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RECENT DEVELOPMENTS AND PLANS FOR TWO BUNCH OPERATION WITH UP TO 1 μs SEPARATION AT LCLS*

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Abstract

Two electron bunches with a separation of up to 1 μs at the Linac Coherent Light Source (LCLS) is important for LCLS-II developments. Two lasing bunches with up to 220 ns separation have been demonstrated. Many issues have to be solved to get that separation increased by a factor of 5. The typical design and setup for one single bunch has to be redressed for many devices. RF pulse widths have to be widened, BPM diagnostics can see only one bunch or a vector average, feedbacks have to be doubled up, the main Linac RF likely needs to be un-SLEDed, and special considerations have to be done for the Gun and L1X RF.

INTRODUCTION

Since the first two bunch test in 2010 [1], many photon experiments have been performed in recent years (Table 1), some already published [2, 3]. They can be categorized into pump-probe and probe-probe experiments. The first typically excites the sample and then probes it, using different photon energies for the two bunches, the first above and the second below an absorbing K-edge. Probe-probe experiments typically have identical bunches only differentiated by arrival time. They study the natural time evolution of the sample without disturbing it with the first pulse.

Table 1: Two Bunch Experiments

P.I.	Experiment	Date	Energy
C. Stan,	water droplets,	May 2015,	MEC, 8.9 keV
LI41:	diff.: *t, E, I,* ***y***;	same *y'* (*x, x'*),	25 ns
M. Seaberg,	skyrmions,	May 2016,	SXR, 1.2 keV
LM23:	diff.: *t* only	mono	0.7, 4.6, 23, 49 ns
P. Fuoss,	probe-probe,	Jun 2016,	XCS, 8.2 keV
LL25:	only diff.: *t*	mono,	4.6, 8.8, 24 ns
I. Schlichting,	proteins,	Jul 2016,	CXI, 7.1 keV
LM18:	diff.: *t,* ***E****, y*;	same *y', I,* (*x, x'*),	8.4 ns
Y. Feng,	GDET >122 ns,	Oct 2016,	XCS, 7.0 keV
X119:	diff.: *t*, high *I*;	same *x, y*; ~ *E*,	122 ns
J. Turner,	skyrmions,	Jun 2017,	SXR, 1.2 keV
LQ76:	diff.: many *t*	mono	0.35-8.4, 23, 49 ns

SHORTER BUNCH SEPARATION

Up to about 25 ns bunch separation is already "standard" operating procedure. This still needs significant attention as different experiments require special setups. A typical setup for probe-probe experiments is described followed by a description of pump-probe setups, wherein the first bunch typically has a higher photon energy above a K-edge and is absorbed while the lower energy second bunch goes through and its scattering pattern is detected.

Same bunch performance, just delayed

To make two bunches with different time separation, two light pulses from independent lasers are combined on the cathode, typically in S-band bucket intervals (0.35 ns). When they overlap in time an interference pattern is generated on the gun cathode (Fig. 1); temporal overlap reduces the total charge emitted from cathode (Fig. 2, *t* = 0 ns). The measured beating is an artefact of the BPM processing frequency (1/140 MHz = 7 ns) [4].

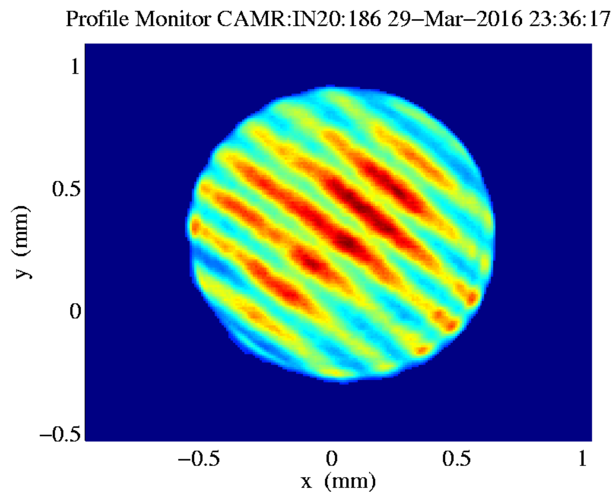

Figure 1: Virtual Cathode Camera showing a 1.2 mm spot with strong interference pattern of temporally overlapped laser pulses.

