ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPMN016

OBSERVATION OF DARK CURRENT DEPENDENCE ON STORED ENERGY IN AN L-BAND RF GUN*

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Abstract

A pin cathode has been used to study the influence of stored energy on field emission in an L-band rf gun. The stored energy was tuned by adjusting the recess of the cathode in order to obtain the same electric field on the cathode tip. At same electric field, we have observed very strong correlation of dark current with stored energy, where five times enhancement of dark current was obtained with the stored energy increased by three fold. Beam dynamics study reveals that the correlation is not from the beam transmission. We'll present the experiment results as well the possible mechanisms about the phenomena.

INTRODUCTION

Field emission (i.e. dark current) plays an important role in high gradient rf devices. Generally, it's very harmful and can cause rf breakdown. It needs to be suppressed to achieve high gradient accelerating structures [1]. Dark current has been well explained by the Fowler-Nordheim formula with quantum mechanism [1, 2], which is governed by three independent parameters, the local field enhancement factor β, the emitter area Ae, and the work function φ. When φ is taken as its nominal value, β and Ae are usually inconsistent with surface analysis [3]. Moreover, they have a very large diversity from different accelerators with similar peak electric field but different frequency, group velocity and so on [1]. This might imply that the field emission might not be a completely local phenomenon, which could also relate with global parameters of a system.

Recent study in which two pins were attached to a WR90 waveguide has revealed that rf breakdown depends strongly on the net rf power flow through the waveguide [4]. As dark current is highly related to rf breakdown, we are motivated to exam its dependence on the net power flow or stored energy in a standing wave cavity. In this paper, dark current dependence on input power/ stored energy is studied with a standing wave rf photocathode gun with mountable cathode.

* Work support by the U.S. Department of Energy Early Career Research Program under contract code LAB 11-572
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EXPERIMENTAL SETUP

The experiment has been carried out on an L-band photocathode gun test stand at Argonne Wakefield Accelerator Facility (AWA), illustrated in Fig. 1. The forward and reflected rf power, and the field of the gun are monitored. A Faraday cup right at the exit of the gun measures the field emission current. Besides, a dark current imaging system is located downstream to index dark current emitters, which consists of a solenoid, a collimator, trim magnets, and YAG screens [5, 6].

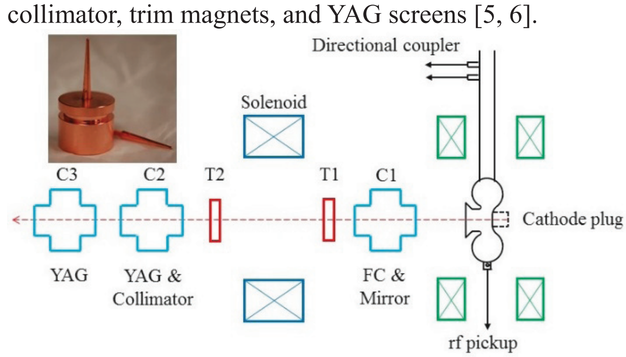

Figure 1: Layout of the L-band test stand. Inset: pin cathodes designed and fabricated in SLAC.

Pin cathodes are used to maintain the highest field in the gun to govern the field emission in the experiment. The field on the tip is at least four times higher than any other place of the gun. The copper pin cathode is 0.8 inch long with a R0.02 inch hemisphere tip as shown in inset of Fig.1.

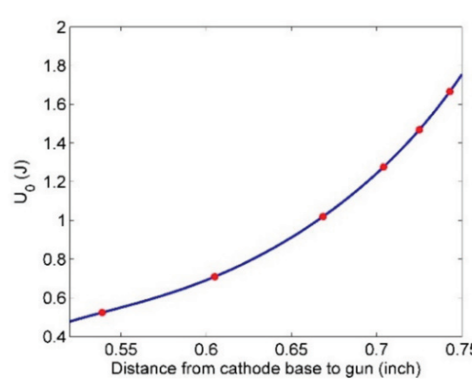

Figure 2: The stored energy at peak field of 625 MV/m vs the cathode positions from simulation, where the red points corresponds the different test sets.

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The stored energy of the cavity can be tuned by adjusting the recess of the cathode while the peak field is kept consistent. Meanwhile a tuner at the bottom of the gun is used to compensate detune of the gun by the cathode. At the same peak field, the stored energy versus the cathode position is simulated with Superfish [7] and Omega3P [8], as shown in Fig.2. In the cold test, the qualify factor of the gun increases from 12850 to 13730 and the coupling increases from 1.36 to 1.47 when the stored energy increased by about three fold. These have been counted to calculate the cavity field.

