PHOTON ENERGIES BEYOND THE SELENIUM K-EDGE AT LCLS*

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Abstract

The Linac Coherent Light Source (LCLS) was designed for photon energies of 830 eV to 8.3 keV [1]. This range was widened and up to 11.2 keV photons have been already delivered to users. The selenium K-edge at 12.6578 keV is very interesting since selenium can replace sulphur in biological structures and then that structure can be precisely measured. To reach 12.7 keV, the electron energy would need to be raised by about 6% which initially did not seem possible. The trick was to change the final compression scheme from a highly correlated energy spread and moderate R56 in the compression chicane to moderate energy spread and large R56. The same bunch length can be achieved and RF energy is freed up, so the overall beam energy can be raised. Photons up to an energy of 12.82 keV (1.3% above the K-edge) with a pulse intensity of 0.93 mJ were achieved. The photon energy spread with this setup is wider at around 40-50 eV FWHM, since less correlated energy spread is left after the compression.

INTRODUCTION

To achieve FEL lasing above the selenium K-edge, it was necessary to increase to electron beam energy to 16.9 GeV which is above the energy reach of the standard LCLS linac configuration. A crucial component of the energy increase was accomplished through raising the beam energy in the second bunch compressor (BC2) by accelerating closer to the crest of the RF in second Linac section (L2). The reduced energy spread from nearer to crest operation required an increase in the R56 of the BC2 chicane to achieve to nominal bunch compression required for FEL performance.

This paper starts with a brief historical perspective. A discussion of the BC2 chicane issues follows along with a note on the changes to L2 and expectations from LiTrack simulations. The paper concludes with a discussion of the FEL performance at the selenium K-edge energy.

HISTORY

In May of 2013 an experiment started with the third harmonic to reach 11.2 keV. The low flux caused a try to use the fundamental at higher than “normal” photon energy. This yielded 50 times more photons. A final test followed quickly by pushing the limits; 11.92 keV was reached. The corresponding wavelength was still 4% longer than an Ångstrom (or 12.4 keV) and even further away from an interesting energy at 12.6578 keV, the selenium K-edge. The corresponding electron energy difference of 6% (five RF stations) seemed too much to overcome easily. Adding a modulator and RF klystron and splitting the four accelerating sections of an existing station into 2+2 would give only 41% more energy, so about 12 additional modulator plus klystrons would be required. In the search for ways to raise the energy and since we had already performed a beam test, we missed the now obvious way to do it (using the available energy better).

This changed in July of 2014 when one of our Variable Voltage Substations (VVS) burnt up. We lost the energy contribution of 16 klystrons and were limited to about 7.0 keV, right where the then current experiment wanted to run. One of us felt the pressure that someone might ask him the next morning: “Why didn’t you think of …?”, and came up with the brilliant idea, that we can trade the correlated energy spread (chirp) in L2 versus the R56 in the BC2 (Bunch Compressor 2) chicane. He also recognised the major limit since the bend magnets have to be raised for the R56 and then again for the higher energy, giving a quadratic behaviour and the power goes then with the fourth order of the required change.

BC2 BEND MAGNETS

The bend magnets for the BC2 bunch compressor have to carry the main burden for the highest energy running. The maximum field strength was raised to 10 kG-m or 250 A current (from 200 A), which is 50% more in the maximum power and about three times than typical running conditions.

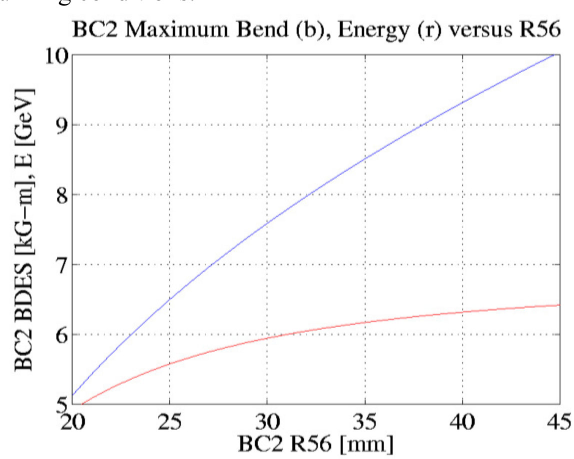

Figure 1: BC2 maximum bend strength and L2 energy versus R56 of the BC2 chicane.

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The Figure 1 shows dependence of the desired bend strength (BDES) versus the R56 value, while the L2 energy is raised to the maximum possible, but still maintaining the same compression. Finally the chicane R56 was raised from 28 to 45 mm, the energy from 5 GeV (with lots of energy overhead) to 6.25 GeV and the bend field from 6.2 to 9.8 kG-m (235 A).

