INCLUSION OF SURFACE ROUGHNESS EFFECTS IN EMISSION MODELING WITH THE MICHELLE CODE *

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Abstract

High-brightness electron beams are needed in millimeter-wave tubes and other high-power RF applications. Cathode surface roughness at the micron scale, commonly due to machining or other effects, can lead to broadening of the velocity distribution of electrons downstream, increasing emittance and lowering beam brightness. In this paper we investigate methods of including surface roughness effects in the MICHELLE code[1,2].

Direct modeling of typical surface imperfections over an entire cathode is not feasible, since it requires representation of features that are 3 to 5 orders of magnitude smaller than the cathode. Moreover, the actual surface imperfections for a given cathode are unknown without a prohibitive microscopic investigation of the surface, and these details vary between cathodes with the same machining history. To avoid these problems we investigated modifications to emission models that can account for these effects in an average sense, allowing the use of a smooth emission surface in a model while retaining the essential effects of the rough surface on the beam. We present the results of this investigation, along with representative solutions for sample structures.

DESCRIPTION OF PROBLEM

The surface finish/roughness properties of the thermionic emitting surface are believed to impact beam brightness. For an atomically flat surface, the angular distribution for electron emission is Lambertian, varying as the cosine of the angle off the surface normal direction. For typical commercial emitters, the surface roughness is often several microns, with open pores distributed among machined surface grooves (see Figure 1). The surface roughness typically exceeds the location of the potential well above the emitting surface during space charge limited operation. As a consequence the effective emission current density is modified and the surface normal direction becomes highly variable within the electron emission zone. The net effect of these factors is believed to cause significant distortion in the emission angular distribution relative to the macroscopic surface normal, favouring thereby increased average traverse velocity content for the emitted electrons. These distortions are viewed as particularly significant at lower ranges of beam voltage operation because of the increased elapsed time for beam entrance into the interaction space.

Detailed modelling of the microscopic structure of the emitter is both computationally prohibitive and likely undesirable, since the actual structure varies unpredictably across samples and so is unknown in the gun design stage.

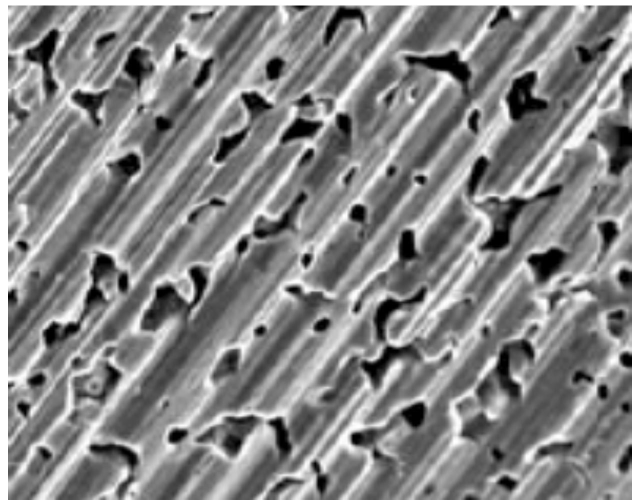

Figure 1: SEM image of an M-type cathode surface, with both structured (machining grooves) and random defects in the M-layer evident.

APPROACH

Since we are interested in the effects of surface roughness on macroscopic beam quantities, such as emittance, we would like to capture the relevant physics in changes to the macroscopic emission model, which could subsequently be applied to a smooth emission surface for modelling purposes. The approach consists of the following steps:

1. Build CAD geometry of small patch of emission region that has characteristics representative of the real surface features.
2. Run the MICHELLE code on the emitter patch to generate a high resolution beam distribution over energies and angles.
3. Collect particle positions/momenta at plane sufficiently far from the rough surface (remove the locality effect).
4. Process particle data by back-projecting trajectories to a plane slightly above the rough surface, thus obtaining effective emission parameters for each particle.
5. Assimilate these data into new angular and energy distribution functions that can be used to control emission in MICHELLE.

The patch that is modelled must be of sufficient size to include all important topology in representative relative concentrations. For the purposes of our initial work we

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have assumed that the surface is periodic, allowing us to use symmetry to model only a single period. While not required by the approach, this assumption allows for minimum model size.

An abstraction of a typical model is shown in Figure 2. The usual Child-Langmuir emission model is used on the entire patch, including the inclusions. The mesh must be fine enough to resolve particle motion near the inclusion surfaces. The anode surface is set far enough away so that the presence of an equipotential surface does not significantly disturb the field variation near the emission surface, and the anode voltage is set to yield the desired average current loading on the emitter.

