IMPROVED ENERGY CHANGES AT THE LINAC COHERENT LIGHT SOURCE*

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Abstract

The user requirements and beam time scheduling of the Linac Coherent Light Source (LCLS) imposes a demand for fast changes in machine energy across the entire operating range of 3.3 - 15 GeV (480 - 10000 eV). Early operational experience during LCLS commissioning revealed this process to be problematic and error-prone, sometimes requiring substantial re-tuning at each change. To streamline the process, a software tool has been developed to gradually ramp the machine energy while the beam remains on, allowing beam-based feedbacks to continue to work during the energy change. The tool has considerably improved the speed and reliability of configuration changes, and also extends the capability of the LCLS, allowing for slow scans of the photon energy over a wide range. This paper presents the basic process, analysis of the performance gains, and possible future improvements.

INTRODUCTION

The LCLS is a pulsed x-ray free electron laser, tunable in photon energy over the range of 480 eV – 10 keV [1]. Many other beam parameters are adjustable to meet user needs, including the x-ray pulse length, pulse energy, and bandwidth. Typical LCLS user operations require at least two configuration changes per day, as user beam time is normally broken into 12-hour alternating blocks that change shift at 9 am and 9 pm. Frequently, the experimenters' needs and accelerator physics programs dictate additional energy changes.

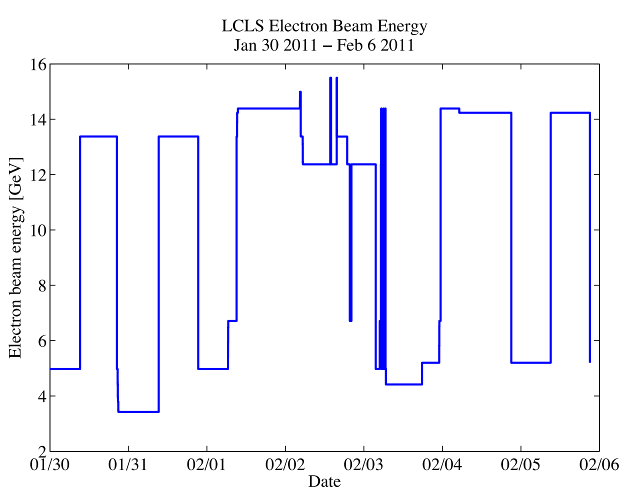

Figure 1: Electron beam energy over a typical week of user operation at LCLS, from Sunday to Sunday. Accelerator physics studies take place in the middle of the week.

Operational experience during LCLS commissioning found that these changes in beam energy were often problematic, sometimes requiring several hours to re-establish a quality beam. The procedure for changing the machine state takes many steps, uses several pieces of software, is highly sensitive to the order of operations, and can still require substantial re-tuning of the accelerator, as saved machine configuration files frequently do not reproduce well.

Energy Ramp GUI

Several solutions to this problem were implemented by the start of LCLS user operations in August 2009. One method incorporated the written procedure into a Matlab program that guided operators through the process, ensuring the correct order of operations and minimizing mistakes. The method described in this paper achieves the same goal by gradually ramping the beam energy up or down while the accelerator is running, allowing beam-based feedbacks to continue to operate. This technique is implemented in a Matlab program called the Energy Ramp GUI (Fig. 2), and has proven highly successful for small- to medium-sized energy changes.

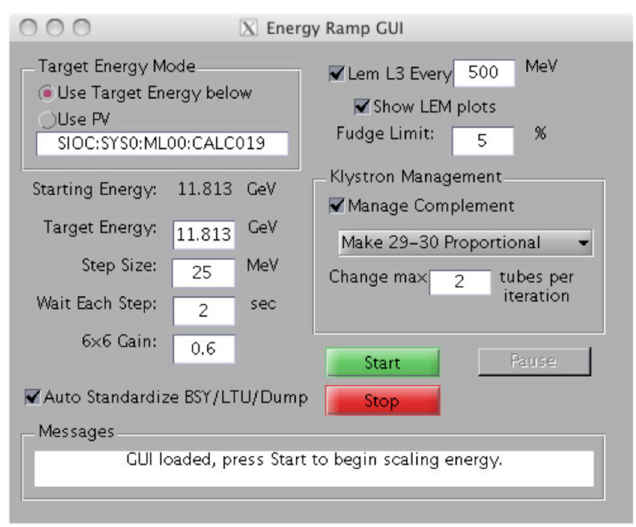

Figure 2: Energy Ramp GUI main screen.

IMPLEMENTATION

Changing the final energy of the electron beam from a starting value E_0 to a new value E_{new} requires a scaling of the magnetic field of each magnet:

$$B_{new} = (E_{new}/E_0)\, B_0 \qquad (1)$$

This simple calculation must be applied to all magnets in the accelerator, including those in the linac where the beam is still under acceleration, and the energy is not the

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final beam energy. The linac lattice is scaled to match the linac acceleration profile by another software tool [2], which calculates the actual beam energy at each magnet's z-location along the accelerator and scales the field strength as in Equation 1.

