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Kiloampere and Microsecond Electron Beams
from Ferroelectric Cathodes

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ABSTRACT

We report experimental results of the operation of two ferroelectric cathodes of relatively large size. The first cathode had a diameter of 10.2 cm and was built in the Pierce cathode geometry by Integrated Applied Physics (IAP). It achieved emission currents of up to 1.2 kA (15.3 A/cm^2) at voltages upto 100 kV, in 150 ns pulses. The second cathode had an annular shape with a diameter of 11.4 cm and a width of 0.25 cm. It was built at MIT to produce an annular electron beam for use in a Gyrotron microwave source. It operated at currents of up to 10 A (1.1 A/cm^2) at 8 kV, in 5 μs pulses. Detailed operating characteristics for each of these electron sources are reported. These results indicate that ferroelectric cathodes can be used to produce electron beams of large area and size, with high total operating current and pulse lengths of several microseconds. These sources should be suitable for use in future microwave generation experiments.

I. INTRODUCTION

Novel ferroelectric cathodes have gained the attention of the community due to lower cost, ease in manufacture and absence of high vacuum requirement for handling and operation. These cathodes can be operated in poor vacuum, and have low emittance and high brightness characteristics. They are superior to thermionic cathodes not only in their ruggedness but also due to their instant turn-on capabilities (thermionic cathodes require heating time). With the demonstration of scalability of ferroelectric cathodes to large sizes of over 10 cm diameter and high total currents of over a kiloampere, these cathodes are potentially attractive for a multitude of high current density (5-50 A/cm^2), long lifetime (as compared to velvet cathodes), pulsed applications i.e. accelerators, microwave sources, flat panel displays, etc. [1-9].

Most ferroelectric cathode experiments have been performed using cathodes with a diameter of 2-4 cm and a thickness of 1-2 mm [1-9]. The currents that have been obtained are of the order of tens of amperes [1-9] with current densities of order 10-100 A/cm^2, and pulse lengths of about 100 ns to 1 μs [see refs. 1-9 and references therein]. Thus our experiments with a 10.2 cm planar cathode built in a Pierce geometry, and an annular beam experiment using a 12.2 cm ferroelectric disk demonstrate the scalability of ferroelectric cathodes to sizes and beam shapes required in many applications. Both the

experiments were successful and while the planar cathode experiment yielded up to 1.2 kA, 150 ns pulses; the annular experiment gave us 10 A, 5 μs flat-top pulses.

In spite of all these advantages and demonstrated scalability, one finds that the process of ferroelectric emission from cathodes is not well quantified. Attempts have been made over the last few years to explain the process of electron emission from ferroelectrics [1,9,10,11,12]. The traditional explanation is that the emission results from a polarization switching effect which is initiated by a pulse across the ferroelectric cathode [12]. The polarization switching causes electrons which are in the surface layer to be emitted. A second explanation is that the electron emission is caused by a plasma layer which is formed on the surface of the ferroelectric when it is switched [9,13]. Recent experiments at Tel-Aviv Univ. [1,14] have confirmed the presence of a plasma with a density of 10^{10}-10^{12} cm^{-3} on the ferroelectric cathode surface. Experiments have also confirmed the presence of high energy electrons, of order a few keV, being emitted from the cathode surface [7,14]. This paper demonstrates the scalability of ferroelectric cathodes to high total currents and long pulselengths.

II. EXPERIMENTS AND RESULTS

For both the experiments described below, there is a pulse applied across the ferroelectric to initiate emission, and another pulse between the anode (stainless steel plate) and cathode (ferroelectric disk emitting side) to transport the electrons from the cathode to the anode. The usual value of the pulse across the ferroelectric is 1-2 kV, and the pulse applied across the anode-cathode gap is in the range of 0-100 kV. The delay between the ferroelectric pulse and the anode-cathode pulse can be arbitrarily varied from 0 to 12 μs in both experiments.