Temperature

The temperatures of the magnet and its cooling water were measured during 250 A operation test. The input water had 35°C and output 55°C, with the highest point on the coil at 62°C. During that initial test an underrated wall breaker tripped, which had to be finally upgraded for continuous running. Going to even higher currents like 300 A (other available power supply) would push the temperature increase to 30°C, the magnet into saturation, and the R56 to its maximum of 50 mm.

Polynomials

The four bend magnets of the chicane have trim windings which are adjusted correspondingly to compensate the measured differences in the IvsB-polynomial. Since the magnets were only measured up to 200 A, (or 8.5 kG-m) the extrapolation to 10 or even 12 kG-m (see Fig. 2) is wrong and has to be extrapolated more carefully. The estimated orbit variation of about 2 mm can be handled with upstream and downstream correctors and was not corrected with the trims (Fig. 3).

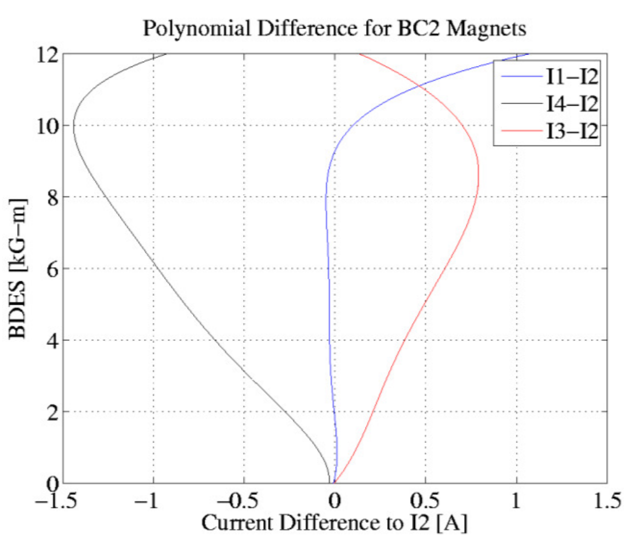

Figure 2: The difference of the bend fields with the respect to the second magnet is plotted versus the required current difference to achieve the same field strength.

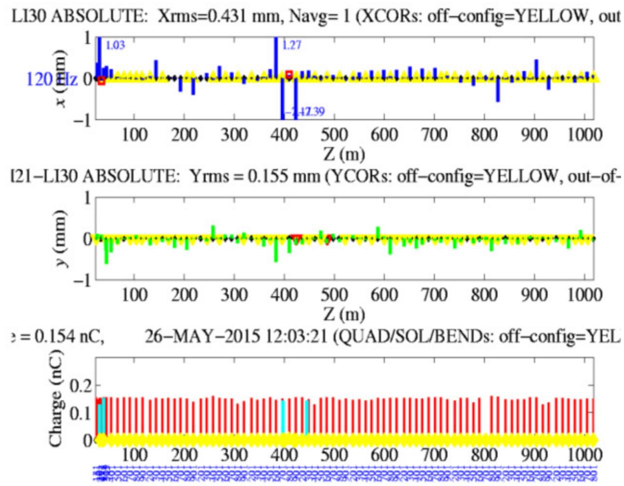

Figure 3: The orbit around BC2 (z = 400 m) had variations of +1.3 mm and -2.4 mm in x, about ten times worse than the rest of the linac.

L2 PHASE

Since R56 of the chicane was raised from 28 to 45 mm, the L2 phase had to be adjusted correspondingly from 35° to 22°, closer to the RF crest to get the same bunch length after compression. This change gains about 0.7 GeV in energy (Fig. 4) corresponding to about three RF stations worth of energy.

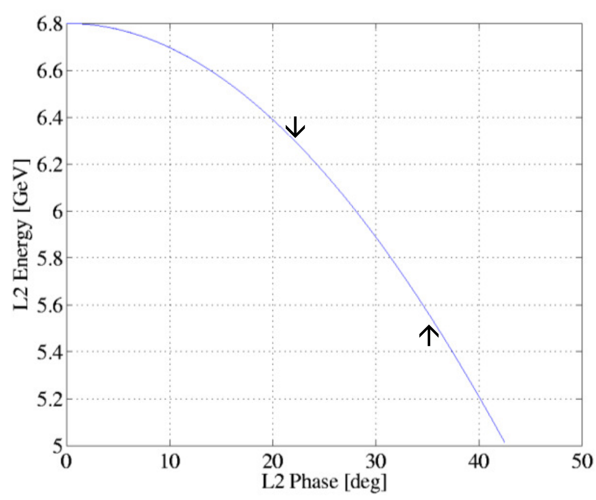

Figure 4: Energy gain due to reduced L2 phase.

