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EMISSION FROM FERROELECTRIC CATHODES

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ABSTRACT

We have recently initiated an investigation of electron emission from ferroelectric cathodes. Our experimental apparatus consisted of an electron diode and a 250 kV, 12 ohm, 70 ns pulsed high voltage power source. A planar triode modulator driven by a synthesized waveform generator initiates the polarization inversion and allows inversion pulse tailoring. The pulsed high voltage power source is capable of delivering two high voltage pulses within 50 ns of each other and is capable of operating at a sustained repetition rate of 5 Hz. Our initial measurements indicate that emission current densities above the Child-Langmuir Space Charge Limit are possible. We explain this effect to be based on a non-zero initial energy of the emitted electrons. We also determined that this effect is strongly coupled to relative timing between the inversion pulse and application of the main anode-cathode pulse. We also have

initiated brightness measurements of the emitted beam. As in our previous measurements at this Laboratory, we performed the measurement using a pepper pot technique. Beamlet profiles are recorded with a fast phosphor and gated cameras. We describe our apparatus and preliminary measurements.

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1. Introduction

New research into fast-switching, ferroelectric emitters promises to dramatically influence the state-of-the-art in pulsed electron device technology. This new class of electron emitter technology has shown extremely high current densities (of order 1 kA-cm^{-2}) and high brightness ($10^{10} \text{ A-m}^2\text{-rad}^2$) [1,2]. The fact that these emitters can be operated at non-UHV pressures, do not require elevated temperatures or a high energy laser system, make them a very attractive alternative to conventional cathode technology.

The emission from a ferroelectric is believed to result from the expulsion of charge from the surface and sub-surface layers [1,3]. This effect occurs upon switching the internal polarization by a fast voltage pulse. Typical durations of the emitted beam, in a Zirconium based material, can be of order 200 ns [4]. As the bound charge is quite high, $0.01 - 0.1 \text{ mC-cm}^{-2}$, the resultant electric fields impart significant energy to the emitted electrons. This latter phenomena has been both verified by direct measurement [5] and explains measured current densities in excess of those predicted by the Child-Langmuir space charge limit for electrons with zero initial kinetic energy.

One of our motivations for pursuing ferroelectric emitter technology is upgrading the cathode brightness of the high power, pulsed accelerators at the Lawrence Liver-

more National Laboratory. The Advanced Test Accelerator or ATA (a 50 MeV, 10 kA electron accelerator) [6] and the Flash X-Ray Radiography Accelerator or FXR (a 20 MeV, 4 kA electron accelerator) [7] utilize velvet cathodes for electron production. Although simple, brightness is typically an order of magnitude below that of a high brightness dispenser cathode used on the Experimental Test Accelerator II (a 7.5 MeV, 2.5 kA electron accelerator) [8]. To implement a dispenser cathode on either accelerator, however, would require major upgrades to the injector. In addition, there are applications where gating the electron beam is required. Again, significant modifications to the injector would be required in these applications.

Recent data taken at 4 A-cm^{-2} , 15 A total, showed a brightness of $1.3 \times 10^{10} \text{ A-m}^{-2}\text{-rad}^{-2}$ (RMS). This result is shown comparatively in Figure 1. The experiment used a 1-2 kV inversion pulse with a variable DC power supply across the anode-cathode (A-K) gap [2], i. e., emission was controlled by the inversion pulse. This data was taken at 10 keV.

It is the eventual purpose of our effort to determine if a similar brightness is attainable for kiloampere electron beams. Further, as the emission appears to be dependent on the inversion pulse, we are also trying to determine to what extent the emission can be controlled by the inversion pulse. We report on our apparatus and preliminary measurements.

2. Apparatus

The cathode test stand is shown schematically in Figure 2. This apparatus was previously used to measure brightness of osmium coated dispenser cathodes, but was modified to allow exploration of ferroelectric emitters [9].

