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ELECTRON BEAMS GENERATED IN FOILLESS DIODES

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Summary

The operation of a foilless diode to generate a hollow relativistic electron beam has been performed on the FX-25, a Van de Graaff charged 3 MV device. The diode consists of a cylinder of carbon (graphite) supporting either a cathode tip of larger diameter or a right circular cylinder of equal diameter and a coaxial anode guide wall having either an abrupt discontinuity in wall diameter or a smooth wall. Six configurations were employed to explore the emitted electron behavior in the crossed electric and magnetic fields. Finite gyroradius effects limit the transmitted current at low applied axial magnetic field strengths. The transmitted current increases with increasing field strength until a critical field is reached, when further increase in field strength results in a decrease to a plateau in transmitted current. This critical field produces an electron gyroradius equal to the gap between cathode guide wall (anode) and is found to satisfy $\omega_c > 2\ \omega_b$ where ω_c is the electron gyro-frequency and ω_b is the beam plasma frequency. At high applied field strengths a very thin beam is transmitted and bounded by the space charge limited current. These features agree qualitatively with recent computer simulations of Jones and Thode.

Introduction

Foilless diodes on pulsed, relativistic electron beam generators are under consideration for many applications including collective effect ion acceleration, generation of microwaves and the heating of high density plasmas. The foilless diode produces, with the aid of a guiding confining magnetic field, annular electron beams that can achieve very high current densities at relatively low temperatures.

Friedman and Ury[1] and Kolomenskii, et al.,[2] have described the production of hollow beams with foilless magnetron injection gun arrangements. Gleizer, et al.,[3] used a coaxial cathode and anode arrangement to examine hollow electron beam current on cathode diameter and applied magnetic field strength. Nation and Read[4] recognized that the upper bound on the transmitted current is the space-charge limiting current. They employed a planar foilless diode and described the generation and propagation of a thin, annular beam in the high magnetic field limit, $\omega_c/\omega_b >> 1$, where ω_c and ω_b are the electron gyro-frequency and beam plasma frequencies, respectively.

We report on a series of experimental investigations on a variety of diode configurations to explore the role of the electron gyroradius and the behavior of the transmittal current and beam profile at applied, axial field strength values less than the high field limit. The choice of low kinetic energy (from the AFWL FX-25) and the geometry placed these diodes in a propagated (space-charge) current limited operation, i.e., the generator and transmission line supplied more current than could be carried forward in a transmitted beam.

Experimental Procedure

The foilless diode consists of a coaxial arrangement field emission cold cathode, a grounded anode guide tube, and a solenoidal magnetic field coil wound to produce a uniform constant axial magnetic field.

Two general classes of foilless diode configurations were employed to examine the transmitted current for a range of applied axial field strengths.

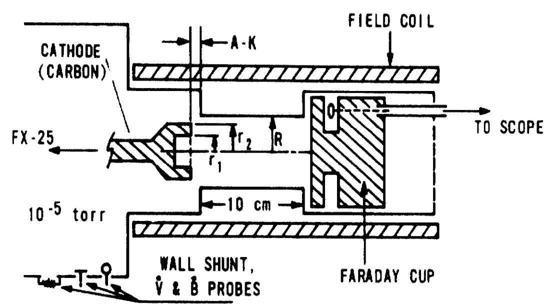

Figure 1. Schematic diagram of diodes C and D. The separation, A-K, between the wall discontinuity and the plane of the cathode tip is zero for C and 1.6 cm for D. The important dimensions are for diode C; R= 1.15 cm, r_2 = 0.95 cm, r_1 = 0.58 cm; for diode D; R= 1.85 cm, r_2 = 1.32 cm, r_1 = 1.0 cm.

All geometries were used in high applied field strengths to test the transmitted current as the space charge limited current. Four foilless diodes were used with a wide range of field strengths particularly at low values to study the transmitted current and beam profile characteristics.

