

X-BAND RF PHOTOINJECTOR RESEARCH AND DEVELOPMENT AT LLNL*

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Abstract

In support of Compton scattering gamma-ray source efforts at LLNL, a multi-bunch test station is being developed to investigate accelerator optimization for future upgrades. This test station will enable work to explore the science and technology paths required to boost the current mono-energetic gamma-ray (MEGa-Ray) technology a higher effective repetition rate, potentially increasing the average gamma-ray brightness by two orders of magnitude. The test station will consist of a 5.5 cell X-band RF photoinjector, single accelerator section, and beam diagnostics. Beam quality must be exceedingly high in order to produce narrow-bandwidth gamma-rays, requiring a robust state of the art photoinjector. The photoinjector will be a high gradient (200 MV/m cathode field) standing wave structure, featuring a dual feed racetrack coupler, elliptical irises, and an optimized first cell length. Detailed design of the RF photoinjector for this test station is complete, and is presented with modeling simulations, and layout plans.

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. 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 operat-

ing 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 achieving multi-bunch operation at very low emittance and energy spread is as follows. 1) Redesign RF photoinjector for more robust high brightness operation, 2) Model effects that will degrade multi-bunch gamma-ray quality including: dark current, wakefields, and beam-loading, 3) Measure simulated effect in experiment, 4) Redesign RF photoinjector as necessary. An independent test station has been planned and designed to carry out multi-bunch experiments to benchmark design performance and theoretical modeling. This paper will summarize the Mark 1 RF photoinjector design, and current plans for the completion of the test station, including location and RF distribution.

TEST STATION LAYOUT

The advanced X-band test station will be an independent beamline capable of performing experiments on future improvements to the LLNL Nuclear Photonics Facility. Until the full facility is built in B391, the test station will be established in the North-South caves of B194. Early establishment of the test station will enable operational experience, and allow multi-bunch experiments to begin in advance of the full B391 facility being available for occupancy. The parameters for the test station are shown in Table 1. The test station layout is shown in Figure 1. The caves are shared with legacy beam transport for another experiment (shown in the upper portion of Figure 1). The test station will consist of a control room with equipment racks, the high power solid-state modulator and XL-4 klystron, RF distribution, a Mark 1 RF photoinjector and single traveling wave accelerator section with beamline transport magnets and diagnostics. The system is discussed in more detail in other work including: the beam dynamics [1], laser systems [2], and RF distribution [3]. A similar system is being built at SLAC for testing X-band RF photoinjectors, as discussed in [4].

RF PHOTOINJECTOR

The Mark 1 X-band RF photoinjector was based on an earlier design (Mark 0) developed by A. Vlieks at

