

SCHOTTKY-ENABLED PHOTOEMISSION AND DARK CURRENT MEASUREMENTS-TOWARD AN ALTERNATE APPROACH TO FOWLER-NORDHEIM PLOT ANALYSIS*

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Abstract

Field-emitted dark current, a major gradient-limiting factor in RF cavities, is usually analyzed via Fowler-Nordheim (FN) plots. Traditionally, field emission is attributed to geometrical perturbations on the bulk surface whose field enhancement factor (beta) and the emitting area (A) can be extracted from the FN plot. Field enhancement factors extracted in this way are typically much too high (1-2 orders of magnitude) to be explainable by either the geometric projection model applied to the measured surface roughness or by field enhancement factors extracted from Schottky-enabled photoemission measurements. We compare traditional analysis of FN plots to an alternate approach employing local work function variation. This is illustrated by comparative analysis of recent dark current and Schottky-enabled photoemission data taken at Tsinghua S-band RF gun.

A critical issue in high-gradient accelerating structures, which remains a bit of a mystery, is RF breakdown. Dark current from field emission (FE) is a major gradient limiting factor in RF cavities and harbinger of breakdown. The accepted FE model is the Fowler-Nordheim (FN) theory. Onset of FE in RF cavities at $E \geq 10$ MV/m is attributed to small surface protrusions enhancing the applied electric field in small areas. This field enhancement is parametrized by a scaling factor β which may be extracted from a FN plot of experimental data. Field enhancement factors obtained this way are generally too high to be accounted for by observed surface roughness. The FN plot also allows the computation of the emitting area. The areas computed are typically on a length scale of 10 nm or smaller, suggestive of unphysically high current densities.

In this paper, FN theory is not being dismissed, instead, we look at it from a slightly different perspective. Conventional FN analysis holds the work function of the metal, ϕ_0 , constant. A different approach is to consider the variation of work function across a broad area and treat ϕ_0 as a free parameter. This may be better understood in the context of the analysis of dark current data. We consider data taken

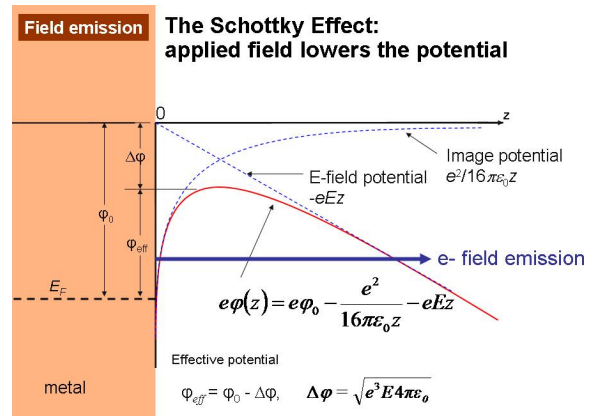


Figure 1: Outside a metal surface, the potential barrier is reduced and re-shaped by the applied E-field and the image charge. The potential barrier is lowered and the width becomes finite, setting the stage for field emission to occur.

at Tsinghua University S-band RF photocathode gun from these two viewpoints under the FN theory: 1) traditional FN analysis and 2) an alternate view using a lower, realistic beta together with a low local work function, an approach suggested by Wuensch and colleagues [1] (also B.M. Cox [2]).

Data was taken in October 2010 at the Tsinghua University S-band RF gun facility in China. The gun is well-designed for FE current measurement. The back wall of the gun is a solid copper plate with an integrated photocathode. This means there is no gap between cathode and the wall as in guns with removable cathodes. Observed FE is from surface only - not from the cathode edge. For the experiment RF peak-field went from 57-73 MV/m. FE current was measured using a Faraday cup just outside the gun.

FE current arises from quantum mechanical tunneling of electrons through the potential barrier at the metal surface. As the barrier is changed by the applied electric field and the image charge, the probability of tunneling increases and so does FE current.

The FN equation was developed by solving the Schrodinger equation for E-field-modified surface potential

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using the WKB approximation under a number of assumptions including flat, defect-free metal surface, free-electron model, one-dimension, $T=0K$, DC electric field[3]. Local field variations due to surface roughness are introduced by means of a field enhancement factor β such that $E_{local} = \beta E_0$. A substitution of $E = E \sin \theta$ is made to account for RF fields (where $\theta=RF$ phase), then integration over an RF period gives an expression for the average field emitted current $I(E_0, A_e, \beta, \phi_0)$, resulting in the FN equation for RF fields [4]:

$$\bar{I} = \frac{6.02 \times 10^{-12} \times 10^{4.52\phi_0^{-0.5}} A_e (\beta E)^{2.5}}{\phi_0^{1.75}} \times e^{\left(\frac{-6.53 \times 10^9 \phi_0^{1.5}}{\beta E}\right)}$$

