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OPTIMIZATION OF GUN PARAMETERS FOR
A PULSED POWER ELECTRON GUN*

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Optimization of Gun Parameters for a Pulsed Power Electron Gun

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ABSTRACT. Extensive simulation work has been done to identify the optimal parameters for a pulsed power electron gun. PBGUNS, an electrostatic beam optics code, was used to optimize the electrode shape and the beam spatial distribution, including modeling the focusing effect of a curved cathode surface. MAFIA, a particle-in-a-cell code, was used to investigate those aspects that required time dependence, such as longitudinal energy spread. The range of agreement between the two codes was also investigated. The transverse phase space at a comparison plane was found to be very close (within 1 % at low currents and 4 % for higher currents), even for bunch lengths shorter than the gap transit time.

INTRODUCTION

This paper is a result of a group of simulations used to determine the optimal parameters for a pulsed power electron gun. Two simulation codes, MAFIA and PBGUNS were utilized. PBGUNS is an electrostatic code, with a shorter average running time and less stringent computational requirements than time dependent codes such as MAFIA. It was therefore beneficial to determine in what regimes these two programs were in agreement, and what objectives of the optimization could be achieved with the DC code. It was also necessary to identify those problems that required time dependence, such as longitudinal variation in an electron bunch. PBGUNS was then used to perform the bulk of the optimization, with only those issues that required time dependence being resolved with MAFIA. The first section of this paper establishes the agreement between the two codes, in terms of the predicted transverse phase space at a comparison plane. The second section describes the optimization of the cathode curvature to provide a nearly collimated output, and the optimization of the laser spatial profile to minimize the detrimental effects of space charge. For the first two sections, the beam was assumed to have no thermal energy. The third section addresses the optimization of the bunch length to provide the highest brightness beam, a discussion of the effect of different values of thermal energy on the beam emittance, and a study of the longitudinal variation of the beam.

The pulsed power gun has been discussed elsewhere [1] and consists of a diode with a flat cathode and a flat anode mounted parallel to one another with an interelectrode spacing of 1 mm. The anode had a .5 mm radius hole allowing the bunch to escape the accelerating gap. The cathode is biased at -1 MV, yielding an accelerating gradient of 1 GV/m within the gap. The anode was 1.5 mm thick and was modeled as a perfect conductor and a perfect particle dump. For the purposes of simulation, the gun was assumed to be cylindrically symmetric. Figure 1 shows the simulated geometry of the gun in MAFIA, along with field lines and an electron bunch from a typical run. Figure 2 shows the geometry as it was used in PBGUNS, along with the equal potentials and particle trajectories from a typical run. Note that in MAFIA, the $z=0$ boundary is used as the cathode, and the potential of -1 MV is set on that boundary, while in PBGUNS the cathode surface is at $z = 1.25$ mm. The beam parameters used for comparison were extracted as close as possible to a plane 2.25 mm from the inner surface of the anode. This plane was chosen so that the particles could be taken to be in the drift region, away from any fringe fields from the accelerating gap. All of the simulations modeled emission from a $.25$ mm radius spot, but a variety of currents were modeled within that spot, all with uniform longitudinal current density.

Fig 1. MAFIA Geometry, field lines and electron bunch

Fig 2. PBGUNS Geometry and particle trajectories

MAFIA is a software package that includes many electromagnetic simulation codes, including both time and frequency domain solvers in both 2.5D and 3D. For this problem, the mesh generator (M) was used to set up the geometry and mesh. For all of the runs discussed below, a mesh dimension of $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ was used. The static solver (S) was used to model the field present in the gun during the emission. The static solver solves Maxwell's equations for a given geometry and set of time-independent boundary conditions. This involves the implicit assumption that the applied field in the gun is constant during the electron bunch duration, which is valid for the device being modeled. The field generated in this manner was read into the 2D-time domain particle pusher (TS2). The particle pusher handles ejection and propagation of the electrons inside the gun. It is here that the bunch duration is defined. The simulation is broken into finite time steps (on the order of 10 fs for these simulations). At each time step the particles are moved under the influence of the last calculated field, while at each half time step the fields are updated due to the presence of the particles. The program combines groups of electrons into macro particles to reduce the computational resources required. Typically 75000 macro particles were used in these simulations, although fewer were used to model the shorter pulse durations. The post processor (P) was used to extract the particle positions and momenta, both longitudinal and transverse, at the plane of interest. The comparisons were made with particles taken from the center of the MAFIA bunch, except where otherwise noted.