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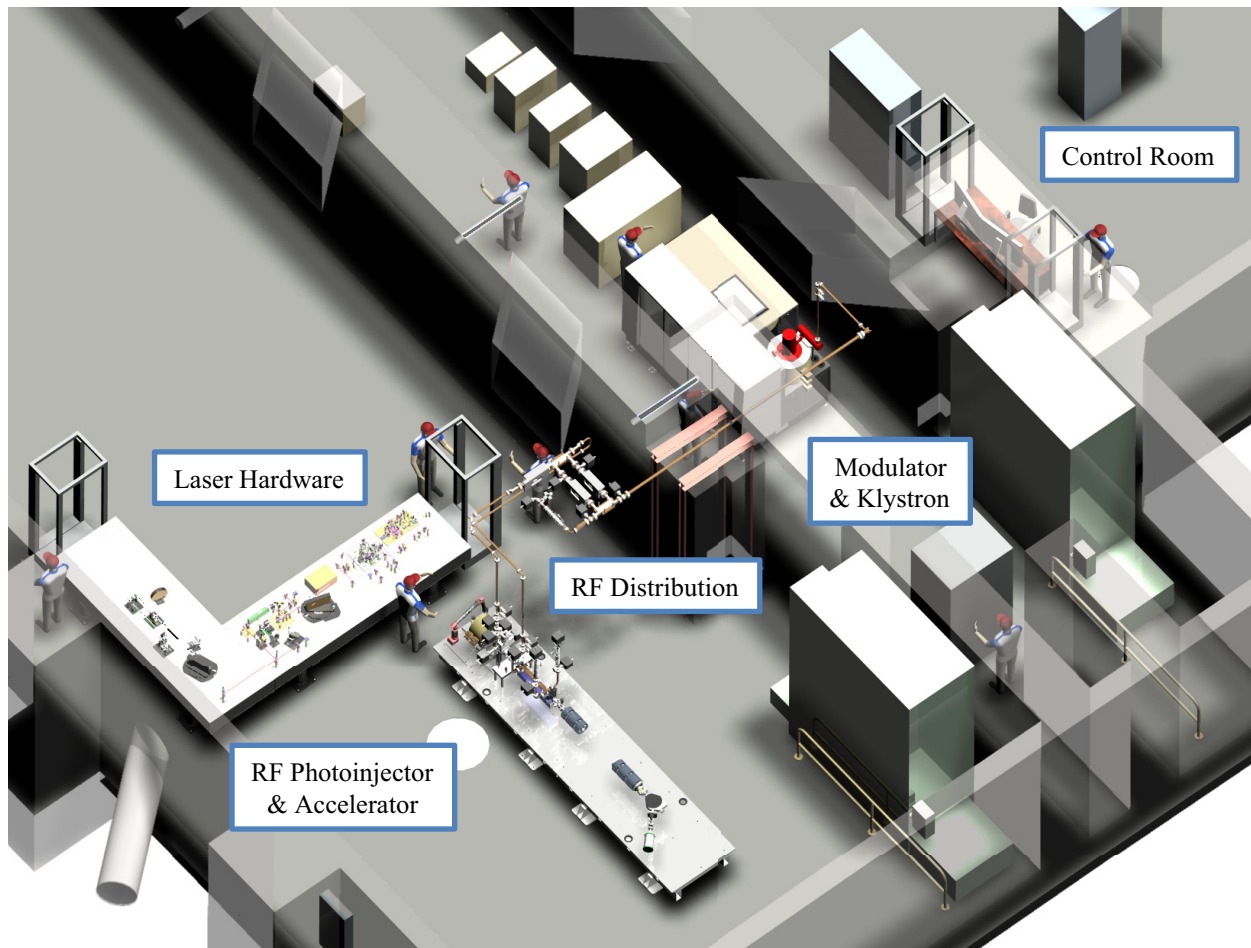


Figure 1: CAD rendering of test station layout in B194.

Table 1: Test Station Parameters

Charge	250 pC
Bunch Duration	2 ps
Bunch Rise/Fall	<250 fs
Normalized Emittance	<1 mm-mrad
Gun Energy	7 MeV
Cathode Field	200 MV/m
Coupling β	1.7
Section Gradient	~ 75 MV/m
Final Energy	30–50 MeV

SLAC [5, 6]. The Mark 0 was the first X-band photoinjector, and was operated successfully at cathode electric fields of 200 MV/m. The Mark 0 photoinjector was a 5.5 cell design, and as such supported 6 eigenmodes near the operating π -mode. The mode separation between the operating mode and its nearest neighbor was less than 10 MHz, leading to simultaneous excitation of both modes by the drive RF, resulting in mode beating of the fields on the cathode, and degradation in achievable beam brightness.

The Mark 1 photoinjector advances on the Mark 0 design by increasing the mode separation to 25 MHz, and

incorporates other significant improvements to enhance its robust operation as the *VELOCIRAPTOR* electron source. A CAD rendering of the Mark 1 RF photoinjector is shown in Figure 2. The major design changes include: iris geometry change from circular cross-section irises to elliptical contoured; iris thickness adjustment to improve mode separation; a longer initial half cell; a racetrack coupler; and coupling optimization to balance pulsed heating with cavity fill time. A description of the detailed design process and supporting simulations will be presented in [7]. A summary follows, reporting only design achievements. A combination of design codes were used including PARMELA, HFSS, and the ACE3P suite of codes developed at SLAC.

Eigenmode excitation modeling showed that the Mark 0 mode separation of 8.7 MHz led to an increase in the photoinjector beam divergence. In order to generate as bright a beam as possible, the mode separation was increased to 25 MHz, at which point mode beating contributed a negligible emittance increase. The final iris parameters were held fixed for the remainder of the design changes, and the mode separation was maintained.

