Electron Beam Generation Using a Ferroelectric Cathode

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Abstract—Data is presented on the production of electron beams from a ferroelectric cathode at voltages of order 0.5 MV and current densities of order 100 A/cm$^2$. In comparison with data at lower voltages, the beam current scales as the three-halves-power of the voltage. An interpretation of the voltage dependent scaling, based on the coupling of electrostatic energy from the ferroelectric to the gun, is presented.

Index Terms—Cathode, electron beam, electron gun, ferroelectric.

I. INTRODUCTION

FERROELECTRIC cathodes have been extensively studied over the last several years [1]–[4] in an attempt to develop a means of emitting a high current electron beam from a robust room temperature cathode for high power microwave generation. Most of the research has focused on the following two types of cathode.

1) PLZT anti-ferroelectric compositions e.g., 4/95/5 in which emission occurs when an applied electric field causes the material to switch from the anti-ferroelectric state to the ferroelectric state. Switching occurs when an electric field of order 15–25 kV/cm is applied across the PLZT [5]. Recent work [6] has suggested that higher fields, of order 52 kV/cm, are required to initiate the electron emission.

2) PZT and PLZT ferroelectric compositions in which the emission is triggered by “switching” around a hysteresis loop. Fields of order 10 kV/cm, typically applied across a 1-mm thick sample, result in the electron emission [7]–[10].

In this paper we present data obtained with a PZT cathode in an electron gun configuration which is used to generate an electron beam at energies in the range 200–550 keV, with a beam current of up to 350 A in pulses having a duration in excess of 200 ns. These results extend emission characteristics previously reported by more than one order of magnitude in voltage and by a factor of three in the current density. A positive polarity trigger pulse is used to initiate emission from the ferroelectric. In this case, the electron emission is from the metallic grid and not from the screening charge on the surface of the ferroelectric. The data also presents the first reported results applicable to electron gun design. The planned application of the source is to high power microwave generation using a TWT amplifier in X and Ka bands. In the following sections we describe the experimental arrangement used for this work, the results obtained, and their interpretation.

II. EXPERIMENTAL CONFIGURATION

The electron gun used in this work employs a pulse transformer system capable of generating a 500-kV, 200-A, 250-ns electron beam and uses a ferroelectric cathode as the electron source. It is designed for use in high power microwave experiments. The system operates at a repetition rate of about 0.1 Hz which is limited by the available power supplies. Vacuum levels are presently in the vicinity of $5 \times 10^{-6}$ torr.

We present a brief description of the modulator and beam generator used in this work. The modulator, which has been recently developed for this application, has been described previously in the Particle Accelerator Conference Proceedings [11], so the description given here will only summarize the system.

The primary power source consists of 12 transmission lines, each having an impedance of about 10 $\Omega$. Half of the lines are positively charged and half negatively to a voltage in the range 20–35 kV. The lines are switched at the load location as indicated in Fig. 1.

Each line uses nine 3.6-nF capacitors in a transmission line arrangement. On closing the switch, a voltage is developed across the load with a rise time which is independent of

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the impedance transfer function of the line. The system is equivalent to three 10-$\Omega$ Blumlein’s in parallel, so that the primary impedance is about 3.3 $\Omega$. The switch employs a rail configuration which is triggered by an 80–100 kV pulse applied to the center electrode. The transformer primary has ten parallel two-turn windings uniformly distributed around the circumference of each of two sets of TDK PE14 ferrite cores. The two sets of primary windings are in parallel with each other and have a total volt-second product of 13.8 mVs. The ferrite cores are reset between pulses by a slow discharge of a capacitor through a single turn coil around the cores. The secondary of the transformer has 12 turns which encircle both cores, hence the overall system acts as a nominal 12 : 1 step-up transformer with an output impedance of about 500 $\Omega$. The final design represents a compromise between a high voltage gain and a short rise time system. Leakage inductance limits the useful gain of each section of the transformer and the use of the two parallel primaries yields a significant advantage over the use of a single-stage 12 : 1 step up transformer. The output of the transformer is connected to a diode/electron gun configuration as shown in Fig. 2. This figure also indicates the amplitude of an applied external magnetic field used to confine the electron flow.

