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TITLE: PARTICLE-IN-CELL SIMULATIONS OF THE LASERTRON

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Introduction

The lasertron [1,2] is a device (either RF or DC) for producing intense, very short, pulsed electron beams (tens of picoseconds). In the DC lasertron, a laser is pulsed repetitively onto a photoemissive cathode [3]. In general, the current is not space-charge limited and follows the laser intensity. The electron pulse is then accelerated out of the device by a constant voltage. By using the laser the need for a subharmonic buncher is eliminated. In the RF lasertron, the diode becomes an RF cavity. This improves the breakdown characteristics of the device, allowing higher voltages to be applied and hence higher currents to be obtained. The calculations are aimed at producing a 10 nC electron beam with an emittance of less than 40 μ m-mrad for use in free-electron laser experiments at Los Alamos [4]. Other applications of the lasertron include efficient microwave or RF generation [3]. A class of electrode shapes [see Eq. (2)] has been obtained which in the absence of space charge produces no emittance growth. These shapes have been studied with the particle-in-cell simulation model ISIS [5], and the electrodes which produce minimum emittance including the effect of space charge have been determined. Unique emittance problems associated with the time dependence of the beam pulse are studied and conditions for reducing these effects are discussed.

Sources of Emittance

In the paraxial approximation, emittance in charged particle beams arises from nonlinear radial electric fields. Thus if E_r is everywhere linear in the radial coordinate r , the dynamics of the particles will be self-similar and no emittance will be produced. The electric field in a diode is produced by the electrode shapes and by the space charge of the beam that is created. Either field can be nonlinear and consequently a source of emittance. In order to minimize the emittance we begin by requiring the field produced by the electrodes be linear.

The solution to Laplace's equation, assuming axial symmetry, which produces only linear radial electric fields can be written as

$$\psi = \zeta + \left[\rho^2(\zeta - \mu)/2 - \zeta^2(\zeta/3 - \mu) \right] / (1 - 2\mu), \quad (1)$$

where ψ is the normalized electric potential, $\psi = -\phi/E_0 z_0$, where ϕ is the potential, E_0 is the value of the (axial) electric field at the origin ($r = 0, z = 0$), and z_0 is the axial position at which the axial electric field, E_z , vanishes for $r = 0$. The spatial coordinates are normalized to z_0 : $\rho = r/z_0$ and $\zeta = z/z_0$. The potential is chosen to vanish at the origin. The only free parameter in the solution is μ , which we refer to as the focussing parameter. The equation for the equipotential surfaces which constitute the electrode shapes can be obtained by solving this equation for ρ as a function of ζ for fixed ψ :

$$\rho^2 = 2 \left[(\psi - \zeta)(1 - 2\mu) + \zeta^3/3 - \mu\zeta^2 \right] / (\zeta - \mu). \quad (2)$$

In order to apply this solution to physically

realizable systems, the region of interest must be bounded by three electrodes, as shown in Fig. 1. If electrodes at the indicated potentials are placed as shown in the figure, the vacuum electric field will be linear everywhere in the region enclosed by the conductors. In practice, this solution can only be approximated. Figure 2 shows the electrode approximation used in an actual ISIS calculation (z_0 is chosen to be 3 cm). The $\psi = 0$ (cathode) and $\psi = 0.85$ (anode) electrodes are truncated and the third electrode is completely absent. It can be expected that this electrode configuration will give a good approximation to the solution of Eq. (1) near the origin. Also, the electrodes pass only through the mesh points of the finite difference grid as shown in Fig. 2.

There are two classes of diodes which can be obtained from this solution. For $0 < \mu < 0.5$, the cathode tilts toward the anode as shown in Figs. 1 and 2 ($\mu = 0$ gives a flat cathode). This causes the beam

Fig. 1 Equipotentials from Eq. (2). Electrodes placed on these equipotentials produce only linear radial electric fields.

Fig. 2 ISIS calculation snapshot showing approximation to electrode structure of Fig. 1 and beam pulse.

to focus as it leaves the cathode. For $\mu < 0$ and $\mu > 0.5$, the cathode bends away from the anode, which causes defocusing. The case $\mu = 0$ produces an axial electric field which is independent of r .

