Abstract

This paper describes computer simulations and measurements on an electron bunch from a pulsed, high gradient gap. MAFIA and PBGUNS were used to calculate the emittance, brightness and energy spread of the electron beam for peak currents ranging from 10 A to 1 kA and pulse durations ranging from 0.3 ps to 10 ps. Under optimum conditions, normalized emittance of 10^{-7} \pi \text{mm-mrad}, beam brightness of 3 \times 10^{15} \text{A/(m-rad)}^2 and energy spread of 0.15 % were obtained. A pulsed high voltage with 1 MV amplitude, and ~ 1 ns duration was applied to the diode with an interelectrode gap ranging from 2 mm to 0.5 mm. Copper cathodes with three different surface preparations, diamond polished, diamond cut and chemically cleaned, have been tested for their voltage hold-off properties under this high gradient and the Fowler-Nordheim plots were generated. The diamond polished OFC class II copper was shown to consistently produce lower dark current and higher hold-off voltage. Photoemission studies have been made using light from a KrF excimer. The field enhancement factor for photoemission was calculated to be 5, an order of magnitude smaller than the dark current beta for a similar surface.

1 SIMULATIONS

Two simulation codes, MAFIA and PBGUNS were utilized. Agreement between these codes has been demonstrated [1]. PBGUNS was then used to perform the bulk of the optimization, with only those issues that required time dependence being resolved with MAFIA.

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Charge (nC)</th>
<th>Bunch length (ps)</th>
<th>Emittance ( \pi \text{mm-mrad})</th>
<th>Brightness ( \text{A/(m-rad)}^2)</th>
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</thead>
<tbody>
<tr>
<td>100</td>
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<td>10</td>
<td>0.167</td>
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<tr>
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<tr>
<td>10</td>
<td>0.01</td>
<td>1</td>
<td>0.045</td>
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</tr>
</tbody>
</table>

Table 1. 1-\sigma normalized slice emittance and brightness as a function of pulse duration and charge.

PBGUNS is a DC code and therefore does not provide information on longitudinal variation. Hence, slice emittance values were used in the optimizations to allow for a direct relationship with PBGUNS. The MAFIA results for the particle’s r and p, are used to calculate the 1-\sigma normalized slice emittance (using the center 1% of the beam for the emittance calculation), using the expression:

\[ \varepsilon = 2 \sqrt{\left( \langle r^2 \rangle \langle p^2 \rangle \right) - \langle r \cdot p \rangle^2} \]  

For the 100A, 10 ps case, the full beam 1-\sigma normalized emittance was found to be .385 \pi \text{mm-mrad}. The slice emittance for the center 1% of the beam under the same conditions was .167 \pi \text{mm-mrad}. It is important to note that the above results assume no random energy distribution at the source (such as might result from thermal effects or photon energy in excess of the work function). A random initial energy of 1eV places a lower bound of .17 \pi \text{mm-mrad} on the emittance, and leads to brightness of 3 \times 10^{15} \text{A/(m-rad)}^2. Beyond 500A the transverse beam spreading due to space charge leads to clipping at the anode aperture.

PBGUNS has been used to investigate the effect of curving the cathode emission region to compensate for the divergence induced by the anode hole. Cathodes with radii of curvature of 1, 1.5 & 2 mm were used for a 100 A beam. It was found that by altering the cathode curvature, a collimated beam could be obtained or a focus could be provided at a desired location beyond the anode.
Simulations have also been done to study the longitudinal energy spread of the beam. Figure 2 shows a MAFIA plot of longitudinal position vs longitudinal momentum for a charge of 1nC and a pulse duration of 10 ps. The RMS energy spread is .15%.

![Longitudinal Momentum Spread](image)

**Fig 2.** Charge induced longitudinal momentum spread. $P_z$ is in $\beta \gamma$.

MAFIA was also used to investigate the longitudinal variation of the transverse emittance. Figure 3 shows the $r$ vs $r'$ curves for three 1% slices taken from the front, middle and back of a 10ps bunch, all at 3.25 mm from the cathode.

![Transverse Phase Space](image)

**Fig 3.** Longitudinal variation of the transverse phase space.

2 EXPERIMENTAL RESULTS

2.1 Dark Current

One advantage of a pulsed power gun is the ability to maintain higher field gradients. Experiments have shown that higher breakdown thresholds of materials can be obtained under short pulse conditions as compared to DC [2]. With our generator pulsed voltages up to 1 MV with a 1 ns duration can be applied to diodes with interelectrode spacing ranging from 2-0.5 mm. Details of the pulse generator and the experimental arrangement can be found elsewhere[3]. The dark current and maximum field before breakdown were measured for chemically cleaned (prepared using SLAC specification C01a.1 without steps 8-9), single point diamond turned and diamond polished (preperation described in [4]) OFC copper cathodes.

