Design and Modeling of Field-Emitter Arrays for a High Brilliance Electron Source

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Abstract

Electrons emitted via field emission from micron sized metallic tips have an intrinsically low emittance. Using a doubled gated emitter geometry, parallel beamlets are produced from these tips, which can be combined with minor losses in emittance into a two dimensional field emitter array to reach the required beam current. The main performance degradation of the double gated structures is due to the presence of nonlinear transverse forces, which can be minimized by a suitable non planar gate geometry. The surface roughness of the tip can give an additional field enhancement of 2-3 and strongly influence the emission properties. This problem is modeled by a new semi-classical algorithm, which obtains the current densities and momentum distribution by computing the size and shape of the quantum mechanical potential barrier on the surface. For synthetically generated surfaces, one sees an increase in the energy spread to 0.5-1.7 eV. High performance field emitter cathodes require giving rise to nonlinear space charge forces. to avoid deterioration by space charge forces. The influence of inhomogeneities in the emission is specially pronounced, if they are spatially correlated, giving rise to nonlinear space charge forces.

CONTEXT

To realize compact Angstrom wave length free electron lasers, electron sources are required with high brilliance and a ultra low emittance. Only these allow both for low beam energies and short undulator lengths, dramatically decreasing the size and cost of such projects. The low emittance gun project (LEG) at PSI focuses on developing suitable field emitter arrays (FEA) emitting a total current of 5.5A with an emittance in the order of 50 nm rad. To preserve that emittance, the FEA should be operated in a pulsed DC diode at 250 MV/m, a device, that is also currently under development at PSI [1]. Numerically modeling all aspects of such a device must be done in steps, which are described in the following sections.

The first shows the beam dynamics inside the micron sized emitter itself and presents the way toward an optimized design. For metallic emitters, the surface roughness on the tips plays an important role in determining the emission. To model that, a new semi classical approach has been developed, which includes the essential quantum mechanical effects and obtains field enhancement factors and momentum distributions Finally, all this is combined into a macro simulation to get at the performance of the full arrays with up to 20000 emitters in a DC gun – first in an ideal world with zero fabrication tolerances and later also including inhomogeneities.

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INDIVIDUAL EMITTERS

With a FWHM energy width in the excess of 150 meV [2], field emission is not a process producing ultra cold electrons. The high brightness and low emittance comes from the small source sizes. A typical metallic tip, carrying up to 1 mA, will emit from areas in the order of 30 nm. With the energy spread cited above, this gives an emittance of a few times 10^{-12} m rad.

A peak current of 1 mA is far below the requirements for free electron lasers, so beamlets from 10^3 to 10^4 tips, arranged in an array over the cathode surface, have to be combined to reach suitable values. To carry over the low emittance of the individual beamlet into one for the full beam, each beamlet needs individual focusing, rotating the phase space ellipse of the emitted electrons from something, which is large in the momentum and extremely small in radius, into an enlarged and relatively parallel beam.

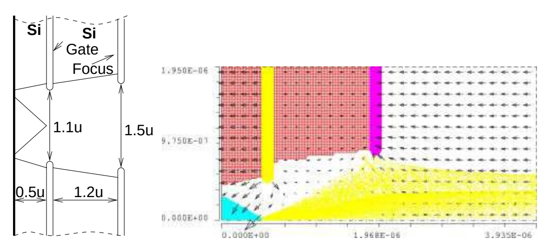

Figure 1: Layout of conventional double gated field emitter and beam trajectories for a current of 0.5 mA.

This can be obtained by a double gated emitter geometry (Fig. 1). The emitter consists of a metallic tip sitting on a metal substrate. After a first isolating layer, the gate layer creates the field extracting the electrons from the tip and simultaneously defocuses the beam. Together with the external main accelerating field, a second metal layer, being at a negative voltage with respect to the gate, refocuses the electrons into a parallel beam. This is also shown in the trajectories, which have been computed with MAFIA TS2 [4]. 500 μA is the limiting case for this layout, higher currents lead to beam loss into the focusing layer.

