Annular Electron Beam Generation Using a Ferroelectric Cathode

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***Abstract*—In this paper, we report on the emission of electrons from a ferroelectric cathode in a coaxial gun geometry. The electrons are emitted from the inner conductor of the coaxial system and are accelerated radially. An axial magnetic field causes the formation of an azimuthal annular electron flow. The electrostatic potential distribution then leads to the ejection of the annular beam from the anode–cathode region into the drift space. A beam energy of up to 50 keV and an electron current of up to 250 A is typical in this proof of principle experiment. The Hull cutoff condition is found to considerably underestimate the magnetic field required to insulate the radial electron current flow in the diode. The results obtained are consistent with earlier data showing that the behavior of the ferroelectric is closely coupled to the changing state of the ferroelectric.**

***Index Terms*—Ferroelectric cathode, magnetron.**

I. Introduction

THE study of electron emission from ferroelectrics has advanced through the last several years to the point that we can now consider ferroelectrics for use as cathodes in high-current electron guns. In a previous paper [1], we described the design of a gun to produce a 200–500-A pencil electron beam at an electron energy of up to 500 keV and presented initial experimental data. In this paper, we describe a configuration which allows the production of an annular electron beam. The annular beam geometry is particularly suited to ultrahigh-power microwave source development [2]. Among the possible advantages of ferroelectric emitters is their insensitivity to poisoning and the possibility of obtaining much larger emission current densities than can normally be obtained from a thermionic cathode. There is also experimental evidence showing their suitability for use at high repetition rates [3], including measurements of focused flow emission at about 20 A/cm^2 at 15 kV and 50 Hz [4], [5].

There is still controversy over the details of the mechanism of electron emission from ferroelectrics. It appears to entail both direct ferroelectric emission of free charge, which screens the polarization fields of the medium from the vacuum of the gun, and field emission from the triple points at the junction between grids on the ceramic surface, the ceramic itself, and the vacuum region. Both processes are, however, controlled by a rapidly changing submicrosecond voltage pulse applied across the ferroelectric as opposed, for example, to the usual field emission, which is controlled by the voltage applied to the anode of the gun, i.e., the electron dynamics are closely coupled to the domain dynamics and internal fields of the ferroelectric sample. During the electron emission pulse, it is expected that the high current densities obtained by emission from triple points will lead to material volatalization, ionization, and, finally, plasma closure within the gun. These processes were described many years ago by Bugaev *et al.* [6] and an extension of that paper applied more recently to ferroelectric emission [7]. Arguments have also been presented by the present authors [8] that the early emission is controlled by the ferroelectric and that the plasma closure is only important at late times in the applied gun pulse. Plasma closure velocities are believed to be of order 1–2 cm/μs, so that for typical anode cathode spacings of several centimeters, the electron current is controlled by the ferroelectric for at least the first microsecond of each pulse.

In the following sections, we shall present new data on the emission of electrons in a coaxial diode geometry in an externally applied axial magnetic field. This leads to the formation of an annular electron beam. Since the observations include emission transverse to an applied magnetic field, this also sheds new light on the effects of the ferroelectric on the emission process. In addition, this article describes the initial development of a ferroelectric gun for the production of annular electron beams.

II. Experimental Arrangement

In this experiment, a 2.5-cm long, 2.5-cm diameter cylindrical PZT sample is mounted in a coaxial diode assembly with an anode cathode separation of 1 cm. The cylindrical sample is commercially produced using a sintering process and consists of a PZT 55/45 composition which is near tetragonal/rhombohedral phase transition. The outer and inner surface are coated with a silver conducting layer approximately 10-μm thick. The surface grid electrode is manufactured by masking the sample and etching with a commercial silver etch. An axial applied magnetic field is used to restrict radial current flow and to lead to the formation of an annular electron beam.

