ELECTRON BEAM DYNAMICS SIMULATIONS FOR THE LOW EMITTANCE GUN

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Abstract

In the scope of the LEG Project at PSI [1][2] a field emitter array (FEA) cathode is being considered as an electron source. We present simulation results for a gun test stand performed with the code MAFIA [3] as well as report on the novel parallel 3D PIC code "Capone" which will allow realistic simulation of particle emission from FEA cathodes with the required sub-micron resolution.

100 KEV TEST STAND

In order to characterize the electron beam generated by pulsing an FEA cathode in vacuum under high voltage and to study emittance minimization by space charge compensation, it was decided to build a 100 keV gun test stand. The test stand will consist of a HV power supply deck, removable in-vacuum electrodes, solenoid magnets, drift line and diagnostic module (faraday cup, pepper pot, slit masks, screen). Construction of the first vacuum sections has just recently began.

Design & Parameter Studies

The specification of the cathode mount, anode structure and diagnostic equipment requires precise knowledge of the beam dynamics within a beam already "stiffened" by relativistic effects on one hand, but not yet highly relativistic ($\gamma = 1.196$ and $\beta = 0.548$ at 100 keV) on the other. Therefore the gun configuration, solenoid structure, drift beam line and diagnostic components have been modeled in 2D with the code MAFIA and extensive parameter studies have been conducted [4]. Key parameters of interest are beam spot size σ_r, divergence $\sigma_{r'}$, normalized transverse emittance $\beta\gamma\epsilon_r$, bunch length σ_z and momentum spread σ_p/p.

We tracked 20k macro-particles from the cathode surface to the end of the drift section. The active emitter radius is expected to be r_{act} = 0.1 mm. The initial particle energy was chosen to be $\gamma_0 = 1.0001$, and the initial divergence was set to zero. The pulse form was Gaussian with a cutoff at $\pm 3\sigma_t$, with σ_t = 20 ps, and a bunch charge chosen to give a peak current of $\hat{I}$ = 100 mA.

The gun geometry has been optimized for minimum emittance at its exit while keeping the accelerating gap large enough ($\approx$ 11 mm) to avoid peak electric field strength larger than 20 MV/m on the anode iris. The minimum anode iris radius allowing the beam to pass without particle loss is r_{iris} = 0.5 mm. The minimum normalized transverse emittance at the end of this gun configuration was found to be $6{\cdot}10^{-8}$ m·rad.

The designed solenoid structure with a maximum current density of 7 A/mm^2 is capable of delivering 200 mT of magnetic field strength on axis. Through proper tuning of the solenoid current we expect to achieve beam focusses at any location in the drift section behind the gun structure with a minimum normalized transverse emittance as low as $1.6{\cdot}10^{-8}$ m·rad.

Furthermore, the parameter studies show that proper adjustment of the solenoid current as well as simple changes to the gun geometry will allow the emittance to be optimized for different emitter radii, bunch charges, or bunch lengths. The obtained simulation results will be compared to experimental data when test stand construction is completed in the fall of 2004.

Slice Emittance

In the LEG project a single-pass SASE FEL is considered as a source of short pulses of coherent 1 Å X-rays [5]. In such a scheme it is found that the critical parameter in order to achieve high brightness laser pulses is the slice emittance (which depends on the location z_0 of the slice within the bunch and the width σ_z of the slice) rather than the projected emittance of the entire bunch [6]. MAFIA by itself delivers only the projected emittance of the bunch, but it can dump the radial and longitudinal phase space of all particles at a certain time t_0 from which the (normalized) slice emittance can be approximated:

$$\varepsilon_{t_0} = \gamma\beta\sqrt{\langle r_{t_0}^2\rangle\langle {r'_{t_0}}^2\rangle - \langle r_{t_0}\, r'_{t_0}\rangle^2}$$

With slice means calculated according to:

$$\langle r_{t_0}^2\rangle = \frac{1}{W_0}\sum_{i=1}^{N} {r_i}^2 \cdot w_{i,0}$$

Where a weighting function has been introduced in order to sample the bunch:

$$w_{i,0} = e^{-\frac{(t_i-t_0)^2}{2\sigma_t^2}} = e^{-\frac{(z_i-z_0)^2}{2\beta^2c^2\sigma_t^2}} \qquad W_0 = \sum_{i=1}^{N} w_{i,0}$$

An example for such a slice emittance calculation is given in Fig. 1. As expected the slice emittances lie well below the projected emittance of the entire bunch. Also, one can see well that the slice emittance is larger at the ends than at the center of the bunch; this is what one would expect due to the fact that non-linear space charge forces (which blow up the emittance) are largest at the bunch ends.