The phase space distribution (Fig. 2) shows strong non linear focusing forces, which are the most important effect limiting beam performance. Actually, here the resulting emittance for a full array is completely dominated by the blow up in the individual emitter [3], resulting in a baseline

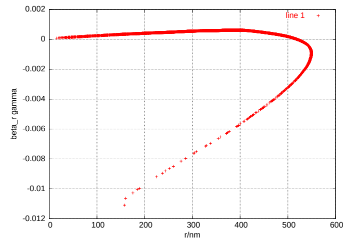

Figure 2: Transverse phase space 4 μm after focusing iris

emittance for a full cathode of 200 nm rad.

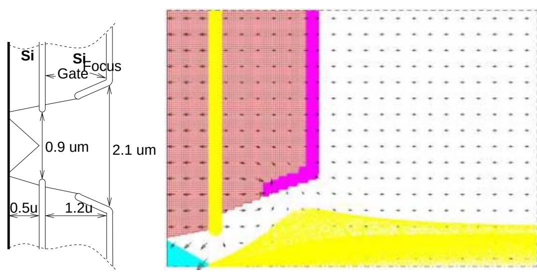

Figure 3: Improved design of double gated field emitter and beam trajectories at a current of 0.5 mA.

An improved geometry is shown in figure 3. The focusing iris is enlarged and its metallic layer extends partially into the isolator hole between focus and gate. To create a parallel beamlet, the focus layer has to be at the same potential as the tip, so that electrons hitting the layer have zero kinetic energy creating no heat up. The onset of focusing forces is more gentle exhibiting less nonlinearities. As the trajectories show, currents of 0.5 mA and more easily pass through the irises. The emittance of the beamlet is strongly improved from 0.31 nm rad to 0.12 nm rad. Results for the total beam are presented later in the article.

SURFACE ROUGHNESS EFFECTS

The surface roughness on a metallic tip can contribute strongly to enhance field emission. Slight edging of the surface may even be introduced in the fabrication process to produce that effect. Additional field enhancements of $\beta = 2 - 3$ are typical [5]. Since the local current density distribution is not homogeneous, an open question is the influence of this on current-voltage characteristics and the momentum distribution.

Typical geometric scales of roughness are in the nanometer range, which is approximately the width of the potential barrier, electrons have to tunnel through. Simply combining the electric field gradients at the emitter surface with the Fowler Nordheim equation to arrive at the current distribution will not work.

A full model requires solving the full quantum mechanical problem on an atomic scale, computing the potential distribution and the localized electron states on the surface as in [6]. The goal here is an intermediate algorithm, able to use measurement data from e.g. secondary emission microscopy without having to specify everything on an atomic level and still capturing the essential quantum aspects.

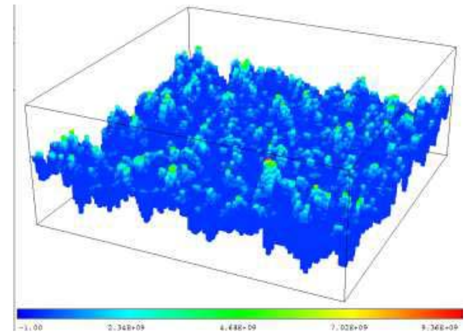

Figure 4: Random surface, color denotes surface gradient computed for an average gradient of 2 GV/m.

Motivating the algorithm, is, that not the surface gradient per se determines the current density. The electrons in the conduction band tunnel into the vacuum through a potential barrier determined by the work function of the material and the field distribution. The width of this barrier is the dominant parameter for the probability of the electrons tunneling through and so also for the resulting current density. Other details can be omitted, leading to the following approach:

- Given a rough metallic surface Γ_0 as in figure 4, compute the potential distribution for a given external average gradient E_{avg}. Γ_0 is assumed to be grounded.
- Determine the equipotential surface Γ_1 corresponding to the work function ϕ_w. The space between Γ_0 and Γ_1 is the potential barrier and we can calculate barrier widths $\delta(r)$ on Γ_1.
- $E_{eff}(r) = \phi_w/\delta(r)$ is the effective gradient, used in the Fowler Nordheim equation to compute the current density $\vec{S}(r)$.
- We have now an problem with emission with the known current distribution $\vec{S}(r)$ from an equivalent cathode surface Γ_1. The emission process is now modeled with a conventional particle in cell code [4] to obtain the the momentum distribution.

