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Field emission from a solid metal surface has been continuously studied for a century over macroscopic to atomic scales. It is a general knowledge that, other than the surface properties, the emitted current is governed solely by the applied electric field. A pin cathode has been used to study the dependence of field emission on stored energy in an L-band rf gun. The stored energy was changed by adjusting the axial position (distance between the cathode base and the gun back surface) of the cathode while the applied electric field on the cathode tip is kept constant. A very strong correlation of the field emission current with the stored energy has been observed. While eliminating all possible interfering sources, an enhancement of the current by a factor of five was obtained as the stored energy was increased by a factor of three. It implies that under certain circumstances, a localized field emission may be significantly altered by the global parameters in a system.

Field emission (aka dark current) was discovered as a quantum phenomenon and is described by the well-known Fowler-Nordheim equation [1–5]. It plays an important role in high gradient dc and rf devices, cold cathode electron sources, and internal electron transfer processes in electronic devices [5]. In particular, field emission is considered to be the trigger of vacuum breakdowns in high gradient devices [3, 6–9]. Better understanding of field emission will benefit the R&D for high gradient accelerating structures to be used in future linear colliders [10], X-ray free electron lasers [11, 12], compact medical and industrial linacs [13, 14], etc. In earlier studied, field emission was considered to be dependent only on the applied electric field (with geometrical field enhancement factors or space charge effects) besides the properties of the surface [1–5]. However, a recent theoretical study has suggested that field emission is essentially coupled to global parameters such as group velocity, frequency and so on, of a macroscopic system [15]. Moreover, an early experiment has revealed that the operational electric field depends strongly on the net power flow in a travelling wave X-band system [16]. In this paper, we report how the dark current depends on the stored energy (or input power) in a standing wave cavity.

An L-band rf gun at Argonne Wakefield Accelerator facility (AWA) is used as a test bed for the study [17, 18]. A pin cathode (Fig. 1) is installed to significantly enhance the electric field on the cathode to govern the field emission in the gun. The stored energy was changed by adjusting the recess of the cathode while the maximum electric field on the cathode tip (denoted as E_{tip}) is kept constant [19].

The cathode recess is adjusted by a micrometer. The position of the cathode inside the cavity is measured by the micrometer and confirmed by a direct measurement with a long stick inserted at the gun exit. The maximum error of the cathode position measurement is ∼0.1 mm which is acceptable for our study. The detuning of the gun by the cathode displacement was compensated by a tuner at the side of the gun. The maximum recess is ∼6 mm, limited by the tuner range which is ∼6 MHz. When the cathode is pushed further into the cavity, the electric field on the cathode tip is enhanced so that a lower stored energy and input power are needed to maintain a constant E_{tip} as illustrated in Fig. 1. The electromagnetic simulation of the cavity has been done in 2D with the Superfish code [20] and in 3D with the Omega3P code [21]. The results of the two simulations are consistent with each other. The cold test data is summarized in Table. I.

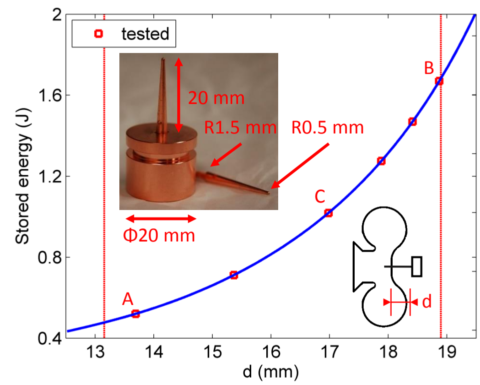

FIG. 1. Stored energy inside the cavity and input power for the same E_{tip} (625 MV/m) at different cathode positions. The red vertical lines show the cathode position boundaries in the experiment. Inset: pin cathodes from SLAC.

The geometry of the cavity with a pin or a flat cathode is illustrated in Fig. 2 (a). The electric field along the

TABLE I. Parameters of the L-band photocathode gun.

Parameter	Value	
	position A	position B[a]
d (mm)[b]	13.7	18.9
Quality factor Q_0	12850	13730
ρ_{ext}[c]	1.36	1.47

[a] position A and B correspond to the minimum and maximum stored energy tested in the experiment, as illustrated in Fig. 1
[b] distance between the cathode base and the gun back surface
[c] coupling between the cavity and the waveguide

cavity surface simulated by Superfish is plotted in Fig. 2 (b), where the surface field of the tip is much larger than any place else in the cavity. Accordingly, the majority of the field emission in the cavity is considered to originate from the tip. The corresponding magnetic field along the pin at both positions is less than 65 kA/m, leading to negligible pulse heating in the experiment [22].

