A DEMONSTRATION OF MULTI-BUNCH OPERATION IN THE LCLS*

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Abstract

The Linac Coherent Light Source at SLAC is a hard X-ray FEL which was designed for single electron bunch operation. Although most user experiments are not interested in multiple bunches from an S-band linac due to their short (ns) separation, there are some advantages with multi-bunch operation. Starting with two bunches where the delayed light of one bunch is used to seed the light of a second bunch, to many more bunches to increase the likelihood of rare target collisions, multi-bunch operation would open more options for the LCLS. In the past the SLAC Linac has operated with a few dedicated bunches for the SLC (Stanford Linear Collider), and up to 1400 bunches for some fixed target experiments, so a few bunches for the LCLS seems possible even with the original single bunch design. This paper will describe how the current RF implementation supports multi-bunch operation. Initial experimental tests with two bunches are presented.

MULTI-BUNCH ADVANTAGES

After the very successful turn-on of the LCLS [1] it is time to reflect on upgrades and improvements. One such thought is the use of multi-bunches [2]. Seeding of the FEL laser to get coherence in the longitudinal direction can be done by using two bunches separated by a few ns [3]. Two or more bunches might be useful for specific experiments, for example increasing the target hit rate. Separating the bunches with RF or magnetic kickers can send them to different undulators or even create two FEL beams in one undulator with a kink in it. Multi-bunches are in the design of future XFEL sources at DESY in Germany and SPring-8 in Japan, but not included in the baseline plan for the LCLS at SLAC. This left many diagnostics optimized for a single bunch, making it difficult to measure a second bunch. Over the years SLAC has delivered many bunches to fixed target experiments [4,5] or solved special problems with the three bunches of the SLC [6], by using fast phase and amplitude adjustments of the RF system.

TWO–BUNCH TEST

At the end of July 2010, an experiment was conducted using two bunches per RF pulse, 8.4 ns apart. The main goal was to achieve and verify two-bunch FEL lasing and additionally check which diagnostics can be used and what physics can influence the two bunches differently.

Generation of Two Light Pulses

Two UV pulses were generated to illuminate the cathode of the RF gun, using the high power Thales drive laser and a two-pulse stacker (Fig. 1), where the P-arm was extended to an 8.4-ns bunch separation.

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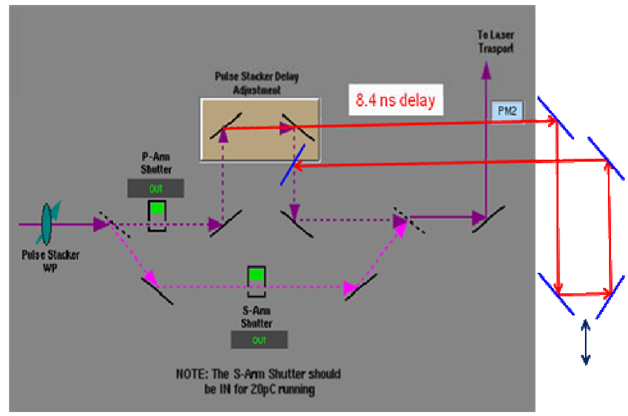

Figure 1: Two UV Pulse Setup using the Pulse Stacker with the Thales laser.

This setup generated two electron bunches each with 250 pC, 8.4 ns apart, with a few possible adjustments. We could have one arm only (S or P) or both together, and the charge ratio of each arm was adjustable with a wave-plate (WP) at the incoming end. The precise timing (or phase) between the two bunches is tuned with a variable delay of up to ±40 ps, with only a 6.5-ps adjustment needed.

BPM Response

The BPM (Beam Position Monitor) response to the two bunches was expected to be quite different for the different BPM processors, since their intermediate frequencies vary. In the injector and linac BPMs, doubling the charge within 8.4 ns shows up as a factor of 1.7, not 2.0, due to the 140 MHz sampling frequency (Fig. 2).

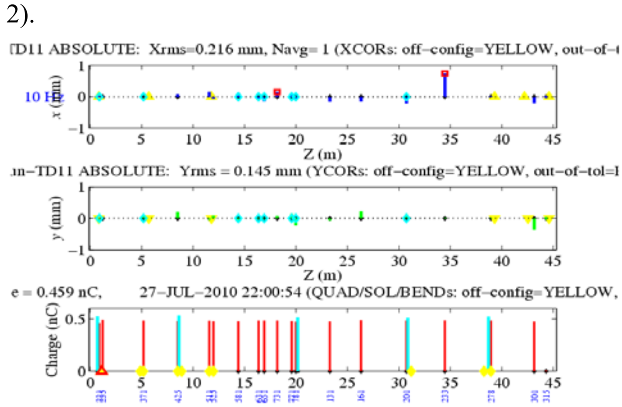

Figure 2: Two bunches add like vectors in the injector BPMs to a factor of 1.7, or 420 pC (red), while the toroids (cyan) accurately sum both bunches to 500pC.

