LCLS-II Technical Note

Chromatic Corrections for the LCLS-II Electron Transport Lines

LCLS-II TN-16-07

3/4/2016

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March 3, 2016

Introduction

The nominal energy spread in the electron bunch after the 4-GeV LCLS-II superconducting linac (SC-linac) is relatively small, with a maximum of 0.15% rms after the linac, and as low as 0.01% rms in either FEL undulator. This level generates no significant chromatic aberrations along the transport lines. However, an alternate machine configuration is also planned requiring a linear energy correlation (chirp) along the bunch by adjusting the bunch compression parameters (*e.g.*, over-compressing the bunch in the BC2 chicane). This intentional large electron energy chirp (up to 1% FWHM in either undulator) is used to generate a large FEL photon bandwidth (2×1%) for users who may request this. The large energy spread, however, requires chromatic correction by adding a total of eight new sextupole magnets in the various transport line sections. There are five sections, all labeled in Figure 1 using indices **1-5**. The five sections all operate at the nominal (SC-linac) electron energy of 4 GeV, and each one is described briefly below.

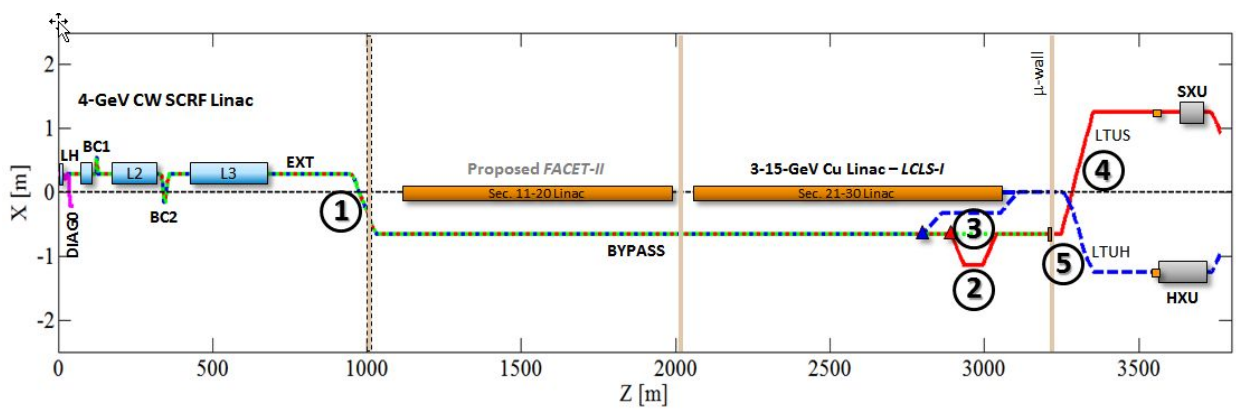

Figure 1: LCLS-II layout (plan view) where the five transport line sections are labeled with circled integers. Some of the bends have large roll angles in order to deflect in both planes, meaning that some of the chromatic aberrations also appear in both planes.

Chromatic Aberrations

The strong quadrupole focusing between bends in the various transport lines can generate chromatic aberrations if the energy spread is too large. An estimate for the relative emittance growth generated by a single (thin-lens) quadrupole in a dispersive area ($|\eta| > 0$) is given by

$$\frac{\Delta\varepsilon}{\varepsilon_0} \approx \frac{1}{2}\left(\frac{\beta}{f}\right)^2 \left(1 + 2\frac{\eta^2\sigma_\delta^2}{\beta\varepsilon_0}\right)\sigma_\delta^2 ,$$

where β is the bend-plane beta function in the quad, f is its focal length, η is the dispersion in the quad, σ_δ is the rms relative energy spread (= σ_E/E_0), and ε_0 is the initial emittance upstream of the quad. The factor of 2 in the second term is a result of assuming a Gaussian energy spread, and evaluating its 4th moment. (The factor of 2 is replaced by 4/5 for a uniform distribution.) For example, using the parameters of one quadrupole magnet in the rolled dog-leg (section-**1**), with $\beta \approx 32$ m, $f \approx 6.9$ m, $\eta \approx 0.44$ m, $\sigma_\delta \approx 0.3\%$ (chirped), $\gamma\varepsilon_0 = 0.35$ μm, and $\gamma = E/mc^2$ (E = 4 GeV), the relative bend-plane emittance growth is $\Delta\varepsilon/\varepsilon_0 \approx 24\%$. In these transport lines, where the dispersion dominates the beam size, $|\eta|\sigma_\delta/(\beta\varepsilon_0)^{1/2} >> 1$, the emittance growth climbs very quickly (as σ_δ^4) for a larger energy spread, as seen in the equation above.

