

# DIAGNOSES AND CONTROLS OF SINGLE e-PULSE EXTRACTION AT THE LCLS-I FOR THE ESTB PROGRAM\*

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## Abstract

A pulsed magnet is used to kick single electron bunches into the SLAC A-line from the 120 Hz LCLS-1 bunch train. These single bunches are transported to the End Station Test Beam facility. It is mandated that extraction from the LCLS beam does not disturb the non-kicked pulses. An 8.7 mrad kick is required to extract a bunch; without compensation the following bunch experiences a 3  $\mu\text{m}$  kick; with compensation this kick is reduced to less than 0.1  $\mu\text{m}$  which is well within the jitter level of about 0.2  $\mu\text{m}$ . Electron and photon diagnostics were used to identify problems arising from eddy currents, beam feedback errors, and inadequate monitoring and control protocol. This paper discusses the efforts to diagnose, remedy, and control the pulse snatching.

## INTRODUCTION

A set of pulsed magnets are used to horizontally extract single electron bunches at 5 Hz into the SLAC A-line from the 120 Hz LCLS-1 [1] bunch train. These single bunches are transported to the End Station Test Beam facility as either primary beam or secondaries created in a Cu target [2]. An 8.7 mrad kick is required to extract primary beam. Anomalous magnetic fields produced by eddy currents deflect subsequent LCLS-1 pulses. Without compensation, the first bunch following extraction (so-called n+1) experiences a 3  $\mu\text{m}$  normalized kick. This disturbance is exacerbated by improper set up of the undulator launch feedback system which in turn drives the full bunch train away from the nominal kicker off trajectory. With proper setup of the feedbacks the disturbance is limited to the first (n+1) and second (n+2) bunches after extraction. An air core, pulsed post kicker is used to compensate the unwanted deflections. With compensation, the 3  $\mu\text{m}$  normalized kick is reduced to less than 0.1  $\mu\text{m}$  which is well within the undulator launch jitter level of about 0.2  $\mu\text{m}$ .

This paper discusses the actions taken to eliminate the disturbance to the non-extracted LCLS-1 bunches.

## PULSED KICKERS

A set of three pulsed magnets are to kick single LCLS-1 bunches into the SLAC A-Line. The first set of magnets are run with a single pulsed current supply [3] and the

and the third pulsed magnet is powered by a second power supply (a fourth pulsed magnet is being prepared for installation in spring of 2017 and will be powered in series with the existing third magnet). At maximum current, the three magnets are sufficient for extraction of beams with energies up to 16.5 GeV. The pulser also generates a controllable reverse current pulse 1 ms after the primary pulse. This back swing pulse is used in the cancellation of eddy currents.

Each magnet consists of a pair of 1-m long, air core coils. Initially the coils were supported in an aluminum frame and mounted on an Al baseplate. The baseplate was supported in the accelerator housing on a steel girder. After the problems of the eddy currents were identified, 80/20 T-slot<sup>TM</sup> Al frame members [4] and Al baseplate were replaced with G10 pieces to break up eddy current flow paths and to remove the baseplate “mirror.” The effect was to reduce the eddy current fields that affected subsequent bunches by a factor of about 10 from about 10  $\mu\text{m}$  to about 1  $\mu\text{m}$ . Figures 1 a,b,c show the pulsed current waveform; the original magnet with Al frame and baseplate; and the G10 modified magnet.



Figure 1a: Pulse kicker current waveform.



Figure 1b: Original Al frame and baseplate kicker magnet.

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Figure 1c: G10 modified kicker magnet.

### BEAM POSITION MONITOR DIAGNOSTICS AND FEEDBACK ISSUES

33 RF cavity beam position monitors (bpms) [5] are installed in the undulator. These bpms have a resolution of about ±1 microns rms. Six bpms located near the entrance to the undulator are used measure the launch error with respect to a reference orbit. The square root of normalized Courant-Snyder launch invariant is calculated from bpm trajectories. The LCLS beam has a typical normalized, launch jitter of ~300 nm rms.

The same 6 bpms are used in a different processor to determine the launch error and feedback on the launch using corrector magnets. The feedback system for the launch error consists of four 30-Hz loops running independently of each other but using the same sensors and actuators. A missing pulse results in a bpm reporting a zero offset. The feedbacks incorporate the zero into the data stream and adjust the correctors accordingly. This problem is fixed by telling the feedback to ignore the missing pulses. Similarly extraction of pulse n resulted in a deflection of the n+1 pulse. Due to the offset of the n+1 pulse, in steady state the launch feedbacks generate a negative going response to the n+5 pulse with an amplitude, A, of

$$A = \frac{G}{1 - (1 - G)^6} \approx \frac{1}{6 - 15G} \quad (1)$$

wherein G is the gain of the feedback loop (G=0.05 for the LTU 30Hz transverse loops). The response is proportional to the residual n+1 kick from extraction of the nth pulse,  $R = A\Delta_{n+1}$ . Because the loops run at 30Hz, every 4th pulse is displaced (n+5, n+9, n+13, n+17, and n+21) [6]. This effect is turned off by masking out the n+1 pulse from the feedback.