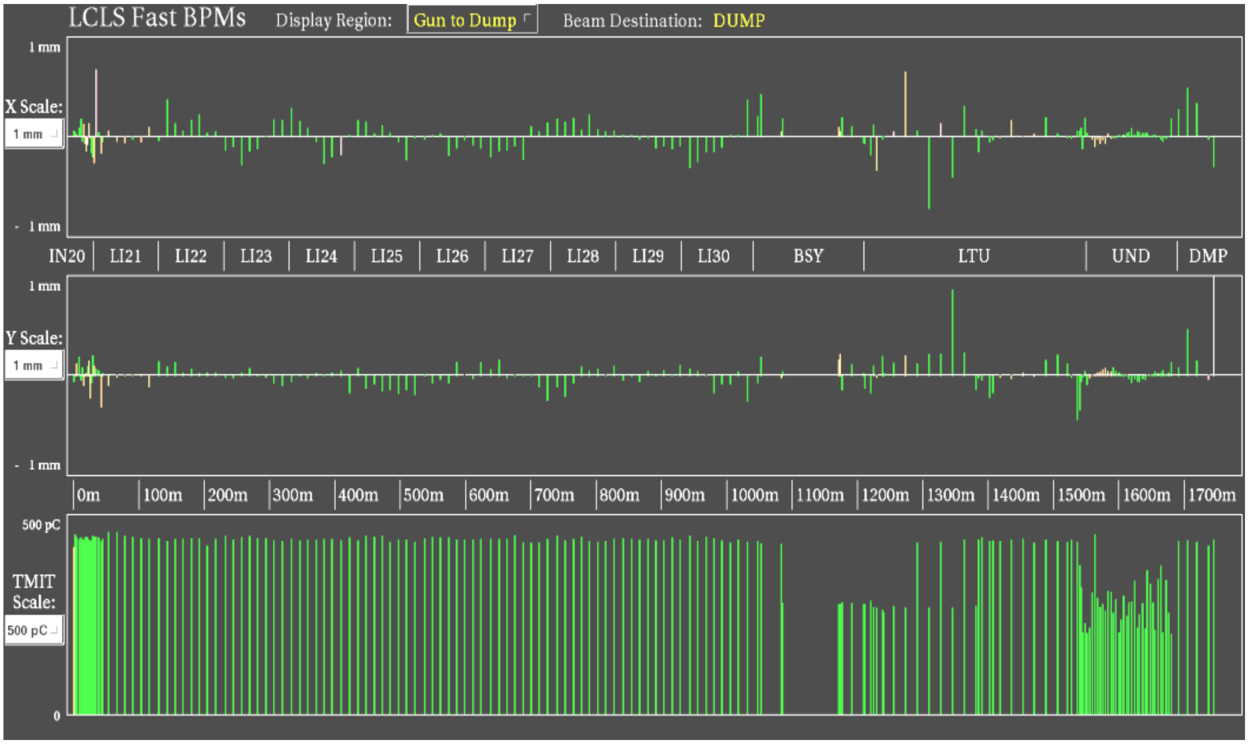

Figure 3: Three different BPM electronics with a 140, 200 and 40 (±5) MHz intermediate frequency, add up the two bunches like vectors to 1.70, 1.07 and 0.8 to 1.2 * 250 pC.

The "FFTB-style" BPMs use a frequency of 200 MHz. They are used in the BSY (Beam Switch Yard) and LTU (Linac To Undulator) area (compare Fig. 3). In the undulator RF-cavity style BPMs are used with a frequency of about 11.424 GHz, which is mixed down to 40 MHz. Since they are not tuned exactly to the same frequency, but have variation of about 5 MHz the expected response should vary around 1.0±0.2, which is actually observed. The response can be calculated as follows: With an RF frequency of 2856 MHz, the shortest bunch spacing is 0.350 ps (8.4 ns is 24 times this). The wave period (or 360°) at 140 MHz is 1/(140 MHz) = 7.143 ns for the injector and linac BPMs. After 8.4 ns or 423° = 360° + 63° the vector of the second bunch is 63° off, resulting in a combined response with an amplitude of 1.70 instead of 2.0.