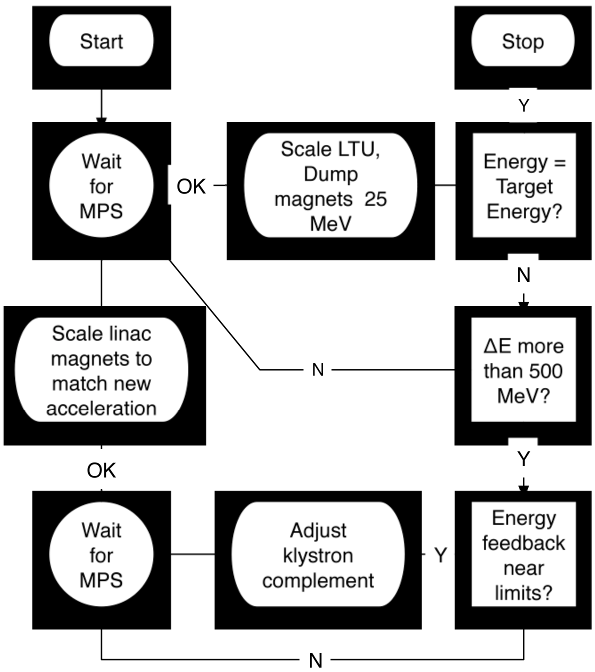

Figure 3: Process flow of the Energy Ramp GUI. The steps marked "Wait for MPS" check that the beam has not tripped off for any reason and that the operator has not pressed the pause button.

Process

The Energy Ramp GUI (Fig. 3) applies the scaling equation to all magnets downstream of the linac (except the quadrupoles between each undulator, which maintains a constant magnetic lattice in the undulator). E_{new} is typically E_0 + 25 MeV, though operators can change the step size. B_{new} for each magnet is calculated at each step and sent to the low-level controls via the *labCA* API [3]. Because of the parallel threading of *labCA* and fast response of the LCLS DC magnet power supplies to open-loop setpoint changes, the magnets all settle at their new settings within several hundred milliseconds.

Just after the magnets have settled, the actual beam energy has a -25 MeV error from the ideal energy of the newly scaled lattice. Since the beam stays on during the entire ramping operation, this error is corrected within ~ 1 second by the beam-based energy feedback, while, in parallel, transverse steering loops correct for any small orbit distortions. A pause of several seconds allows the feedbacks to sufficiently converge before another iteration is applied. Over the course of minutes, the final beam energy gradually ramps to the desired value.

At each step, the program checks to ensure that the beam has not tripped off, and that the feedbacks have sufficient range in their actuators; otherwise it pauses and allows the operators to intervene. Periodically, the beam is blocked for several seconds to adjust the number of active linac klystrons, since the energy feedback has limited range. The entire process takes several minutes, as illustrated in Fig. 4.

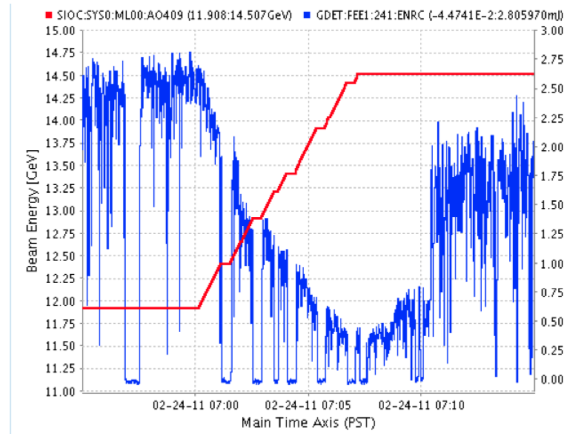

Figure 4: A typical energy change from 11.8 GeV to 14.5 GeV using the Energy Ramp GUI. The electron beam's energy (red) ramps up while the x-ray intensity (blue) appears to fall. At the 10-minute mark, operators recalibrate the x-ray detector and the energy change is complete.

PERFORMANCE

The efficiency improvements from the Energy Ramp GUI can be objectively evaluated by measuring the time spent changing the energy configuration. Data on energy changes were collected from LCLS Run 3 (January – March 2011) and from early user operations (April – October 2009) using the time stamps recorded in the SLAC operations electronic logbook. Each discrete energy change was sorted by type (Energy Ramp GUI or manual procedure) and assigned a time duration. Downward energy changes were corrected by subtracting out the 7 minutes required to correct for magnetic hysteresis, and the resulting distributions were fitted with a Gaussian (Fig. 5).

When using the Energy Ramp GUI, the mean time required to change the beam energy is 6.0 minutes, whereas energy changes carried out manually require on average 20.0 minutes. While the time spent changing energy is not tracked as downtime for reliability purposes [4], LCLS operations require on average 4 to 5 energy changes per day. This amounts to roughly an additional hour per day of useful beam time available to users. Furthermore, the distribution in times is much narrower for the energy ramp, which indicates the technique is less prone to error and more predictable.