The ferroelectric emitter is located in the cathode surface and has a diameter of 1.9 cm. The emitter is a 1-mm thick PZT sample, commercially available from Transducer products and identified as LTZ2. It is pre-poled and mounted with the Polarization vector pointing into the vacuum region. The configuration reported in this work was chosen to provide the data needed on the emission characteristics of the ferroelectric at the high anode–cathode voltages required for subsequent electron gun design. In the configuration employed in this work, the axial field strength was about 3.2 kG in the center of the 15-cm long field coil system. The windings were energized by an electrostatic capacitor bank of about 2.5 mF at 150 V. The system generated the axial magnetic field in the drift tube section which, when operated at rated voltage, is capable of producing a solenoidal field in our 5-cm bore drift section of up to about 9 kG. The present measurements were limited to injection of the beam into the 3.2-kG field where the beam was collected in the 5-cm diameter drift tube. The magnetic field penetration time into the drift section was less than the experimentally measured rise time of about 1 ns. The magnetic field at the cathode field surface is about 250 Gauss, so we have significant beam compression. Since the beam dynamics are governed by the conservation of canonical angular momentum, and in the present experiments no effort was made to match the beam to the cathode emission, the beam envelope scallops during propagation through the drift section.

The ferroelectric emitter has a surface polarization charge density of about 6 $\mu$C/cm$^2$. Surface electric fields, derived from Gauss’ Law, are in excess of 1 GV/m and result in surface charge neutralization by free electrons. A thin (<1 $\mu$m) grounded grid consisting of a number of 200-$\mu$m width silver strips spaced from each other by 200 $\mu$m is deposited on the front surface of the ferroelectric. Normally, emission is produced by the application of a negative voltage pulse to the metalized rear surface of the ferroelectric. In these experiments, however, a positive trigger pulse is applied to the rear surface of the ferroelectric. This results in electron emission from the metallic grids which drives Fowler–Nordheim field emission in the vicinity of the metallic grid, ferroelectric, vacuum triple lines. The duration of the field emission is determined by the applied pulse duration (∼100 ns) and by the hysteresis properties of the ferroelectric so that the total emission may exceed 1 $\mu$s [7]. The use of a positive polarity pulse was found to yield a consistent electron current. The 100-ns trigger pulse used to initiate the electron emission is derived from a charged cable configuration switched by a krytron into a 50-Ω cable which is wound around the ferrite transformer core close to the secondary winding. The inductively decoupled pulse is fed via a 2 : 1 step down transformer to the back of the ferroelectric. The electric field applied across the ferroelectric is about 10 kV/cm.

### III. Experimental Observations

The pulser is typically run at 0.1 Hz for about 100 shots prior to taking data. Subsequently, each data series is preceded by a sequence of about 20 or more shots. During the initial break-in of the cathode there is spiking in the emission with ∼10–20 ns current bursts, probably associated with outgassing of the ferroelectric. Benedek et al. [5] have suggested that the current bursts are due to variations in the polarization current. Following use, the incidence of spiking seems to decrease and the emission pulses are similar to the data presented in Fig. 3. From top waveform to bottom waveform, the data in Fig. 3(a) and Fig. 3(b) show the voltage across the secondary; the ferroelectric trigger pulse; the beam current, which is measured by a Rogowski coil after collection by a graphite...
collector located well into the magnetic field coil region; and finally the current through the transformer primary. In both sets of data the cathode-collector separation was typically 11 cm.

The two sets of data shown in the figure yielded output voltages of 300 and 500 kV and beam currents of 80 and 200 A, respectively, for a cathode-to-drift tube spacing of 6.6 cm. The diode was shunted by a 2000-Ω resistive divider that served as the gun voltage monitor and also minimized possible open circuit transients. At a given gun voltage, the beam current was limited by the cathode area and the gap spacing and was not affected by the value of the shunt resistive voltage monitor. The traces are approximately time correlated with the exception that the trigger pulse shown in the figures should be delayed by 110 ns to show the correct timing relative to the other traces. Consistent beam emission as shown in the figures was obtained with the ferroelectric trigger pulse occurring at the start of the voltage maximum on the secondary. The beam emission varied considerably with the timing and amplitude of the ferroelectric trigger pulse with respect to the output voltage. While the output voltage rises in about 200 ns, the current rise time is less than or equal to 20 ns and is instrument-limited in the data shown. With earlier initiation of the beam current, the rise time of the current is degraded and is comparable to or longer than that of the secondary voltage pulse. With both 4.5- and 6.5-cm cathode-drift tube spacing, the electron emission from the ferroelectric did not occur until after the ferroelectric trigger pulse was applied. Computer modeling shows the vacuum electric field at the surface of the cathode reaches 100 kV/cm with an applied secondary gun voltage of 500 kV and with a 4.5-cm cathode-drift tube spacing.

The primary beam current and the secondary voltage waveforms show clearly the effects of the core saturation, namely an increase in the primary current and a decrease in the secondary pulse duration. The beam design output parameters required for the microwave experiments are 500 kV, 200 A with a pulse duration of 250 ns.

