THEORETICAL ELECTRON DYNAMICS IN THE LOW EMITTANCE GUN

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For the pulsed DC gun planned for the LEG project, we explore suitable operating regimes. Assuming smooth current distributions at the cathode, gradients of 500 MV/m and peak currents of 5 A are reasonable design targets. For lower gradients, conventional RF guns start to become competitive. Using a self developed parallel 3D particle-in-cell (PIC) code, more refined simulations are presented, showing the effect of the granularity in the transverse current distribution on the resulting slice emittance of the beam. In order to assess the effect of real world variations in the emissivity of FEAs, spatially uncorrelated tip failure is simulated. The result shows a relatively robust behavior with respect to tip failure rates up to 50%. The emitter model still is in the process of refinement, further results are forthcoming in 2005.

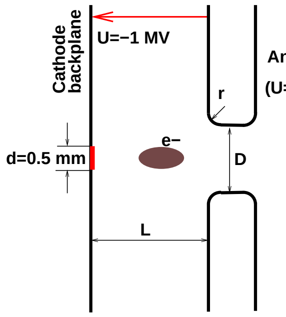
INTRODUCTION

A crucial point in the design of the LEG gun is creating and preserving the emittance of a relatively high current beam emitted from a field emitter array (FEA) through the gun, where space charge effects and field nonlinearities are particularly obnoxious.

In the first part, we present a parameter study that was conducted to see the influence of different field gradients and beam currents on the resulting emittance. For simplicity, the computations were done in $2{}^1\!/_2$ D using a smooth current distribution.

In order to see the effect of the granularity in the transverse current distribution, a high-performance 3D Maxwell time-domain field solver with relativistic collisionless PIC particle tracking has been implemented in C++ using the POOMA II[11] framework for parallel computing on the Linux platform. Sophisticated C++ expression templates techniques deliver Fortran performance combined with high-level programming and development comfort.

As a first step towards a realistic model, we investigate the effect of random emitter failure, as observed in real FEAs.



E_{avg} (MV/m)	100	200	500	1000
L (mm)	10	5	2	1
D (mm)	4	2	1.5	1
r (mm)	0.5	0.25	0.2	0.12

Fig. 1: Basic diode structure

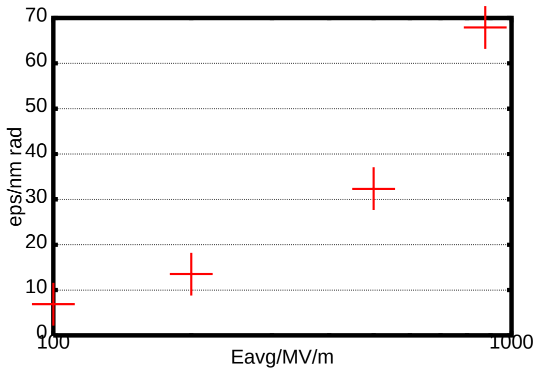


Fig. 2: Emittance due to nonlinear transverse fields in the iris at near zero current (I=1μA).

BASIC PARAMETER SCAN

In the following we concentrate on the parameter important for FEL operation, the sliced emittance, where only the particles in the center slice (a 1 psec slice length was used) are included in the emittance calculation.

We assumed a 1 MV total accelerating voltage in a diode configuration as shown in figure 1. The gap was adjusted for various average gradients between 100 and 1000 MV/m, the dimensions of the anode iris was likewise adjusted to avoid beam loss up to 10 A and simultaneously minimize field distortion effects.

A cathode diameter of 0.5 mm was assumed, emitting with a constant current density. Both a Gaussian as well as flat top pulse shape of 20 psec FWHM length were used for the temporal current distribution, no major differences in terms of the sliced emittance have been found.

The emittance growth within the gun is mainly determined by two effects. One is due to nonlinearities of the transverse components of the main accelerating field, which are caused by the iris opening in the anode. The effect is determined by the accelerating field and the gun geometry and is completely independent of the beam current (Fig. 2). Remarkably, this baseline effect is reaching the limit of $5 \cdot 10^{-8}$ m rad for extremely high gradient designs ($\geq$ 1 GV/m). This is due to the fact, that with increasing gradient the iris hole gets closer to the cathode, causing field distortions and emittance blow up shortly after emission.