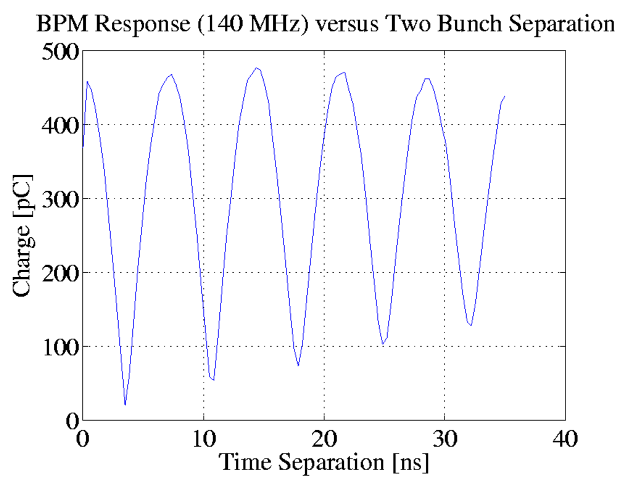

Figure 2: BPM charge response for different bunch separations. The beating vector sum of both bunches shows that at certain separations (3.5 + *n* * 7 ns), the BPM signals are not very useful.

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RF Setup The RF timing has to be set up so that the two bunches have a flat energy gain versus time, this is especially problematic for long separations (> 100 ns).

Wakefield Kicks It was observed that at certain bunch separations the second bunch did not lase (Fig. 3, top). The rms beam trajectory in the undulator has to be less than 40 µm to produce significant FEL energy.

