

## Tuning of R56 in the LCLS-II

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## 1 Introduction

$R_{56}$ is a term of a first order transfer matrix which describes transformation of particle longitudinal position in a bunch (in linear approximation) from initial point $i$ to final point $f\left(z_{i} \rightarrow z_{f}\right)$ as a function of relative momentum deviation $\left(\delta=\frac{p-p_{0}}{p_{0}}\right)$, where $p$ is the particle momentum and $p_{0}$ is the nominal momentum:

$$
\begin{equation*}
z_{f}=z_{i}+R_{56} \delta_{i} \tag{1}
\end{equation*}
$$

Dependence of longitudinal position on momentum is mainly caused by transverse dispersion ( $\eta$ ) in bending magnets resulting in different path lengths for particles with different momenta. The $R_{56}$ from these magnets can be expressed through the dispersion and the bending radius $\rho$ or bending angle $\theta$ :

$$
\begin{equation*}
R_{56}=\int \frac{\eta}{\rho} d s=\sum_{k} \bar{\eta}_{k} \theta_{k} \tag{2}
\end{equation*}
$$

where $\bar{\eta}$ is an average dispersion in a magnet. The $R_{56}$ is therefore created in magnets which have both nonzero dispersion and bending angle; most contributions are from the main dipoles and to a lesser extent from steering correctors and offset quadrupoles. Sign convention for dispersion, dipole bending radius and angle in Eq. (2) is as defined in MAD [1]. The sign of $R_{56}$ used in this note, however, is opposite to the one in MAD. From Eq. (2), one can see that $R_{56}$ of a four-bend symmetric chicane without inner quadrupoles is negative. Analytic estimate of the four-bend chicane $R_{56}$ is

$$
\begin{equation*}
R_{56}^{c h} \approx-2 \theta^{2}\left(\frac{2}{3} L_{B}+L_{D}\right) \tag{3}
\end{equation*}
$$

where $L_{B}$ is the straight dipole length and $L_{D}$ is the drift length between the first and the second dipoles, projected to the straight axis of the incoming beam.

Both bending and non-bending parts of a beamline make an additional contribution to $R_{56}$ proportional to the length of the section:

$$
\begin{equation*}
R_{56}^{L}=-\frac{L}{\beta_{L}^{2} \gamma_{L}^{2}} \tag{4}
\end{equation*}
$$

where $L$ is the length of the section where the $R_{56}^{L}$ is measured, and $\beta_{\mathrm{L}}, \gamma_{\mathrm{L}}$ are Lorenz factors. This fixed contribution is generated along the entire length of beamline even with dipoles turned off. The $R_{56}^{L}$ may be noticeable only at beam energies well below 1 GeV , for example, $R_{56}^{L}=-1 \mu m$ is generated over every 61.3 m of beamline at 4 GeV , but at every 3.83 cm at 0.1 GeV . Analytically calculated from Eq. (4), the accumulated $R_{56}^{L}$ along the LCLS-II from the injector to the beginning of undulator is shown in Figure 1. The total accumulated $R_{56}^{L}$ is about -2.6 mm . Most of it is generated in the beginning of the beamline where energy is low. Optics codes such as MAD [1] automatically include the $R_{56}^{L}$ term in the calculated $R_{56}$.
Ability to tune the $R_{56}$ is important in a Free Electron Laser (FEL) for optimization of the bunch length compression and achieving maximum peak current. Also, some beamline sections generate unwanted $R_{56}$, and an ability to compensate it is found to be critical for mitigating the micro-bunching instability [2].
In the LCLS-II [3], large sources of $R_{56}$ are intentionally included in the design in the form of the Laser Heater (LH) chicane [4] and the bunch compressor chicanes BC1 [5] and BC2 [6]. Unintentional smaller contributions of $R_{56}$ come from other dipoles which are used to guide the beam in the LCLS-II tunnel. Among the latter are dipoles in the Bypass dogleg, the Hard X-Ray (HXR) and Soft X-Ray (SXR) beam Spreader lines, and the HXR and SXR LTU doglegs. Finally, weak tunable Compensation Chicanes (CC) [7] are included near the main dipoles in the Bypass and LTU doglegs to mitigate the formation of microbunching instability by compensating the local $R_{56}$ [2].
Design values of $R_{56}$ for each bending section of the LCLS-II are listed in Table 1, where the $R_{56}^{L}$ term is included. The beam energy and the $R_{56}$ tuning capability of each section are also indicated. The listed values correspond to the LCLS-II lattice version dated January 22, 2021. Note that the HXR LTU dogleg in this table is presented as two parts, dogleg-1 and dogleg-2, which are separated by a quadrupole section.


Figure 1: Beam energy and accumulated $R_{56}^{L}$ term along the LCLS-II from the injector to the beginning of undulator. Absolute $\left|R_{56}^{L}\right|$ value is shown.

The $R_{56}$ settings may continue to be further optimized following the lattice development, subsequent beam studies and for the machine operation. The optimal $R_{56}$ values may also depend on the operational beam parameters. For beam optimization, a sufficient $R_{56}$ tuning capability is built in the LCLS-II design. This is mainly done through the dedicated Laser Heater chicane, the BC1 and BC2 compression chicanes, and the $R_{56}$ Compensation Chicanes. Additionally, optics of the HXR and SXR beam Spreader lines and the HXR LTU dogleg allow limited $R_{56}$ variation using quadrupole adjustment.

Table 1: Design $R_{56}$ values in the LCLS-II (per lattice version "January 22, 2021"). The $R_{56}^{L}$ term is included.

| Section | Bending magnets | $\mathbf{R}_{56}$ (mm) | E (GeV) | Tunable |
| :---: | :---: | :---: | :---: | :---: |
| Laser Heater chicane | BCXH1 / 2/3/4 | -3.50 | 0.1 | Yes |
| BC1 | BCX11 / 12 / 13 / 14 | -53.0 | 0.25 | Yes |
| BC2 | BCX21 / 22 / 23 / 24 | -45.0 | 1.5 | Yes |
| Bypass dogleg CC (u/s) | BCXDLU1 / 2 / 3 / 4 | -0.132 | 4.0 | Yes |
| Bypass dogleg | BRB1/2 | +0.198 | 4.0 | No |
| Bypass dogleg CC (d/s) | BCXDLD $/ 2 / 3 / 4$ | -0.132 | 4.0 | Yes |
| HXR spreader | BKYSP1H / 2H / 3H, BLXSPH, BYSP1H / 2H, BRSP1H / 2H, BXSP1H | 0 | 4.0 | Yes |
| HXR LTU vertical bend | BY1 / 2 | +0.001 | 4.0 | No |
| HXR LTU dogleg-1 CC (u/s) | BCX311/312 / 313 / 314 | 0 | 4.0 | Yes |
| HXR LTU dogleg-1 | BX31/32 | +0.066 | 4.0 | Yes* |
| HXR LTU dogleg-1 CC (d/s) | BCX321 / 322 / 323 / 324 | -0.088 | 4.0 | Yes |
| HXR LTU dogleg-2 CC (u/s) | BCX351 / 352 / 353 / 354 | -0.044 | 4.0 | Yes |
| HXR LTU dogleg-2 | BX35 / 36 | +0.066 | 4.0 | Yes* |
| HXR LTU dogleg-2 CC (d/s) | BCX361 / 362 / 363 / 364 | -0.044 | 4.0 | Yes |
| SXR spreader | BKYSP1S / 2S / 3S, BLXSPS, BYSP1S / 2S, BXSP1S / 2S / 3S | 0 | 4.0 | Yes |
| SXR LTU dogleg CC (u/s) | BCX31B1 / 31B2 / 31B3 / 31B4 | -0.201 | 4.0 | Yes |