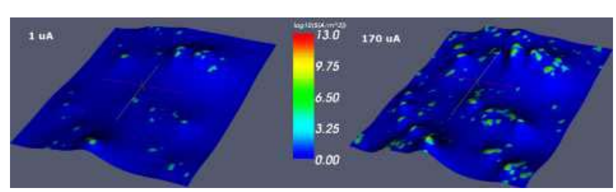

Figure 5: Equipotential surfaces Γ_1 of 4.2 eV with the current density (logarithmic scale in color) for 1 μA ($E_{avg} = 1.6\, GV/m$) and 170 μA ($E_{avg} = 3.5\, GV/m$) total current, as computed for the surface in 4.

Equipotential surfaces are shown in figure 5 and the particle emission in figure 6. With increasing gradient, the

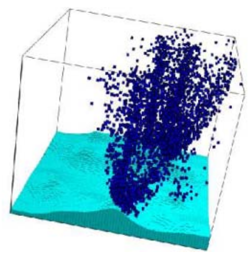

Figure 6: Particle distribution during emission for 16 μA total current ($E_{avg} = 2.8\,GV/m$))

width of the potential barrier comes down and Γ_1 conforms more and more to Γ_0. Only a small part of the surface actually contributes to emission, very minor for low currents and increasing in size, as the field strength goes up.

Table 1: Calculated emission properties (N_{95} number of strongest emission sites carrying 95% of current, σ_E/meV energy spread, β_{eff} field enhancement)

I/μA	N_{95}	σ_E/meV	β_{eff}
1.0	3	1158	2.7
16.0	4	1760	2.6
170.0	13	1458	2.1
1000.0	24	603	1.7

An interesting result is the variation of current density with the field strength. For a current of 1 μA, defining only three tiny emission sites is sufficient to describe 95% of the total current. As the gradient and total current goes up, more and more emitters join in going up to 24 sites at 1000 μA. This is actually an effect also seen in reality. Comparing the emission to that of a perfectly planar surface, the field enhancement factor can be calculated, which has the highest values for minimum current (Tab. 1). The energy spreads are in the order of 0.5-1.7 eV. To find out, whether there are current dependencies, more statistics – best with real, measured surface data – is needed. Nonetheless the values are in a range, where we do not expect detrimental effects on the beam.

COLLECTIVE BEHAVIOR

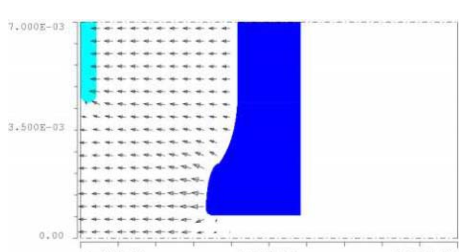

Figure 7: Gun geometry in cylindric coordinates together with accelerating field.

Finally we take a look at the beam dynamics of the whole field emitter array inserted in a DC diode gun (Fig. 7). It is designed to be pulsed with a voltage of 1 MV giving a mean accelerating gradient of 250 MV/m.

The simulation code [7] uses an equivalent emission model for the field emitter array, assuming a charge and phase space distribution on a planar cathode, which corresponds to that seen after the focusing iris of the individual emitters. Still the particle in cell simulations require micron precision leading to mesh sizes of 10^8 to 10^9 cells.

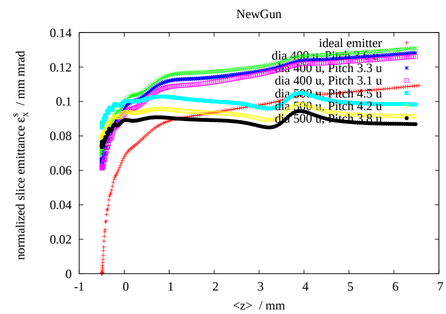

Figure 8: Evolution of slice emittance during emission for a reduced gradient of 125 MV/m. Shown are cases with different cathode diameters and array pitch. The idealized emitter has zero initial emittance.

High initial accelerating gradients are a prerequisite for a good initial emittance (Fig. 8). Reducing the gun voltage by a factor two lets space charge forces dominate the emittance growth. Even an ideal field emitter array with zero initial emittance gives slice emittances in excess of 100 nm rad.

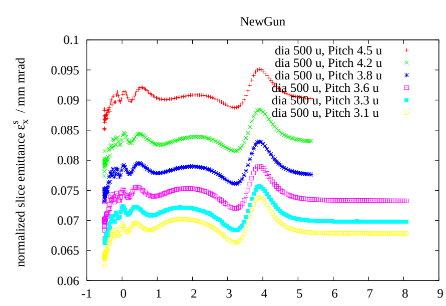

Figure 9: Evolution of slice emittance during emission showing the effect of the array pitch (emitter density).

