A SIMPLE, LOW COST LONGITUDINAL PHASE SPACE DIAGNOSTIC*

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Absract

For proper operation of the *LCLS* [1] x-ray free-electron laser (FEL), and other similar machines, measurement and control of the electron bunch longitudinal phase space is critical. The *LCLS* accelerator includes two bunch compressor chicanes to magnify the peak current. These magnetic chicanes can generate significant coherent synchrotron radiation (CSR), which can distort the phase space distribution. We propose a diagnostic scheme by exciting a weak skew quadrupole at an energy-chirped, high dispersion point in the first *LCLS* bunch compressor (BC1) to reconstruct longitudinal phase space on an OTR screen after BC1, allowing a time-resolved characterization of CSR effects.

INTRODUCTION

To shorten the *LCLS* electron bunches, the electron beam is linearly energy-chirped, then compressed in two bunch-compressor chicanes (BC1 and BC2). The bend magnets in these chicanes can give rise to coherent synchrotron radiation (CSR), which can add a time-correlated energy spread to the bunch. This energy spread can lead to residual dispersion after the chicane, causing blow-up of the bend-plane emittance and potentially reducing the FEL gain.

A transverse RF cavity can be used to streak the bunch vertically [2], time-resolving the CSR effects by measuring the longitudinal phase space directly. But this can be a costly and unavailable diagnostic.

Here we present an alternate, simpler method to enable time-resolved electron bunch measurements using a weak skew quadrupole at an energy-chirped, high dispersion point in the bunch compressor beamline. The horizontal beam size at the skew quad should be dominated by the time-correlated energy chirp induced by the off-crest-phased RF system upstream of the compressor. The skew quad then couples the horizontal beam extent into the vertical plane, resulting in a large vertical beam size on a screen after the bend system (after the horizontal dispersion has been fully cancelled), revealing the time coordinate along the bunch. The screen image is then used to time-resolve various horizontal bunch parameters (centroid position, beam size, emittance, etc) along the bunch length, including the temporal distribution.

CALCULATIONS

Treating the skew quad as a thin lens, the vertical kick angle, y', of a particle at a horizontal position, x, in the skew quad is given by: $y' = x/f$, where f is the focal length of the skew quad, and $1/f = GL/(B\rho)$, with G as the quadrupole field gradient, L as its magnetic length, and $(B\rho)$ as the standard magnetic rigidity.

Also noting that x is dominated by the horizontal dispersion at the quad, η, and the time-correlated rms relative energy spread, σ_δ, then: $x \approx \eta\delta$, where δ ($\equiv \Delta E/E$) is the relative energy deviation of the particle at position x, and we have: $y' = GL\eta\delta /(B\rho)$. Here we assume the horizontal beam size at the skew quad is completely dominated by the upstream time-correlated energy chirp, a typical situation in bunch compressors for high brightness electron beams.

Now introducing the time-correlated energy chirp as $\delta = hz$ (assuming an insignificant uncorrelated energy spread, which is also typical), where h ($\approx \sigma_\delta/\sigma_z$), is the ratio of rms relative energy spread divided by the rms bunch length prior to compression, and z ($= ct$) is the bunch length ('time') coordinate, we have: $y' = GL\eta hz/(B\rho)$.

Finally, transporting this vertical kick downstream to the screen where it becomes a vertical position, y ($= R_{34}y' = (\beta_q\beta_s)^{1/2}\sin(\Delta\psi)$), we have:

$$y = \frac{GL\eta h\sqrt{\beta_q\beta_s}\,\sin(\Delta\psi)}{(B\rho)}\cdot z\,, \qquad (1)$$

where β_q and β_s are the vertical beta functions at the quad and screen, respectively, and $\Delta\psi$ is the vertical betatron phase advance from quad to screen.

Similarly, the rms vertical beam size, σ_y, on the screen is related to the rms bunch length (upstream of the compressor), including the nominal vertical beam size on the screen with skew quad off ($\sigma_{y0} = (\beta_s\varepsilon)^{1/2}$), as:

$$\sigma_y = \sqrt{\beta_s\varepsilon\left(\frac{(GL\eta h)^2\beta_q\sin^2(\Delta\psi)}{\varepsilon(B\rho)^2}\sigma_z^2 + 1\right)}\,, \qquad (2)$$

where ε is the rms vertical beam emittance. From this formulation we can estimate the necessary skew quadrupole gradient and length necessary to dominate the screen (*i.e.*, to render the 2nd term insignificant).

Using the *LCLS* first bunch compressor (BC1) as an example (see Table 1), and choosing a skew quad bore radius, r, at least 10-times larger than the largest possible chirped horizontal rms beam size in the skew quad ($\sigma_{x\text{-max}} \approx |\eta_{max}|\sigma_{\delta\text{-max}} \approx$ (290 mm)(1.7%) $\approx$ 4.9 mm), then at 250 MeV the skew quad has a maximum pole-tip field of $B \approx 0.3$ kG, a pole radius of $r \approx 50$ mm, and a length of $L \approx 0.16$ m. This produces an 8.6-m focal length, which easily justifies the thin-lens approximation of a 0.16-m long skew quadrupole magnet.

