OPERATION AND UPGRADES OF THE LCLS*

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Abstract

The LCLS FEL began user operations in September 2009 with photon energies from 800eV to 2 KeV and pulse energies above 2 mJ. Both long pulse (50-200 femtosecond FWHM) and short pulse (<10 femtosecond FWHM at 150 uJ) pulses were delivered at user request. In addition the FEL was operated at fundamental photon energies up to 10 KeV in preparation for hard X-ray experiments. FEL operating parameters, performance and reliability results will be presented, in addition to plans for upgrades to the facility.

LCLS LINAC

The LCLS project modified the last 1 kilometer of the SLAC high energy physics LINAC to provide a 15 GeV driver for an X-ray FEL. An RF gun and laser heater system were installed in an off-axis tunnel to produce a 250pC, beam with a typical normalized emittance of 0.5um. Two bunch compressors were added at the 250MeV and 4.3 GeV points on the LINAC to provide peak currents typically between 1 and 3 KA. (Fig. 1) [1]

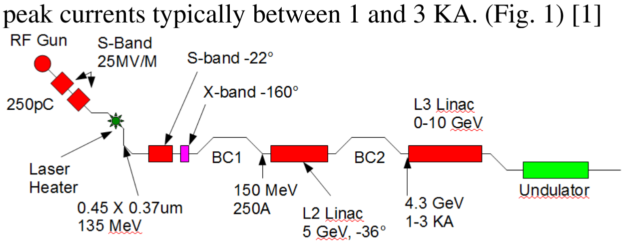

Figure 1: LCLS Accelerator Layout.

Emittance

The LCLS gun operates at 2856 MHz with a peak cathode field of 120 MV/M. A 1.2 mm diameter laser spot is used for normal 250pC operation with a 1.5ps RMS pulse length, and a 0.6 mm spot for low charge (20pC). Typical emittance is < 0.5 um at 250pC, and <0.2 um at 20pC (Fig. 2,3) Note that emittances are for a 95% cut in the injector, and an asymmetric Gaussian fit to X and Y profiles in the LINAC.

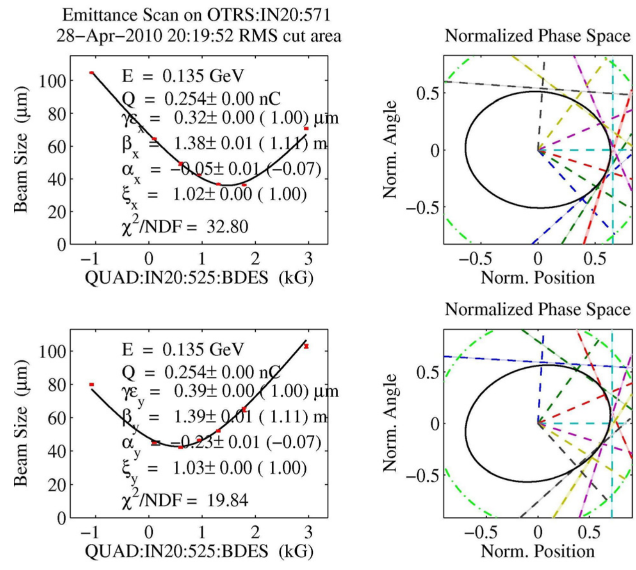

Figure 2: Emittance at 250pC 0.32 X 0.39 um.

