

Linac Coherent Light Source II injector commissioning and early operational experience

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(Received 25 June 2026; accepted 11 September 2026; published 15 October 2026)

The Linac Coherent Light Source II (LCLS-II) is designed to generate 4 GeV electron bunches at an up-to-1-MHz-high repetition rate to drive x-ray free electron lasers. It has been in user operation since 2023 and has progressively ramped up the beam repetition rate to 93 kHz to date. The LCLS-II 1-MeV electron source was successfully commissioned between 2018 and 2020. The full-scale LCLS-II injector, operating above 75 MeV, began commissioning in 2022 and transitioned to operations a few months later. The LCLS-II injector has demonstrated the ability to deliver a high-brightness, low-emittance electron beam at high repetition rates, meeting key performance targets. However, several operational challenges have emerged during commissioning and early user operations. These include substantial gun dark current, the dependence of bunch charge generation and free-electron laser pulse intensity on the beam repetition rate, the formation of cathode quantum efficiency craters and bumps, significant emittance growth through the laser heater chicane, beam breakup, and the presence of beam halos. This paper presents recent progress in addressing these challenges, along with injector emittance measurements and optimizations, and the first demonstration of operating a laser heater undulator at the third-harmonic resonance.

DOI: [10.1103/1wk3-p29y](https://doi.org/10.1103/1wk3-p29y)

I. OVERVIEW

X-ray Free Electron Lasers (FELs) [1–4] have proven to be revolutionary tools for photon science research. The Linac Coherent Light Source II (LCLS-II) at SLAC National Accelerator Laboratory [5] represents a major advance by providing bunch repetition rates of up to 1 MHz, a substantial increase over the 120 Hz repetition rate of the existing LCLS facility. This higher repetition rate enables experiments requiring large numbers of photon-pulse interactions to resolve molecular structures and ultrafast molecular dynamics. The photons are generated in two x-ray undulator lines using electrons from a 4 GeV continuous wave (cw) rf linac based on 1.3 GHz superconducting radiofrequency (SRF) technology. The CW RF injector for this SRF linac is designed to produce up to 1-MHz electron bunches with energies above 75 MeV, a nominal charge of 100 pC, a peak current of 12 A, and a normalized emittance of 0.4 μm level [6,7]. Table I summarizes the major injector design parameters.

Currently, the beam rate is limited to 93 kHz until the safety system is fully implemented in March 2027.

Figure 1 shows a schematic layout of the full-scale injector system, including major components and diagnostics. The injector consists of the 1-MeV electron source, a standard cryomodule (CM01) providing acceleration above 75 MeV, a laser heater chicane, and multiple diagnostic stations. The electron source includes a 186 MHz normal conducting (NC) cw rf gun, one NC

TABLE I. Major design parameters of the LCLS-II gun and injector.

Parameter	Nominal value
Gun energy (keV)	750
Gun photocathode gradient (MV/m)	20
Cs ₂ Te cathode quantum efficiency (QE) (%)	>0.5
Drive laser pulse length (full width at half maximum [FWHM], ps, Gaussian)	15–20
RF for injector and linac	cw
Maximum bunch repetition rate (MHz)	0.93
Nominal bunch charge (pC)	20–100
Initial beam current (μA)	30
Injector energy (MeV)	>75
Normalized emittance (μm) at 50–100 pC	≤ 0.4
Bunch length (mm rms)	<1

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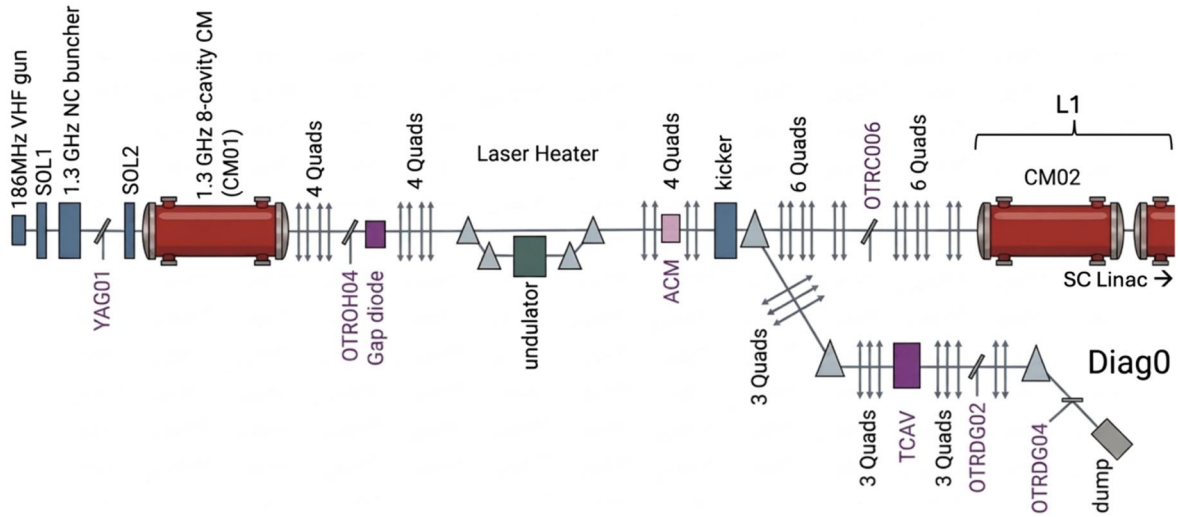


FIG. 1. Schematic of the LCLS-II full injector systems, including injector main beamline up to L1 entrance and dedicated off-axis diagnostics beamline, Diag0.

cw rf buncher, two solenoids, and one YAG screen (YAG01) with circular collimators. The cw rf gun and buncher were designed and built by Lawrence Berkeley National Laboratory [8–10]. Major diagnostics of the injector include: (i) The first emittance station—OTR0H04—screen-based emittance measurement station located downstream of the CM01, with four matching quads. (ii) One gap diode for relative bunch-length measurement, positioned upstream of the laser heater chicane and undulator, which generates correlated energy spread for suppressing the microbunching instability. (iii) The second emittance station—OTRC006—screen-based emittance station located downstream of the laser heater chicane, with six matching quads. (iv) Average current monitor, cavity-based diagnostics to measure beam current for the safety system. (v) One dedicated off-axis diagnostics beamline (Diag0) equipped with a transverse S-band deflecting cavity for absolute bunch-length measurements, as well as projected and slice energy-spread measurements at the screen (OTRDG04), together with an additional screen-based emittance measurement station (OTRDG02), using a kicker and septum to steal pulses from the main beam. The Diag0 allows measuring beam performance without interfering with main beam delivery.

