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ELECTRIC FIELD ENHANCEMENT STUDY USING AN L-BAND PHOTOCATHODE GUN

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Abstract

RF breakdown in high gradient accelerating structures is a fundamental problem that is still needed better understanding. Past studies have indicated that field emission, which is usually represented by electric field enhancement (i.e. β) produced from the Fowler-Nordheim plot, is strongly coupled to the breakdown problem. A controlled surface study using a high gradient L-band RF gun is being carried out. With a flat cathode, the maximum electric field on the surface reached 103 MV/m. And electric field as high as 565 MV/m on the surface was achieved by a pin-shaped cathode. The field enhancement factor was measured at different surface field during the conditioning process. Initial results of the study are presented in this paper.

INTRODUCTION

RF breakdown is a very complicated physical phenomenon that has been studied for tens of years. Despite previous extensive experimental and theoretical efforts, the nature of RF breakdown is still not clear. Past studies have indicated that field emission is strongly coupled to the breakdown problem [1, 2].

The field emission at different surface electric field is described by the Fowler-Nordheim function which contains three parameters: the field enhancement factor β, the emitter area A_e and the work function ϕ. β can be fitted out by the Fowler-Nordheim plot and it's usually in a range of few tens to hundreds. However, such high field enhancement factor has not been observed on a well-prepared surface. In fact, the observed β is only 1.2 on a copper cathode surface [3].

A series of experiments is being carried out on an L-band photocathode gun at Argonne Wakefield Accelerator facility (AWA). Initially, the evolution of β during RF conditioning process is studied for a flat cathode obtained at different pulse length. Then we studied two pin-shaped cathodes, which were able to be operated at very high RF electric field range (as high as 565 MV/m).

EXPERIMENTAL SETUP

The experiments are carried out on a test stand at AWA. The single-cell standing-wave photocathode gun operates at 1.3 GHz and its geometry has been optimized to achieve high gradient at moderate input power [4]. The copper cathode plug is mountable so that cathodes with different shape or material can be tested. Apart from the original flat copper cathode, two identical pin-shaped copper cathodes (0.8 inch in length, 0.12 inch in bottom diameter, and 0.02 inch in radius of top hemisphere) have also been tested, as shown in Fig. 1.

Figure 1: Pin-shaped cathodes.

A schematic layout of the experiment is shown in Fig. 2. Diagnostics involved in the experiment are a bidirectional coupler to monitor the input and reflected RF signals, an antenna (pickup) to monitor the RF signal inside the cavity, a Faraday cup (also serves as a mirror) outside the gun to measure the field emission current, and a CCD camera to monitor the RF breakdown. In addition, a Photo Multiplier Tube (PMT) is used to trigger the interlock when a breakdown occurs to stop the next RF pulse.

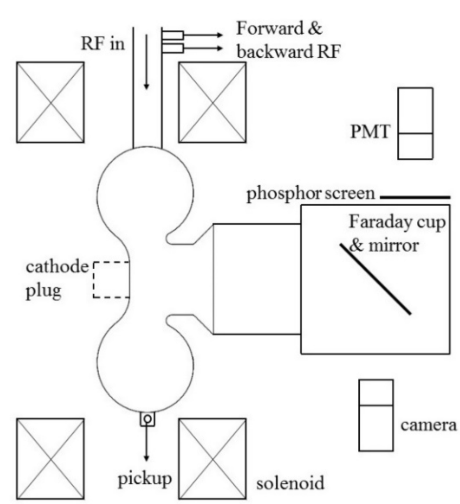

Figure 2: Layout of experiment setup.

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COLD TEST AND SIMULATION

Compared with the flat cathode, pin-shaped cathodes need to be pulled 0.75 inch backward to keep the gun at 1.3 GHz. The electric field on the tip is very sensitive to the cathode position. Thus we have measured the distance between the cathode base and the gun inner surface directly using a stick inserted from the downstream cross. Frequency shift at different cathode positions was recorded and agrees well with the Superfish [5] simulation results, as shown in Fig. 3.