A pre-poled, 1 mm thick x 5.1 cm diameter Lead Titanate-Zirconate Piezo Ceramic (LTZ-2) [10] was placed behind a highly transparent grid. The emission side was optically polished; the grid was a square mesh composed of 0.025 mm diameter tungsten wires spaced approximately 0.75 mm on centers. Sample orientation was such that the bound positive charge (negative screening charge) was positioned toward the A-K gap. All but a 3 cm diameter central area of the sample was apertured. The grid-emitter assembly was recessed into the cathode shroud approximately 0.4 cm; the distance from the emitter surface to the anode was approximately 1.8 cm. A copper plate mask, 0.16 cm thick, served as the anode. The entire vacuum system and housing was fabricated from stainless steel; ceramics are used as insulators. Turbo-molecular pumps were used throughout. Base pressures in the 10^{-7} T range were easily achieved and maintained.

Main current was measured by resistive current monitors; A-K potential was measured by a capacitive probe calibrated by a standard resistive probe. Data was recorded with fast analog oscilloscopes.

Core brightness measurements were accomplished with a

central hole, of sufficiently small radius (100 μ), to minimize beam space charge effects. Further, the hole was counterbored slightly to minimize any errors caused by beam scraping. A fast phosphor, ZnO(Ga), was coated onto the vacuum window opposite the anode mask. Charging was eliminated with a thin graphite layer placed over the phosphor coat. Drift distance from the anode mask to the phosphor was 24.5 cm.

Microchannel plate intensified, CCD gated cameras, allowed observation of the phosphor image. Minimum gate width was 5 ns. The images were recorded digitally for analysis; our preliminary data presented here was obtained by direct measurement of the on screen image.

The polarization inversion pulse was coupled to the back plane of the ferroelectric emitter via a short length of 10 ohm, coaxial cable. The modulator system was at ground potential while the ferroelectric assembly and cathode stalk were elevated to the accelerating potential. The anode was maintained essentially at ground potential through the resistive current monitor. A stack of ferrite material placed along the 10 ohm coaxial cable provided the isolation impedance from the cathode stalk to ground. In these initial measurements, the system is mismatched so that ferrite reset was provided by the arrival of the first positive reflection; electron current was then initiated at the following reversed polarity pulse.

A polarization inversion pulse was supplied by a set of 32 planar triodes in parallel (Figure 3) [11]. A total

current of approximately 0.5 kA at a maximum voltage of 20 kV could be obtained by discharging a 0.05 μ F capacitor connected to the ferroelectric backplane via the 10 ohm coaxial cable. The bandwidth of the system was approximately 70 MHz.

The high voltage pulsed power was supplied by a water filled blumlein. At present, for the double pulse capability, we are using a magnetically delayed low pressure switch (MDLPS) [12]; double pulses as closely spaced as 50 ns were possible. The system was capable of 5 Hz continuous repetition rate. The blumlein and power supply system were capable of output pulses on the order of 250 kV into 12 ohm.

3. Experimental Results

Emission from the ferroelectric emitter was achieved with a positive, fast rising (approximately 20 ns), 2 kV square pulse, 100 ns in length. Approximately 20,000 shots were placed on the ferroelectric emitter at 1 pps with no discernable degradation in the emission characteristics. A-K potential was varied from approximately 15 to 60 kV. Peak currents of approximately 150 A were achieved during these initial measurements. As was generally observed, the measured currents were unipolar, consistent with electron flow, and above the Child-Langmuir limit, J_{CL} , for electrons with zero initial kinetic energy.

During the inversion processes, we characteristically observed multiple discharges between the wire mesh and the

ferroelectric emitter. In addition, upon application of an A-K potential a time integrated photograph showed a brilliant discharge filling the A-K volume (Figure 4).

To optimize the emission, timing between the inversion pulse and the main A-K pulse was varied from approximately 580 to 320 ns prior to arrival of the main voltage pulse (Figure 5). For a fixed A-K potential of 25 kV, the emitted current varied from approximately $0.5J_0$ to $2.8J_0$ over this timing variation. The optimum timing varied sharply about the peak showing a 25% decrease in the emission current for a timing variation of ± 20 ns from the optimum.

The emitted current from the ferroelectric was measured as a function of the applied A-K potential (Figure 6). In this data the A-K potential was varied from 16 kV to 41 kV; the emitted current varied from 32 A to 85 A. A significant amount of scatter was present in the data and consistent with those previously measured by others [4]. A best fit to the data indicated that the emitted current exceeded J_{CL} by a factor of approximately two.

