FAST, ABSOLUTE BUNCH LENGTH MEASUREMENTS IN A LINAC USING AN IMPROVED RF-PHASING METHOD

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Abstract

There is great demand for a fast, accurate method to measure the absolute bunch length of an electron beam in a linac. Many ideas are available, with one of the most attractive based on the transverse RF deflector [1]. Since this specialized technology can be costly and unavailable, we revive an old method using accelerating RF, but with the same robust characteristics of the transverse deflector (fast, accurate, and absolute). The method is based on the standard "RF zero-phasing" scheme [2], but includes several significant improvements based on experience with the RF deflector method.

INTRODUCTION

Electron bunch length measurements using transverse RF deflectors have become standard in FEL applications and are now quite routine at the *FLASH* [3] and *LCLS* [4] FEL facilities. Although there are actually two separate deflectors at *LCLS*, one before the first bunch compressor (BC1) and one after the second compressor (BC2), there is no deflector between compressors, leaving the intermediate bunch length rarely measured. Similarly, at *FLASH* there is only one deflector at the end of the machine, and future FELs are planning multiple deflectors. In lieu of this costly option, or as a backup method to cover more of the machine, we present a simple method requiring no new hardware, using the existing accelerating RF, and providing a fast (~1 minute), accurate measurement. It is easily calibrated using beam screen data and only the RF frequency needs to be known.

Using a section of linac with nominal off-crest RF phase (standard with bunch compression), the method is first calibrated by fitting the linear slope of beam position, measured on a screen at a dispersive location after the linac, versus small RF phase variations. The dispersed beam size is then measured on the same screen at the nominal off-crest RF phase, then again at nominal, but opposite sign phase, and finally again at crest phase. A parabola is fitted to these three data points and the bunch length is extracted from one of the three fitted parabolic coefficients, using the calibration coefficient.

METHOD

The energy of each electron, $E(z)$, as a function of the bunch length coordinate, z, after a section of linac with peak accelerating voltage V_0 and RF phase φ (with $\varphi = 0$ defined at the crest phase), is

$$E(z) = E_i + eV_0\cos(\varphi + kz) + E_0 hz\,, \qquad (1)$$

where E_i is the initial electron energy prior to the linac section, k (= $2\pi/\lambda_{rf}$) is the RF wave number, h is the final linear energy chirp along the bunch, and e is the electron charge. The chirp, h, is the additional linear energy-z correlation (measured in m^{-1}) along the bunch due to the initial correlation (prior to the linac section) and also encompasses any wakefield-induced linear chirp over the linac section. The nominal energy, E_0, after the linac section is

$$E_0 \equiv E_i + eV_0\cos\varphi_0\,, \qquad (2)$$

with φ_0 as the nominal (reference) RF phase.

Defining the relative energy deviation as $\delta = (E - E_0)/E_0$, using Eq. (1) and (2) and assuming $k|z| << 1$ (*i.e.*, a short bunch compared to λ_{rf}), we have

$$\delta(z) \approx eV_0[\cos\varphi - \cos\varphi_0 - k\sin\varphi\, z]/E_0 + hz. \quad (3)$$

At this point it is useful to express these results in terms of a more directly measured quantity, namely the transverse beam position at a dispersive location (*i.e.*, after a bend magnet) following the linac section. Such a location is usually easily identified, since a bunch compressor chicane or other bend system commonly follows such a linac section. The transverse dispersion is defined as η and the transverse position, y, of each on-axis electron is then: $y = \eta\delta$.

Measuring the centroid of the ensemble of particles and using $\langle z\rangle = 0$, the transverse position centroid as a function of the variable RF phase, φ, taken from Eq. (3) is

$$\langle y\rangle = \eta\langle\delta\rangle \approx eV_0\eta[\cos\varphi - \cos\varphi_0]/E_0\,. \qquad (4)$$

A voltage calibration can then easily be done by measuring the sensitivity of the position centroid, $\langle y\rangle$, using small variations of the RF phase, φ (note that φ_0 is the reference phase and is not variable).

$$\partial\langle y\rangle/\partial\varphi = -eV_0\eta\sin\varphi\,/E_0 \equiv a \qquad (5)$$

Here the calibration slope, a, is defined (see Fig. 1).