Representative schematics of the two general classes of diodes used are shown in Figures 1 and 2. Figure 1 displays the configuration having an abrupt guide wall (anode) diameter change resulting in the presence of axial electric field components at the cathode tip for diode C. Figure 2 is a schematic diagram of the coaxial foilless diodes using various cathodes inside a uniform guide wall (anode).

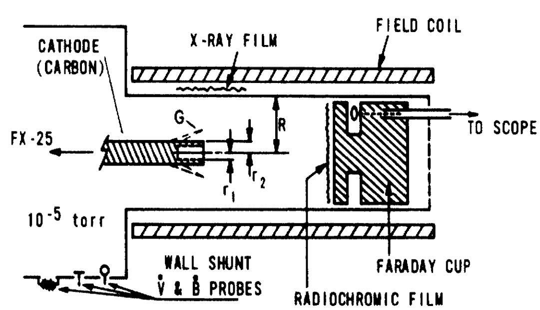

Figure 2. Schematic diagram of diodes G, H, I, and J. As depicted the cathode tip for diode G ended in a 1.32 cm radius thin tip supported on a 0.64 cm radius shank. The dimensions are: R = 2.35 cm; for G, r_2 = 1.32 cm, r_1 = 1.27 cm; for H: r_2 = 0.64, r_1 = 0; for I: r_2 = 0.64, r_1 = 0.54; for J: r_2 = 1.27 cm, r_1=0.

The cathodes were fabricated from high density carbon (graphite) into either right circular cylinders having solid or hollow ends or cylindrical rods terminating in a cone of larger diameter than the shank. These carbon ends, at least 10 cm in length were supported on aluminum rods in the vacuum diode envelope. Independent mountings for guide tube and field coils allowed for centering of both on the diode (cathode) axis. The guide tube consisted of standard 2 in vacuum stainless (0.19 cm thick) pipe of 2.35 cm inside radius. The diodes in Figure 1 employed smaller tubes of 1.15 cm radius and 1.85 cm inside radius for diodes C and D, respectively, mounted on the 2.35 cm radius tube. The cathode of diode C had a hollow tip as shown in Figure 1, but the tip was placed close to the wall discontinuity so that the separation, A-K, was zero. The cathode for diode D was of similar shape but entered the 1.85 cm radius guide wall a distance of 1.6 cm. With the exception of diode G, the diodes of Figure 2 employed right circular cylinders, diodes H and J having solid ends.

The negative potential applied to the cathode of the diode arrangement was obtained from the Ion Physics FX-25, a Van de Graaff charged generator. The energy stored is command switched via gas breakdown to the diode tube envelope with a pulse width approximately twice the electrical length of the Van de Graaff column, about 40 nsec (FWHM).

Diagnostics consisted of voltage measurements on the cathode shank via a $\dot{V}$ probe and generator current measurements with a return current wall shunt and a $\dot{B}$ loop mounted close to the $\dot{V}$ probe. Transmitted current was monitored with a Faraday cup having a magnetic loop pickup instead of the conventional shunt to ground via the oscilloscope. Radiochromic films placed inside the guide intercepted the beam and gave "time integrated" beam profiles. Single sheets of photographic film (Polaroid type 57) were sometimes used around the exterior of the guide wall. With magnetic field strengths insufficient to allow total beam transport, electrons striking the tube wall will X-ray fog the film giving an "autoradiograph" and a qualitative measure (along with the radiochromic film) of beam trajectories at low fields.

The pulsed magnetic field, derived from a capacitive energy store, had a risetime of 0.6 msec providing a homogeneous, quasistatic guide field for foilless diode operation. The FX-25 was triggered at the peak field amplitude which could be varied from pulse to pulse from 0 to 30 kgauss.

Results

The general feature common to all diode configurations is the similarity of transmitted current versus applied external field. As displayed in Figures 3 and 4 the current rises with applied field, B_z, to a maximum and then decreases to a plateau for further increase in B_z. This behavior has been observed by Gleizer, et al,[3] and by Jones and Thode[5] in computer simulations.