| SXR LTU dogleg | BX31B / 32B | +0.306 | 4.0 | No |
| :--- | :--- | :---: | :---: | :---: |
| SXR LTU dogleg CC (d/s) | BCX32B1 / 32B2 / 32B3 / 32B4 | -0.201 | 4.0 | Yes |
| SXR LTU vertical bend | BY1B / 2B | +0.002 | 4.0 | No |

* $R_{56}$ of the HXR LTU dogleg-1 and 2 cannot be tuned independently, they have to be tuned together.

In this paper, we summarize the $R_{56}$ tuning ranges of the LCLS-II bending sections including the Laser Heater chicane, the BC1 and BC2 chicanes, the HXR and SXR beam Spreader transfer lines, and the HXR and SXR LTU doglegs. For each section, we describe the optics adjustments used for the $R_{56}$ variation which include tuning of dipole and/or quadrupole strengths. In case of the SXR LTU, we present an option of $R_{56}$ tuning using steering correctors. We also quantify the $R_{56}^{L}$ contribution which exists even if the dipoles are turned off. In low energy cases, this fixed term is subtracted from the total $R_{56}$ in order to show the net effect from the dipoles. The calculations are performed using MAD [1] and elegant [8] codes.

## 2 Laser Heater Chicane

A four-bend horizontal chicane in the Laser Heater (LH) [4], where beam energy is 0.1 GeV , is designed to produce an adjustable closed orbit bump with maximum orbit in the range from 0 to 75 mm . The corresponding range of the dipole bending angle is shown in Figure 2 (left), where $\left|\theta_{\max }\right|=22.11 \mathrm{mrad}$. The chicane dipoles are rectangular, aligned parallel to the incoming beam straight axis, and permanently installed on beam trajectory corresponding to the 75 mm bump. The dipole chamber is wide enough to accept the orbit in the full design range from 0 (dipoles off) to 75 mm (maximum field). The chicane horizontal dispersion is nearly identical and opposite in sign to the orbit.

At 0.1 GeV the fixed term $R_{56}^{L}$ in this chicane is equal to -0.223 mm . This term exists even if the chicane is turned off. When plotting the $R_{56}$, we subtract this fixed term, so the resulting $R_{56}$ arises only from a nonzero bending angle and fits the form of Eq. (3).

The sign of chicane $R_{56}$ is always negative per Eq. (3), but here we use the absolute $\left|R_{56}\right|$ value which is more in line with its use in the LCLS-II control software. Figure 2 (right) shows the $\left|R_{56}\right|$ versus the bump peak orbit $|X|$, where the term $R_{56}^{L}$ is subtracted. For the design range of the chicane bump amplitude from 0 to 75 mm the corresponding range of $\left|R_{56}\right|$ is from 0 to 3.280 mm without the $R_{56}^{L}$, and from 0.223 mm to 3.503 mm with the $R_{56}^{L}$. These results are for the case, where the Laser Heater undulator is turned off.


Figure 2: Dipole bending angle $|\theta|$ (left) and chicane $\left|R_{56}\right|$ (right) versus peak horizontal orbit $|X|$ in the Laser Heater chicane. Absolute values are shown. Equations represent the data fit. Fixed term $R_{56}^{L}$ is subtracted from the $R_{56}$.

Changing the dipole bending angle not only changes the chicane orbit and dispersion, but also affects beta functions due to the dipole weak focusing. In rectangular dipoles, horizontal focusing in the dipole body
and horizontal defocusing at the dipole edges cancel each other. Hence, the only remaining effect is vertical focusing at the dipole edges. Due to the straight alignment of the chicane dipoles, only one edge (entrance or exit) of each dipole produces non-zero vertical focusing corresponding to the matrix term $R_{43}=$ $-\frac{1}{\rho} \tan \theta \approx-\frac{\theta^{2}}{L_{B}}$ [9] where $L_{B}$ is the dipole length. The edge focusing perturbs the beta functions downstream of the chicane which need to be corrected. Note that the sign of the bump orbit does not make difference for the $R_{56}$ and the dipole focusing since both effects depend on $\theta^{2}$.

To correct the perturbed $\beta_{\mathrm{x}, \mathrm{y}}$ and $\alpha_{\mathrm{x}, \mathrm{y}}$ functions, a minimum of four quadrupoles are required. For match in the Laser Heater, we use four quadrupoles immediately downstream of the chicane, namely QHD01 to QHD04. Since the chicane bending is not large, the dipole focusing effect is relatively small. Figure 3 shows the Laser Heater matched optics functions for two extreme dipole settings corresponding to bump with 75 mm peak orbit and no bump (dipoles turned off). Beta functions in these two cases are practically the same; this implies that the quadrupole adjustments are very small. This is confirmed in Figure 4 showing nearly flat quadrupole K -values as a function of the bump peak orbit $|X|$, where the maximum relative change of K -value is less than $0.8 \%$.

Second order polynomial fit of the K-values versus the bump peak orbit $|X|$ is provided below, where Kvalues are in units of $1 / \mathrm{m}^{2},|X|$ is in mm , and the design $|X|$ range is from 0 to 75 mm :

KQHD01 $=-1.14373 \mathrm{e}-5|\mathrm{X}|^{2}+2.46571 \mathrm{e}-5|\mathrm{X}|-8.35670$
KQHD02 $=+3.84534 \mathrm{e}-6|\mathrm{X}|^{2}-8.85390 \mathrm{e}-6|\mathrm{X}|+6.26992$
KQHD03 $=+7.58986 \mathrm{e}-6|\mathrm{X}|^{2}+5.60087 \mathrm{e}-6|\mathrm{X}|-8.81928$
KQHD04 $=-4.42469 \mathrm{e}-6|\mathrm{X}|^{2}+1.11222 \mathrm{e}-6|\mathrm{X}|+6.98911$

Quadratic fit of the chicane $\left|R_{56}\right|$ (in mm$)$ versus the bump peak orbit $|X|$ (mm), where the $R_{56}^{L}$ term $(-0.223$ mm ) is subtracted, is:
$\left|\mathrm{R}_{56}\right|=5.83111 \mathrm{e}-4|\mathrm{X}|^{2}$
Optics calculations are performed using MAD, and the polynomial fit is obtained with MS Excel.


Figure 3: Beta functions and horizontal dispersion in the Laser Heater for the chicane peak orbit $|X|$ of $75 \mathbf{m m}$ (left) and 0 mm (right).


