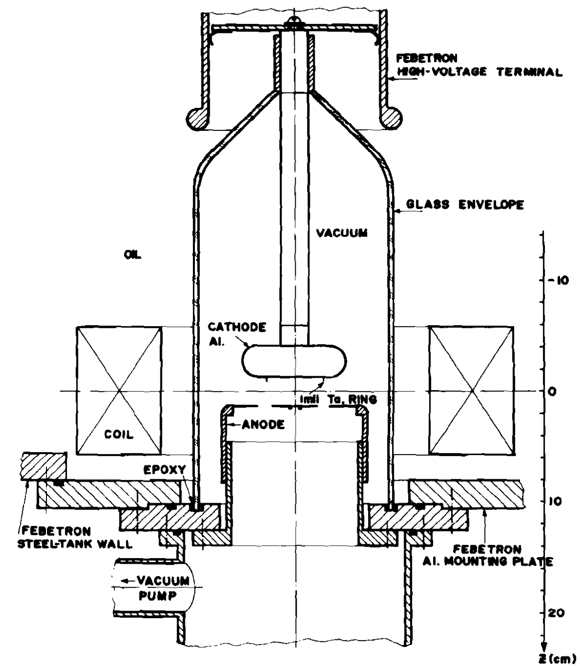

Fig. 1. Cross-sectional drawing of cylindrical field-emission-diode assembly for Febetron 705. Coil for producing magnetic field in emission region is shown. Febetron high-voltage terminal, mounting plate and iron tank structure also are shown.

The anode is a copper plate with a 5 cm diameter concentric annular opening in it[5]. (Wires that support the central conducting plate are also shown in Fig. 1.) Both cathode and anode are easily accessible in this arrangement. The cathode position can be altered by shortening or lengthening the supporting tube and the anode is itself an adjustable structure. The positions of the cathode and anode were chosen so that the center of the magnetic-field coil was located at the center of the cathode - anode gap. The 2.5 cm gap spacing was chosen so that the diode would be roughly matched to the impedance of the Febetron. At the usual charging voltage of 28 KV, a peak voltage of 1.4 MV rather than 1.8 MV was observed from which an approximate impedance for the diode and connections to the Febetron high voltage terminal of $\sim$250 ohms is deduced.

The cylindrical beam produced with the modified Febetron diode of Fig. 1, as expected, was found to expand in the decreasing axial magnetic field produced by the short solenoidal coil. A plot of the beam radius, R, as a function of the axial distance,

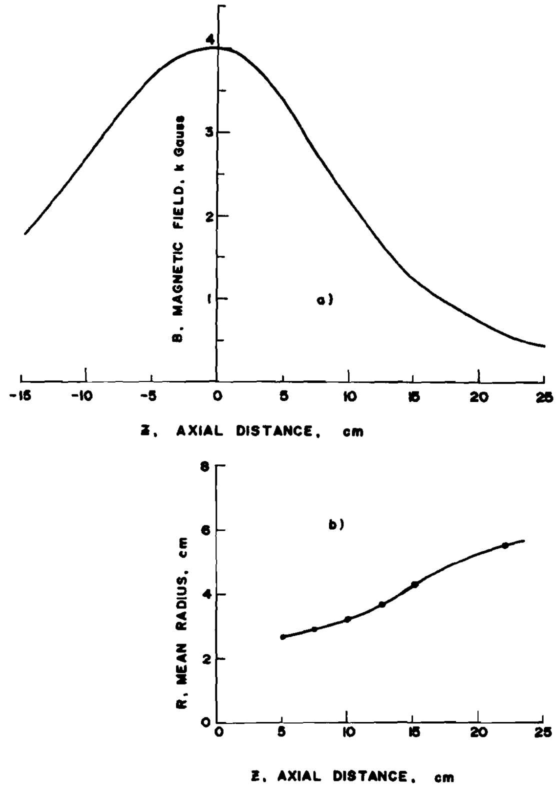

Fig. 2. a) Axial magnetic field, B, and b) mean radius of cylindrical beam R, are plotted as a function of the distance from the gap center, z. Febetron charging voltage 28 KV.

z, from the center of the gap is shown in Fig. 2 b). In Fig. 2 a) a plot of the axial magnetic field also is shown[6]. During these observations as well as those to be described later, the Febetron was operated at a charging voltage of 28 KV. The current measured with a fast-rise Faraday cup (rise time ∿2 ns) traversing an angular slice of 20° (5.6 %) at z = 22 cm was 300 A. The output current pulse along with the voltage pulse on the high-voltage terminal of the Marx generator of the Febetron are shown in Fig. 3 a) and 3 b), respectively. These results suggest also a maximum diode impedance of ∿250 ohms.