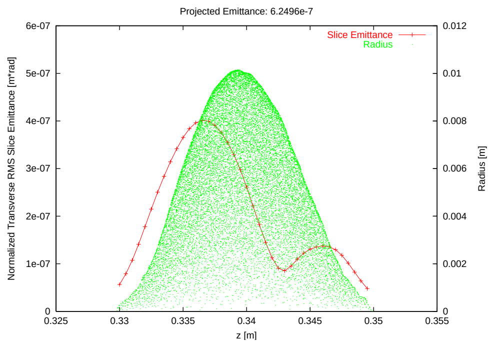

Figure 1: Slice emittance calculation from MAFIA data: Each green dot represents a single macro-particle. The red curve is the calculated slice emittance (slice width σ_z = 0.3 mm). The projected normalized transverse emittance of the entire bunch is 6.2496$\cdot 10^{-7}$ m$\cdot$rad which is well above the values for the slice emittances.

SIMULATIONS WITH CAPONE

In the following, we present the parallel 3D PIC code “Capone” which was used as a complementary simulation tool to MAFIA.

Dynamic Field Solver

The numerical simulation of the electromagnetic field dynamics uses the Finite Integration Technique (FIT) [7] [8]. A complete discretization of the calculation volume on two dual rectilinear grids G, $\tilde{G}$ is done, described by cells with volumes V_i, $\tilde{V}_i$, cell faces A_i, $\tilde{A}_i$ and grid lines L_i, $\tilde{L}_i$. Integrated field components $e_j = \int_{L_j} \vec{E} \cdot d\vec{s}$ etc. are stored at positions indicated in Fig. 2.

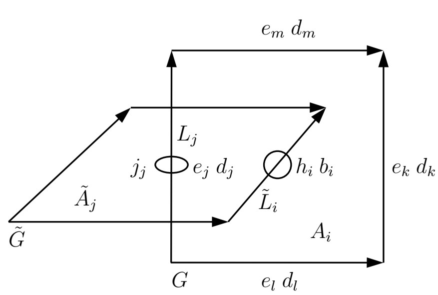

Figure 2: Topological structure of the Finite Integration Algorithm.

Maxwell’s equations are mapped to this topological space, using discrete curl and divergence operators C, $\tilde{C}$, S, $\tilde{S}$ as well as discrete material operators D_ϵ, D_μ, resulting in the following set of discrete Maxwell’s equations:

$$C\,e = -\frac{\partial b}{\partial t} \qquad (1)$$

$$\tilde{C}\,h = \frac{\partial d}{\partial t} + j \qquad (2)$$

$$\tilde{S}\,d = q \qquad (3)$$

$$S\,b = 0 \qquad (4)$$

$$d = D_\epsilon e \qquad (5)$$

$$b = D_\mu h \qquad (6)$$

Non-homogeneous distributions of ϵ and μ are permitted, with material boundaries given by cell boundaries and cell diagonals. In addition to Dirichlet and Neumann boundary conditions, open boundaries have been implemented.

The system is solved in the time domain by integrating the two curl equations using the leap frog algorithm. Due to the orthogonality of the discrete curl and div operators, the continuity equations remain fulfilled throughout the iteration process. There is no systematic accumulation of spurious space charges.

The discrete electric current density j in Eq. 2 is obtained with a Nearest-Grid-Point (NGP) scatter interpolation in combination with a scheme fulfilling the continuity equation in discrete space [9]. A spatial smoothing filter is used to smoothen out the electric current density after all particle currents have been scattered.

Static Field Solver

For the generation of a consistent initial electrostatic field solution, exactly the same grid and the same material distribution as for the FIT solver are used. In our parallel approach, we are using an iterative conjugate gradient solver together with an incomplete Cholesky preconditioner IC(0) with additional red/black checkerboard type domain decomposition. For details on these techniques, see [10].