A. Planar beam experiment

The planar cathode experiment employed a 10.2 cm diameter, 1 mm thick LTZ-2 ferroelectric disk (made by Transducer Products [16]), which was patterned and tested at Integrated Applied Physics (IAP). The pattern etched into the silver on the emitting side of the ferroelectric consisted of a honeycomb with an opening of 200 μm. It was constructed to have an emitting diameter of 10.0 cm (part of the 10.2 cm disk was covered by the mechanical holding structure for the ferroelectric disk) and had a Pierce

geometry which was designed using EGUN [17]. Thus the total emitting area was 78.5 cm^2. The ferroelectric was poled and had a relative dielectric constant of 2100 [16]. The schematic of the gun is shown in Fig.1. The anode and cathode were separated by a cylindrical glass insulator whose diameter was 24.8 cm and length was 23.5 cm. The anode-cathode distance was 4 cm. The base pressure was maintained at 10^{-6} Torr.

The electrical setup used to drive the ferroelectric had an isolation transformer and a stack of Aluminum plates to grade the high anode-cathode voltage down in steps. The ferroelectric pulse was thus applied to the 130 nF ferroelectric cathode through the metglass core isolation transformer. The ferroelectric driver pulse was 1 kV, < 300 ns risetime, 700 A. The isolation transformer itself was built by IAP for this experiment, and had a metglass core with a 3:1 step-down ratio. A 10 • transmission line with a Thyratron switch was used to provide the pulse at the primary of the metglass transformer.

The diode was rated at 200 kV with a design electric field strength of 50 kV/cm at the cathode. A glass insulator holding the ferroelectric cathode was suspended in an oil tank as shown in Fig.1. The pulse applied across the ferroelectric, V_{fe}, is shown in Fig.2, where a positive potential of 1 kV is applied to the back of the ferroelectric (with respect to the front emitting side of the ferroelectric). The accelerating potential, V_{ak}, and the observed beam current are shown in Fig.3. One observes that the total beam current, I_{ak}, obtained in this shot was ~1000 A. From the time axis one can see the shot shown in Fig.3 has a delay of 6 µs with respect to the beginning of the pulse across the ferroelectric (Fig.2). The accelerating potential (V_{ak}) was applied using a Marx bank whose output voltage was varied in the range of 15 - 100 kV, although most of the data presented here is of voltages upto 65 kV. The diagnostic for measuring current was a custom-made Rogowskii coil mounted around the glass insulator (Fig.1). The anode was a steel cylinder maintained at a distance of 4 cm from the cathode. One of the parameters measured was the beam current versus the delay between the application of the pulse across the ferroelectric and the application of the anode-cathode accelerating potential. The results of the observed current vs. the delay are shown in Fig.4. This measurement was made with the anode-cathode voltage set at 50 kV. The V-I characteristic of this gun is shown in Fig.5. One observes that the maximum current in

this case was just 325 A and the diode impedance was ~200 • (data at 2 µs delay). One should note that the V-I curve shown in Fig.5 was for 2 µs delay, while higher currents were obtained for delays ~5 µs. Also shown in Fig.5 is the current predicted for the diode with space charge limited flow i.e. the Child-Langmuir [18] limit. Current in excess of the Child-Langmuir limit has been observed in previous experiments [1-10] and discussed therein.