In order to examine the effect of the magnetic field near the cathode on beam characteristics, a series of radial beam profiles were made at a fixed axial position (z = 2.8 cm) with a constant charging voltage but with various values for the axial magnetic field. These tests were performed on a beam produced by a 5 cm dia. cylindrical cathode with a foil edge 7.5 cm from the anode. The radius of the cylindrical beam, R, did not noticeably change as would be expected. The beam thickness of 2ΔR was found to be a strong function of the magnetic field. The half of the full width (at ∿10% of the maximum intensity) ΔR_{max} has been plotted as a function of the average axial magnetic field, B, in Fig. 4. One notes that ΔR_{max} is approximately inversely proportional to B.

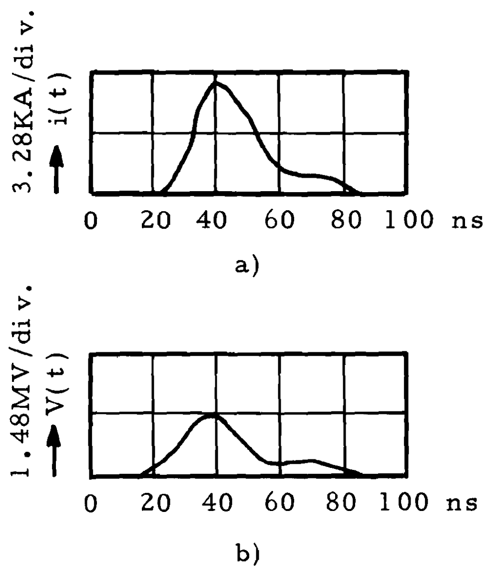

Fig. 3. a) Diode total output current (assumes beam symmetry) and b) output voltage at Marx-generator terminal plotted as a function of time in ns. Febetron charging voltage 28 KV. Magnetic field in gap ∿4000 G.

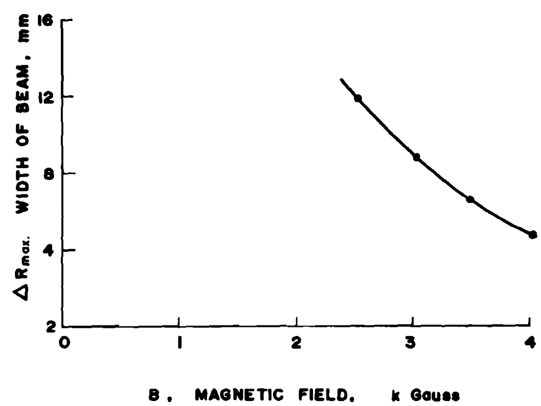

Fig. 4. Width of beam envelope, ΔR_{max}, at z = 2.8 cm as a function of the average axial magnetic field, B. Mean radius of beam 2.6 cm. Febetron charging voltage 28 KV.

III. Beam Energy-Current Characteristics

The beam energy as a function of time would be known were it possible to determine the cathode voltage wave shape. This is not possible as no voltage sensors conveniently could be placed near it. Instead the procedure used was to determine the practical range and thus the energy of electrons as a function of time. This measurement was obtained with the diode configuration of Fig. 1 from series of exposures in which the current wave shape of the beam was recorded with a Tektronics 519 oscilloscope after various aluminium thicknesses[7]. These measurements were made on the fraction of the beam passing through an 20° angular aperture at z = 23 cm. The results giving the energy, ε(t), and the current, i(t), as functions of time in ns are shown as two curves in Fig. 5. From these curves the number of electrons per 40 KeV energy interval was determined and the result is shown in Fig. 6.

