

TIME-RETARDATION EFFECT CAUSING BEAMLOSS IN THE RF PHOTOINJECTOR *

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Abstract

Near the cathode in a photoinjector, the electron beam is emitted with low energy, and its dynamics are strongly affected by the beam's space-charge fields. This can cause beam loss at the cathode due to virtual cathode formation. In general, a fully electromagnetic code can correctly predict the beam space-charge fields, beam dynamics, and beam loss. However, an electrostatic type algorithm would show a difference in the space-charge fields compared to an electromagnetic code since it does not incorporate relativistic time-retardation effects. IRPSS (Indiana RF Photocathode Source Simulator) can calculate the electromagnetic space-charge fields using a Green's function method to a high-precision, and can track beam dynamics in the rf photoinjector. Using IRPSS, we simulated the beam dynamics and beam loss near the cathode for the Argonne Wakefield Accelerator 1.3 GHz gun [1] and compared those results to an electrostatic code.

INTRODUCTION

For a finite size bunched beam, the head of the bunch will generate electromagnetic fields, and these fields will affect the remainder of the bunch. The effect of these space-charge fields is important since the beam velocity at the point of cathode emission is small. For a critical bunch charge, one finds that the decelerating longitudinal space-charge force on the back of the bunch will cancel the accelerating rf-field force. For bunch charges greater than the critical value, one finds beamloss at the cathode. At the point of bunch emission, the effects of time-retardation can be important since the space-charge forces "felt" by any point within the bunch are not due to all other points in the bunch. Hence, time-retardation effects can be important for longitudinal beam dynamics and beamloss at bunch emission.

Previous studies have investigated the predictions of fully electromagnetic space-charge fields compared to electrostatic approximations for bunch lengths greater than or equal to 10 psec [2, 3]. However, a systematic study for smaller bunch lengths was not performed.

In order to see the time-retardation effect in the rf photoinjector, we utilize two Green's function based space-charge solvers, one is electromagnetic and the other is electrostatic, i.e. the fields are transmitted instantaneously

without the effect of time-retardation. The electromagnetic space-charge solver, called IRPSS, has an ability to calculate the time-retardation effect [4, 5].

We test the effects of time-retardation Parameters of ANL AWA 1.3 GHz rf photoinjector are used for space-charge field calculations and beam tracking simulations. We vary the laser pulse length from 1 to 10 psec, and two beam radii, i.e. $r_b = 1$ mm and $r_b = 1$ cm, are used. Other gun parameters are given by the following [1]:

- Rf frequency: $f_0 = 1.3$ GHz,
- Cavity radius: $a = 9.08$ cm,
- Peak rf E field: $E_0 = 50$ MV/m,
- Injection phase: $\phi = 65$ degree.

In Sec. 2, we will show how time-retardation effects change space-charge fields by comparing results from electromagnetic and electrostatic space-charge field solvers. Beam dynamics simulation, especially focused on beam loss simulation, will be shown in Sec. 3. Finally, we will conclude our results of the time-retardation effect in the rf photoinjector.

CRITICAL E_z SPACE-CHARGE FIELDS

The onset of beam loss will occur at the bunch location where the longitudinal space-charge field has the greatest decelerating effect. For a beam which has a radial distribution function which is maximum in the beam center, this point is located at the back of the bunch in the beam center. In our simulations we set the cathode location to be at $z=0.0$ m and the center of the beam to be $r = 0.0$ m. Hence, in order to find the critical E_z space-charge field which will give rise to beamloss, one needs to compute the field at $r = 0.0$ m and $z = 0.0$ m at the instant of time when the back of the bunch is emitted.

In order to see the effect of time-retardation in the rf photoinjector, we also compute the maximum electrostatic space-charge fields on the cathode, using an electrostatic Green's function method. Both the electrostatic, as well as, the electromagnetic field calculations, utilize a parabolic radial beam distribution, and both methods divide the beam into a finite number of slices, which are evenly distributed in time at the point of beam emission. In our previous papers, we found the computational criterion for accurately resolving the beam space-charge fields in IRPSS to less than 1 % field error [6, 7].