Energy Adjustments in the Linac

At 250 pC an electron bunch loads the RF down by about 6.6 MeV over a 1-km accelerator structure length or about 0.1% at 6.71 GeV. To compensate this we can time the RF early (-70 ns), so that the accelerating structure is not yet totally filled and it is filled more for the second bunch compensating the beam loading. For this we made two timing variables one for the L2-linac (between bunch compressors BC1 and BC2) and one for the L3-linac (after BC2). The measured energy spread on an OTR (Optical Transition Radiation) screen in bunch compressor BC2 and at the end of the Linac on a dispersive screen (PR55) was minimized separately using these two time variables. How good this procedure works was checked by separating the two bunches, see next part.

Observing Two Separated Beam Spots

We used the S-band transverse RF deflector in the L3-linac (TCAV3) to separate the two bunches vertically. TCAV3 runs slightly off the nominal S-band frequency at a temperature of 113°F, whereas it was designed for a 79°F S-band operation. Since that cooling temperature is not readily available we run it effectively off frequency, by adjusting the I and Q of its RF drive in a sine and cosine manner (Fig. 4).

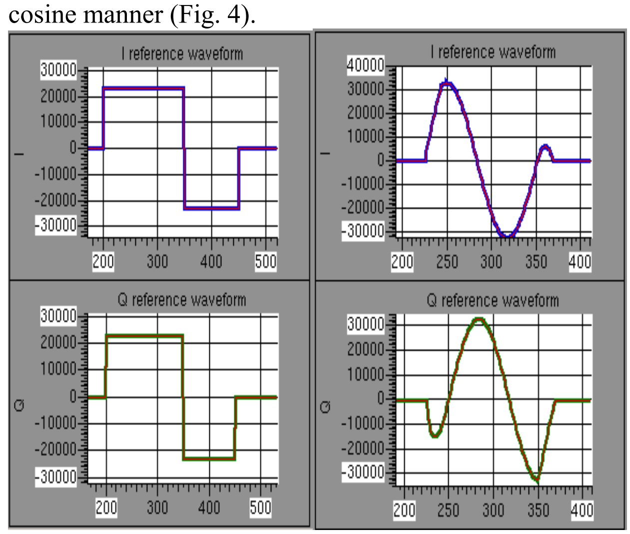

Figure 4: Instead of a typical 180° phase switch (left) the transverse cavity TCAV3 has a constantly changing phase (sin and cos) to compensate its off-frequency running. A 90° phase change in 300 ns separates the two bunches enough in 8.4 ns to be visible as separated beam spots.

The nearly 1 mm difference orbit between the two bunches in y cannot be detected with BPMs, but a screen at the end of the linac documented their separation (Fig. 5).

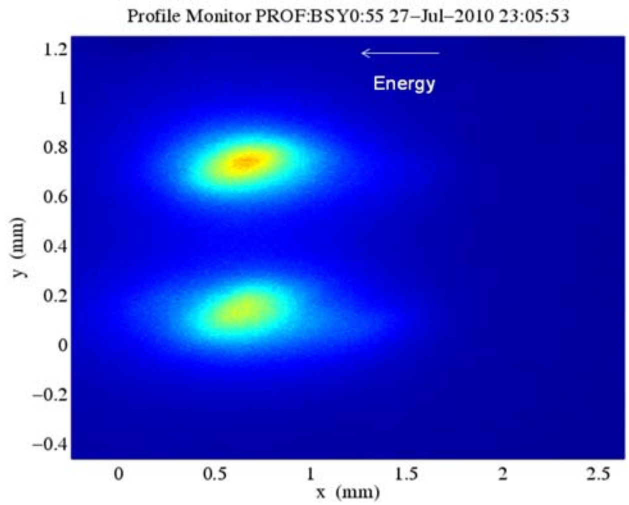

Figure 5: Using TCAV3, the two bunches are separated vertically on a screen which has horizontal dispersion: Both bunches have the same energy here.

Sending Two Bunches through the Undulator

Since there is a concern of losing beam in the permanent-magnet undulator, we equipped one BPM in front of the undulator with timing information by connecting all four signals to a scope, which indicated that the two bunches had similar charge and trajectories (Fig. 6).