Slow Scans

One particularly useful aspect of the Energy Ramp GUI is that x-rays can be continually delivered to the users during the ramping operation. Since the step size and rate can be set arbitrarily small, this allows for slow scans, essentially over the entire operating range of the accelerator.

An option in the Energy Ramp GUI allows the program to run in an infinite loop, ramping the beam energy up or down to follow a PV that acts as an energy setpoint. This allows the accelerator energy to be scanned by some other tool, such as correlation plot software, or even by the LCLS experimenters. In recent example, the setpoint was linked to the grating angle of the x-ray monochromator in the SXR instrument located at LCLS Hutch 2. Illustrated in Fig. 6, this process effectively slaved the entire accelerator configuration to the experimental data acquisition system, allowing the users to simply enter the desired photon energy and have monochromatic x-rays available at their sample within seconds.

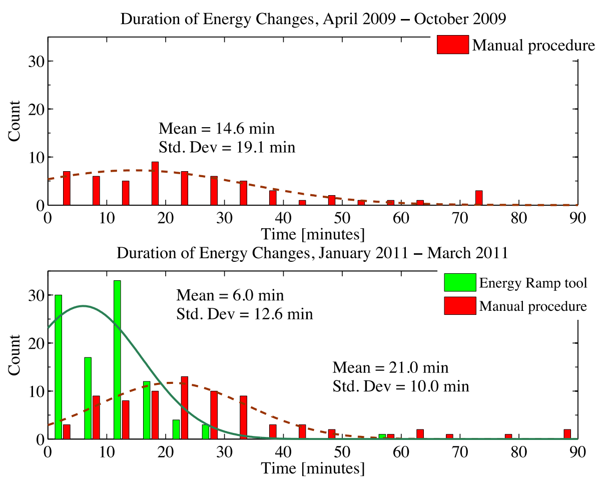

Figure 5: Energy change statistics for the Energy Ramp GUI (green) vs. the written procedure (red). Data were collected from the LCLS operations logbook and histogrammed into 5-minute bins. The Energy Ramp GUI is both faster on average and more predictable.

Limitations

Due to the nature of the ramp technique, the time spent changing the energy is roughly proportional to the magnitude of the energy change, $\Delta E=|E_{stop}-E_{start}|$. Many of the energy changes at the LCLS entail switching between soft and hard x-ray regimes, where $\Delta E \cong 10$ GeV. For these changes, the default energy ramp rate, 750 MeV/minute, is marginally slower than the average manual change.

The limiting factor in the ramp rate is the bandwidth and gain of the beam-based feedback. Since the increase in January 2011 of the LCLS repetition rate to 120 pulses per second, and with the recent commissioning of faster beam-based feedback, we expect to be able to significantly increase the ramp speed, further reducing the time. Faster yet configuration changes may come from better understanding of static fields, magnetic field errors, magnet alignment, and transverse kicks from accelerating RF, as well as other improvements like global steering feedback and faster diagnostics.

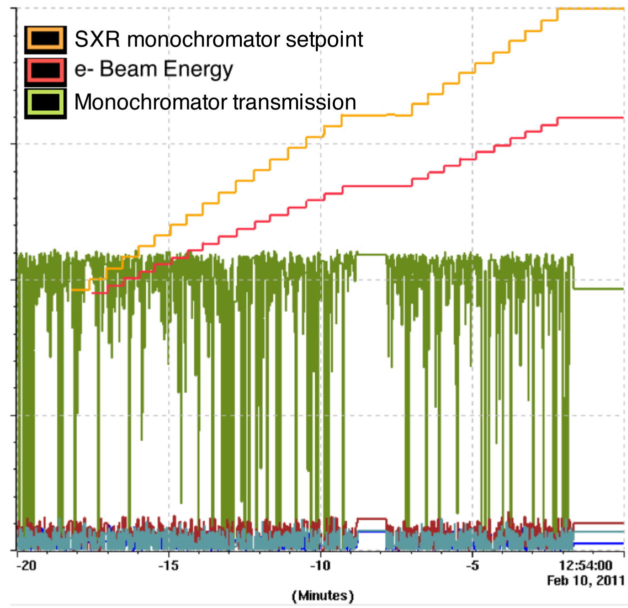

Figure 6: Controlling the electron beam energy with the SXR monochromator. As the monochromator grating (yellow) is tilted to scan from 810 to 840 eV, the Energy Ramp GUI scales the electron beam energy (red) to match.

REFERENCES

[1] P. Emma *et al.*, "First Lasing of the LCLS X-ray FEL at 1.5 Å", PAC '09, Vancouver, May 2009, TH3PBI01, p. 3115 (2009).

[2] P. Chu *et al.,* "Linac Energy Management for LCLS", IPAC '10, Kyoto, May 2010, WEPD057, p. 3224 (2010).

[3] T. Straumann, "labCA – An EPICS Channel Access interface for *scilab* and *matlab*" (2003); http://www.slac.stanford.edu/grp/cd/soft/epics/extensions/labca/manual/manual.html.

[4] U. Wienands *et al.*, "Reliability in the LCLS era at SLAC", PAC '09, Vancouver, May 2009, FR5REP034, p. 4846 (2003).