In order to check the validity of the electrostatic code, we also formulated an exact bunch charge and current density

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fluid model assuming zero current density compressibility, which represents the physics at beam emission. We have found that both the electrostatic fluid model and the electrostatic code agree precisely. One of the advantages of developing the analytical fluid model is that we can produce an exact formula for the longitudinal space-charge field at the critical location $r = 0.0$ m and $z = 0.0$ m. This formula is given by,

$$E_z^{ES}(0,0) = \frac{4Q}{\pi\epsilon_0 r_b^2} \sum_m \sqrt{\frac{\pi}{j_{0m} z_b/a}} \frac{\text{Erf}\left(\sqrt{j_{0m} z_b/a}\right)}{j_{0m}^2 J_1^2(j_{0m})} \times \left[\frac{2}{j_{0m} r_b/a} J_1\left(j_{0m} \frac{r_b}{a}\right) - J_0\left(j_{0m} \frac{r_b}{a}\right) \right],$$

where Erf is the error function, and r_b and z_b are the bunch radius and bunch length, respectively.

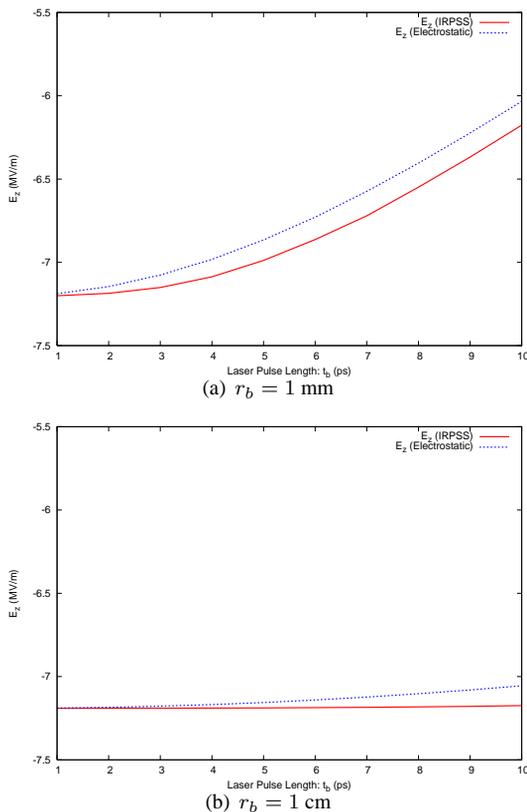


Figure 1: The longitudinal space-charge fields at $r = 0.0$ and $z = 0.0$ computed by IRPSS (red) and electrostatic methods(blue)

Fig. 1 shows the critical E_z space-charge fields at $r = 0.0$ and $z = 0.0$ for different laser pulse lengths at 0.1 nC (for $r_b = 1$ mm) and 10 nC (for $r_b = 1$ cm). The primary result is that as the laser pulse length is increased, the discrepancy between electrostatic and electromagnetic space-charge fields is gradually increased. The size of the discrepancy also depends on the beam radius. Qualitatively, as the beam radius is increased, i.e., the beam becomes more pancake like, and the discrepancy becomes smaller.

Moreover, the maximum electric field for both the electrostatic, as well as the electromagnetic cases occurs when they have a zero bunch length beam, which acts as a sheet of charge near the cathode. In this case, the electric field is exactly found to be σ/ϵ_0 where σ is the local charge density (charge/area) on the beam axis. For a parabolic (radial) and uniform (longitudinal) beam with $Q = 100$ pC, σ is given by $2Q/\pi\epsilon_0 r_b^2$, hence $\sigma/\epsilon_0 = -7.19$ MV/m. Both electromagnetic and electrostatic results show that they agree extremely well for shorter bunch lengths, i.e., pancake-like beam, as seen in Fig. 1(b).