Tracking and Chromatic Correction of the Transport Lines

To evaluate all chromatic aberrations, particle tracking is done using *Elegant* [1] over each of the five transport line sections individually. Since the beam size is completely dominated by dispersion, the chromatic aberrations are dominated by second-order dispersion (see Figure 2), while the betatron chromaticity is insignificant.

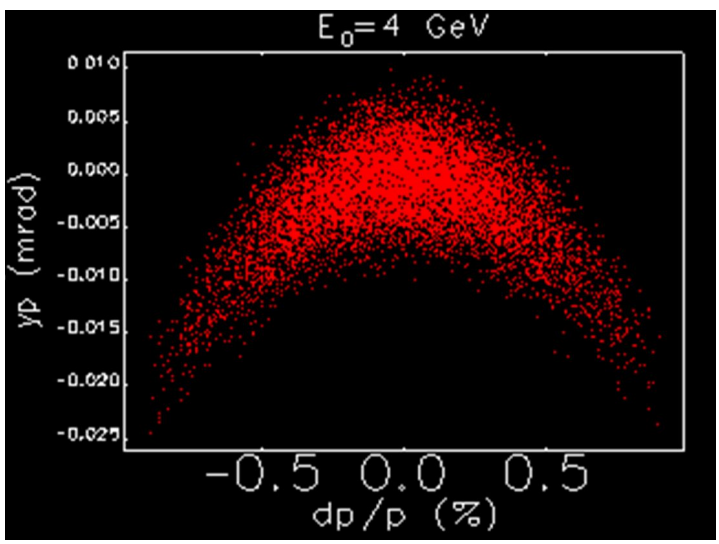

Figure 2: Scatter plot of tracked particles after the rolled dog-leg, with sextupoles switched *off*, showing the vertical angle coordinate, y', on the vertical axis, and the relative energy (momentum) coordinate, $\Delta p/p$, on the horizontal axis. This quadratic mapping, $\Delta y' \sim (\Delta p/p)^2$, indicates 2nd-order dispersion as the dominant chromatic aberration in this transport line.

Like any beam trajectory, second-order dispersion has both spatial and angular components. Therefore, for bends in only one plane, the sum of the 2nd-order dispersion errors from each dispersion-dominated quadrupole can be corrected with just two sextupoles separated in phase advance ideally by ~π/2 (*i.e.*, sine-like and cosine-like correctors). If the bends are rolled, then the total 2nd-order dispersion in both x and y can be corrected again with two sextupoles, but each

with a properly chosen tilt (roll) angle[1]. With this guide, the chromatic aberrations are corrected using *Elegant*, numerically minimizing the product of the projected *x* and *y* emittance values while solving for two sextupole strengths and their tilt angles, where necessary. This exercise is repeated for each of the four bend sections where chromatic aberrations are an issue, leading to eight new sextupole magnets required in LCLS-II in order to allow chirped-FEL operations at a 1% FWHM electron energy spread (2% FWHM photon bandwidth). The electron beam parameters used in the tracking are listed in Table 1.

Table 1: Electron beam parameters from SC-linac in FEL-chirp mode.

Parameter	**Symbol**	**Value**	**Unit**
Electron energy after the SC-linac	E	4	GeV
Hor. & vert. norm. initial emittance	$\gamma\varepsilon_0$	0.35	μm
Relative rms energy spread (chirp mode)	σ_E/E_0	0.3	%
Relative FWHM energy spread	$\Delta E/E_0$	1.0	%
Relative FWHM photon bandwidth	$\Delta\omega/\omega_0$	2.0	%

The particle tracking is done in each of the five transport line sections individually.

1. The first transport line (Figure 1) of interest is the rolled dog-leg (section-**1**), which is common to both the SXR and the HXR electron beam paths. This dog-leg includes rolled bends, generating both horizontal and vertical dispersion, as shown in the Twiss parameter plot of Figure 3. The strong focusing here, with 8 quadrupole magnets between the two bends, can generate chromatic aberrations if the beam has a large energy spread. Without two new sextupoles here (*SX* and *SY*), and with σ_E/E_0 = 0.3%, the horizontal emittance growth based on particle tracking is 21% and the vertical emittance growth is 57%. The two sextupoles reduce this to 0.1% in each plane. The new *SY* sextupole should be located 10-30 cm (edge to edge) away from the *QDOG2* quadrupole, with *SX* at 10-30 cm from the *QDOG3* location. These can be placed on either side of the quads as space allows. Table 2 lists the two sextupole locations, strengths, tilt angles, and minimum beam stay-clear radius, R_{bsc}, after emittance minimization in chirped mode. Note the $|T_{566}|$ value is also reduced by ~3 in each section described below.