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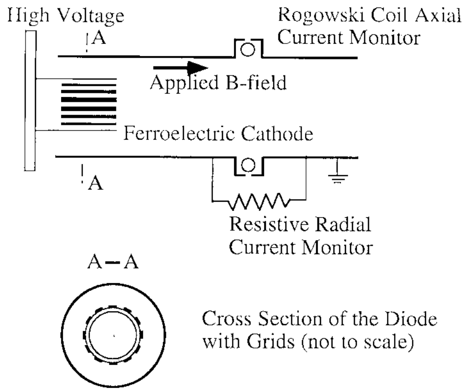

Fig. 1. Schematic showing the experimental arrangement.

In Fig. 1 we show a schematic of the radial diode assembly used. The inner 2.5-cm diameter ferroelectric cylinder is pulsed to a high negative voltage ($\leq$50 kV) by a 300-ns duration artificial Blumlein transmission line, which is switched to the cathode by a triggered spark gap via a 1 : 1, 2 : 1, or 3 : 1 pulse transformer. The output impedance of the Blumlein is 20 Ω. The outer conductor (drift tube), which has a 4.5-cm diameter, is grounded. The ferroelectric emission is triggered by the discharge of a submicrosecond length of charged 50-Ω cable through a transformer to the inner surface of the ferroelectric cylinder. The ferroelectric is 0.1-cm thick and has a silvered inner surface. Its outer surface is etched to give a series of silver stripes aligned along the axis of the ceramic and parallel to the applied magnetic field. The stripes are about 200-μm wide and are spaced from each other by about 200 μm. Unlike the samples used in our previously reported work, the initial silvered layer is quite thick ($\sim$10 μm) and is heavily etched. The masking technique used to set up the grid structure causes a substantial undercut of the remaining silvered strips. The etching is continued until the sample is found to emit on application of a trigger pulse of about 1.5 kV to the solid inner surface of the cylinder. An applied axial magnetic field of up to 2.5 kG is applied to the complete system.

Measurements are made of the trigger and gun voltages and, using resistive monitors and Rogowski coils, of the radial and axial currents generated in the electron gun. The timing delay between the applied gun and trigger voltages is controlled by a delay unit and is typically less than 1 μs. If the delay exceeds 2 μs, no gun current is detected, as shown in Fig. 5 and discussed later. In some experiments, the Blumlein/transformer arrangement was replaced with a charged 50-Ω cable. In this case, the gun voltage, which was then less than 5 kV, was held steadily across the gap until the trigger pulse was applied. Other than the effects associated with the delay mentioned above, the results were very similar to those obtained with the Blumlein arrangement.

A. Experimental Results

We show in Fig. 2 typical data from the radial and axial current monitors for an anode cathode gap voltage of 5 kV for both low $\sim$0.01 T, intermediate $\sim$0.05 T, and high $\sim$0.14 T axial magnetic fields. The terms low, intermediate, and high magnetic fields refer to measures relative to the measured strength of the magnetic field required to cause magnetic insulation of the radial anode cathode gap. Thus, the values are gap voltage dependent. As the magnetic field is increased, the radial current drops to a value close to zero, while, as expected, the axial current increases. Peak axial currents of about 250 A have been monitored at a gap voltage of about 50 kV. The axial beam has been imaged with Gafchromic radiochromic film placed 7.5 cm from the cathode. The downstream image is annular with an inner diameter of $\sim$2.1 cm and an outer diameter of $\sim$3.0 cm. There are some irregularities in the azimuthal symmetry of the cylindrical beam. While the axial current waveform tends to follow the applied voltage, the radial current waveform depends on the strength of the applied magnetic field. At low magnetic field strengths, the radial current waveform follows that of the voltage, whereas at higher magnetic fields, the waveform varies erratically from shot to shot and may bear little relation to that of the voltage pulse. This phenomenon is well known in cylindrical magnetrons, where an instability leads to current flow across the anode/cathode gap at field strengths in excess of that given by the magnetron cutoff condition.