PBGUNS [2] is a PC compatible, 2-D code that solves Poisson's equation using iterative relaxation technique on a rectangular array of squares. It computes trajectories of charged particles in electrostatic and magnetostatic focusing systems including the effects of space charge and self-magnetic fields. Either rectangular or cylindrically symmetric geometry may be used. The Poisson equation is solved by an alternate column relaxation technique known as the semi-iterative Chebyshev method. The transverse phase space plot was extracted at the measurement plane.

PHASE SPACE COMPARISON

Fig 3 shows transverse phase space predicted by MAFIA for the center 1% slice of a 1 nC, 10 ps bunch accelerated in a field of 1GV/m across the gap of 1 mm. Fig 4 shows the DC transverse phase space predicted by PBGUNS for identical conditions. It is important to note that a DC code effectively measures only the slice phase space (since there is no long. variation in the beam). The transverse phase space does not vary significantly for bunch durations of 3 ps, 1ps, and 300 fs. The agreement between PBGUNS and MAFIA is very good, even for bunches much shorter than the gap transit time of 3 ps.

Fig 3. MAFIA r - r' plot 1 nC, 10 ps, center 1% of beam

Fig 4. PBGUNS x - x' plot, 100 A. PBGUNS output comes as x - x' , but for the cylindrically symmetric case the values in the 1st quadrant are equivalent to r - r'

The treatment of space charge effects in high current cases was investigated for MAFIA and PBGUNS. Table 1 gives the predicted maximum spot size and maximum divergence for various currents using these codes. For MAFIA, a bunch length of 10 ps was used. As shown on the Table, good agreement was found between MAFIA and PBGUNS for the beam radius and the max divergence. A current of 1000A is not possible in PBGUNS, as it is above the predicted DC Child's Law limit for this gun. The MAFIA results for a beam of 10 nC (corresponding to 1000 A in 10 ps) show a significant increase in bunch size, both transverse and longitudinal. While the beam is 1000A initially, by the time it leaves the gun it has increased in pulse duration to about 13 ps, thus reducing the effective current to ~750 A. The current density is further reduced due to increase in the transverse spot size.

	PBGUNS		MAFIA		
CATHODE	BEAM	MAX	BEAM	MAX	NORM.
CURRENT	RADIUS	DIVERG.	RADIUS	DIVERG.	EMITTANCE
Ampere	mm	mrad	mm	mrad	π mm-mrad
1	0.47	100	0.475	99	0.118
100	0.5	112	0.503	112	0.162
200	0.535	125	0.533	126	0.241
300	0.6	140	0.577	141	0.292
600	0.65	165	(+) 0.633	170	0.617
(*) 1000			(+) 0.707	173	2.16

Table 1. Max Spot Size, Divergence & Emittance for 1A, 100A, 200A, 300A, 600A, 1000A for PBGUNS & MAFIA. (*) The 1000 A case is above the DC limit of Child's Law for the gun. The bunch length begins stretching immediately after emission, so that the effective current is only ~ 750A. (+) For the 600A and 1000A cases, the beam is larger than the anode aperture, and is clipped by the anode. The values shown are for the surviving particles.

The MAFIA results for the particle's r and p_r are used to calculate the 1- σ normalized slice emittance (using the center 1% of the beam for the emittance calculation), using the expression:

$$\varepsilon = 2\sqrt{\langle r^2 \rangle \langle p_r^2 \rangle - \langle r \cdot p \rangle^2} \quad (1)$$

OPTIMIZATION USING PBGUNS

Beam Collimating and Focusing

The electric field in the vicinity of the anode hole has a radial component, and therefore acts as a defocusing lens. To counteract this effect, studies were done into the effect of adding a curvature to the surface of the cathode. This introduces a negative radial electric field component, and acts as a focusing lens. It was found that the optimal curvature depended on the operating current of the gun. For a given current, it was possible to choose the curvature to provide a collimated beam. More severe curvature (smaller radius of curvature) could be employed to bring the beam to a focus anywhere beyond to anode, allowing the possibility to focus at the entrance to second stage linac. PBGUNS was used to shape the cathode to provide a converging, collimated or diverging beam at the exit of the anode. Fig. 5 shows the focusing effect of a 1 mm radius of curvature for a current of 100 A from a .25 mm radius spot. The beam is only convergent for cathode radii of curvature of 1.5 mm or less.