Figure 4: K-values of Laser Heater matching quadrupoles versus peak horizontal orbit $|X|$ in the chicane.

## 3 BC1

BC1 [5] is the first LCLS-II bunch compressor chicane located in the superconducting RF linac (SRF) at beam energy of 0.25 GeV . It is composed of four rectangular horizontal dipoles aligned parallel to the incoming beam trajectory. The design operational range of $\left|R_{56}\right|$ from 0 to 75 mm is achieved by variation of the dipole bending angle. This corresponds to a large variation of the chicane bump amplitude from 0 to 318 mm . To accommodate the large orbit range and have reasonable magnet aperture, two inner dipoles and diagnostics at the BC 1 center are installed on a common translation stage which can move transversely in order to always keep the magnets and devices centered on the beam.

Variation of the $\mathrm{BC} 1\left|R_{56}\right|$ within the design range as a function of the dipole bending angle is shown in Figure 5, where the maximum bending angle $\left|\theta_{\max }\right|=120.05 \mathrm{mrad}$. The fixed term $R_{56}^{L}$ at 0.25 GeV is equal to -0.031 mm and subtracted from the data in the plot. The MAD calculated data points are fit to the fourth order polynomial shown below, where $\left|R_{56}\right|$ is in mm and $|\theta|$ is in rad:
$\left|\mathrm{R}_{56}\right|=+6156.88|\theta|^{4}-50.6504|\theta|^{3}+5143.59|\theta|^{2}-0.05121|\theta|+3.2 \mathrm{e}-6$
The fit is dominated by the quadratic term, as expected from Eq. (3).


Figure 5: BC1 chicane $\left|R_{56}\right|$ versus dipole bending angle $|\theta|$. Absolute values are shown. Equation represents the data fit. Fixed term $R_{56}^{L}$ is subtracted from the $\boldsymbol{R}_{56}$.

Due to the larger operational bending angles, effect of the BC 1 dipole edge focusing $\left(\sim \frac{\theta^{2}}{L_{B}}\right)$ on beta functions is significantly stronger than in the Laser Heater chicane. Although four quadrupoles are sufficient to correct the downstream beta functions, six matching quadrupoles are needed. The two extra quadrupoles are used to preserve the small horizontal beta waist at the last chicane dipole; this feature is built into the nominal optics design in order to minimize the effects of Coherent Synchrotron Radiation (CSR) on the transverse emittance during bunch compression. For the match, we use two quadrupoles located immediately upstream of the BC 1 (QCM03, Q1C01) and four downstream quadrupoles (QC101, QC102, QC103, QC105). The specific last four quadrupoles are selected based on the better beta match they provide compared to other available quadrupole choices.

The impact of the BC 1 dipole focusing on the optics is demonstrated in Figure 6, where the matched optics is shown for the cases of $\left|R_{56}\right|$ equal to $75 \mathrm{~mm}, 53 \mathrm{~mm}$ (nominal), 15 mm , and 0 mm . The most noticeable effect is a growth of vertical beta function near the exit of the chicane for the $\left|R_{56}\right|$ setting near zero.


Figure 6: Beta functions and horizontal dispersion in the BC 1 and adjacent area at $\left|R_{56}\right|$ values of (from left to right): 1) $\mathbf{7 5} \mathrm{mm}$, 2) nominal 53 mm , 3) 15 mm , and 4) 0 mm .

The matching quadrupole K-values versus the $\mathrm{BC} 1\left|R_{56}\right|$ are presented in Figure 7, where the curves represent the second order polynomial fit of the data points. The polynomial fit values are provided below, where the K -values are in units of $1 / \mathrm{m}^{2}$ and $\left|R_{56}\right|$ is in mm :

KQCM03 $=-4.39076 \mathrm{e}-8\left|\mathrm{R}_{56}\right|^{2}-6.07376 \mathrm{e}-5\left|\mathrm{R}_{56}\right|+0.23556$
KQ1C01 $=+3.31476 \mathrm{e}-7\left|\mathrm{R}_{56}\right|^{2}-2.12196 \mathrm{e}-4\left|\mathrm{R}_{56}\right|+0.98102$
KQC101 $=+1.78269 \mathrm{e}-4\left|\mathrm{R}_{56}\right|^{2}+1.07790 \mathrm{e}-2\left|\mathrm{R}_{56}\right|-1.51969$
KQC102 $=+4.92828 \mathrm{e}-5\left|\mathrm{R}_{56}\right|^{2}+1.26586 \mathrm{e}-2\left|\mathrm{R}_{56}\right|+1.37044$
KQC103 $=-8.91917 \mathrm{e}-5\left|\mathrm{R}_{56}\right|^{2}-1.36834 \mathrm{e}-2\left|\mathrm{R}_{56}\right|+0.94253$
KQC105 $=+4.29310 \mathrm{e}-5\left|\mathrm{R}_{56}\right|^{2}+1.05705 \mathrm{e}-2\left|\mathrm{R}_{56}\right|-2.22263$

One can see that adjustments required for the first two quadrupoles (QCM03, Q1C01) are much smaller than those for the other four quadrupoles. This is because these two quadrupoles are used to control the low horizontal beta function at the last BC 1 dipole which is not as much affected by the dipole edge focusing as compared to the vertical beta function. This can be seen in Figure 7, where the corresponding K-value curves are nearly flat. The optics calculations are performed using MAD, and the polynomial fit is obtained with MS Excel.


Figure 7: K-values of BC1 matching quadrupoles versus BC1 $\left|R_{56}\right|$. Fixed term $R_{56}^{L}$ is subtracted from the $R_{56}$.

## 4 BC2

BC2 [6] is the second LCLS-II bunch compressor chicane located in the SRF linac at beam energy of 1.5 GeV . The chicane is composed of four rectangular horizontal dipoles aligned parallel to the incoming beam straight trajectory. As in BC 1 , the BC 2 design $\left|R_{56}\right|$ range is from 0 to 75 mm achieved by variation of the dipole bending angle. Beam energy at the BC 2 is six times higher than at BC 1 , therefore to achieve the same $R_{56}$ with a reasonable dipole field, the BC 2 has a factor of 2.7 longer dipoles and a factor of 4 longer distance between the outer and inner dipoles. As a result, the BC 2 is a factor of 3.2 longer than the BC 1 . The design range of $R_{56}$ corresponds to a large variation of the BC 2 orbit amplitude from 0 to 630 mm . To accommodate this large orbit range with reasonable magnet aperture, two inner dipoles and diagnostics at the BC2 center are installed on a common translation stage which can move transversely in order to always keep the magnets and devices centered on the beam.
Variation of the $\mathrm{BC} 2\left|R_{56}\right|$ within the design range as a function of the dipole bending angle is shown in Figure 8, where the maximum bending angle $\left|\theta_{\max }\right|=60.48 \mathrm{mrad}$. The fixed term $R_{56}^{L}$ at 1.5 GeV is small and equal to -0.003 mm ; it is subtracted from the plot. The MAD calculated data points are fit to the fourth order polynomial shown below, where $\left|R_{56}\right|$ is in mm and $|\theta|$ is in rad:
$\left|\mathrm{R}_{56}\right|=+23873.1|\theta|^{4}-46.2591|\theta|^{3}+20454.3|\theta|^{2}-0.036204|\theta|+1.6 \mathrm{e}-8$
The fit is dominated by the quadratic term, as expected from Eq. (3).
Effect of the BC2 dipole edge focusing $\left(\sim \frac{\theta^{2}}{L_{B}}\right)$ on beta functions is an order of magnitude weaker than in the BC 1 due to a factor of 2 smaller bending angle and a factor of 2.7 longer dipole. Hence, dependence of the BC 2 matching quadrupole strengths on $R_{56}$ is expected to be more flat as compared to BC 1 strengths in Figure 7. For the BC2 match, we use the total of eight quadrupoles. Four quadrupoles match beta functions in the downstream area. Two additional quadrupoles maintain the small horizontal beta waist at the last BC 2 dipole for reduction of the CSR effects on transverse emittance. Finally, two more quadrupoles are needed to preserve the $x / y$ beta waist at the wire scanner WSEMIT2 downstream of the BC2 for emittance measurement. In this scheme, the first two matching quadrupoles are located immediately before the BC2 (QCM15, Q2C01) and the six other quadrupoles are directly after the BC2 (QE201, QE202, QE203, QE204, QCM16, QCM17).