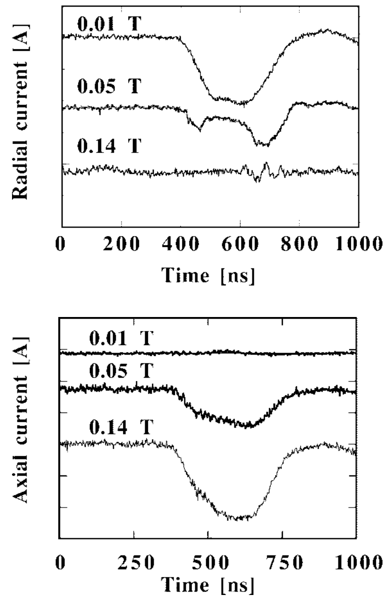

Fig. 2. Waveforms of radial (upper) and axial (lower) currents at an applied voltage of 5 kV. The upper trace is at magnetic field of 0.01 T, the middle trace is at magnetic field of 0.05 T, and the lower trace is at magnetic field of 0.14 T. The measured critical field $\sim$0.05 T. One division equals 50 A.

We have quantitatively examined the variation of both current amplitudes and the radial current waveform with the applied axial magnetic field strength to identify the radial cutoff condition. Note that, for the axial current, the average and peak values are approximately equal, whereas the instantaneous value of the radial current may be much larger than its average value, reflecting instability in the radial flow when the applied magnetic field exceeds a certain value. Whether the radial current flow follows or does not follow the diode voltage pulse serves to define the critical magnetic field B_c

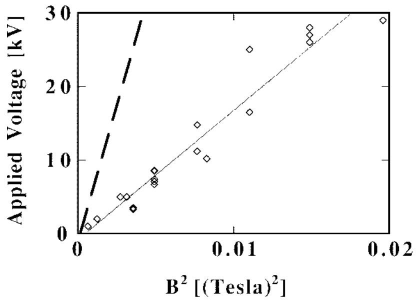

Fig. 3. Diode voltage achievable as a function of the square of the critical magnetic field B_c. The dashed line corresponds to (1).

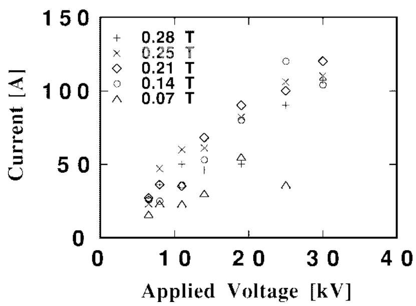

Fig. 4. Current–voltage characteristics of the axial current for various values of the applied magnetic field.

for magnetic insulation. The magnetic field at which the radial current drops is also a good measure of the Hull cutoff found in magnetron flow. In a cylindrical diode, the onset of magnetic insulation is determined by the following criterion:

$$B_c^2 = \left(\frac{8m}{e}\right) \frac{R_a^2}{(R_a^2 - R_c^2)^2} V \tag{1}$$

where B_c is the Hull cutoff field, V is the applied voltage, e and m represent the electron charge and mass, and R_a, R_c the anode and cathode radii, respectively. The magnetic field required to insulate the flow increases quadratically with increasing anode cathode voltage. We show in Fig. 3 a plot of the diode voltage versus the square of the magnetic field strength at which magnetic insulation develops. The line drawn through the data is a best-fit line. To a very good approximation, the fit is as expected proportional to B^2. To the left of the boundary, radial current flows freely, whereas, to the right of the boundary, the magnitude of the radial current flow is primarily determined by instability.

In Fig. 4, we show the axial current–voltage characteristics of the radial diode. For all but the lowest value of the axial magnetic field, the axial current increases monotonically with the anode–cathode potential difference. The 0.07-T field case corresponds to the regime where the diode is magnetically insulated for voltages of less than about 7 kV, but allows radial beam current for higher voltages. The result of this is that the radial current flow increases and the axial current decreases as the insulation condition is violated. Similar data has been obtained for the radial current flow showing the decrease in the current magnitude as the insulation condition is exceeded. Due to the erratic nature of the radial current flow for magnetic fields in excess of that required to insulate the diode, there is more scatter in the data.