2. The next section (**2**) is the SXR-chicane (red-solid in Figure 1). This is part of the beam spreader system and transports electrons on the SXR path. The optics include horizontal dispersion only, with no rolled bends here (see Figure 4). Without two new sextupoles here, and at σ_E/E_0 = 0.3%, the horizontal emittance growth is 60%. The sextupoles reduce this to <0.1%, with Table 2 listing the two sextupole locations and strengths.

[1] A positive "tilt" angle represents a clock-wise rotation of the magnet, seen as beam leaves the observer.

3. The third section (**3**) is the HXR cross-over line (blue-dashed in Figure 1), which is also part of the spreader system and transports electrons on the HXR path. The optics are rolled and include horizontal and vertical dispersion (see Figure 5). Without two new sextupoles here, and at σ_E/E_0 = 0.3%, the horizontal emittance growth is 210% and the vertical is 3%. The sextupoles reduce this to < 0.1% in the horizontal and 3% in the vertical plane. Table 2 lists the two sextupole locations, strengths, and tilt angles.

4. The fourth section (**4**) is the SXR dog-leg (red-solid in Figure 1), which transports electrons on the SXR path. The optics include only horizontal dispersion (see Figure 6). Without two new sextupoles here, and at σ_E/E_0 = 0.3%, the horizontal emittance growth is 51%. The sextupoles reduce this to <0.4%. Table 2 lists the two sextupole locations and strengths.

5. The fifth section (**5**) is the (existing) HXR dog-leg (blue-dashed in Figure 1), which transports electrons on the HXR path. The optics include only horizontal dispersion. This system has been in operation in LCLS-I since 2009 and needs no chromatic corrections, even with up to a 1% FWHM electron energy chirp (see Figure 7).

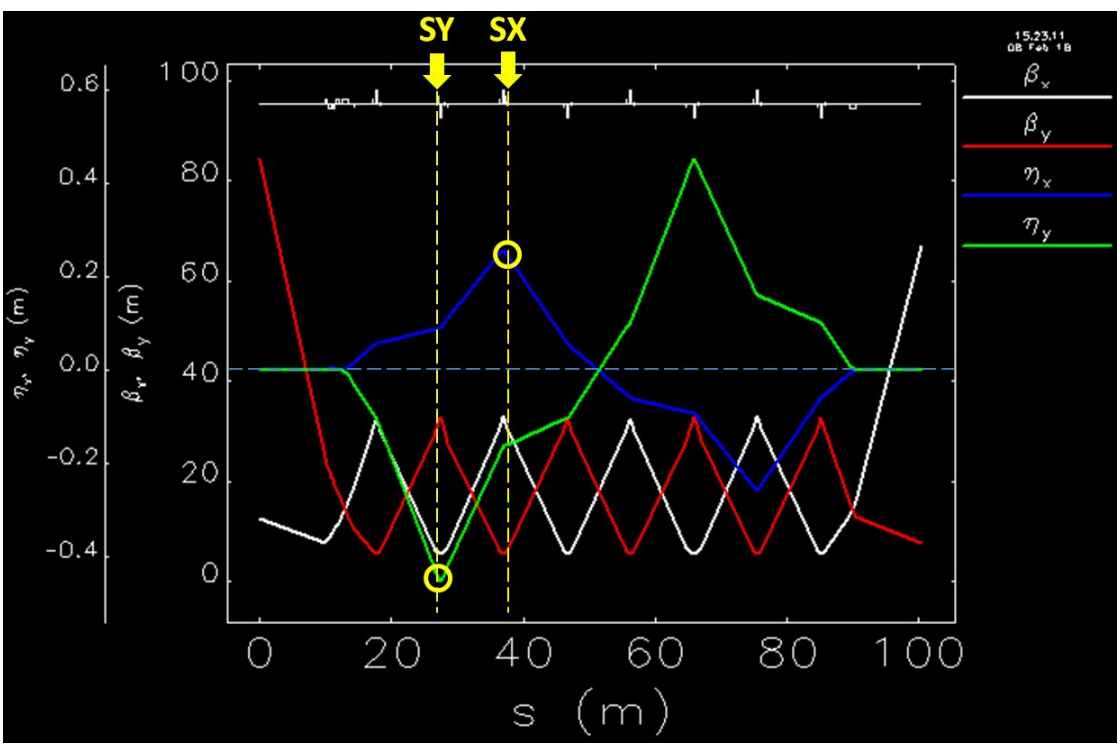

Figure 3: Twiss parameters over the rolled dog-leg (section-**1**) with new sextupole locations (*SY* & *SX*) shown at top. The two rolled bends generate both horizontal (blue) and vertical (green) dispersion requiring two rolled sextupoles.