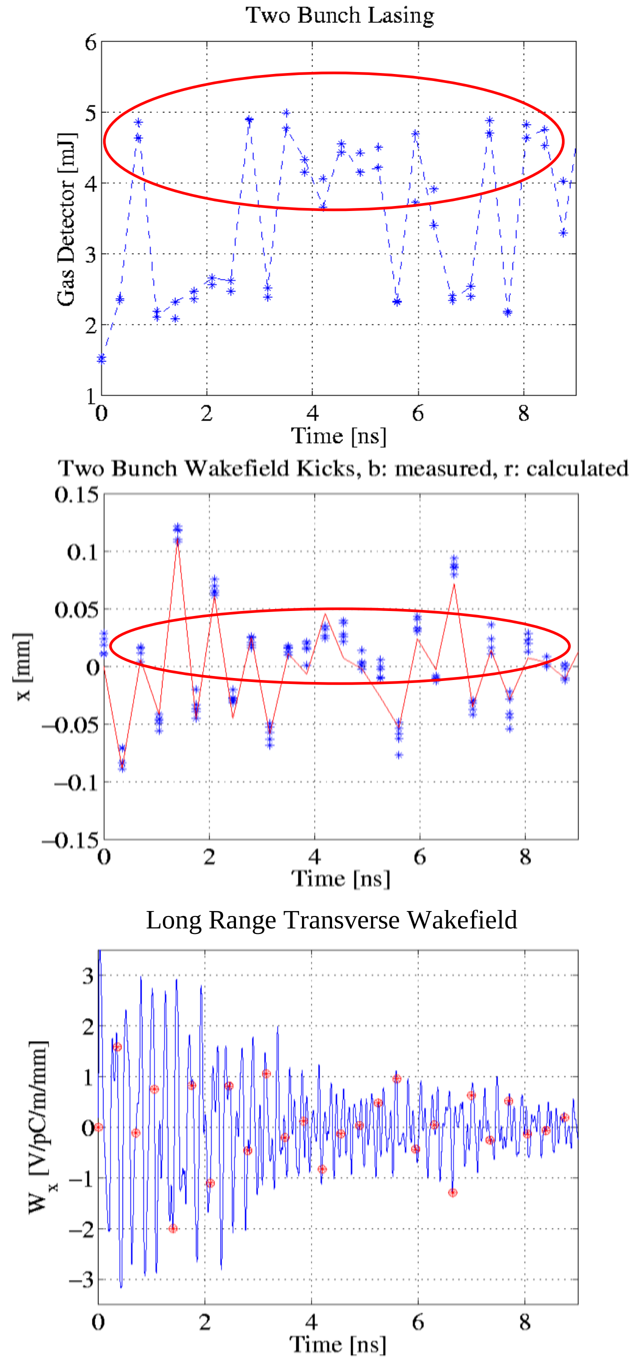

Figure 3: Timing scan of the second bunch. At certain bunch separations the second bunch gets kicked by wakefields and has therefore enough transverse displacement in the undulator (middle) so that it does not produce any FEL radiation detected by the gas detector (top). The transverse wakefield (bottom) explains the behaviour.

A two-mode wakefield calculation predicted a too simplistic picture of the transverse kick which slowly increases up to 2.5 ns, then decoheres around 5 ns, and recoheres afterwards [5]. The observed behaviour was consistent with the 5 ns decoherence where both bunches typically lase. But the kicks are more complicated. With a two-bucket separation both bunches always lase since the second bunch does not get kicked (Fig. 3 middle). A new time domain wakefield calculation (Fig. 3 bottom) revealed that modes 3, 6 and 10 are important and produce the observed kicks. The peak wakefield at 1.4 ns is: $W_x = -2$V/(pC-m-mm) for an S-band structure. The X-band cavity, L1X, has 16 times larger transverse wakefields, which decohere faster; the only significant effects are at one and two bucket separation ($W_x = +38$ and -16 V/(pC-m-mm)).

X-Ray Diagnostics

It was understood early on that it is important that the intensity of each of the two bunches is known separately.

Gas Detector The gas detector raw signal is analysed and fitted for the two bunch intensities, which then can be strip-charted so operators can equalize them (Fig. 4).

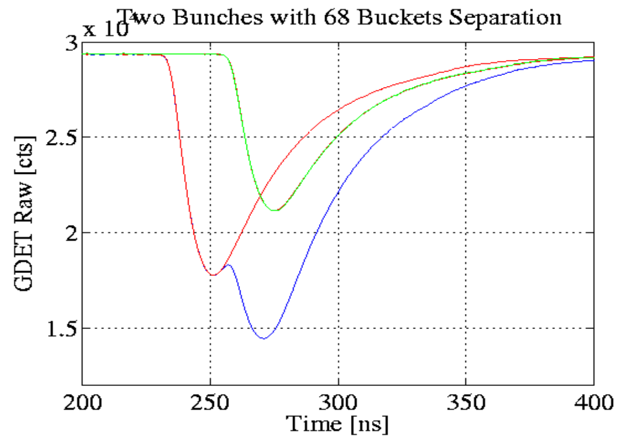

Figure 4: Gas Detector raw waveform for a 23.8 ns (68 buckets) delay. From the blue two-bunch waveform, a single-bunch-only amplitude-fitted waveform (red) is subtracted (black). A delayed single-bunch-only waveform with a different amplitude fit is overlaid in green.

At lower soft x-ray energies or shorter delays, this method is difficult since the signals are too slow and pile-up. It also does not work when the photons go through a monochromator making their measured intensities sensitive to different photon energies.

Fast Diode, Microchannel Plate A fast photodiode at high photon energies or a microchannel plate at low photon energies can resolve the separate bunch intensities down to one bucket (0.35 ns) separation. A fast code was written to deal with the issues of timing jitter, amplitude noise, and ringing of the raw signals. Figure 5 shows that even a fast signal with significant ringing can see the two bunches. In this case, the second bunch had on average about 50% more intensity.