It is clear that the FE current depends on both β and ϕ_0 . The usual experimental approach is to take data using a Faraday cup or ICT, then plot current and RF field on a FN plot and do a linear fit. β is computed from the slope and the emitting area from the intercept. Using $\phi_0 = 4.6$ eV,

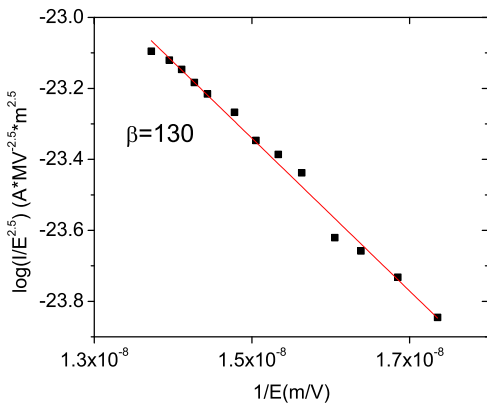


Figure 2: Fowler-Nordheim plot of data from S-band RF gun, Tsinghua U, . Applying traditional analysis, field enhancement factor $\beta=130$ is extracted from the slope of the plot using $\phi_0 = 4.6$ eV as nominal work function of copper.

field emission data from Tsinghua was plotted and fitted the usual way, (Fig. 2), yielding $\beta = 130$. This is consistent with typical SLAC data [4].

Schottky-enabled photoemission occurs when the photon energy is below the photoemission threshold due to the Schottky effect. A detailed discussion of the method is available here[5]. For Tsinghua S-band gun the parameters are: photoemission threshold=work function of copper= $\phi_0 = 4.6$ eV, photon energy $h\nu = 3.1$ eV (below threshold), and two laser pulse lengths: short (0.1 ps) and long (3 ps). The results are plotted in Fig. 3. The plots are of charge Q vs. total laser energy; Q was measured using an Integrating Charge Transformer (ICT) and laser energy was measured with a photodiode. Fig. 3 shows a linear trend which becomes non-linear as laser energy increases above $400 \mu J$, likely indicating onset of multi-photon emission at higher laser intensity.

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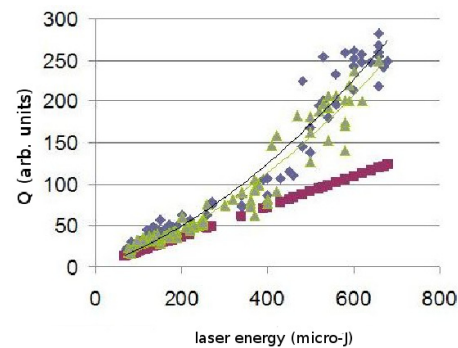
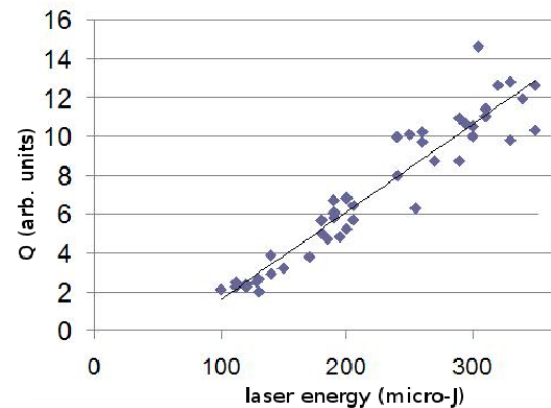
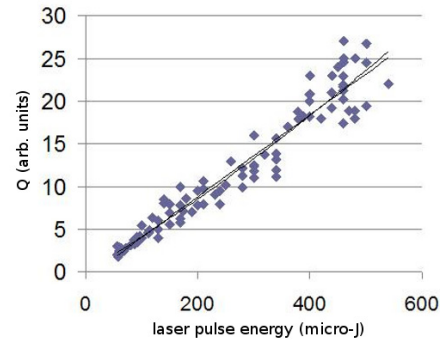


Figure 3: *Top*: Short pulse (0.1 ps). $E_{peak} = 55$ MV/m, inj. phase = 80° , $E_{accel} = 54$ MV/m. Data with linear fit; charge Q vs. laser energy. *Middle*: Photoemission data from S-band RF gun, Tsinghua U. Long Pulse, same parameters as above; linear-indicating this is single photon emission regime, well above threshold for Schottky-enabled emission. *Bottom*: $E_{peak} = 50$ MV/m, injection phase = 30° , $E_{accel} = 25$ MV/m. Schottky-enabled photoemission threshold. The plot becomes non-linear at laser energy above $400 \mu J$, indicating multi-photon emission regime. Data with laser energy $< 400 \mu J$ with linear fit, data with laser energy $> 400 \mu J$, polynomial fit.

