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RELATIVISTIC ELECTRON BEAMS FROM CATHODES
AT 1 GV/m GRADIENT*

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Relativistic Electron Beams from Cathodes at 1 GV/m Gradient

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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.

An added advantage of these high fields on metal surface is the lowering of the work function due to Schottky effect. For a field of 1 GV/m, and a field enhancement factor of 3, the change in the work function can be calculated to be ~ 2 eV[5]. This opens up the possibility of using either the infrared or visible radiation to overcome the work function and to extract the electrons from low work-function metals such as yttrium or magnesium. The complexity and cost of the laser system associated with the photocathode is then significantly reduced.

Development of a high brightness electron source using this scheme requires a pulse generator, a laser pulse of sufficient energy to trigger and synchronize the electrical pulses, and a short laser pulse to irradiate the photocathode and generate electron pulses to be accelerated. In the following sections, the designs of these components are described. Critical issues to be addressed are the capability of metals to withstand the high fields without causing electrical breakdown, relative contributions of field emission current and the photocurrent, change in the work-function of the metal as well as its quantum efficiency to photoemission and synchronization of the high voltage pulse and the laser pulse driving the photocathode. The first two critical issues, and synchronization between the trigger laser and the electrical pulse have been investigated and results are presented in this paper. Detailed simulations of electron emission and transport in this diode using MAFIA and PBGUN are presented in a companion paper in this conference.

EXPERIMENTAL APPARATUS:

The breakdown studies conducted by Juttner et. al. [6] and Mesyats et. al. [7] indicate that metals could withstand field gradients of a few GV/m if the duration of the field is $\sim$ few ns. According to these studies, for HV pulses with pulse duration less than 10 ns, both cathode initiated and anode initiated breakdowns become less probable. In addition, the breakdown voltage becomes relatively insensitive to the cathode and anode materials. Formation of microscopic craters due to explosive emission become less frequent and the erosion of the electrodes decreases significantly. Hence uniform field gradients of $\sim$ 1 GV/m on macroscopic surfaces would necessitate a HV pulse with voltage amplitude $\sim$ 1 MV, pulse duration of a few ns with subns rise and fall times.

A photograph of the pulse generator that would meet these criteria are shown in Figures 1a and 1b. Detailed description of the pulser can be found in Reference 8. This pulse generator is capable of delivering 1 MV with a duration of $\sim$ 1 ns and rise and fall time of $\sim$ 150 ps to a 80 Ohm load. The HV pulse is synchronized to an external clock by triggering one of the sharpening switches (a gas switch with SF₆ or its mixture with argon) with a laser.

Fig.1b. Photograph of the HV pulse generator, electron gun, and cube containing the diagnostics. A 70 cm ruler is shown nearby for dimensions of the device

The SF₆ gap consists of a hemispherical electrode connected to the HV transformer and a flat electrode connected to the transmission line with an electrically isolated stainless steel wire in the middle of the gap to aid in laser triggering. Two CaF₂ windows centered on the wire permit the laser to irradiate the wire normal to the gap. The laser beam was focused between the stainless steel wire and the high voltage electrode of the SF₆ gap such that the beam nearly fills the gap between the two. In the current scheme, the laser beam triggering the gas switch is derived from a KrF laser. Jitter measurements with this laser arrangement are discussed in the following section

The electron gun generating the high brightness electron beam consists of a photocathode and a grounded anode held parallel to the cathode with the high voltage pulse applied to the cathode. A stainless steel cube enclosing the electrodes maintains a vacuum level of $\sim 10^{-8}$ Torr in the vicinity of the electrodes and surrounding diagnostic equipment. Both the 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, by changing the SF₆ gas pressure, the amplitude of the low voltage and the length of the pulse forming line, without breaking the vacuum.

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 pulser and the diode with its diagnostics are housed in an enclosure designed to filter the electromagnetic noise associated with such a system. A joule meter to measure the energy of the laser beam irradiating the

cathode and an imaging system to measure the spot size of the laser on the cathode provide the laser beam diagnostics.

MEASUREMENTS AND DISCUSSION:

JITTER MEASUREMENTS:

The amplitude of the HV pulse, 15 cm upstream of the cathode, can be measured using a capacitive probe built in the transmission line. This probe also has sufficient bandwidth to measure the rise and fall times of the pulse. The signal from this probe is fed directly to a digitizing oscilloscope with 7 GHz bandwidth. The probe has been precalibrated such that 1 V signal in the scope corresponds to 575 kV at the transmission line. A typical voltage trace from the oscilloscope is shown in Figure 2. Deconvoluting the response time of the scope and the attached delay line yields a rise and fall time of ~150 ps. The maximum voltage obtained is ~900 kV.

