Performance of a second generation X-band rf photoinjector

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rf photoinjectors produce incredibly bright electron beams enabling advanced photon science applications such as the current generation of free electron lasers and high energy x-rays and gamma-rays via laser-Compton scattering. A second generation 5.59 cell X-band rf gun has been developed, installed, conditioned, commissioned, tuned, and used to produce laser-Compton x-rays and multiple electron bunches. A charge per bunch from a few pC to 500 pC has been measured, consistent with a quantum efficiency of 5×10^{-5} using a 263 nm 10 Hz photocathode drive laser. The rf gun has operated close to design performance at high gradient, and more reliably at lower gradient achieving a root mean square normalized emittance of 0.3 mm mrad at both 80 pC at 185 MV/m, and 40 pC at 165 MV/m. Thermal emittance is estimated at 0.55 mm mrad/mm. Energy spread of 0.03% has been achieved. These results agree very well with modeling predictions for the operating conditions under which the measurements were made. Unusually disruptive breakdowns were observed with an applied magnetic field of 0.5T used for emittance compensation.

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I. INTRODUCTION

The latest generation of light sources has been made possible by the advances in peak electron brightness due to modern rf photoinjectors [1,2]. rf guns offer low emittance beams that can be accelerated to the necessary operating energy to lower the geometric emittance, and temporally compressed to the required peak current for free-electron laser (FEL) operation [3–5]. X-band rf technology is capable of up to 200 MV/m accelerating gradients, making novel compact accelerator systems possible. The combinations of high peak fields at the cathode with sub-mm spot size and sub-ps duration laser pulses in an X-band photoinjector produces high current and low emittance beams that can be used to drive fourth generation light sources, generate THz radiation [6], probe structural dynamics at the ultrafast timescale [7], or serve as injectors for laser-based compact accelerators [8]. The shorter wavelength of X-band can lead

to intrinsically shorter initial electron bunches, which can eliminate bunch compression stages and further shorten FEL length [9,10].

At Lawrence Livermore National Laboratory (LLNL), X-band accelerator technology has been developed to enable laser-Compton light sources spanning a wide range of x-ray and gamma-ray energies in a system that fits in a small laboratory space. Laser-Compton light sources can serve as high peak brightness, high flux, tunable sources of x-rays and gamma-rays from 10s of keV to 10s of MeV. The photons that are produced can be collimated to produce narrow bandwidth x-rays and gamma-rays with a source size and bandwidth limited by the electron beam quality. Examples of such facilities are the high intensity gamma-ray source (HIGS) [11], and the under construction Extreme Light Infrastructure Nuclear Physics Gamma-Beam System in Romania (ELI-NP GBS) [12]. LLNL has a long history of work on narrowband gamma-ray light sources [13–20], and designed the all X-band VELOCIRAPTOR linac [21]. The X-band photoinjector [22] discussed here was originally designed to serve as the electron source for the VELOCIRAPTOR, and LLNL commissioned the MEGa-ray (Mono-Energetic Gamma-ray) Test Station (MTS) to leverage hardware in hand into a platform for developing the critical technologies

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for optimized Laser-Compton scattering with an X-band accelerator [23].

Extensive modeling efforts [16,19,20] have been motivated by nuclear resonance fluorescence applications and the capability of compact X-band accelerators built off of the Mark 1 design parameters [21]. In order to increase the flux of these narrow-band sources, multi-bunch architectures have been developed and novel lasers have seen promising initial success as photocathode sources [24–26]. Multiple electron bunches have been produced and x-rays have been generated and seen to scale [24,27]. New controls have been developed and the extension of the field-programmable gate array-based architecture to a closed-loop system has opened the possibility of interrupting a long rf pulse (such as the phase-flipping low level rf (LLRF) signal for pulse compressor operation) mid-pulse when an arc is detected [28,29]. X-rays have been generated and used to confirm the electron beam energy as reported in this paper, characterized [30,31], used with modeling as an emittance beam-diagnostic [32], and other applications such as medical imaging and therapy [33].

This paper describes the first test results on a Mark 1 X-band photoinjector. Measured parameters are consistent with design specifications and have been obtained without damage to the photocathode surface. This paper is organized as follows. The MTS rf system is described in detail including rf source, klystron testing, and controls. The Mark 1 rf gun is then described including background, design performance, dark current, fabrication, and breakdown results. The full MTS accelerator is then described, including alignment, as well as the photocathode drive laser system. rf gun measurements follow including beam performance metrics and comparison with modeling. Conclusions include an outline of major improvements and design considerations for the next generation X-band photoinjector, i.e. a Mark 2 rf gun.

II. rf POWER

A. Source

The master clock for the accelerator runs at 2.856 GHz and is supplied by a Wenzel Associates MXO-PLMX Multiplied Crystal Oscillator. An integrated 4x frequency multiplier then provides the 11.424 GHz rf for the accelerator systems. Phase and amplitude control of the low level rf signal relies on a Marki microwave IQ0714LXP I/Q mixer with driving voltages on the in-phase and quadrature-phase arms to control the output rf signal. This provides –30 dB attenuation on the LLRF drive and 100 MHz of control bandwidth. The mixer is driven by an Active Technologies AT-1212 2-channel, 1.25 GHz, 14-bit arbitrary function generator connected to an National Instruments PXI-7954R Flex-RIO board, part of the PXI-based rf control chassis. This architecture provides the freedom to explore a variety of operational modes by

allowing for fine-tuning to flatten the final rf pulse delivered to the accelerator, compensate for beam loading effects in multibunch operational modes, and to provide proper phase jumps for the implementation of rf compression schemes.