Fig 5. Trajectories and equipotentials for a cathode with a 1 mm radius of curvature.

Spatial Charge Distribution

PBGUNS was also used to identify the optimal transverse spatial charge distribution to minimize the effect of space charge on the beam transverse phase space. Three cylindrically symmetric profiles were investigated: Gaussian, Uniform and Hollow. These profiles were investigated for both flat and curved cathodes. Fig. 6 shows the cathode density distributions for the curved cathode case.

Fig 6. Pictorial of the calculated current distributions.

Fig. 7 shows transverse phase space for the three initial current distributions at the simulation exit plane (E3). Also shown is the exit plane current distribution.

Fig 7. Phase space diagram and current density at exit plane for a 100 A current. The cathode has a 1 mm radius of curvature.

For a beam current of 100 A, there are clear differences in the output beam for the three density distributions. The gaussian current distribution, which gives a high current density near the axis, results in a somewhat distorted output phase space and an output (or exit plane) density distribution with a peak at the outer edge of the beam. The uniform and hollow distributions both give good exit plane density distributions and phase space plots.

Finally, in order to test the robustness of the computations, a 100 A uniform current density distribution case was executed for different anode exit apertures and different field gradients. For different anode exit apertures, it was found that the exit plane density distributions and phase space plots are quite insensitive to the anode exit aperture. This is due to the fact that the curved cathode surface tends to focus the beam at the anode plane so that the field that the beam experiences is similar in all configurations.

The results for applied field gradients of 0.5 GV/m and 1.5 GV/m show that lowering the gradient by a factor of two does not significantly alter the output beam character. However, increasing the gradient by 50% gives rise to an over focused beam and this results in some distortion of the exit plane phase space plot. The beam radius at E3 with this gradient is less than 100 μm.

OPTIMIZATION USING MAFIA

MAFIA was used to optimize the temporal bunch length using the condition of maximum brightness. MAFIA was also used to investigate the longitudinal energy spread, the variation of the transverse phase space along the beam and the effect of the initial energy on the beam emittance.

Bunch Length Optimization

Four bunch lengths were investigated: 10 ps, 3 ps, 1 ps, and 300 fs, all with uniform spatial and temporal profiles. The optimal pulse duration was found to be 1 ps, although the difference between 1 ps and 300 fs was within the error of the calculation. Several current values were run at 1 ps pulse length, again optimizing for the highest brightness. The highest brightness was found with a 1 ps bunch length at a current of 50 A. Table 2 shows the pulse duration, charge, current and brightness for each of these simulations. Emittance is calculated using eq. 1.

Current	Charge	Bunch length	Emittance	Brightness
A	nC	ps	π mm mrad	$A/(m^2 rad^2) (10^{14})$
100	1	10	0.16734	3571
100	0.3	3	0.0882	12854
100	0.1	1	0.062	26014
100	0.03	0.3	0.0728	18868
500	0.5	1	0.207	11668
250	0.25	1	0.132	14348
50	0.05	1	0.0386	33557
10	0.01	1	0.0446	5027

Table 2. Optimization of 1- σ normalized emittance and brightness with respect to pulse duration and charge. It is important to note that the calculated emittance includes no thermal component.

Longitudinal Phase Space & Front/Back Variation

One aspect where time resolution is clearly required is the study of the longitudinal variation of the electron beam, both in terms of energy and transverse phase space. Fig. 8 shows the longitudinal momentum spread across the beam when the center of the beam is at the measurement plane for a 10 ps, 1nC bunch. It is interesting to note that this shape is independent of charge – the absolute extent of the front/back variation is charge dependent, but the shape is not. Fig. 9 shows the longitudinal momentum spread for a 10 ps, 3nC bunch.

Fig 8 & 9. Charge induced longitudinal momentum spread. P_z is in $\beta_z \gamma$.

Fig. 10 shows the MAFIA predictions for the transverse phase of slices taken from the front, middle and back of the bunch (relative to the cathode). The variation from front to back is small. It is important, however, since most diagnostic techniques measure only the integrated phase space, which would involve drawing an ellipse, which encompassed all three slices. The emittance calculated from this ellipse would be much larger than the emittance of the individual slices.