The LCLS-II 1-MeV electron source was successfully commissioned between 2018 and 2020 after addressing several significant technical challenges [11]. In 2022, the full-scale injector operating above 75 MeV was first commissioned and transitioned to early user operation shortly thereafter. Since the start of FEL user operations in 2023, a variety of operational challenges have been encountered in the injector systems. This paper presents recent progresses in addressing these challenges, along with emittance measurements and optimizations and the first demonstration of operating laser heater undulator at

the third-harmonic resonance: (i) improvements of gun vacuum and gun energy measurement; (ii) gun operational challenges, including dark current, and mitigations; (iii) laser system operational challenges and progresses; (iv) photocathode operational challenges and mitigation strategies; (v) beam breakup, beam halo formation, and corresponding mitigation methods; (vi) emittance growth caused by stray magnetic fields and its mitigation; (vii) emittance measurements and optimization; and (viii) operating laser heater at the third-harmonic resonance.

II. INJECTOR OPERATIONAL CHALLENGES AND PROGRESSES

A. Gun system and recent progresses

The single-cell gun cavity is designed for cw operation at 185.7 MHz, the seventh subharmonic of the 1.3 GHz superconducting linac frequency. The gun has been operated conservatively at a voltage gain of up to 690 kV, corresponding to a cathode surface gradient of about 19 MV/m, despite a design voltage gain of 750 kV. Beam emittance exhibits only minor differences between operating energies of 690 kV and 750 kV. We may ramp-up the gun energy toward the design voltage, as increasing the gun energy can help reduce the load force on the mechanical tuners used to compensate for the gun cavity frequency, while also potentially improving the longitudinal phase space of the beam.

The gun body is equipped with two rf probes to measure the cavity amplitude for feedback control and light detectors on two rf windows and the gun body to shut off the rf power in the event of arcing. In each waveguide feed line, three permanent solenoid magnets are installed in the short section between the rf coupler and the vacuum window to suppress multipacting. Due to the large cavity

volume, rf heating produces a substantial frequency shift of approximately 250 kHz, significantly larger than the 6 kHz cavity half-bandwidth. To compensate for this effect, a system of four mechanical tuners is used to deform the anode plate and adjust the cavity frequency. Routine cw operation of the gun has been successfully established. Detailed descriptions of the gun design and commissioning results have been reported previously [11]. The following subsections present recent developments in gun performance improvements and the gun energy measurements.

1. Ten-fold improvement in gun vacuum

During operation, the gun vacuum gradually degraded from approximately 8×10^{-10} Torr in 2023 to 2×10^{-9} Torr by Dec. 2024, as shown in Fig. 2. In Oct. 2024, a small steplike increase in vacuum pressure was observed; however, the source of the change remained unidentified until Dec. 2024, when a vacuum leak was discovered in one of the two rf windows. After identifying the leak, the faulty rf window was replaced, and the entire gun assembly was baked at 150–170 °C. Subsequent rf conditioning of the gun with the newly replaced window successfully processed all multipacting barriers, eventually resulting in a 10-fold improvement in gun vacuum. Additionally, the gun vacuum no longer exhibited any measurable change when switching the rf operating mode from pulsed to cw, confirming that the low-energy multipacting barriers had been effectively mitigated or even eliminated. Previously, rf processing intentionally avoided the low-energy multipacting regions. As a result, about a factor-of-3 reduction in vacuum pressure was observed when transitioning from pulsed operation to cw operation, suggesting that the pulse tails' presence during pulsed

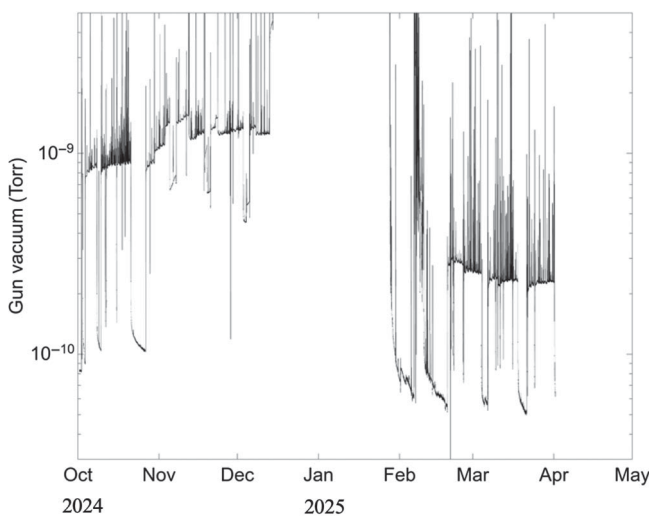


FIG. 2. Gun vacuum trends before and after gun window replacement. The period from Dec. 15, 2024, to Feb. 8, 2025, was dedicated to gun window replacement and systems recovery.

operation was generating multipacting. In the year following the rf processing, the gun vacuum remained relatively stable at $2\text{--}3 \times 10^{-10}$ Torr. Figure 2 shows the vacuum trend before and after replacement of the leaking rf window.

During the 2026 long shutdown (Jan. 2026 to March 2027 for LCLS-high-energy installation), all gun vacuum pumps and the other aging rf window were replaced with new ones. Further improvement in gun vacuum performance is expected following subsequent rf conditioning.

2. Ten-fold improvement of the gun energy measurement accuracy

Initially, we used five methods to measure the beam energy from the gun [11]. The first method was based on the signals from the two rf probes that are installed on the gun body. The second method was based on the measured input power to the gun, which relies on factory-calibrated directional couplers. Both methods require knowledge of the cavity rf parameters: R/Q was computed from the gun geometry, and Q_L and the probe and power coupler betas were measured *in situ* with a network analyzer. The third method was to measure the electron momentum by its deflection on the YAG screen caused by a change in a corrector dipole magnet setting (i.e., from the slope of the position versus corrector strength). The fourth method was based on the upstream solenoid setting that produced the minimum beam size on the YAG screen for low charge (~ 1 pC) bunches. The fifth method was based on measuring the beam time-of-flight using the signals from the two beam position monitors. These five methods yielded beam energies that agree within about 10% for the same cavity input power. The 10% discrepancy is not sufficient for reliable beam modeling due to uncertainty in the actual gun energy.

