BEAM BASED FEEDBACK FOR THE LINAC COHERENT LIGHT SOURCE*

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Abstract

Beam-based feedback control loops are required by the Linac Coherent Light Source (LCLS) program in order to provide fast, single-pulse stabilization of beam parameters. Eight transverse feedback loops, a 6x6 longitudinal feedback loop, and a loop to maintain the electron bunch charge have been commissioned on the LCLS, and have been maintaining stability of the LCLS electron beam at beam rates up to 120Hz. This paper will discuss the design, configuration and commissioning of the beam-based Fast Feedback System for LCLS. Topics include algorithms for 120Hz feedback, multicast network performance, actuator and sensor performance for single-pulse control and sensor read back, and feedback configuration and runtime control.

INTRODUCTION

The Linac Coherent Light Source at SLAC requires several beam-based feedback systems to stabilize electron beam parameters. In April 2010 the LCLS began operating at a 120Hz beam rate. Several architectural changes were made to the LCLS control system in order to stabilize the beam at 120Hz. These changes were implemented in two phases over the last two years, and finalized this summer with the successful commissioning of the LCLS Fast Feedback system. This paper discusses the architectural changes required to achieve single-pulse stabilization at the 120Hz beam rate, the commissioning process and the performance of the feedback system.

FEEDBACK REQUIREMENTS OVERVIEW

The LCLS feedback systems stabilize several beam parameters through feedbacks of three basic types, transverse feedback loops, a longitudinal feedback loop, and a few simple single parameter general feedback loops. These feedback loops were prototyped in MATLAB and had been maintaining stability of the LCLS beam until the summer of 2011.

Transverse Trajectory Feedbacks

Transverse trajectory feedbacks have been commissioned at nine locations along the linac where the launch into the downstream section is important. They stabilize the X and Y position and angle of the beam. The majority of them run at 10Hz rep-rate. The Linac-to-Undulator (LTU) Feedback operates at beam rate, up to 120Hz, for single-pulse stabilization of the beam position and angle before entering the undulator region. See Figure 1.

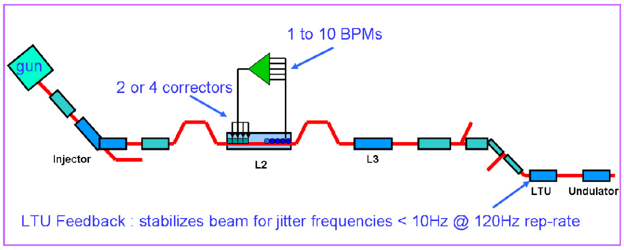

Figure 1: Transverse Feedbacks.

Longitudinal Energy and Bunchlength Feedback

The longitudinal feedback is responsible for single-pulse stabilization of the beam energy at four locations along the LCLS linac, and the bunch length at two locations along the linac. This feedback maintains all six parameters simultaneously using a 6x6 matrix of transfer coefficients [1]. Figure 2 is a schematic of the longitudinal energy (δ) and bunchlength (σ) feedback. The longitudinal feedback operates at beam rate, up to 120Hz.

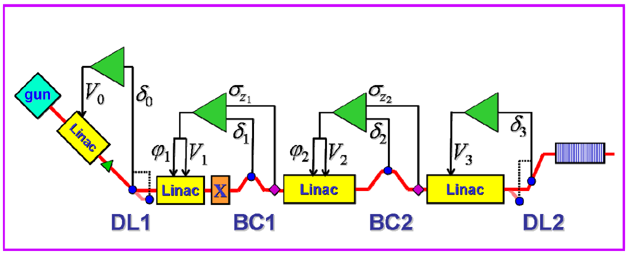

Figure 2: Longitudinal Feedback [2].

Other Simple Feedbacks

The Fast Feedback system allows for addition of feedbacks through its modular ‘framework’ design. The feedback engineer can define a feedback by entering a set of sensors, actuators, an algorithm, and identifying the parameters to maintain. Several simple single sensor, single actuator feedbacks were planned for the LCLS. The Bunch Charge feedback is an example; it maintains the charge by adjusting the laser intensity based on the charge reading of a beam position monitor.