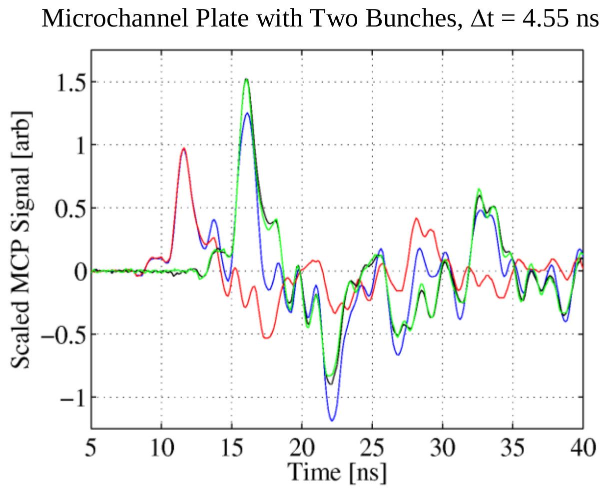

Figure 5: MCP signal: Two bunches (blue), with first bunch overlaid (red), or subtracted (black). With the single bunch signal delayed and scaled (green) it nearly covers the black signal.

Different Bunch Parameters

For pump-probe experiments the two bunches might be quite different in intensity, photon energy, and transverse offset at the target.

Intensity The two bunch intensities might need to be set up so that the first just excites a change, while a stronger probe tries to get the best signal to noise response. This is typically set up with the laser intensity on the gun cathode, or can be influenced by mistuning the first bunch.

Energy Different photon energies can be set up by sitting on the rising or falling slope of the SLED RF pulse (Fig. 7). This works sufficiently when the bunch separation is 8.4 ns or greater. For shorter separations the two bunches have to start at different times (around 10 ps) at the gun, which then causes them to have different energies at Bunch Compressor 1 (BC1) and beyond. This makes the standard horn-cutting at BC1 not possible. A different injector optimization is required. This second mode is typical for twin-bunches with up to 100 fs separation [6] but has not yet been tried for ns-separations.

Transverse Offset Different transverse positions at the target of the experiment are the most difficult requirement. This can be done in two different ways. Since the electron bunches have different energies a vertical dispersion in the undulator will separate them and therefore the photon beams. The maximum separation should be at the source point which gets imaged onto the target. If it is not perfectly at that location, the two bunches will be more separated on the guiding and focussing mirrors and might be differently collimated. Since the dispersion will also separate the different energies inside a bunch, the following setup is preferred. The two bunches get different kicks by TCAV3 (transverse deflecting cavity) after BC2. For this method to work best the betatron phase advance has to be adjusted so it is $90° + n{\cdot}180°$ from the source point. Both methods will result in a much lower photon intensity since the two bunches will make betatron oscillation inside the undulator around the preferred middle (Fig. 6).

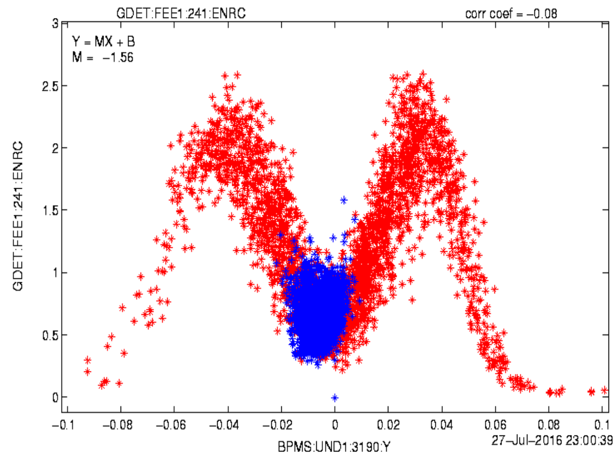

Figure 6: Gas detector signal for two bunches. The two bunches are about 60 µm apart at the end of the undulator (blue) and produce together about 0.6 mJ. They are about ±35 µm off the peak of 2.0 mJ. The red distribution shows the FEL intensity under a very jittery TCAV3 condition where the centroid of both bunches varies from −100 µm to +100 µm. When the centroid is at −40 µm or +30 µm one or the other bunch is in the middle of the undulator and produces equally 2.0 mJ.