This shaped pulse is supplied to an Applied Systems Engineering 117X traveling wave tube amplifier (TWTA). The $\sim$ kW power from the TWTA is further amplified using a SLAC National Accelerator Laboratory (SLAC) XL-4 klystron capable of producing 50 MW rf power for 1.6 microseconds at 11.424 GHz. The klystron is powered by a Scandinova K2-3X modulator, providing 420 kV, 330 A pulses. The modulator is equipped with its own manufacturer-supplied control hardware, which provides network-based access to all necessary controls and readbacks. This system also controls the klystron solenoid magnets and monitors water flow through the system.

B. Testing

The XL-4 klystron was fully high voltage and high power rf conditioned as part of its production at SLAC. Initial testing of the klystron at LLNL was into a temporary load tree. The output of the klystron was connected to a –55 dB directional coupler to measure the forward power from the klystron, and any power reflected back to the klystron from the loads during conditioning. The load tree consisted of an overheight –3 dB coupler capable of handling several hundred MW and three medium average power loads (one for matching and two to share the power load). Diagnostics were calibrated for high voltage and rf measurements during processing, with typical high voltage traces shown in Fig. 1 and the klystron output rf shown in Fig. 2. Vacuum pumping was via the through ports on the loads and mode converter spools on the klystron output window and –3 dB coupler. Pressure was logged using a hot cathode gauge. Baking of all components was done

FIG. 1. Measured traces of klystron voltage (calibrated capacitive divider on the modulator output) in blue and current (klystron gun current transformer) in purple. 400 ns flat top used for rf generation.

FIG. 2. Measured 400 ns XL-4 klystron rf output power pulse. Small reflections observed at start and end of pulse from reflections in the directional coupler and load tree.

at $\sim 120^\circ\text{C}$ for several days to achieve low 10^{-8} Torr base pressure.

Processing proceeded over approximately 80 run hours at up to 10 Hz, and a total of ~ 2.2 million pulses. A final rf power of 50 MW was achieved for 400 ns with very low breakdown rates. Extremely good stability and flatness were measured, meeting all requirements for ideal linac integration and operation. High voltage pulse flatness was measured and observed to be 0.05%. The rf pulse flatness was comparable at 0.1%, with some small contribution from the initial low-level rf setup implemented for klystron testing. The shot-to-shot stability of the rf pulse was 0.01%. rf phase stability was measured both by direct mixing and I/Q mixing and was better than $<0.5^\circ$.

The rf pulse shape included rising and falling edge features that were not a direct result of the high voltage and rf systems, but were a product of the load tree components or their assembly. *In situ* cold test measurements were completed after testing to confirm reflections were present from the load tree that caused transient reflections from the frequency content of the sharp edge pulse. The loads are reasonably broad band around 11.424 GHz, and the WR-90 and overmoded round waveguide are both used well inside their frequency bands, so very little response was expected. The entire assembly does represent a larger resonant structure, which could have natural modes excited by the high power rf; or a single flange could be poorly assembled resulting in a localized mismatch. In either case the pulse shape is not a limitation of the rf system, merely a feature of the specific testing method.

C. Distribution

The most complex component in the distribution system is the variable attenuator, which consists of two -3 dB H-plane hybrid couplers and two variable phase shifters. A microwave pulse entering the attenuator will be evenly split in power, but with a 90° phase difference between two output ports each with an independent phase shifter. The two pulses then enter the second hybrid and are combined

at the output ports such that by adjusting the phase, the amount of input power going to the photoinjector is changed, with the difference going to the accelerator section [34].

The photoinjector and 53 cm traveling wave accelerator section (T53 [35]) were both designed to achieve accelerating gradients near 100 MV/m, which corresponds to 200 MV/m peak surface electric field on the gun cathode surface. In order to reach these high field levels, a lengthy period of rf conditioning was required, processing through many breakdown events to reach higher and higher electric field levels with less chance of further breakdown and less emitted dark current. Recovery varied from immediate turn on, to slow ramp back to full power, to prolonged shutdown for vacuum recovery.

Long pulses in the full accelerator distribution exhibited step features resulting from unwanted rf reflections, from either the tube itself or more likely the rf distribution and mode converters near the klystron. These features have a potential impact on the rf amplitude and phase flatness for longer pulse operation (e.g., for pulse compression), but the system was generally operated at pulse length of 120 ns which avoided the formation of the features. In theory this pulse can be exactly compensated for in the LLRF using the arbitrary function generator and hardware in place. Performance of this system is detailed in [28,29].

D. Diagnostics and arc detection

rf power detector diodes monitor transmitted and reflected rf power at the klystron output, the photogun input, and each section input. These signals, along with signals from the integrating current transformer are fed to a bank of 1 GHz, 8-bit Digitizers (National Instruments PXI-5154) in the rf control chassis. These traces are processed to provide klystron, gun, and section power, gun gradient, and current charge measurements. The traces are also available to look for operational anomalies.

The traces from these digitizers are also monitored in real time to look for evidence of arcing in the system. This could be either the trace exceeding some trip level within a gated window or the integral of the difference between two consecutive shots exceeding some threshold level. If any channel shows either of these conditions, the chassis inhibits firing of the modulator and low-level rf pulses. The system can then automatically ramp the rf power back up to the set point, to avoid arc-induced damage.

III. rf GUN

Though frequency scaling does not bring the high gradients hoped in initial Loew-Wang scaling [36], the short pulse length inherent at higher frequency does mean higher gradients are achieved [37], which can mean shorter accelerators and faster energy gain in photoinjectors and thus the potential for brighter beams [21]. The original

TABLE I. Mark 1 rf gun parameters.

Frequency	11.424 GHz
Unloaded quality factor	7055
Coupling β	1.7
First cell length	0.59 cell
Coupler type	Dual feed racetrack
Iris shape	Elliptical, 1.8 major/minor
Mode separation	25 MHz
Cathode material	OFHC Copper
Cathode peak field	200 MV/m
Gun kinetic energy	7 MeV

X-band gun (dubbed the Mark 0) was designed and tested by Vlieks [38] with a design gradient of 200 MV/m, much higher than the typical 120 MV/m S-band gradient. The design gradient was reached, but dark current was a problem [39]. A spare set of parts for the Mark 0 gun existed, and these were leveraged to develop a modified Mark 0 gun which was tested by Limborg-Deprey [9,10].