Figure 8: BC2 chicane $\left|R_{56}\right|$ versus dipole bending angle $|\theta|$. Absolute values are shown. Equation represents the data fit. Fixed term $\boldsymbol{R}_{56}^{L}$ is subtracted from the $\boldsymbol{R}_{56}$.

The effect of the BC2 dipole focusing is demonstrated in Figure 9 showing matched optics for the $\left|R_{56}\right|$ of $75 \mathrm{~mm}, 45 \mathrm{~mm}$ (nominal), and 0 mm . Similar to BC1, the most effect is a growth of vertical beta function near the exit of the BC 2 at $\left|R_{56}\right|$ values near zero, however it is more modest than in the BC 1 .


Figure 9: Beta functions and horizontal dispersion in the BC 2 and adjacent area at $\left|R_{56}\right|$ of 75 mm (left), 45 mm (center), and 0 mm (right).

The matching quadrupole K -values versus the $\mathrm{BC} 2\left|R_{56}\right|$ are shown in Figure 10 , where the curves represent the second order polynomial fit of the data points. The polynomial fit is provided below, where the Kvalues are in units of $1 / \mathrm{m}^{2}$ and $\left|R_{56}\right|$ is in mm :

KQCM15 $=+5.0746 \mathrm{e}-10\left|\mathrm{R}_{56}\right|^{2}-4.18815 \mathrm{e}-5\left|\mathrm{R}_{56}\right|+0.069129$
KQ2C01 $=-3.60359 \mathrm{e}-9\left|\mathrm{R}_{56}\right|^{2}+4.96182 \mathrm{e}-5\left|\mathrm{R}_{56}\right|+0.50687$
KQE201 $=+3.34081 \mathrm{e}-6\left|\mathrm{R}_{56}\right|^{2}+1.50476 \mathrm{e}-3\left|\mathrm{R}_{56}\right|-1.37582$
KQE202 $=-1.01617 \mathrm{e}-6\left|\mathrm{R}_{56}\right|^{2}-2.82407 \mathrm{e}-4\left|\mathrm{R}_{56}\right|+2.00469$
KQE203 $=+3.25838 \mathrm{e}-5\left|\mathrm{R}_{56}\right|^{2}+1.16752 \mathrm{e}-3\left|\mathrm{R}_{56}\right|-1.91687$
KQE204 $=-1.08362 \mathrm{e}-5\left|\mathrm{R}_{56}\right|^{2}-2.42748 \mathrm{e}-4\left|\mathrm{R}_{56}\right|+1.67814$
KQCM16 $=+1.97698 \mathrm{e}-6\left|\mathrm{R}_{56}\right|^{2}-2.89948 \mathrm{e}-4\left|\mathrm{R}_{56}\right|-0.30831$
KQCM17 $=+3.52098 \mathrm{e}-7\left|\mathrm{R}_{56}\right|^{2}+1.42407 \mathrm{e}-4\left|\mathrm{R}_{56}\right|+0.25203$

The quadrupole K-values in Figure 10 are mostly flat with the $\left|R_{56}\right|$ as expected from the reduced dipole edge focusing as compared to BC1. As seen from the polynomials, the K-value adjustment for the first two quadrupoles (QCM15, Q2C01) is the smallest since they control only the horizontal beta functions which are less affected by the dipole focusing. The optics calculations are performed using MAD, and the polynomial fit is obtained with MS Excel.


Figure 10: K-values of BC2 matching quadrupoles versus $\mathbf{B C} 2\left|R_{56}\right|$. Fixed term $R_{56}^{L}$ is subtracted from the $R_{56}$.

## 5 HXR Spreader

The beam Spreader [10] distributes the LCLS-II bunches between the HXR and SXR undulators and the BSY dump. The beam is deflected on a bunch by bunch basis using high frequency vertical kickers and horizontal Lambertson septum magnets. Further separation between the three lines is achieved using DC dipoles. The Spreader layout is fixed, therefore, unlike the LH chicane and the BC 1 and BC 2 , the bending angles of the Spreader dipoles cannot be changed for $R_{56}$ adjustment.
The HXR Spreader is a dogleg which connects the LCLS-II Bypass line with the existing LCLS beamline in the Beam Switch Yard (BSY), thus directing the beam towards the HXR undulator. Geometry of the dogleg is determined by the bending magnets: vertical kickers, a horizontal Lambertson septum, two vertical dipoles, two rolled DC dipoles, and one horizontal DC dipole. Hence, the beam is transported in both horizontal and vertical planes. Dogleg quadrupoles match the beta functions and locally cancel the horizontal and vertical dispersion while satisfying the nominal condition of $R_{56}=0$.
$R_{56}$ contributions from the first and the last bending magnets of the dogleg (the kicker/septum and the last DC dipole) are fixed since the bending angles and dispersion in these magnets are determined by the layout and dispersion cancellation condition at each dogleg end. Therefore, variation of $R_{56}$ is only possible by modifying dispersion in the inner dogleg dipoles which is achieved by changing the dogleg quadrupole focusing. This adjustment should be local, i.e. it should not affect the optics outside of the dogleg; also the modified beta functions, dispersion and quadrupole strengths should be within an acceptable range.
Most of the Spreader magnets are located and powered symmetrically with respect to the center. Minor asymmetry is due to the use of kicker/septum system at one end and DC bend at the other end of the dogleg; also two vertical dipoles are included in the beginning of the beamline to cancel the vertical orbit from the kicker. Consequently, the dogleg optics functions are nearly symmetric (beta) or anti-symmetric (dispersion) with respect to the center.
There are total of 13 HXR Spreader quadrupoles. The quadrupole powering scheme implemented in the machine is nearly symmetric, where symmetrically located pairs of quadrupoles use the same power supply, except one pair (QSP2H, QSP12H) and the single center quadrupole (QSP7H) which are powered individually. This results in total of 8 independent quadrupole K -values in the dogleg.

