COMPARATIVE STUDIES OF ELECTRON SOURCES FOR A FREE ELECTRON LASER AT PSI

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Abstract

Within the scope of the low emittance gun project (LEG) at PSI, research is conducted into the development of a high brightness electron source suitable for compact, short wavelength free electron lasers. The gun, supposed to generate up to 5.5 Amperes of beam current, consists of a pulsed DC diode followed by a 1 1/2 cell RF gun. Using specialized codes, the performance of field emitter arrays is evaluated assuming realistic geometries. As an alternative, we examine the performance of conventional photo emission using copper cathodes, which we compare to that of field emitter arrays.

INTRODUCTION

High brilliance electron sources are an essential ingredient for a compact free electron laser in the Angstrom wavelength region. Their low emittance simultaneously reduces the required beam energy and saturation length for the lasing process, decreasing the cost and size of such a facility.

A study at the Paul Scherrer Institut (PSI)[1] focuses on developing suitable technologies toward a low emittance gun (LEG). We see double gated field emitter arrays as an option for a electron source with a strongly reduced initial thermal emittance, the objective being a current of 5.5 A with a slice emittance of 50 nm rad. Development of a suitable emitter is under way at PSI's laboratory for micro- and nanostructures (LMN)[2]. To avoid space charge forces destroying the emittance, fast acceleration in a pulsed DC diode gun running at high gradients up to 250 MV/m is a second focal point of research.

To simulate these devices with the required accuracy, special codes and techniques have been developed[3]. Special care has been exercised in modeling all real world effects using a realistic initial phase space distribution including also inhomogeneities in the emission density. In the following, we give an overview of current results. For comparison, similar simulations have been performed assuming emission from a copper cathode.

FIELD EMISSION CATHODES

Also known as Fowler-Nordheim tunneling, field emission is a form of quantum tunneling in which electrons pass through a barrier in the presence of a high electric field [4]. Being a cold emission process, it is seen as a possible alternative to photo emission, the advantages being a more simple, robust setup and the potential for a higher brightness.

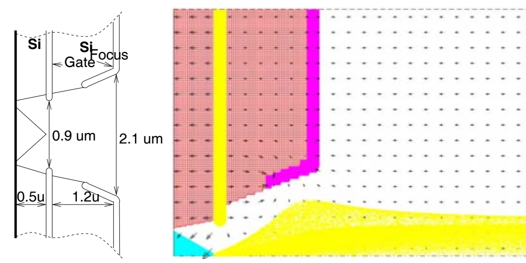

Figure 1: Geometry of double gated field emitter with beam trajectories ($I_b = 0.5mA$).

To create the required current, micron sized field emission tips are grouped into arrays, typically with a gate creating the necessary field to extract the electrons. The beamlet out of a tip will diverge strongly due to field forces and space charge effects resulting in a large emittance. A double gated geometry as in fig. 1, where the second gate acts as an electrostatic lens, avoids that in minimizing the transverse momentum spread.

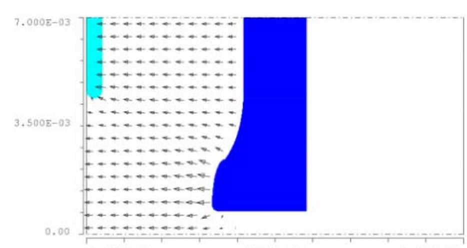

Figure 2: Gun geometry in cylindric coordinates together with accelerating field.

Parameterizing the phase space of the individual tip, we compute the beam dynamics in the pulsed DC gun[6]. The geometry is shown in Figure 2. The nominal accelerating gradient is 250 MV/m. Optimizing the cathode layout resulted in a cylindrical array of emission tips with a diameter of 500 μm. Figure 3 shows, how the slice emittance evolves from emission at the cathode ($z = -0.5mm$) to the drift following the anode. The emittance is dominated by the initial momentum spread of the individual beamlets. If, as in the second trace in Figure 3, we assume an ideal emitter geometry producing a zero emittance and divergence beamlet, a much better total performance with an emittance value of 23 nm rad could be obtained. So, optimizing the initial momentum spread of the emitted electrons further is of high interest.

