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DARK CURRENT MEASUREMENTS AT FIELD
GRADIENTS ABOVE 1 GV/m*

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Dark Current Measurements At Field Gradients Above 1 GV/m

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Abstract. In this paper, we report the results of dark current studies on copper cathodes and stainless steel anodes held at a field gradient > 1 GV/m. The field emission current is < 1 A for fields less than 1 GV/m. As the field is increased, the dark current increases rapidly to 150 A for applied fields of ~ 1.7 GV/m. Fowler-Nordheim plots in this range of applied fields indicate a field enhancement factor of 10-20 for a copper cathode with a work function of 4.6 eV.

INTRODUCTION

In the past decade, there has been extensive research [1] in the development of low emittance, high brightness electron injectors for linear collider and free electron laser applications. RF injectors with a few nC charge in a few ps, with an emittance of $\sim 1-5 \pi$ mm mrad are operational in a number of facilities [2-4]. In these devices, a laser beam irradiates a photocathode embedded in an RF cavity. The photoelectrons released by the laser are immediately accelerated to relativistic velocities, thereby reducing the space charge effects. The frequency of the RF and the design of the cavity are chosen to minimize the RF and space charge effects on the electron bunch so that low emittance, high brightness electron beam could be generated. Minimization of RF effects on emittance growth require a low RF frequency while minimizing the space charge effects require high field and hence high RF frequency. The design is hence a compromise between these two conflicting requirements. Some of these limitations could be overcome by using a large pulsed electric field at the cathode rather than a RF field. The duration of the pulsed field should be chosen so that it is longer than the electron bunch length and the transit time in the accelerating region, but short enough to avoid breakdown problems.

Major issues in such a scheme is the capability of the cathode material to hold off the high field gradients without suffering electrical breakdown and the

degradation of the electron beam due to the presence of dark current. In this paper we present the preliminary results of the behavior of copper cathodes subjected to fields in excess of 1 GV/m and the characteristics of the dark current emitted from this cathode.

EXPERIMENTAL ARRANGEMENT

A 1 MV pulse with rise and fall times of ~ 150 ps and duration of ~ 1 ns was used to bias the electrodes and measure the dark current. The high voltage pulse generator that provides this pulse is described in detail in Ref[5]. In this pulser, the voltage from a low voltage pulse generator is multiplied using a resonant transformer. The high voltage pulse is then sharpened by a pair of spark gaps and transported along a transmission line and terminated at the cathode with a matched load. The voltage can be varied by changing the gas pressure in one of the sharpening gaps. The voltage at different locations along the transmission line is measured using resistive and capacitive probes. The voltage measurements used in this paper are derived from the capacitive probe 15 cm upstream of the cathode. The field across the electrodes in the diode can be varied either by varying the applied voltage or the interelectrode gap.

The diode where the field effects are measured consists of a 6 mm diameter copper cathode biased to -1 MV. A flat stainless steel anode of 1.5 mm thickness is held at ground potential in front of the cathode. A small hole in the anode allows transport of the electron beam beyond the diode region. The size of the hole can be varied depending on the measurement requirement. For measuring the magnitude of the dark current, an anode with a central hole of 3 mm aperture was used. The interelectrode spacing can be varied from 5 mm to 0.5 mm and has been maintained at either 1 or 0.5 mm for these measurements. An ion pump attached to a stainless steel cube enclosing the electrodes maintains a vacuum level of $<10^{-7}$ Torr in the vicinity of the electrodes and surrounding diagnostic equipment. Both electrodes are removable and hence the performance of the diode for different electrode material and geometry can be investigated without changing the characteristics of the applied voltage significantly. Alternately, for a given electrode material and geometry, the performance of the diode can be studied for various shapes and amplitudes of the voltage pulse. This can be achieved by changing either the SF_6 gas pressure in the sharpening switch, the amplitude of the low voltage or the length of the pulse forming line, without breaking the vacuum. The pulser and the diode with its diagnostics are housed inside a RF shield to filter the EMI associated with such a system