For high perveance beams, another source of emittance is nonlinear space-charge forces. Because the current emitted by the lasertron is controlled by the laser, the current density can be made radially uniform by using a uniform laser illumination. However, space-charge forces tend to retard the particles near the axis. This causes the radial charge density to become nonuniform, producing nonlinear radial electric fields and emittance growth. This effect can be minimized by choosing the vacuum fields to have the opposite effect, i.e., accelerate particles faster near the axis. From Eq. (1) it can be seen that the solutions which accelerate the particles on axis faster, at least near the cathode, are the focussing solutions ($0 < \mu < 0.5$). Precisely which value of μ minimizes the velocity shear of the space charge depends on the current density in the beam.

The time dependence of the current pulse in the lasertron introduces a further source of emittance related to the space charge. Even if the diode parameters were chosen to minimize the effects of nonlinear space charge for the steady state case, the leading and trailing ends of the beam will not be properly handled. This is because the beam expands under its own space charge more in the center of the beam than at the ends. Thus the expansion is not self-similar and an emittance measurement detects these end effects as increased emittance.

Simulation Method and Results

Simulations for a wide variety of diode configurations and parameters have been performed with the 2-dimensional, relativistic, electromagnetic particle-in-cell simulation code ISIS. The laser controlled emission is modelled by placing an upper bound on the current density emitted by the cathode. Most of the calculations use a step-function laser pulse, but other temporal profiles, including trapezoidal were used. The emittance numbers quoted here are a normalized rms emittance measured as the beam exits the simulation region (to the right in Fig. 2). The rms calculation is carried out over a time interval long enough to obtain a good statistical sampling of particles. For pulsed beams this interval is chosen long enough to sample all the particles in the pulse, typically 5 to 10 thousand.

The calculations use a system of dimensionless variables in which the space variables scale with a parameter λ and the time variable scales with λ/c , where c is the speed of light. For example, the calculation shown in Fig. 2 is labeled as if λ is taken to be 1 cm. Thus the calculation is for a diode with a 0.56 cm radius emitting cathode and a 50 ps laser pulse. However, choosing λ to be 10 cm for example, the calculation represents a 5.6 cm radius cathode and a 500 ps laser pulse. The electric fields and current densities scale similarly. Because emittance has units of length it scales linearly with λ as well. The graphs show emittance normalized to the square root of the cathode area, A_c ($\lambda = A_c^{1/2}$). Variables which do not scale are the voltage and current.

Several simulations were performed with electrode shapes based on Eq. (2), with low laser intensity (<1ma total current). These calculations gave emittances of $0.3 - 0.5 A_c^{1/2}$ mrad. With space charge, the emittances increased significantly. Figure 3 shows emittances measured from ISIS calculations as a function of the electrode shape expressed through the parameter μ . The voltage on the diodes was 0.85 MV, and the current, controlled by the laser, was 200 A. These calculations assumed a long laser pulse and were

Fig. 3 Effect of focussing on steady state beam emittance from ISIS calculations. Larger μ means more focussing.

run to steady state. Thus the end effects associated with a short beam pulse are not present in these calculations. It can be seen that with less focussing (μ small) the emittances are larger. The minimum emittance, for this voltage and current, occurs for μ between 0.15 and 0.2. As with all the data presented here, the curve is a cubic spline fit to guide the eye. The simulations indicate that overfocussing the beam slightly is more forgiving than underfocussing.

Figure 2 shows a snapshot of the particle positions for a pulsed beam with pulse length, $c\tau/A^{1/2} = 1.5$, soon after the laser is switched off. The other parameters are the same as the calculations in Fig. 3, and $\mu = 0.15$. The emittance measured for this calculation was $\epsilon = 2.8 A_c^{1/2}$ mrad, compared with the steady state value shown in Fig. 3 for $\mu = 0.15$,