Schottky-enabled photoemission was observed for all field levels. For the parameters listed above, the difference between the photon energy and the photoemission threshold is $\Delta\phi = 1.5$ eV. The Schottky effect equation: $\Delta\phi = \sqrt{e^3\beta E 4\pi\epsilon_0}$. Using the lowest field level where emission was measured $E=25\text{MV/m}$, $\beta = 60$. Emission was observed at still lower field levels, implying a somewhat larger β , but the signal was noisy.

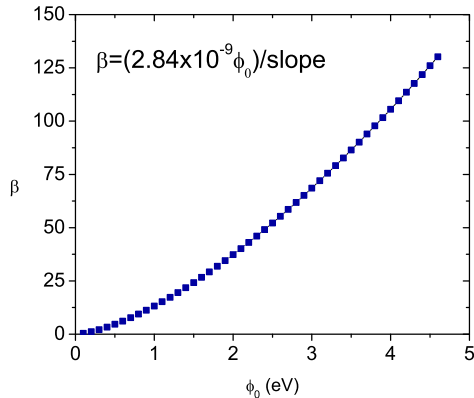


Figure 4: β vs ϕ_0 plotted using the slope of the FN plot for the Tsinghua data. Each point on the plot represents a possible combination of field enhancement factor and local work function which match the Tsinghua data.

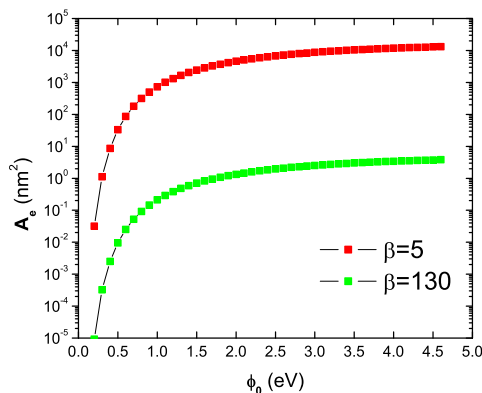


Figure 5: Emitting area A_e computed from the intercept of the FN plot (Fig. 2) using two different values of β .

The Fowler-Nordheim Law (RF fields) as previously discussed, depends on the field enhancement factor β , and the work function ϕ_0 . The typical approach is to hold ϕ_0 fixed at the nominal value of the material (ie. copper $\phi_0 = 4.6$ eV). The result is unrealistically high field enhancements. As ample, the value $\beta = 130$ we computed using this approach seems unphysical. For the surface of a RF cavity machined to ≈ 10 nm roughness, this implies emission features 10 nm tall by 1 nm wide. These type of features are

not there. If one assumes the perfect metal surface, then in order for field emission to occur, the local field has to be extremely high, $E=O(\text{GV/m})$, requiring a large value of β . This view is unrealistic. We think a good alternative is to look at the data, and choose a reasonable value of $\beta \leq 5$). Next, assume that something lowers the work function at points of emission. We posit a distribution of work function across the surface which includes some sites of very low work function in the tail. We believe it is the low work function which sets the threshold level for field emission. To explore this idea that work function may vary greatly across the surface, we looked at the effect of different combinations of local work function and beta. It turns out that it is possible to fit the same data on a Fowler Nordheim plot many ways (Fig. 4). Each point on the plot represents a (ϕ_0, β) pair based on the data and satisfying the FN theory.

Another quantity extracted from a FN plot is the emission area, A_e . This area is typically smaller than the measured surface roughness. The resulting current density is unphysically high. Choosing the point on the curve in Fig.5 which represents the usual FN approach applied to the data, $(\phi_0, \beta) = (4.6, 130)$, it can be seen that the total emission area for this data set is extremely small, $A_e \approx 3 \text{ nm}^2$. An area of this size would have a current density of about $4 \times 10^9 \text{ A/cm}^2$. We did a simple-minded calculation of the expected temperature rise due to Joule heating of the emission site, neglecting heat conduction away from the site. Using the RMS current, the emission area and material constants, Joule heating calculation yields a temperature rise of $5 \times 10^5 \text{ }^\circ\text{C}$, per 100 ns of RF, an obviously unphysical result (melting point of Cu is 1083°C .) Using our alternate approach, we choose the point on the upper curve $(\phi_0, \beta) = (0.5, 5)$ which gives a much more reasonable $A_e \approx 100 \text{ nm}^2$. Doing the same calculation with this area results in a more moderate temperature increase of 800°C . This calculation, though not rigorous, does suggest that the usual analysis does not work very well.

We observed field emission and photoemission from the S-band RF photocathode gun and analyzed the data from two points of view. A cross-check of the data indicates that low work function sites combined with reasonable field enhancement factor $\beta \leq 5$ explains the data better than the usual approach assuming constant work function with high β . In our view, these low ϕ sites are responsible for dark current emission and are potential RF breakdown sites. Future careful studies of the surface are called for to provide a definitive explanation.

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