A second point is the influence of the distance between emitters, the pitch, on the beam quality. As it shrinks, the number of tips on the cathode increases and the current per tip decreases. Nonlinear optical effects within the emitter get less pronounced, so the initial emittance of the beam falls. Less granularity of the transverse current density at the micron scale may also lead to less space charge effects. But given the relatively parallel curves in figure 9, this seems to be a relatively small effect.

Stochastic inhomogeneities

Fabrication tolerances, impurities, adsorbents all lead to variations in the emissivity of field emission tips. A part of the emitters will emit reduced or not at all, decreasing the peak current to be obtained by the array. Emitters will operate outside their designed working point generating beamlets with non zero divergence. Spatially correlated variations (e.g. due to fabrication) may produce increased space charge effects.

All of this is captured in a stochastic cathode model. Emission is described by the field enhancement factor β with a given mean (10 in the cases shown) and a standard deviation σ. A second parameter ζ describes the spatial correlation between adjacent emitter such that:

$$\mathrm{cov}(\beta_i, \beta_j) = \sigma^2 e^{-|r_i - r_j|/\zeta} \tag{1}$$

Putting the random β_i into the Fowler Nordheim equation yields a current distribution. A parametrization using single tip simulations gives corresponding values for beam radius, divergence and initial emittance. Asymmetries, as in the alignment between gate iris and tip, are not included, since they should not occur due to the fabrication process.

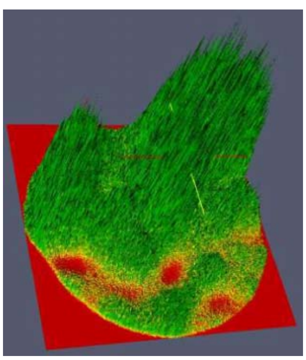

Figure 10: Stochastic transverse charge distribution at the exit of the gun ($\beta = 1$, $\zeta = 15\mu m$)

Using results from the previous subsection, a FEA with 500 μm diameter with an array pitch of 3.1 μm corresponding to approximately 20000 emitters was chosen. Figure 10 shows one of the resulting charge distributions, as seen at the exit of the gun. Apart from the inhomogeneities, the figure also demonstrates, how the granular structure of the beam as an array of beamlets is conserved during acceleration.

For all cases except the perfectly homogeneous one ($\sigma = 0, \zeta = 0$), eight runs with different random seeds were done to obtain statistics for each set of values, results are given in table 2. For iid distribution ($\zeta = 0$), we see some increase with σ, which becomes more pronounced for the spatially correlated cases. Here, nonlinear space charge forces due to the inhomogeneities dominate the growth in emittance. A curiosity is the one result with $\sigma = 1$ and $\zeta = 0$, giving an emittance of 47 nm rad. Here, the random generator produced a distribution with a good rotational symmetry, even outperforming the homogeneous case. Quite interesting, but not an effect to be relied on . . .

Table 2: Slice emittance in nm rad in the bunch center. (Average field enhancement $< \beta >= 10$, σ standard deviation of β, ζ correlation length in μm)

σ	ζ	min(ϵ)	$< \epsilon >$	max(ϵ)
0.0	0.0	68.0	68.0	68.0
1.0	0.0	96.7	98.9	103.1
1.0	15.0	256.1	373.0	469.4
1.0	50.0	47.1	284.2	474.4
2.0	0.0	169.7	175.0	183.6
2.0	15.0	372.4	419.3	458.0
2.0	50.0	246.4	403.3	572.6

CONCLUSIONS

Double gated field emitter arrays are interesting candidates for high brilliance electron sources. Nonlinear transverse forces are dominating the performance of the individual emitter and require special geometric layouts. In order to model the effect of the surface roughness at the emitter tip on the beam quality, a new semi classical algorithm is presented. First results with synthetic geometries show a yet manageable increase in the energy spread, a result, which has to be confirmed with more simulations.

Within a high gradient DC gun, the low emittance beam generated by the full array can be preserved during acceleration. Still the emittance is highly sensitive to spatially correlated inhomogeneities in the current density due to nonlinear space charge forces.

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