# X-BAND PHOTOINJECTOR BEAM DYNAMICS*

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*Abstract*

SLAC is studying the feasibility of using an X-band RF photocathode gun to produce low emittance bunches for applications such as a mono-energetic MeV γ ray source (in collaboration with LLNL) and a photoinjector for a compact FEL. Beam dynamics studies are being done for a configuration consisting of a 5.5-cell X-band gun followed by several 53-cell high-gradient X-band accelerator structures. A fully 3D program, ImpactT, is used to track particles taking into account space charge forces, short-range longitudinal and transverse wakefields, and the 3D rf fields in the structures, including the quadrupole component of the couplers. The effect of misalignments of the various elements, including the drive-laser, gun, solenoid and accelerator structures, are evaluated. This paper presents these results and estimates of the expected bunch emittance vs cathode gradient, and the effects of mixing between the fundamental and off-frequency longitudinal modes.

## OVERVIEW

An X-band gun at SLAC has been shown to operate reliably with a 200 MV/m acceleration gradient at the cathode, which is nearly twice the 115 MV/m acceleration gradient in the LCLS gun. The higher gradient should roughly balance the space charge related transverse emittance growth for the same bunch charge but provide a 3-4 times shorter bunch length [1]. The shorter length would make the subsequent bunch compression easier and allow for a more effective use of emittance exchange. Such a gun can also be used with an X-band linac to produce a compact FEL or γ ray source that would require rf sources of only one frequency for beam generation and acceleration. The feasibility of using an X-band rf photocathode gun and accelerator structures to generate high quality electron beams for compact FELs [2] and γ ray sources [3] is being studied at SLAC. Results from the X-band photoinjector beam dynamics studies are reported in this paper.

## BEAM DYNAMICS

A powerful, fully 3D code, ImpactT [4], is used to track particles considering nearly all effects such as space charge, short range wakefields, off-frequency modes, 3D rf fields in the gun and accelerator structures, and element misalignments.

### *Bunch Emittance without Errors*

For the purpose of this study, the X-band photoinjector consists of a solenoidal focused, 5.5-cell, 7.3 MeV, X-band rf gun with a 200 MV/m cathode field followed by two ~ 0.5 m long, 70 MV/m X-band structures for subsequent acceleration to 75 MeV. A transversely uniform and longitudinally trapezoidal (0.4 ps rise and fall time and a 2 ps flattop) laser profile is used for the simulations. The laser radius is 0.6 mm and 0.2 mm for 250 pC and 20 pC bunch charges, respectively. A thermal emittance of 0.9 micron per mm rms laser spot size, same as measured at LCLS, is included in the simulations. Figure 1 shows examples of the simulated bunch size (green lines) and bunch projected emittance (blue lines) evolution through the gun (starting at z = 0) and two structures (starting at z ~ 0.55 m). The resulting normalized projected emittances are 0.12 μm for a 20 pC bunch and 0.43 μm for a 250 pC bunch. These emittances are comparable to those measured at LCLS for the same bunch charge, but the bunch length in this case is about three-times shorter. The core slice emittance of the 250 pC bunch is ~ 0.32 μm, as shown in Fig. 2.

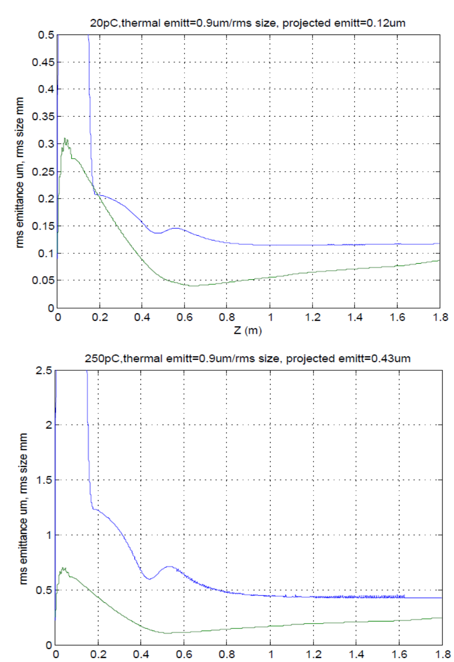


Figure 1: Normalized projected emittance and rms beam size along the injector beamline for 20 pC (top) and 250 pC (bottom) bunch charges.