LONGER BUNCH SEPARATION

For longer bunch separation above about 100 ns, additional effects need to be considered. The RF pulse is not flat for most RF stations which are SLEDed (SLAC Linac Energy Doubler) wherein a 4 µs pulse gets compressed into 825 ns, which corresponds to the accelerator fill-time. Figure 7 shows the effective energy gain for Linac 3 (L3, the Linac after BC2). For up to 1 µs bunch separation two choices can be made.

SLEDed Mode

The first is to run with the typical SLED pulse mode and run with the two bunches ±500 ns off the peak. This will reduce the L3 energy gain from 10 to 7 GeV, or scaled for the whole Linac the maximum photon energy will reduce from 13 to about 6 keV. In this configuration the two bunches will experience different RF kicks since for the first bunch the accelerator structure is barely half filled with RF, while for the second pulse the main RF pulse is already gone and only some left in the second half of the structure. This can be avoided by running unSLEDed. This reduces the energy by a factor of about 1.65. The maximum photon energy will be about 4.5 keV ($= 0.36 \cdot 13$ keV) under perfect conditions.

Up to 210 ns separation in the SLEDed mode lasing was achieved with both bunches lasing (Fig. 8).

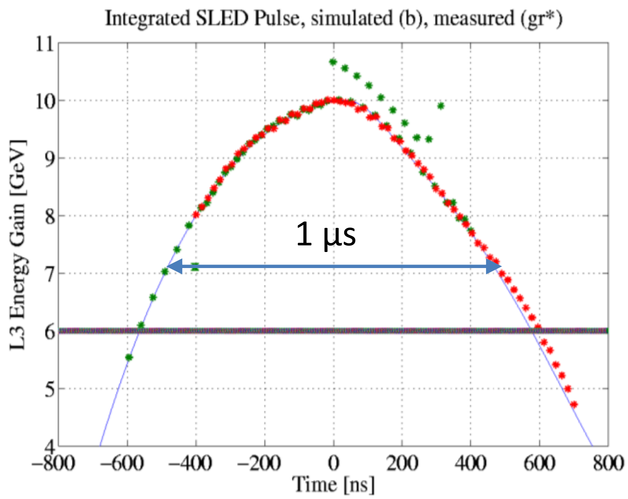

Figure 7: Energy gain in L3 due to the SLED pulse. Green and red are scaled measurements, while blue is the simulated curve. The flat line at 6 GeV indicates the energy for running unSLEDed.

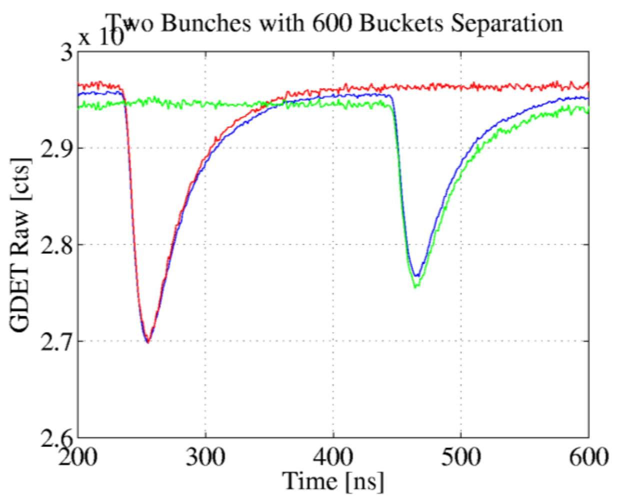

Figure 8: Gas Detector raw waveform for 600 buckets delay (210 ns). The two bunches can easily be separated (red and green out of the combined blue).

UnSLEDed Mode

It seemed difficult to achieve longer separations with the SLEDed mode above 220 ns. Since we thought it was due to RF kicks, we decided to run unSLEDed. As it turned out this was also problematic until we discovered that one trigger (of two) for the sub-boosters were not adjusted with the "PSK" timing knob. After fixing this we achieved two bunches with a 2000 buckets (700 ns) separation having the same energy all the way through the undulator. (There was not any beam time left for tuning lasing.)