For the $R_{56}$ tuning and optics match, in addition to the 8 dogleg independent K -values, 4 additional quadrupoles downstream of the dogleg (Q4, Q5, Q6, QA0) are used. This allows to satisfy all the matching conditions ( $\beta_{\mathrm{x}, \mathrm{y}}, \alpha_{\mathrm{x}, \mathrm{y}}, \eta_{\mathrm{x}, \mathrm{y}}, \eta_{\mathrm{x}, \mathrm{y}^{\prime}}$ and $R_{56}$ ) without affecting the downstream area. The resulting $R_{56}$ range is from -2 mm to +1 mm . Outside of this range, large beta peaks start to develop. Optics functions for the
nominal, minimum and maximum $R_{56}$ values are presented in Figure 11. One can see that at the negative $R_{56}$ larger beta functions develop near the center of the Spreader and there is growth of vertical dispersion, while at the positive $R_{56}$ the beta functions increase near the Spreader ends and the impact on dispersion is mostly in the horizontal plane. The optics perturbations are smaller for smaller changes of $R_{56}$.


Figure 11: Beta functions and dispersion in the HXR Spreader and BSY at $R_{56}$ of 0 mm (left, nominal), $-\mathbf{2} \mathrm{mm}$ (center), and +1 mm (right).

The matching quadrupole K -values versus the Spreader $R_{56}$ are presented in Figure 12, where each curve is a sixth order polynomial fit of the data points, and a quadrupole name with " $/$ " represents two symmetric quadrupoles connected to the same power supply (e.g. the name QSP1H/13H is for QSP1H and QSP13H symmetric quadrupoles). The fixed term $R_{56}^{L}$ at 4 GeV in the HXR Spreader is $-5.4 \mu \mathrm{~m}$, and it is not subtracted from the result. The polynomial fit values are listed below, where the K-values are in units of $1 / \mathrm{m}^{2}$ and $R_{56}$ is in mm . All optics calculations are performed using MAD, and the polynomial fit is obtained with MS Excel.

$$
\begin{aligned}
& \mathrm{KQSP} 1 \mathrm{H} / 13 \mathrm{H}=-9.7805 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}-3.1575 \mathrm{e}-3 \mathrm{R}_{56}{ }^{5}-4.1593 \mathrm{e}-4 \mathrm{R}_{56}{ }^{4}+5.3153 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+8.9102 \mathrm{e}-4 \mathrm{R}_{56}{ }^{2}+7.5241 \mathrm{e}-2 \mathrm{R}_{56}+0.49247 \\
& \text { KQSP2H } \quad=+8.8930 \mathrm{e}-3 \mathrm{R}_{56}{ }^{6}+2.7988 \mathrm{e}-2 \mathrm{R}_{56}{ }^{5}+1.0097 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}-5.2061 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-1.9814 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-4.2561 \mathrm{e}-2 \mathrm{R}_{56}-1.0030 \\
& \text { KQSP3H/11H }=-1.4060 \mathrm{e}-2 \mathrm{R}_{56}{ }^{6}-4.4759 \mathrm{e}-2 \mathrm{R}_{56}{ }^{5}+4.1287 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+8.8672 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-5.0468 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}-6.2253 \mathrm{e}-2 \mathrm{R}_{56}+0.30647 \\
& \text { KQSP4H/10H }=+2.7859 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}+1.0424 \mathrm{e}-3 \mathrm{R}_{56}{ }^{5}-1.0433 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}-2.6872 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+1.9401 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-7.7991 \mathrm{e}-3 \mathrm{R}_{56}-0.30023 \\
& \text { KQSP5H/9H }=+4.1235 \mathrm{e}-3 \mathrm{R}_{56}{ }^{6}+7.1962 \mathrm{e}-3 \mathrm{R}_{56}{ }^{5}-1.7032 \mathrm{e}-2 \mathrm{R}_{56}{ }^{4}-2.2962 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}+3.1071 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-1.2338 \mathrm{e}-2 \mathrm{R}_{56}+0.17849 \\
& \mathrm{KQSP} 6 \mathrm{H} / 8 \mathrm{H}=+6.7861 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}+4.1522 \mathrm{e}-3 \mathrm{R}_{56}{ }^{5}+5.4499 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}-8.2086 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}-1.7040 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}+1.6884 \mathrm{e}-2 \mathrm{R}_{56}-0.22258 \\
& \text { KQSP7H }=-1.8665 \mathrm{e}-2 \mathrm{R}_{56}{ }^{6}-5.7053 \mathrm{e}-2 \mathrm{R}_{56}{ }^{5}-8.3049 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+1.1541 \mathrm{e}-1 \mathrm{R}_{56}{ }^{3}+1.3949 \mathrm{e}-1 \mathrm{R}_{56}{ }^{2}+9.7678 \mathrm{e}-2 \mathrm{R}_{56}+0.44972 \\
& \mathrm{KQSP}_{12} \mathrm{H}=+8.2081 \mathrm{e}-3 \mathrm{R}_{56}{ }^{6}+2.6917 \mathrm{e}-2 \mathrm{R}_{56}{ }^{5}+4.7871 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}-4.4608 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-1.9148 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-4.5563 \mathrm{e}-2 \mathrm{R}_{56}-1.0026 \\
& \text { KQ4 } \quad=+2.6977 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}+2.0374 \mathrm{e}-3 \mathrm{R}_{56}{ }^{5}+4.5999 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+2.5440 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}-2.4443 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}-2.1175 \mathrm{e}-3 \mathrm{R}_{56}-0.21977 \\
& \text { KQ5 } \quad=+1.3975 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}+3.5998 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}-2.3789 \mathrm{e}-4 \mathrm{R}_{56}{ }^{4}-1.0418 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}-3.3171 \mathrm{e}-4 \mathrm{R}_{56}{ }^{2}+3.1595 \mathrm{e}-4 \mathrm{R}_{56}+0.11032 \\
& \text { KQ6 } \quad=-3.6942 \mathrm{e}-4 \mathrm{R}_{56}{ }^{6}-5.7372 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}+2.0539 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+4.0414 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+3.8301 \mathrm{e}-4 \mathrm{R}_{56}{ }^{2}-1.5645 \mathrm{e}-3 \mathrm{R}_{56}-0.11003 \\
& \text { KQA0 } \quad=+7.6279 \mathrm{e}-5 \mathrm{R}_{56}{ }^{6}+2.5642 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}+9.5416 \mathrm{e}-5 \mathrm{R}_{56}{ }^{4}-3.6870 \mathrm{e}-4 \mathrm{R}_{56}{ }^{3}-2.7286 \mathrm{e}-4 \mathrm{R}_{56}{ }^{2}+1.8785 \mathrm{e}-5 \mathrm{R}_{56}+0.096593
\end{aligned}
$$



Figure 12: K-values of matching quadrupoles in the HXR Spreader and BSY versus the Spreader R56. Fixed term $R_{56}^{L}=-5.4 \mu \mathrm{~m}$ is not subtracted.