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Table 1: *LCLS* BC1 and beam parameters at 0.25 nC of charge.

Parameter	Sym.	value	unit
Electron energy	E	250	MeV
Magnetic rigidity	$(B\rho)$	8.34	kG-m
Initial rms bunch length	σ_z	0.75	mm
Chirped relative rms energy spread	σ_δ	1.4	%
Linear energy chirp ($\approx \sigma_\delta/\sigma_z$)	h	19	m^{-1}
Horizontal dispersion at skew quad	η	230	mm
Vert. beta function at skew quad	β_q	5	m
Vert. beta function at screen	β_s	1	m
Vert. betatron phase advance	$\Delta\psi$	103	deg
Vert. rms emittance	ε	<2.0	nm
Skew quadrupole magnetic length	L	0.16	m
Skew quadrupole field gradient	G	6	kG/m
Skew quadrupole pole-tip radius	r	50	mm
Skew quadrupole pole-tip field (Gr)	B	0.3	kG
Skew quadrupole focal length	f	8.6	m
Vert. beam size with skew quad OFF	σ_{y0}	0.05	mm
Vert. beam size with skew quad ON	σ_y	0.75	mm

Note that Eq. (2) also shows that the beta function at the skew quadrupole, β_q, can be used to minimize the skew quad strength, but the beta function at the screen, β_s, only scales the measured spot size (skew quad on or off).

It is tempting to use this arrangement to measure the initial bunch length (prior to compression), and this is certainly possible. However, knowledge of the chirp coefficient, h, is then required, and if h is well known, then a simple screen in the compressor which measures the horizontal beam size would easily suffice ($\sigma_x \approx \eta h \sigma_z$). It is also important to recognize that such a measurement represents the bunch length prior to compression, even though the screen is downstream of the compressor.

It is also possible to calibrate the scaling coefficient, dy/dz, from Eq. (1) by somehow varying z upstream of the compressor and recording the accompanying y-centroid variations on the screen. This is perfectly reasonable, but it should be remembered that the z-variations need to be generated in such a way as to sample all of the RF which induces the chirp, h (*e.g.*, vary z at the electron source). Even this method, however, may be somewhat inaccurate, since these z-variations will only sample external fields (RF), but not the contributions to the chirp, h, due to self fields, such as longitudinal wakefields and space charge forces. If these are small contributions, then dy/dz beam calibration is valid (as done using a transverse deflector).

The strength of this arrangement is in its ability to enable time-resolved measurements of the bunch after the compressor, including CSR phase space distortions which occur within the compressor.

TRACKING SIMULATIONS

Beam simulations show that this skew quadrupole will streak the bunch quite well vertically, with no adverse effects on bunch compression. Figure 1 shows the *LCLS* BC1 chicane layout with OTR screen and Twiss parameters: β_x, β_y, η_x, η_y plotted, with skew quadrupole magnet switched on near the center of the chicane.

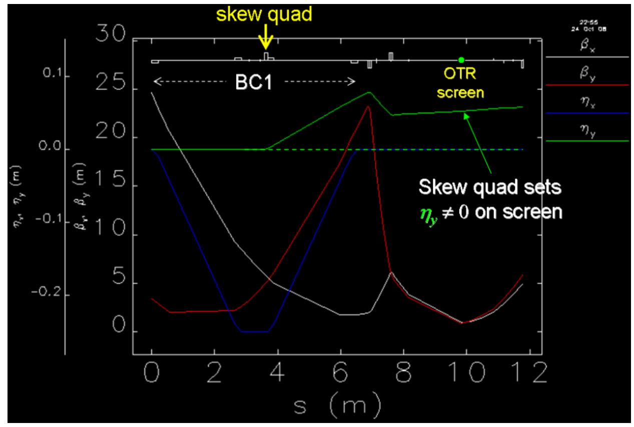

Figure 1: *LCLS* BC1 chicane and OTR screen layout with Twiss parameters: β_x, β_y, η_x, and η_y plotted and skew quad switched on near the center of the chicane.

A simulated image (and its projections) at the OTR screen downstream of the BC1 chicane is shown in Fig. 2, including the effects of CSR [3]. The horizontal beam size has increased from 48 μm rms to 177 μm rms due to the effects of CSR, and the horizontal distribution (lower-left, green) is distorted. The plot shows the simulated screen image (upper-left, red) with the skew quad switched off, while Fig. 3 shows the image (upper-left, red) with the skew quad switched on. The skew quad maps the bunch time coordinate onto the vertical axis of the screen, revealing the x-z correlation generated by CSR in the BC1 bends. In addition, the temporal bunch profile (upper-right, blue) is now visible in Fig. 3.