B. Annular beam experiment

The annular beam experiment was conducted using a 12.2 cm diameter, 1.5 mm thick, APC-851 ferroelectric disk (made by American Piezo Ceramics [19]). The annular emitting strip (on the 12.2 cm diameter disk) was centered at a diameter of 11.4 cm and had a width of 2.5 mm. Thus, the total emitting area was about 8.95 cm^2. The emitting side was patterned with a honeycomb silver pattern. The open areas of the honeycombs were of diameter 200 µm and had a closely packed structure with a total open area of about 40%. The capacitance of the ferroelectric cathode was measured to be 40 nF. The ferroelectric was poled and had a dielectric constant of 2200 [19]. The cathode and emitter shape were optimized using the code EGUN [17], to produce a high quality electron beam for possible use in a 1 MW Gyrotron experiment. One should also note the novelty of this Gyrotron gun is that it uses a flat cathode, as opposed to the usual Magnetron Injection Guns (MIG) which use an emitting strip at an angle with the magnetic axis. The EGUN design was made with an effort to keep the velocity spread to a few percent, to keep the electric field strength below 50 kV/cm, and to get a transverse to parallel velocity ratio (of the electron beam) of about 1.6. This had to be done while maintaining a flat cathode shape, and was designed as shown in Fig.6. The vertical lines in this figure are lines of constant potential while the thick wavy horizontal line is the electron beam emanating from the cathode. The magnetic field is shown increasing across the gun from 0.13 T to 0.25 T.

The mechanical setup of the gun is shown in Fig.7. Care had to be taken in holding the ferroelectric firmly but without any stresses which would crack the disk. This was done by using spring plungers which were etched to weaken them, and gold contacts to provide a mechanically soft but an electrically strong contact. The anode-

5

cathode distance was 2.16 cm. The electrical circuit used to apply a pulse across the ferroelectric consisted of a pulse forming network, a Thyratron switch, and a 3:1 iron-core isolation transformer. The pulse applied across the ferroelectric (V_{fe}, I_{fe}) was usually in the range of 1.1 - 1.8 kV, 20 Amps. The accelerating voltage applied across the anode- cathode gap (V_{ak}) was in the range of 0 - 15 kV. For testing the gun, we used a simple aluminum plate as the anode. The plate has a diameter of 16.5 cm, a thickness of 8 mm and was maintained 2.16 cm from the emitting ferroelectric surface. This whole diode was then held inside a 21.3 cm diameter, 22.8 cm long ceramic (MACOR) cylinder with metal flanges brazed on both the ends. The anode plate was grounded, and the cathode had the negative high voltage. The V_{fe} was applied to the ferroelectric through an isolation transformer. The base pressure was maintained at 2×10^{-7} Torr.

Using this setup, experiments were carried out with typical pulses applied across the ferroelectric (V_{fe}, I_{fe}) shown in Fig.8 (top). The anode-cathode accelerating voltage applied (V_{ak}) and the emitted current (I_{ak}) are shown in Fig.8 (bottom). Note that the two traces are plotted on the same time scale, and thus the delay of emission in this case is ~5 μs. The emission delay is the measured delay in time between the application of the switching pulse across the ferroelectric cathode and the observation of current at the anode. The V-I characteristic curve for this diode gun was measured over several shots and is shown in Fig.9. The gap impedance from this curve was estimated to be in the range of 600-800 •.

III. DISCUSSION

The dependence of emitted current on delay (Fig.4) can be partly explained by the expansion of a plasma across the surface. Once the plasma is created at small microplasma points [1] (also called triple points [9] where the vacuum, metal, and the dielectric meet), it can then propagate across the ferroelectric cathode surface at a finite velocity leading to an optimum point of time (and thus delay) when the plasma is well established across the surface (the plasma emitting area is maximal) and the maximum current can be extracted from the cathode surface. The exact manner in which this plasma would propagate would be dependent on the geometry of the diode as well as the ratio of the size of the cathode to the anode-cathode gap distance, as well as other

geometrical considerations such as a solid or annular beam. If one assumes that the microplasma point is at the center of the cathode then spreads towards the edge, the lower bound of the plasma expansion velocity can be estimated as the radius divided by the optimum delay which is ~1 cm/μs. This is in agreement with the experimentally observed values of 1-4 cm/μs [20,21,22,23]. This optimum delay effect has also been observed in experiments by Sampayan et. al. [5], and Flechtner et. al. [20] where the plasma expansion velocity can be calculated to be ~2 cm/μs. Other observations such as shot-to-shot inconsistency, are also characteristic of a surface plasma spreading across a cathode. The explanation provided is speculative. It would be very useful to make detailed spatial and temporal measurements in order to verify this explanation or an alternate one. Such measurements are being conducted in other laboratories and are beyond the scope of this work.