Recently, we developed a method to accurately determine the gun energy by measuring the beam size (red solid curve) on the YAG01 located downstream of the buncher as a function of the first-solenoid field strength (SOL1) at a bunch charge of 50 pC, with the aid of beam dynamics simulations performed using the ASTRA code [12] (dashed curves), as shown in Fig. 3. The buncher cavity was turned off during these measurements and simulations. Simulations of beam size versus the solenoid strength were performed with three sets of gun energies: 626 keV, 645 keV, and 664 keV. The simulations used the actual laser spot size and pulse length at the cathode employed during measurements. The beam-size waist depends on both the gun energy and the SOL1 field strength, given the same laser spot size and pulse length at the cathode. Since the solenoid field strength is well characterized, the gun energy primarily determines the beam size waist. The measured beam-size waist aligns well with the simulation for a gun energy of 645 keV. Given the 70 kW of input power, 645 keV of gun energy is quite

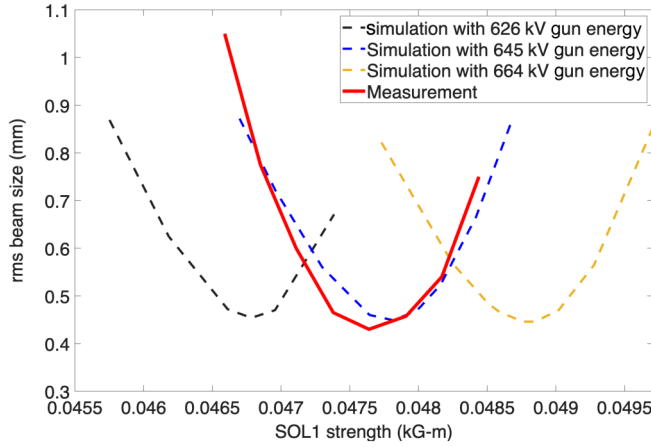


FIG. 3. Measured (red solid curve) and simulated (dashed curves) beam size waist for different gun energies.

reasonable based on the known rf parameters. The results also indicate that the gun energy measurement can resolve <10 keV energy, representing a substantial improvement over the past energy measurement uncertainty of about 70 keV.

B. Laser performances and upgrades

The laser system uses an infrared (IR) front-end manufactured by Amplitude Systems. Its main components include an ytterbium-based fiber oscillator operating at 46.43 MHz, a pulse picker that reduces the repetition rate from 46.43 MHz to 1 MHz, a diode-pumped fiber amplifier (Tangerine), an acousto-optic modulator for repetition-rate selection, and a compressor. The oscillator is phase-locked to the accelerator reference frequency. The IR front-end produces 50 μ J pulses at 1030 nm with an adjustable repetition rate up to 1 MHz and pulse durations tunable from 330 fs to 30 ps. To maximize frequency-conversion efficiency, the compressed subpicosecond IR pulses are used for frequency conversion. For IR-to-ultraviolet (UV) conversion, the system employs two critically phase-matched beta-barium borate (BBO) crystals. The UV pulse is subsequently stretched to the desired 20 ps FWHM using a two-pass reflective grating stretcher. The details of the laser system and its parameters have been reported in Refs. [11,13]. Although the system has been in operation since 2018, several significant issues remain: (i) The laser energy jitter is typically $>4\%$ rms, substantially larger than the desired 1% rms level. (ii) The laser pointing stability is insufficient. (iii) The transverse laser spatial shape is irregular and lacks smoothness.

To address these limitations, the Tangerine amplifier is being replaced by the Carbide laser system during the 2026 long downtime. The Carbide laser has demonstrated several important advantages over the Tangerine laser, including: (i) approximately, 10-fold lower energy jitter, (ii) about 3-fold improved pointing stability, and (iii) roughly 2-fold higher pulse energy.

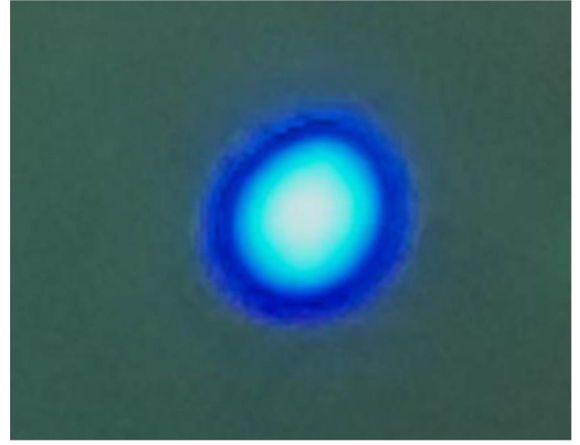


FIG. 4. Smooth spatial UV laser profile operating at 1 MHz with noncritical phase matching.

In addition, replacing the critically phase-matched BBO crystals with noncritically phase-matched (NCPM) Long-barium borate (LBO) crystals for second harmonic conversion from IR to green light is under consideration to improve the far-field image. Spatial distortions in critically phase-matched crystals arise primarily from walk-off effects. In NCPM LBO, the walk-off is negligible compared to its critically phase-matched counterpart. This diminished spatial walk-off provides the advantage of using longer crystals and achieving higher conversion efficiency without requiring excessive beam focusing. Consequently, this results in a more predictable and stable beam shape. Furthermore, the wide wavelength acceptance range and broad angular tuning capability of NCPM make crystals like LBO ideal for producing homogeneous, high-quality beams. Figure 4 shows the improved spatial profile obtained during 1-MHz operation at the laser test lab [14]. Compared with the UV profile at 1 MHz reported in our previous work [13], which was obtained using critically phase-matched crystals for IR-to-UV conversion, the UV laser profile shown in Fig. 4 has been significantly improved.

During the operation, a dependence of the bunch charge generation and the FEL pulse intensity on the beam repetition rate has been observed. Further investigations indicate that these effects are caused by differences in the thermal load on the harmonic conversion crystals at different repetition rates, which therefore affect the laser conversion efficiency as well as laser pointing variation. Detailed studies aimed at mitigating this thermal effect are currently underway.

With these ongoing upgrades, substantial improvements are expected in laser energy stability, beam-pointing stability, and transverse spatial uniformity, along with a significant reduction in the dependence of UV laser energy output through the harmonic conversion as well as FEL pulse intensity on beam repetition rate.

C. Gun dark current and mitigations

LCLS-II cw rf gun generates large dark current up to 3–4 μA [11] with about 19 MV/m of gradient at cathode. The primary dark current originates from localized emission sites near the rim of the 10-mm-diameter cathode plug. This dark current presents a significant risk to various electronics and permanent magnets in the undulator sections due to potential radiation-induced damage, as well as the formation of localized hot spots and beam loss events that trigger the machine off. Following subsections are to discuss recent two mitigations in place.

1. Initial gun dark current reduction with a circular collimator

Installing a circular collimator immediately after the buncher is desired to block the major dark current at low energy (< 1 MeV), avoiding transport of the large gun dark current to a high-energy region. It is observed that the major dark current is transversely separated from the electron bunch. Considering that feature, a ladder-based multifunction device was designed and installed in 2021, including four circular collimators with different apertures (aperture diameters of 12 mm, 16 mm, 20 mm, and 24 mm), a YAG screen, and a YAG screen with a central 8-mm hole for beam halo measurements. Figure 5 shows the multifunction device of collimators and YAG screens, which has been installed and operated during LCLS-II