Particle Dynamics

Like in MAFIA, electron macro-particles are created inside of designated source materials and drift towards the emission surface with their initial velocity where they start to interact with the fields. Time distribution as well as the various initial position and momentum distributions are given by user input and are independent of local field strengths. An adapted leap-frog scheme is used for the numerical integration of the classical relativistic collisionless equations of motion.

Program Structure

Capone is based on the C++ POOMA II framework on the Linux platform and uses MPI for parallelization [11]. A schematic of the program structure is shown in Fig. 3.

Efficient parallelization is performed by partitioning the calculation domain into patches associated to individual processors. Fields are statically distributed with an overlapping guard layer to optimize communication. Particles are concurrently distributed to processors according to their positions. The disadvantages of this approach are a strong dependency of the parallelization efficiency on the particle

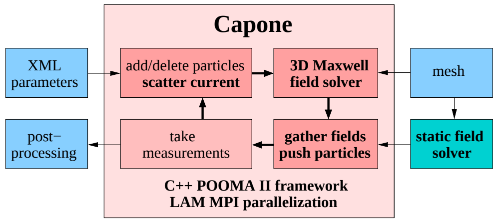

Figure 3: Schematic program structure of the 3D PIC code Capone.

distribution and communication overhead. The advantage is having fast local interpolations of the most CPU intensive part of the code.

Results

Calculations of the test stand gun design were done with Capone 3D and MAFIA 2.5D. For Capone 3D, one symmetric quarter of the gun was discretized with 4M grid points (140x140x205 / 3x3x5.5 cm^3). For MAFIA 2.5D, 170k grid points (196x878 / 3x35 cm^2) were used. Further simulation parameters were: 100 mA peak current, 100 kV gap voltage over 11 mm gap, 20k macro-particles, homogeneous initial radial distribution with r = 0.1 mm and a pulse length of σ_t = 20 ps. Zero initial transverse emittance was assumed. Results are shown in Fig. 5 and 6.

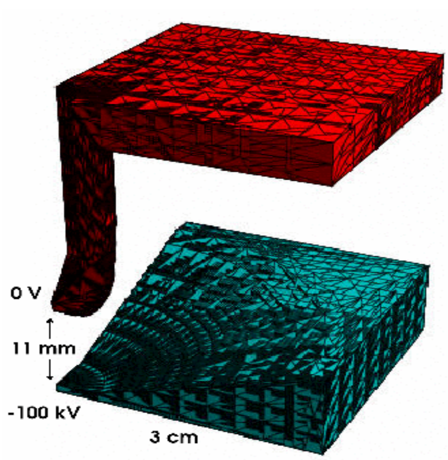

Figure 4: Discretization of the test stand gun design with 4M grid points, used for Capone 3D simulations.

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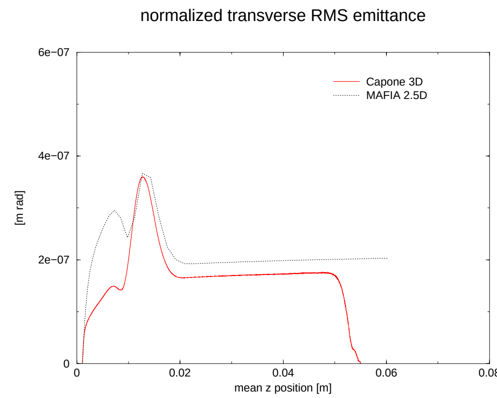

Figure 5: Total normalized RMS emittance ϵ_x as a function of mean z position.

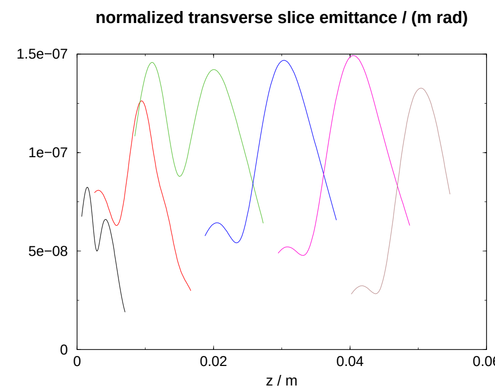

Figure 6: Transverse normalized slice emittance at different longitudinal bunch positions.

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