Changing the iris geometry can spread the electric field maximum over a wider surface area, and decrease the peak

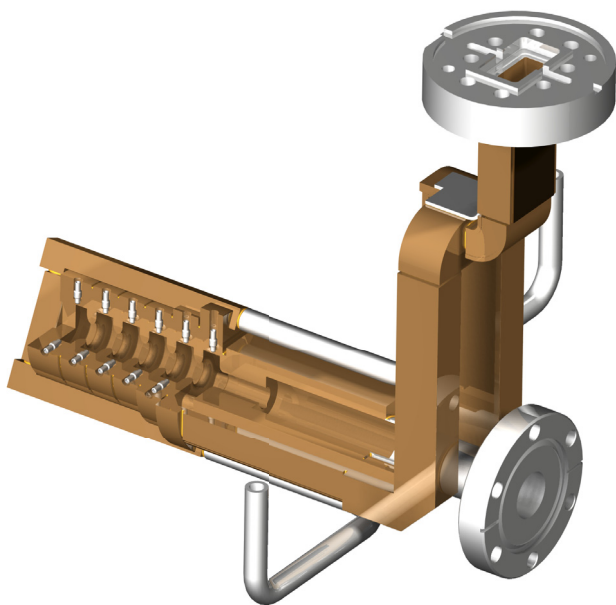


Figure 2: CAD rendering of Mark 1 X-band RF photoinjector.

surface electric field for a given gradient. The optimal iris ellipticity is dependent on the exact iris radius and thickness. For the Mark 1 design this geometry was fixed by the changes made to improve the mode separation. An improvement of 10% was accomplished in the achieved axial electric field relative to the peak surface field by adopting irises with an elliptical axial contour. The irises remained cylindrically symmetric with respect to the beam axis, the elliptical contour is only visible in their cross-section, e.g. the cutaway in Figure 2.

The half cell in the Mark 0 photoinjector was slightly under an exact half cell in length. Running beam dynamics simulations to optimize the emittance after compensation, an optimal half cell length was determined.

The coupler for the Mark 0 photoinjector was a dual feed design, but continued to have a small quadrupole component that would increase the head to tail beam asymmetry, and increase the beam emittance. In order to lower this effect to ignorable levels, a racetrack coupler was designed similar to that used in the Linac Coherent Light Source injector. The decrease in RF quadrupole between the Mark 1 and Mark 0 designs is a factor of 100, virtually eliminating this source of emittance growth.

The optimal coupling into the photoinjector is a balance between the power available, the pulse length used, and the resulting pulsed heating. Circuit models were used to determine the balance achievable, and then choose an operating point that is relatively insensitive to fabrication tolerances.

Water cooling will be accomplished in the same manner as the Mark 0 design, with a single brazed water channel. Vacuum will be provided by a circularly symmetric pump-out port on the beamline, and waveguide pump-outs on the feed waveguide. Final electromagnetic design incorporated

all of the features described, and achieved a π -mode frequency of 11.424 GHz, a uniform field balance of $<1\%$ flatness variation, and a coupling β of ~ 1.7 .

TEST STATION PLANS

Future modeling efforts will focus on the predicted performance of the new RF photoinjector, specifically on the multi-bunch performance of the RF gun. Simulation of beam loading will determine the predicted bunch to bunch energy spread, and drive compensation efforts. The test station experimental program will focus on installation and commissioning. Utility work and preparation are currently underway in B194. The solid state modulator has been delivered, and will soon be installed with supporting hardware. Klystron installation and high power RF commissioning will begin this Summer, with completion pending delivery and installation of the Mark 1 RF photoinjector and accelerator section this Fall.

Experiments will benchmark modeling results and focus future research and development on solving the technical challenges to increasing gamma-ray flux and repetition rates. The technology developed on the test station will serve as the basis for future upgrades to LLNL's center for gamma-ray applied science to further increase the gamma-ray production. A fully functioning multi-bunch high brightness X-band RF photoinjector and accelerator section make the test station a valuable platform for future X-ray and gamma-ray research; both as a test bed for upgrades, and as an independent source of electrons for further study.

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