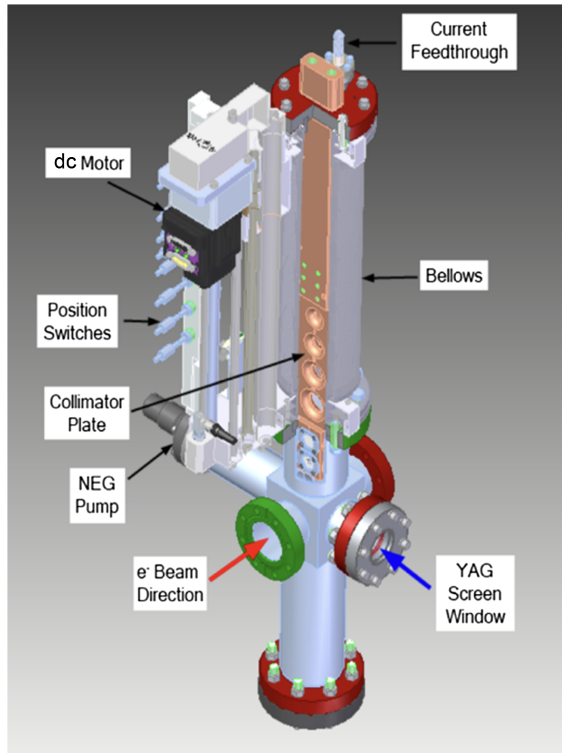


FIG. 5. Multifunction device, including four sets of circular apertures and screens.

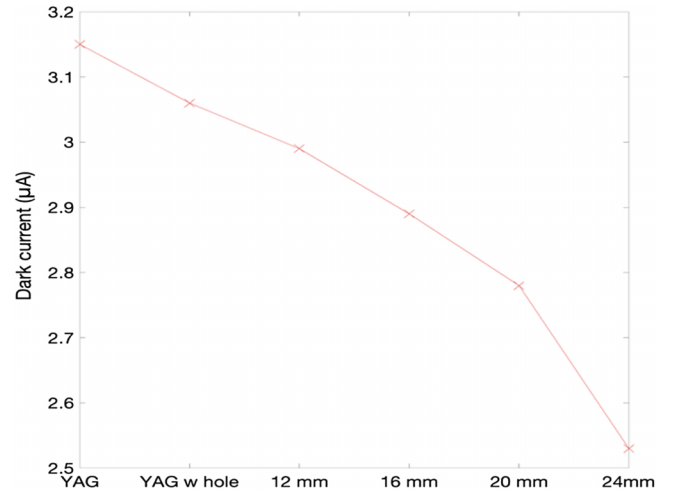


FIG. 6. The dark current loss versus aperture size, YAG screen, and YAG screen with an 8-mm hole.

injector commissioning and operation. The collimating function works well with the 20 mm diameter of the aperture, sufficient to block the majority of the dark current, while posing negligible impact on electron beam performance. The collimator intercepting the dark current is equivalent to a Faraday cup for the dark current collection. The dark current is directly measured with the aid of a pico-ammeter. The current measurement capability of the collimator plate turns out to be a valuable bonus from the device, making it possible to have a convenient and reliable monitor of the dark current performance. Figure 6 shows the typical dark current loss versus the collimator apertures. It shows that with a 20-mm collimator aperture, $> 80\%$ of gun dark current is intercepted at < 1 MeV beam energy, corresponding to 2–3 W power loss only. About 15%–20% of dark current is still through the aperture and is accelerated through the downstream cryomodules, which may still damage cameras' electronics and laser power meters and trip the machine off due to rest dark current loss from time to time. We adjusted the two solenoids' strength to reduce dark current losses; however, the resulting changes in the solenoid strengths led to a degradation of the beam emittance. Further efforts are required to mitigate dark current without compromising emittance to improve machine performance and availability.

2. Further gun dark current mitigation with overinserted cathode

Overinserted cathode [15,16] was thoroughly studied in 2024 and finally designed. Figure 7 illustrates the electric field profile with 1 mm of overinserted cathode plug. The cathode plug with an elliptical corner and slight over-insertion can increase the electric gradient on the cathode, as shown in Fig. 8 (left), and produce a bonus “shielding effect” for the surface electric field on the copper nose

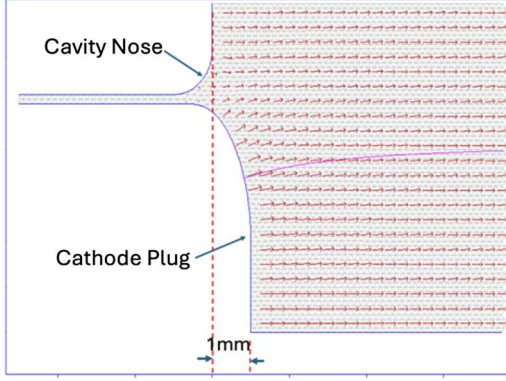


FIG. 7. Illustration of electric field profile in the gun with a 1-mm overinserted cathode plug.

cone, where the gun dark current usually originates. The more the insertion, the more the surface electric field is reduced on the copper nose cone, and the acceleration field increases on the cathode (left) and the transverse field increases (right), as shown in Fig. 8. For electrons in a rotationally symmetric field, the transverse field can be expressed by:

$$E_r = \frac{-r}{2} \frac{dE_z}{dz}$$

where r is the radius and E_z is the longitudinal electric field. Since the field of a flat cathode peaks at the cathode surface, the dE_z/dz is negative at the surface and $z > 0$ through the gun when the gun's exit defocusing is included. Therefore, the plug fields are transversely defocusing for all plug insertions. The increased defocusing from the transverse field has two sides of controversial effects. On the one hand, it can further steer the dark current away from the cathode axis, significantly reducing the amount transported through the first cryomodule.

On the other hand, the increase in defocusing may deteriorate electron beam emittance when the electron beam has a transverse offset from the beam axis. Additionally, the more the insertion, the more the increase in the accelerating field on the cathode, which improves emittance. Therefore, the depth of the insertion needs to be optimized for optimum dark current suppression and beam emittance. Our simulations show that with 1 mm of overinsertion, very little dark current is transported through the first cryomodule, and the electron beam emittance is slightly improved. The 1-mm overinsertion is selected for installation and operation.

The 1-mm overinserted cathode was deployed at the LCLS-II injector on Feb. 25, 2025, immediately leading to the reduction of gun dark current by about 500-fold, as shown in Fig. 9, measured at the YAG01 location of 1.5 m away from the cathode. Figure 10 shows the dark current images taken at the YAG01 screen downstream of the gun with the overinserted cathode in comparison to the flat one with the same gun operating conditions. The dark current images are almost invisible on the screen with the overinserted cathode, which is consistent with the quantitative dark current measurements. This dramatic improvement has substantially enhanced machine availability and electron beam quality. No obvious change in emittance is observed with 1-mm overinsertion during operation, although simulations indicate that the emittance can be slightly improved.