4. Discussion

A Child-Langmuir solution for charged particles with non-zero initial kinetic energy is presented in the Appendix. It is shown that the increased current results from two effects. The first is a contraction of the effective A-K gap to the distance between the virtual cathode formed beyond the ferroelectric surface and the anode. The second

arises from an effective increase in the A-K potential due to the initial electron energy. From Figure 6 and Equation A-13, we infer the initial electron energy to be approximately 5 keV.

This initial energy is 2.5 times the energy that can be imparted by the polarization inversion pulse of 2 kV. We presume that the increased energy results from the exposed bound charge after the polarization inversion [1].

The observed luminescence from the cathode surface would indicate plasma formation on the ferroelectric surface. The increased emitted current density, however, indicated a high initial electron energy. This increased electron energy was generally inconsistent with emission from a plasma cathode. Further, late time gap closure is generally observed with a plasma cathode. Late time closure was not observed here or reported in other ferroelectric emitter experiments with a DC A-K potential [2]. These preliminary facts led us to believe that the emission process was different than a simple plasma cathode.

A strong dependence of the emitted current on the relative timing of the polarization inversion pulse to the applied A-K potential existed. Optimized electron emission occurred within a relatively short timing window.

Application of the A-K potential early would result in decreased electron current charge expulsion from the ferroelectric surface if a non-zero time was required for charge expulsion. Others presented data on the same ferroelectric material which indicated of order 50 ns rise-

time to peak emission currents [4].

Decreased electron currents from late A-K potential application could be explained by electron diffusion from between the A-K region. Qualitatively, the ejected screening charge would produce a radial electric field component which would impart transverse energy to the emitted electrons. With no acceleration potential, diffusion of the electron cloud and decreased electron density would result. Application of the A-K potential late would therefore result in decreased currents.

A brightness measurement was attempted using the single aperture in the anode copper plate mask; the attempt was unsuccessful. It was not clear if uniformity of the beam was at issue. We are presently expanding our measurements to determine beam uniformity during the brightness measurements.

5. Summary

We have begun initial experiments on ferroelectric emitters. As with previous researchers, we observed emitted currents greater than the Child-Langmuir space charge currents for electron emitted with zero initial energy. To explain this effect, we qualitatively concluded that the emitted energy was non-zero. Further, we deduced that the emitted energy was significantly above that which the polarization pulse could impart to the emitted beam. A plasma discharge was observed on the ferroelectric surface. Based on our observations, however, we believe that the

emission process was not dominated by this plasma. Optimization of the polarization inversion pulse qualitatively indicated that the electron cloud formed on the surface of the ferroelectric surface did not occur instantaneously and further, decayed on the same time scales.

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Figure Captions

Fig. 1 - Cathode brightness versus current for various cathodes [9].

Fig. 2 - Cathode test stand schematic.

Fig. 3 - Inversion pulse modulator. Sixteen parallel units provide the polarization pulse.

Fig. 4 - A-K gap luminosity during emission. Anode is to the left in photograph.

Fig. 5 - Electron current as a function of the timing between polarization inversion pulse and beginning of emission at $t=0$.

Fig. 6 - V-I character of A-K gap.

Fig. A-1 - Virtual cathode formation.

Fig. A-2 - Solution to equation A-13.

Figure 1

Fig. 1

Fig. 2

Fig. 3

Fig. 5

Fig. 6

APPENDIX

Child-Langmuir Solution With Non-zero Initial Electron Velocities

We consider the problem of a one dimensional, non-relativistic electron diode where the electrons are assumed to be launched with some initial, non-zero velocity. We assume for simplicity that the distribution of initial electron velocities is a delta-function. We will also assume that the pulse length is much longer than the time it takes an electron to cross the A-k gap so that the electron flow is in steady state.

Without loss of generality we take the potential ϕ to be zero at the cathode. If x represents the distance along the axis of the diode then the equation of motion of an electron is given by

$$v \frac{\partial v}{\partial x} = \frac{e}{m} \frac{\partial \phi}{\partial x} \quad (\text{A-1})$$

which may be immediately integrated to give

$$v^2 = v_o^2 + \frac{2e\phi}{m} \quad (\text{A-2})$$

where v_o is the initial velocity of the electron at the cathode. Since the initial electron velocity is non-zero an electron can more easily overcome the space charge potential barrier in the A-k gap. Thus, the current that must be emitted in order to satisfy the condition for space charge limited flow will be larger than in the case of zero initial velocity. As a result, the increased space charge (due to the increased current) will cause the electrons to decelerate until a *virtual cathode* is formed where $v=0$ (see figure A-1) at $x=x_v$. This will occur when the potential reaches its minimum value

$$\phi_{\min} = -\frac{mv_o^2}{2e}. \quad (\text{A-3})$$

Beyond the virtual cathode, the electrons will accelerate again until they reach the anode.

