

LCLS-II Technical Note

Using an Energy-Chirped Bunch to Provide Time-Resolved Measurements

LCLS-II TN-18-01

4/11/2018

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1 Introduction

The off-axis diagnostic line design in the LCLS-II injector includes one horizontal (TCAV_x) and one vertical (TCAV_y) S-band RF-deflector to allow time-resolved measurements of the 100-MeV electron bunch in the beam spectrometer at the end of the diagnostic line. Figure 1 shows the injector line from gun to spectrometer screen (OTRDG04), where a vertical kicker is fired at low rate and low average power ($f \leq 120$ Hz, $\langle P \rangle \leq 5$ W) to steal pulses into the diagnostic line in order to correct and characterize the electron beam almost continuously. These diagnostics (OTR screens and wire-scanners) are used to measure bunch length, temporal profile, transverse emittance in both planes, and relative energy spread using the spectrometer [1].

In order to enhance these diagnostics, the beamline design includes two S-band RF deflectors, as shown in Figure 1, to also allow time-resolved measurements of emittance, and time-resolved measurements of the relative energy spread. Unfortunately, these two RF-deflectors are not yet included in the project baseline cost, and there is some risk that they will not be available during initial linac commissioning. For this reason, we present here an alternate approach, allowing a subset of time-resolved measurements without any RF-deflectors, where instead we apply a large energy chirp established by running the 8th RF cavity of the first cryomodule (CM01) at its zero-crossing phase and with its nominal gradient of 16 MV/m. This imparts an energy-time correlation along the beam so that the large vertical dispersion of the spectrometer streaks this chirped beam vertically on the OTRDG04 screen (indicated in Figure 1). The simulations that follow show that, with no RF-deflectors installed, the absolute bunch length and its detailed temporal profile can still be measured with sub-picosecond resolution, the horizontal time-sliced emittance might still be measured (with some optics adjustments), while the vertical time-sliced emittance cannot be measured. Finally, the small time-sliced energy spread of the heater (~ 5 keV rms) is difficult to resolve, and is not improved by applying the energy chirp described here. These conclusions are summarized in Table 1 at the end of the note.

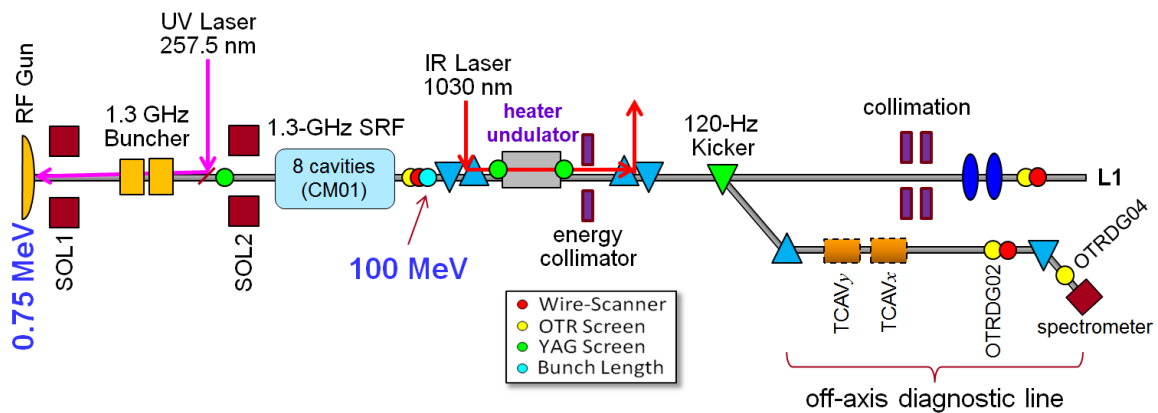


Figure 1: The beamline layout from RF gun to off-axis diagnostic line, terminating in the spectrometer OTR screen (OTRDG04). There are 8 RF cavities in the first cryomodule (CM01) for a 100-MeV beam.

2 Simulations

Absolute Bunch Length Measurement

The 100-MeV, 1-mm long (rms) bunch exiting the CM01 cryomodule nominally has no significant linear energy chirp, as shown in Figure 2 (upper left), where only a small quadratic energy- z correlation exists. This results from the near-crest RF cavity phasing.