The second generation Mark 1 X-band rf photoinjector includes the following state-of-the-art improvements: elliptical contoured irises; larger mode separation; an optimized initial 0.59 cell length; a racetrack input coupler; and coupling that balances pulsed heating with cavity fill time. rf and beam dynamics modeling was done using a combination of codes as reported in [22]. The Mark 1 parameters are summarized in Table I and a photograph is shown in Fig. 3.

Beam dynamics modeling was used to optimize the overall photoinjector design, by adjusting the bunch phase, solenoid strength and the gun-to-accelerator-structure spacing to achieve the best emittance compensation. A thermal emittance of 0.9 mm mrad per mm root mean square (RMS) of laser spot size was assumed following [40]. An emittance of 0.3 mm mrad and an energy spread of 0.03% are expected at 30 MeV for a 100 pC bunch, which requires the use of the Mark 1 rf gun and a single T53 accelerator structure operating at 45 MV/m [35]. The emittance at the end of the 250 MeV *VELOCIRAPTOR* linac was expected

FIG. 3. Photograph of the Mark 1 X-band rf gun.

to be 0.35 mm mrad for a 250 pC bunch [21], which includes the Mark 1 rf gun and six T53 accelerator structures operating at 75 MV/m. Modeled operation at a reduced peak surface electric field of 180 MV/m results in a $\lesssim 10\%$ increase in emittance, and operation at 140–160 MV/m results in a $\lesssim 50\%$ increase in emittance.

Dark current is always a concern in high gradient structures, and is especially critical in photoinjectors because the charge emitted by the cathode can be captured and accelerated to high energy. The predicted dark current was simulated to provide a reasonable source term for radiation shielding calculations as part of the building safety basis for accelerator operations. Dark current was modeled using Fowler-Nordheim [41] current density spread over the structure surface and tracked using the General Particle Tracker code similar to work reported in [42].

Dark current emitted from the high field iris surfaces was simulated as discrete emission with a 5° spacing along the iris. Most (95%) of the particles emitted strike the surface with an energy below 1 MeV, and a small number (1.5%) escape the gun with a flat energy spectrum between 4 and 7 MeV depending on how many cells of acceleration they experience. Emission from the cathode occurs preferentially at higher field, and thus higher than the design launch phase and are non optimally accelerated but attain higher energy and escape the gun more easily. Approximately half the emitted dark current has an energy below and half above 1 MeV, with the high energy electrons having a relatively flat energy spectrum based on nonoptimal cell-to-cell acceleration due to phase slippage. The ratio of dark current emitted from the cathode versus the irises depends on the β assumed in the Fowler-Nordheim equation [41]. For β between 30–50, about half of the dark current exiting the gun is from the cathode.

The Mark 1 gun was fabricated at SLAC National Accelerator Laboratory. The gun was cold tested and tuned for field balance across all cells, as measured by bead drop. The measured unloaded quality factor shows good agreement with the design simulation value, and the coupling β was tuned to the design value of 1.70 ± 0.01 . Network analyzer traces for the 6 modes present show the design mode separation of 25.3 MHz from the nearest mode, and the correct frequency of 11.424 GHz after correcting for air and temperature. Once the gun was aligned prior to high power conditioning it was cold-tested in-situ and the cooling water temperature was tuned to 44.0°C for a resonance at exactly 11.424 GHz.

Conditioning of the photoinjector and accelerating structure took place in stages at 60 Hz, using the variable splitter to distribute power to the gun and section. The section was processed to 25 MW at 250 ns, the highest power level it was likely to see in normal operation; this corresponds to an accelerating gradient of 50 MV/m, significantly de-rated from the high gradient testing this

design has seen at $100 + \text{MV/m}$, but with the benefit of very low breakdown rates and low dark current emission. The gun was processed up to 200 MV/m with and without the emittance compensation solenoid on, which was found to have a significant effect on breakdown physics. The primary goal of the gun conditioning was to avoid damaging the cathode, given that it was fixed, not removable, and any significant damage has been seen to increase dark current, lower quantum efficiency, and increase emittance [9].

Three different varieties of breakdown were qualitatively observed during the gun processing, with typical scope traces shown in Fig. 4. Arcing on what was believed to be the medium power vacuum window on the gun input waveguide occurred reliably at peak input powers exceeding 20 MW . These were characterized by high frequency noise on the reflected diode, large power reflections to the T53 power arm of the divider, and no dark current. Breakdown on the cathode surface could be somewhat differentiated from arcing on the dual feed input coupler of the gun, but all high field breakdown events in the gun were similar. Breakdown occurring in the gun was also extremely sensitive to the presence of the emittance compensation solenoid. Ramping the field quickly is capable of causing arcs, and the breakdown events that occur with the solenoid on appear to cause more significant surface damage, requiring a longer recovery time. Once a gradient level was reached without the solenoid on, reprocessing was accomplished relatively quickly. The most expedient method for recovering from breakdown events was to recover from all arcs without the solenoid on. The system was then reramped with the solenoid on. Observations with this 11.424 GHz vacuum structure can be compared to 800 MHz gas filled structure results [43]. They are similar in that the conditioning was observed to be less stable and required longer recovery with a magnetic field present, but significantly different in that the breakdown threshold appeared independent of magnetic field.

FIG. 4. Scope traces of forward power (blue solid line), reverse power (purple fine dashed line), and ICT current (yellow coarse dashed line) for a typical breakdown shot.