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LITRACK SIMULATIONS

LiTrack simulations were done at 16.9 GeV (Fig. 5) and compared with the typical design setup at 13.6 GeV (Fig. 6). Since the wakefields relative to the higher energy are less, the energy spread is remarkably good. The distribution has some more tails. The horns in the longitudinal distribution split into two peaks near the front and end of the bunch.

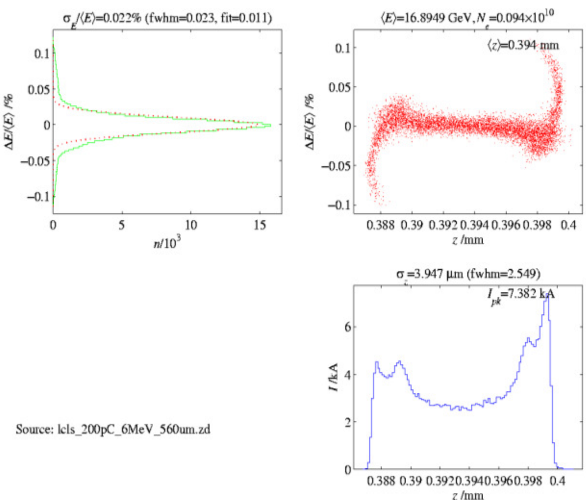

Figure 5: 16.9 GeV, R56 = -45 mm.

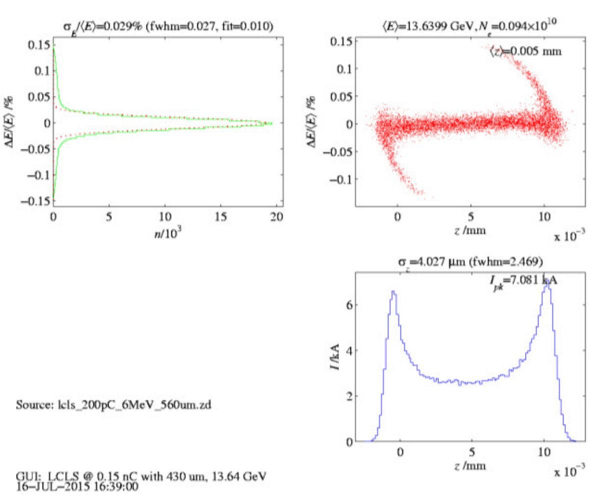

Figure 6: 13.6 GeV, R56 = -28 mm.

FEL PERFORMANCE

The initial FEL performance was very bad by a factor of 10-20 and tuning efforts were hampered by a low FEL gas detector signal. The R56 was even temporally reduced to increase tuning efficiency. Finally from a low jittery intensity the beam was tuned up and most of the jitter was non-linearly correlated with the peak current in BC2 (IMAX) (red in Fig. 7). Launch set points and vertical dispersion correction into the undulator reduced the peak current dependency and stable beam up to 1.2 mJ was achieved (blue in Fig. 7). The high energy of 12.82 keV with the initial performance of 0.93 mJ put us off the chart (Fig. 8).

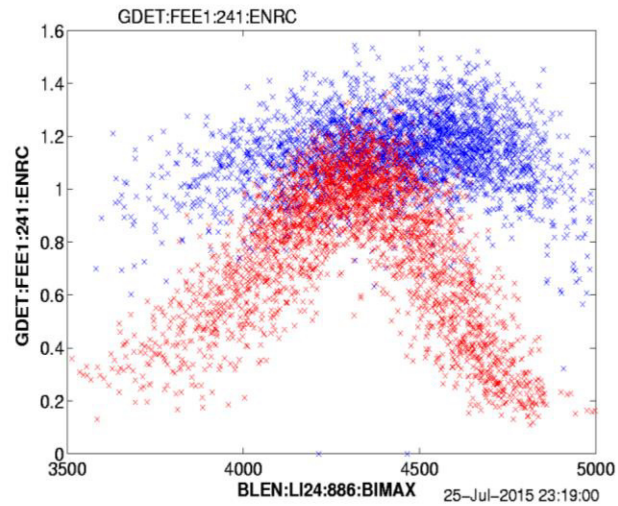

Figure 7: FEL performance via Gas Detector (GDET) [mJ] versus the BC2 peak current [A]. The initial red distribution shows a strong the dependence to peak current, while the tuned up data in blue shows the final performance.

