GENERATION AND DIAGNOSIS OF TW/cm^2 ELECTRON BEAMS

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Pulsed electron accelerators driving small cathodes have been used to generate self-focusing beams with power densities well in excess of 10^{12} W/cm^2 and current densities in excess of 1 MA/cm^2. These beams appear to follow conventional space charge limited flow dynamics which predict a divergent beam until the diode current exceeds a critical current, $I_C = I_a\beta_o\gamma_o R/d$, when the beam focuses sharply into the center. Immediately after the focus, the diode current is the parapotential current, $I_p = R/d\ I_a\gamma_o \ell n[\gamma_o + (\gamma_o^2-1)^{1/2}]$, and increases as anode debris approaches the cathode. Theoretical considerations predicting more intense focusing at higher voltages will be discussed and compared with experimental results. Diode impedances measured to date have been in the 10 to 40 ohm range which is compatible to source impedances on existing large accelerators.

Introduction

A number of high power electron accelerators have been built, the largest of which, AURORA, has a peak power of 2.4×10^{13} W, a total energy in the electron beam of approximately 3 MJ and an efficiency, delivered energy/stored energy, of approximately 60%.[1] We and other investigators have been working on means of concentrating the electron beam from similar machines with an eventual goal of developing an intense beam for pellet ignition or plasma heating. For these applications an electron beam has certain advantages, primarily that the accelerators exist, and secondly their self-magnetic field may aid in confining a target and reducing the power required to ignite the target.[2] All experiments on beam focusing to date have been on accelerators having energies in the kilojoule range, where probably at least hundreds of kilojoules are required to ignite a target; hence, these experiments are more feasibility studies than actual attempts to initiate a fusion "burn." The simplest and most successful method used to focus an electron beam to date uses a dielectric rod cathode several millimeters in diameter. This was first reported by Morrow, et al.,[3] where they implied current densities on the order of 10^8 A/cm^2 or greater at $\sim$ 3 MV. Since then, a number of experimenters have used the very intense beams for ion acceleration[4-6] and for neutron production.[7-10] With a group from Lawrence Livermore Laboratory led by W. C. Condit, we have been undertaking experiments to understand the mechanism of emission, acceleration and focusing of the dielectric cathodes and also to develop diagnostic techniques to measure beam power densities. The results have been reported in a number of papers and will be summarized in this paper.[11-14]

Diode Operation

The anode-cathode configuration used for our experiments along with an apertured Faraday cup is shown in Fig. 1. The diode is instrumented to provide instantaneous reading of voltage across the diode envelope and current flowing in the cathode stalk. The Faraday cup is apertured to read either total anode current or average current through the aperture. The temperature rise in the Faraday cup collector can also be measured to give total energy retained in the anode.

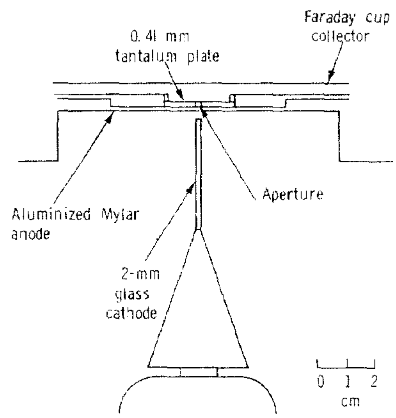

Fig. 1 Diode configuration with dielectric cathode.

The beam is initiated by switching a coaxial structure, which is pulse charged to $\sim$ 2 MV, into the cathode. The cathode geometry is such that the electric field is axial to the rod. When the cathode potential rises to 100-200 kV in $\sim$1 ns the rod breaks down or tracks, generating a highly conductive plasma along the rod surface from which electrons are emitted into the gap and accelerated through the gap potential difference. The beam is initially divergent due to its negative space charge and effect of the negative cathode. But as the current increases and the gap fills with positive ions from the anode, the attractive force from the self-magnetic field of the beam overcomes the electrostatic repulsion and the beam self pinches. No general theory for a high current diode is available, but Creedon[15] has derived equations for various geometries including a plane parallel cathode-anode structure similar to that on our cathodes, but with assumptions that limit the generality to ratios of radius to anode-cathode spacing (R/d) to 1 or greater. The theory predicts the beam will self pinch when the current exceeds a "critical current"