Fig 9. Longitudinal variation of the transverse phase space.

Effect of Initial Energy on Beam Emittance

There exist several possible sources of random initial energy for electrons leaving a photocathode. Thermal energy would account for a random distribution with a magnitude of about .03 eV at room temperature. Photoemission results in electrons being "born" with initial energies up to $(h\nu - \phi)$, where $h\nu$ is the photon energy and ϕ is the cathode work function. For metal photocathodes irradiated with UV lasers, this difference can be a 1-3 eV, especially considering the expected reduction in ϕ due to the Schottky effect in GV/m fields. It is also possible that surface irregularities on the cathode may give rise to field lines containing a transverse component. For a rough cathode surface, the field in the area of a protrusion will be perpendicular to the local surface of the protrusion and not perpendicular to the macroscopic surface. The skin depth of the applied voltage is considerably larger than the optical penetration depth of ~ 10 nm [3], thus the field experienced by an electron traveling to the surface of the cathode inside a protrusion will be the nearly the same as the field at the surface of the protrusion. With even a modest value of the field enhancement, in a 1 GV/m field an

electron will gain several tens of eV before being emitted, and some fraction of this energy will be transverse. All three of these sources of initial energy can be corrected for to some extent, by cooling the cathode, choosing a photon energy well matched to the work function and carefully polishing the cathode. It is instructive, however, to investigate the expected degradation of the beam emittance due to these effects.

The geometry used for these calculations differed from the geometry shown in Fig. 1. Instead of an anode which was 1.5 mm thick with a .5 mm radius hole, a closed anode (no hole) of 50 μm thickness was used. The anode material was set to be transparent to electrons but not to electric fields, thus simulating a thick foil (no scatter occurred within the anode, however, unlike a real foil). This was done to remove the bending of the field near the anode hole and the resulting defocusing effect on the beam, allowing a more accurate calculation of the beam emittance. This new geometry is shown in Fig. 10.

Fig 10. Geometry used for thermal emittance calculation, including field lines and electron bunch.

Using this geometry, simulations were performed for 0, 1, 10, and 100 eV initial energies. In each case an initial angle was randomly assigned to each macro-particle. Table 3 shows the resulting emittance values for both 1 nC and 100 pC bunch charge. A bunch length of 10 ps was used in this calculation, with uniform spatial and temporal profiles.

Current	Charge	Initial Energy	Emittance
A	nC	eV	π mm mrad
100	1	0	0.251
100	1	1	0.287
100	1	10	0.597
100	1	100	1.704
10	0.1	0	0.023
10	0.1	1	0.171
10	0.1	10	0.530
10	0.1	100	1.682

Table 3. Effect of initial random energy distribution on emittance

The results yield the expected [4] scaling (the emittance increases as the square

root of the initial energy once the initial energy is the dominant contribution). Above 1 eV initial energy, this is the dominant contribution to the beam emittance for the 100 A beam. Even at 1 eV initial energy, the 10 A beam is dominated by these effects. To preserve the emittance of the 10 A beam, the beam's initial energy needs to be kept to room temperature thermal levels (~ 0.03 eV).

SUMMARY

A comparison of two codes suitable for electron gun simulation was performed. Good agreement in transverse phase space values was found between the electrostatic code (PBGUNS) and the time dependent code (MAFIA) for a variety of pulse durations, even for pulse durations short compared to the electron transit time of the accelerating region. The electrostatic codes have an advantage in terms of required computational resources and run time, and are therefore a good choice for modeling jobs in which the longitudinal variation is unimportant.

PBGUNS was used to model the effects of curving the cathode surface to provide a focusing effect. The curvature of the cathode can be chosen so that it counteracts the defocusing effect of the anode aperture, allowing for a collimated beam. A deeper curvature can be chosen to provide a focus at a specific location. PBGUNS was also used to investigate the effect of different initial spatial current distributions.

MAFIA was used to optimize the bunch length and beam current to provide the highest brightness beam and to investigate the effect of varying levels of random initial energy on the beam emittance. MAFIA was also used to explore the energy spread and the longitudinal variation of the transverse phase space, both of which require time dependence.

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