The cathodes were installed in a vacuum gap with 1.5 mm interelectrode spacing. The voltage amplitude on the cathode was slowly increased from 300 kV to 800 kV, allowing the cathode to condition. The field on the conditioned cathode was then gradually reduced. The dark current from the cathode, collected on a faraday cup positioned 5 mm from the cathode, is then measured as a function of the applied voltage. The gap was then reduced to 1 mm and the process was repeated. The criterion for breakdown was assumed to be a sudden, irrevocable increase in the dark current accompanied by a visible flash. A Fowler-Nordheim[5] plot was generated using the data prior to breakdown for the chemically cleaned cathode (1.5 mm interelectrode spacing) and the diamond polished cathode (1 mm and 1.5 mm spacing). The field enhancement factor, $\beta$, has been calculated for each case, assuming a cathode work function of 4.65 eV[6]. For the diamond turned sample, surface could not be conditioned using the standard technique, and no dark current measurements were taken for this sample. The field enhancement factor $\beta$ for chemically cleaned copper, conditioned to ~500 MV/m was measured to be 76. $\beta$ for the diamond polished sample under similar conditions was 46. The same sample when conditioned up to 800 MV/m field had an enhancement factor of 30. This reduction in $\beta$ from a 1.5 mm to 1 mm electrode spacing for the polished sample is likely an effect of the conditioning process.

![Fowler Nordheim plot](image)

**Fig 4.** Fowler Nordheim plot for chemically cleaned and diamond polished Cu cathodes.

Both the chemically cleaned and diamond turned samples suffered breakdown when the electrode spacing was set to 1mm, and both had significantly higher currents. Of the three surface preparation methods tested, diamond polish seemed to have a lower dark current and higher hold-off voltage. A similarly prepared surface was tested to hold-off field gradients up to 1.66 GV/m [1]. Further increase in the field was limited by our experimental arrangement.
2.2 Photocurrent

Photoemission measurements have been made by illuminating the cathode with light from a KrF excimer (248 nm, photon energy of 5 eV) laser. The laser spot illuminated the center 1 mm diameter of the cathode at normal incidence. The interelectrode spacing was set at 2 mm, and voltage amplitudes from 200 kV to 500 kV were applied to the cathode coincident with the laser pulses. The cathode was diamond polished, and was conditioned to 250 MV/m. The emitted charge was then collected on the Faraday cup in the same manner as the dark current. At these applied fields, the dark current was negligible and did not contribute to the photocurrent. Collected charge was measured as a function of laser energy and voltage amplitude. The laser pulse duration was 23 ns FWHM, much longer than the voltage pulse duration of 1 ns. For this measurement, the pulser was run in self-triggered mode leading to a jitter with respect to the laser of 20 ns. Only those shots falling into a 3 ns window at the peak of the laser pulse are considered in this analysis. The charge collected was found to have a linear dependence on the laser energy for a constant applied voltage. This finding is in agreement with the expected dependence for a laser with a photon energy greater than the work function of the copper cathode (4.65 eV), in the space charge free regime.

For a work function of 4.65 eV, the slope and the intercept obtained from Figure 5 result in a field enhancement factor of 5 for photoemission, significantly smaller than that for the dark current. The origin of this difference is not yet fully understood. More systematic analysis of the photoemission data and measurement of dark current from this surface under higher applied fields are currently underway to help better understanding.

3 CONCLUSION

Simulations have been performed to study the beam parameters at the output of a 1 MeV pulsed power gun. It was found that emittance of 0.2 π mm-mrad and brightness of 3x10¹⁵ A/(m-rad)² were predicted, with an energy spread of 0.15% for a 100 A beam with 10 ps pulse duration. Measurements of dark current have been made on copper cathodes with three different surface preparations. The behavior of the polished sample was significantly superior in terms of lower dark current and higher breakdown threshold. Field enhancement values for field emission were measured to be ~30 for the polished surface and 76 for the chemically cleaned surface. Measurements of photocurrent were performed with a KrF excimer. The emitted charge was measured to be linear with the laser energy. Dependence of the charge on the applied field indicate a field enhancement factor of 5 for photoemission, significantly lower than the dark current field enhancement factor for a similar surface.

4 ACKNOWLEDGEMENTS

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5 REFERENCES