At high applied field strengths the current was limited by the space-charge of the beam. The generator-diode tube envelope impedances were low: beam voltages ranged from 0.9 to 1.8 MeV with total currents of 36 to 12 kA, respectively. At low field values the total diode impedance decreased (I_{total}/V_{diode}) from the high field values of about 40 ohms to 28 ohms, for diode C, for example.

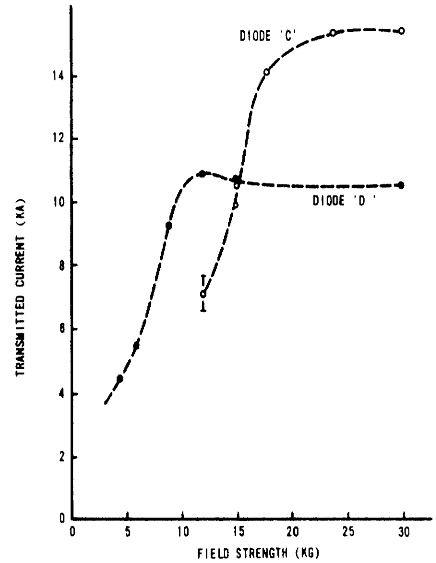

Figure 3. Transmitted current versus applied axial magnetic field strength for diodes C and D. The error in current measurements is ± 0.5 kA.

At low applied field strengths, the large relativistic electron gyroradius limits the emitted electron beam. The electrons expand away from the cathode tip and wipe off on the anode guide wall. Below the maximum in the transmitted current collected by the Faraday cup, beam particles strike the guide wall as

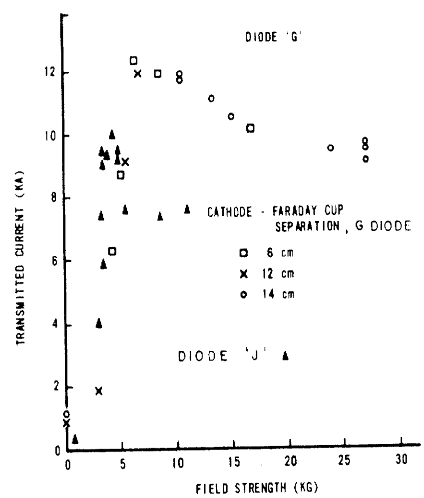

Figure 4. Transmitted current versus applied axial magnetic field strength for diodes G and J. The error in current measurements is ± 0.5 kA.

observed in the X-ray "autoradiographs" seen in Figure 5 for diode J. Identical behavior was exhibited for diode G which had a very thin, annular cathode tip. The bulk of the electrons that strike the wall do so at the axial position of the cathode tip not "downstream" as one might expect. Radially moving electrons in the pulse, when magnetic insulation is weak, are probably responsible. In the coaxial diodes, the applied electric field is radial. The possibility that electrons created "upstream" from the cathode tip impact the wall should not be discounted.

It was also observed, as seen in the diode G behavior in Figure 4, that the transmitted current was independent of the distance traveled to the detector. (This is always true as long as the cathode-detector separation is greater than the guide diameter.)

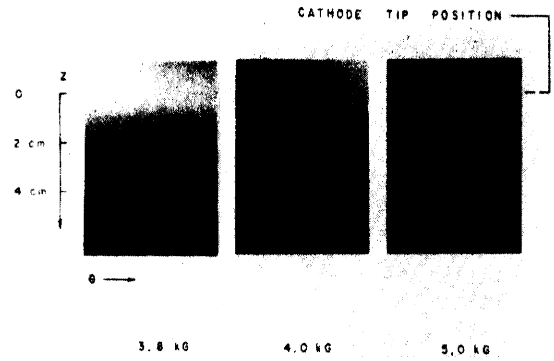

Figure 5. X-ray autoradiographs for diode J for three values of magnetic field near the critical field strength, 4.5 kG.