EXPERIMENTAL RESULTS

We've tested two identical pin cathodes 7# and 15#. For the 7# pin, the pulse length of input power was 8 µs and the flat top of the gun field was ~5.5 µs. For the other one, the pulse length and the flat top were shortened to 6.5 µs and ~4 µs due to a new klystron configuration. Initially both pins have been conditioned up to the peak field (noted as E_{tip}) of 700 MV/m with breakdown rate of 10^{-3}/pulse at the position for the maximum stored energy. The total pulses were ~190,000 and ~50,000, and the repetition rate was 10 Hz and 2 Hz for the 7# and the 15# pin during conditioning, respectively.

After the initial conditioning, the repetition rate was dropped to 1 Hz and the E_{tip} was kept below ~640 MV/m to avoid any breakdown for the dark current measurement. At each cathode position, dark current level was taken at several different peak electric fields, where the gun focusing solenoid was scanned correspondingly to maximize the capture rate. At each position, the test lasted about 2 hours and the dark current measurement was repeated twice to ensure that the surface condition of the pin was not changed. Accordingly the dark current at any given E_{tip} for each position (i.e. different stored energy) can be interpolated from the experimental data.

The 7# pin has been tested at six different positions illustrated as red points in Fig. 2. The 15# pin has been re-measured at the most right 4 positions of the 7#. The captured current of the two pins at different positions with E_{tip} of 625 MV/m are shown in Fig. 3 and 4, respectively. Clearly, dark current at the same E-field decreases with reduction of the stored energy. Particularly there is 5~20 times reduction in dark current at various solenoid setting, while the stored energy is reduced by a factor of 3.2 (1.67/0.52).

DYNAMICS STUDY

A modified version of ASTRA code [9] is used to simulate the emission from the hemisphere tip of the pin as well as the transmission to the Faraday cup, which helps to understand the significant variety of dark current. The emission position is labelled by two angle parameters, α and θ as in Fig. 5. In the simulation, we assume that 1) the initial kinetic energy of the dark current is 7 eV (Fermi energy of Cu), which turns out an overestimation and leads to larger error bar of capture ratio in comparison with the real energy distribution [10]; 2) the temporal structure of the emitted current is approximated by Gaussian distribution [11] with β of 15, which falls in 10 to 30 from the experiment (noted: the simulation results is only slightly affected by β value within this range); 3) space charge and mirror effect are not included because they have minor effect on the simulation results of capture ratio. The capture ratio of different emission positions on the tip at different solenoid field is shown in Fig. 6 for the cases of the minimum and maximum stored energy.

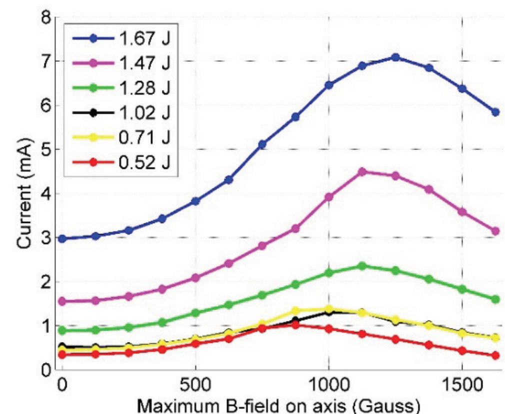

Figure 3: Test results of the 7# pin.

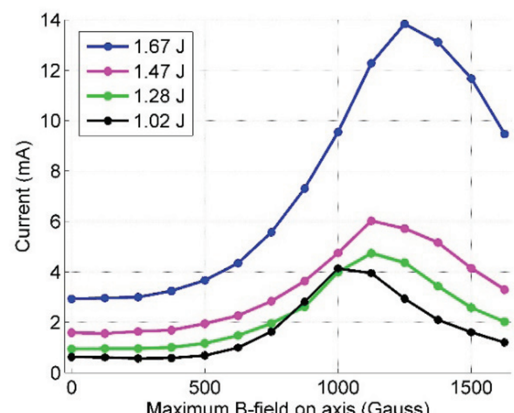

Figure 4: Test results of the 15# pin.

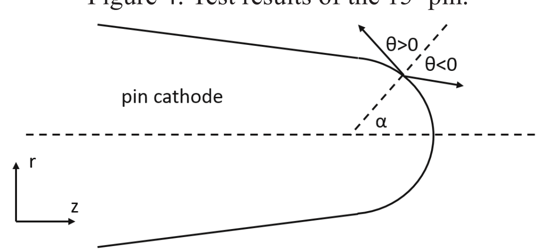

Figure 5: Pin cathode in dynamics study.

It indicates that the transmission from the pin cathode to the Faraday cup is highly related to the stored energy as well as the solenoid field. However, at solenoid field of 625 Gauss, the capture ratios overlaps with each other. For the other positions of the pin cathode, the same feature of beam capture has also been found. Thus we can conclude that the current difference from the different stored energy is irrelative to beam transmission. Besides, at solenoid field of 500 and 750 Gauss, the capture ratio

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of the maximum stored energy is respectively higher and lower than that of the minimum one. Thus the difference of emission current at these two solenoid field can serve as the upper and lower limit for comparison. Interpolated from Fig. 3 and 4 at solenoid field of 625 Gauss, the relative dark current (normalized to the current of the maximum stored energy) versus the stored energy is in Fig. 7.