Now we express the position of each particle, using the calibration slope, a, at the nominal phase by setting $\varphi = \varphi_0$ in Eq. (3) and again using $y = \eta\delta$.

$$y = (\eta h + ak)z \qquad (6)$$

With $\sigma_y = \langle y^2\rangle^{1/2}$ and $\sigma_z = \langle z^2\rangle^{1/2}$ it is clear that the rms transverse beam size, σ_y, is linearly dependent on the rms bunch length, σ_z, as

$$\sigma_y^2 = (\eta h + ak)^2\sigma_z^2 + \sigma_{y0}^2\,, \qquad (7)$$

where the chirp, h, is unknown and we introduce σ_{y0} as the non-dispersed (minimum) beam size at the screen.

To eliminate the unknown chirp we note that the sign of a follows the sign of φ, and introduce x as the sign of

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φ (*i.e.*, $x = -1$, $x = +1$, or $x = 0$ corresponding to $\varphi = \varphi_0$, $\varphi = -\varphi_0$, and $\varphi = 0$), resulting in $a \rightarrow |a|x$.

$$\sigma_y^2 = a^2k^2\sigma_z^2(|\eta|h/|ak| + x)^2 + \sigma_{y0}^2 \tag{8}$$

This form is now that of a simple parabola, such as

$$\sigma_y^2 = A(B + x)^2 + C\ , \tag{9}$$

with $A = a^2k^2\sigma_z^2$, $B = |\eta|h/|ak|$, and $C = \sigma_{y0}^2$.

If the rms beam size squared, σ_y^2, is measured at $\varphi = \varphi_0$ (*i.e.*, $x = -1$), $\varphi = -\varphi_0$ ($x = +1$), and $\varphi = 0$ ($x = 0$), these three data point pairs can then be linearly fit to the parabola of Eq. (9) resulting in numerical best-fit values for A, B, and C, with the rms bunch length calculated easily using: $\sigma_z = A^{1/2}/|ak|$, with a as the calibration slope.

SIMULATIONS

LCLS particle tracking simulations with *LiTrack* [5], including longitudinal wakefields of 330 meters of SLAC-type S-band RF accelerating structures prior to the BC2 chicane at 4.3 GeV, are used to more realistically verify the method. A simulated *LCLS* calibration is shown in Fig. 1 as described in Eq. (5) with $a = 4.377$ mm/deg.

The rms beam size measurements are simulated in Fig. 2 with the parabolic fit repeated 25 times with random 5% rms errors applied to each beam size. The average rms bunch length from the fit is 106 ± 3 µm, with the "true" value (from simulation) as 107 µm.

Tracking results are in Fig. 3 where longitudinal phase space is shown at the three pre-BC2 RF phase settings of the measurement ($\varphi = \varphi_0$, $\varphi = 0$, and $\varphi = -\varphi_0$, where $\varphi_0 = -36.2$ deg here). The bunch charge is 250 pC and the beam energy in the BC2 chicane is 4.3 GeV.

For shorter bunches, Fig. 4 and Fig. 5 show the method for ten bunch lengths (by varying the RF phase, φ_1, of the 1st compressor stage) from 107 µm to <7 µm rms. Results are precise up to ~15 µm rms for under-compression ($\varphi_1 > -26°$), and eventually limited by the wakefield-induced chirp (increased with shorter bunches), and also the dispersed beam size sensitivity (decreased with shorter bunches). A faster, *2-point* measurement is also possible, ignoring the crest phase beam size if it is much smaller than the other two. In that case: $\sigma_z \approx (\sigma_{y1} + \sigma_{y2})/|2ak|$.

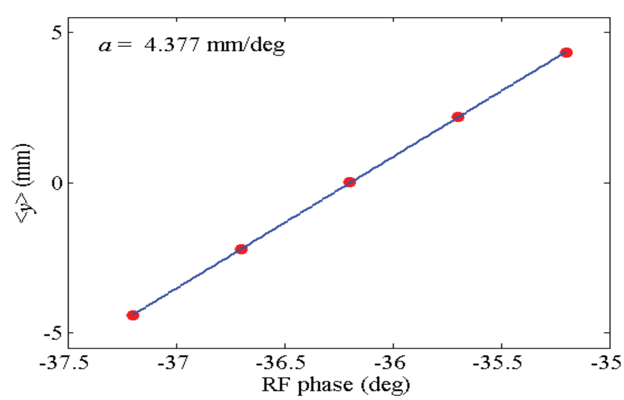

Figure 1: Simulated calibration curve as described in Eq. (5) with $a = 4.377$ mm/deg (or 250.8 mm/rad).