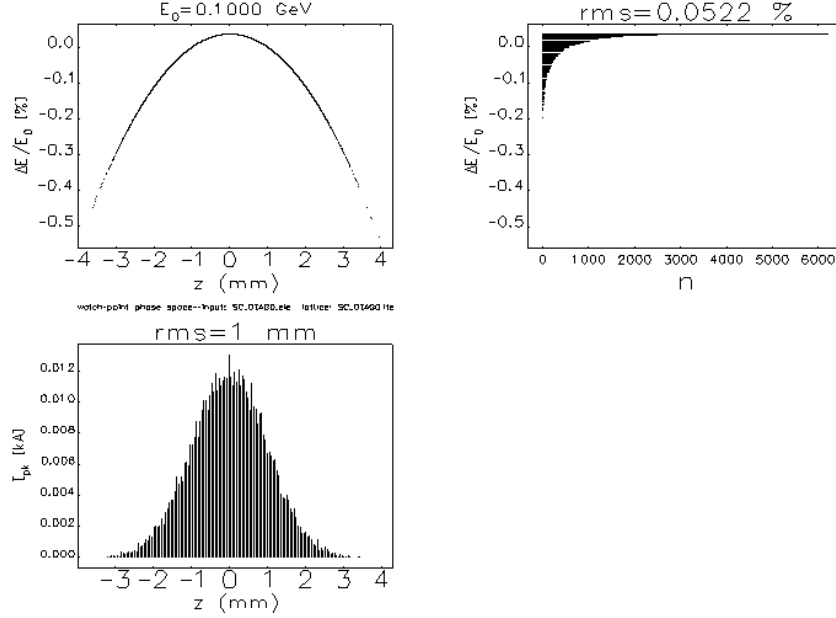


Figure 2: Longitudinal phase space and projected distributions of the nominal 100-MeV beam exiting the CM01 cryomodule. With the nominal CM01 RF phase settings near accelerating crest, there is no linear energy chirp on the bunch, except for the small “quadratic chirp” seen here (upper left).

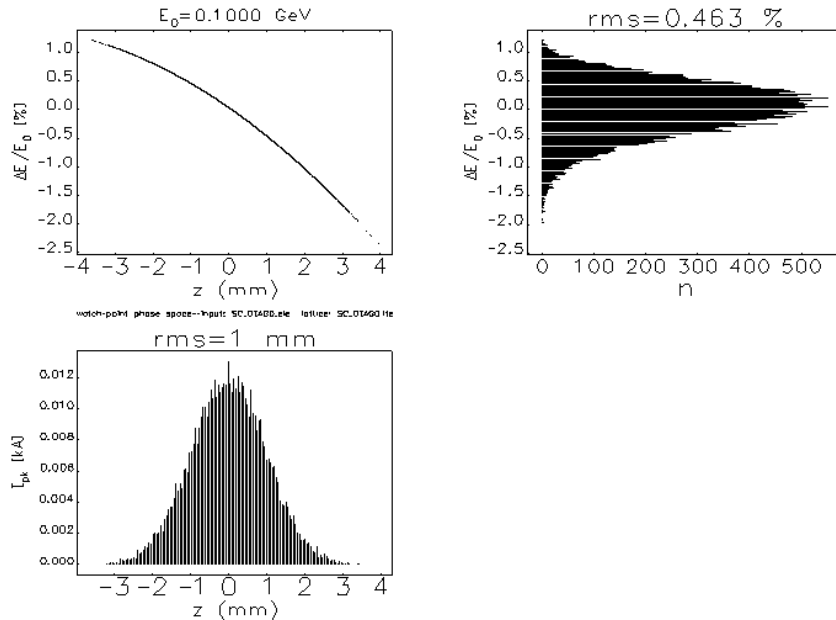


Figure 3: Longitudinal phase space of the 100-MeV beam exiting the CM01 cryomodule, but now the 8th cavity is ON (16 MV/m) and set at zero-crossing phase, generating a large and nearly linear energy chirp. The other possible zero-crossing (flipped by 180 deg) is not shown here, but has the opposite sign chirp.

For this simulation, we now switch ON the 8th cavity of CM01 to 16 MV/m, and phase the RF to one of the two zero-crossing phases, generating a large energy chirp, as seen in Figure 3 (upper left). The energy- z correlation is nearly linear and has a large projected rms value of 0.46% (upper-right plot). This means that particles at the bunch head ($z < 0$) see acceleration, while particles at the bunch tail ($z > 0$) see deceleration. With the large vertical dispersion (540 mm) at the spectrometer screen (OTRDG04), the beam will be seen to streak vertically across the screen, similar to an RF deflector (see Figure 4).