## 6 SXR Spreader

Layout of the SXR Spreader has the form of a 4-bend chicane, but also includes quadrupoles between the dipoles. The chicane allows to separate the SXR Spreader beamline from the HXR line and the BSY dump line. The SXR Spreader beamline geometry is determined by vertical kickers, a horizontal Lambertson septum, two vertical dipoles, and three horizontal DC dipoles. The beam transport is primarily in horizontal plane since the effect of the vertical kickers and the two compensating vertical dipoles on the geometry is relatively small. The Spreader quadrupoles match the beta functions and cancel dispersion while satisfying the nominal condition of $R_{56}=0$.

Similar to the HXR Spreader, the $R_{56}$ contributions from the kicker/septum and the last dipole of the SXR Spreader are not adjustable due to the fixed bending angles and the dispersion cancellation condition at either end of the chicane. Therefore, the $R_{56}$ can only be adjusted by modifying horizontal dispersion at the inner dipoles by changing the quadrupole focusing. The optics should be locally matched with reasonable beta functions, dispersion and quadrupole strengths.

The SXR Spreader magnet layout is mostly symmetric, where the nominal beta functions and horizontal dispersion are nearly symmetric with respect to the chicane center. Slight asymmetry is due to the use of the kicker/septum system at one end and horizontal DC dipole at the other end of the chicane. There are total of 9 quadrupoles in the chicane. The powering scheme implemented in the machine is exactly symmetric, where each pair of symmetrically located quadrupoles uses the same power supply, yielding 5 independent quadrupole strengths. The latter are used for the $R_{56}$ tuning providing the range from -2.3 mm to +1.9 mm . Here, the maximum positive $R_{56}$ value is limited by the strength of the unipolar QSP5S quadrupole which wants to change sign for a larger $R_{56}$. The maximum negative $R_{56}$ is limited by the maximum allowed K-value of the paired QSP4S and QSP6S quadrupoles. However, the K-value limit is determined in the assumption of the SXR beam energy up to 10 GeV . For a lower operational energy, higher K-values can be reached, therefore larger negative $R_{56}$ values are possible, but not studied here.
Optics functions for the nominal, minimum and maximum $R_{56}$ are presented in Figure 13. The matching quadrupole K-values versus the SXR Spreader $R_{56}$ are shown in Figure 14, where the curves represent the sixth order polynomial fit of the data points. The fixed term $R_{56}^{L}$ at 4 GeV in the SXR Spreader is $-2.8 \mu \mathrm{~m}$, and it is not subtracted from the result.


Figure 13: Beta functions and dispersion in the SXR Spreader and BSY at $R_{56}$ of $\mathbf{0} \mathbf{m m}$ (left, nominal), $\mathbf{- 2 . 3 \mathrm { mm }}$ (center), and $\mathbf{+ 1 . 9 ~ m m}$ (right).

The polynomial fit values are listed below, where the K -values are in units of $1 / \mathrm{m}^{2}$ and $R_{56}$ is in mm . All optics calculations are done using MAD, and the polynomial fit is obtained with MS Excel.

KQSP1S/9S $=+9.4655 \mathrm{e}-5 \mathrm{R}_{56}{ }^{6}-2.7337 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}-1.0387 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+1.8529 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+1.9203 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}+2.3437 \mathrm{e}-2 \mathrm{R}_{56}+0.63524$
KQSP2S/8S $=-2.4536 e-4 R_{56}{ }^{6}+7.5277 e-4 R_{56}{ }^{5}+2.7352 e-3 R_{56}{ }^{4}-4.9963 e-3 R_{56}{ }^{3}-5.2043 e-3 R_{56}{ }^{2}+3.0188 e-3 R_{56}-0.56302$
KQSP3S/7S $=-4.2007 \mathrm{e}-5 \mathrm{R}_{56}{ }^{6}+2.7122 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}+5.4785 \mathrm{e}-4 \mathrm{R}_{56}{ }^{4}-2.6166 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+3.7165 \mathrm{e}-4 \mathrm{R}_{56}{ }^{2}-2.5412 \mathrm{e}-2 \mathrm{R}_{56}+0.65029$
KQSP4S/6S $=+7.2090 \mathrm{e}-5 \mathrm{R}_{56}{ }^{6}-6.9449 \mathrm{e}-4 \mathrm{R}_{56}{ }^{5}-9.5914 \mathrm{e}-4 \mathrm{R}_{56}{ }^{4}+5.5518 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}+4.7198 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}+2.5343 \mathrm{e}-2 \mathrm{R}_{56}-0.49353$
KQSP5S $=+1.9763 \mathrm{e}-6 \mathrm{R}_{56}{ }^{6}+5.5372 \mathrm{e}-5 \mathrm{R}_{56}{ }^{5}-1.4276 \mathrm{e}-4 \mathrm{R}_{56}{ }^{4}-7.3605 \mathrm{e}-4 \mathrm{R}_{56}{ }^{3}-6.6256 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}-7.7351 \mathrm{e}-2 \mathrm{R}_{56}+0.18398$


Figure 14: K-values of matching quadrupoles in the SXR Spreader versus the Spreader $\boldsymbol{R}_{56}$. Fixed term $R_{56}^{L}=$ $-2.8 \mu \mathrm{~m}$ is not subtracted.

## 7 HXR LTU

The HXR LTU dogleg is located within 4-cell periodic optics shown in Figure 15. It is made of two Double Bend Achromat (DBA) cells with horizontal dipoles, separated by a cell without dipoles. The DBA cell includes two identical horizontal dipoles located symmetrically relative to a focusing quadrupole at the cell center. The two DBA cells are the same except for the opposite dipole polarities. Linear dispersion is locally cancelled in each cell, yielding two dispersion bumps of opposite sign as can be seen in Figure 15.

Four $R_{56}$ Compensation Chicanes are included adjacent to the two DBA cells to provide capability for local compensation of the dogleg positive $R_{56}$.


Figure 15: Nominal beta functions and horizontal dispersion in the HXR LTU dogleg and adjacent area. Two large dispersion bumps are in the two DBA cells. Three tiny dispersion bumps outside of the DBA cells are produced by three $R_{56}$ Compensation Chicanes; the fourth Compensation Chicane (upstream of the first cell) is turned off.

Variation of the dogleg $R_{56}$ can be obtained by changing dispersion at the DBA dipoles, according to Eq. (2). Note that dispersion may be changed only at the inner dogleg dipoles, since at the outer dipoles it is locked by the dispersion cancellation condition. The change of dispersion is achieved by varying quadrupole focusing in the two DBA cells with dipoles. Changing focusing only in one DBA cell would create residual dispersion freely propagating into the downstream area. Hence, one needs to adjust focusing in both DBA cells, so the residual dispersion from the first cell is cancelled by proper focusing adjustment in the second cell. The modified focusing also perturbs beta functions which should be corrected downstream of the dogleg.