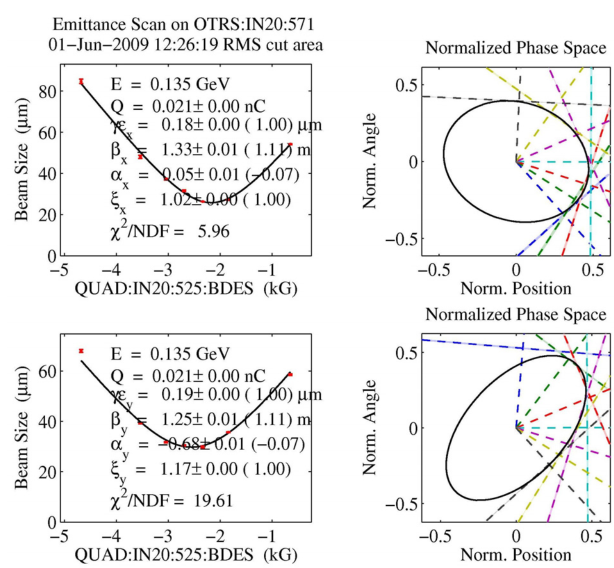

Figure 3: Emittance at 20pC 0.18 X 0.19um.

The LINAC can degrade the the emittance through wake fields and dispersion, and the bunch compressors

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can introduce CSR emittance growth. With careful tuning, emittances of 0.7 microns can be obtained at the end of the linac at 14 GeV (Fig 4), though more typically emitances of 1-2 microns are measured.

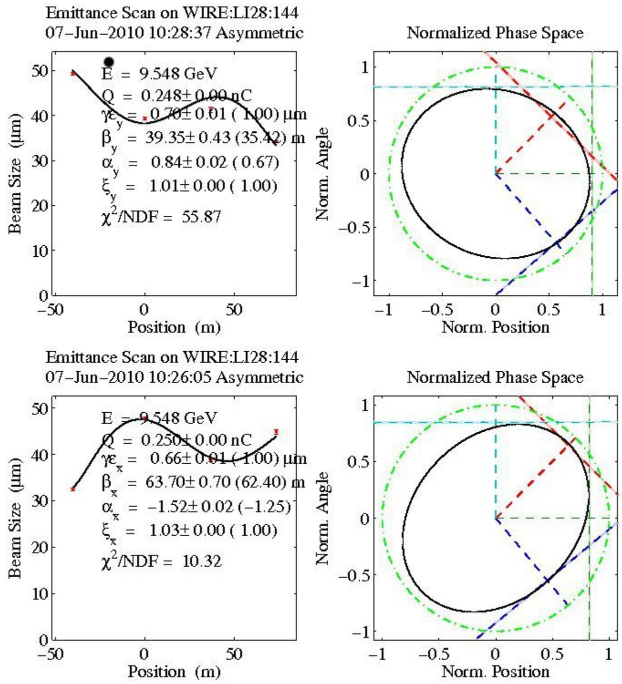

Figure 4: Emittance near the end of the LINAC.

USER OPERATIONS

The LCLS second user run was from May 2010 to September 2010. Typical schedule was two 12-hour experiment shifts per day, with one day a week for machine maintenance and upgrades, and one day for machine development experiments and tuning.

X-rays were delivered to users for 89% of scheduled time, with 4% time when the experiments were not ready to accept beam, 4% for machine tuning (wavelength and pulse length changes), and 3% machine down time

Photon Energy

The LCLS has operated from 480eV to 10 KeV with beams delivered to users from 530eV to 9 KeV. The low energy limit is set by beam transport issues through the SLAC beam switch-yard (designed for 50 GeV) and by radiation safety issues. The high energy limit is set by the number of available RF stations (including spares). Small wavelength changes can be made in a few minutes at user request. Large changes require about an hour.

Pulse Length

The LCLS normally operates with a bunch charge of 250pC and delivers 70-300 fs FWHM electron pulses. Pulse length adjustment within this range can be done rapidly at user request. The electron beam pulse length can be measured with a transverse cavity, but there is no direct measurement of the X-ray pulse length.

The LCLS can also operate in low charge mode at 20 or 40 pC to produce pulses which are too short to measure with the transverse cavity (< 10 fs FWHM). Based on CSR emission it is possible to identify the accelerator phase that results in peak compression, and the FEL operates well at degree of RF phase to either side of this point. Simulations indicate a bunch length of approximately 5 femtoseconds FWHM.