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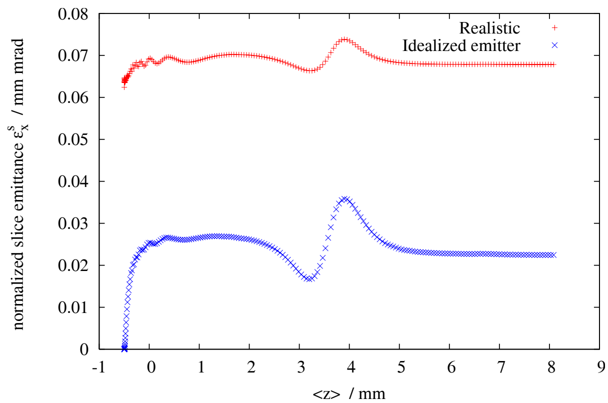

Figure 3: Evolution of slice emittance for homogeneous field emitter array ($E_{acc} = 250MV/m$). Upper trace uses phases space computed from geometry in fig. 1, lower trace assumes ideal emitter with zero initial momentum spread.

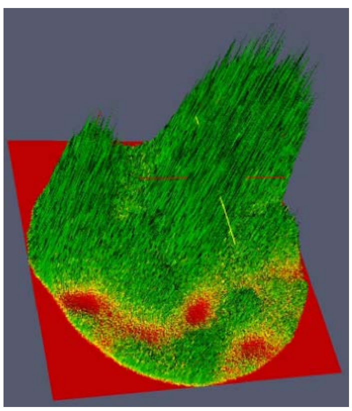

Figure 4: Stochastic transverse charge distribution at the exit of the gun ($\beta = 1$, $\zeta = 15\mu m$)

Typical field emitter arrays are subject to strong variations in the tip to tip emission current. We hope to be able to reduce that by advanced conditioning techniques, as discussed for example in [7]. Nonetheless, we cannot hope to eliminate the problem completely and any realistic simulation should take account of that. As a model, we assume a stochastic distribution of the field enhancement factors of

Table 1: 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

the individual tips with mean $< \beta >$, a standard deviation σ and a spatial correlation length ζ. Inserting it into the Fowler Nordheim equation, we obtain the current distribution used in the gun simulation. Figure 4 shows an example. As can be seen in Table 1, an inhomogeneous field enhancement distribution has a relatively small influence on the emittance, as long as it is spatially uncorrelated. In this case, the voltage of the focusing gate is no more perfectly matched to the tip currents, which leads to increased momentum spread of the emitted electrons. The initial emittance is increased, but still inhomogeneities in transverse charge distribution are very localized, so that the amount of additional nonlinear space charge forces stay limited. Dangerous are any spatial correlations. These lead to macroscopic space charge forces and result in emittance growth in the gun.

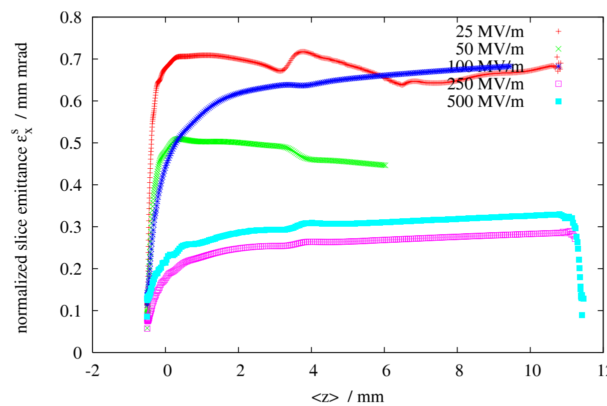

Figure 5: Evolution of slice emittance for an inhomogeneous field emitter array ($\sigma = 2$, $\zeta = 50\mu m$) for various accelerating gradients. The initial current densities have different distributions (but same stochastic momenta) and are not perfectly comparable.

As space charge effects are relatively minor in the homogeneous case, lowering the accelerating gradient only has small effects on the emittance. The situation looks quite different, if one includes inhomogeneities. Here space charge dominates the emittance growth and high gradients help to avoid major deteriorations. Fig. 5 shows results from runs with different gradients. When comparing the traces, one should keep in mind, that the initial current densities had the same stochastic momenta,but differed in their actual distributions generated, so that we cannot do an exact comparison. Nonetheless, it is clearly visible, that for gradients below 250 MV/m, we get strong space charge effects. In conclusion, elevated gradients are an interesting tool to compensate for higher tolerances of the field emitter array.

