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MODELING MULTI-BUNCH X-BAND PHOTOINJECTOR CHALLENGES *

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Abstract

An X-band test station is being developed at LLNL to investigate accelerator optimization for future upgrades to mono-energetic gamma-ray technology at LLNL. The test station will consist of a 5.5 cell X-band rf photoinjector, single accelerator section, and beam diagnostics. Of critical import to the functioning of the LLNL X-band system with multiple electron bunches is the performance of the photoinjector. In depth modeling of the Mark 1 LLNL/SLAC X-band rf photoinjector performance will be presented addressing important challenges that must be addressed in order to fabricate a multi-bunch Mark 2 photoinjector. Emittance performance is evaluated under different nominal electron bunch parameters using electrostatic codes such as PARMELA. Wake potential is analyzed using electromagnetic time domain simulations using the ACE3P code T3P. Plans for multi-bunch experiments and implementation of photoinjector advances for the Mark 2 design will also be discussed.

INTRODUCTION

Extremely bright, narrow bandwidth gamma-ray sources are expanding the application of accelerator technology and light sources in new directions. Mono-energetic gamma-rays enable new features in nuclear applications by tapping into the very narrow unique nuclear resonances of various isotopes [1]. Advancements in nuclear material detection, fuel rod assay, and waste management only begin to hint at the possibilities made possible by this transformational technology. Narrow bandwidth gamma-rays place very stringent demands on the laser and electron beams that interact to produce them. Next generation advancements in gamma-ray production require these demands be satisfied, while simultaneously increasing the average flux of gamma-rays at a specific energy (that is, $N/eV/sec$ at the energy of interest). In order to increase the total flux, the machine currently being constructed at LLNL will operate at 120 Hz, while researching methods to raise the effective repetition rate of the machine to greater than kHz.

The effective repetition rate will be increased by operating the RF photoinjector in a multi-bunch mode, accelerating multiple electron bunches per RF pulse. This multi-bunch mode will require the same stringent requirements

for the electron bunch properties including low emittance and energy spread, but across multiple bunches.

The strategy for modeling multi-bunch operation at very low emittance and energy spread, and the outline of this paper is as follows. (1) Beam dynamics modeling of the Mark 1 rf gun with the *VELOCIRAPTOR* [2] linac design to examine charge scaling, and changes to engineering tolerances. (2) Wakefield modeling to determine effect of multiple bunches on bunch-to-bunch uniformity. (3) Experiments on the Mark 1 rf gun to benchmark design and begin multi-bunch measurements.
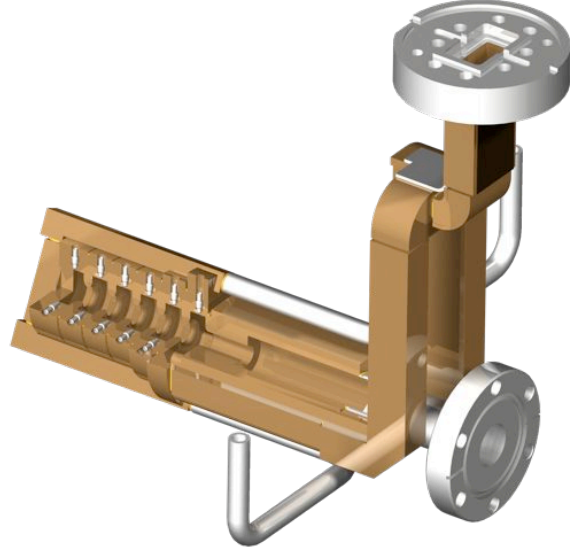

Figure 1: CAD rendering of Mark 1 X-band RF photoinjector.