D. Formation of nonuniform QE and mitigation strategies

Cs₂Te cathodes grown by SLAC have been used for LCLS-II operations since 2020. We observed formation of QE craters and bumps [17] during cathode operation within weeks. The presence of a QE crater and/or bump leads to beam emittance degradation and beam instability

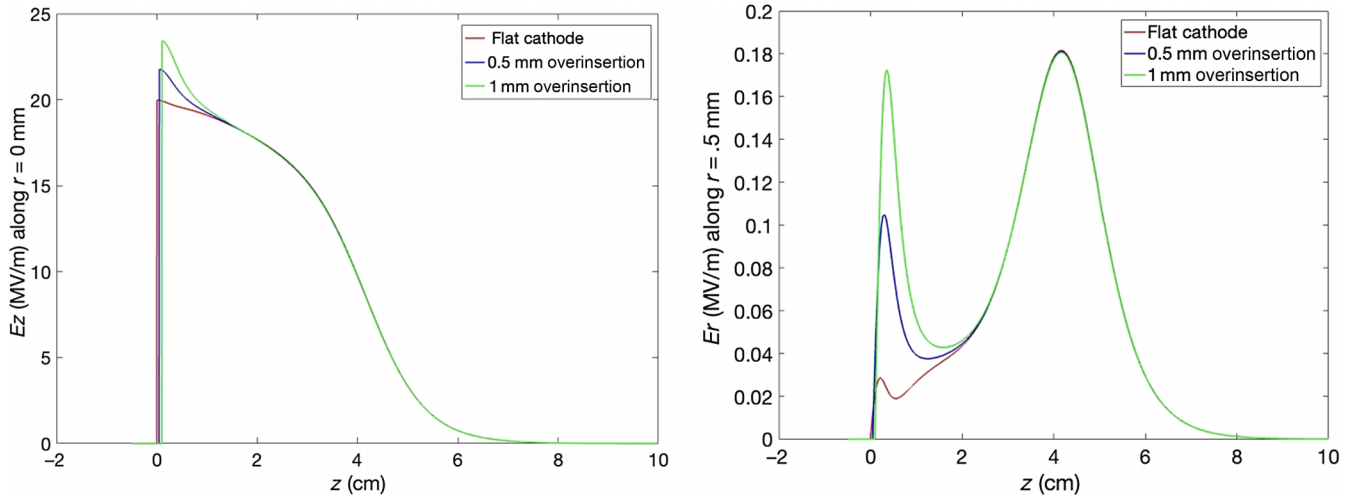


FIG. 8. Electric field on axis (left) and transverse field (right) at 1 mm of off-axis for different depths of cathode overinsertion.

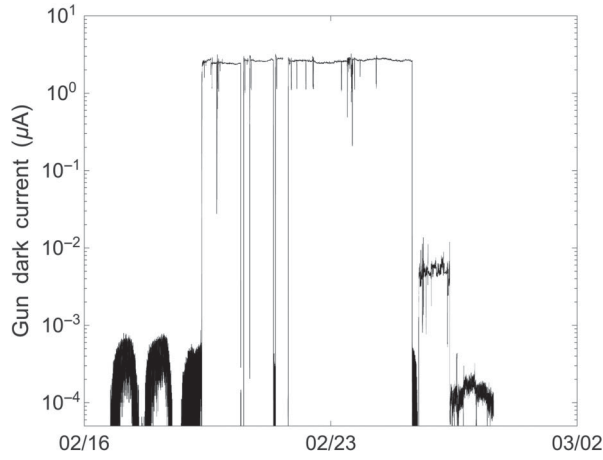


FIG. 9. Gun dark current vs months with standard flat cathode and overinserted cathode beginning Feb 25, 2025. The dark current is reduced from 2.5 μA to about 5 nA with the 1-mm overinserted cathode.

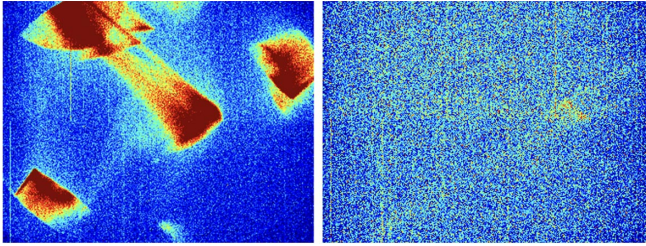


FIG. 10. Dark current images taken on the YAG01 screen with flat cathode (left) and 1-mm overinserted cathode (right).

due to nonuniform QE. Before Feb. 2025, we used standard flat cathodes, which have large dark current. The QE of the laser illumination spot developed an obvious QE crater on 4th day of operation of the cathode, as shown in Fig. 11 (top middle), and its QE became a bump on the 18th day of operation. In late Feb. 2025, we replaced the standard flat cathode with an elliptical overinserted cathode; the QE crater was not seen until the 9th day of operation, and on the 12th day of operation, the QE crater for the laser illumination disappeared and moreover was higher than the other area. It shows the QE crater develops much slower with the overinserted cathode than the standard flat cathode, while the QE recovery develops much faster with the overinserted cathode than the flat one. The gun operating conditions for both types of cathodes are the same, except for much lower dark current with the overinserted cathode. The formation of these QE developments might be related to the gun dark current, which can ionize gases such as H_2 and C_2H_2 near the cathodes. Simulations show that these ionized gases within about 1 mm from the cathodes can back-bombard the cathode and damage then as these ions are energetic enough to sputter Cs and Te atoms. This may at least partially explain why the formation of the QE crater with an overinserted cathode is much slower, and QE recovery is much faster because of fewer ions generated due to its lower dark current.

Further observations show that the QE diminishes over several weeks after the laser is moved away from a spot, following the formation of a localized QE bump, as shown in Fig. 12. Beam operation begins at laser spot 1. After a

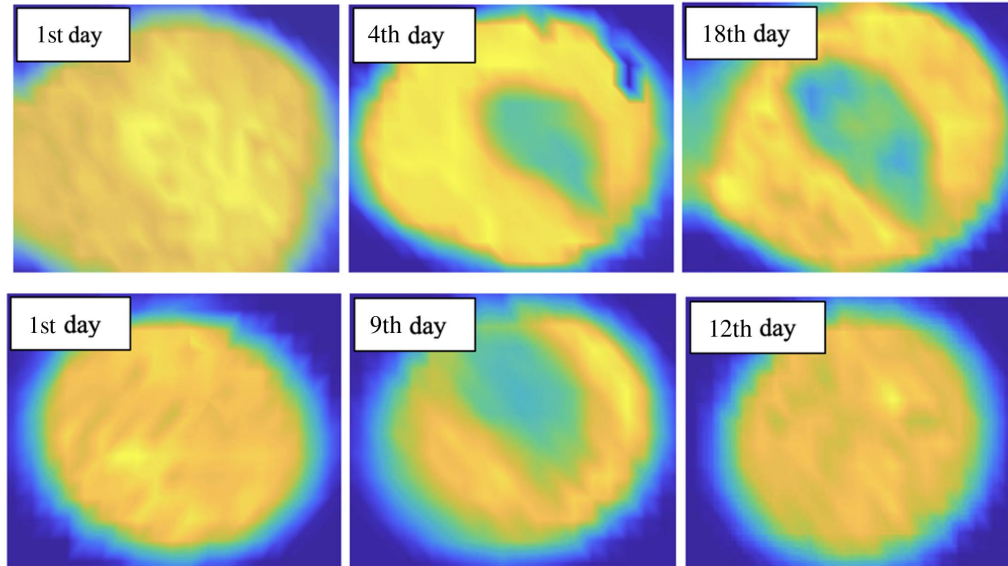


FIG. 11. QE uniformity evolution over time: with standard flat cathode (top row) and with the 1-mm overinserted cathode (bottom row). Cs_2Te area is about 3.5 mm in diameter. Laser size on the cathode is 0.8 mm in diameter.