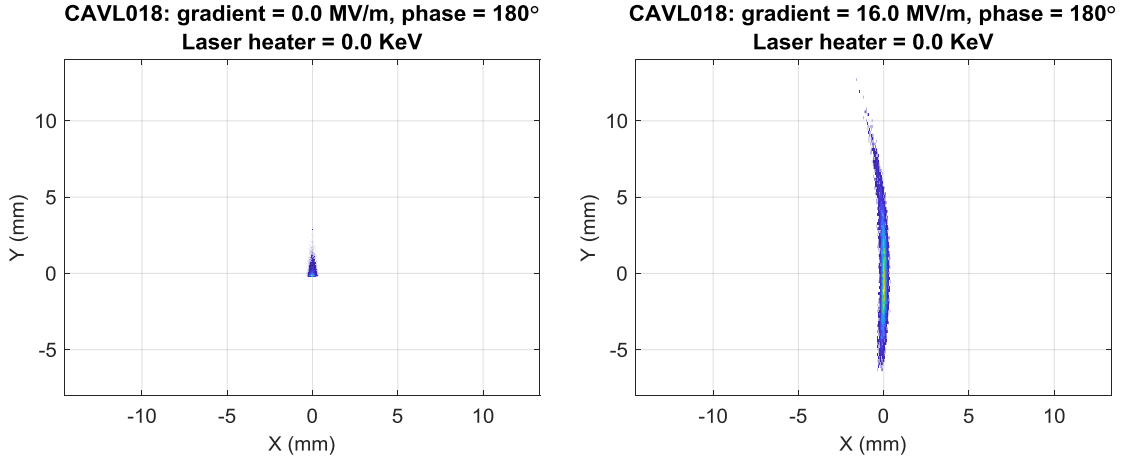


Figure 4: Simulated screen image on OTRDG04 with energy chirp OFF (left) and chirp ON (right).

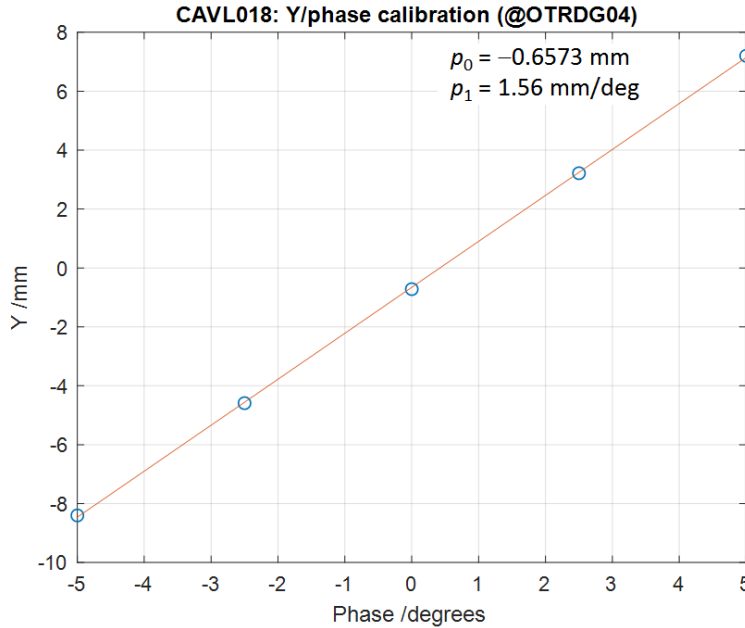


Figure 5: Calibration scan of the cavity-8 RF phase ± 5 deg around the zero-crossing. The fitted linear slope is 1.56 mm/deg which is used to convert the screen scale (mm) to L-band degrees (or picoseconds).

This vertically streaked image is a direct replication of the bunch length and can be calibrated in terms of RF degrees by applying a calibration scan, as shown in Figure 5. By scanning the RF phase a few degrees around the zero-crossing phase, and recording the vertical centroid position of the beam on the screen for each phase setting, a linear fit

produces the first-order coefficient ($p_1 = 1.56$ mm/deg) that can be used to scale the screen dimensions (mm) into degrees of L-band (1.3 GHz or 2.1296 ps/deg). Figure 6 shows the simulation of a ‘measured’ temporal profile with the vertical axis calibrated in picoseconds. The “true” simulated bunch length is 1.00 mm rms (3.34 ps), while the screen-generated estimate shown in Figure 6 is 0.99 mm (3.31 ps). In addition, any significant temporal modulation at the sub-ps-level should be quite clear using this energy-chirp technique.

