SIMULATION OF FIELD-EMISSION CATHODES FOR HIGH CURRENT ELECTRON INJECTORS

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Abstract

From the prospect of the high average current electron injectors, the most important advantage of the field-emission cathodes is their capability to generate very large current densities. Simulation of field-emission cathodes is complicated by the large range of spatial dimensions: from sub-micron scale, for a single field-emission tip, to millimeter scale, for a field-emitter array. To overcome this simulation challenge our numerical model is split in two steps. During the first step, only electrons emitted by a single tip are considered. In the second step, the beams originating from many single emitting tips are merged together to mimic the field-emitter array configuration. We present simulation results of injector based on field array emitters cathodes.

MOTIVATION

Since the gain of a Free Electron Laser (FEL) increases with the electron beam current [1], to achieve megawatt-class FELs the injector should be upgraded to ampere level of average beam current. This can be done with standard photoinjectors but problems related to low quantum efficiency and limited lifetime of the photocathodes still need to be addressed. The upgrade of the Jefferson Lab IR FEL [2], requires a complete replacement of the old photoinjector. The new photoinjector [3] can deliver average beam current at ampere level, but, according to our simulations both transverse and longitudinal emittances exceed the specifications. New electron sources (like field-emitting cathodes) could eventually have better performances than standard photoinjectors. Diamond made field-emitters are mechanically robust, can carry large density currents, and because of the large external fields in the emitting area, the emittance growth due to space charge is diminished.

THEORETICAL MODEL

Quantum tunneling allows extraction of electrons from atoms when large enough external electric field is present. The current density is given by Fowler-Nordheim (FN) equation:

$$j = \frac{K_1 E^2}{\phi} exp(-\frac{K_2 \phi^{1.5}}{E}) \quad (1)$$

where E is the external electric field, ϕ the work function of the material and K_1, K_2 constants. Throughout this analysis we use the same values of the constants as in [4], $K_1 = 1.54 \times 10^{-6}$ A eV/V^2, $K_2 = 6.83 \times 10^7$ V/ (cm eV$^{3/2}$) and the work function for diamond $\phi = 4.15$ eV. The graph of the current density as a function of external electric field is shown in Fig. 1.

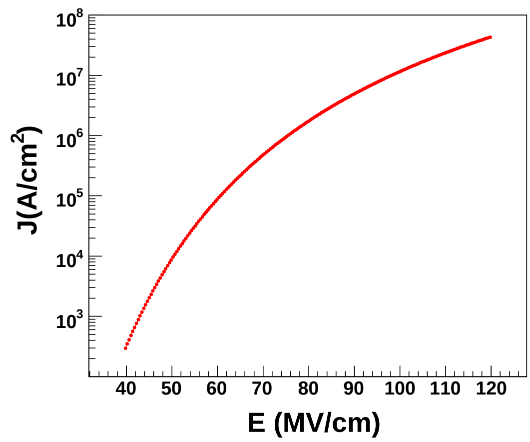

Figure 1: Fowler-Nordheim equation with the values of the constants indicated in the text.

In this paper we consider cylindrically symmetric diamond made field-emitters of conical shape. The tip of the cone is assumed spherical with a small curvature radius to favor a large external field enhancement in the region of the tip. The results shown in this paper are based on the assumption that the curvature radius of the field-emitting tip is 0.1 μm, but smaller tip radii of 0.05 μm and 0.01 μm were also considered. A field-emission cathode consists of an array of diamond made single field-emitters separated by distances of the order of a few tens of microns.

The simulation of electron beams from field-emission arrays is complicated by the large range of spatial dimensions: microns in the region of a single field-emitter and millimeters for the whole cathode. Therefore, as in [6], we split the simulation into two parts: first we simulate the electron beam from a single field-emitter and then in the second part the beamlets are merged together to mimic the beam extracted from the whole array of single field-emitters.

SINGLE FIELD-EMITTERS

A typical single field-emitter consists of a conical shape diamond made cathode, an accelerating control electrode (gate) and at least one focusing layer (Fig. 2). To control the injection phase of the electrons into the gun, it is convenient to apply on the gate a time dependent voltage such that the electrons are emitted only during a narrow time window [5]. Since time constants to reach steady state inside the emitter are in the subpicosecond range, it is reasonable to assume that external fields are static [6].