With the intermediate magnetic fields, at the position of the maximum transmitted current, the relativistic electron gyroradius was found to be equal to the separation of the cathode and anode wall. The results are summarized in Table I for four diodes, C, D, G and J, along with ratio comparisons of electron gyrofrequency, $\omega_c = eB/mc$, and beam plasma frequency, $\omega_b = (4\pi ne^2/m)^{1/2}$. The ratio ω_c/ω_b is seen to be higher than that of the critical value of Read and Nation[4] ($\omega_c^2 = \omega_p^2$). The critical field seems to be the one that provides an electron gyroradius just small enough to "fit" in the guide pipe. The diodes employed by Read and Nation had substantial axial electric field components, thus relaxing the critical magnetic field to satisfy $\omega_c^2 = \omega_b^2$. The gyroradius, r_g, was obtained from the expression

Table I. Comparisons of Electron Gyrofrequency, ω_c and Beam Plasma Frequency, ω_b; Electron Gyroradius, r_g and the Gap Between Cathode and Guide Wall, $R-r_2$; All Calculated at the Maximum Transmitted Current

Diode	B_z Field (at Max. I_{tr}) (kG)	$\frac{\omega_c}{\omega_b}$	r_g (cm)	$R-r_2$ (cm)
C	25.0	6.9	0.21	0.20
D	12.0	4.5	0.39	0.50
G	5.1	2.1	1.01	1.10
J	4.5	2.1	1.05	1.13

$$r_g = \frac{mc^2}{eB_z}\left(\gamma_o^2 - 1\right)^{1/2} \quad (1)$$

where γ_o is the injected beam relativistic factor using the voltage monitor values.

At the maximum in transmitted current, the beam is thick and expands to an equilibrium radius greater than the cathode tip. Witness foils or radiochromic films (blue cellophane) indicate, for diode J for example, that the beam is 0.5 cm thick and 1.8 cm in outer radius, r_o, at 4.2 kg. The beam has considerable thickness but not as great as that expected on the basis of the electron gyroradius. Structure exists on the beam (azimuthally and radially) but the outer radius remains fixed down the guide. There was some evidence of diocotron unstable propagation for low fields with the small diameter cathodes, H and I.

With the increasing axial field strengths, the transmitted current decreases because the outer radius of the beam envelope decreases.

Maximum power transfer did not occur in this study because conditions were imposed to examine the role of the space charge limiting current of the hollow transmitted beams. Calculation of the limiting current is based on the expression

$$I_L = \frac{mc^3}{e}\,\frac{(\gamma^{2/3} - 1)^{3/2}}{G(R, r_o, r_i)} \quad (2)$$

where $(\gamma-1)$ is electron kinetic energy in rest mass units mc^2, e is charge, and $G(R, r_o, r_i)$ is the Genoni-Proctor geometry factor[6] with R being the guide wall radius, r_o is the beam outer radius, and r_i, is the inner radius. For the infinitessimally thin beam $G(R, ro, r_i)$ becomes $\ln R/r_o$, and for a solid beam ($r_i \to o$) this factor becomes $1 + 2 \ln R/r_o$. Comparison of the transmitted current with the limited current using equation (2) at the two limits is presented in Table II. The transmitted current is comparable or slightly lower than what is the lower theoretical bound, the limiting current for a solid beam, even though witness foils indicate that the beams were quite thin. Some reduction in current may occur because of local impedance mismatch conditions at the transition region from the 10 cm radius diode tube envelope to the 2.35 cm radius guide tube.

Table II. Injected Relativistic Factor, γ_o, Experimentally Observed Transmitted Foilless Diode Current, I_{tr}, and Theoretical Space-Charge Limiting Current at the Highest Applied Mangetic Field Strengths.

Diode	γ_o	R/r_o	I_{tr} (kA)	$I_L(r_i \to 0)$ (kA)	$I_L(r_i \to r_o)$ (kA)
C	3.3	1.2	15.2	14.7	53.5
D	2.9	1.4	10.2	10.8	26.8
G	3.2	1.8	9.5	9.9	18.3
H	4.5	3.8	6.3	10.6	14.4
I	4.5	3.8	6.8	10.6	14.4
J	3.2	1.9	7.5	8.4	14.9

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