Pulse Energy

The X-ray pulse energy is measured by the change in electron energy at the beam dump spectrometer when lasing is disabled by an orbit oscillation in the undulator. The maximum recorded LCLS pulse energy was 4.5mJ at a 2 KeV photon energy, with typical operating pulse energies of 1-2 mJ throughout the operating wavelength range (Fig 5). Typical pulse energy at 20pC is 160uJ.

The intensity stability has been measured as low as 2% RMS, with typical stability in the 5-10% range.

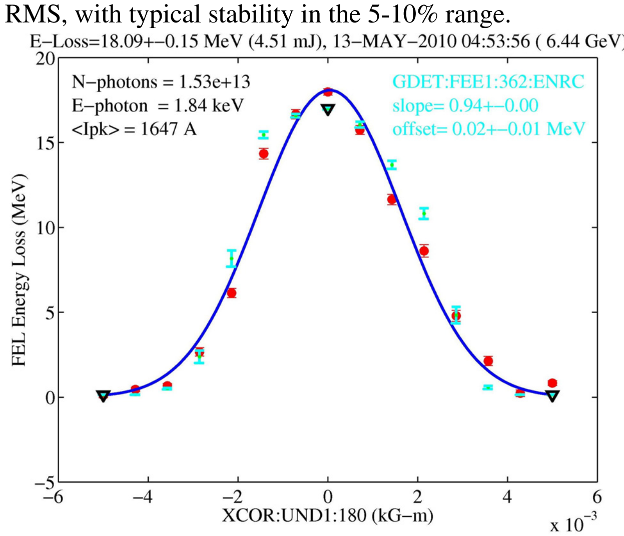

Figure 5: Maximum pulse energy 4.5mJ at 2 KeV from energy loss measurement.

The FEL power has decreased gradually during the 2010 LCLS user run.(Fig. 6). This decrease is not fully understood and will be studied during the October 2010 development beam time. One cause is that later in the run there was increased operation under non-standard conditions, with the “slotted foil” (described later), low charge, short bunches or other unusual tuning as requested by experiments.

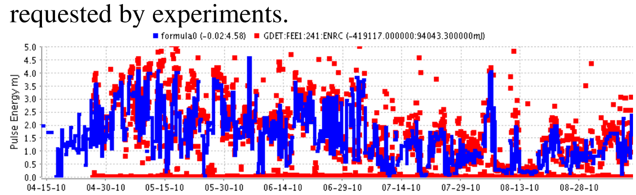
Figure 6: FEL pulse energy during last user run. Blue lines are E-beam energy loss measurements, red dots are from a gas detector, 5mJ full scale.

RECENT UPGRADES

Slotted Foil

The use of a thin metal foil installed in the second bunch compressor to spoil the emittance of all but a small temporal part of the beam is described in [2]. This scheme (Fig 7) was tested and within the limits of the beam diagnostic capability worked as designed.

The use of the slotted foil with the normal 250pC LCLS beam allows rapid changes from normal to ultra-short bunch lengths, although for the same bunch lengths the FEL power is somewhat lower than for low charge operation. A number of user experiments made use of the slotted foil.