The difference in current density from the two experiments is partly due to the lower anode-cathode voltage used in the annular beam experiment (in spite of the lower gap distance for the annular experiment) and the slower risetime of the pulse across the ferroelectric (which also decreases current density [7]). These two effects make the annular beam current density an order of magnitude lower than the planar beam one. Thus, one can assume that the lower risetime of a pulse across a ferroelectric leads to lower plasma density on the cathode surface and lower emitted current, has been observed by Gundel et. al. [7].

IV. CONCLUSIONS

Two different gun geometries using large ferroelectric cathodes have been tested successfully. The two results can be summarized as a planar cathode (IAP) producing a 1.2 kA, 150 ns beam for accelerator applications, and an annular cathode (MIT) producing a 10 A, 5 μs beam for microwave generation (using a Gyrotron). These results successfully demonstrate the use of ferroelectric cathodes in high total operating current, as well as long pulse (multi microsecond) regimes.

Along with these results of scalability, one should note that previous results [2] have demonstrated a normalized emittance of 5 mm-mrad, and a beam brightness of 1.2×10^{11} A/m^{2}rad^2. No evidence of aging of the cathode was observed after tens of

thousands of shots [2,4,5]. The present results have now demonstrated that the cathode size can be scaled up and that this promising new class of cathodes warrants greater investigation.

Among the drawbacks regarding this cathode which need to be addressed before widespread application in practical settings is the shot-to-shot reproducibility of the emitted current, as well as decreasing the capacitance of the ferroelectric material to reduce the requirements on the pulser (for the pulse across the ferroelectric). Also, optimization of the material composition of the ferroelectrics, and a better understanding of the exact emission process of ferroelectric electron emission need to be investigated.

Acknowledgments

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Figure Captions

Fig. 1. Schematic of the planar ferroelectric cathode gun at IAP with a diameter of 10.2 cm and a anode-cathode gap of 4 cm.

Fig. 2. Pulse applied across the IAP planar ferroelectric cathode to excite emission - V_{fe}(solid line), I_{fe}(dashed line).

Fig. 3. Accelerating potential (~30 kV) and emitted current (~1000 A) for the planar ferroelectric gun. This pulse follows that in Fig.2 by 6 μs.

Fig. 4. Beam current vs. delay between the pulse applied across the ferroelectric and the accelerating pulse across the anode-cathode (V_{ak} =50 kV).

Fig. 5. V-I characteristics of the planar ferroelectric gun. Diode Impedance ~ 200 •.

Fig. 6. EGUN design of the annular ferroelectric gun at MIT. The velocity spread (at the cavity injection point) is 6.9 %, and the transverse to parallel velocity ratio is 1.6.

Fig. 7. Mechanical setup used to test the annular ferroelectric gun.

Fig. 8. Pulse applied across the MIT annular ferroelectric cathode to excite emission - V_{fe}, I_{fe} (top). Emitted current reaching the anode and acceleration voltage - I_{ak}, V_{ak} (bottom). The delay in this case is ~5 μs.

Fig. 9. V-I characteristics of the annular ferroelectric gun at MIT. The diode impedance can be estimated as 600-800 •.

DC Bias
Voltage

Anode-Cathode
Pulse Voltage

Current
Monitor

Voltage
Monitor

Ferroelectric
Pulse Voltage

Anode

Glass
Insulator

R_{ch}

C

R_{load}

Aluminum
plates

Oil
Tank

Ferroelectric Cathode

Isolation Transformer (3:1)
with Metglass core

ANODE

FE CATHODE

5 CM

Current (Anode) Amps vs Voltage (Anode) kV

- Current (Experimental) Amps
- Current (Child-Langmuir) Amps

Child-Langmuir limit