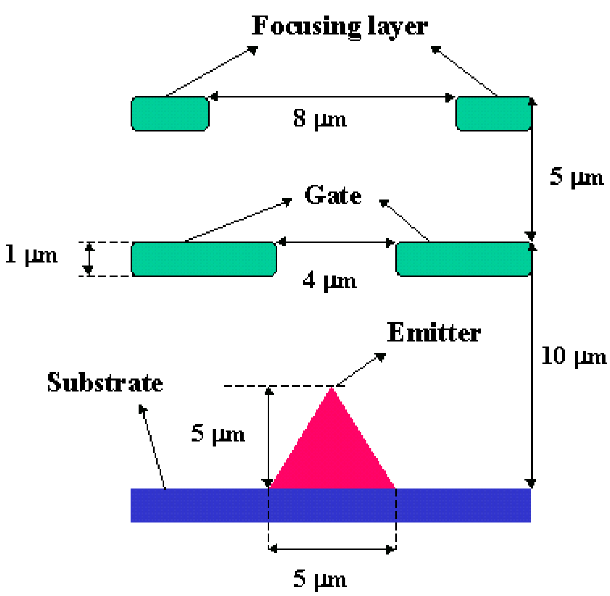

Figure 2: Geometry of single field-emitters.

In the first step of the simulation the map of the electric field is used to generate a particle distribution located just underneath the emitting surface. The electric field distribution (generated with LANL Poisson code [7]) depends on emitter geometry (Fig. 2) and on the constant voltages applied between the gate and cathode (V_1) and between the focusing layer and the gate (V_2). The accuracy of the field calculation is determined by the integration step used by Poisson software to evaluate the fields. This parameter was set at $10^{-2}\mu$m in both transverse directions for the most part of the integration domain. In the proximity of the tip, were the gradient of the electric field is significantly higher the integration step was lowered at $10^{-3}\mu$m.

The electric field at the tip of the diamond made cathode is a factor of $\beta \approx 30$ higher than the average accelerating field. An additional 4-5 enhancement factor is due to the surface roughness in the nanometer range [8]. To exemplify, the acceleration voltage should be about 530 V to obtain a total current of 57 μA if the surface roughness enhancement factor is conservatively assumed to be 4.

Our simulations show that the external electric field decreases rapidly with the radial distance from the emitter tip. In fact, external field is large enough to produce any significant field emission only in the region of the spherical portion of the field emitter. Figure 3 shows that the probability for field emission drops rapidly outside of the spherical region of the field-emitter. This observation may not be true

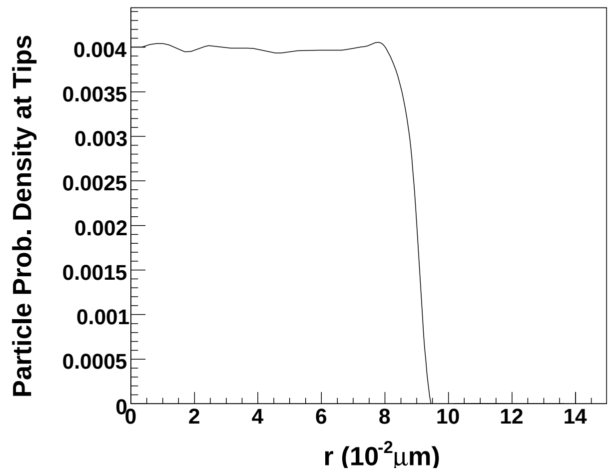

Figure 3: Probability of field emission as a function of the radial distance from the emitter tip.

in the case of pyramidal field-emitters because the electric field enhancement could be also large at the pyramid edges.

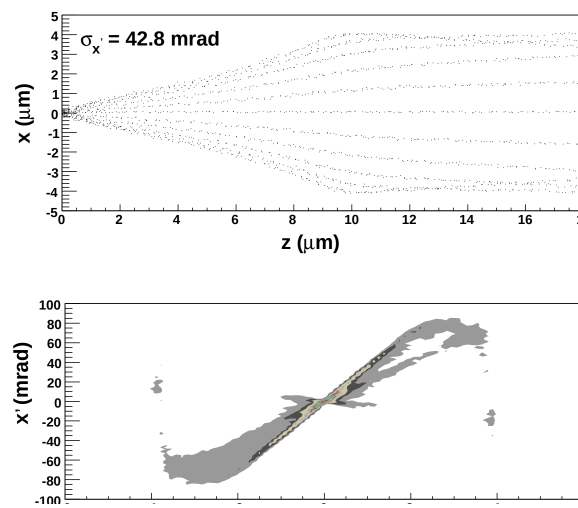

Figure 4: Top: electron trajectories when acceleration and focusing voltages are $V_1 = 530$ V and $V_2 = -400$ V respectively. Bottom: longitudinal phase space just after the focusing layer.