120 Hz Feedback

In April 2010 the LCLS began operating at 120Hz beam rate. For 120Hz feedback the time-critical devices

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are the corrector magnets, which require 6ms to settle to within 85% of the reference point. Figure 3 is a diagram of the message timeline required to correct the 120Hz beam. This diagram shows that the feedback calculations must be completed within 2ms to successfully make corrections with the magnets. We further divided the 2ms, giving the sensors 1ms to produce measurements, and the feedback processors 1ms to calculate and send corrections to the actuators. [3]

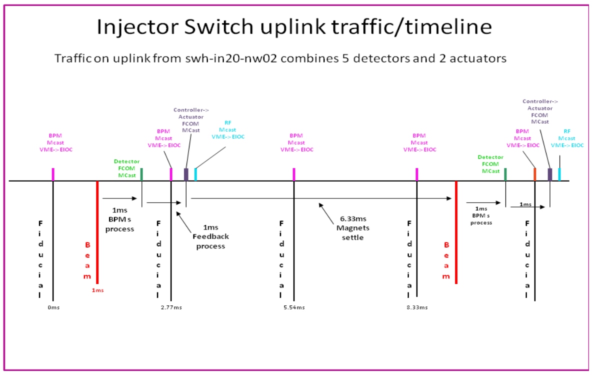

Figure 3: LCLS Fast Feedback message timing diagram.

120 Hz beam operation draws power from two interleaved 60 Hz power line phases which have differing noise characteristics that must be corrected independently by the feedback. The LCLS timing system assigns a ‘pattern’ for each pulse that indicates from which 60Hz “timeslot” the pulse is generated. This pattern-based timing is quite complex and can indicate other properties on each timeslot, such as whether there is a pulse, or the beam-rate.

The feedback processors must interface to the timing system in order to properly correct for each 60Hz timeslot variation. Since these differing noise characteristics include a large DC offset it was further required that the RF and magnet actuators interface to the timing system so that they can manage these power differences as ‘offsets’ even when the feedback is off.

Additional Requirements

The LCLS has additional features that prove challenging for continuously running feedback loops. Figure 4 shows where the final energy can be set automatically to a value anywhere between 4.3 GeV and 14GeV. The linac configuration can change using bend magnets to direct the beam into dumps at various locations along the linac, or to move the chicanes. A kicker magnet upstream of the undulator region can kick out pulses on a pulses-by-pulse basis, and is used to protect the undulator magnets. The beam charge can be changed from as low as 20pC up to 250pC

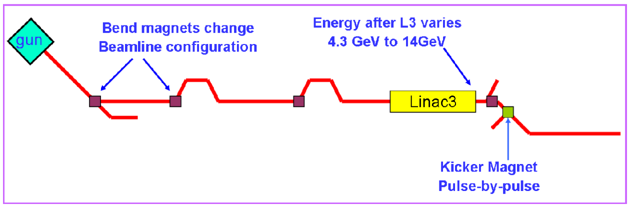

Figure 4: LCLS Changing beam line.

LCLS FEEDBACK COMMISSIONING

In order to meet the 120Hz single-pulse stabilization requirement, and correct for the 60Hz differences the final production feedback system required several architectural changes and additions to the LCLS. These upgrades are described in detail in [4]. The significant changes include:

- Faster network communications
- Timing pattern based processing
- Faster feedback processing

The system upgrades were first developed in a test environment that included a dedicated network with three switches and a router, a timing system processor, two sensor devices and their control processors, a magnet subsystem, an RF control subsystem, and a feedback processor. See Figure 5.

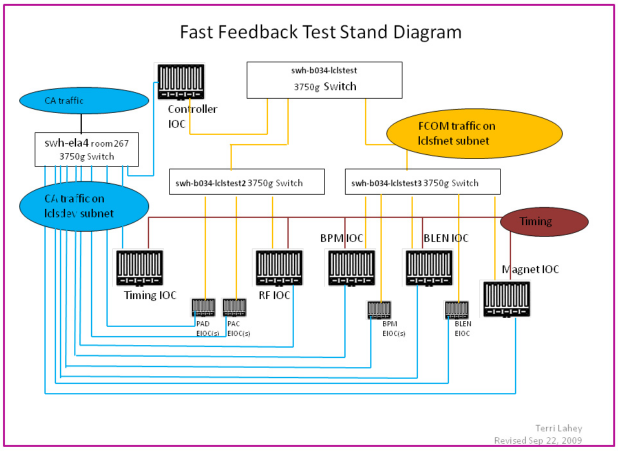

Figure 5: LCLS Fast Feedback test stand.