The second source of deteriorations lies in the self field of the bunch. With a constant transverse current

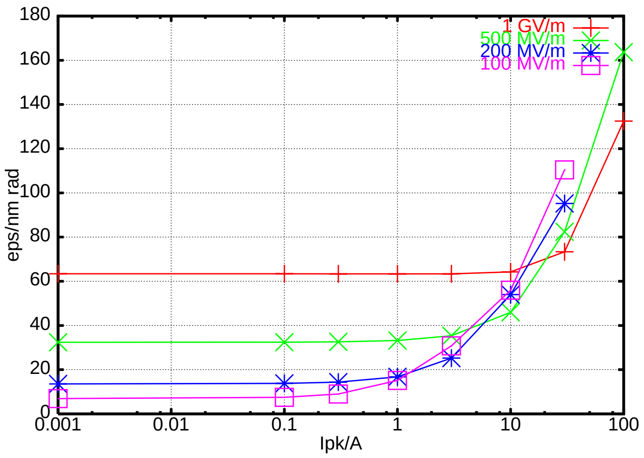


Fig. 3: Sliced emittance for the different designs and peak currents

distribution and highly relativistic velocities, these are purely linear functions of the radial offset and do not cause emittance growth. This is quite different for the nonrelativistic regime shortly after emission, with nonlinearities in the self field and subsequent emittance blow up – more or less proportional to the current and inversely proportional to the accelerating field. An additional effect would be wake fields, but we did not see any major influence for the parameters used.

Overall, one expects the following picture. For gun designs with low gradients, the baseline emittance due to geometry is relatively small, but we get a fast deterioration with increasing current. As we increase the gradient, this baseline rises, the advantage being a lower sensitivity to high beam currents (Fig. 3). As can be seen, reasonable performance could be expected for around 500 MV/m with a beam current of 5 A.

Alternative options: RF gun

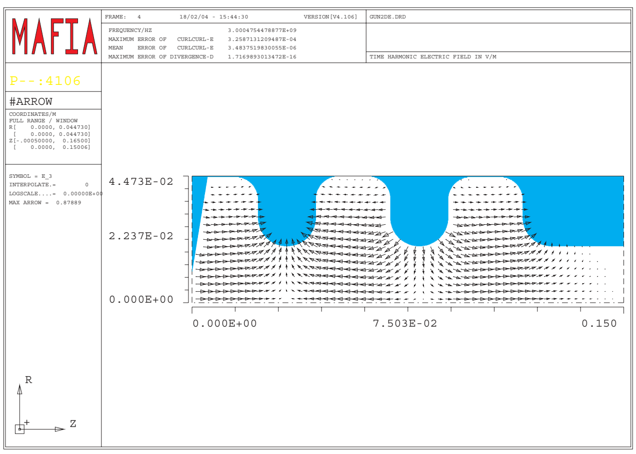


Fig. 4: Accelerating field in CTF gun 4.

An interesting question is how the performance in a diode configuration compares to an RF gun. Certainly, current RF guns offer peak gradients of only about 100 MV/m, but acceleration goes up to a few MeV total energy and geometric field distortion can be expected to be less due to larger cavity lengths and iris dimensions.

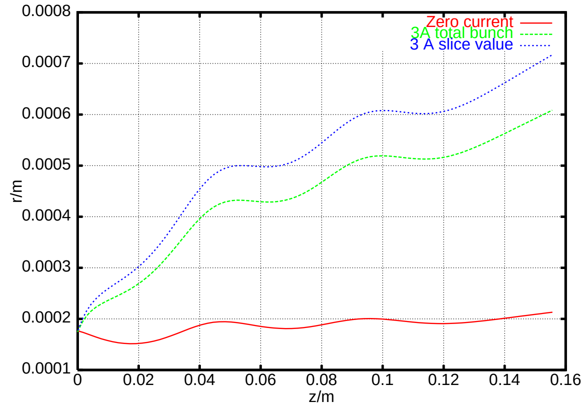


Fig. 5: Rms beam radius inside the gun for various currents.

For the comparison, we used a real world design, a RF gun, which has been used for the drive beam generation in the CLIC test facility CTF II [1], the main accelerating π-mode is shown in figure 4. The simulation uses a peak gradient of 100 MV/m, a value, which was employed in CTF II routinely for this kind of gun. As in the diode gun, a cathode diameter of 500 μm is used with a 20 ps FWHM current distribution. Due to the prolonged first half cell, emission is at an RF phase of 30 degree, or 60 degrees off crest. At the gun exit, a beam energy of approximately 6.5 MeV is reached.