of $\epsilon = 0.85 A_c^{1/2}$ mrad. In order to understand how the time dependence of the pulsed beam affects emittance the series of simulations in Figs. 4 and 5 were performed. The geometry was chosen from Eq. (2) with $\mu = 0$. This choice gives a steady state emittance of $\epsilon = 3.9 A_c^{1/2}$ mrad for a current of 200 Amps. This is far from optimal as shown in Fig. 3. Figure 4 shows two sets of simulations as a function of pulse length with a common point at $c\tau/A^{1/2} = 1.5$. The squares show emittance measurements keeping the step-function current constant at 200 A. Increasing the pulse length increases the amount of total charge in the beam pulse. As can be seen, ϵ is a weak function of pulse length and actually goes up slightly with increasing τ . All the pulsed beams had a higher emittance than the steady state beam, indicating the increased emittance was from particles in the head and tail of the beams. The circles show the emittances from a series of simulations keeping the total charge in the beams constant and varying the current. The emittance is now a strong decreasing function of the pulse length. As the pulse gets longer, not only do the particles in the ends constitute a smaller fraction of the total particles and contribute less to the emittance but the space-charge forces which cause the nonself-similar expansion decrease.

Figure 5 shows the same set of simulations at constant charge (circles) as a function of current. Of course the pulse length changes. Also shown, by the squares, is another set of calculations performed with the constant pulse length of $c\tau/A^{1/2} = 1.5$. As the current increases the space-charge forces become larger and the end effects give increased emittance. This effect is ameliorated in the case of the constant charge beams because at high current the total charge is less and the space charge fields are consequently

Fig. 4 ISIS calculations showing the effect of pulse length on emittance.

Fig. 5 The effect of current on beam emittance from simulations.

smaller. All these calculations were performed with step-function laser profiles. Similar, but smaller, effects were found associated with finite rise time, i.e., longer rise times produce higher emittance.

RF Lasertron

The simulations have shown that the lasertron suffers from a unique source of emittance associated with the end effects of the space charge in the finite length pulses. This effect is minimized by reducing the effect of the space charge. Other simulations not presented in the previous section show reduced emittance in pulsed beams with increased voltage. This just reflects the fact that lower perveance diodes have smaller space charge effects.

By making the diode into a RF cavity one can use higher peak electric fields and still avoid sparking. For a fixed total charge in the beam, if one tries to reduce the emittance by using longer pulses as suggested by the simulation results in Fig. 3, one is faced with the problem that the beam must leave the cavity before it is decelerated and turned around by the reversing RF. Simple guidelines for design can be obtained from the following analysis.

We will assume that the TM_{010} mode is excited.

The axial electric field produced will be uniform in a pill box cavity and vary sinusoidally in time. Actually the presence of the anode hole causes the field to decrease away from the cathode but we neglect this effect and the effect of space charge in this calculation. The one-dimensional equation of motion for a charged particle in this field is

$$du/dt = eE_0/mc \sin(\omega t) \quad (3)$$

where u is the axial momentum normalized to mc , and m is the mass of the particle. The peak electric field amplitude is E_0 , ω is the angular frequency of the RF, t is time, and e is the charge of the particle. The particle is emitted at rest from the cathode at $t = t_0$. Integrating Eq. (3) we get

$$u = eE_0/mc [\cos(\omega t_0) - \cos(\omega t)] \quad (4)$$

Immediately, we see two things about this solution. A particle will obtain maximum energy at $\omega t = \pi$, independent of when it is emitted, and the particle emitted closer to $t = 0$ will attain the highest energy. The position of the particle, x , given by

$$dx/dt = cu/(1+u^2)^{1/2} \quad (5)$$

Defining $a = eE_0/mc$, $x = ax/a$, the solution to Eq. (5) can be written

$$x = \int_{t_0}^{\pi} dt [\cos(\omega t_0) - \cos(\omega t)] / (1+a^2[\cos(\omega t_0) - \cos(\omega t)]^2)^{1/2}$$

where $t_0 = \omega t_0$. In the nonrelativistic approximation ($a \ll 1$) the integral becomes elementary. Qualitatively, the solution shows that the particles emitted nearer to t_0 travel farther and are closer together at any given time. The RF lasertron will debunch the beam unless only a small fraction of the RF cycle is used, but this effect is minimized by operating near to $\pi = 0$. This solution can be used to determine the A-K gap of the diode to give the particles maximum energy. The problem with operating too near $\pi = 0$ is that the electric field may be so low that the current can be space-charge limited so the beam profile will not follow the laser. A good rule of thumb appears to be to operate in the first quarter cycle of the RF ($\pi < \pi/4$) and choose the gap to be the distance the last emitted particle attains at $\pi = \pi/2$.

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