In order to measure the synchronization of the high voltage pulser, the SF₆ switch was irradiated with the KrF laser. A laser beam of 75 mJ energy, 2x0.2 mm² spot size and ~20 ns pulse duration irradiated the gap between the high voltage electrode and the stainless steel wire in the gap. The synchronization of the HV pulse depends critically on the location and the arrival time of the laser beam at the gap, the gas mixture and gas pressure. Each of these parameters was varied keeping the other parameters constant. The optimum set of parameters, defined as the ones resulting in maximum voltage with minimum delay and jitter, was established. The maximum voltage amplitude measured at the last probe was 0.92 MV with

Fig. 2. Shape of the high voltage pulse. The maximum amplitude is 0.9 MV and deconvoluted rise and fall times are ~150 ps.

pure SF₆ at 6 atmospheres. As seen in Figure 3, the corresponding delay between the arrival of the laser at the gap and the breakdown of the gap was ~30 ns, with a jitter of 0.7 ns. A 5:2 mix of argon:SF₆ at this pressure reduces the voltage by 10% and jitter to 0.5 ns and the delay to 5 ns. Since these jitter values include the fluctuations in the laser energy and hence the trigger time of the oscilloscope, the real jitter between the laser and the HV pulse is expected to be much smaller than the measured 0.5 ns. Jitter values of ~150 ps have been reported [9] with similar arrangements.

Fig. 3. Delay (o) and jitter (+) of the HV pulse with reference to the laser pulse for 90 psi of SF₆

DARK CURRENT MEASUREMENTS:

The dark current measurements were done with the pulser in the self-trigger mode, without the laser irradiating the SF₆ gap. This enabled us to apply the maximum field on the diode. Two different cathode materials, stainless steel and copper, were tested for their voltage hold off properties and dark current emission. Fields exceeding 1 GV/m could be applied to both the cathodes. As can be expected, the dark current depended critically on the background pressure between the electrodes. The dark current from stainless steel after conditioning, in a field gradient of 0.7 GV/m, was below the detection limit of our system even at background pressures of $\sim 10^{-3}$ Torr. Copper on the other hand yielded a dark current of 200 A under similar conditions. When the background pressure was reduced to 10^{-7} Torr, the dark current fell below the detection limit of our system, 0.5 mA. The interelectrode gap was then decreased to 0.5 mm so that field gradients exceeding 1 GV/m can be explored. A typical current trace with copper cathode and stainless steel anode at 1.7 GV/m gradient is shown in Figure 4. The fast rise time of the first peak indicates that this peak is caused by the fast rising voltage pulse. The subsequent pulses, however, have a slower rise time. In addition, the locations of these peaks do not match exactly with the modulation in the voltage waveform, although the number of peaks matches the number of modulations observed in the voltage waveform. The origin of the current peaks appearing after a delay of 5 ns is still under investigation. The possible sources could be secondary emission from either the cathode or the anode, and transport of the primary electrons modulated by the voltage waveform.

Fig. 4. Dark current trace for an applied field of 1.7 GV/m. 16 traces are overlapped on each other.

A Fowler-Nordheim plot for the current in the first peak alone was created. If the work function of copper is assumed to be 4.6 eV [10], the field enhancement calculated from these data is ~ 25 , implying that surface fields exceeding 40 GV/m can be sustained by copper cathodes without causing high voltage breakdown. This is in agreement with the pulsed high voltage breakdown measurements reported by Messyats [8]. Experiments are now in progress to characterize the field emission current further.

CONCLUSION:

In conclusion, a high voltage pulser capable of delivering up to 1 MV with a duration of ~ 1 ns and rise and fall times of ~ 0.15 ns has been constructed and tested. Copper and stainless steel cathodes have been tested to withstand 1 GV/m gradient. Under background pressures of 10^{-7} Torr, the dark current is below the detection limit of our system at 1 GV/m gradient and hence would not contribute significantly to the photocurrent. Copper cathode and stainless steel anode have been shown to withstand applied fields of 1.7 GV/m without experiencing high voltage breakdown. Dark current measurements and Fowler-Nordheim plot for fields exceeding 1 GV/m indicate that surface fields experienced by these electrodes could

be as high as 40 GV/m. Further characterization of this field emitted current is currently in progress.

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