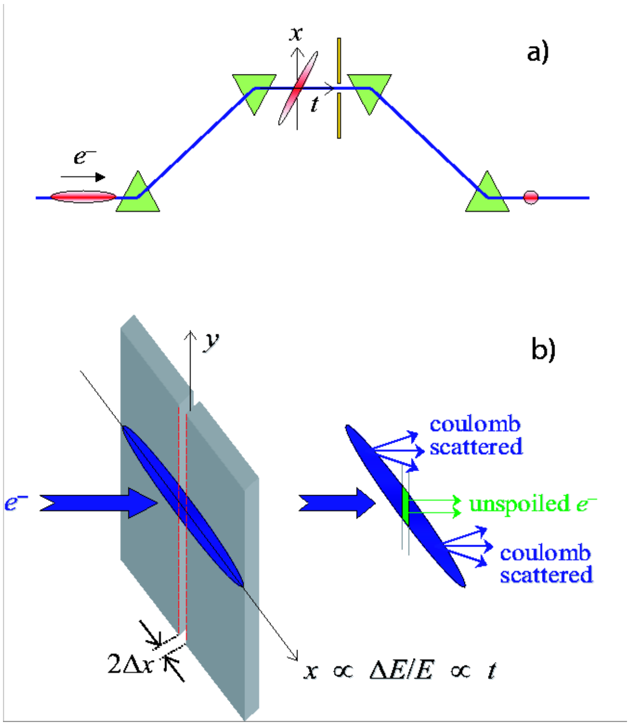

Figure 7: Slotted foil concept.

The slotted foil can be combined with 20pC operation to produce what are believed to be even shorter pulses. Spectra suggest single-spike FEL operation with soft X-rays, corresponding to pulse lengths around a single femtosecond, though this has not been verified by direct measurement. (Fig. 8). Work is underway to develop a femtosecond resolution X-ray pulse length measurement.

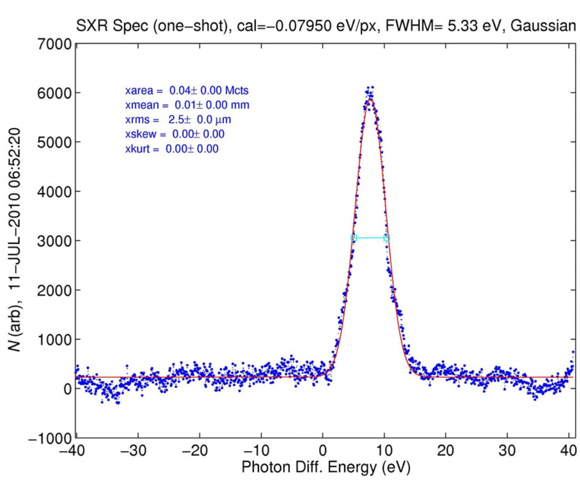

Figure 8: FEL spectrum at 20pC with slotted foil suggests single spike operation.

Requirements for Fast Timing Experiments

The LCLS is capable of producing pulses that are believed to be a few femtoseconds or shorter. Conventional lasers can also produce few femtoseond pulses (shorter in the UV). In order to take advantage of these short pluses for pump / probe experiments to study dynamic systems on femtoseocond time-scales, precision timing systems beyond the ~50 fs present state of the art will be required. [3]

NEAR TERM UPGRADES

Harmonic "Afterburner"

A FEL produces a beam bunched at the fundamental wavelength and its harmonics. If the bunched beam is sent through an undulator resonant at the 2[nd] harmonic, as much as 10% of the fundamental power is available [4]. This has been tested at LCLS and approximately 100uJ of X-rays at 18 KeV was produced. (Fig 9)

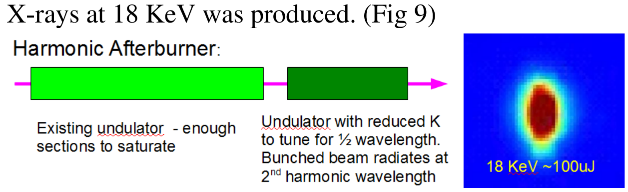

Figure 9: Harmonic "afterburner" at LCLS.

The harmonic afterburner extends the wavelength range of the LCLS from 10KeV to 20 KeV (at reduced power), Above 20KeV the normal undulator 3[rd] harmonic (at ~1% of the fundamental power) is available.

Self Seeding for Hard X-Rays

Following a suggestion from G. Geloni, V. Kocharyan and E. Saldin [5] the LCLS is investigating using a crystal band-stop filter for self-seeding hard X-rays. The crystal Bragg reflects a narrow band of X-rays, resulting in a ringing in the pass band that can be used to seed the second undulator. The chicane delays the electrons so that they interact with the ringing tail of the X-ray pulse.(Fig 10). This method is appropriate for short (few femtosecond) bunches, longer bunches will require a more complex seeding system.