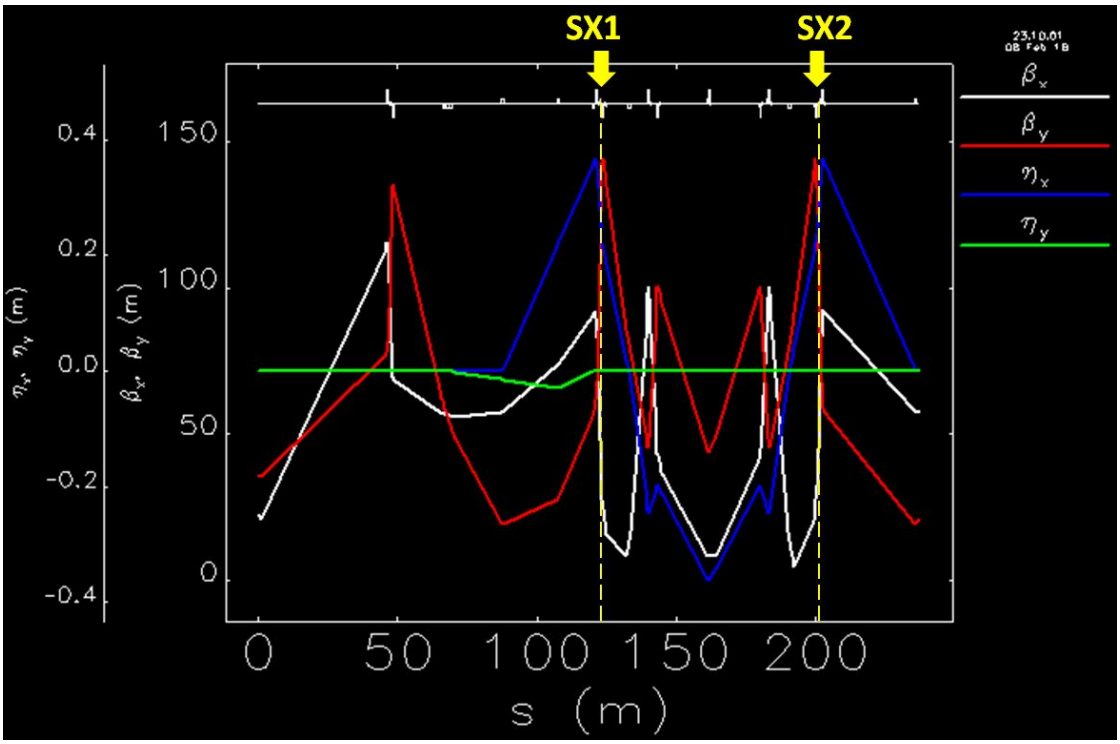

Figure 4: Twiss parameters over the SXR-chicane (section-**2**) with two new sextupole locations shown. The chicane has large horizontal (blue) dispersion and ignorable vertical (green), allowing unrolled sextupoles here.