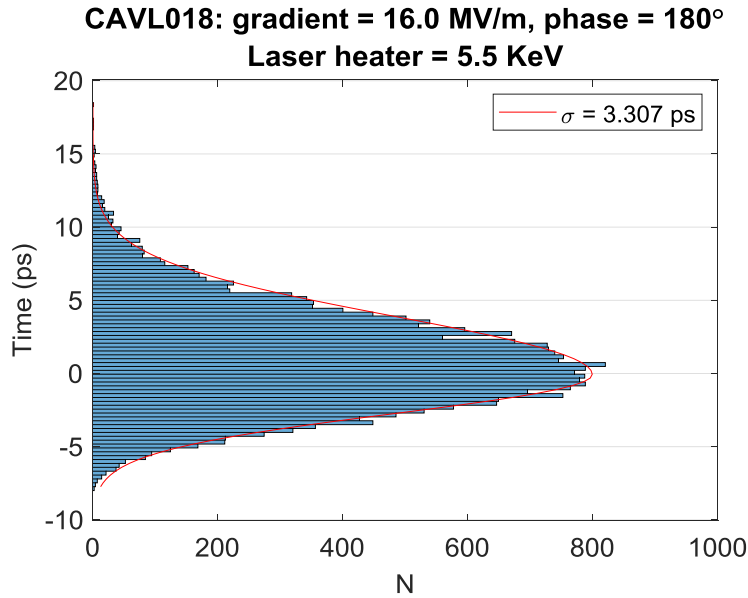


Figure 6: Temporal profile of the bunch plotted by scaling the vertical axis of OTR screen image into degrees (or picoseconds, as shown above). Note that the “true” simulated bunch length is 1.00 mm rms (3.34 ps), while the screen-generated estimate is 0.99 mm (3.31 ps), showing good accuracy.

From this simulation it appears that the absolute rms bunch length can still be measured accurately without an RF deflector. With the very large streak generated on the screen, the temporal resolution should also be quite good. Using Figure 4 (left plot), the temporal resolution on this screen with the 8th cavity at 16 MV/m is ~0.3 ps rms.

Time-Sliced Emittance Measurements

In addition to measuring the absolute bunch length, an RF deflector is also used to measure the time-sliced transverse emittance in at least one plane, depending on its installation orientation. For the LCLS-II diagnostic line, two RF deflectors are envisioned (see Figure 1), one that deflects horizontally (TCAV_x) and another that deflects vertically (TCAV_y), allowing both horizontal and vertical time-sliced emittance measurements. Since a strong energy chirp on the spectrometer can only streak the beam vertically (the bend magnet orientation), the time-sliced emittance using an energy chirp can only be measured horizontally. In addition, a high-quality emittance measurement using a quad-scan method requires that the scan ‘pass-through’ a beam waist during the measurement. This waist requirement is already arranged in the optics design for the RF

deflector measurements using OTRDG02 (see Figure 1), but has not been studied with beam on OTRDG04. Without delving into these optical details, it is expected that a beam waist can likely be arranged and the horizontal time-sliced emittance measurements in OTRDG04 should be possible using the energy chirp method. Vertical time-sliced emittance measurements are, however, not possible without the TCAVx.

Time-Sliced Energy Spread Measurements

In addition to measuring bunch length, and time-sliced emittance, an RF deflector is also used to measure the small time-sliced relative energy spread in the beam, which is an important feature used to set the laser-heater power properly. Unfortunately, using just an energy chirp, the spectrometer bend only streaks vertically, which is the same direction as the vertical dispersion, so there is no way to resolve the time-sliced energy spread without TCAVx.

It is, however, possible to estimate the time-sliced energy spread without the TCAVx or the energy chirp. The approach is to measure, with no chirp, the vertical beam profile on OTRDG04, taking the FWHM divided by the known vertical dispersion at the screen, and comparing laser-heater ON to heater OFF profile measurements, as shown in Figure 7.