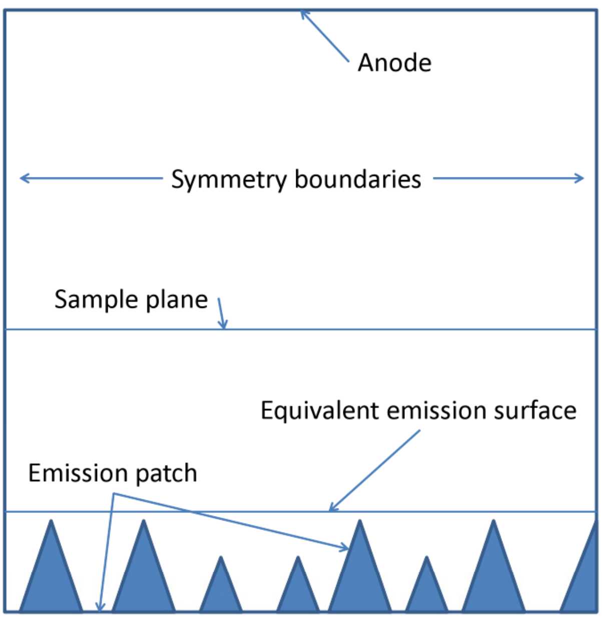

Figure 2: Canonical model geometry for obtaining rough-surface emission parameters from a MICHELLE analysis.

The projection of the particles back to the equivalent emission surface is accomplished using the following expression:

$$\cos(\theta_l) = \sqrt{1 - \frac{\beta_{s\perp}^2}{1 - \frac{1}{\gamma_l^2}}}\ , \quad \gamma_l = \gamma_s - \frac{q_e V_s}{m_e c_0^2}$$

Where θ_l is the equivalent polar angle of emission of the particle and quantities with subscript *s* are measured at the sample plane.

ANALYSIS OF SMOOTH EMITTER

To test the algorithms and implementation we analysed a simple planar diode with the geometry shown in Figure 2. In our model the anode-cathode spacing was 2 cm, with an anode voltage of 1 KV. The sample plane was 1 mm above the cathode, and the equivalent emission surface was coincident with the cathode. Using the usual thermal emission model in MICHELLE, particles are emitted at discrete polar/azimuthal angles, and in one or more discrete energy bins. For the parameters chosen for this test the polar angles are given by 0, 33, 45, 57, and 73 degrees, and we expect an equal amount of current to be emitted in each of these polar angle bins. Results from the simulation show that the back-projection algorithm can indeed reproduce the correct emission angles from the particle data collected at the sample plane (see Figure 3). Similar results were seen for the emission energies. These results are generated with space-charge neglected, since space-charge effects smooth the back-projected emission angles. When space-charge is included, we also get agreement with expected distributions. For example, Figure 4 shows good agreement between the projected result and the expected emission probability-vs.-angle distribution given by $\cos(\theta)$.

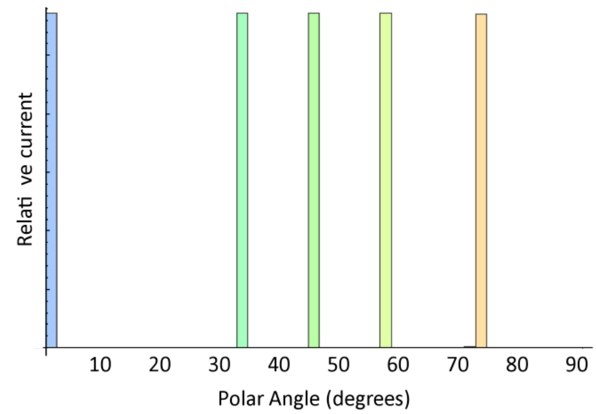

Figure 3: Emission current vs. emission polar angle as determined by back-projecting particles from sample plane to cathode surface. The emission current is localized to the expected discrete polar angles.

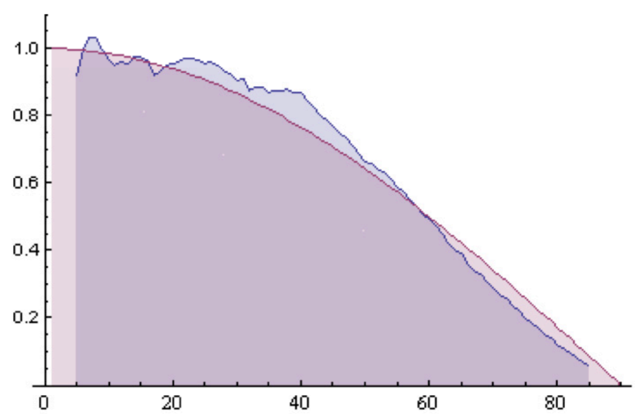

Figure 4: Normalized emission probability vs. polar angle, showing good agreement between the back-projected result and the expected distribution.