In Fig. 4(a) and (b) we show plots of the gun current versus the three-halves power of the gun voltage for gap spacing of 6.5 and 4.5 cm, respectively. The dashed line on each curve represents the results found for space charge limited emission, as measured using the EGUN code, with the actual geometry and magnetic field arrangement. The experimental data are based on representative results obtained over several thousand events with most of the data obtained with a 6.5-cm anode–cathode spacing. The shorter gap data was used to illustrate the dependence of the emission on the gun geometry and to illustrate that the ferroelectric disks do not emit until triggered at surface fields of 100 kV/cm. We have as yet not operated the gun with shorter gaps or with higher cathode electric fields. The exposed cathode area of the ferroelectric disk was 2.8 cm², i.e., the outer 3 mm of the 25-mm diameter disk was lost in the mounting of the cathode. This data indicates that emission current densities of up to 125 A/cm² were obtained while still yielding reasonably shaped beam current pulses. It should be noted that a linear V-I scaling was obtained in previous diode experiments at V < 50 kV.

IV. DISCUSSION OF RESULTS

The emission data reported in this article considerably expands the range of the emission characteristics previously reported for PZT and provides the data needed for an electron gun design. The emission scaled with the three-halves power of the gun voltage and was found to be within a factor of about two of that expected in space charge limited flow as predicted by the EGUN code. This result should be compared with the linear voltage scaling reported at low (<50 kV) voltages. The large spacing between the cathode and the collector surfaces make it very unlikely that plasma closure, especially that due to plasma formed by collector bombardment, plays any significant role in determining the diode dynamics. The possibility of explosive field emission, and hence plasma formation, on the cathode surface, is however not precluded. In fact, ion Faraday cup data obtained at lower voltages in a similar geometry confirm the presence of ions in the diode but shows that their velocity is always of order of or less than 2–3 cm/µs. These results have been presented in detail in [7]. The importance of surface plasma formation on the emission...
characteristics has been pointed out previously by Shur et al. [12]. In their work, they reported plasma expansion across a diode gap and also across the cathode surface. Krasik has also recently obtained similar data that shows plasma formation at the triple points [13] followed by gap closure with a plasma velocity of 1–2 cm/μs [14]. In our experiments, the emission starts with the application of the trigger pulse to the rear surface of the ferroelectric and terminates with the end of the main gun acceleration pulse. It is consistent with field emission from the metallic grid at the vacuum/grid/dielectric boundary. The effect of any plasma formation on the cathode surface will undoubtedly modify, and probably reduce, the field emission. Note, however, that field emission does not necessarily lead to explosive emission and plasma formation as described by Mesyats [15].

Schächter [16] has calculated the emission from a metallic wedge on the front surface of a high dielectric constant material when a negative voltage is applied to the wedge. He showed that the triple point electric field is increased by a factor of $\varepsilon_r$, the dielectric constant of the substrate, over that calculated in the absence of the dielectric. As a result of this enhancement, the Fowler–Nordheim emission is increased by a factor which may be several orders of magnitude greater than that found from the same wedge in the absence of the dielectric. The result depends solely on Fowler–Nordheim emission and does not require explosive emission, although this process might be expected to develop at high enough current densities emitted for a sufficiently long time to locally volatilize the metal. It is of interest to note that our processing of the ferroelectric cathode involves sputtering a 1–2-μm layer on the ceramic and then preferentially etching the surface to form the grid using standard photo-resist techniques. To initiate the emission it is usually necessary to further etch the metallic grid. This process will produce a tapered edge rather than the standard undercut associated with etching in the presence of the photo-resist. The resulting grid surface is therefore similar to that employed in the modeling outlined above and will enhance the field emission process.

More recent work [17] has examined the emission from an array of ferroelectric/metallic strips in a geometry similar to that used in the experiment described above. This work shows that the coupling of energy stored in the ferroelectric material into the diode gap can, on application of the trigger pulse, account for the excess energy needed to drive currents in excess of the space charge vacuum limit. The energy coupled to the gap exceeds that stored in the gap (due to the anode potential) at low (<50 kV) gun voltages by a factor of up to several thousand. At high gun voltages (~500 kV) the factor drops to a value of less than unity, and the emission is expected to revert to that predicted by conventional space charge limited flow. The ratio of the coupled energy from the ferroelectric to that stored in the gun is plotted in Fig. 5 for a range of gun voltages and spacing. The excess energy coupled into the gap may be expected to decrease rapidly as one moves from the gridded region into the anode–cathode gap, decaying on a scale length of the periodicity (~400 μm) of the grid.