A plot of the rms beam diameter can be seen in figure 5. A near zero current (computed with 1 μA) gives a relatively constant beam waist, with oscillations introduced by transverse RF fields near the structure's irises. For a current of 3 A, space charge forces become visible provoking a significant beam divergence, most pronounced for the center slice carrying the peak current.

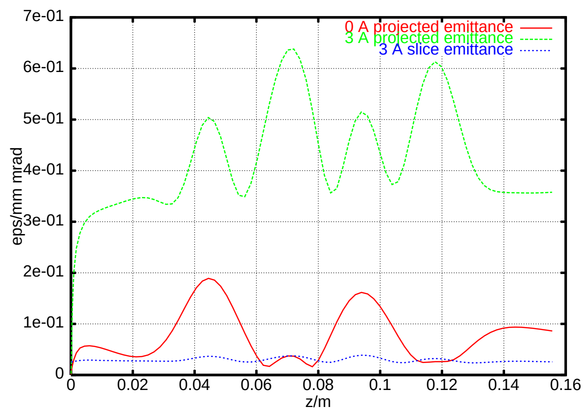


Fig. 6: Evolution of emittance (projected for zero current and 3 A and projected for 3 A) in the gun.

Figure 6 shows the emittance growth inside the gun for the different cases. The total or projected emittance for zero current shows some oscillations, which are due to the bunch head being rotated differently in phase space than the tail. This RF induced emittance turns out to be 0.1 mm mrad. Things become different for a current of 3 A. The space charge forces act most strongly in the first few millimeters, we get a strong jump in the beginning. In the following we see mainly the wiggles caused by transverse RF field resulting in a total value of 0.36 mm mrad. Emittance growth due to space charge forces seem to be mainly due to a defocusing action proportional to the current in the local bunch segment and not to nonlinear defocusing, since this effect is strongly reduced when looking at the slice emittance. Here we see a jump at the beginning to 0.03 mm mrad, a value which stays more or less constant up to the end.

GRANULARITY EFFECTS

In order to capture the intra beam forces due to strong transverse variations of the current density on the μm scale, a parallel 3D particle in cell code was written, whose structure is described in the following.

Methods

The numerical simulation of the electromagnetic field dynamics uses the Finite Integration Technique [5]. This method is also used in the commercial code MAFIA because of its good convergence behavior [6]. The electric current density created by the electrons is numerically obtained with a charge conserving scatter scheme [7] in combination with a spatial smoothing filter. Both particles and fields are integrated in time-domain using leap-frog split-operator techniques [10]. For the generation of a consistent initial electrostatic field solution, we are using an iterative conjugate gradient solver together with an incomplete Cholesky pre-conditioner with additional red/black checkerboard type domain decomposition. For details on these techniques, see [8]. All modules are based on POOMA II and are fully parallelized.

Results

We present simulations of the DC gun shown in figure 1. The used parameter set is E$_{avg}$ = 500 MV/m, L=2 mm, D=1.5 mm, r=0.2 mm.

The effect of a given rate of field emitters in a FEA not contributing to the emission is investigated. Spatially uncorrelated tip failure probabilities were assumed. One goal is to compute the effect of the granularity in the current density distribution due to an emitter array, as compared to a smooth density expected from e.g. a photocathode. A second goal is to analyze the influence of imperfections in the homogeneity of real life FEAs on the beam quality.

The performance of FEAs is typically degraded by several effects. First are variations in the emission of individual tips due to production and aging. Typically only a part of the emission sites contribute to the beam, with some global, highly correlated variation over the whole region.

Another effect inherent even in perfect field emitters is noise in the emission current due to adsorbate diffusion and adsorbates switching between emission states [13]. For low current emission at room temperature, the switching adsorbates jumping between emission sites leading to current variations are the dominant process. The resulting current fluctuations are in the millisecond range. Talking about the whole array, the noise effects from individual tips are uncorrelated.

For the numerical simulation, a discretization of one symmetrical quarter of the gun with 8M (158x158x310) grid points with focus on good transverse resolution of 4 μm in the beam region was used. Up to a maximum of 2000 micro bunches with a FWHM pulse length of 2 ps and a diameter of 2 μ m are emitted from a circular FEA of radius $r = 0.25$ mm with a pitch of 10 μ m.

Failure probabilities of the emitters were varied from 0% to 80%. A total current of 5 A modeled by 200'000 macro particles was used in all cases.