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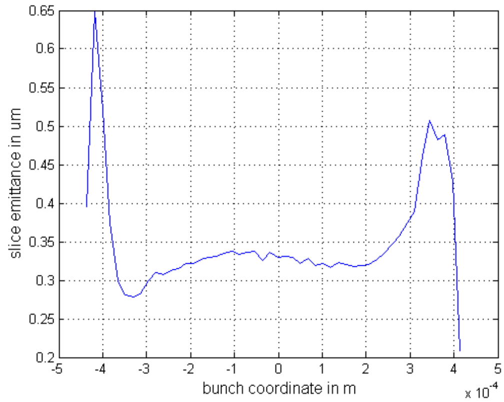


Figure 2: Slice emittance of a 250 pC bunch at the end of the injector. The assumed thermal emittance is 0.23 μm.

### *Emittance versus Gradient*

Figure 3 shows the simulated emittance versus cathode gradient for a 333 pC bunch charge. The emittance decreases with increasing gradient, but above 210 MV/m, the rf emittance component may start to dominate. For a 33 pC bunch charge, the rf emittance component at 200 MV/m is only 0.016 μm because of the short bunch length and small beam size. This value is much smaller than the 0.09 μm thermal emittance. For low bunch charge, the emittance should continue to decrease at gradients above 200 MV/m.

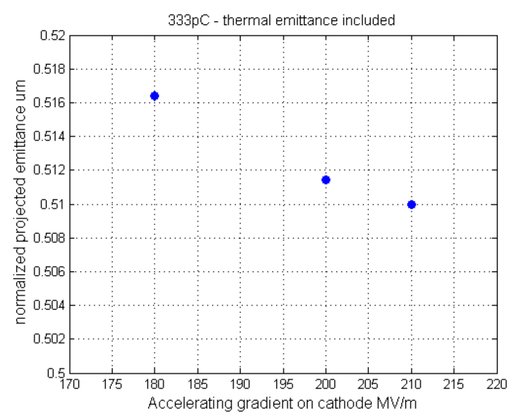


Figure 3: Emittance versus cathode gradient for a 333 pC bunch charge. Thermal emittance is included.

### *Coupler Quadrupole Field*

Dual feed couplers are helpful to cancel dipole fields in the gun and accelerator coupler cells but an rf quadrupole field component remains. Its effect on a bunch depends on the bunch size and quadrupole field strength. The rf quadrupole component induces a bunch slice angular divergence given by:

$$\delta\sigma x'(s) = \frac{\sigma p_x(s)}{p_z} = \frac{\left(\frac{\gamma\beta_\perp}{x_0}\right)\sigma x_0(s)}{\gamma}\sin(ks+\phi) \qquad (1)$$

where $\gamma\beta\perp/x_0$ is the rf quadrupole amplitude (normalized transverse momentum kick per transverse offset), $\sigma x_0(s)$ is the bunch transverse size at slice position s, γ is the energy Lorentz factor, k is the rf wave number and ϕ is the relative rf-to-bunch phase. The worst case for emittance growth occurs when the center slice of the bunch is at the rf zero-crossing (i.e., ϕ = 0). For example, with a normalized quadrupole amplitude of 300/m and a 0.14 mm rms bunch size at first accelerator input coupler, the estimated worst case emittance growth using Eq. 1 is 3.5%, close to the ImpactT result of 6%. For the X-band gun coupler, where the beam size is larger (~ 0.7 mm rms), a racetrack shape cell has been designed with a normalized quadrupole amplitude of 2.3/m. This amplitude would yield an emittance growth of around 10% at worst. The accelerator structure input/output coupler amplitudes will be reduced to 3.6/m (racetrack) from the nominal 100/m (mode-launcher) for a 70MV/m gradient [5], and the resulting emittance growth should be negligible based on both simulations and analytic estimates.

### *Gun and Accelerator Structures Tolerances*

Figure 4 shows simulations of emittance growth versus transverse bunch offset in the X-band gun. The emittance growth is caused by the time-dependent rf kicks witnessed by the offset bunch (not including wakefields in this case). The transverse offset needs to be kept below 100 μm for < 4% emittance growth. Here 200 μrad of pitch is assumed. The required tolerance is tight but manageable.

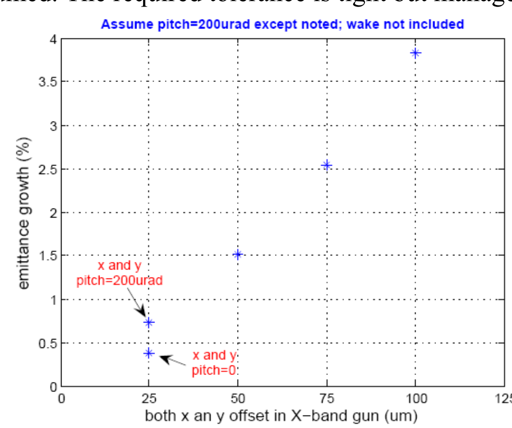


Figure 4: Emittance sensitivity to the gun alignment. A 200 μrad pitch is assume except as noted in the plot.