IV. ACCELERATOR

The test station is in B194 at LLNL with a control room upstairs, and hardware underground in the North, South, and Magnet caves of B194: equipment racks, a high power solid-state modulator and XL-4 klystron, rf distribution waveguide, a Mark 1 rf gun and a single traveling wave accelerator section with beamline transport magnets and diagnostics. The photoinjector and accelerator section can be seen in Fig. 5. The various subsystems have been presented in some detail previously: the beam dynamics in [44,45], laser systems in [24], rf distribution system in [34], and complete test station assembly [46].

The system was built and aligned using procedures developed in the planning of *VELOCIRAPTOR*. Vacuum baking region by region allowed base pressures of 10^{-9} Torr to be reached by ion pumps alone.

The system was aligned with a coordinate measuring machine (CMM) from ROMER with $\pm 75 \mu\text{m}$ repeatability and volumetric accuracy. The coordinate system of the arm is based on geometric features of individual components such as the cross-section of magnet pole pieces, or the outer radii of pillbox cell cups, combined with tooling ball external fiducials when features may be less accessible. Magnet metrology measurements at SLAC confirmed that the magnetic and physical axes of the emittance compensation solenoid were aligned to within $25 \mu\text{m}$. Solenoid alignment set the coordinate system for subsequent components, with the beamline axis zero set by the mid plane of the Helmholtz pair outer pole faces: this is where the center for the rf gun is positioned so that there is no field on the cathode surface. Beam-based measurements confirm the gun alignment to $< 50 \mu\text{m}$. The gun centerline was used for the remainder of the linac alignment. Small micron level discontinuity in the alignment of the cells was measured with the arm, as expected from fixed CMM measurement and drawing specification. This precision alignment strategy meant that first beam was immediately observed with the first rf-to-laser phase scan attempted.

FIG. 5. Photograph of compact high gradient accelerator capable of 100 MeV in a few meters.

V. PHOTOCATHODE LASER

The Photocathode Drive Laser, responsible for generation of the electron bunches, is a commercial 10 Hz Titanium-doped Sapphire-based chirped pulse amplification system [24]. The laser is seeded with a MenloSystems C-Fiber 780 fiber oscillator. To maintain synchronization between the laser pulse train and the accelerator rf, the signal from a fast photodiode monitoring the laser output is mixed with the master rf clock (2.856 GHz), and the resulting error signal is fed-back to a combination of piezo and motor actuators on one of the oscillator end mirrors. Because this laser is shared with an S-band system in the same facility, the reference rf signal and the laser pulses have to travel 75 m between the laser and accelerator. The thermal stability of these two paths results in a slow drift of the relative phase between the laser and the rf in the injector over the course of the day, as well as a small alignment drift, but hasn't shown any impact on the shot-to-shot alignment or timing stability.

The pulse is amplified in a Centaurus X system from Amplitude, consisting of an Offner stretcher, and a regenerative amplifier and 4-pass amplifier relying on a flash-lamp-pumped frequency doubled Neodymium-doped Yttrium Aluminum Garnet pump. This amplification chain provides up to 20 mJ of uncompressed 780 nm laser light, although only 3 mJ is transported to the accelerator, where the pulse is compressed to ~ 200 fs measured via GRENOUILLE [47] traces. A low-temperature beta-phase Barium Borate based frequency tripler converts the light to 263 nm. After compression and frequency conversion, around 120 μ J of ultraviolet (UV) light is available. This beam then passes through a clipping aperture to generate the desired beam diameter (typically 0.5 mm), and relay imaged 10 m to the photocathode via a two-lens vacuum imaging telescope. A typical image on the virtual cathode with vertical and horizontal lineouts is shown in Fig. 6. The UV image and cathode spot quality were affected by

FIG. 6. Laser profile taken on virtual cathode for 0.5 mm diameter pinhole aperture used for $\sim 40 \pm 2$ pC operation with 3.5 ± 0.2 μ J energy for a quantum efficiency of 5×10^{-5} . Horizontal and vertical lineouts for image.

B-integral in the transport line, preventing proper relay imaging and contributing to the soft edge and diffraction rings shown in Fig. 6.

Beam alignment onto the cathode is controlled with two steering mirrors just prior to the laser vacuum entry window. The alignment and beam profile are monitored via beam leakage through a fixed mirror after the steering optics by a camera located at the same image plane as the cathode. A sample profile is shown in Fig. 6. Typically, 3.5–10 μ J of UV light is used to illuminate the cathode, but that varies with the size of the clipping aperture. The energy density is typically maintained at $\lesssim 15$ μ J/mm².

VI. MEASUREMENTS

A summary of measured electron beam parameters is shown in Table II. Initial measurements of quantum efficiency were promising ($> 2 \times 10^{-5}$). First beam accelerated through the T53 section was easily achieved due to precise alignment, and allowed the gun-to-section phase to be adjusted. The optimal solenoid field strength was observed to be far from the design point, and it was found that the rf gun power measurement calibration was inaccurate and thus underestimated the gradient.

The cathode center was accurately determined using the beam images on the first Yttrium Aluminum Garnet (YAG) screen between the gun and T53 section. Launch phase ramping shows the effect of electromagnetic focussing effects in the gun, and defines the electromagnetic center of the cathode. Solenoid field ramping shows the effect of the multipole moments of the solenoid, and defines the magnetic center of the emittance compensation solenoid.

A. Quantum efficiency

Schottky scans measured the charge as a function of launch phase, and were used to define the zero field phase to degree level precision. A typical curve is shown in Fig. 7, and was used to determine the operating phase of the gun, which typically requires phase length adjustment by a few degrees from day to day to maintain a fixed operating phase. The charge is measured with an absolutely calibrated Bergoz integrating current transformer (ICT) mounted

TABLE II. Summary of measured electron beam parameters.