BEAM DYNAMICS

The Mark 1 X-band RF gun was designed to produce a single 250 pC bunch [3] for a 250 MeV linac [2]. Lowering the bunch charge can improve the emittance and energy spread, as shown in Fig. 3.For these *PARMELA* simulations the laser intensity was kept constant (as quantified by $\mu J/mm^2$) and the laser spot size was scaled to give the charge (pC) indicated. The entire 250 MeV linac was tuned for low emittance while retaining the lowest energy spread possible. A thermal emittance of 0.9 mm mrad per μm of laser spot size was assumed for the initial electron distribution, and though the final linac includes a chicane, the effects of coherent radiation was not included for the data in
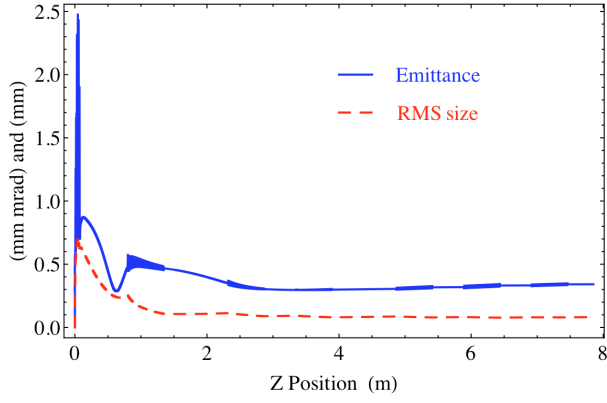
Figure 2: *PARMELA* output for 150 pC bunch charge.

Fig. 3. Lowering the bunch charge shows great promise in lowering the electron energy spread significantly, as well as producing much lower emittance bunches. An ideal bunch charge is dependent on effects beyond the scope of these calculations, and will ultimately be determined by a combination of specific application and what is experimentally achievable.
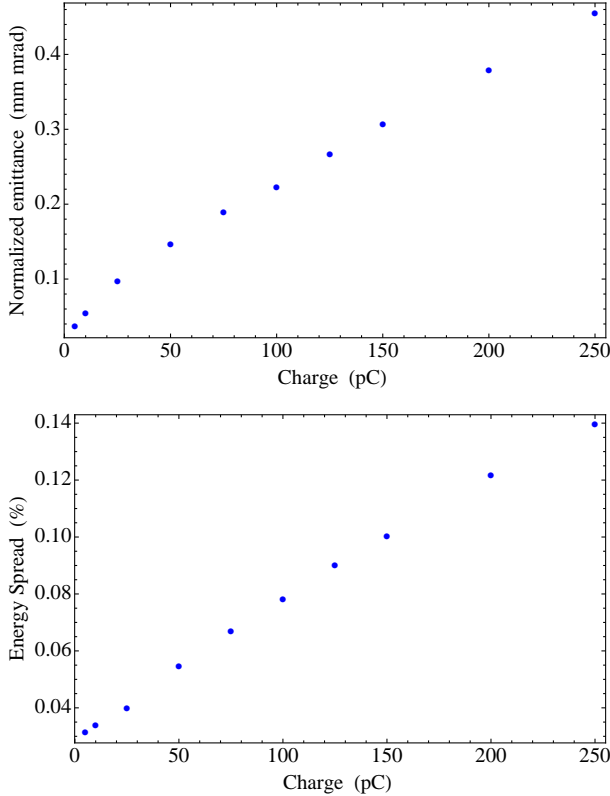

Figure 3: Scaling of emittance (top) and energy spread (bottom) with bunch charge.