Figure 7 shows the effect on the transverse particle distribution. Some minor differences in transverse phase space can be observed, leading to rms emittance growth. A growth of the normalized slice emittance at the center of the bunch from $2.5 \cdot 10^{-2}$ mm mrad (0% failure probability) to $4.1 \cdot 10^{-2}$ mm mrad (50%) and $7.7 \cdot 10^{-2}$ mm mrad (80%) is shown in figure 8.

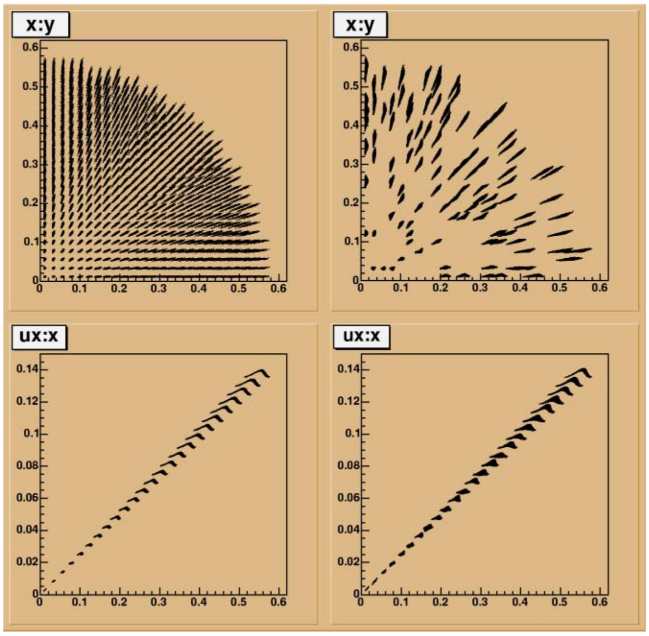


Fig. 7: *Effect on transversal particle distribution and phase space for FEA simulations with 0% and 80% failure probability, at $z = 9$ mm. Positions are indicated in mm.*

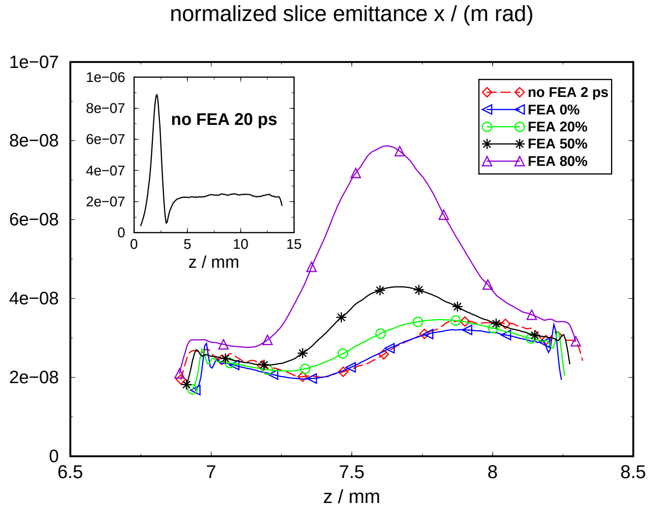


Fig. 8: *Normalized slice emittances of the 2 ps FWHM bunches. "no FEA" refers to a smooth initial current distribution, whereas "FEA x%" denotes an emission from a FEA with x percent single emitter uncorrelated failure probability. Comparison with the slice emittance of a 20 ps FWHM bunch shows the influence of wake fields. All slice emittances have been calculated using a Gaussian weighting function with a sigma of* $1/100$ *of the bunch length (about* $13\mu m$ *for the 2 ps cases).*

CONCLUSION

The design of a DC gun for LEG is a compromise of two different effects. One is the baseline emittance growth caused by the gun geometry itself, which calls for an elongated gun geometry with low gradients. The other is space charge induced emittance blow up, which necessitates short gap lengths with high gradients. A good compromise for a 1 MV total voltage seems to be a design with a 500 MV/m allowing currents up to 5 A.

RF guns are reasonable alternatives in particular for smaller currents and lower field gradients. Electron beams up to 3 A con be generated with an excellent emittance.

A parallel high-performance 3D DC gun Maxwell PIC code with many features has been implemented using the C++ POOMA II / MPI framework on Linux. Validation shows good agreement with Mafia TS3. First results on simulations of FEAs show the stability of slice emittance growth with respect to uncorrelated tip failure rates up to 50 percent.

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