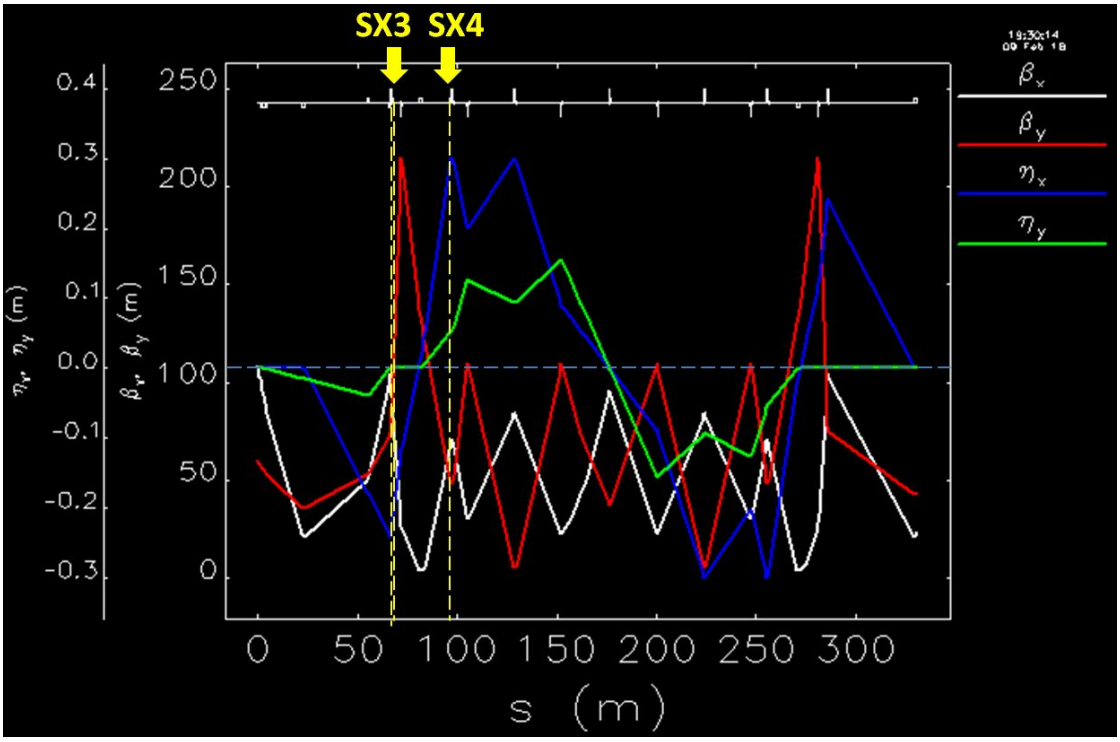

Figure 5: Twiss parameters over the HXR cross-over (section-**3**) with two new rolled sextupoles shown. Rolled bends generate both horizontal (blue) and vertical (green) dispersion.

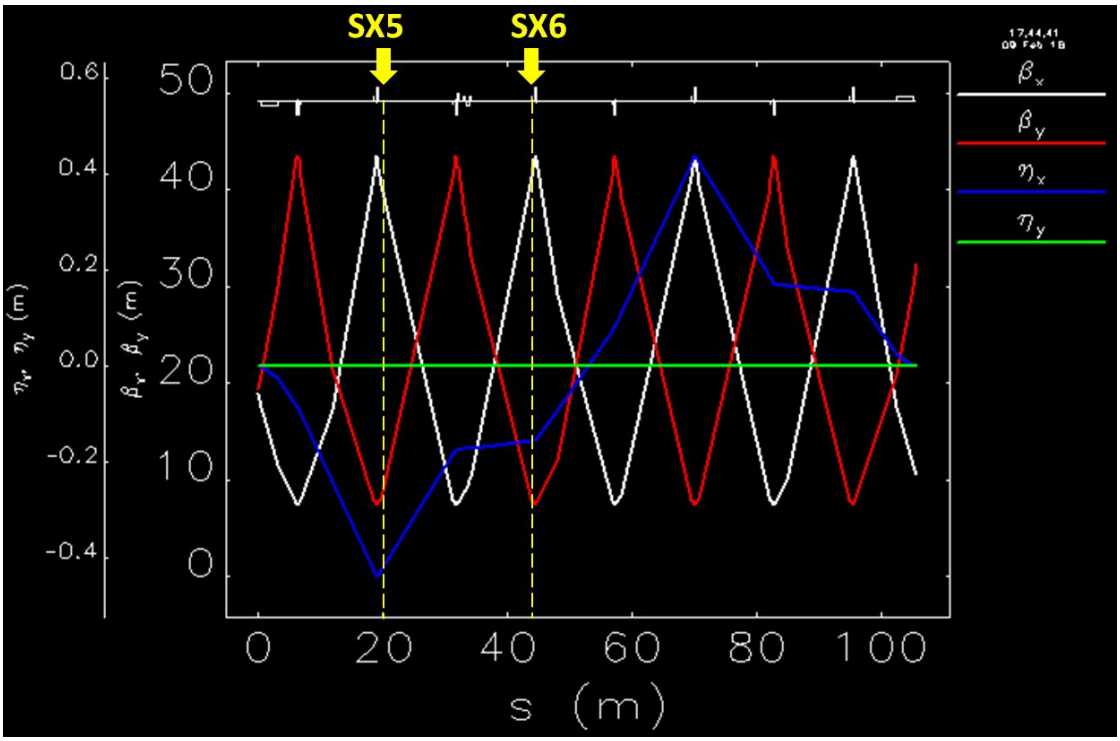

Figure 6: Twiss parameters over the SXR dog-leg (section-**4**) with two new unrolled sextupoles shown. The bends are horizontal with no rolls, generating horizontal (blue) dispersion only.