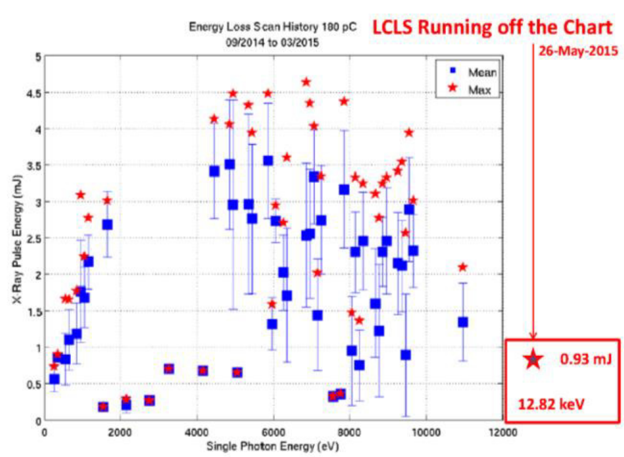

Figure 8: Pulse energy [mJ] versus Photon Energy [eV] shows the 12.8 keV nearly 30% above the typical hard x-ray running conditions.

Energy Spread

The relative energy spread of 0.023% FWHM (30 eV at 12.8 keV) is close to the typical energy spread of 20 eV at 9 keV (0.022%), see Fig. 9. Two effects play a role. It gets smaller due to the higher energy, but also gets bigger since the lower correlation of the energy spread is less reduced by wakefields.

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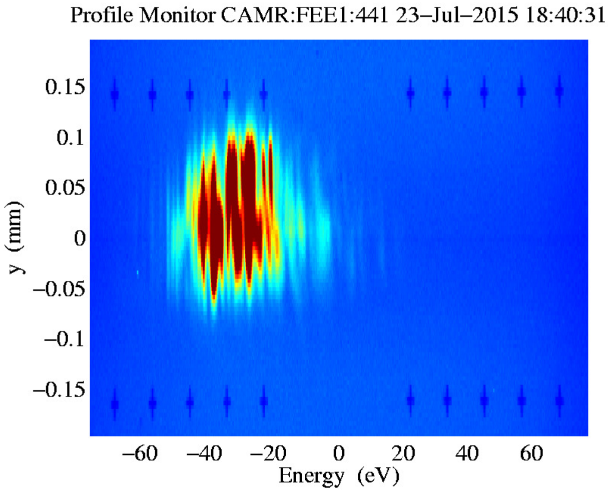

Figure 9: SASE energy distribution at 12.8 keV.

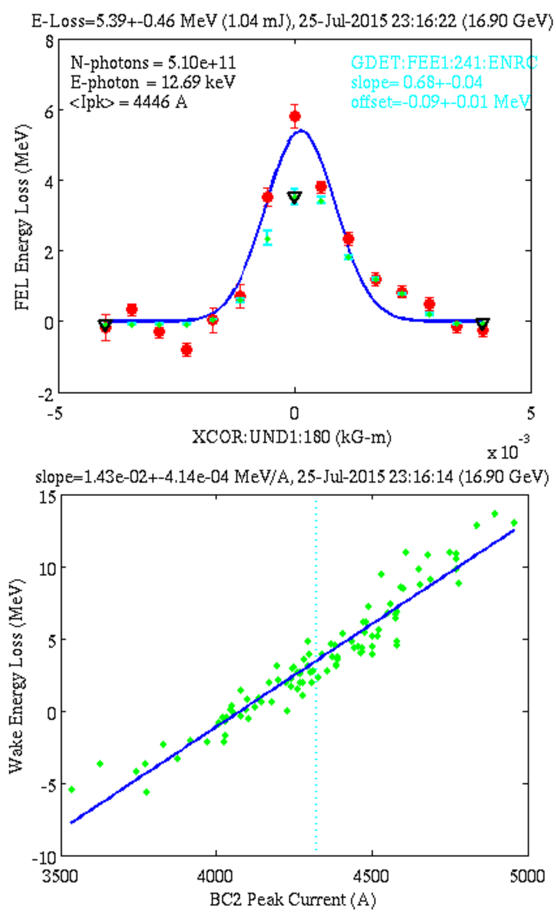

Figure 10: Energy loss scan at 12.8 keV (top) and the calibration measurement with peak current (bottom).

Performance Measurement

Typically the FEL performance is measured by an energy loss measurement, where the FEL process gets suppressed by introducing a trajectory oscillation in the undulator [2]. From the measured energy loss in MeV the FEL intensity in mJ is calculated (Fig. 10). The plot is more jittery than typical, which might have two reasons. The energy is higher, therefore the relative energy change is smaller and the typical correction due to peak current fluctuations is not smaller. And second it seems to be not just a linear dependence to peak current, but a slightly quadratic term too (Fig. 10 bottom).

CONCLUSION

The run at a photon energy of 12.8 keV was a big success.

ACKNOWLEDGMENT

Without the dedicated work of Power Electronic Maintenance and the RF group the 12.8 keV run would not have been possible. With their preparation, they achieved the high reliability which was necessary for the success. Also the Radiation Physics group was involved solving the problem at running at or just beyond the typically allowed electron energy limit of 17 GeV.

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