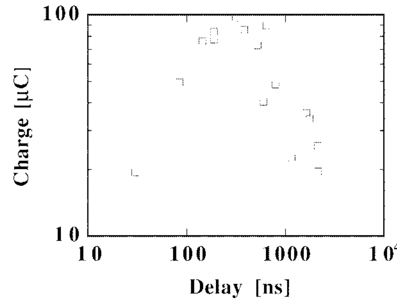

Fig. 5. Charge transferred through the diode as a function of the delay between the main diode voltage and the ferroelectric trigger pulses.

We show in Fig. 5 a plot of the charge transfer between the anode and cathode as a function of the delay between the application of the ferroelectric trigger and the main diode pulse. The data are presented for a 5-kV diode voltage at a magnetic field strength less than that required to magnetically insulate the diode flow. In this condition, the radial current is much greater than that flowing axially. The data are very similar to that reported previously in planar diodes, which shows that the current flow is a strong function of the delay time and that, for times greater than about 2 μs, drops to zero. The data presented earlier was all obtained in the regime with delays close to 300 ns, where the current flow is a maximum.

III. Discussion of Results

Physically, the cutoff in the radial current flow is determined by the magnetic flux linking the anode–cathode gap and not on the details of the magnetic field distribution. In these experiments, the magnetic flux is initially uniform in the radius, but is substantially modified by the electron diamagnetic current flow. The flux between the anode and cathode is, however, independent of the field distribution, since the flux cannot diffuse through the conducting surfaces during the ~300-ns pulse lengths.

We also show in Fig. 3 a line indicating the cutoff condition for the magnetic flux density as calculated from (1), the Hull cutoff condition. The experimentally observed cutoff flux density is much larger than that calculated. For example, at 30 kV, the calculated cutoff occurs at a magnetic field strength of about 0.07 T. The magnetic field strength corresponding to the cutoff condition in the experiment is about twice this value. If we interpret the difference between our observations and the calculations as due to an initial energy of the electrons, then the energy required would be about 100 keV. As a result of the linear experimental and theoretical relations between the cutoff voltage and the square of the magnetic field, the implied initial electron energy of 100 keV is independent of the applied voltage. We have obtained no evidence in our experimental data of high energy emission of electrons from the cathode. The largest electron injection energy found, albeit in planar geometry diodes, from back-biased collectors was 1 keV, about two orders of magnitude lower than that implied from the experimental data.

Alternate explanations for the high measured value of the cutoff field include:

1) the formation of a deep potential well in the diode, due to the effects of the pulsing of the ferroelectric on the electron dynamics;
2) plasma formation at the cathode and subsequent ion flow across the anode–cathode gap.

The first of these mechanisms arises from and is due to the ejection of electrons from the cathode into the anode–cathode gap. The emitted electrons and the deep potential well are present, even in the absence of an applied diode voltage. However, if the diode voltage is applied without pulsing the ferroelectric, no gap current is observed. In this circumstance, both the anode and cathode are at ground potential, so the injection of electrons results in the formation of a potential well. The depth of the well achievable, based on the measured current through the ferroelectric and assuming that 90% of the emitted electrons flow to the adjacent grid and the remaining 10% enter the gap, can easily reach the 100-kV value inferred from the cutoff condition. The well depth is, of course, only indirectly related to the cutoff condition, since the well is quasi-static and does not result in current flow until the assumed equilibrium is perturbed. The value of the magnetic insulation cutoff field would, however, be expected to be larger than that found in thermionic emission, since the presence of the high-energy electrons associated with the well formation implies the presence of large Larmor radius orbit electrons in the diode gap. The characteristic radius would in zero order match that of the highest energy electrons in the gap. The 100-kV potential is comparable to that estimated from the observed enhancement of axial current flow in a planar diode over that determined from the Child–Langmuir law with zero initial electron energy [9], [10]. The energy required to account for the excess current flow is provided on triggering by a redistribution of the electrostatic energy stored in the ferroelectric.