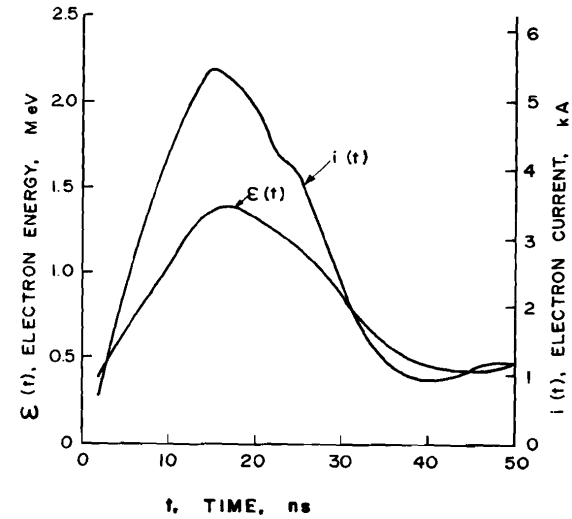

Fig. 5. Electron energy, ε(t), and current i(t) plotted as a function of time in ns. Febetron charging voltage 28 KV. Magnetic field in gap ∿4000 G.

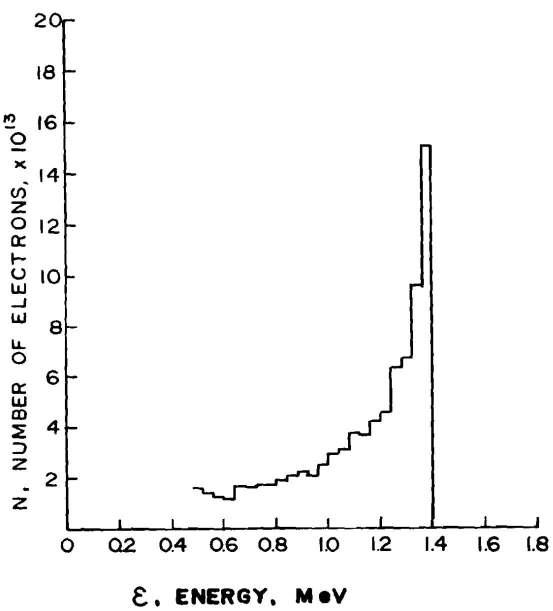

Fig. 6. Energy spectrum for electrons deduced from Fig. 5.

IV. Phase Space Measurements of the Beam[8]

For a particle beam propagating along the z axis, the total beam can be represented by

$$N = \int_0^\infty \int_0^{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D(r,\theta,r',\theta') \; J\left(\frac{x,y,x',y'}{r,\theta,r',\theta'}\right) dr\, d\theta\, dr'\, d\theta' \tag{1}$$

where $D(r,\theta,r',\theta')$ is the four-dimensional phase-space density, $r' = dr/dz$, $\theta' = d\theta/dz$, and J is the Jacobian of coordinate transformation which, in this case, is easily found to equal r.

If cylindrical symmetry is assumed with the z axis taken along the center of the beam, then the total number of particles, N, is given by:

$$N = 2\pi \int_0^\infty \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D(r,r',\theta')_{\theta=0} \; r\, dr\, dr'\, d\theta' = 2\pi \int_0^\infty \int_{-\infty}^{\infty} \rho(r,r')\, r\, dr\, dr' \tag{2}$$

where $\rho(r,r') = \int_{\infty}^{\infty} D(r,r',\theta')_{\theta=0}\, d\theta'$. (3)

The fraction of N included in the phase-space area within the contour $\rho_j' = 2\pi\rho(r,r')r$ is given by

$$N_f = 2\pi \iint_{\rho_j'} \rho(r,r')\, r\, dr\, dr' \tag{4}$$

The ratio of N_f to N is then

$$\frac{N_f}{N} = \frac{\iint_{\rho_j'} \rho(r,r')\, r\, dr\, dr'}{\iint_{tot} \rho(r,r')\, r\, dr\, dr'} \; . \tag{5}$$

The two-dimensional emittance in r-r´ space associated with a given ρ_j' may be defined as:

$$E_r = \iint_{\rho_j'} dr\, dr' \; . \tag{6}$$

The phase space of the beam was determined by measuring $\rho(r,r')$ defined by equation (3) for discrete values of r_i. This quantity $\rho(r_i,r')$ can be obtained from measurements of the optical density distribution of a radiation-sensitive film[9] placed after a series of circular slits. The radial width of the density distribution for each slit gives the angle, r´, and the position of each slit the value for r_i. It should be noted that this optical density distribution represents the integral in θ´-direction of the diverging beam as represented in equation (3).