It is worth noting that the one-dimensional result for space charge limited current flow (The Child–Langmuir current) underestimates the actual current flow for a real emitter, even when the emission is thermionic. This effect was shown by Luginsland et al. [18] and may be readily interpreted for the case where the emission area is surrounded by a nonemitting conducting surface. The electric field normal to the cathode surface is reduced in the emission region by the presence of the space charge and asymptotes to the vacuum field at the metallic surface in the surrounding region. The normal electric field varies smoothly between these two limits. The reduction of the surface field in the nonemitting region implies that more space charge can be allowed close to the cathode without reversal of the field direction, i.e., the onset of space charge limited flow. We show in Fig. 6 a plot of the magnitude of the ratio of the space charge limited current flow from a circular emission region of radius $r_e$ divided by the product of the calculated one-dimensional Child–Langmuir current density and the area of the emitter. This ratio, denoted in the figure as $A_e$, is plotted as a function of the ratio of the planar gap width $d$ to the radius of the emission region of the cathode. In realistic geometries, the effect can easily increase the magnitude of the space charge limited current flow over the one-dimensional Child–Langmuir value by a factor of ten. In these experiments, the average
cathode current density is increased by a factor of about three. As in the Luginsland paper, this data was obtained using a PIC code to solve for the emission current in an axi-symmetric two-dimensional \((r, z)\) diode.

As expected, the operation of the gun in a repetitive mode has been found to offer new opportunities for conditioning. After a few hundred shots at the 0.1-Hz repetition rate, there was very little evidence of current spiking. A similar reduction in spiking of the emission current was previously seen in 50-Hz data reported earlier [19] at lower voltage and current levels.

Finally, we note the analytic solution described above does not include any nonlinear effects such as the hysteresis of the ferroelectric material. In spite of the fact we pulse the rear surface of the ferroelectric positively, that is from remnant polarization to saturation in the same sense of the polarization vector, there is still a significant hysteresis as was shown experimentally several years ago. The material does not return instantly to its original state, but the dynamics depend on the material and are consistent with a characteristic relaxation time of the order of 1 ms after the removal of the trigger pulse. Since the applied pulse is over well before this time, the emission is likely to continue for the duration of the gun voltage.

V. Conclusions

We have, in this paper, described the electron emission process from a ferroelectric cathode in an electron gun device. Emission is at the level of a few hundred amperes at 500 keV and at a current density of about 100 A/cm\(^2\). The emission was produced in a 250-ns pulse produced in a repetitive mode at a frequency of 0.1 Hz. The resulting beam will be used in high power TWT amplifier experiments.

The emission is triggered by the application of a 1-kV positive polarity pulse applied to the rear surface of the 1-mm thick PZT sample. In comparison with data obtained at lower voltages (\(<50\) kV), where the current scaled linearly with the anode cathode potential difference, the emission current scaled with the three-halves power of the applied voltage. These processes are consistent with Fowler–Nordheim emission from the triple points. In a recent paper, Schächter [16] has shown that the electric field in the vicinity of the triple point is enhanced by the dielectric constant of the substrate. The switching of the ferroelectric state by an applied pulse couples energy into the vacuum gap close to the cathode [17], and this may account for the previously observed high current flows in low voltage diodes. At the higher voltages used in these experiments, the energy coupled is less than that in the anode cathode gap due to the accelerating voltage. The triggering pulse then mainly serves to initiate the electron emission, and the current flow is close to that predicted for space charge limited current flow in the gun.

The rise time of the beam current was observed to be much less than that of the gun voltage and to be less than 20 ns. It is thought that the emission at the triple points is due to field emission and that local high current densities close to the triple points may lead, in some cases, to plasma formation. Electron atom collisions with desorbed gases may also cause plasma formation. The latter process will decrease with operation as was observed in the experiments. In related work, we and others have observed plasma formation on the cathode surface by monitoring visible light emission. The formation of plasma on the surface of the ferroelectric, when triggered with a positive polarity pulse, has been discussed by Benedek et al. [20]. Measurements of the ion current flow in a similar geometry, albeit at 50 kV and 10 A/cm\(^2\), have indicated plasma closure velocities of less than a few centimeters per microsecond. In the current experiments, this velocity is too low to have any significant effect on the beam current. The voltage scaling data reported here, combined with that at lower voltages, provides good evidence for the role of the ferroelectric in the emission process. In particular, the coupling of energy originally stored in the ferroelectric into the diode gap may provide the energy required for the high current densities observed in the low voltage experiments.
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