PHOTO EMISSION

For comparison purposes, we present computations with the 2 1/2 particle in cell module MAFIA TS2[8] using a photo emission model. As in the last section, the diode geometry is that of fig. 2. We assume photo emission by a laser with a wave length of 260 nm from a smooth copper cathode of diameter 500 μm. The laser pulse has a flat top shape of 40 ps length generating the design current of 5.5 A.

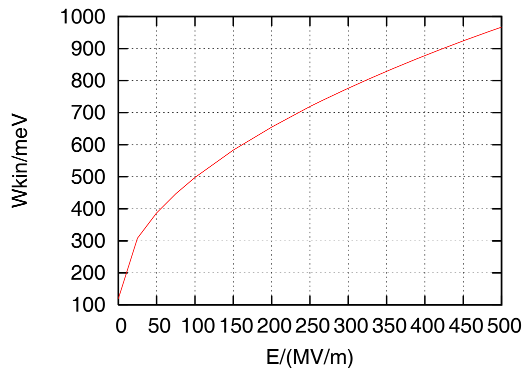

Figure 6: Initial momentum spread at cathode versus accelerating gradient

The transverse current density is taken to be homogeneous. As the accelerating gradient increases, the effective work function at the cathode surface is lowered due to the Schottky effect and, due to the difference between the energy of the laser photons and the work function, we have to assume a larger initial momentum spread of the emitted electrons (Fig. 6).

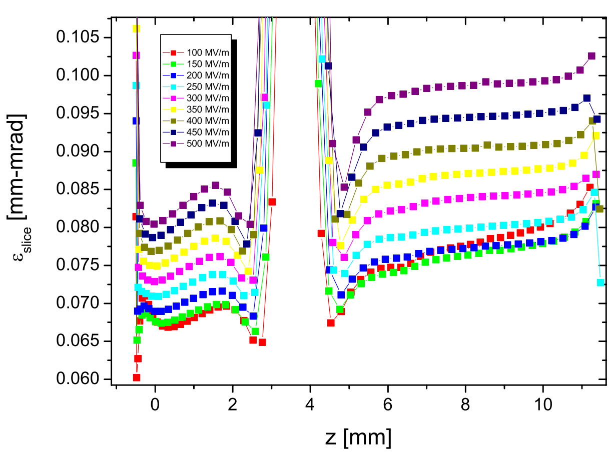

Figure 7: Emittance of center slice of 40 ps bunch for various gradients.

Fig. 7 shows in fine resolution the emittance of the center slice in the beam, as the bunch gets accelerated through the gun. Of special interest is the variation of the final slice emittance as a function of the gradient. For low fields, the initial (thermal) emittance is low because electrons are emitted with low kinetic energy. But there is not enough acceleration and the emittance grows due to dominating space charge effects. For high gradients, emitted electrons are immediately accelerated but the initial thermal emittance is starting to dominate. At 150 MV/m, both effects balance out, so that a theoretical minimum of 75 nm rad is reached.

An open question is the influence of inhomogeneities either in the transverse current distribution or ripples of the emitted current on the optimum gradient and the minimum emittance. Further simulations are under way to clarify these points.

DISCUSSION

We present simulation results for a field emitter based electron source. Using the realistic emitter geometry and assuming a perfect homogeneity of the emitter array, a slice emittance below 70 nm rad can be obtained for the design current of 5.5 A. This value is mainly determined by nonlinear optical effects in the individual emitter and emittance growth in the diode. Inhomogeneities lead to deteriorations, which are most pronounced, if their spatial distribution lead to increased space charge effects. As we go up in gradient, the beam gets accelerated early into relativistic velocities and becomes more tolerant to imperfections in its initial distribution.

Under idealized assumptions, photo emission can reach similar levels of performance. In terms of sensitivity to transverse inhomogeneities, we expect a similar behavior as for field emission cathodes. Additional deteriorations may come from current ripples due to spikes in the incoming laser pulse creating short range wake fields.

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