A scheme for the $R_{56}$ adjustment in the LTU dogleg was originally developed for the LCLS [11]. This system is directly applicable to the LCLS-II HXR which reuses the LCLS LTU optics. The original $R_{56}$ tuning knob uses approximation of linear $R_{56}$ dependence on quadrupole strengths in the range of $R_{56}=$ $\pm 0.5 \mathrm{~mm}$. We redo these calculations for the LCLS-II HXR using exact match in MAD including the nonlinear dependence. In addition to cancellation of the residual dispersion, we also correct the perturbed beta functions using downstream matching quadrupoles; the latter were not included in the original knob.

The LCLS $R_{56}$ tuning knob is based on adjustment of three independent quadrupole strengths: 1) a common K-value of four identical quadrupoles QDL31 - QDL34 which are on the same power supply, 2) K-value of "tweaker" quadrupole CQ31, and 3) K-value of "tweaker" quadrupole CQ32. The knob represents the differential $R_{56}$, i.e. the change of $R_{56}$ relative to the nominal value due to the change of the quadrupole Kvalues. The total dogleg $R_{56}$ is, therefore, the sum of the nominal $R_{56}$ (knob off) and the knob $R_{56}$ values. We will denote the changes of the three K -values as $\Delta \mathrm{K}_{\mathrm{QDL}}, \Delta \mathrm{K}_{\mathrm{CQ} 31}$ and $\Delta \mathrm{K}_{\mathrm{CQ} 32}$, respectively. The three $\Delta \mathrm{K}$-values are required in order to satisfy three constraints: create the desired $R_{56}$ and cancel the perturbed spatial and angular horizontal dispersion at end of the dogleg.

The QDL31, QDL32, QDL33, QDL34 quadrupoles, which have the same K-value, are located at four periodic beta waist points, which can be seen in Figure 15, approximately $180^{\circ}$ in $x$-phase from each other. The QDL31 and QDL33 are the center quadrupoles of the two DBA cells with dipoles. They are separated from each other by about $360^{\circ}$ in $x$-phase, and are $90^{\circ}$ away from their cell dipoles. The optical periodicity and the above phase advance make these two quadrupoles most effective for creating and closing a dispersion bump for the $R_{56}$ manipulation. The $\Delta \mathrm{K}_{\mathrm{QDL}}$ in the first quadrupole QDL31 initiates the change of the horizontal dispersion $\Delta \eta_{\mathrm{x}}$ which propagates as a betatron wave: $\Delta \eta_{x}=-\eta_{x 0}(\Delta K L)_{Q D L} \sqrt{\beta_{x 0} \beta_{x}} \sin \Delta \mu_{x}$, where L is the QDL31 length, $\eta_{\mathrm{x} 0}$ and $\beta_{\mathrm{x} 0}$ are the nominal horizontal dispersion and beta function at the QDL31, and $\Delta \mu_{\mathrm{x}}$ is the $x$-phase advance from the QDL31 to a downstream point where beta function is $\beta_{\mathrm{x}}$. The $\Delta \eta_{\mathrm{x}}$ is maximized at the inner dipole of the first DBA cell since it is $90^{\circ}$ away. The $\Delta \eta_{\mathrm{x}}$ is then also
maximized (but with an opposite sign) at the inner dipole of the second DBA cell because of another $\approx 180^{\circ}$ phase advance. Note that these two inner dipoles have opposite bending angles ( $\pm \theta$ ) and opposite change of dispersion $\left( \pm \Delta \eta_{\mathrm{x}}\right)$, hence they make equal contributions to $R_{56}\left(\theta \cdot \Delta \eta_{\mathrm{x}}\right)$, thus doubling the effect. Due to the shared power supply, the same $\Delta \mathrm{K}_{\mathrm{QDL}}$ is applied to QDL33 of the second DBA cell; the latter, therefore, also creates a dispersion change which is the same as $\Delta \eta_{\mathrm{x}}$ from the QDL31, but of opposite sign due to opposite $\eta_{\mathrm{x} 0}$ in the second DBA cell. Since the QDL31 and QDL33 are separated by $\approx 360^{\circ}$ in $x$-phase, the two opposite $\Delta \eta_{\mathrm{x}}$ waves nearly cancel each other after QDL33. The small deviation from the exact $360^{\circ}$ phase advance results in a small residual dispersion at the end of the dogleg. To complete the dispersion cancellation, two weak quadrupoles CQ31 and CQ32 are used. These "tweaker" quadrupoles are inside the second DBA cell, positioned between dipole and the center quadrupole QDL33, symmetrically on two sides. The CQ31 and CQ32 are used only for tuning and nominally are turned off. The remaining QDL32 and QDL34 quadrupoles of the knob have minimal impact on dispersion and $R_{56}$ since they are located in the nominally dispersion-free region. They are not required for the knob, but included since they are on the same power supply with the QDL31 and QDL33. Since the four periodic QDL31 - QDL34 quadrupoles are approximately $180^{\circ}$ in $x$-phase from each other, their perturbations of $\beta_{\mathrm{x}}$ due to the same $\Delta \mathrm{K}_{\mathrm{QDL}}$ are in synch with each other, where $\frac{\Delta \beta_{x}}{\beta_{x}} \approx-\beta_{x 0}(\Delta K L)_{Q D L} \sin \left(2 \Delta \mu_{x}\right)$ from each quadrupole, and therefore the total effect is quadrupled. The $x$ and $y$ beta perturbations created by the adjusted quadrupoles are corrected downstream of the dogleg.
For $R_{56}$ calculation, we define the dogleg region starting from the beginning of the first dipole in the first DBA cell and ending at exit of the last dipole in the second DBA cell. This area includes two inner $R_{56}$ Compensation Chicanes located between the DBA cells - see Figure 15. The nominal $R_{56}$ of the dogleg with the contributions of the two chicanes is $-0.6 \mu \mathrm{~m}$ (including the contribution $R_{56}^{L}=-1.7 \mu \mathrm{~m}$ from the dogleg length at 4 GeV ). This nominal value is subtracted when calculating the knob $R_{56}$.
For correction of the perturbed beta functions, we use the existing four matching quadrupoles QEM1 QEM4 located downstream of the dogleg. Their K-values are fit to match the beta functions to the nominal periodic values in the LTU diagnostic FODO cells shown at the right end in Figure 15.
The calculations are performed for the range of $R_{56}= \pm 0.5 \mathrm{~mm}$ as in [11]. The resulting matched optics functions for the minimum and maximum $R_{56}$ values are presented in Figure 16. The latter can be compared to the nominal optics in Figure 15. One can see that dispersion is mostly changed between the two DBA cells, but cancelled at the end of the dogleg. Peak beta functions can grow up to $\sim 50 \%$ inside the dogleg at negative $R_{56}$. Beta functions are matched back to their nominal values in the downstream diagnostic FODO cells.


