TWO AND MULTIPLE BUNCHES AT LCLS*

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Abstract

The LCLS X-Ray FEL at SLAC typically delivers one bunch at the time. Different schemes of two pulses have been developed: Two bucket, Twin bunch, split undulator, and fresh slice. Here we discuss a four bunch or even eight bunch setup, where the separation between the individual bunches is two RF buckets: 0.7 ns.

INTRODUCTION

After an initial test with two bunches in 2010, many photon experiments have been carried out using two bunches with separations up to 122.5 ns [1]. The setup for shorter separations (up to 50 ns) is already done almost routinely, while longer delays are trickier. We will discuss the different issues. But two bunches seem enough for some users but questions came up how to increase the number of bunches. A "simple" split and delay, and then combine system, two times in a row, seems to be the answer.

TWO BUNCHES

A long separation of two bunches has two major issues: a) the beam diagnostics start to fail, and b) the electron bunches experience different RF kicks and therefore will have different orbits in the undulator and may not lase.

Beam Diagnostics

BPMs Beam Position Monitors (BPMs) measure the trajectory along the Linac and Undulator; in dispersive regions they measure the beam energy. Feedbacks use the BPMs to keep the beam stable. For two bunches the average position is measured and the charge is a vector addition resulting typically in a lower charge than the sum of both (see Fig. 2 in [1]). This has some consequential influence where ever the charge is used. For instance the peak current measurement is "normalized" to charge and then shows twice the normal value when the "measured" charge is half. This peak current is used for a small correction of the reported photon energy derived from electron energy resulting in an overcorrection.

But this is not the only BPM problem. The four signals of the BPM are digitized at 120 MHz (some at 118 MHz) and Fig. 1 top shows the raw signals of all BPMs inside 4 times 128 bits. Two bunches with 2000 buckets separation (700 ns) barely fit into the digitizer window (128*8.33 ns = 1067 ns) since the signal is about 250 ns wide. At 200 ns and beyond the "measured" charge is typically $\sqrt{2}$ and not 2 times the single beam charge.

RF BPMs in the undulator have even another problem. While the charge is measured correctly, the "measured"

position goes to zero and only the fixed BPM offsets are displayed making them useless. It turned out a "clever" software zooms in only around the "center" of the signal, which is zero when there are two bunches separated by a lot, so offline analysis of the raw signals has to be done (Fig 1 bottom).
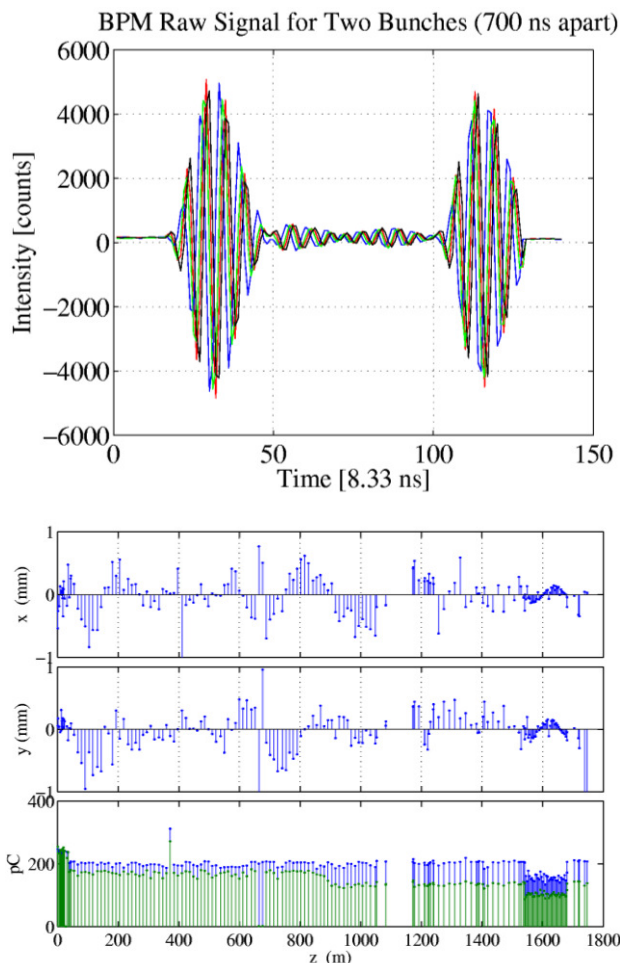

Figure 1: BPM raw signals (top) for two bunches with 700 ns separation fit barely into the 128 bit digitizer window. The bottom shows an offline BPM difference display for 400 ns separation. Excursions up to 1 mm are present and the second bunch (green) loses some of its charge at the collimators (z = 900 m).

Screens Screens are used to look at the transverse profile of the beam. To diagnose two bunches separately they must be influenced so they show up at different position.