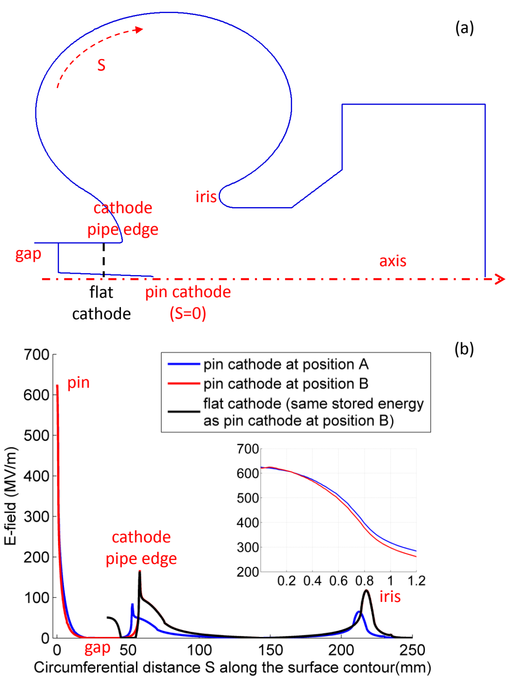

FIG. 2. (a): 2D geometry of the cavity (the pin cathode at position A or the flat cathode at its fixed position). (b) Electric field along the cavity surface contour (start from the pin). Inset: zoom-in view at the tip.

Electrical contact between the cathode and the cavity is ensured by a spring located ~ 5.5 mm behind the cathode base. The low field at the ~ 0.03 mm gap leads to negligible field emission from this area.

The layout of the L-band photocathode test stand at AWA is shown in Fig. 3. 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, and a Faraday cup with an integrating circuit located at the exit of the gun to measure the dark current. A dark current imaging system is located downstream to index dark current emitters on the cathode with $\sim$100 μm resolution. This consists of a solenoid, a collimator with small apertures, trim magnets, and YAG screens [23]

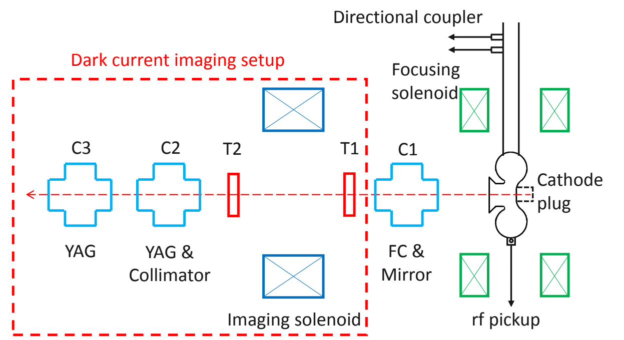

FIG. 3. Layout the L-band photocathode test stand at AWA.

Two identical pin cathodes, No.07 and No.15, have been tested in the experiment. Before the dark current measurement, both pins had been carefully conditioned up to E_{tip}~700 MV/m at cathode position B (corresponding to the maximum stored energy). The parameters of the conditioning history are summarized in Table. II.

TABLE II. Parameters of the pin cathodes' conditioning history[a].

Parameter	Value	
	No.07	No.15
pulse length (μs)	8	6.5
flat top of electric field (μs)	6.5	4.0
repetition rate (Hz)	10	2
total pulses	$\sim 190,000$	$\sim 50,000$
number of breakdown	~ 100	~ 30
maximum E_{tip} (MV/m)	~ 700	

[a] The difference in pulse length, flat top of electric field, and repetition rate is caused by different klystron and waveguide configurations.

After the conditioning, the repetition rate was dropped to 1 Hz and E_{tip} was kept below 660 MV/m to avoid any breakdown. Dark current was then measured at fairly consistent surface conditions. At each cathode position, the dark current was measured at different tip fields. The gun focusing solenoid was adjusted correspondingly to maximize the capture rate. For a given cathode position, the test usually took about 2 hours and the dark current measurement was repeated under selected focusing solenoid strengths at the end to ensure that the surface conditions of the cathode had not changed. The No.07 and No.15 pin cathodes have been measured at six (positions A to B) and four (positions C to B) different positions respectively, illustrated as red squares in Fig. 1, to confirm the observation.