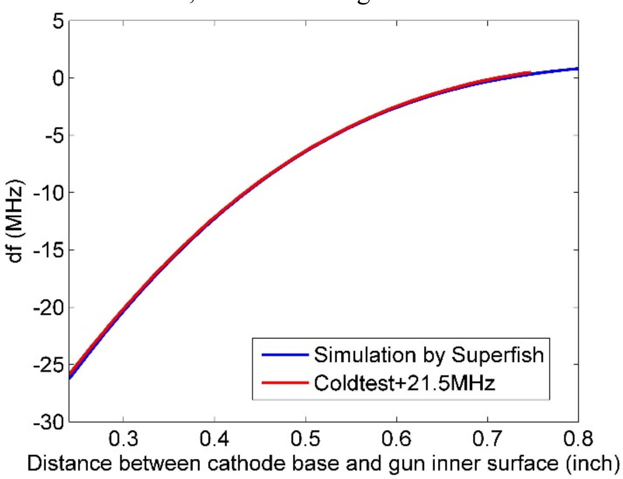

Figure 3: The frequency shift of the gun versus the pin-shaped cathode plug position.

The cold test results together with Superfish simulation results are in Table 1, where P_0 is the required input power to get 1MV/m at the centre of the cathode for the flat cathode or at the tip for the pin-shaped cathode (Q_0 and coupling factor from cold test have been taken into account). P_0 has also been checked by the Omega3P code [6]. Compared with the flat cathode, a field enhancement of 8.5 is achieved by the pin.

Table 1: Parameters of the Gun with Different Cathodes

Parameter	flat cathode	pin-shaped cathode
Q_0	13824	13805
Q_e	5616	5590
P_0 (W)	200	2.83

The simulated normalized electric field along the surface is shown in Fig.4. The curve of the flat cathode has been shifted and scaled to match that of the pin-shaped cathode. Three peaks are in the later one, which are at the tip of pin, the sharp edge between the gun and the pin-shaped cathode, and the nose cone at the downstream of the gun respectively.

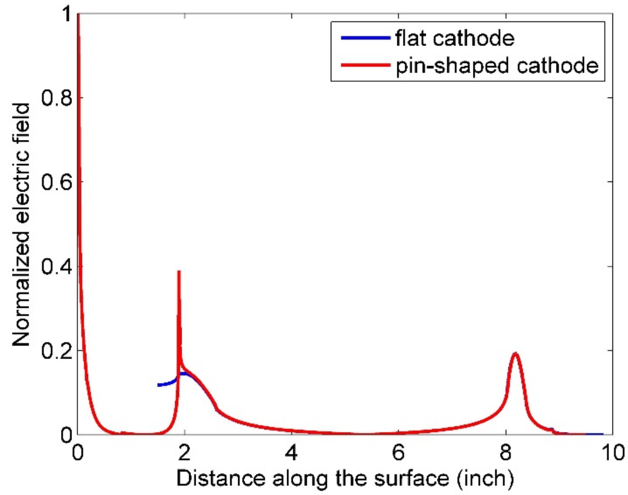

Figure 4: Normalized electric field along the surface.

EXPERIMENTAL RESULTS

For each cathode, the gun has been conditioned at a breakdown rate of ~10^{-3} / pulse with a fixed pulse length (typically 8 µs) and 10 Hz repetition rate for several days. We will lower the input power and slowly ramp it back, after a breakdown. The field emission measurement were carried out at different power level with 1 Hz repetition rate.

The Fowler-Nordheim function is

$$\bar{I}_F = \frac{5.7\times10^{-12}\times10^{4.52\phi^{-0.5}}A_e(\beta E_0)^{2.5}}{\phi^{1.75}} \times \exp\left(-\frac{6.53\times10^9\times\phi^{1.5}}{\beta E_0}\right)$$

where E_0 is the macroscopic surface field in V/m. Accordingly β can be fitted out as [1],

$$\beta = -2.84\times10^9\phi^{1.5}/\frac{d(\log_{10}\bar{I}_F/E_0^{2.5})}{d(1/E)}$$

and emitter area A_e can be calculated then.

Flat Cathode

After ~450000 pulses, the electric field on the flat cathode was able to be conditioned to 103 MV/m with 2.1 MW input power and 8 µs pulse length. Figure 5 shows the evolution of β and relative emitter area during RF conditioning process. The field enhancement factor is decreased from 140 to 100 after conditioning. However, the emitter area is found to be strongly correlated with the field enhancement factor, as

$$A_e\beta^k = const$$

where k is 7.021 (95% confidence interval 6.450 to 7.592). The physical of this phenomenon is still unclear.

The measurement was also carried out with different pulse length from 4 µs to 8 µs. No significant difference was observed in β nor A_e. Besides, we also measured β with the external static magnetic field by the gun solenoid. The maximum magnetic field at the centre of the cathode is below 100 Gs. No remarkable difference in β was found with such low magnetic field. While as the emitted electrons were focused or over-focused by the magnetic field, the capture efficiency of the Faraday cup

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varied correspondingly so that the calculated emitter area can be varied by one order of magnitude.