Charge	40 pC
Charge stability	$\pm 5\%$
Normalized emittance	0.3 mm mrad
Emittance error	0.03 mm mrad
Final energy	30 MeV
Energy systematic error	0.03 MeV
Energy spread	0.03%
Energy jitter	0.06%
Final focus spot (X $\times$ Y)	10 $\times$ 8 μ m
Final focus jitter (X $\times$ Y)	5 $\times$ 3 μ m
Final focus resolution	1 μ m

FIG. 7. Schottky scan used to determine rf phase. Shape due to capture dynamics changing at higher charge and field for fixed emittance compensation solenoid setting.

in-flange on the gate valve that isolates the gun vacuum. The absolute charge measurement combined with power measurements on the photocathode laser allow for a direct quantum efficiency calculation. The typical operating parameters have used 3.5–10 μJ of 263 nm UV laser photons and produces 40–80 pC of charge depending on the gradient, for a quantum efficiency that has ranged from the conservative design point of 2×10^{-5} , to as high as 1×10^{-4} , with very stable performance at 5×10^{-5} at 165 MV/m.

B. Emittance

A quadrupole scan technique was used to measure the emittance following [48–50], and to optimize the fine tuning of all parameters, especially the emittance compensation solenoid, for minimal emittance [51]. The set of quadrupoles located after the accelerating section and a YAG screen pop-in located after a 1 m drift length were used for the scans. A triggered gigabit ethernet camera captured 12-bit images, and 10 or 20 stills per position were captured. Background images were taken used for subtraction. X and Y sizes are taken from root-mean-square calculations using super-Gaussian fits, which proved to be faster and insensitive to shot-to-shot fluctuations while agreeing with direct calculations when each image was analyzed in detail. The spot size as a function of field strength, shown in Fig. 8 are used to independently calculate the X and Y emittances by fitting the Twiss parameters using the beam current and energy as inputs.

After tuning, the final emittance and energy spread were checked against new *PARMELA* simulations for the laser spot size, charge, gradient and launch phase that were used for the lowest measured emittance. Excellent agreement is seen for the final energy spread and emittance. The normalized emittance and beam size a function of longitudinal position for the *PARMELA* simulation are shown in Fig. 9. A normalized emittance of 0.26 ± 0.02 mm mrad

RMS in X and 0.28 ± 0.02 mm mrad RMS in Y has been measured at 80 ± 4 pC. Slightly more effort was put into the X optimization, and that may be the source of the small asymmetry. Typical numbers for recent operations at 165 ± 5 m have been 0.3 ± 0.03 mm mrad at 75 ± 4 pC.

Emittance scaling with charge is an important design consideration for photoinjector performance, especially with low charge, extremely low emittance operation becoming standard for current generation FELs. Linear scaling of emittance with charge was seen in simulation [45]. The emittance was measured for varying photocathode laser aperture sizes ranging from 0.5 mm up to 1.3 mm which increased the laser energy and electron bunch charge. The predicted emittance as a function of charge is shown in Fig. 10 as well with contributions to emittance from beam dynamics predictions from charge variation, and from thermal emittance from the laser spot size variation. The typical 0.9 mm mrad/mm spot size was used in the design [40], but seems to predict much larger emittances than were observed. Other intrinsic emittance measurements [52] suggest different scaling. The points in Fig. 10 vary from linear and are at much larger charge than required for small space charge contributions to intrinsic emittance measurements but are more consistent with less intrinsic emittance, such as the 0.55 mm mrad/mm spot size line.

C. Energy

The electron beam energy is measured by a spectrometer at the end of the beamline. A large bending dipole has been calibrated using a gauss probe scan along the beam path and correlating the field integral to both a gauss probe mounted external to the dipole vacuum chamber and beam dynamics simulations to determine the electron beam energy. A quadrupole triplet can be used to focus the beam onto a YAG screen, which has been calibrated using the beam at varying dipole currents and observing the range of movement. The vertical extent of the beam on the screen is used as an estimate of the betatronic component to the energy spread measurement which is observed to be small. The energy spread is then the width of the spot, while the jitter is the width of the distribution of the centroid. The beam energy was measured at 30 ± 0.03 MeV as expected, the RMS energy spread was 0.031%, and RMS jitter was 0.061% [53]. The small systematic error in the energy measurement is due to the uncertainty in accurate measurement of the dump angle of 23.65 ± 0.05 and resolution on the spectrometer magnetic field to 0.1%. Scattering a high intensity laser off the electron beam produces an x-ray spectrum correlated with the electron beam parameters. The mean energy, energy spread and divergence of the electron beam can be deduced from laser-Compton scattered x-rays filtered by a material whose K-edge is near the energy of the x-rays [32]. K-edge measurements corroborate the measured energy and energy spread using the spectrometer.

FIG. 8. YAG screen images with lineouts from quadrupole scan for X emittance calculation above, and independent Y emittance scan below. RMS beam size as a function of quadrupole field strength used for Twiss parameter fit.

D. Final focus

For laser-Compton interaction a tight final focus spot is desired to maximize the photon flux and enable high resolution imaging. Optimal settings produced a small, bright spot of optical transition radiation from the electron beam which could be analyzed. A spot size of $8\ \mu\text{m}$ vertical and $10\ \mu\text{m}$ horizontal has been measured with jitter on the

order of $3\ \mu\text{m}$ and $5\ \mu\text{m}$ respectively [53]. The resolution of these measurements was limited by the resolution of the imaging optics and camera to $\sim 1\ \mu\text{m}$. Electron beam measurements including jitter are used to model the predicted x-ray flux accurately, as discussed in [30–32].

FIG. 9. *PARMELA* simulation results for the Mark 1 X-band rf gun and a single T53 accelerator section: normalized transverse emittance in solid blue and RMS beam size in dashed red as a function of Z position.

FIG. 10. Scaling of emittance with charge. Comparison of beam measurements taken by varying laser pinhole aperture to vary charge (blue bars) with simulation results using *PARMELA* and differing thermal emittance based on laser spot size. Lines plotted for thermal emittances of 0.55 (red fine dashed line) and 0.9 mm mrad/mm spot size (yellow coarse dashed line).