There are two steps in the typical dark current signal as illustrated in the inset of Fig. 4. The first is caused by field emission. The second results from multipacting, which is verified by two features reported by another group [24]: 1) the amplitude of this step is independent of the input power; 2) the delay t_{rear} between the start of this step and the end of the rf pulse follows the relation

$$E_{MP} = E_{max} exp(-t_{rear}/\tau) \quad (1)$$

where τ is the fill/decay time of the cavity, E_{max} is the maximum field on the tip during the pulse, and E_{MP} is the field on the tip when the multipacting occurs. τ is obtained by fitting the data as 1.48 μs, which is in reasonable agreement with the value of ~1.33 μs deduced from the cold test results. In the following calculation and analysis, only the first step (field emission) is taken into account.

The standard Fowler-Nordheim plot for different cathode positions is shown in Fig. 4, where the corresponding different stored energies at E_{tip} of 625 MV/m are labeled. The nonlinear dependence at the low field end for the lowest two stored energies is considered to be caused by multipacting at the beginning or during the rf pulse. Based on a previous study by another group, this phenomenon is likely to occur when the surface field is very low where resonant multipacting can be easily developed [24]. Because of the low time resolution of the integral Faraday cup signal, we can't distinguish this particular multipacting current from the field emission current. We examine the field emission dependence on stored energy at E_{tip} of 625 MV/m, illustrated in Fig. 4 by the red dashed line, to minimize the influence from multipacting.

The collected dark current from the No.07 and No.15 pin cathodes at different positions (labeled by the different stored energies) and focusing solenoid strength at E_{tip} = 625 MV/m are shown in Fig. 5 (a) and (b), respectively. Clearly, dark current at the same E_{tip} is enhanced when the stored energy is increased. In particular, a dark current enhancement by a factor of 5 ~ 20 is observed at various solenoid settings, while the stored energy is increased by a factor of 3.2 (1.67/0.52). Further on, the dark current capture ratio from the cathode tip to Faraday cup has been simulated with the ASTRA code [25]. We found that at a focusing solenoid strength of 625 Gauss, the capture ratio is consistent for the cathode at different positions [19]. The relative dark current (normalized to the current of the maximum stored energy) versus the stored energy is shown in Fig. 5 (d) at this focusing strength. When the stored energy in the

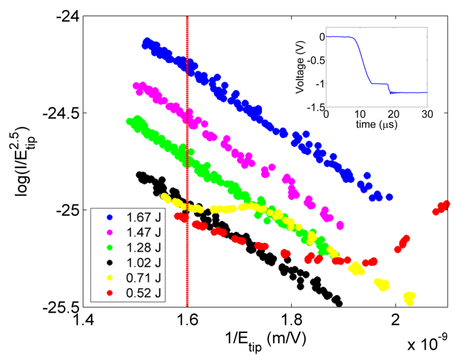

FIG. 4. Fowler-Nordheim plot of measured data from the No.07 pin cathode. The red line indicates the interpolation point for the following data analysis. Inset: typical Faraday cup signal after the integrating circuit.

cavity is increased by three fold while keeping the same E_{tip}, the dark current will be enhanced by a factor of five. The results from the two pin cathodes agree very well with each other.

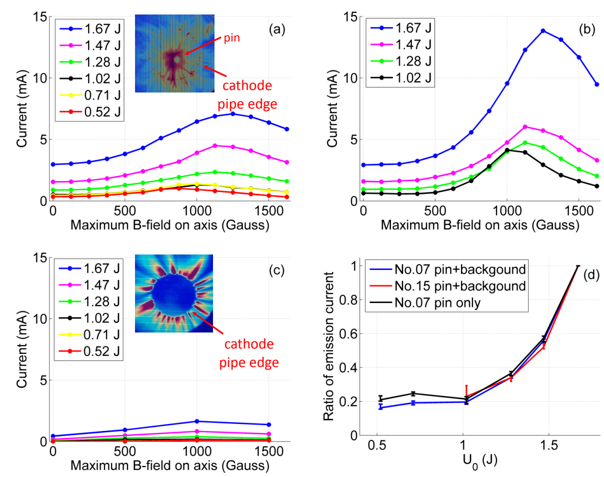

FIG. 5. (a-c): Captured dark current of the No.07 and No.15 pin cathodes at E_{tip} of 625 MV/m, and the flat cathode with different stored energies in the cavity. (d): Relative dark current with different stored energies. Insets of (a) and (c): dark current images with the pin and the flat cathode taken at the second cross (C2 as shown in Fig. 3).