The effect of the strong wakefields in the small aperture X-band structures is a major concern. The transverse wakefield at distance s behind an electron is derived in Ref. [6]:

$$W_\perp = \frac{4z_0 c s_0}{\pi a^4}\left[1-\left(1+\sqrt{\frac{s}{s_0}}\right)\exp\left(-\sqrt{\frac{s}{s_0}}\right)\right] \qquad (2)$$

$$s_0 = 0.169\frac{a^{1.79}g^{0.56}}{L^{1.17}}$$

where a is the cell iris radius, and g and L are the gap and period of the structure cell, respectively. The angular divergence caused by the wakefield is calculated using:

$$\sigma x' = \int \frac{eq \cdot \Delta x \cdot W_{\perp}(\sigma_S)\, dz}{E(z)} \approx \frac{eq \cdot \Delta x \cdot W_{\perp}(\sigma_S) \cdot l}{E(z=0)} \qquad (3)$$

where q is the bunch charge, $\Delta x$ is the transverse bunch offset, $W_{\perp}$ is the wakefield, l is the structure length, E is the beam energy and $\sigma_s$ is the rms bunch length. This equation overestimates the wake effect but it is useful to crosscheck the simulations. For a 333 pC bunch charge, a 200 μm transverse offset causes 12% emittance growth based on ImpactT simulations, roughly the same level as the analytical estimate of 34%. Figure 5 shows the simulated emittance growth versus the accelerator structure transverse offset. The offsets in position and angle need to be below 100 μm and 250 μrad for 1% emittance growth. The longitudinal wakefield induces ~160 keV of energy loss in one structure for the 333 pC bunch charge.

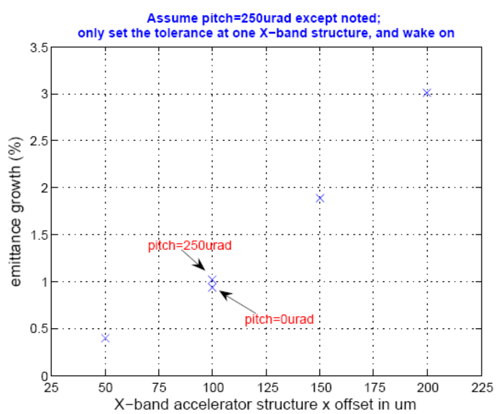


Figure 5: Emittance growth vs the structure transverse offset for a 333 pC bunch charge.

### *Tracking with 3D Fields*

3D rf fields have been included in ImpactT to better model the asymmetrical couplers and the effect of the power flow through the SW rf gun. Figure 6 shows the emittance evolution using 1D on-axis $E_z$ fields and 3D fields in the gun with rf attenuation, although for an ideal axial-symmetric coupler. The emittance is about 20% larger with the 3D fields. There is an ~8 deg rf phase shift through the gun in the 3D case, which may be the reason for the emittance difference. The plan is to eventually use full 3D fields to model all structures.

### *Other Longitudinal Modes*

Since the gun consists of several cells, there are other longitudinal modes in same band as the fundamental pi-mode. The modes that are close in frequency to the fundamental will be weakly excited during the fill period, and this will lead to a slight 'beating' of the cell field patterns. Preliminary simulations with ImpactT show that the emittance growth from the extraneous modes is negligible if the mode nearest to the fundamental is separated by at least 20 MHz.

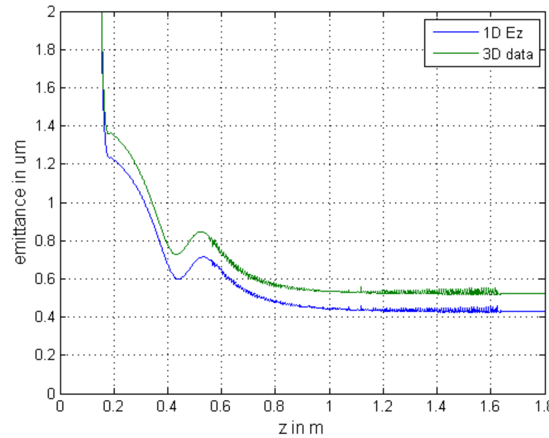


Figure 6: Comparison of simulations using on-axis 1D $E_z$ fields and 3D fields.

## SUMMARY AND FUTURE WORK

A 75-MeV X-band photoinjector has the potential of producing bunch emittances that are comparable or better than those at the LCLS injector, but with a three times shorter bunch length, which would make subsequent bunch compression simpler. To achieve such low emittances, racetrack couplers need to be used for the gun and structures. The simulations so far have shown that only modest alignment tolerances are required. Work continues to model all possible effects, including those from the full 3D fields in the gun and structures.

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