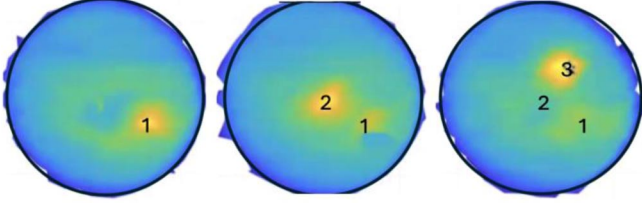


FIG. 12. Formation of QE bumps and diminishments.

few days, a QE crater is initially observed (not shown in Fig. 12), similar to the middle plots in Fig. 11. The QE at spot 1 then gradually increases over several weeks, eventually forming a localized bump (Fig. 12, left). As beam performance, including emittance and beam stability, deteriorates due to the QE bump, the laser illumination spot is moved to a new location, spot 2. At spot 2, the QE initially decreases after a few days of operation, then gradually increases, eventually forming a QE bump (Fig. 2, middle) similar to that previously observed at spot 1. Meanwhile, the QE at spot 1 diminishes once it is no longer illuminated by the laser (Fig. 12, middle). When the laser is subsequently moved to spot 3, the same sequence of behavior is observed (Fig. 12, right), indicating a reproducible pattern of QE evolution across different locations on the cathode. We have not yet moved the laser spot back to evaluate the emittance at the location after the

QE recovery. Additional systematic measurements are planned to further investigate the phenomena. The underlying physics for the QE evolution is not yet fully understood, but Cs migration has been observed in a separate experiment on a Cs_2Te cathode under laser illumination at the NSLS-II beamline [18], which may at least partially explain the observed phenomena. Obvious emittance growth is observed when the laser is operated at these spots. This is likely due to a combination of nonuniform QE emission and off-center laser illumination.

The QE crater and bump behaviors are related to cathode parameters, such as base material, cathode thickness, and growth temperature, which impact laser-induced desorption and diffusion. Optimization of the cathode parameters and related studies are currently underway. The goal is to mitigate the QE crater and bump formations to avoid uneven QE evolution, which degrade the beam emittance and stability.

E. Correction of stray field from a magnetic structure

A normalized emittance of $\sim 0.4 \mu\text{m}$ can be achieved at the first injector emittance station (OTR0H04). However, significant emittance growth, by a factor of 2–3, was consistently observed at the second injector emittance station (OTRC006), located downstream of the laser heater chicane. Figure 13 (top) shows the

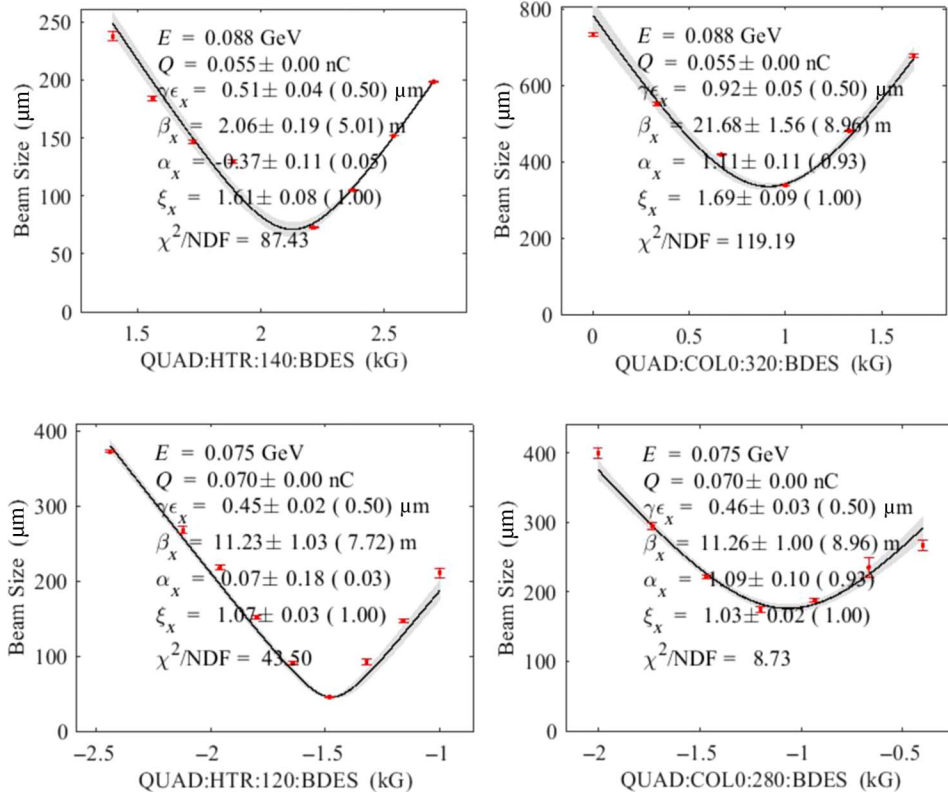


FIG. 13. Emittance before (top) and after (bottom) correction of the low-carbon steel at the first (left) and second (right) emittance stations.

measured emittances at the first (top left) and second (top right) emittance stations, where a typical doubling of emittance is evident after the beam passes through the chicane. Additionally, achieving consistent beam optics matching at the second station was found to be challenging.

To investigate the cause of this emittance growth, a series of systematic studies were conducted. These investigations ultimately revealed that low-carbon steel plates had been used to support a lead shielding near the second bend of the laser heater chicane. Electromagnetic modeling indicated that these magnetic steel supports introduced magnetic field perturbations of 1%–3% for the second bend, which distorted the beam optics and contributed to emittance degradation. To correct this, the low-carbon steel was replaced with a nonmagnetic stainless steel for the shielding support structures. Following this modification, emittance preservation through the chicane improved immediately, and beam optics matching at the second station became consistently reliable. Figure 13 includes a comparison of emittance measurements taken before (top) and after (bottom) the correction, demonstrating the effectiveness of this correction.