### POST KICKER

An air core pulsed magnet was designed and installed to compensate to the residual kick at the n+1 pulse. The magnet is an X-Y set of nested PEP-I corrector coils (24 turns, 20.3 cm long, 15.2 cm wide, 12.7 cm separation 2.1e-4 kGm/A ) A unipolar power supply is used since the

direction of the residual kick does not vary. This scheme was initially installed as a test and found to work well and was subsequently extended to being pulsed on the n+1 and n+2 pulses. Figures 2 a,b show the beam displacement without and with correction. This data was collecting using the Beam Synchronous Acquisition utility [7] with records data from 1149 monitors for up to 2800 sequential beam pulses. The 2800 beam pulses are averaged in 24 bins corresponding to 5 Hz pulse extraction from a beam rate of 120 Hz. Figures 3 a,b show the corrector current waveform and the installed corrector pair.

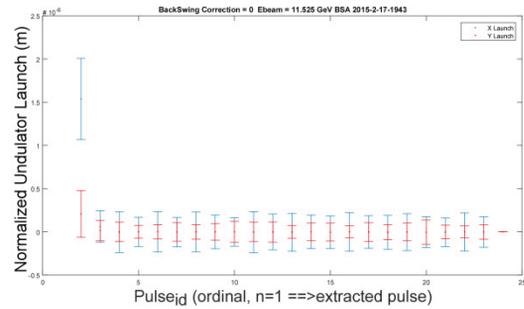


Figure 2a: Normalized undulator launch without post kicker correction.

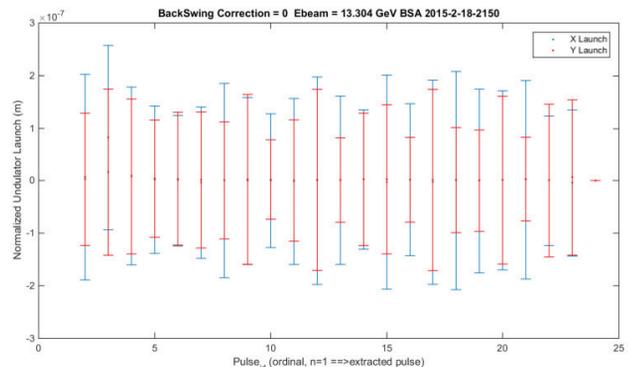


Figure 2b: Normalized undulator launch with post kicker correction.

In figures 2a and 2b, the horizontal axis is the ordinal Pulse<sub>id</sub> wherein n=1 is the extracted pulse; the vertical axis is the normalized undulator launch.

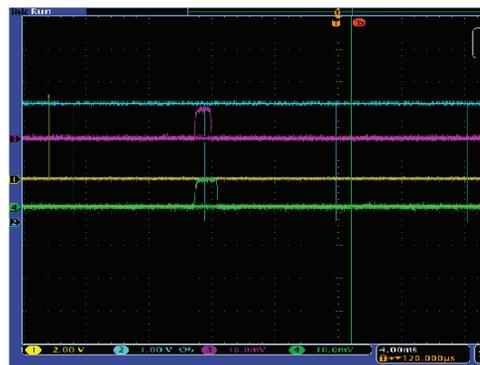


Figure 3a: Post kicker current waveform; note toroid calibration = 100A/V.

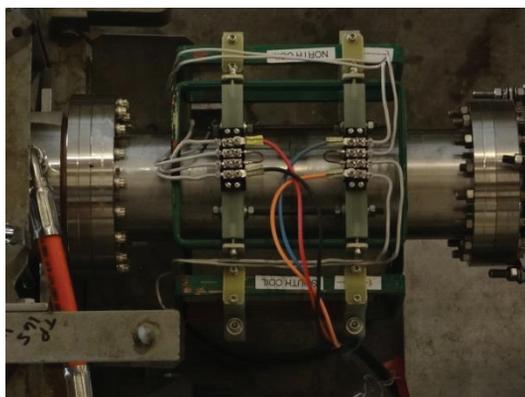


Figure 3b: Post kicker corrector coils installed in the SLAC BSY.

### END STATION A (ESA) EXTRACTION CONTROL

An online, live time launch monitor system was developed to ensure that the kicker compensation was properly set up and did not drift off. Called Tuning Diagnostics, this program calculated the launch into the undulator on a pulse-by-pulse basis. To protect against flyers, each new orbit was added with a damping factor to a running average of the previously measured orbit. This averaging effectively reduces the bandwidth of the measured launches. Alarm and abort set points on the measured launch error are used to (1) warn an Operator that the launch error exceeds a warning threshold and (2) shuts off pulse extraction if the launch error exceeds the acceptable tolerance. Shut off requires Operator intervention to manual restart pulse extraction after having diagnosed and remedied the offend cause of the launch error. Figure 4 a,b shows the Control System displays used to set up, monitor, and control A-Line extraction. An extensive Operations procedure has been developed. This procedure is used by the control room staff to set up and maintain beam delivery to ESTB



Figure 4b: Time system interface panel.