This full test setup was instrumental to developing these significant changes on schedule. The individual subsystems were debugged, the network was developed and characterized, the configuration tool and EDM displays were developed, and much of the feedback timing and control between subsystems could be worked out without requiring time on the production system. The following sections detail the architectural changes made to the LCLS and describes the performance improvements of the system.

120HZ PHASE I

The 120 Hz Fast Feedback system was installed and commissioned on the LCLS in two phases. Phase I included installing the dedicated feedback network, and adding a new timing system interface to the actuator devices. During phase I we were allotted three 8 hour shifts with beam to commission the network, sensors and actuators.

Dedicated Network

A dedicated gigabit Ethernet network was added to the LCLS infrastructure, to isolate the feedback communications from all other network traffic. The feedback IOC applications communicate over this new network using an IP-Multicast/UDP based protocol called FCOM, developed at SLAC [5], which works similar to a reflective memory communication scheme. The network interface software provides a simple API and has been developed as a software module that can be added to any IOC that must become part of the LCLS Feedback system. Figure 6 shows the added network. Each IOC used in feedback communicates on this network via a second on-board NIC and the FCOM software module.

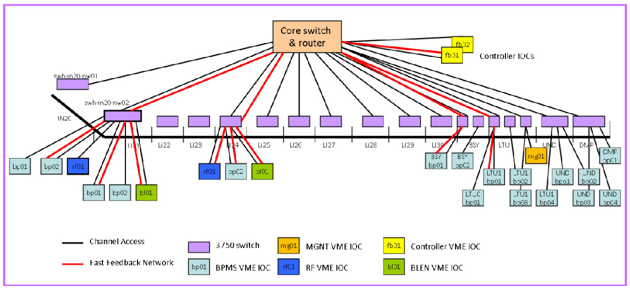

Figure 6: An isolated Feedback network added to the LCLS infrastructure, shown in red.

The Feedback Network is defined as a separate VLAN and includes its own uplinks from the LCLS sector switches to the main switch and router. Test-stand testing demonstrated the feedback communications capable of transporting round-trip messages from a sensor IOC to the feedback controller IOC and back in under 200us.

Timing System Interface

The timing system interface for actuators and feedback loops includes an Event Receiver and interface software module developed at SLAC called a Pattern-aware Unit (PAU) [6]. The PAU is a 'multiplexer' software module, which allows the actuator or feedback IOC to accept set point values per timing pattern. This software module registers with the timing system to receive a fiducial event. It queries the timing system for the current pattern pipeline and chooses the correct set point based on the current pattern. See the diagram in Figure 7.

The PAU allows any LCLS actuator device to discover the 'timeslot' pattern assigned to each pulse in order to synchronize its processing with the pulse.

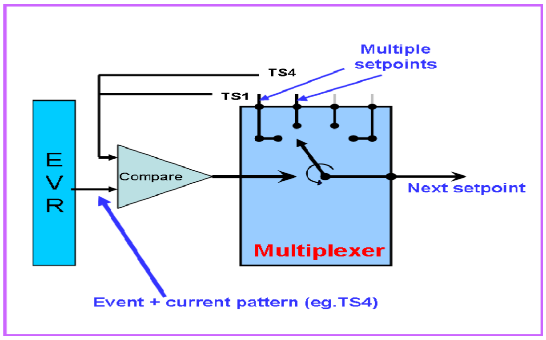

Figure 7: Each PAU input has an assigned timing pattern and actuator set point.

Sensor Devices

LCLS sensors already had an EVR and were interfaced to the timing system. The beam position monitors (BPMs) and bunch length monitors, (BLENs) were made available to the Fast Feedback by integrating the BPM and BLEN control processors with the FCOM software module. On the FCOM network the BPM measurements take less than one msec. to arrive at the feedback IOCs after a pulse, meeting the 1ms requirement.

The BLENs were not able to meet this requirement, but the flexible feedback configuration options allowed us to adjust the longitudinal feedback to delay processing and make up the difference by sending corrections to the RF actuators later in the timeline (the RF system does not require settling time as the magnets do).