VII. CONCLUSION

The Mark 1 X-band rf gun shows marked improvement in emittance over the first generation (Mark 0) results of 0.7 mm mrad at 100 pC [9] and good agreement with modeling [22]. A charge per bunch from a few pC to 500 pC has been measured, consistent with a quantum efficiency of 5.3×10^{-5} (± 0.4). The rf gun has operated at close to its 200 MV/m design gradient, and more reliably at lower gradient achieving an RMS normalized emittance of 0.3 ± 0.03 mm mrad at both 80 ± 4 pC at 185 ± 5 /m, and 40 ± 2 pC at 165 ± 5 /m. Thermal emittance is estimated at 0.55 mm mrad/mm, consistent with other estimates. Energy spread was measured at 0.03%; jitter was measured at 0.06%. These results agree very well with modeling predictions for the operating conditions under which the measurements were made. Longer breakdown recovery, similar to [43] was observed with an applied magnetic field of 0.5T used for emittance compensation.

A. Outlook

The Mark 1 performance has been close to modeling predictions, and serves as a good benchmark of simulations and starting point for further refinement. Learning from the Mark 1 experience, a Mark 2 X-band photoinjector should include: (1) A removable photocathode for cathode material studies, improved peak gradient, and prolonged structure lifetime, (2) Increased mode separation for shorter pulse operation in order to improve breakdown rates, and improve emittance, (3) Detailed alignment procedure investigating components prior to linac alignment at least as good as what was achieved using the CMM, (4) Dual feed for dipole and quadrupole minimization, (5) Uniform cooling geometry, since the single channel seemed sufficient but was only tested to 10–60 Hz, (6) Amplitude and phase field pickups in the gun for accurate field sampling to measure cathode gradient more directly, and insure stable gun phase, (7) The first cell length optimum is shorter for lower gradient and should be retuned in parallel with other design changes. The design peak gradient was not achieved for prolonged operations in the Mark 1 gun. The peak field attainable for low breakdown rates (<1 /day at 10 Hz operations) crept down over time from 180 MV/m to 160 MV/m while x-ray generation experiments were performed. One cathode surface and gun structure were all that was available, and so the system was operated conservatively to avoid damage and maximize experimental availability. A next generation gun should be designed for fields in this range depending on how often cathode exchanges are scheduled. QE crept down by a similar margin, by about a factor of 2 in charge for fixed laser energy, but laser cleaning has not yet been attempted.

B. Facility

The MTS accelerator is a state-of-the-art X-band source and electron beam and many other nonlaser-Compton

applications for it are currently being pursued. A compact rf pulse compressor has been designed and fabricated at SLAC to provide up to 200 MW of rf power from a single XL4 klystron. A second accelerator section has been installed and aligned, and the final rf transport components have been designed and fabricated. If implemented, these upgrades would enable an electron energy of 90 MeV and x-rays up to nearly 300 keV, and could be orders of magnitudes more bright than the current system with the appropriate interaction laser [54].

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- [1] J. S. Fraser and R. L. Sheffield, High-brightness injectors for rf-driven free-electron lasers, *IEEE J. Quantum Electron.* **23**, 1489 (1987).
 - [2] D. T. Palmer *et al.*, Emittance studies of the BNL/SLAC/UCLA 1.6 cell photocathode rf gun, in *Proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada*, edited by M. Comyn, M. K. Craddock, M. Reiser, and J. Thomson (IEEE, Piscataway, NJ, 1998), p. 2687.
 - [3] R. Akre *et al.*, Commissioning the Linac Coherent Light Source injector, *Phys. Rev. ST Accel. Beams* **11**, 030703 (2008).
 - [4] Y. Ding *et al.*, Measurements and Simulations of Ultralow Emittance and Ultrashort Electron Beams in the Linac Coherent Light Source, *Phys. Rev. Lett.* **102**, 254801 (2009).
 - [5] E. Prat, M. Aiba, S. Bettoni, B. Beutner, S. Reiche, and T. Schietinger, Emittance measurements and minimization at the SwissFEL Injector Test Facility, *Phys. Rev. ST Accel. Beams* **17**, 104401 (2014).
 - [6] Y. Shen, X. Yang, G. L. Carr, Y. Hidaka, J. B. Murphy, and X. Wang, Tunable Few-Cycle and Multicycle Coherent Terahertz Radiation from Relativistic Electrons, *Phys. Rev. Lett.* **107**, 204801 (2011).
 - [7] P. Musumeci, J. T. Moody, C. M. Scoby, M. S. Gutierrez, and M. Westfall, Laser-induced melting of a single crystal gold sample by time-resolved ultrafast relativistic electron diffraction, *Appl. Phys. Lett.* **97**, 063502 (2010).
 - [8] X. F. D. Stragier, O. J. Luiten, S. B. van der Geer, M. J. van der Wiel, and G. J. H. Brussaard, Experimental validation of a radio frequency photogun as external electron injector for a laser wakefield accelerator, *J. Appl. Phys.* **110**, 024910 (2011).
 - [9] C. Limborg-Deprey *et al.*, Performance of a first generation X-band photoelectron rf gun, *Phys. Rev. Accel. Beams* **19**, 053401 (2016).