In the second step of the simulation the particle distribution generated in the first step is propagated from field-emitter to anode ($\approx 15\ \mu$m), with the particle tracking code Impact-T [9]. Slight modifications of the code were made to extract the particles from the beamlet once they arrive the anode and to store the new particle distribution. To focus the beam the voltage between the focusing layer and the gate (V_2) must be opposite to the accelerating voltage V_1. The lowest beam angular spread ($\sigma_{x'}$) is obtained when $V_2 \approx -0.75 \cdot V_1$ (Fig. 4).

For the case of $I = 57\ \mu$A, $V_1 = 530$ V and $V_2 =$

-400 V, the most important beamlet characteristics are: $(\epsilon)_{x,rms} = 8.3 \cdot 10^{-2}$ μm, $\sigma_x = 2.4$ μm, $\sigma_{x'} = 42.8$ mrad, $E = 0.34$ keV, and $\delta E/E = 4.5$ %.

Finally, the coordinates of the particles are translated in the transverse direction to mimic a distribution generated by an array of field-emitters. The longitudinal particle distribution depends on the accelerating and focusing voltages, but the pattern is similar to the initial distribution.

COMPARISON WITH PHOTOEMISSION-CATHODES

The JLab IR FEL injector electron source consists of a DC-voltage GaAs photocathode gun driven by a mode-locked Nd:YLF laser. The electric field at the surface of the cathode is about 6 MV/m and the kinetic energy at the gun exit is 0.5 MeV. The typical electron bunch has 135 pC and its volume is relatively large in order to minimize the space charge effects. During normal operation the laser pulse duration is about 20 ps (rms) and the radius of the spot is 4 mm.

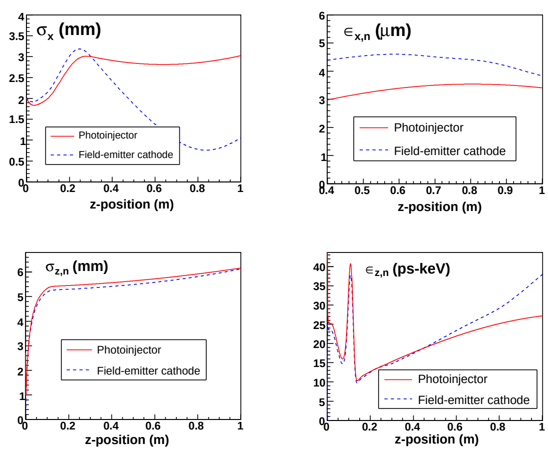

Figure 5: Beam moments at gun exit for a standard photoemission cathode and for a field-emitting cathode.

For comparison, we consider a field-emission array with individual emitters separated by 33 μm and with the same size as the regular photoemission cathode. To match the peak current of the standard photoemission cathode, each field-emitter should contribute with about 57 μA. The most important beam moments at the exit from the gun are shown in Fig. 5 for both standard photoemission cathode and field-emission array. The beam quality, measured by transverse and longitudinal emittances, is about the same in both cases.

CONCLUSIONS

Since the field-emission effect occurs when the external electric field is of the order of several GV/m, the most challenging problem is to build field-emitting structures that do not break under such intense fields. Recent work [10] show that somewhat simpler field-emitting structures (array of field-emitting diamond made pyramids and just one metallic layer) are very reliable and the fluctuation of the extracted current is remarkably low.

A comparison based on simulations between the Jlab FEL DC-gun and the same gun equipped with a field-emission array shows that beam quality is about the same when the average current is set at the normal operating value of 100 mA. The next goal for the high current Jlab FEL injector is to deliver beam current at ampere level and this is out of reach with the existing photoemission cathode. An important candidate could be a field-emission cathode because even a small increase of the external field would lead to a substantial increase of the peak current. For the field-emitter arrays considered here, an increase of the external field from 50 to 60 MV/m would bring the peak current from 50 μA to milliamp range. A field-emitting array consisting of a few thousands single emitters can deliver beam current at the desired level.

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