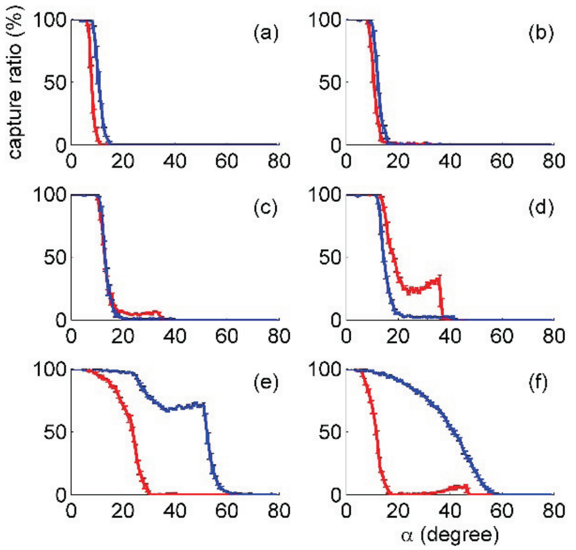

Figure 6: Capture ratio vs. α for the maximum (blue line) and the minimum (red line) stored energy at different on axis peak solenoid field (a-f: 0, 500, 625, 750, 1250, and 1500 Gauss).

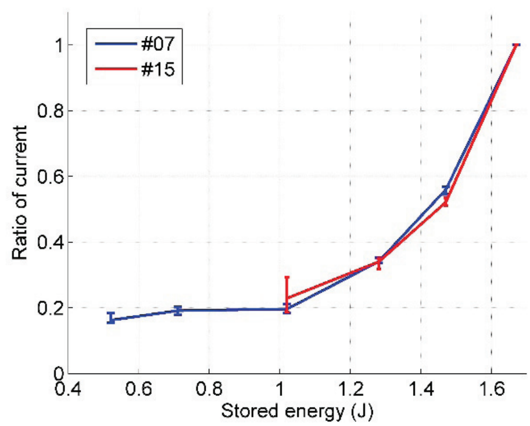

Figure 7: Normalized dark current at E_{tip} of 625 MV/m at different stored energy in the gun.

DISCUSSION

The results of the two pin cathodes agree well with each other. When varying the stored energy in the gun by three fold while keeping the same E_{tip}, there is five times difference in dark current. This can't be explained by the FN theory, where the field emission is governed by local surface electric field only.

We've examined several possible mechanisms that may contribute to this observation. The first one is emission from other parts of the gun. Previous dark current imaging study clearly revealed that the cathode pipe edge dominates the dark current for a flat cathode [5, 6]. As the field of this edge is not perturbed by the pin cathode, the emission from the edge by the previous experiment can be treated as background in this experiment. It is about an order of magnitude lower than we measured with the pin cathode. Thus emission from other parts only has minor effect on our observation.

The second one is beam loading or space charge limited field emission which can lower the surface field. The later has been well studied and can be judged by the nonlinearity dependence of $\log(I/E^2)$ on $1/E$ [12]. In our study, such feather is not observed. Besides, the charge emitting during one rf cycle is less than 1 pC with maximum energy of 0.9 MeV at the minimum stored energy, resulting beam power of 1.2 kW. As the input power is ~350 kW, beam load is negligible at this level.

The third possible mechanism is multipacting which has been suggested in a dc study with metallic electrodes [13]. For rf guns, multipacting and dark current can be well distinguished from the Faraday cup signal [14]. In our study, a minor dark current pulse due to multipacting can also be detected after rf pulse where E_{tip} decays below 10 MV/m. The current is not included in our previous data analysis. Thus the difference is neither caused by multipacting.

None of these known factors listed above has remarkable effect on our observation. A hypothesis of localized higher order modes (HOM) excitation by emission current has been proposed recently [15]. Based on this hypothesis, HOMs will interact with the fundamental mode and change the actual field on the surface. The whole process depends on the global parameters of a system. We are planning to model the pin cathode gun with the method.

CONCLUSION

At the same peak electric field, we've observed strong dependence of dark current on the stored energy in an L-band rf gun. Beam dynamics study reveals that the difference is a fundamental phenomenon indicating a strong correlation of field emission with stored energy. This observation suggests that the field emission at stead state is not only micro phenomenon by FN theory but also a macro phenomenon, which might couples strongly to global parameters of a system (e.g. stored energy here).

ACKNOWLEDGEMENT

We would like to thank Dr. Klaus Floettmann from DESY for his great help with the ASTRA code and useful discussion. The work by the AWA group is funded through the U.S. Department of Energy Office of Science under Contract No. DE-AC02-06CH11357. The work at Tsinghua University is supported by National Natural Science Foundation of China under Grant No. 11135004.

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