To proceed further with the development we must use Poisson's equation

$$\frac{d^2 \phi}{dx^2} = -4\pi\rho. \quad (\text{A-4})$$

First we note that in the steady state, current is conserved so that we may write the charge density ρ as

$$\rho = -\frac{J_o}{v} = -\frac{J_o}{\sqrt{v_o^2 + \frac{2e\phi}{m}}} \quad (\text{A-5})$$

where J_o is the magnitude of the (constant) diode current density.

It will prove convenient to define a dimensionless potential $\psi \equiv 2e\phi / mv_o^2$. Then equations A-4 and A-5 can be combined to yield

$$\frac{d^2\psi}{dx^2} = \frac{\alpha}{\sqrt{1+\psi}} \quad (\text{A-6})$$

where the quantity α is defined as

$$\alpha \equiv \frac{8\pi e J_o}{mv_o^3}. \quad (\text{A-7})$$

We may integrate equation A-6 immediately to obtain

$$\frac{\psi'^2}{2} = B + 2\alpha\sqrt{1+\psi} \quad (\text{A-8})$$

where B is a constant of integration and where a prime denotes differentiation with respect to x. We note that at the virtual cathode ($x=x_v$) we have $\psi=-1$ and $\psi'=0$. Thus we have that

$$\psi' = \pm\sqrt{4\alpha}(1+\psi)^{1/4}. \quad (\text{A-9})$$

From figure A-1 we see that ψ has the value zero at the cathode and decreases towards the virtual cathode. Thus in this region we choose the negative sign in equation A-9 which may then be integrated to give x_v , the position of the virtual cathode

$$x_v = -\frac{1}{\sqrt{4\alpha}} \int_0^{-1} \frac{d\psi}{(1+\psi)^{1/4}} = \frac{2}{3\sqrt{\alpha}}. \quad (\text{A-10})$$

We can now integrate equation A-9 (choosing the plus sign) from the virtual cathode to the anode which we take to be at $x=d$ to yield

$$d - x_v = \frac{2(1+\psi_o)^{3/4}}{3\sqrt{\alpha}}. \quad (\text{A-11})$$

The quantity ψ_o is the value of ψ at the anode.

Adding equations A-10 and A-11 permits us to find the value of α as

$$\alpha = \frac{4}{9} \frac{[1 + (1+\psi_o)^{3/4}]^2}{d^2}. \quad (\text{A-12})$$

Using equation A-7 and the definition of ψ_o we can write the current density J_o as

$$\frac{J_e}{J_{CL}} = \frac{[1 + (1 + \psi_o)^{3/4}]^2}{\psi_o^{3/2}} \quad (A-13)$$

where J_{CL} is the Child-Langmuir current density

$$J_{CL} = \frac{1}{9\pi} \sqrt{\frac{2e}{m}} \frac{\phi_o^{3/2}}{d^2}. \quad (A-14)$$

Now the quantity ψ_o is equal to the ratio of $e\phi_o$ to the initial kinetic energy E_o , of the electrons. Equation A-13 is plotted against the ratio $E_o/e\phi_o$ (or $1/\psi_o$) in figure A-2. As this ratio becomes large we see that J_o can become much larger than the Child-Langmuir current. An examination of figure A-1 shows how this can occur. The increase in current density arises from two effects. The first effect is a contraction of the effective A-k gap to the distance between the *virtual* cathode and the anode. The second effect arises from the increase in the effective diode voltage from ϕ_o to $\phi_o + E_o/e$. When the ratio of $E_o/e\phi_o$ becomes very large we see that the effective diode voltage becomes many times the applied voltage thus leading to very high current densities as compared to the Child-Langmuir current density.

Fig. A-1

Fig. A-2

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