In the present study circular slits were approximated by straight slits placed perpendicular to the radial direction. A drawing of the slit arrangement is shown in Fig. 7. The location of the slits is also indicated.

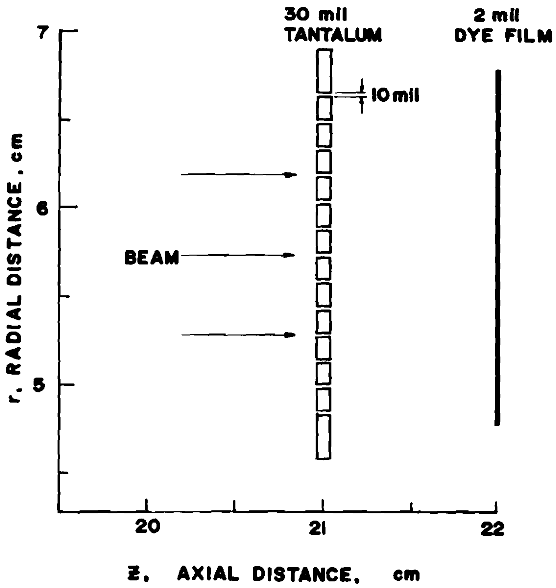

Fig. 7. Drawing of slit arrangement used to measure the phase space of the hollow-cylindrical beam.

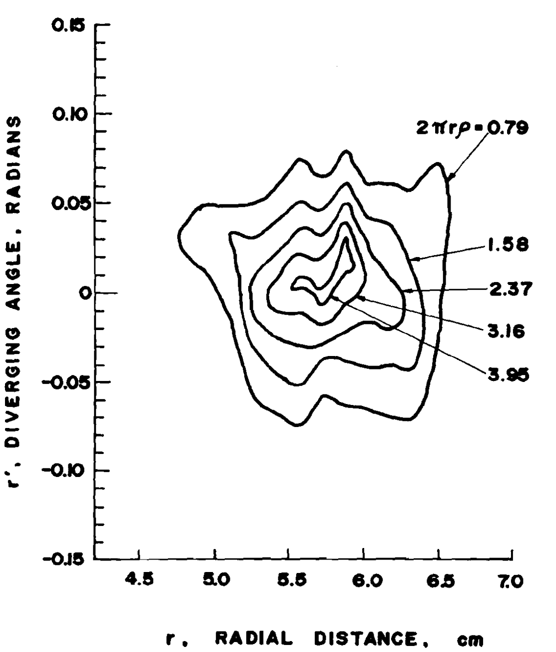

Fig. 8. Contours of constant brightness in r-r′ phase space. Febetron charging voltage 28 KV. Magnetic field in the gap ∿4000 G.

The phase-space diagram in r-r′ is shown in Fig. 8. The contours refer to lines of constant brightness or ρ_j' = constant. The area inside the contours determine the emittance E_r and the number of particles inside each contour is N_f. The values calculated for E_r and N_f/N (the fraction of all particles in the beam) are given in Table I.

In our case, the more conventional x-x′ phase space and emittance would be approximately twice the values given for r-r′ phase space.

Table I. Fraction of Beam, N_f/N, within a Brightness, $2\pi r\rho$, and an Emittance, E_r.