One concern with operation at lower charge is that alignment tolerances are reasonable and can be met. The sensitivity of emittance on transverse emittance compensation solenoid alignment is shown in Fig. 4. For a 250 pC bunch 100 μm displacement results in a reasonably small increase in emittance; at 25 pC the same displacement produces much more relative emittance growth. In order to achieve the promising emittances of Fig. 3, the alignment tolerances must be significantly tightened. Other parameters show some increase in sensitivity at lower charge, while other parameters show little dependence, and remain tolerable within their 250 pC specifications.
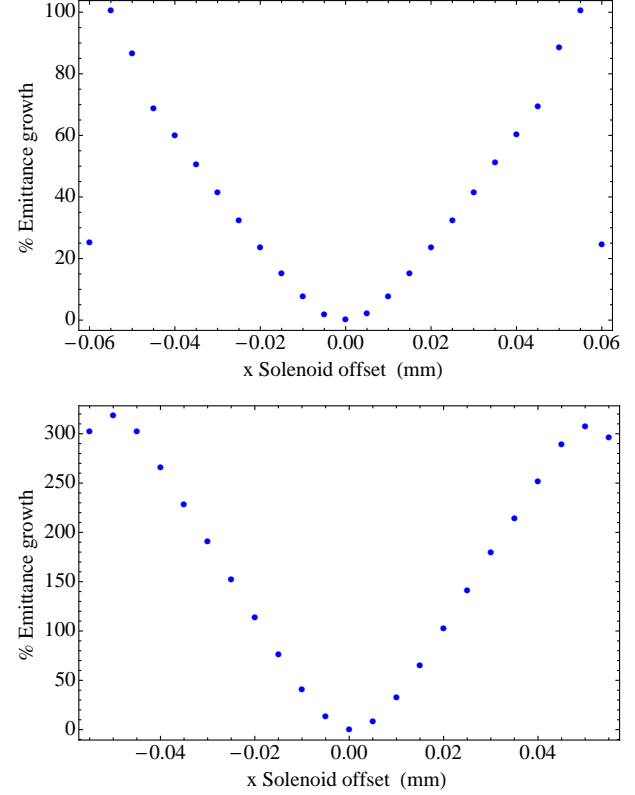

Figure 4: Solenoid offset effect on emittance growth for 250 (top) and 25 pC (bottom) designs.

MULTI-BUNCH EFFECTS

Another concern with multi-bunch operation is wakefield effects degrading the bunch-to-bunch emittance. *ACE3P* simulations have been made on the Mark 1 RF gun, including full *PIC3P* particle-in-cell runs and *T3P* time domain excitation and wake potential calculation. The results for converged wake calculations are shown in Fig. 5. Wakefield modeling of the Mark 1 gun shows small effect from transverse wakefields degrading emittance.

Longitudinal wakefields, or beam-loading as a result of multiple bunches extracting power from the rf gun must be compensated so that each bunch has close to the same energy. This is especially important given the strong (γ^2) dependence of gamma-ray energy on electron energy. Numerous techniques exist, including: phase amplitude manipulation ($\Delta\phi$-A [4]), matched filling [5], amplitude
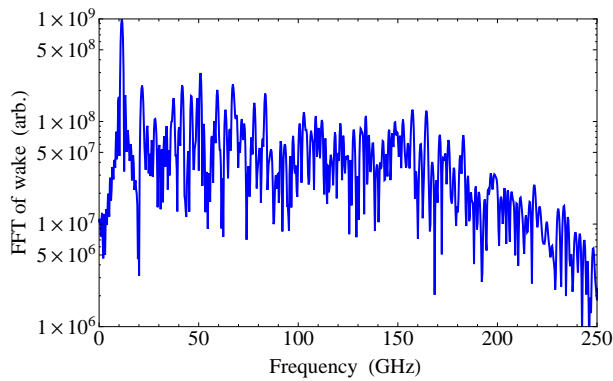
Figure 5: Wake potential from a single bunch in the Mark 1 X-band rf gun.

modulation (ΔT method), staggered timing [5], frequency shifting (Δf method) [6]. A combination of techniques will be necessary for compensation for a complete linac design, but compensation in the gun will require primarily shaping the RF drive to compensate for beam-loading so that flexibility can be maintained in the bunch spacing, timing and frequency.

CONCLUSION

Multi-bunch modeling is in direct support of experimental testing of the Mark 1 RF gun on the LLNL test station [7]. Initially the gun will be processed to full operating power, which corresponds to 200 MV/m peak electric field on the cathode surface. Single bunch benchmarking of the Mark 1 design will provide confidence that this first structure operates as designed, and will serve as a solid starting point for subsequent changes, such as a removable photocathode, and the use of various cathode materials for enhanced quantum efficiency. Charge scaling experiments will follow, partly to confirm the predictions of Fig. 3, as well as to identify important causes of emittance growth, and their scaling with charge. Multi-bunch operation will conclude testing of the Mark 1 RF gun, and allow verification of code predictions, direct measurement of bunch-to-bunch effects, and initial implementation compensation mechanisms. Modeling will continue and focus on both Mark 2 RF gun design, as well as supporting the experimental program.

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