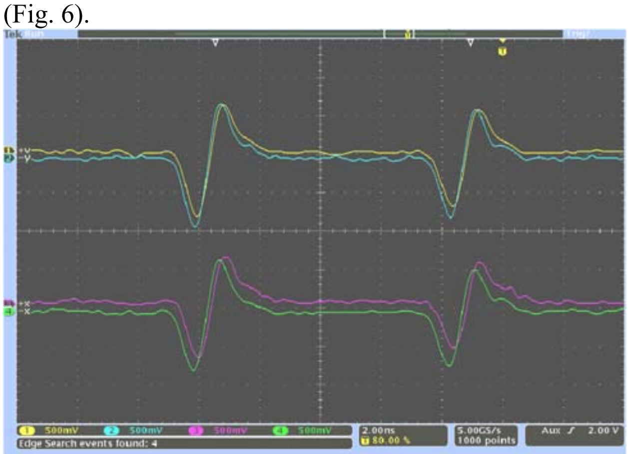

Figure 6: Four stripe-line signals from a BPM just in front of the undulator were put on a scope to be sure both beams were equal enough in charge and trajectory.

A small difference orbit of about 100 μm was observed between the two bunches when transported separately. This error seemed to start in the BC1 chicane early in the linac, likely from uncorrected dispersion or wakefields in the x-band cavity nearby. BPM data for each bunch separately (the S-arm and P-arm alone) and the combined orbit were taken, but the precise cause is not yet known. Nevertheless, this 100-μm x-difference orbit in the undulator (Fig. 7) does not impact the lasing too much with the difference split to ±50 μm.

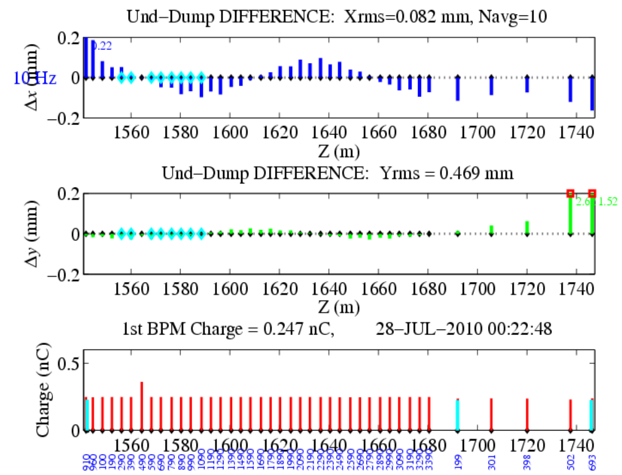

Figure 7: Difference Orbit two bunches showing 100 μm separation in the undulator, causing somewhat different FEL performance.

After the undulator and after the point, where the electron beam is bent away from the x-ray beam, the x-rays are intercepted on a YAG screen where the 2-keV FEL light is seen as a concentrated spot. Detecting this light by a fast photo diode we see two pulses about 8.4 ns apart with the second pulse about half the strength (Fig. 8). Besides this fast response, there is also a slow response from the YAG screen leaving an elevated level after the two pulses. Sometimes two steps up were observed without the fast response.

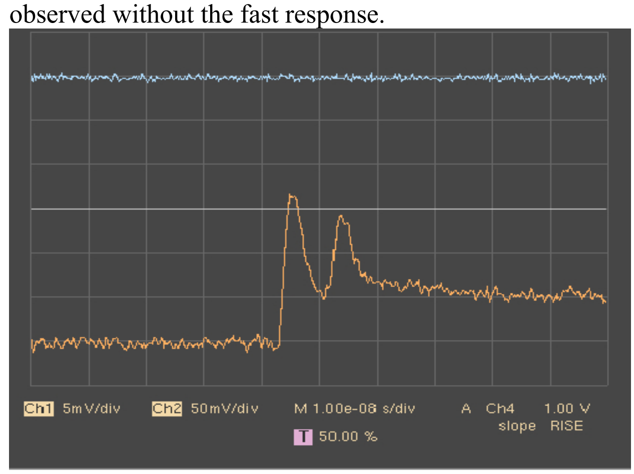

Figure 8: First evidence of two XRAY FEL laser pulses (2 keV) on a YAG screen and fast photodiode.

Experimental Instrument of SXR in Hutch 2

The Soft X-ray Research (SXR) instrument in hutch 2 at LCLS has two features which are interesting for observing the two bunches. One is its capability to have an antenna consisting more or less of a very short SMA cable and a fast scope, the other is a photon energy spectrometer. With the antenna the two bunches were easily separated in time (Fig. 9) and could be equalized in intensity by adjusting the orbit into the undulator. Steering only the first (or last) bunch flat made the other bunch lase only with about 20% intensity. Turning the existing feedback on for both bunches was close to optimum.