Special RF Setups

Besides the SLEDed, or unSLEDed setups there are a few RF stations which require special setups.

Special RF Stations The injector stations (L0A, L0B, L1S) run typically unSLEDed. Their pulse lengths were widened to 2 µs (minimum: 1 µs + 825 ns for fill time) and the timing is set so that the first bunch is close to the time when the structure is just filled and the flat part starts. The high voltage pulse of the modulator has to be reasonable flat over 2 µs.

L1X The X-band linearizer (L1X) needed a special treatment. Its fill-time is only 100 ns and its RF pulse was raised to 300 ns (from 200 ns) to have room for short delays. For separations beyond 200 ns a wider pulse would be necessary, but since the RF average power would be too high, a different solution was chosen. The RF is double pulsed with two 150 ns pulses, where the second pulse can be adjusted in amplitude and phase. Initially the phase for the second bunch was adjusted so that it went through the middle of BC1. It turned out the bunch phase was about -40° off (–220° instead of –160°) and the bunch was not being compressed (no charge reduction due to the horn-cutting collimators). Because the high voltage pulse of L1X is not flat but has a more rounded top, the phase of the second RF pulse was adjusted by +65° to get the result of Fig. 9.

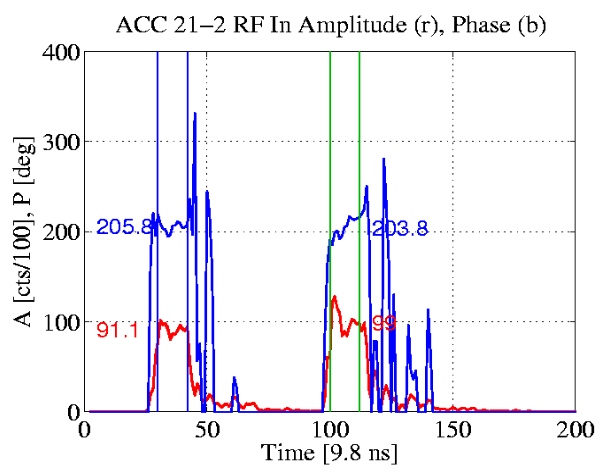

Figure 9: L1X (aka 21-2) with double RF pulsing 700 ns apart (for 2000 buckets separation). The phase measurement in blue is between the two vertical lines (green for the second pulse). Since the high voltage is already falling off, there is some phase change over this second pulse.

Gun The gun RF setup is special on many fronts. First it is a standing wave setup, which reaches its highest field for a flat RF pulse exponentially. To get a flat RF amplitude in the 1.6 cell structure for some time period after the initial rise, the incoming RF pulse has to be lowered to a value which is right for the steady state condition. But the real world is more complicated. Just after the time for the first bunch (1.4 µs) the initial RF reflection starts to be seen reaching the gun. This has to be counteracted by a much lower RF pulse with a certain phase offset. After that we got a reasonable flat pulse over 500 ns. But the second part changes daily by about ±2% probably due to temperature changes of the waveguide for the reflected part.

XTCAV The transverse deflecting cavity XTCAV after the undulator has to run unSLEDed too. The phase of the waveform was adjusted so both bunches were close on the screen.

RF Kicks

The transverse RF kicks can be measured by taking the difference trajectory between RF off and RF on. The measurements for all RF stations revealed that the klystron station 21-3 right after BC1 caused a significant kick in the horizontal (x) (Fig. 10).

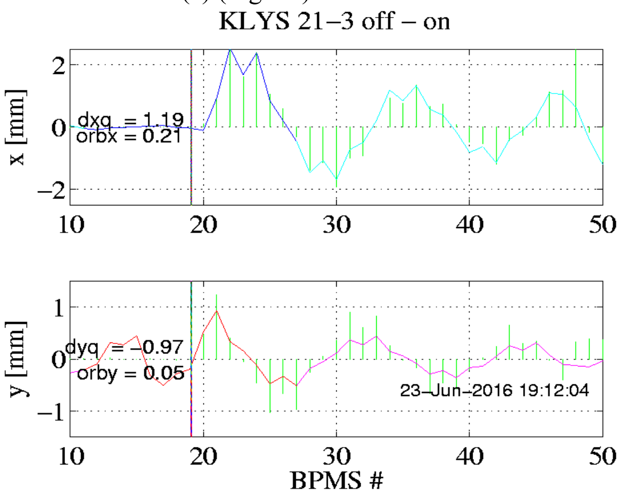

Figure 10: Difference trajectory between RF off and on for Klystron 21-3.