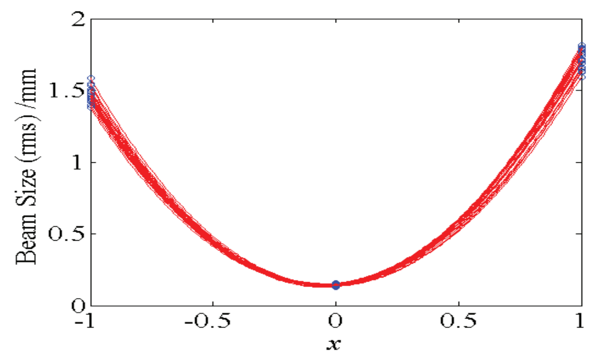

Figure 2: Twenty-five simulated bunch length measurements with parabolic fits (σ_y, not σ_y^2 shown) with 5% rms random errors on each beam size measurement resulting in an average rms bunch length of 106 ± 3 µm ('true' value is 107 µm).

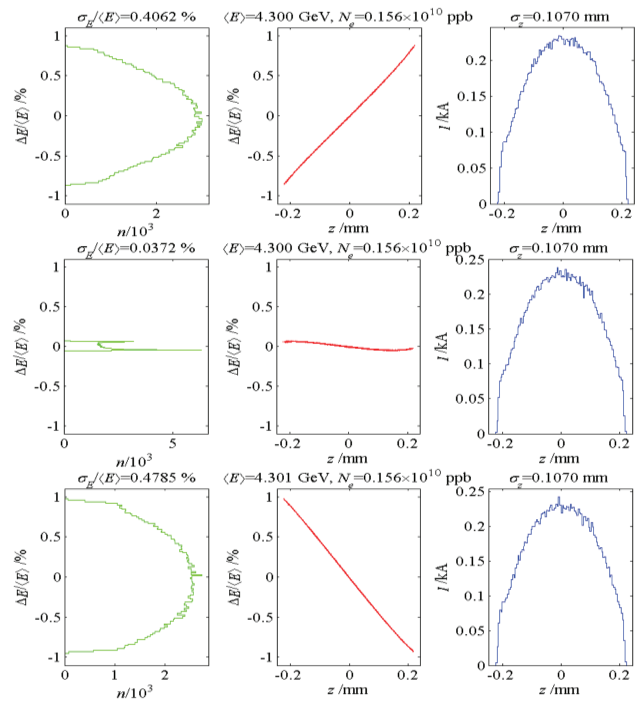

Figure 3: Tracking simulations for $\varphi = -36.2°$ (top row, nominal), $\varphi = 0$ (center row), and $\varphi = +36.2°$ (bottom row), at 4.3 GeV in *LCLS* BC2 at 0.25 nC ($\sigma_z = 107$ µm). Bunch head is at $z < 0$ here.

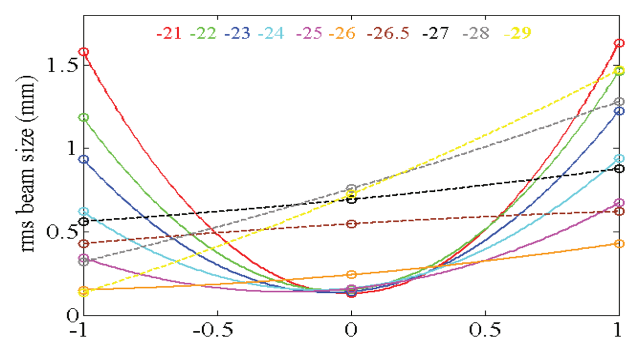

Figure 4: Simulations of bunch length measurements for 10 bunch lengths (color coded w.r.t. Fig. 5 phase). Over-compressed cases (dashed lines) are too linear due to the large chirp, h, and do not produce precise results.

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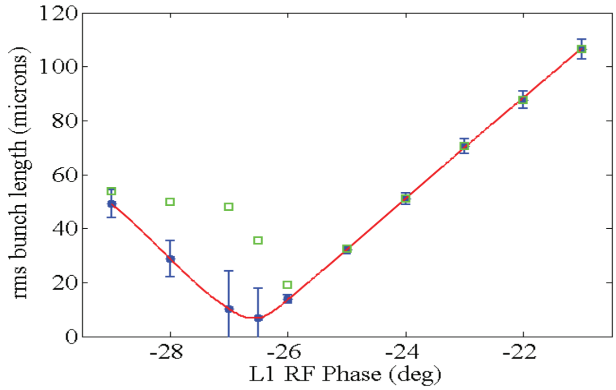

Figure 5: Simulations of Fig. 4 with red curve as tracking results (*i.e.*, 'true' σ_z), blue circles as parabolic measurement simulations (which agree well), and green squares as *2-point* measurement simulations, which agree only at $\varphi_1 > -26°$. Error bars, based on 5% rms beam size resolution, show the method diverges for strongly- or over-compressed bunches ($\varphi_1 < -26°$).