IDEALIZED PROTRUSIONS

Our preliminary modelling of simulated rough surfaces has focussed on simplified geometries that are periodic and have a single protrusion per period. The inclusion is cylindrically symmetric and has a profile given by:

$$z = r_0 \cos(\theta)^n \qquad r = r_0 \sin(\theta)$$

where θ is the polar angle.

Examples of protrusions for different values of n are shown in Figure 5.

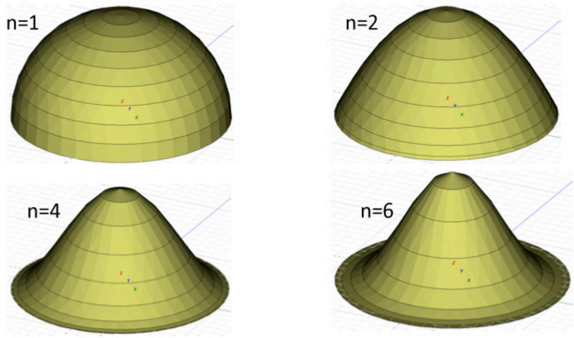

Figure 5: Parametric idealized protrusion shapes for different parameters of the power n.

We have modelled several of these profiles, and a comparison of results for n=4 surface to a smooth surface are shown in Figure 6. MICHELLE is being configured to read these data, along with the distributions for azimuthal angles and energy, in the form of a fitted curves for use in a modified emission model for rough-surface emitters. We are also planning to look at asymmetric structures under more typical current loading conditions in the near future.

CONCLUSION

Cathode surfaces often show microscopic roughness on the few-micron scale that can degrade macroscopic beam properties such as beam brightness. Since modelling such effects in detail is impractical, we have developed a technique to capture the changes to emission characteristics caused by surface roughness, and then use these distributions to modify emission from a numerically smooth cathode in order to include surface roughness effects in a practical fashion. Results on planar cathodes validate the back-projection algorithm that is used to determine effective emission profiles from simulation data. Preliminary results from modelling idealized rough-surface topologies show that effective emission characteristics can differ substantially from those of smooth emitters, and work is ongoing to incorporate the effective rough-surface emission distributions into MICHELLE for use in design studies.

REFERENCES

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[2] J. Petillo, et al., “Recent Developments in the MICHELLE 2D/3D Electron Gun and Collector Modeling Code”, IEEE Trans. Electron Devices Sci., vol. 52, no. 5, May 2005, pp. 742-748.

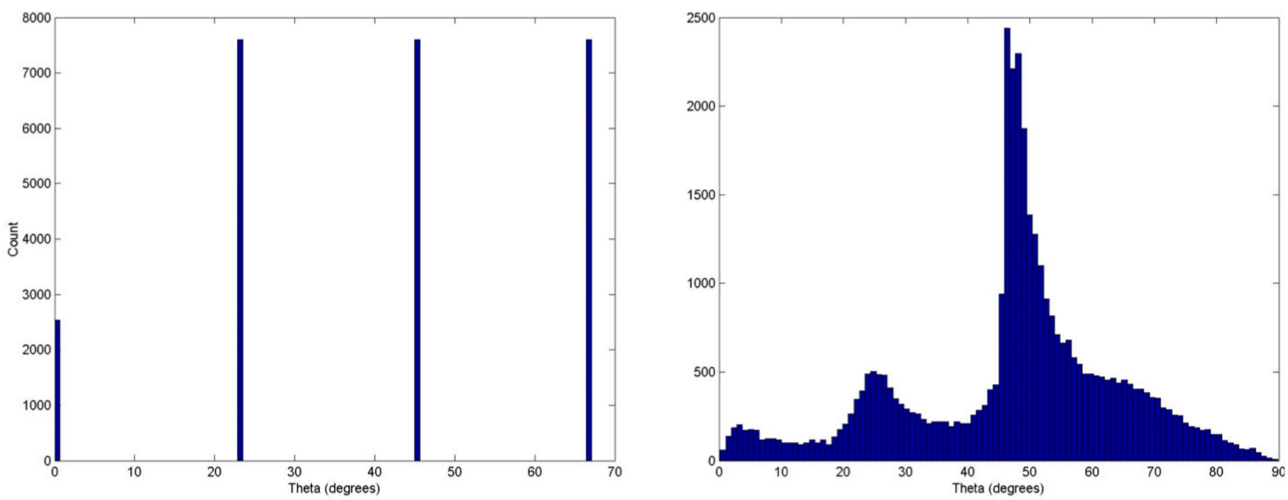

Figure 6: Results for smooth emitter (left) compared to n=4 protrusion (right). Plots show particle counts binned by effective polar emission angle showing the dramatic effect of the protrusion on the angular distribution. For this case we used 3 off-normal polar emission angles (23, 45, and 67 degrees). These cases were both for relatively small current loading: the smooth emitter had 19.1 mA/cm^2, and the n=4 protrusion had 18.4 mA/cm^2.