The second mechanism listed above is based on the concept of an ambipolar-like motion of ions from the cathode plasma moving across the anode–cathode gap. The concept is based on the assumption that, during the application of the energizing pulse to the ferroelectric, two processes happen simultaneously; the screening electrons are expelled from the surface of the ferroelectric and ions accelerated across the gap by the combined space-charge and ferroelectric fields. The electric field above the surface of the ferroelectric, due to the voltage pulse applied to the material, results in field emission from the triple point junctions and this, in turn, results in volatalization and ionization of the cathode material, leading ultimately to a surface breakdown and plasma formation. This process has been described in detail by Mesyats [6], [7]. The expelled electrons, which are above the surface of the ferroelectric, cross the gap and have been detected experimentally in planar diode experiments. The peak energy we have found in these experiments is about 1 keV. Ions on the surface of the ferroelectric are accelerated into the gap by the resulting space-charge field. This process continues as long as the well exists and the ferroelectric is in an off-equilibrium state. The accelerated ions partially neutralize the electrons in the well, which is then able to expand into the gap at a rate set by the ion cloud motion. Experimental evidence for the moving well in the anode–cathode gap is mainly based on the presence of a plasma in the diode gap which allows a reverse direction current in the diode at late times in the pulse [5]. In addition, more recent and as yet unpublished data have been obtained of ion motion in a planar diode. A direct measurement of the ion flux crossing the diode shows typical ion velocities of 0.5–2.0 cm/μs for the trigger pulse amplitudes used in these experiments. In other laboratories, the presence of a plasma has been detected experimentally with fast cameras. The expansion velocities both across the gap and along the surface of the ferroelectric were slower than those reported here [11]. On the other hand, the ferroelectric pulsing was also much slower than that used in these experiments. Based on the measured injection electron energies ($<$1 keV), a limited number of protons could achieve velocities of more than 10 cm/μs (higher atomic number ions would have lower velocities). Gap closure, albeit with low plasma density, could then occur in the 1-cm radial gap in times of order 100 ns. The observation of reverse diode current flow at late times ($>$0.6 μs) indicates that the diode eventually fills with plasma. At the highest voltages ($\sim$40 kV) used in these experiments, the sense and magnitude of the applied electric field would tend to result in the ion motion being suppressed close to the anode and negate this process. In addition, as shown in classical discharge theory, the effect of a transverse magnetic field on ambipolar diffusion is to inhibit ion motion with the ion expansion limited by the suppressed radial electron flow. The presence of the transverse magnetic field limits the well penetration into the gap, but does not prevent its development during the switching process.

We note, from events in which the ferroelectric is switched during the main anode–cathode voltage pulse, that axial current flow dominates at high magnetic fields and follows the applied voltage pulse with approximately zero delay following the start of the ferroelectric switching current. The radial current flow is much smaller than the axial flow in these conditions and does not start typically until there has been a sufficiently large change from the remnant polarization of the medium. This is consistent with the time taken to form a deep potential well. Based on these observations, especially at low gap voltages, we conclude that these experiments support the deep potential well as the dominant mechanism at early times and that plasma controlled flow may be important at later times.

Of particular interest in the observations is the fact that we have established a technique for the production of an annular electron beam from a ferroelectric cathode. The annular beam geometry is advantageous for ultrahigh-power microwave generation. The ferroelectric cathode may provide a suitable source for the high-density emission needed for the microwave sources. A similar proposal for the production of annular beams, albeit not with a ferroelectric source, was made several years ago by Lebedev *et al.* [12].

IV. Conclusions

The observations reported in this paper show that intense electron beams can be produced from ferroelectric cathodes at interesting current and voltage levels for high-power microwave generation. The production of 200–300-A beams in both radial and axial emission configurations at current densities of up to 75 A/cm^2 has been achieved. The use of ferroelectrics in coaxial diodes at beam energies of about 500 keV has still to be demonstrated, and the experimental data reported here serves as a step on the route to establishing their utility for high-power applications. At higher gun voltages, near the 500-kV level used in gigawatt high-power microwave sources, it seems likely that the deviation from the Hull cutoff condition will be smaller.

The data obtained in the radial flow configuration experiment sheds additional light on the emission mechanisms from ferroelectrics, including the interesting observation that the magnetron cutoff condition must be modified with ferroelectric emitters. This observation provides additional support for the recognition of the importance of the coupling between the state of the ferroelectric and the dynamics of the electrons in the anode–cathode gap.

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