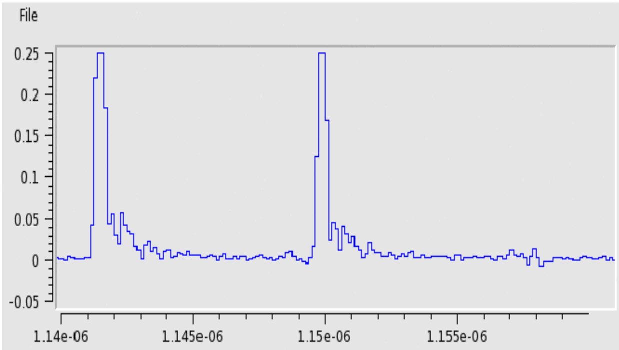

Figure 9: Two-x-ray-pulse timing resolution on the SMA cable antenna in the SXR experimental hutch. The FEL photon energies (2 keV) were the same, so the two pulses could be only separated using the timing signal.

The energy spectrometer showed only one energy peak indicating that the FEL radiation wavelengths for both pulses were equal.

Different Wavelengths for the Two Bunches

By adjusting the timing variable for filling the RF accelerating structures of L3 from about -70 ns to +200 ns the energy of the second electron bunch could be lowered by about 0.45%, which was measured by using a wire scanner in a dispersive area (Fig. 10). The second bunch (left side) might indicate some additional energy jitter.

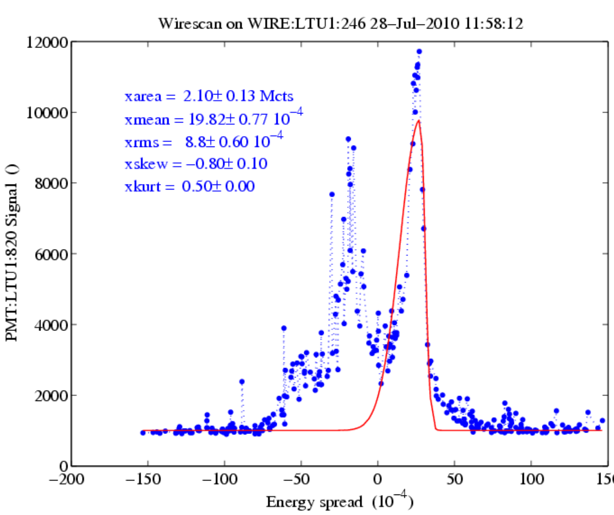

Figure 10: Here the two bunch energies were intentionally separated by 0.45% by delaying the RF fill-time into the accelerating structure, causing a 0.9% photon separation (18 eV).

The expected energy difference for the photons should be twice as much as the electrons, or 0.9 %. At 6.71 GeV electron energy the photon energy is 2.0 keV, so 0.9% is an 18-eV photon energy separation, which was observed in the SXR spectrometer (Fig. 11).

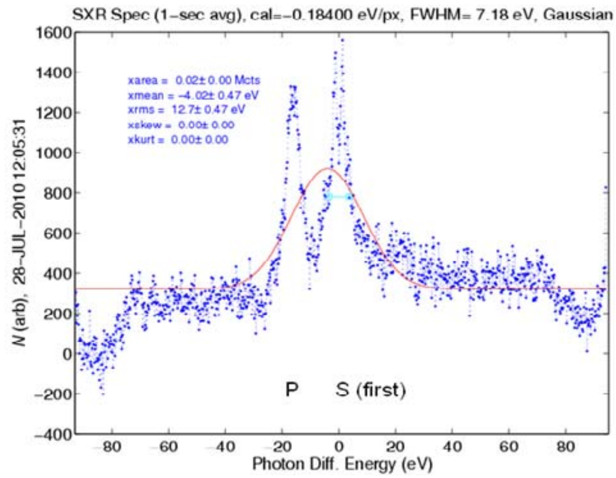

Figure 11: The photon spectrometer in the SXR experimental hutch can resolve the 18 eV energy separation. Here the first beam has the higher energy.

SUMMARY AND OUTLOOK

Multi-bunch operation in LCLS has been demonstrated experimentally, showing that each electron bunch generates a 2-keV x-ray FEL pulse with an 8.4-ns spacing. Due to an orbit difference in x of about 100 μm in the undulator the two bunches had different FEL power when the trajectory for only one of the bunches was optimized. A compromise between the two trajectories gave a better result.

Further analyzes of BPM data might give some indication of the source for the different orbits. Additional tuning tools for influencing the energy and also the chirp difference between the two bunches seem to be necessary for each linac section.

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