Figure 1. Diode with the Faraday cup inside the vacuum cell

The diagnostics for the electron beam consist of an electrically isolated Faraday cup to measure the charge, a pepper pot, phosphor screen and relay optics system to measure the spot size of the electron beam and hence calculate the emittance. The schematic of the Faraday cup along with the diode is shown in Figure 1. It is an electrically isolated copper rod of 1 cm diameter with a tubular sleeve of 1.1 cm diameter around it so that the distance between the Faraday cup and the anode can be altered. In these measurements, this distance is 3 mm so that all the primary electrons from the cathode, exiting the anode can be collected by the Faraday cup. The dimensions of the Faraday cup are such that with the grounded metallic vacuum housing surrounding it will simulate a transmission line of 90 Ω impedance. This rod is connected directly to a 7 GHz oscilloscope (Tektronix SCD 5000) for current measurements with a time resolution of 100 ps.

MEASUREMENTS

The copper cathode was polished with diamond polishing compounds with grain sizes of 9,6 and 1 μm . The polished surface was rinsed with deionized water and ultrasonically cleaned in a hexane bath. The copper was then inserted in the vacuum system. When the background pressure was $\sim 10^{-7}$ Torr, the voltage on the cathode was gradually increased and the cathode was slowly conditioned. The

applied voltage from the capacitive probe and the current signal from the Faraday cup were continually monitored during this conditioning process. Care was taken not to have more than one breakdown for a given voltage during this process to minimize the damage on the copper surface and deposition of copper onto the anode. When reproducible current traces were obtained from the cathode at maximum applied voltage, the cathode was assumed to be conditioned. The behavior of the cathode under high field gradients was studied by observing simultaneously the dark current and the applied field.

As mentioned before, the field gradient between the electrodes could be changed by changing either the applied voltage or the interelectrode gap. With the interelectrode gap of 1 mm, and a background pressure of $<10^{-7}$ Torr, dark current was below noise level of 1 A even at an applied voltage of 750 kV. The field between the electrodes was then doubled by reducing the interelectrode gap to 0.5 mm and the dark current was measured for various applied voltages. The applied voltage and the dark current at this voltage for 16 consecutive shots are shown in Fig. 2 a and b. The variation in the voltage curve is a measure of the shot to shot fluctuation of the applied voltage. In order to normalize this fluctuation, individual traces of voltage and corresponding current were then recorded using two oscilloscopes simultaneously.

Figure 2 a. The applied field on the cathode, based on the voltage measured at the last probe.

Figure 2 b. Corresponding current measured by the Faraday cup

Figure 3. Fowler-Nordheim plot for the dark current

At fields of ~ 1.2 GV/m, the dark current was just above the noise level of 1 A. As the field was increased, the dark current increased rapidly to ~ 150 A for a field of ~ 1.7 GV/m. The Fowler-Nordheim plot for this data, in the field range of 1.2 GV/m to 1.7 GV/m is shown in Fig.3. The field induced current can be expressed as

$$J = K E^2 \exp(-2.89 \times 10^9 \phi^{3/2}/E) \quad (1)$$

The slope of $\ln(j/E^2)$ vs $1/E$, the Fowler-Nordheim plot, can then be written as

$$S = (-2.89 \times 10^9 \phi^{1.5})/\beta \quad (2)$$

If the work function ϕ of copper is assumed to be 4.6 eV, the field enhancement factor β can then be calculated to be ~ 20 .

In conclusion, copper cathode has been tested under field gradients of 1.7 GV/m, using 1 MV pulses lasting for ~ 1 ns. No electrical breakdown was observed after conditioning. Up to field gradients of ~ 1.2 GV/m, the dark current is below 1 A. At 1.7 GV/m, dark currents of ~ 150 A has been measured. The Fowler-Nordheim plot of current and field yields a field enhancement factor of ~ 20 for a work function of 4.6 eV. This implies that properly prepared copper surfaces with minimum field enhancement could withstand applied fields > 30 GV/m.

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