MEASUREMENTS

This refined RF phasing method has been tested at *LCLS* in the injector at 20 pC and the results are compared to those of the transverse deflector.

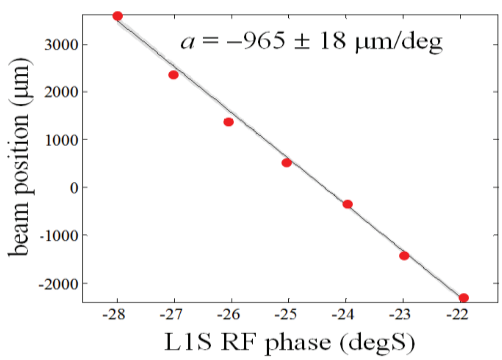

Figure 6: Measured calibration scan where the beam position on the BC1 screen is plotted against the RF phase setting scanned around its –25-degS nominal phase.

An actual calibration plot (as simulated in Fig. 1) is shown in Fig. 6 where the horizontal beam position on the BC1 chicane OTR screen is plotted vs. the pre-BC1 accelerating RF (L1S) phase setting, scanned around its nominal value of –25 degS (degrees of S-band RF).

Figure 7 shows an injector bunch length measurement at 20 pC, where the rms beam size (on an OTR screen at 135 MeV just after the first "TCAV0" RF deflector) is plotted versus the RF deflector's phase (left plot), and also the rms beam size (on at OTR screen at 250 MeV at the center of the BC1 chicane) versus the pre-BC1 RF (L1S) accelerating phase (right plot). The left-side plot is the 'standard' method using an RF deflector, while the right-side plot is the RF phasing scheme. The two independent rms bunch length measurements agree to within 5% here. Figure 8 shows this same measurement, but now at 40 pC, and again with 5% agreement. The asymmetry in these plots (right side only) is due to the X-band RF linearizer, which is constant at –160 deg here.

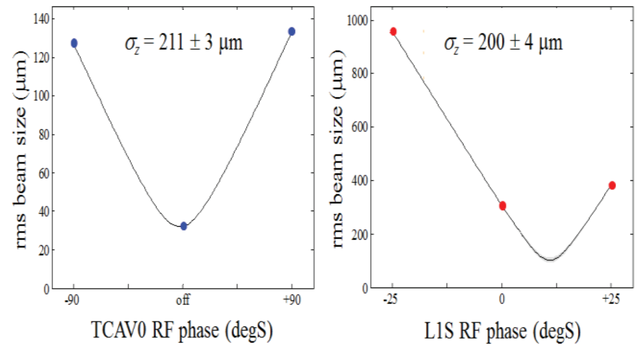

Figure 7: Measured rms beam sizes in *LCLS* injector at 20 pC vs. RF phase (transverse cavity phase at left, and pre-BC1 accelerating phase, L1S, at right). The two independent bunch length measurements agree to within 5% here.

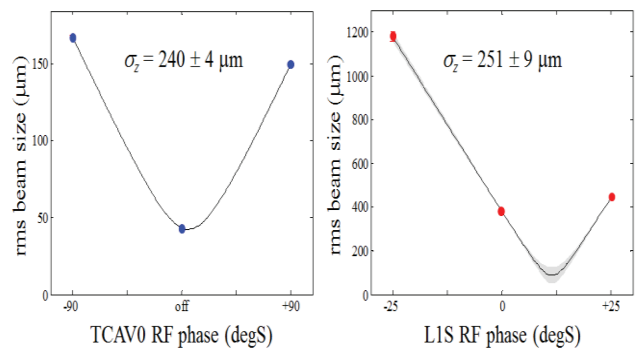

Figure 8: Bunch length measurements in *LCLS* injector exactly as shown in Fig. 7, but now at 40 pC.