Fig. 2 shows the percentage difference between electromagnetic and electrostatic critical E_z fields. And this effect can become larger by increasing the bunch length with fixed beam radius. However the percentage discrepancy between electromagnetic and electrostatic fields has a maximum around 2.4 % for $r_b = 1$ mm with laser pulse length of 10 psec and around 1.6 % discrepancy for $r_b = 1$ cm.

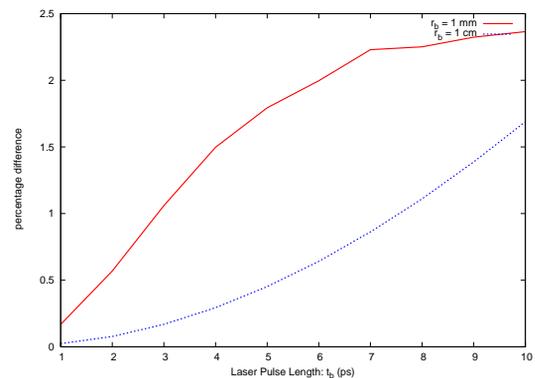


Figure 2: Percentage difference between critical electromagnetic and electrostatic space-charge fields for different beam radii

EXPERIMENTAL BEAM LOSS MEASUREMENT

We performed an experimental beam loss measurement on the 1.3 GHz rf gun at the ANL AWA experiment [1]. Fig. 3 shows plots of the measured bunch charge from the exit of the gun as a function of laser pulse intensity. If no beam loss was to occur then the plot should be linear with a uniform slope. However, at a critical bunch charge, i.e., $E_z^{rf} = E_z^{critical}$, for fixed laser pulse length and radius, one would expect beam loss to occur and a reduction in the slope of the curve. Our theory predicts that this critical point should happen approximately at 1.2 nC for a uniform radial bunch distribution. But the preliminary data suggest a change in slope, i.e., onset of beam loss, at around 300 – 400 pC. A possible explanation for this is non-uniformity of the laser spot. We plan to continue these measurements, look at possible ways to increase the E_z field discrepancy by changing the magnitude of the rf field and injection phase.

Beam Dynamics and Electromagnetic Fields

D05 - Code Developments and Simulation Techniques

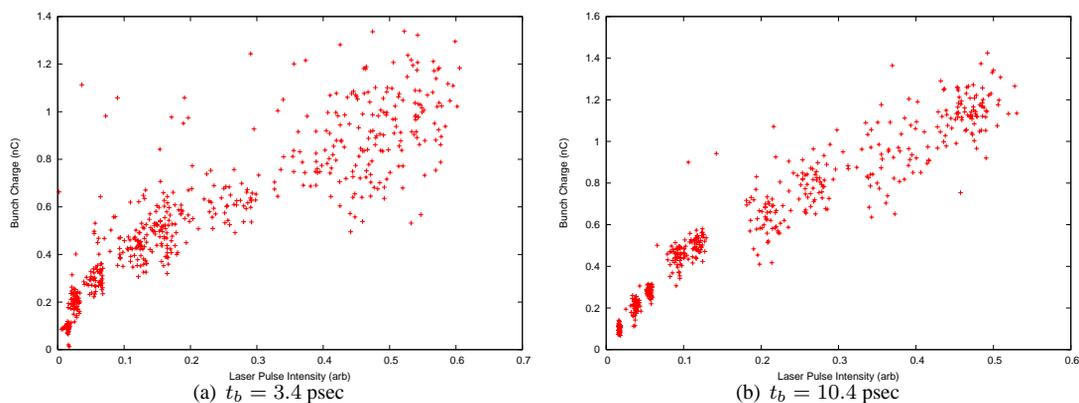


Figure 3: Experimental results of bunch charge vs. laser pulse intensity for different bunch lengths.

CONCLUSION

The effect of time-retardation in the rf photoinjector at the emission process of the electron beam has been studied using electromagnetic and electrostatic space-charge field solvers. Discrepancies were found between two critical space-charge fields, especially, for the beam with longer bunch length. In future, we will perform further beam loss measurements to verify the simulation results.

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