$$I_c = \frac{R}{d} I_A\beta_o\gamma_o = 8500\ (\gamma_o^2-1)^{1/2}\ R/d$$

where $\gamma_o = eV+M_oc^2/M_oc^2$ and V is the accelerating potential. This is also the current where the Larmor radius equals the anode cathode spacing. Immediately after the focus the current is the parapotential current

$$I_p = R/d\ I_a\gamma_o \ell n[\gamma_o + (\gamma_o^2-1)^{1/2}]$$

and the current increases as the exploding debris from the anode approaches the cathode. The diode shorts when the debris reaches the cathode. Figure 2 is a graph of critical

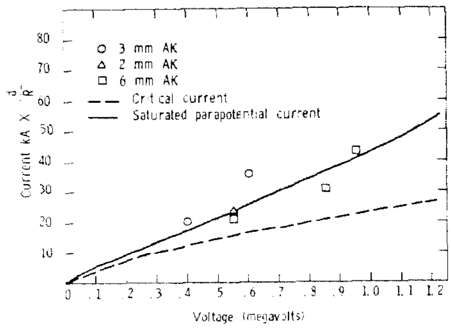

Fig. 2 Plot of critical current and parapotential current vs accelerating voltage with points from 5 mm diameter cathode.

current and parapotential current along with data points taken on a 5 mm diameter glass rod. The current and voltages were taken at peak voltage, i.e., after the focus occurred but before the anode debris had closed the gap appreciably. Plots taken with smaller cathodes show similar fits to the curve but the currents are somewhat higher than one would predict from strict parapotential theory. We attribute this to a plasma sheath on the outside of the cathode increasing the effective emitting radius.

One question that was brought up immediately when we began our research was if the accelerating region was along the rod or in the anode-cathode gap as we suspected. It was logical to compare the voltage and current characteristics of identical sized and spaced metal and glass rods; within the reproducibility of the experiments the voltage-current relationships were identical.[12] Since the conductive cathode is unable to sustain any great potential difference along its length it is reasonable that the electrons are emitted from the tips of both with relatively low initial energy and the acceleration region in both cases is in the gap rather than along the length of the rod. Another test we made was to compare short circuit current and voltage waveforms from metal and glass cathodes and measure the energy deposited and retained in the anode. The major difference between the cathodes was that it required 1-2 ns to generate sufficient voltage to flash the surface of the glass cathode, after which the voltages on both were zero and currents virtually identical. Total energy deposited in the anode (on the shorted shots) from both metal and glass cathodes was less than the 10 J our calorimeter could resolve. Since the total charge passed was 10^{-2} C, this implies that the average electron energy at the tip of the rod was less than 1 keV.

All of this evidence further reinforces our contention that the emission from a glass cathode is from the tip, the electrons are emitted with low energy relative to the accelerating potential, and the current flow is space charge limited.

This is not to say that glass cathodes do not have superior focusing qualities over metal cathodes. Stringfield, et al.,[16] report superior focusing from dielectric cathodes and we have not made systematic enough studies to draw positive conclusions.

Diagnostics

The problem of diagnosing the power and current density of the beams has proven to be as difficult as generating them. We have proven conclusively that there is little voltage drop along the rod, so our measurement of cathode stem voltage is the accelerating potential and hence very nearly the electron energy at the anode.

The three methods we have finally used to measure beam power density are:

1. Apertured Faraday cups
2. X-ray pinhole photography
3. Back surface blowoff velocity measurements.

Use of apertured Faraday cups has been described in several papers.[14,17,18] With Condit, et al., we have passed 21 kA through a 1 mm diameter aperture for an average current density of 2.7 MA/cm^2. As with all techniques it has limitations. The technique only measures the average current through the aperture and not a peak. The Faraday cup will accurately show the early time structure and the focus, as is shown in Fig. 3. The cup face appears to flash over or be shorted by exploding debris 5 to 10 ns after the focus, and hence is probably reading low. Another limitation is that any electrons striking or grazing the inside of the aperture can cause it to explode inward and close.