$2\pi r\rho$ (cm O.D.)	E_r (cm rad)	N_f/N
0	0.345	1
0.79	0.190	0.86
1.58	0.101	0.61
2.37	0.052	0.38
3.16	0.021	0.18
3.95	0.005	0.05

V. Discussion of Results

The general dynamics of the beam can be understood from Fig. 2 and Fig. 4. In Fig. 2 a) and 2 b) it is seen that the mean radius of the beam increases along z and that this radius varies, approximately, as the square root of the axial magnetic field, i.e. $R^2B \sim$ constant. The implication of this result may be understood in terms of the conservation of canonical angular momentum, P_ϕ. P_ϕ may be written as follows:

$$P_\phi = Rp_\phi + \frac{q\, R^2\, B}{2}$$

where Rp_ϕ is the mechanical angular momentum. With P_ϕ conserved and R^2 B a constant, it follows that the mechanical angular momentum of the beam changes little along z and therefore remains very small.

The beam width, $2\Delta R_{max}$, is found to be strongly dependent on the axial magnetic field in the cathode anode gap. As seen in Fig. 4, ΔR_{max} varies inversely as the square of B i.e. $B^2\Delta R_{max}$ constant. As a small value for ΔR_{max} is desired for the Maryland ERA, the value of B in the cathode-anode gap should be as large as possible.

Estimates for the emittance requirements of the beam for the Maryland ERA have been made[10] and indicate that a value of 0.09 rad cm at 1.4 MeV and an energy spread of 0.1% would be satisfactory. From Table I we note that ∿0.6% of the beam has an emittance of less than 0.09 rad cm. If we assume that the emittance is the same for particles at all energies, then the results of Figs. 5 and 6 can be used to deduce the number of particles within this emittance which have energies within 0.1% of the maximum value (1.4 MeV). The value of 9×10^{12} electrons so deduced, is similar to that which was found in the previous study of a 1.84 MeV beam produced by a rod-like cathode[2].

As noted above, the change of mechanical angular momentum is very small along z and thus there should be little change in the axial velocity of the electrons as they traverse the changing magnetic field. It then follows that the four-dimensional phase space of the beam is also conserved along z and therefore the emittance of the beam measured downstream should be approximately equal to that at the anode. Assuming an adiabatic condition, the beam thickness near the anode for that fraction of the beam with an emittance of 0.09 rad cm was estimated to be $2\Delta R \sim 6$ mm. In this calculation the effect of space charge has been ignored.

Analytical studies and computer analyses of trajectories including the effect of space charge are in progress. These will serve as a means of guiding further experimentation to improve beam quality.

Acknowledgements

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References

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[1] M. Reiser, IEEE Trans. on Nuclear Science, Vol. NS-18, 460 (June 1971).

[2] M. J. Rhee, et al, IEEE Trans. on Nuclear Science, Vol. NS-18, 468 (June 1971).

[3] Some discoloration of the glass envelope due to radiation damage has appeared near the cathode with this configuration after $\sim 10^3$ pulses and some glass failures have occured during insertion due to excessive mechanical stresses.

[4] Stainless steel was not used as it is slightly paramagnetic.

[5] Initially grids of 250μ stainless steel and platinum wires spaced 2.5 mm were used to form an anode. These had a limited life ($\sim$10-20 Pulses) and were subsequently replaced by an anode with a concentric slit.

[6] The observed asymmetry about the coil center of the axial magnetic field is due to the presence of the spherical-steel-tank structure of the Febetron in which the diode is mounted. See Fig. 1.

[7] The method used is described in a Field Emission Corp. report by F. M. Charbonnier. Practical-range data have been summarized by L. Katz and A. S. Penfold, Rev. Mod. Phys. 24, 28 (1952).

[8] See Reference 2 for a more complete treatment both of the phase space calculation and of the methods of measurements.

[9] The film used was Hexa-Hydroxy-Ethyl-Para-Rosalinine Dye Cyanide and was 50 microns thick. For this film the optical density is proportional to the dose up to 10^8 rad.

[10] J. G. Kalnins, H. Kim, and D.L. Nelson, IEEE Trans. on Nuclear Science, Vol. NS-18, 473 (June 1971). The value of 0.027 rad cm given for 5.5 MeV was referred to 1.4 MeV to give 0.09 rad cm. This is, no doubt, an underestimate as the emittance measurement made was energy integrated and refers to a mean energy less than 1.4 MeV.