- [10] C. G. Limborg-Deprey *et al.*, An X-band gun test area at SLAC, in *Proceedings of the 24th Particle Accelerator Conference, PAC-2011, New York, 2011* (IEEE, New York, 2011), p. 133, MOP15.
- [11] Triangle University Nuclear Laboratory, HIGS Proposal, <http://www.tunl.duke.edu/Local/proposal/higs/>.
- [12] Technical Design Report EuroGammaS proposal for the ELI-NP Gamma beam System, <https://arxiv.org/abs/1407.3669>.
- [13] F. V. Hartemann, W. J. Brown, D. J. Gibson, S. G. Anderson, A. M. Tremaine, P. T. Springer, A. J. Wootton, E. P. Hartouni, and C. P. J. Barty, High-energy scaling of Compton scattering light sources, *Phys. Rev. ST Accel. Beams* **8**, 100702 (2005).
- [14] J. Pruet, D. P. McNabb, C. A. Hagmann, F. V. Hartemann, and C. P. J. Barty, Detecting clandestine material with nuclear resonance fluorescence, *J. Appl. Phys.* **99**, 123102 (2006).
- [15] F. V. Hartemann, F. Albert, C. W. Siders, and C. P. J. Barty, Low-Intensity Nonlinear Spectral Effects in Compton Scattering, *Phys. Rev. Lett.* **105**, 130801 (2010).
- [16] F. Albert *et al.*, Isotope-specific detection of low-density materials with laser-based monoenergetic gamma-rays, *Opt. Lett.* **35**, 354 (2010).
- [17] D. J. Gibson *et al.*, Design and operation of a tunable MeV-level Compton-scattering-based γ -ray source, *Phys. Rev. ST Accel. Beams* **13**, 070703 (2010).
- [18] F. Albert *et al.*, Characterization and applications of a tunable, laser-based, MeV-class Compton-scattering γ -ray source, *Phys. Rev. ST Accel. Beams* **13**, 070704 (2010).
- [19] F. Albert, S. G. Anderson, D. J. Gibson, R. A. Marsh, S. S. Wu, C. W. Siders, C. P. J. Barty, and F. V. Hartemann, Design of narrow-band Compton scattering sources for nuclear resonance fluorescence, *Phys. Rev. ST Accel. Beams* **14**, 050703 (2011).
- [20] F. Albert, S. G. Anderson, D. J. Gibson, R. A. Marsh, C. W. Siders, C. P. J. Barty, and F. V. Hartemann, Three-dimensional theory of weakly nonlinear Compton scattering, *Phys. Plasmas* **18**, 013108 (2011).
- [21] S. G. Anderson *et al.*, VELOCIRAPTOR: An X-band photoinjector and linear accelerator for the production of Mono-Energetic γ -rays, *Nucl. Instrum. Methods Phys. Res., Sect. A* **657**, 140 (2011).
- [22] R. A. Marsh *et al.*, Modeling and design of an X-band rf photoinjector, *Phys. Rev. ST Accel. Beams* **15**, 102001 (2012).
- [23] R. A. Marsh, F. Albert, S. G. Anderson, D. J. Gibson, S. S. Wu, F. V. Hartemann, and C. P. J. Barty, Ultracompact accelerator technology for a next-generation gamma-ray Source, in *Proceedings of the 3rd International Particle Accelerator Conference, New Orleans, LA, 2012* (IEEE, Piscataway, NJ, 2012), p. 3190, THYA02.
- [24] D. J. Gibson, G. G. Anderson, S. G. Anderson, R. A. Marsh, M. J. Messerly, M. A. Prantil, and C. P. J. Barty, Multi-GHz pulse-train X-band capability for laser-compton x-ray and γ -ray sources, in *Proceedings of the 2015 International Particle Accelerator Conference, Richmond, VA, USA* (JACoW, Richmond, 2015), p. 1363, TUBC2.
- [25] D. J. Gibson, E. Courmier, M. J. Messerly, M. A. Prantil, and C. P. J. Barty, A drive laser for multi-bunch photoinjector operation, in *Proceedings of the 2016 North American Particle Accelerator Conference, Chicago, IL, USA* (JACoW, Chicago, 2016), p. 2657, WEPPD060.
- [26] M. A. Prantil, E. Cormier, J. W. Dawson, D. J. Gibson, M. J. Messerly, and C. P. J. Barty, Widely tunable 11 GHz femtosecond fiber laser based on a nonmode-locked source, *Opt. Lett.* **38**, 3216 (2013).
- [27] R. A. Marsh, D. J. Gibson, and Y. Hwang, Initial performance measurements of multi-GHz electron bunch trains, in *Proceedings of the 2017 International Particle Accelerator Conference, Copenhagen, Denmark* (JACoW, Copenhagen, 2017), p. 795, MOPIK111.
- [28] D. J. Gibson, R. A. Marsh, G. G. Anderson, and C. P. J. Barty, Integrated control system for an X-band-based laser-Compton x-ray source, in *Proceedings of the 2016 North American Particle Accelerator Conference, Chicago, IL, USA* (JACoW, Chicago, 2016), p. 408, TUPOA61.
- [29] D. J. Gibson, G. G. Anderson, R. A. Marsh, and C. P. J. Barty, Compact X-band accelerator controls for a laser-Compton x-ray source, in *Proceedings of the 2016 International Particle Accelerator Conference, Busan, Korea* (JACoW, Busan, 2016), p. 3996, THPOW027.
- [30] Y. Hwang, T. Tajima, G. Anderson, D. J. Gibson, R. A. Marsh, and C. P. J. Barty, LLNL laser-Compton x-ray characterization, in *Proceedings of the 2016 International Particle Accelerator Conference, Busan, Korea* (JACoW, Busan, 2016), p. 1885, TUPOW052.
- [31] Y. Hwang, T. Tajima, G. Anderson, D. J. Gibson, R. A. Marsh, and C. P. J. Barty, LLNL laser-Compton x-ray characterization, in *Proceedings of the 2016 North American Particle Accelerator Conference, Chicago, IL, USA* (JACoW, Chicago, 2016), p. 977, WEPOB35.
- [32] Y. Hwang, T. Tajima, D. J. Gibson, R. A. Marsh, and C. P. J. Barty, Electron beam diagnosis using K-edge absorption of laser-Compton photons, in *Proceedings of the 2017 International Particle Accelerator Conference, Copenhagen, Denmark* (JACoW, Copenhagen, 2017), p. 473, MOPAB146.
- [33] Y. Hwang, T. Tajima, G. G. Anderson, D. J. Gibson, R. A. Marsh, and C. P. J. Barty, Study of medical applications of compact laser-Compton x-ray source, in *Proceedings of the 2017 International Particle Accelerator Conference, Copenhagen, Denmark* (JACoW, Copenhagen, 2017), p. 3656, THOAB1.
- [34] R. A. Marsh *et al.*, 50 MW X-band rf system for a photoinjector test station at LLNL, in *Proceedings of the 24th Particle Accelerator Conference, PAC-2011, New York, 2011* (IEEE, New York, 2011), p. 1082, TUP132.
- [35] C. Adolphsen, Normal-conducting rf structure test facilities and results, in *Proceedings of the 2003 Particle Accelerator Conference, Portland, OR* (IEEE, New York, 2003), p. 668, ROPC006.
- [36] G. A. Loew and J. W. Wang, RF breakdown studies in room temperature electron linac structures, Originally part of an invited presentation to 13th Int. Symp. on Discharges and Electrical Insulation in Vacuum, Paris, France (1988).
- [37] W. Wuensch, A. Degiovanni, S. Calatroni, A. Korsbäck, F. Djurabekova, R. Rajamäki, and J. Giner-Navarro, Statistics of vacuum breakdown in the high-gradient and low-rate regime, *Phys. Rev. Accel. Beams* **20**, 011007 (2017).