Other Diagnostics Toroids for charge measurements and pyroelectric detectors for the raw peak current measurement are slower and therefore get mostly the sum of both beams as a result.
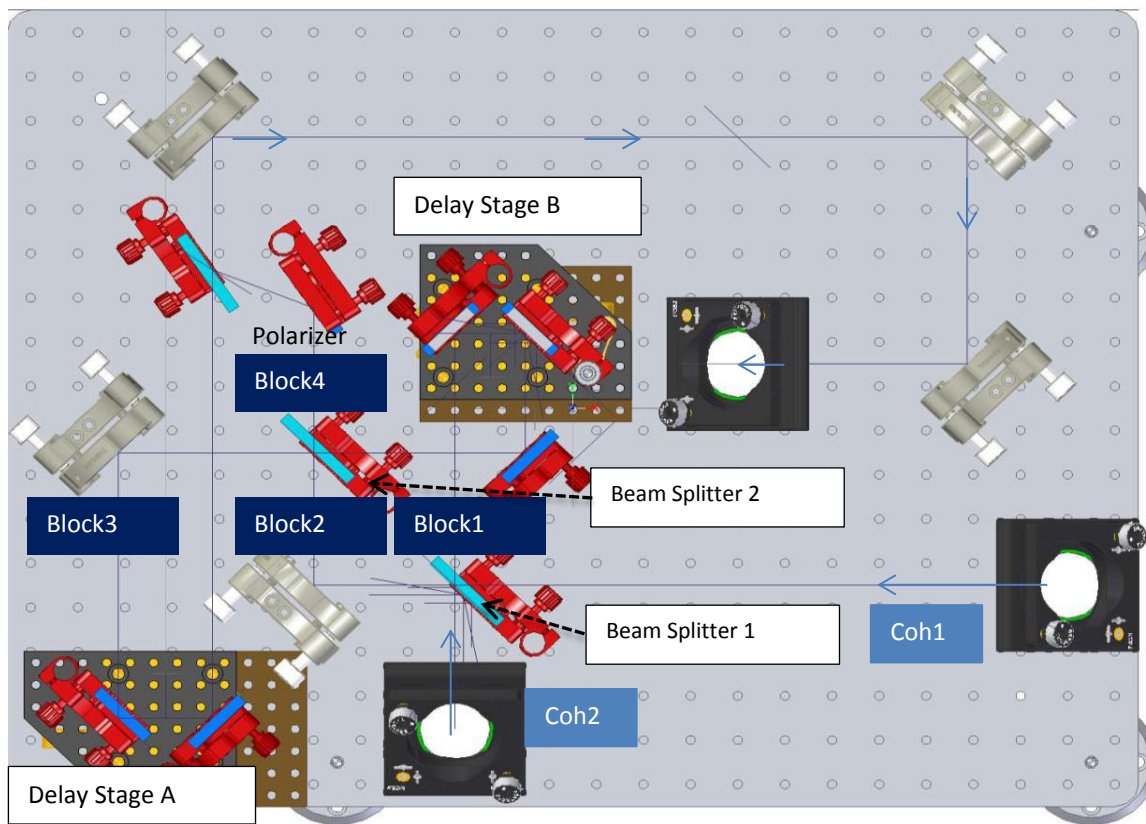
Figure 2: Multi Pulse Pulse-Stacker setup to create up to eight laser pulses for the injector gun. The two Coherent lasers (Coh1 and Coh2) enter the elevated 18x24 inch board from below. Beam splitter 1 creates two pulses of which one gets delayed by Delay Stage B (0.7 ns), they get combined and split again by beam splitter 2. The combined pulses 1 and 2 get rotated by a polarizer and go to the final combiner with a Brewster angle. The splitter pulses 3 and 4 get further delayed by Delay Stage A (1.4, 2.1 ns) before finally being combined again and send back down to the main laser table. Four beam blocks can be inserted to create four different combinations of two bunches and four combinations two blocks can be inserted to get a single pulses of the four different pulses.

RF Kicks

While wakefield kicks are the biggest source for separating two bunches for short distances (<50 ns), RF kicks seem to cause most of the transverse separation for longer delays. If the two bunches have different energies (required for some photon experiments) they can be influenced by introducing dispersion and finally overlap them in the undulator.

This is not possible for two bunches with the same end energy, they are only different in time and experience different RF kicks especially with a SLEDed RF pulse which varies over the pulse time. This could be explained by different alignments of the front and back end of the accelerator structure. Some partial alignment measurements have been done and they confirm at least the order of magnitude. Quantifying the RF kicks for different RF timing tries to localize the biggest contributors.

MULTIPLE BUNCHES

For more than two bunches we employed a system similar to the first two bunch test, where the laser beam is split and delayed and finally recombined. Doing that twice with a provision for two laser inputs it can generate up to eight pulses 2 * 4, which each of the four pulses 700 ps apart (Fig. 2). A lot of combinatorics has to be figured out (Tab. 1 and more below).