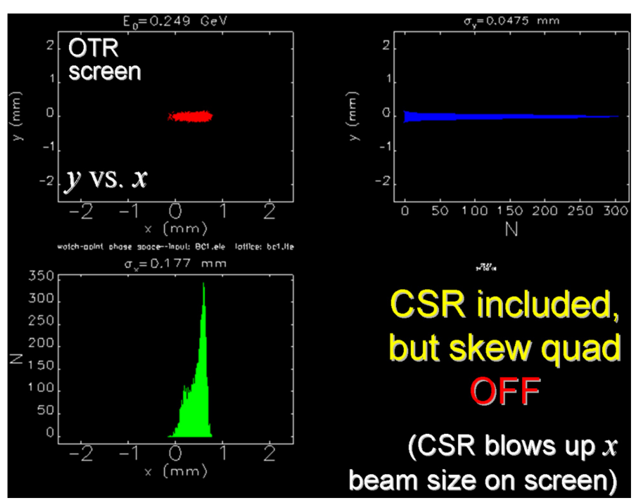

Figure 2: Simulated screen image (upper-left, red) with CSR effects included and skew quad off. No temporal resolution of the distorted horizontal distribution (lower-left, green) is possible here, with the skew quad off.

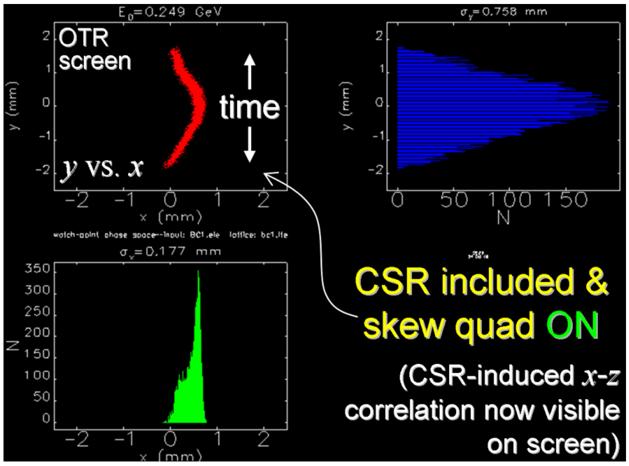

Figure 3: Simulated screen image (upper-left, red) with CSR effects included and skew quad switched on. The temporal bunch profile (upper-right, blue) is also now clearly visible.

SKEW QUADRUPOLE MAGNET

The skew quadrupole required for this diagnostic is quite weak (about 1 kG length-integrated quadrupole field gradient) but must have a large bore (about 10 cm diameter). Due to space limitations, it cannot be installed at the desired location in the center of the chicane. It will be installed just past the third bend magnet of the four-magnet chicane, where the dispersion is about 80% of maximum.

Because of the low required excitation, we will use an inexpensive quasi-air-core magnet. The design is essentially an air core quadrupole with a thin iron outer tube, which acts as a flux return and magnetic shield. A Poisson simulation of an octant of this quad is shown in Fig. 4. Radial adjustment of the coil positions will allow canceling the 12-pole aberration. Residual 20-pole aberrations will be about 10^{-7} (normalized to the quadrupole field at a 1 cm radius).

This skew quadrupole is about 11 cm ID, 20 cm physical length (16 cm effective length), with about 100 turns per quadrant. Its weight is about 15 pounds. Excitation at 10 A will produce a gradient of 60 G/cm, yielding an integrated field gradient of 1 kG.

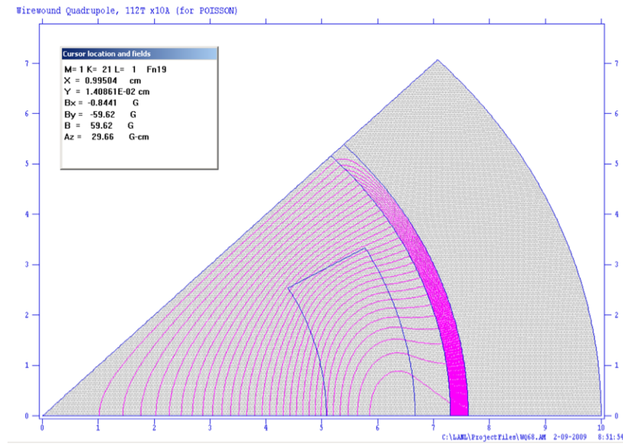

Figure 4: Poisson simulation of skew quadrupole.

SUMMARY AND CONCLUSIONS

We have presented an inexpensive and simple diagnostic which can be used to enable time-resolved bunch measurements. This skew quad will allow measurement of the time-sliced x-emittance after the *LCLS* BC1 chicane and characterization of disturbances to the longitudinal and transverse phase space due to CSR. The skew quad will be installed at *LCLS* in mid-2009 and may be useful to other high-brightness electron beam projects where time-resolved measurements are important but funds are limited.

REFERENCES

[1] J. Arthur *et al.* "Linear Coherent Light Source (LCLS) Conceptual Design Report," SLAC-R-593 (2002); http://www.slac.stanford.edu/pubs/slacreports/slac-r-593.html

[2] R. Akre *et al.*, "A Transverse RF deflecting structure for bunch length and phase space diagnostics," PAC'01, Chicago, June 2001, p. 2353 (2001).

[3] M. Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287 (Sep. 2000).