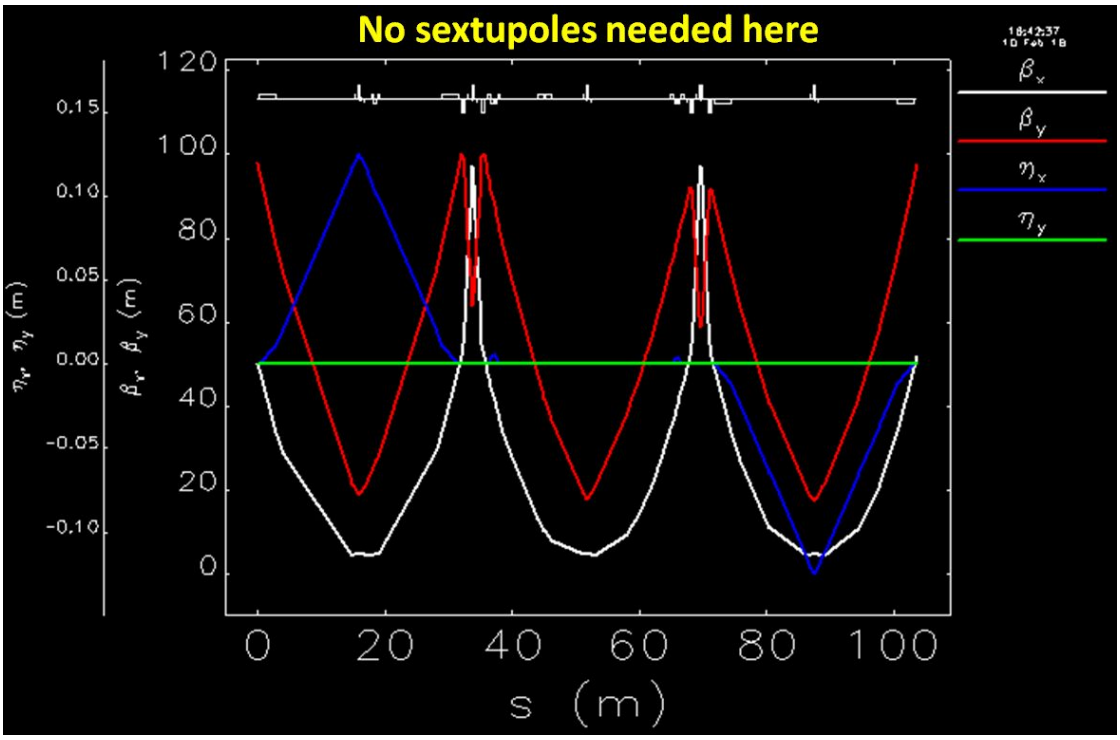

Figure 7: Twiss parameters over the (existing) HXR dog-leg (section-**5**). No sextupoles are needed here due to the much smaller peak dispersion. The bends are horizontal with no rolls, generating only horizontal (blue) dispersion.

Table 2: Sextupole magnet settings for LCLS-II chirp, including beam stay-clear radius, R_{bsc}. The "Quad Name" is the name of quadrupole magnet nearest (10-30 cm) each sextupole. No sextupoles are needed in the HXR dog-leg (section-**5**).

Transport Line Section	**Sext. Name**	**Adjacent Quad Name**	K_2 (m^{-3})	**Tilt** (deg)	R_{bsc} (mm)
Rolled Dog-Leg (**1**)	*SX*	*QDOG3*	-20.6	19	16
	SY	*QDOG2*	-9.8	-13	12
SXR-Chicane (**2**)	*SX1*	*QSP1S*	12.6	0	14
	SX2	*QSP9S*	11.7	0	14
HXR Cross-Over (**3**)	*SX3*	*QSP1H*	-18.5	14	12
	SX4	*QSP3H*	20.3	17	13
SXR-Dog-Leg (**4**)	*SX5*	*QDL13*	-8.24	0	16
	SX6	*QDL15*	-24.7	0	9