A ~mm accelerator structure misalignment was confirmed by looking at the wakefield kicked orbit. Instead of looking at one BPM (Beam Position Monitor) as in Fig. 3 (middle), the difference orbit of the two extremes, 4-bucket and 1-bucket separation, is plotted along the Linac (Fig. 11). The main kick in x starts at BPM number 20, which is the same location like the RF kick. To quantify the misalignment a betatron oscillation was fitted with kicks at different locations. At three locations of BPM # 25, 30, and 35 a 2 mm offset each would "explain" the strange oscillation, but only a 1 mm offset was necessary to get the big initial kick at BPM # 20. The induced non-linear oscillation looks as if caused by an offset and is probably increased by the addition of the wakefield tail of the bunch being kicked. After making a local 1 mm orbit bump, the wakefield and RF kick were reduced by an order of magnitude.

MULTIPLE BUNCHES

After the successful run of several photon experiments with two bunches, people are interested in multiple bunches. We are currently setting up a split and delay and combine system for the injector lasers to get two times four bunches, each of the four separated by two buckets (0.7 ns, Fig. 12, [7]).

CONCLUSION

Two bunches with many ns separation has opened up many different scientific fields.

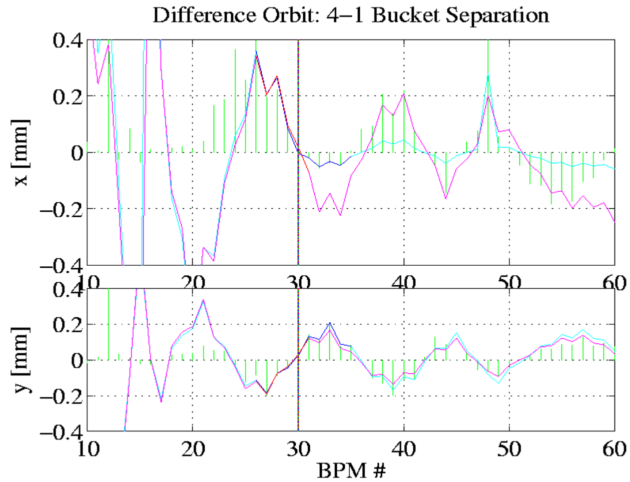

Figure 11: Difference orbit of two-bunch orbits with 4 and 1 bucket separation, indicating the location of the strongest wakefield kicks.

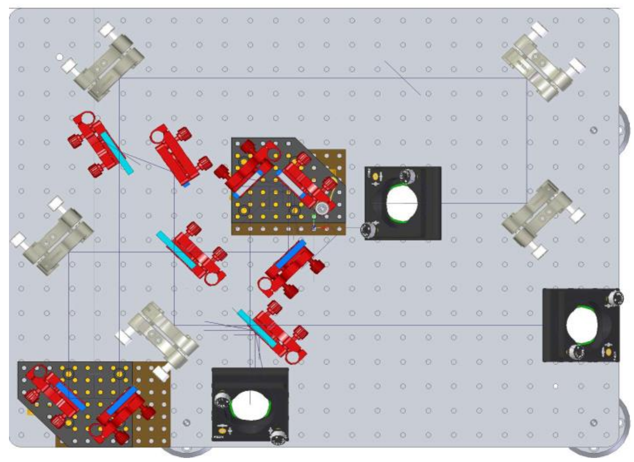

Figure 12: Laser stacker setup to produce 2x4 bunches.

ACKNOWLEDGMENT

We would like to thank the laser group for all the special laser setups to make two and multi bunch scenarios possible.

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