- [38] A. E. Vlieks, G. Caryotakis, W. R. Fowkes, E. N. Jongewaard, E. C. Landahl, R. Loewen, and N. C. Luhmann, Jr., Development of an X-band rf gun at SLAC, *AIP Conf. Proc.* **625**, 107 (2002).
- [39] A. E. Vlieks, G. Caryotakis, C. DeStefano, J. P. Heritage, E. Landahl, N. C. Luhmann, Jr., D. Martin, and A. Menegat, Initial tests with an X-band photoinjector at SLAC, *AIP Conf. Proc.* **691**, 358 (2003).
- [40] D. H. Dowell and J. F. Schmerge, Quantum efficiency and thermal emittance of metal photocathodes, *Phys. Rev. ST Accel. Beams* **12**, 074201 (2009).
- [41] R. H. Fowler and L. Nordheim, Electron emission in intense electric fields, *Proc. R. Soc. A* **119**, 173 (1928).
- [42] K. L. F. Bane, V. A. Dolgashev, T. Raubenheimer, G. V. Stupakov, and J. Wu, Dark currents and their effect on the primary beam in an X-band linac, *Phys. Rev. ST Accel. Beams* **8**, 064401 (2005).
- [43] A. Moretti, Z. Qian, J. Norem, Y. Torun, D. Li, and M. Zisman, Effects of high solenoidal magnetic fields on rf accelerating cavities, *Phys. Rev. ST Accel. Beams* **8**, 072001 (2005).
- [44] S. G. Anderson *et al.*, An optimized X-band photoinjector for the LLNL MEGa-ray project, in *Proceedings of the 24th Particle Accelerator Conference, PAC-2011, New York, 2011* (IEEE, New York, 2011), p. 334, MOP128.
- [45] R. A. Marsh, S. G. Anderson, D. J. Gibson, F. V. Hartemann, and C. P. J. Barty, Modeling multi-bunch X-band photoinjector challenges, in *Proceedings of the 3rd International Particle Accelerator Conference, New Orleans, LA, 2012* (IEEE, Piscataway, NJ, 2012), p. 658, MOPPP042.
- [46] R. A. Marsh *et al.*, X-band test station at Lawrence Livermore National Laboratory, in *Proceedings of the 24th Particle Accelerator Conference, PAC-2011, New York, 2011* (IEEE, New York, 2011), p. 235, MOPC067.
- [47] Swamp Optics, <http://www.swampoptics.com>.
- [48] Helmut Wiedemann, *Particle Accelerator Physics: Basic Principles and Linear Beam Dynamics* (Springer-Verlag, New York, 1993).
- [49] S. G. Anderson, J. B. Rosenzweig, G. P. LeSage, and J. K. Crane, Space-charge effects in high brightness electron beam emittance measurements, *Phys. Rev. ST Accel. Beams* **5**, 014201 (2002).
- [50] C. Limborg, S. Gierman, and J. Power, A modified quadscan technique for emittance measurement of space charge dominated beams, in *Proceedings of the 2003 Particle Accelerator Conference, Portland, OR* (IEEE, New York, 2003), p. 2667, WGG03.
- [51] B. E. Carlsten, New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator, *Nucl. Instrum. Methods Phys. Res., Sect. A* **285**, 313 (1989).
- [52] C. P. Hauri, R. Ganter, F. Le Pimpec, A. Trisorio, C. Ruchert, and H. H. Braun, Intrinsic Emittance Reduction of an Electron Beam from Metal Photocathodes, *Phys. Rev. Lett.* **104**, 234802 (2010).
- [53] R. A. Marsh, G. G. Anderson, D. J. Gibson, C. P. J. Barty, and Y. Hwang, LLNL X-band rf gun results, in *Proceedings of the 2016 International Particle Accelerator Conference, Busan, Korea* (JACoW, Busan, 2016), p. 3993, THPOW026.
- [54] D. J. Gibson, F. Albert, C. P. J. Barty, A. J. Bayramian, C. A. Ebberts, F. V. Hartemann, R. A. Marsh, and M. J. Messerly, Laser systems for Livermore's mono-energetic gamma-ray source, in *Proceedings of the 24th Particle Accelerator Conference, PAC-2011, New York, 2011* (IEEE, New York, 2011), p. 2540, THP223.