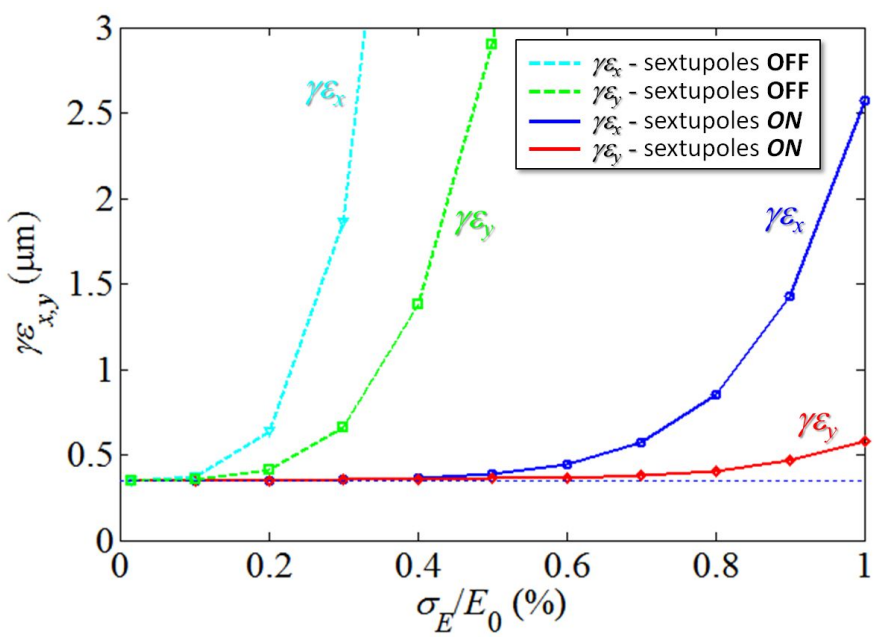

Figure 8: Chromatic emittance growth from the end of the SC-linac to the entrance of the SXR undulator with the six sextupole magnets *off* (dashed lines), and then with them *on* (solid lines). The corrected chromatic bandpass of the system is about 0.5% rms, well above the 0.3% goal.

In order to verify effective chromatic correction over the full transport system, from end of SC-linac to undulator entrance, we also performed particle tracking over the full SXR path, including sections **1**, **2**, and **4** (since the SXR system has more chromatic effects than the HXR branch). The tracking is shown in Figure 8 with all six SXR sextupoles (2 per section) switch *off* (dashed

lines), and again with all sextupoles switched *on* (solid lines). The relative x and y emittance growth is plotted vs. the rms relative Gaussian energy spread transported through the full SXR system. The chromatic bandpass of the full transport system is about 0.5% rms, which is well above the goal of 0.3% rms (1% FWHM). The HXR system is expected to be similar or better.

The Sextupole Magnets and Power Supplies

The sextupole magnet settings required for chromatic corrections are summarized in Table 2, including temporary magnet names, nearest quadrupole magnet, nominal sextupole strength [$K_2 = (\partial^2 B/\partial x^2)/(B\rho)$], roll angle, and beam stay-clear radius (R_{bsc}) at each location (smallest cylindrical bore radius allowed at that location). These requirements suggest the use of an existing SLAC/FFTB sextupole magnet design shown in Figure 9, which have a specific type name "*1.38S3.00*" (1.38-inch bore and 3.00-inch length). These magnets are described in Table 3. Note that the maximum $|K_2|$ setting for the "*1.38S3.00*" magnet is 65 m^{-3}, which means that the magnets will still produce a $|K_2|$ value of 26 m^{-3} (> 24.7 m^{-3}) at 10 GeV, in case of a long-term, high-energy upgrade of the SC-linac. The 17.5-mm sextupole pole-tip radius, r, avoids the beam stay-clear limits in all cases (assuming a thin vacuum pipe) fitting well to this application.

The eight sextupole magnets will be powered independently requiring eight new MCOR-12 bipolar power supplies with < 1% rms relative field regulation stability required.