### PHOTON DIAGNOSTICS

Prior to the initial fixes to the kicker magnets, feedback process, and improved operations procedures, the presence of 5 Hz pulse extraction could be seen on the intensity profile of the LCLS xray pulse intensity. This was directly observed on the gas detector displays. After the initial fixes but with still a measurable ~1 μm n+1 orbit disturbance, the gas detectors were essentially blind to the finite albeit small orbit distortions and most users could run compatibly with A-Line extraction. However some users were sensitive to the small pointing errors even though there were no total intensity fluctuations. With the addition of the post kicker systems, there were effectively no orbit distortions. To resume Operations, tests were made in each hutch for each mode of operation to ensure that properly set up pulse extraction did not measurably disturb the quality of the xray beam delivered to the samples. These measurements were made using direct images of the xrays on screens located at the sample positions [8]. The images were acquired at 120 Hz and analyzed. Figures 5a,b,c show the xray spot profiles measured at XCS YAG2 The xray energy was 7.87 keV at a corresponding electron energy of 13.3 GeV. The data has been binned into the 24 event periods. At present, A-Line extraction is compatible with nearly all modes of LCLS-1 operations.

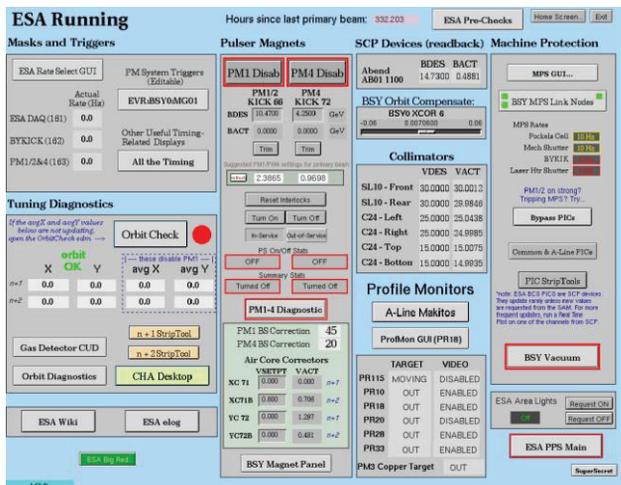


Figure 4a: Control system operator interface for A-Line extraction.

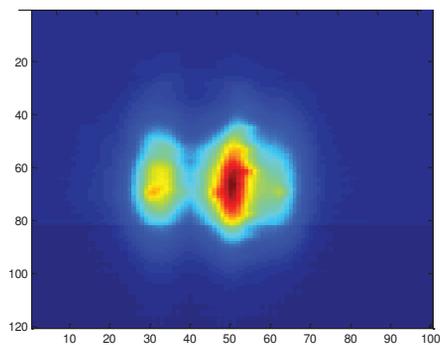


Figure 5a: 7.87 keV xray spot on XCS YAG2.

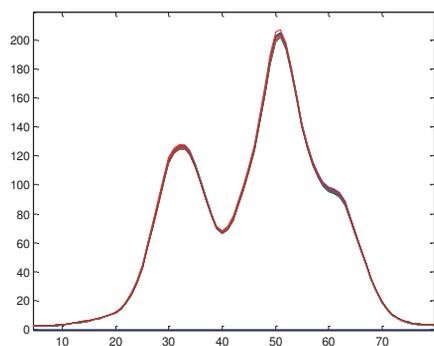


Figure 5b: Horizontal projection of XCS YAG2.

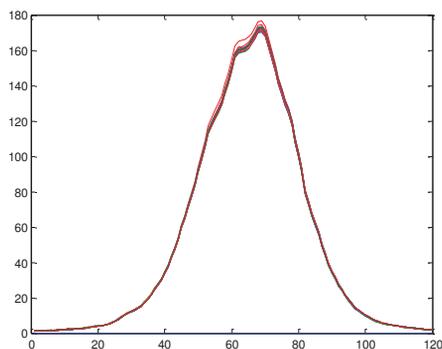


Figure 5c: Vertical projection of XCS YAG2.

The double lobe of the xray spot is a consequence of the imperfections of the surface of the xray imaging mirrors. The effect of perturbing the 120 Hz pulse train is seen in Figures 5a and b as a single trace out of the 23 overlaid projection that is slightly different from the others. This perturbation is not observable on the electron diagnostics or on the xray intensity monitors.

## SUMMARY

Initial A-Line extraction has found to be disruptive to the quality of xray beams delivered to the LCLS users. The problems arose for eddy current effects, electron feedback errors, a lack of diagnostic methods, and inadequate operations procedures. These issues have been fixed through modifications to the primary kicker magnets, the addition of a low strength post kicker corrector pair, the development of real time electron launch diagnostics, controls to limit errant operation, and the development of operations procedures. A-Line extraction to the ESTB runs concurrent with LCLS-1 users.

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