F. Beam breakup and beam halo mitigations

A beam breakup or donut-shaped beam profile was often observed on both injector screens OTR0H04 and OTRC006, particularly when scanning quadrupole strength for emittance measurement, as shown in Fig. 14 (left) as an example. The beam deformation had a direct and detrimental impact on FEL performance. Thorough beam modeling [19] indicated space charge effects due to the small laser size on the cathode as the primary cause of the observed beam distortion. To address this issue, the laser diameter was slightly increased from about 0.65 mm to 0.8 mm. With proper solenoid field strength, the split beam structure was eliminated, as shown in Fig. 14 (right), without compromising beam emittance with a slightly larger laser size at 60 pC.

The NC rf buncher was used to compress the injector bunch length typically by a factor of about 3 from 8 to 3 ps rms. However, a beam halo due to the velocity bunch compression through the low-energy rf buncher had been

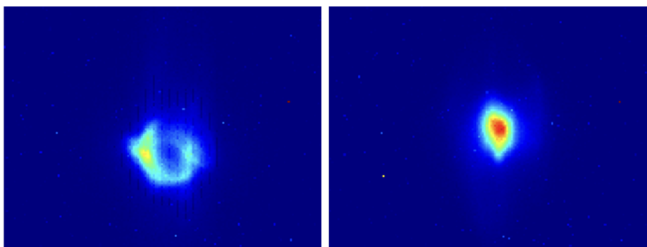


FIG. 14. Examples of beam breakup (left) and regular clean beam on the injector screen (right).

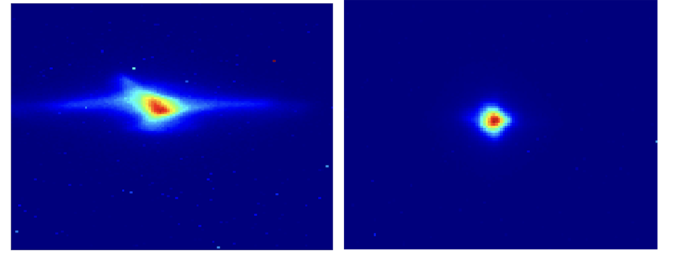


FIG. 15. Examples of beam images on the injector screen for the two different bunching schemes: with rf buncher only (left) and with rf buncher and second cavity (right).

consistently observed on the injector screens, posing a significant challenge to machine operation at high repetition rates, larger than tens of kHz. Thorough simulations [19] reveal that (1) the rf buncher induces an energy-radius correlation, (2) velocity bunching through the buncher transforms this correlation into hollow density structures, and (3) differential overfocusing of these structures by downstream focusing forms the beam halos. To mitigate this effect, we implemented a two-stage velocity bunching scheme that achieves bunch compression comparable to that with a single rf buncher. The rf buncher contributes partial bunching only, while the remaining bunching is contributed by the second cavity (at zero-crossing phase) of the CM01. With this approach, the space charge effect is significantly mitigated due to 1) less bunching from the rf buncher at the low energy and 2) more bunching coming from the second cavity of CM01 at relatively higher energy, about 6 MeV. Experimental results confirm that beam halo has been mitigated with the new bunching scheme compared to the complete bunching with low-energy rf buncher only. Figure 15 shows the typical beam images at the injector screen with rf buncher only (left) and the combination of the rf buncher and the second cavity of CM01 (right). The beam halo is much less with the combined bunching scheme compared with the rf buncher only. No obvious emittance number change is observed between the two different bunching schemes, although simulations show the emittance can be slightly improved with the new bunching scheme. The new bunching scheme has been used for routine operation since then.

G. Injector emittance optimization

The LCLS-II injector emittance is measured at the OTR0H04 screen downstream of CM01 using a quadrupole scan. The bunch length is measured with the S-band transverse cavity located at the off-axis diagnostics beamline, Diag0. Figure 16 presents both the measured and simulated emittance at a bunch charge of 75 pC. The simulations use the operating parameters: gun energy of 690 keV, a cathode thermal emittance of 1 $\mu\text{m}/\text{mm}$, and a purely Gaussian laser pulse with an 18 ps FWHM duration. The detailed simulations of the injector optimization using

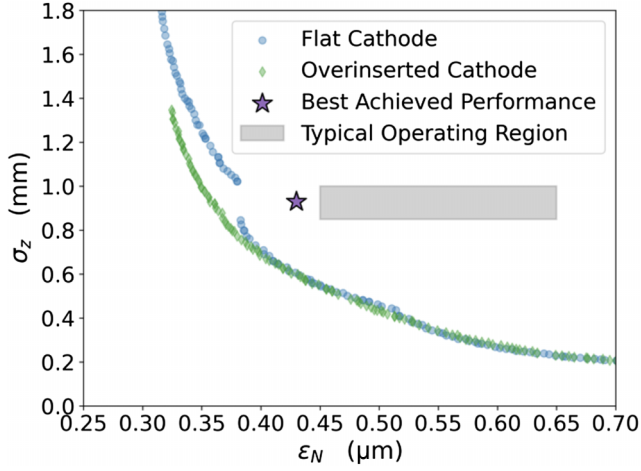


FIG. 16. Emittance measurement in comparison to simulations at 75 pC.

a genetic algorithm can be found in [20]. The results show that the best measured projected emittance at the injector, 0.42 μm is close to the simulated one at the target bunch length of 1 mm. Although emittances as low as this value can be achieved intermittently, they cannot be routinely reproduced or maintained. In normal operation, the typical achieved projected emittance ranges from 0.45 to 0.65 μm . The primary factors limiting the reproducibility and long-term maintenance of lower emittance values are variations in the laser spatial profile and nonuniform electron emission from the cathode, as discussed in the previous sections. During the 2026 long downtime, several upgrades are underway: (1) improvements to the laser system to enhance stability (both pointing and energy) and spatial profile quality, and (2) optimization of cathode parameters—including base material, cathode thickness, and cathode growth temperature—to mitigate QE crater and bump formations and improve QE uniformity. These upgrades and ongoing research and development efforts are expected to improve the emittance and beam operational stability. A machine learning tool for autonomous emittance measurements and Bayesian optimization using Xopt [21] has been tested for emittance optimization. We plan to use the tool for routine emittance optimization when the machine operation is resumed in March 2027. In addition, an autonomous six-dimensional phase-space reconstruction has been established for the Diag0 beamline using machine learning methods, enabling real-time monitoring of the beam phase space and emittance at the Diag0 entrance [22].

H. Operating laser heater at the third-harmonic resonance

The laser heater undulator was originally designed to operate at >95 MeV for optimum energy modulation under the fundamental resonance with our 1030 nm laser.