Actuator Devices

LCLS RF stations and corrector magnets were integrated with the feedback network with the FCOM module, and the timing system using the PAU module. The new PAU software module proved very successful in aiding beam stability for users before the Fast Feedbacks were commissioned in 2011, and seamlessly handled the addition of the FACET program, which drew additional power on one of the 60Hz power line phases, creating a 30Hz disturbance. Thus the PAU allowed the magnets and RF to correct with an offset at 60Hz and two offsets at 30Hz.

120HZ PHASE II

The second phase of the Fast Feedback commissioning was accomplished in 2011. During this run the Fast Feedback controllers were installed and 11 feedbacks were commissioned using one to four hours of machine development time once per week over several months.

Feedback Controller and Software Framework

In order to gain processing speed, as well as interface to the timing system and the new network, the feedback loop calculations were implemented in EPICS IOCs. The LCLS IOCs consist of a VME6100 processor with two NICs, an EVR, and run the RTEMS real-time operating system.

The Feedback Loop Controller IOC application uses EPICS records for data and configuration storage, and is a multi-threaded application using the EPICS OSI library. This Feedback Controller application can run one or more feedback loops. The Controller IOC application is developed as a software 'framework' that handles common functions, such as managing operational limits on sensor readings, actuator set points, feedback calculated parameters, managing changing machine conditions, and error checking and reporting

Four Controller IOCs were installed and commissioned. The first transverse feedback loop was commissioned over two test days, and then five more were quickly added. The configuration tool described in [4] made it very simple to configure and install the remaining feedbacks, since the framework had already been commissioned. The 120Hz LTU feedback was the last transverse feedback commissioned. The transverse feedbacks average a processing time of less than 400us, meeting the overall 1ms requirement. Figure 8 shows the plots of the working 120 Hz LTU feedback.

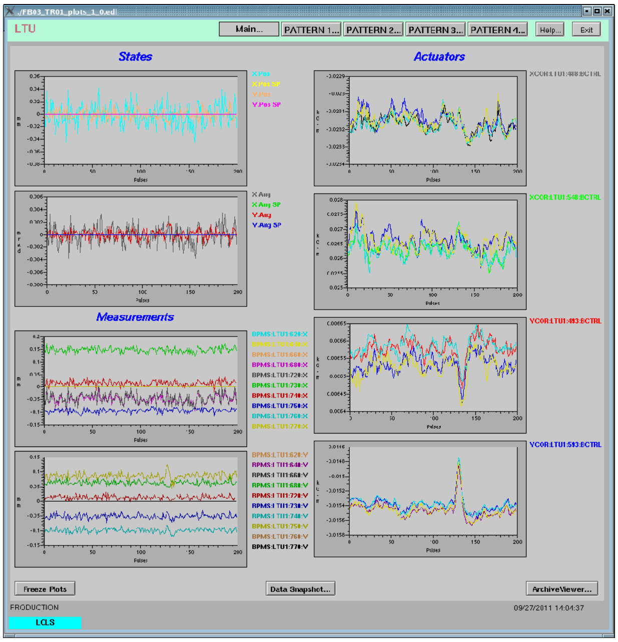

Figure 8: LTU Feedback plots.

The Longitudinal Feedback was the biggest commissioning challenge. As a global feedback, it must maintain energy stability of the beam through the many transitions of the LCLS machine, such as energy changes, charge changes and beam tune-up for each new user. This feedback had to be integrated and tested with many other machine tuning high-level applications and in many different machine configurations.

SUMMARY

Commissioning a feedback system on a production machine is a complex, difficult task. The demands on a working accelerator leave little time for global system commissioning. It is often useful to review the project as a whole and identify efficiencies in hindsight:

- Prototyping the feedbacks in MATLAB allowed machine operation with a fairly stable beam for users until Fast Feedbacks were fully commissioned.
- Investing in an extensive test stand for development allowed engineers to develop enhancements to a near-complete point.
- A 'virtual machine' in the test stand might have reduced even further our need for production test time.
- The network upgrade was inexpensive as it used mainly existing network infrastructure, but it cannot support 360Hz beam rate. A reflective memory solution might have been better for future growth.

Most importantly, commissioning in two phases gave us a fast network and timeslot aware actuators to use at 120Hz before full feedback installation. This allowed us to 'shake out' the bugs for half of this complex upgrade before moving on to the full feedback installation, and later allowed us to stabilize beam adequately during production shifts while commissioning feedbacks on development days.

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