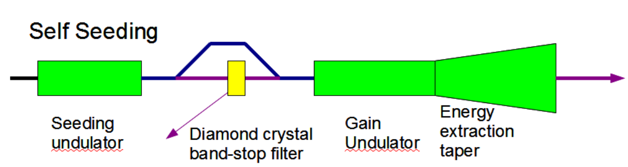

Figure 10: Self Seeding scheme.

LONGER TERM PROJECTS

LCLS_II

LCLS is planning a significant upgrade over the next several years. The order in which various components will be installed and the details of the final design are still under discussion.

The existing LCLS uses the last kilometer of the 3 kilometer SLAC LINAC. For LCLS_II the second kilometer will be modified in a similar way with a new RF gun and bunch compressors. This LINAC section can be used to provide an independent 14 GeV source or could be combined with the existing LCLS LINAC for beam energies up to 28 GeV. The remaining 1/3 of the LINAC remains available for future expansion.

One option under consideration is to construct a new tunnel that will contain variable gap soft and hard X-ray undulators. The soft X-ray undulator would be built in two sections to allow for self seeding, and will have an option for ECHO seeding. The hard X-ray undulator would also use self-seeding. (Fig. 11)

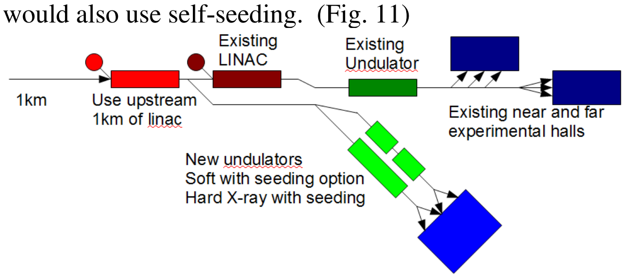

Figure 11: LCLS_II one layout option.

Additional LCLS Options

If there is scientific need, the high beam energy (up to 28 GeV) from 2 kilometers of the SLAC LINAC could be used to to drive a FEL operating with a fundamental photon energy of 30-50KeV. Calculations suggest this can be done with the existing LCLS 250pC beam brightness. In short bunch mode the lower emittance would allow even higher energies.

An alternate scenario is to use the high energy beam with a longer wavelength undulator to produce very high peak power radiation at 13 KeV. Simulations suggest that with a self-seeded long undulator, peak powers in excess of 1TW would be possible. (Fig. 12)

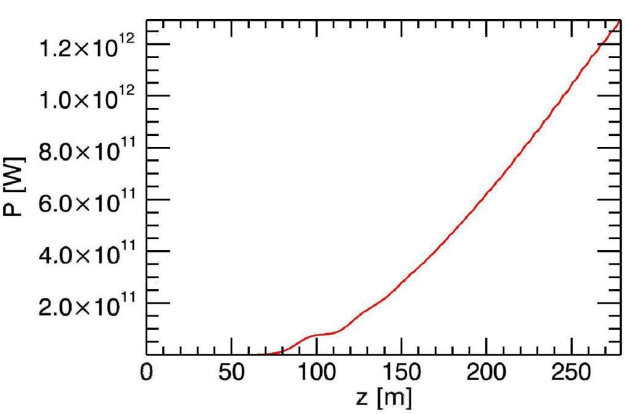

Figure 12: Genesis simulation of a 27 GeV electron beam, 5KA, producing >1TW at 1 angstrom.

The LCLS has operated with 2 FEL bunches separated by 8.4 nanoseconds.[6] The existing RF pulse length would support 10 bunches per pulse. These could be used to produce a bunch train from a single undulator, or divided among multiple undulators with a RF separator.

CONCLUSIONS

The 40 year old SLAC LINAC is being used to drive a X-ray FEL for experiments at user requested wavelengths and pulse lengths. The system has been upgraded to provide wider wavelength range and shorter pulse operation. Future upgrades will expand the number of users and depending on the developing science requirements will allow higher energy or high power FEL operation.

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