Table 1: Block Combinations and Power Measurement

Blocks in	Bunches	E_{new} [μJ]
None	1+2+3+4	153±2
1	1 + 3	76
2	2 + 4	80
3	1 + 2	77
4	3 + 4	79
1 + 3	1	40
2 + 3	2	38
1 + 4	3	39
2 + 4	4	42

The single bunches 2 and 3 were created and the delay stages set up within 150 μm (0.1 deg S-band) using BC1 (bunch compressor) energy BPM, which measures 1 mm for 1 ps delay. After that the electron beams were sent to the undulator to create x-rays. It was quickly figured out that the bunches 1 and 3 were lasing fine, while bunch 2 was too long and bunch 4 was over-compressed and required different compression settings for lasing (Fig. 3).
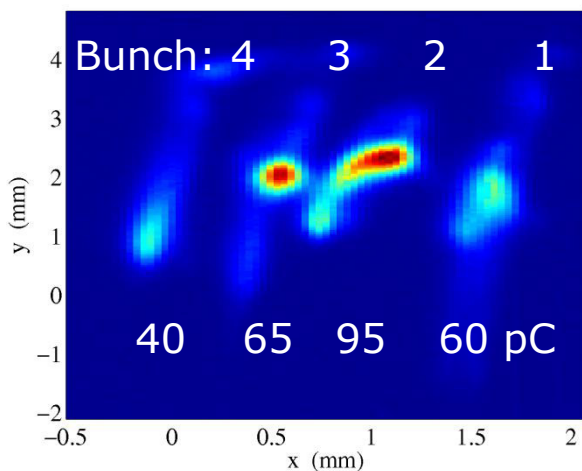

Figure 3: Four bunches visible on the OTR dump screen. The vertical is correlated with energy (700 mm dispersion), while the horizontal axis is correlated with time, bunch length are of the order of 100 fs. The visible separation is due the fact that the phase of transverse deflecting cavity (XTCAV) is changing enough during 700 ps.

Different Bunch Charges

It was quickly figured out that the bunch charges were different as indicated in Fig. 3. The root cause was unknown and it is still unknown why different charges, actually quite low charges, cause different compressions.

Beam Splitters   The 50/50% beam splitters turned out to be more like T/R = 42/57% for transmission and reflection. For Coherent 1, which was used for the Fig. 3 measurements, Bunch 2 has three reflections (RRR) and is therefore favoured. Bunch 1 has TTR, Bunch 3 has TRT, and Bunch 4 has RTT. Using Coherent 2 the reflection-transmission patterns for Bunches 1 to 4 are RTR, TRR, RRT, and TTT disfavouring the last bunch. Most of the measured beam charges can be understood with the carefully measured reflection and transmission numbers of the lasers (Fig. 4). Why Bunch 4 is so much worse with Coh 1 is not totally explained.

Since the beam splitters were not good enough, four better ones were ordered and carefully measured in April 2018. Using two of the four splitters and orienting them is such a way that the reflective side is on the front or back side gives all together 48 different combinations. Combination "B4B1" was chosen so the intensity is within 1%

for Coh 2, while for Coh 1 only Bunch 2 and 4 will be 10% low, much better than the observed +60 and -30% with the initial 42/57% beam splitters. The last column in Tab. 1 is the new measured result for Coherent 1.

Polarization   For measuring the laser power a small percentage of the laser light is coupled out onto a power meter. This setup is typically very sensitive to the polarization of the beam. The Multi Pulse Pulse-Stacker setup creates 4 pulses 1+2 are S-polarized while 3+4 are P-polarized. So the "measured" relative intensities can be different for the differently polarized pulses and have to be compared with the actually generated bunch charges on 9/5 and 10/17 (Fig. 4).
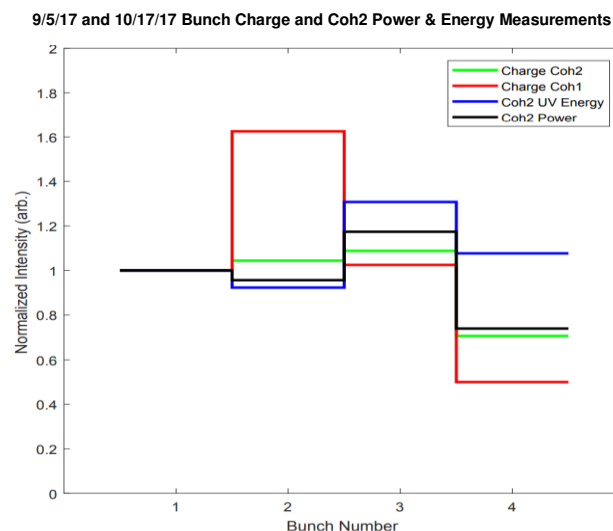

Figure 4: Initial measured intensities for the two lasers (Coh1 and Coh 2) and for the four bunch charges. The laser power meter agrees with the charge measurements better than the UV energy measurement. The laser measurements are often polarization sensitive.

CONCLUSION

Two bunch set ups with short delay (50 ns) are nearly standard, while longer delays and special requests like transverse offsets and different energies at short delays are challenging. Multiple bunches of four or eight pulses are in the early exploration stage, but seem to soon be possible since the different charge issue has be identified and resolved.

REFERENCES

[1] F.-J. Decker et al., "Recent Developments and Plans for Two Bunch Operation with up to 1 μs Separation at LCLS", FEL2017, Santa Fe, USA, TUP023 and SLAC-PUB-17128 (full version).