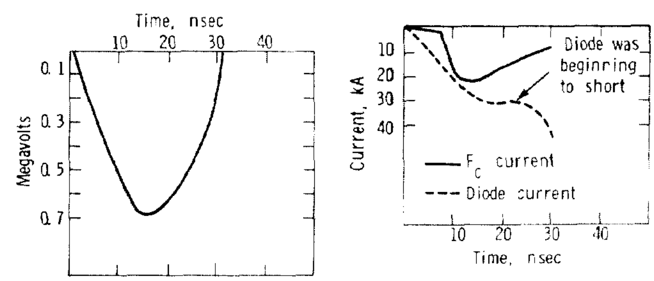

Fig. 3 Voltage, diode current, and current through a 1 mm aperture vs time.

X-ray pinhole photography has proved to be a valuable tool for determining beam focal spot sizes. In this technique a thin tantalum foil is used as an anode and the beam impinges on it and generates X-rays. A small aperture is placed between the tantalum X-ray source and a film pack which is exposed by the X-rays, creating an image of the tantalum source. Focal spot sizes less than 1/2 mm in diameter have been recorded on occasion but data reduction has been made difficult by the energy sensitivity of the film, the energy sensitivity of X-ray production, and photon shine through the thin part of the aperture. Also the image is time integrated, and invariably displays a halo that probably was generated before the beam self pinched.

Blowoff velocity measurements involve simply taking time resolved photographs of the back surface of the exploding tantalum anode, from which velocities are calculated. Hydrodynamic studies[19] show that the leading edge velocity of vaporized material will be

$$V = \sqrt{6\, e_o}$$

where e_o is the dose in units of 10^5 J/gm and V is in cm/µsec.

Our highest measured velocity is 2.5 cm/µsec, which implies a dose of 10^5 J/gm. We can compare this to our peak shot on the Faraday cup where peak power was 1.8 TW/cm^2 for approximately 10 ns. Monte Carlo calculations of energy deposition versus depth for 700 keV electrons predict the back surface dose in the tantalum anode to be ~5 J/gm/J/cm^2. This value of normalized dose multiplied by the measured energy per unit area gives a dose of about 0.9x10^5 J/gm. Hence, the two methods give consistent results. Blowoff velocities have also been compared with pinhole photograph exposure densities, with results shown in Fig. 4.

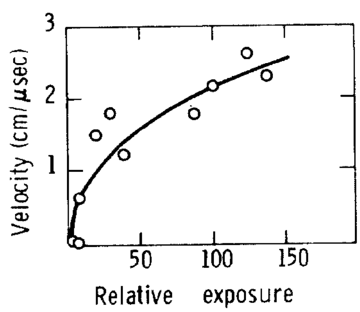

Fig. 4 Correlation of blowoff velocities vs peak film exposure; Courtesy of W. C. Condit.

Summary

Our experiments have demonstrated reasonably conclusively that electron beams in the 20-30 kA range at approximately 1 MeV can be focused into spots on the order of 1 mm in diameter or smaller to give electron beam densities as high as 2.7 MA/cm^2. We have confirmed this measurement by several independent diagnostic techniques. We have also determined that the beam current is space charge limited and appears to follow the parapotential law

$$I_p = \frac{R}{d} I_a \gamma_o \ \ln[\gamma_o + (\gamma_o^2 - 1)^{1/2}]$$

Since the critical current is only proportional to R/d · γ_o, the ratio of

$$I_{diode}/I_{critical}$$

(for a given R/d) will become larger at a rate

$$\ln[\gamma_o + (\gamma_o^2 - 1)^{1/2}].$$

This strongly suggests that the beam will self focus even more intensely at higher voltages. A limited number of tests at 3 MeV have indicated beam core spots smaller than 1/2 mm, the smallest we have observed to date. Our tests imply that an extension to AURORA-size beams (12 MeV) is feasible and would result in dramatic increases in delivered power together with further reduction in beam area.

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