Meanwhile, the field enhancement factor and emission areas of the four straight lines in Fig. 4 can be fitted based on the Fowler-Nordheim equation [3]. It is found that when the stored energy is increased by a factor of 1.6 (1.67/1.02, positions B to C as shown in Fig. 1), the field emission factor remains ~ 15 while the emission area decreases from $\sim 8\times10^{-15}mm^2$ to $\sim 3\times10^{-15}mm^2$. These observations are inconsistent with the Fowler-Nordheim theory which predicts the same dark current at the same E_{tip} and the same surface conditioning. Possible mechanisms that may contribute to this observation have been examined.

(a) Background emission from other surfaces Although E_{tip} is kept constant for different stored energies by adjusting the cathode recess, the electric field on other parts of the cavity will be different and leads to different field emission currents. To extract field emission from other places, a flat cathode was placed at ∼2.9 mm behind the flush position to create the same surface fields on other cavity surfaces as in the case of the pin cathode, as shown in Fig. 2. The flat cathode was polished to a roughness of less than 20 nm with a diamond suspension. As the field on the flat cathode is 3.2 times lower than that on the cathode pipe edge, field emission will be dominated by the latter, which has been confirmed also by a previous dark current imaging experiment [23]. When the flat cathode is fixed at this position, the background emission was measured at different stored energies corresponding to those using the pin cathodes, as illustrated in Fig. 5 (c). At the same focusing solenoid strength of 625 Gauss (interpolated from the measured data), the dark current is about 5 times lower than that when the pin cathodes were present. From the insets in Fig. 5, the dominant field emission from the pin can also be vividly confirmed by the dark current images taken by the imaging system [23]. Thus background emission only leads to minor corrections to the observation, as illustrated in Fig. 5 (d).

(b) Secondary electron yield (SEY) from the Faraday cup SEY from the Faraday cup strongly depends on the incident electron energy, and can lower the detected current [26]. To examine the effect on our observations, a dc bias voltage up to 500 V was applied to the Faraday cup to capture all the secondary electrons. When the stored energy is varied from 1.67 J to 1.02 J (positions B to C as shown in Fig. 1), the maximum electron kinetic energy varies from ∼1.6 MeV to ∼1.2 MeV. With the No.15 pin cathode, SEY has been measured to increase from ∼ 9% to ∼ 13% correspondingly, which also leads to minor correction to the measurements.

(c) Beam loading effect Beam loading lowers the stored energy inside the cavity and has also been investigated [27]. The charge emitted during one rf cycle is less than 1 pC with maximum energy of ∼0.9 MeV at the minimum stored energy (0.52 J), resulting in a beam power of 1.2 kW. As the input power is ∼350 kW, the beam loading effect is negligible during the measurements.

(d) Space charge limited emission Space charge can lower the field emission remarkably and its effect can be characterized by the deviation from the Fowler-Nordheim equation at higher surface electric fields [28, 29]. This has not been observed in this experiment (as illustrated in Fig. 4), so the space charge limited emission effect should not contribute to the phenomenon.

All the error mechanisms considered are insignificant to our main observations. The correlation of field emission current and stored energy may be fundamental. The observation is consistent with the recently developed model of macroscopic field emission, which describes how the micro field emission couples fundamentally with the global parameters of a system [15]. Based on the model, the surface field is the sum of the fields excited by the external rf source and those induced by the emission current, which strongly depends on the geometry of the cavity and is associated with global parameters (e.g. the stored energy in our case). Thus when the position of the pin cathode changes, the self-induced field by the current will change accordingly. This will in turn lead to the variation of the field emission.

In summary, a strong correlation between the field emission current and the stored energy has been observed on pin cathodes. This study has excluded mechanisms that may affect the conclusion, such as multipacting in the cavity, background emission from other surfaces, secondary electron emission from the Faraday cup, the beam loading effect and the space charge limited emission effect. We conclude that the observation is fundamental and inconsistent with the Fowler-Nordheim equation. This indicates that macroscopic parameters like stored energy are affecting the microscopic emission. The findings suggest a new territory to be explored while developing FE electron sources and high gradient devices.

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