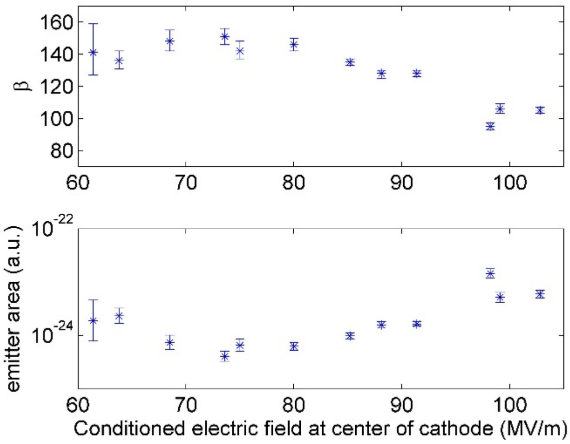

Figure 5: Evolution of β and relative A_e during RF conditioning process of the flat cathode.

Pin-shaped Cathode

Two identical pin-shaped cathodes have been tested in the experiment. The 1st pin has been conditioned up to 900 kW input power and the corresponding electric field on the tip is 565 MV/m after ~450000 pulses. However, the 2nd pin was limited to 385 MV/m with 420 kW input power after ~320000 pulses. It was very hard to condition the pin, which incurred frequently RF breakdown at higher power level. The evolution of dark current from the pin-shaped cathodes is in Fig.6. The current of the 2nd pin-shaped cathode is much larger. We are investigating the difference of the test.

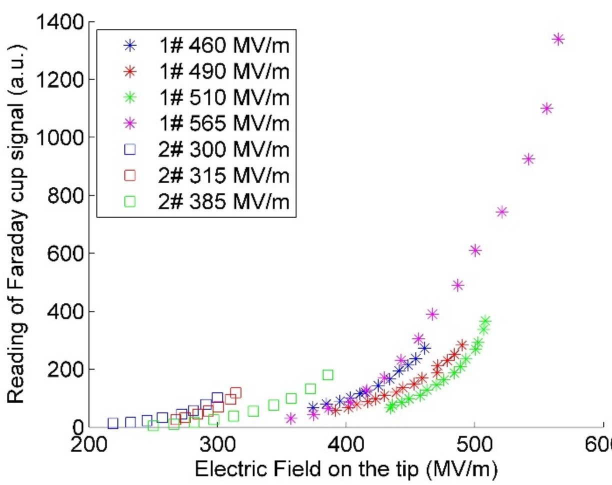

Figure 6: The field emission current versus electric field on the tip after cathodes has been conditioned to certain level.

The field enhancement factor is saturated at 25 and 40 for 1# and 2# pin-shaped cathode respectively, much smaller than that of the flat cathode. The evolution of the emitter area is also observed to be inversely related to β, as shown in Fig.7.

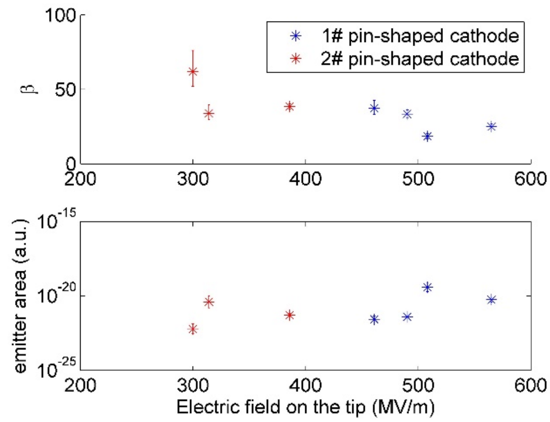

Figure 7: Evolution of β and relative A_e during RF conditioning process of pin-shaped cathodes.

SUMMARY AND FUTURE PLAN

The field emission study was started with an L-band single-cell gun at AWA. Field enhancement factor and emitter area have been measured during RF conditioning with different shaped cathodes. With a pin-shaped cathode, the maximum operational electric field on the pin reached 565 MV/m with 8 μs pulse length which is about an order magnitude higher than the conventional cathode. Most likely it is because the RF power is reduce by ~70 times for a given electric field at the centre of the cathode. Moreover we found that there is very strong correlation between β and A_e, as $A_e\beta^7 = const$, which is still unclear. We'll continue the test and investigate the influence of the net power on RF breakdown.

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