The method has also been tested downstream of the *LCLS* BC1 compressor. Figure 9 shows this measurement at 20 pC, but with no accompanying transverse RF confirmation made here yet. The BC2 dispersion OTR screen and the pre-BC2 RF phase (L2) are used here.

Finally, Fig. 10 shows the temporal beam profile measured using the RF phasing method in BC2 (same data as right-side plot of Fig. 9), where some micro-structure also appears. Here the beam size on the crest phase is very small and not critical for bunch length measurements (*i.e.*, a *2-point* measurement is sufficient).

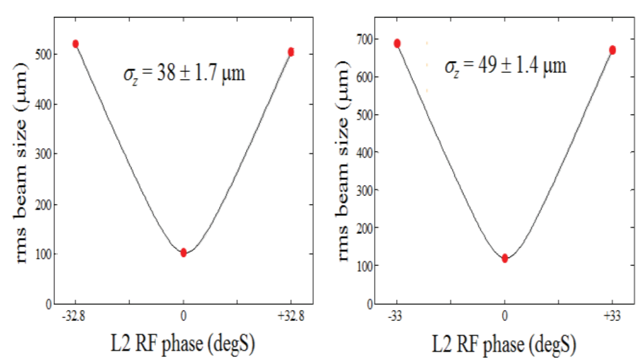

Figure 9: Measured bunch length (RF phasing method in both cases) in *LCLS* just prior to BC2 at 20 pC (left) and 40 pC (right). The transverse RF deflector has not yet been used to confirm this. The rms bunch length values are 38 μm and 49 μm, respectively, and the scale of the beam size data suggests that much smaller values can be measured as well.

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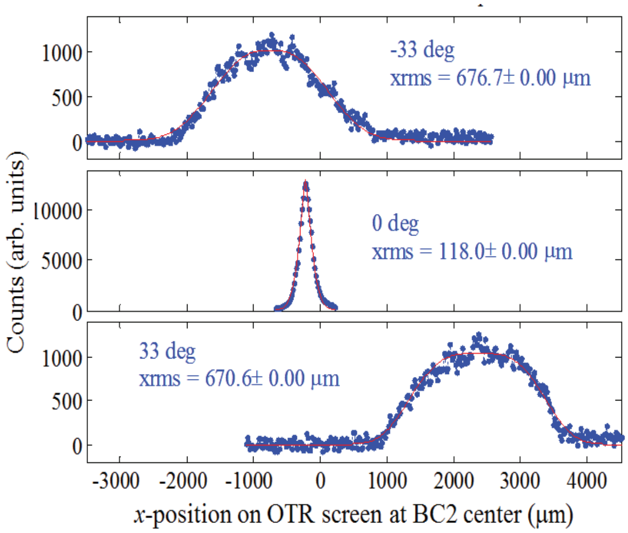

Figure 10: Measured temporal profiles for an L2 RF phase of –33º (top), zero (middle), and +33º (bottom) at 40 pC in the BC2 chicane (same data as shown at right in Fig. 9). The temporal shape is revealed at top and bottom using the nominal (–33º) and flipped (+33º) RF phases prior to BC2. A *2-point* measurement is more than adequate here.

COMMENTS

This method requires no new hardware and uses the off-crest RF phasing typical in a linac-based FEL, with no need to shift the phase to the "RF zero-crossing", which otherwise requires a large energy change and linac magnet strength rescaling. Its application requires a simple calibration (see Fig. 1 and Fig. 6), which takes about one minute and eliminates the need for knowledge of the RF voltage, the scale of the screen, or the dispersion value at the screen. Only the RF frequency needs to be known, and the calibration is required only occasionally.

A bunch length measurement requires just 2-3 beam size measurements on the screen at a dispersive location where the dispersion nominally dominates the beam size. The three measurements are done at: 1) the nominal RF phase setting (*e.g.*, $\varphi = -36°$); 2) a flipped-sign nominal phase setting (*e.g.*, $\varphi = +36°$), preserving the electron energy; and possibly 3) the crest phase ($\varphi = 0$), requiring a voltage reduction. In most cases the crest phase setting is not required (see Figs. 5, 9, and 10), allowing very fast and convenient measurements. Finally, precise RF phase knowledge is not needed since it is part of the calibration, and the actual RF phase flip can be guided by keeping the beam centered on the screen. Several similar schemes (*e.g.*, tomography) have been published as well [6, 7, 8], but are not as well targeted towards the fast, convenient, and absolute bunch length measurements described here.

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