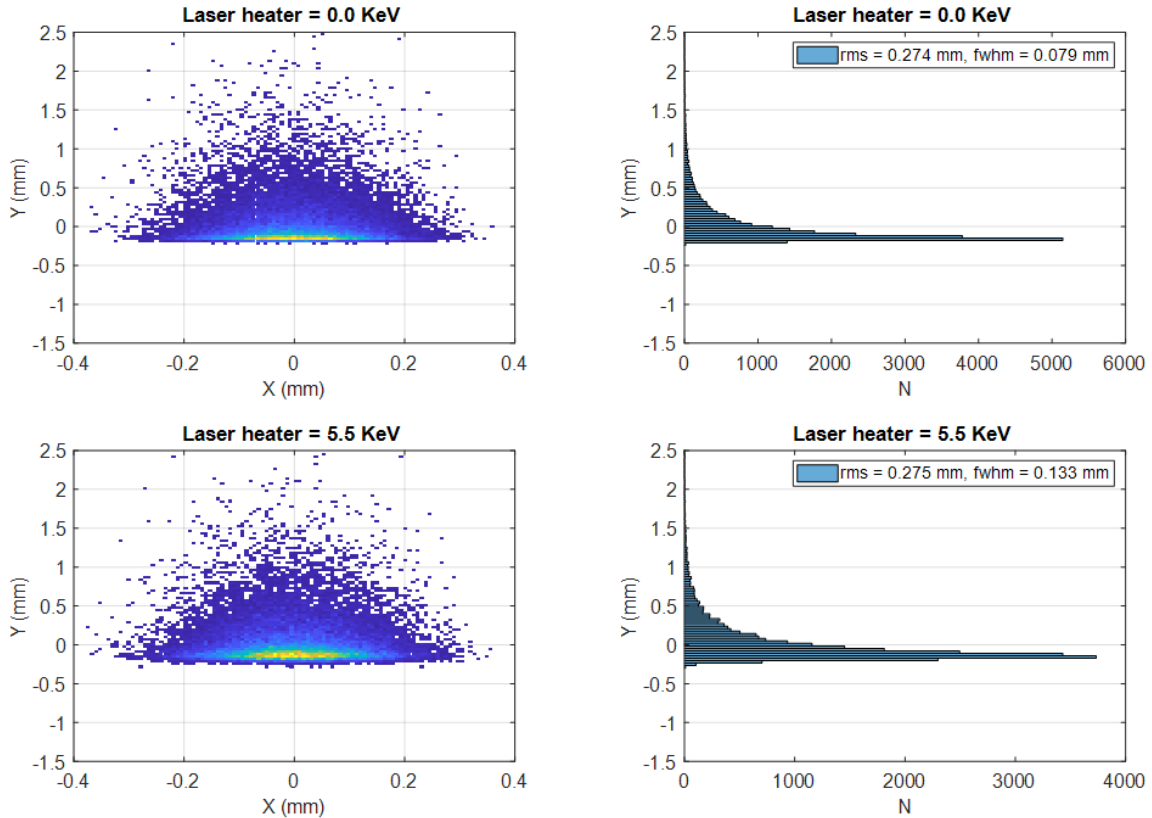


Figure 7: The time-sliced energy spread, with no TCAV and no energy chirp, is estimated by comparing the vertical beam profile on OTRDG04 with laser-heater OFF (upper 2 plots), and again with laser-heater ON (lower 2 plots). The vertical FWHM with heater OFF (top-right) is 0.079 mm, while the FWHM with heater ON (bottom-right) is 0.133 mm (with a 5.5-keV rms heater-induced slice energy spread).

3 Conclusions

As described in detail above, the nominal LCLS-II design includes two RF deflectors in the off-axis diagnostic line, which provide measurements of the absolute bunch length, the temporal bunch profile, both x and y time-resolved emittances, and the time-resolved relative energy spread. Unfortunately, these two RF-deflectors are not yet included in the project baseline cost, so an alternate method may be needed. These results show that the energy chirp method (without RF deflectors) has some very useful measurement capabilities and also some limitations. These conclusions are summarized in Table 1 below.

Table 1: Measurement limitations for the energy-chirp method as compared to both x & y RF deflectors.

Measurement	RF Deflectors	Energy Chirp	Notes
Absolute Bunch Length	OK	OK	Resolution: 0.3 ps
Temporal Bunch Profile	OK	OK	Resolution: 0.3 ps
Hor. Time-Sliced Emittance	OK	Likely OK	Needs optics waist
Ver. Time-Sliced Emittance	OK	No	Not possible
Time-Sliced Rel. Energy Spread	OK	No	Estimate possible



References

- [1] LCLS-II PRD, “Post-LH Diagnostic Beamline Requirements”, LCLSII-2.4-PR-0068.