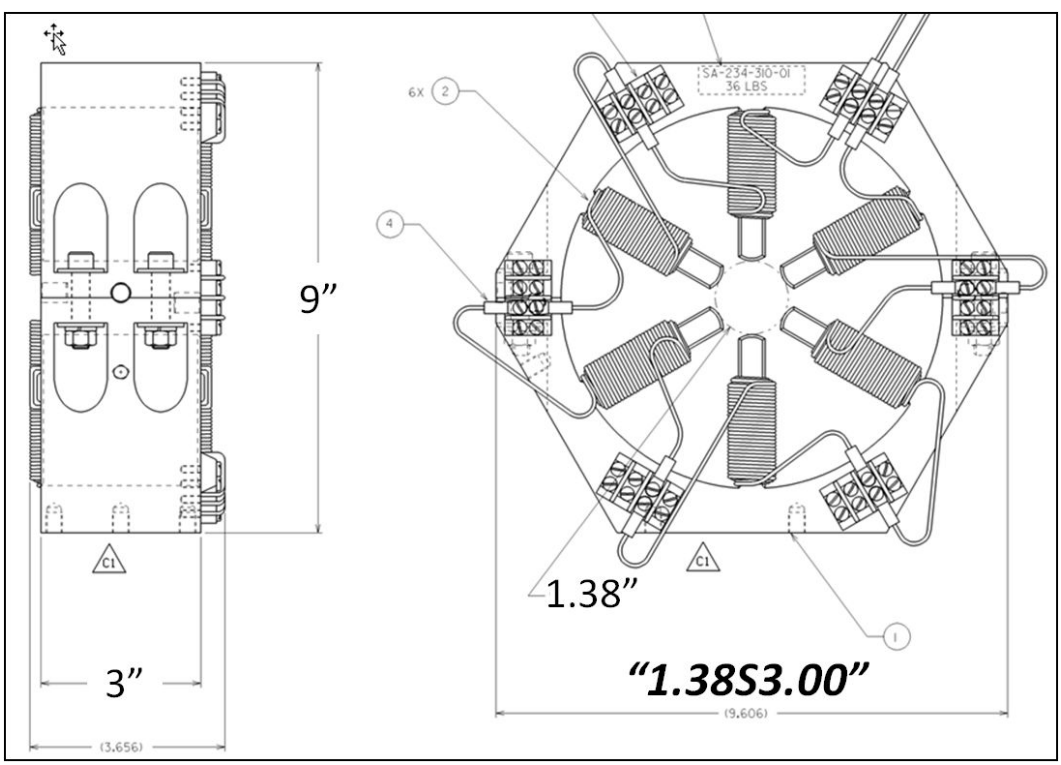

Figure 9: Sextupole magnet design ("*1.38S3.00*") for each of the eight magnets needed in LCLS-II. The bore diameter is 1.38" (35 mm), the effective magnetic length is 0.1 m (needs verification), and the maximum derivative of the field gradient is 870 kG/m at 8 Amperes.

Table 3: Existing FFTB sextupole magnet parameters ("*1.38S3.00*").

Parameter	**symbol**	**value**	**units**
Magnetic length (approx.)	L	0.1	m
Magnet exterior height/width (approx.)	h, w	24	cm
Pole-tip radius (without vacuum chamber)	r	17.5	mm
Maximum length-integrated 2nd field derivative	$\lvert\partial^2 B/\partial x^2\rvert L$	870	kG/m
Maximum K_2 value achievable (at 4 GeV)	$\lvert K_2\rvert$	65	m^{-3}
Maximum pole-tip field achievable	$\lvert B_{pt}\rvert$	1.3	kG
Maximum associated excitation current	$\lvert I_{max}\rvert$	8	A

Alignment Tolerances

A misaligned *normal* sextupole magnet located in a beamline where the dispersion dominates the beam size, $|\eta_x|\sigma_\delta/(\beta_x\varepsilon_{x0})^{1/2} >> 1$, will generate horizontal dispersion with a horizontal offset, Δx, and vertical dispersion with a vertical offset, Δy. The projected emittance dilution per plane for these dispersion errors is given by

$$\frac{\Delta\varepsilon_x}{\varepsilon_{x0}} \approx \frac{1}{2}(K_2 L\beta_x)^2 \left(\frac{\eta_x^2\sigma_\delta^2}{\beta_x\varepsilon_{x0}}\right)\Delta x^2 ,$$

$$\frac{\Delta\varepsilon_y}{\varepsilon_{y0}} \approx \frac{1}{2}(K_2 L)^2 \beta_x\beta_y \left(\frac{\varepsilon_{x0}}{\varepsilon_{y0}}\right)\left(\frac{\eta_x^2\sigma_\delta^2}{\beta_x\varepsilon_{x0}}\right)\Delta y^2 ,$$

where the symbols have been introduced previously and we assume the dispersion dominates both the horizontal and vertical beam sizes in the sextupole.

As an example we take the *SX5* magnet ($K_2 \approx 8.24$ m^{-3}) in the SXR dog-leg (section-**4**), with $\beta_x \approx 43$ m, $\beta_y \approx 7.5$ m, $\eta_x \approx 0.154$ m, $\sigma_\delta \approx 0.3\%$, $\gamma\varepsilon_{x0} = \gamma\varepsilon_{y0} = 0.35$ μm. A horizontal offset of $\Delta x = 0.3$ mm generates a 5% horizontal emittance dilution, and a vertical offset of $\Delta y = 0.3$ mm generates an 8% vertical emittance dilution. This dilution also includes the beta-mismatch errors produced by the linear dispersion errors. These are the typical alignment tolerances (0.3 mm) for all eight sextupoles. Note also that these alignment tolerances are only important with the large, chirped energy spread. In normal conditions, with a low energy spread beam, all eight sextupoles can be switched off with no significant impact on FEL operations.

References

[1] *Elegant*, M. Borland *et al.*, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, Sep. 2000.