However, energy gain from the CM01 is limited to about 88 MeV, due to field emission from a few cavities inside the CM01 [23]. In practice, we run at a beam energy of only 75 MeV because the second cavity operates near the zero-crossing to control the bunch length. As a result, we tune the laser heater undulator to the third-harmonic resonance. The induced energy spread [24] can be expressed by the following formulae:

$$\sigma_E = \sqrt{\frac{\sigma_r^2}{2(\sigma_x^2 + \sigma_r^2)}} \sqrt{\frac{P_L K[JJ] N_u \lambda_u m c^2}{P_0 \gamma \sigma_r^2}}$$

where σ_x is the electron beam size, 175 μm rms, σ_r is the laser size, 380 μm rms, P is the peak laser power (16 μJ with 18 ps FWHM—nominal or 2 ps FWHM—demonstration purpose), $P_0 = 8.7$ GW, K is the undulator dimensionless parameter, JJ is the usual Bessel function factor associated with a planar undulator, $N_u = 8$ the number of full undulator periods, $\lambda_u = 5.4$ cm the undulator period, and $\gamma m c^2 = 75$ MeV the electron beam energy. According to the calculations based on the above parameters with a 2 ps FWHM laser, the third-harmonic resonance generates a stronger energy modulation than the fundamental resonance, as shown in Fig. 17(a). At LCLS-II, two separate lasers are used for photocathode illumination and laser heating, respectively. We adjust the heater laser timing to coarsely overlap with the electron beam signal on the photodiode [Fig. 17(b)] installed downstream of the laser heater undulator with 250 ps resolution on the oscilloscope. The third harmonic resonance bandwidth is much narrower than the fundamental one and sensitive to small errors in the gap or beam energy. To help tune the resonance, we installed a spectrometer, which we use to align the undulator radiation with the heater laser by finely changing the undulator gap [Fig. 17(c)]. To observe the pronounced heating effect, the heater laser pulse length is shortened from the nominal 18 ps FWHM to 2 ps FWHM with the maximum heater laser energy of about 16 μJ . The timing of the 2 ps heater laser is finely scanned to fully overlap with the electron beam timing. Figure 17(d) shows the experimental demonstration of the 2 ps central slice energy modulation within the bunch at the third-harmonics resonance of the undulator. As the electron bunch has about 20 ps full width in length, much longer than the laser pulse, this results in a localized sliced energy modulation within the bunch.

III. SUMMARY

The LCLS-II injector has made significant advances over the past few years, including a 10-fold improvement in gun vacuum, a 10-fold improvement in gun energy measurement accuracy, a 500-fold reduction in gun dark current, effective mitigation of beam breakup and beam halo formation, and correction of stray magnetic field for

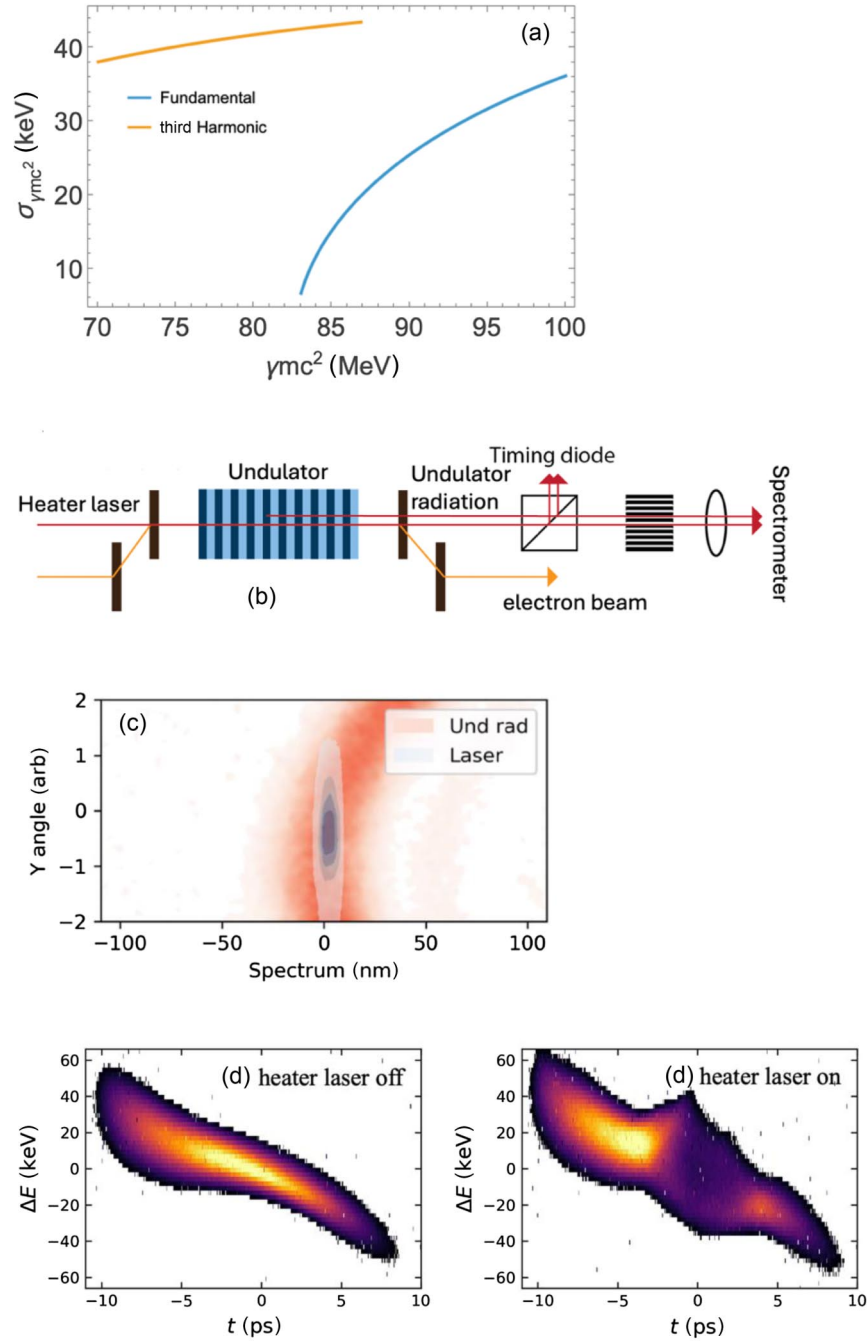


FIG. 17. Energy modulation at the third-harmonic resonance: (a) calculated energy modulation near 75 MeV, (b) cartoon of the laser heater and the longitudinal overlapping diagnostics including the photodiode and spectrometer, (c) overlapping spectrum of the undulator radiation and the heater laser, and (d) experimental demonstration of 2 ps central sliced energy modulation within the bunch at the third-harmonic resonance.

emittance preservation. The injector has demonstrated beam emittances close to the design value, although continued efforts to improve the laser systems and cathodes are aimed at routinely achieving and maintaining the ultralow emittance. In addition, the first demonstration of laser heater energy modulation at the third-harmonic resonance has been successfully established.

ACKNOWLEDGMENTS

The work is supported by U.S. DOE under grant No. DE-AC02-76SF00515. We would like to thank T. Luo (LBNL) for the design of the overinserted cathode and A. Edelen, A. Fisher, Z. Huang, B. Jacobson, G. Lanza, A. Marinelli, T. Maxwell, J. May, N. Pandya, and J. Tang for support.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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