Figure 16: Beta functions and horizontal dispersion in the HXR LTU dogleg and adjacent area at $R_{56}$ of $\mathbf{- 0 . 5} \mathbf{m m}$ (left) and $\mathbf{+ 0 . 5 ~ m m ~ ( r i g h t ) . ~}$

The three matched $\Delta \mathrm{K}$-values of the dogleg quadrupoles versus the knob $R_{56}$ in the range of $\pm 0.5 \mathrm{~mm}$ are shown in Figure 17 (left). The dependences exhibit small quadratic behavior as opposed to the linear approximation used in the LCLS knob. The plotted curves in Figure 17 (left) represent the fourth order
polynomial fit of the data points obtained with MAD. The corresponding fit values are listed below, where the $\Delta \mathrm{K}$-values are in units of $1 / \mathrm{m}^{2}$ and $R_{56}$ is in mm :

```
\(\Delta \mathrm{K}_{\mathrm{QDL}}=+3.6432 \mathrm{e}-5 \mathrm{R}_{56}{ }^{4}-2.6514 \mathrm{e}-5 \mathrm{R}_{56}{ }^{3}+1.2217 \mathrm{e}-3 \mathrm{R}_{56}{ }^{2}-1.0202 \mathrm{e}-1 \mathrm{R}_{56}-1.362 \mathrm{e}-6\)
\(\Delta \mathrm{K}_{\mathrm{CQ} 31}=-6.3295 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+1.2659 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-1.3826 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-3.4465 \mathrm{e}-2 \mathrm{R}_{56}-7.396 \mathrm{e}-7\)
\(\Delta \mathrm{K}_{\mathrm{CQ} 32}=-1.5198 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+6.4425 \mathrm{e}-3 \mathrm{R}_{56}{ }^{3}-2.7079 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}+7.0354 \mathrm{e}-2 \mathrm{R}_{56}+1.231 \mathrm{e}-6\)
```

This non-linear fit can be compared to the original LCLS linear knob [11] shown below (for the same definition of $R_{56}$ sign):
$\Delta \mathrm{K}_{\mathrm{QDL}}=-1.023 \mathrm{e}-1 \mathrm{R}_{56}$
$\Delta \mathrm{K}_{\mathrm{CQ} 31}=-5.671 \mathrm{e}-2 \mathrm{R}_{56}$
$\Delta \mathrm{K}_{\mathrm{CQ} 32}=+4.717 \mathrm{e}-2 \mathrm{R}_{56}$
Comparison of linear terms in these two knobs shows that the LCLS linear knob represents the matched $\Delta \mathrm{K}$-values of the stronger QDL31 - QDL34 quadrupoles reasonably well, but is not as accurate for the weaker CQ31 and CQ32 "tweaker" quadrupoles (they are a factor of 3 shorter than the QDL31 - QDL34) which exhibit a noticeable non-linear dependence on $R_{56}$ as seen in Figure 17 (left).
K-values of the QEM1 - QEM4 quadrupoles which are used to match the beta functions are shown in the right plot of Figure 17, where the curves represent the fourth order polynomial fit of the data points. Variation of the K-values with the $R_{56}$ is relatively small, typically a few $\%$ in this range, where the maximum $|\Delta \mathrm{K} / \mathrm{K}|<7 \%$ for QEM 4 . The polynomial fit values are listed below, where the K -values are in units of $1 / \mathrm{m}^{2}$ and $R_{56}$ is in mm :

KQEM1 $=+4.5373 \mathrm{e}-2 \mathrm{R}_{56}{ }^{4}-7.7011 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-1.0105 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}+3.2213 \mathrm{e}-2 \mathrm{R}_{56}-0.39085$
KQEM $2=-1.5333 \mathrm{e}-2 \mathrm{R}_{56}{ }^{4}+4.0398 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}-2.3221 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-2.8722 \mathrm{e}-2 \mathrm{R}_{56}+0.43223$
KQEM3 $=-2.6017 \mathrm{e}-2 \mathrm{R}_{56}{ }^{4}+2.6058 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}+1.7758 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}+3.9719 \mathrm{e}-3 \mathrm{R}_{56}-0.59343$
KQEM4 $=-4.5522 \mathrm{e}-3 \mathrm{R}_{56}{ }^{4}+1.6984 \mathrm{e}-2 \mathrm{R}_{56}{ }^{3}+1.8747 \mathrm{e}-2 \mathrm{R}_{56}{ }^{2}-5.2116 \mathrm{e}-2 \mathrm{R}_{56}+0.42049$


Figure 17: $\Delta \mathrm{K}$-values of the three $R_{56}$ knob quadrupoles (left), and $K$-values of the downstream matching quadrupoles (right) in the HXR LTU dogleg versus $R_{56}$. The nominal $R_{56}=-\mathbf{0 . 6} \mu \mathrm{m}$ is subtracted from the plotted results.

The described knob uses six quadrupoles (QDL31 - QDL34, CQ31, CQ32) for the dispersion adjustment. However, the minimum required number of quadrupoles is three. The QDL31 - QDL34 are on the same power supply and, therefore, are used together, even though not all of them are needed. To study an option with only three quadrupoles, we constructed a knob where a new "tweaker" quadrupole CQ33 is used instead of the four QDL31 - QDL34 quadrupoles. Here, the CQ33 is used only for the study and is not part of the nominal design. We "inserted" the CQ33 in the first DBA cell at the nearest available location to the center quadrupole QDL31. This provides close to optimal $x$-phase advance to the dogleg inner dipoles for dispersion manipulation. The existing CQ31 and CQ32 quadrupoles in the second DBA cell are reused in this knob to close the dispersion bump. The results show that for the same change of $R_{56}$, this knob requires
significantly larger changes of K-values compared to the original knob. The stronger quadrupoles appear to be due to less efficiency of the CQ31 and CQ32 for cancellation of the dispersion perturbation as compared to the QDL33 in the original knob. The QDL33 is in the same phase with the QDL31 and therefore at an optimal position for cancellation of the dispersion generated by the QDL31. In the original knob, the CQ31 and CQ32 correct the small remaining dispersion after the QDL33 correction. In the three-quadrupole knob, however, the QDL33 is not used. Hence, the CQ31 and CQ32 must correct the full incoming dispersion perturbation. They are about $\pm 70^{\circ}$ away from the optimal QDL33 phase. For this reason, they are less efficient for the full correction, yielding higher K-values. The stronger quadrupoles also increase distortion of beta functions which require larger adjustments of the downstream matching quadrupoles. Based on these findings, we conclude that replacing the QDL31 - QDL34 in the present $R_{56}$ knob with a single CQ33 quadrupole in the first DBA cell is not a satisfactory option due to the stronger quadrupoles and larger changes of beta functions. It may be possible to improve the three-quadrupole knob by optimizing positions of the existing CQ31 or CQ32 quadrupoles, but this involves more changes to the design and was not studied.

## 8 SXR LTU

Doglegs which contain only two dipoles do not allow $R_{56}$ adjustment without leaking dispersion into downstream area. These include the Bypass dogleg and the SXR LTU dogleg where the bending angles and dispersion at the dogleg dipoles are locked by the fixed geometry and dispersion cancellation condition at either end of the dogleg.
In these areas, a minor $R_{56}$ adjustment is available through $R_{56}$ Compensation Chicanes (CC) included near the dogleg dipoles. The $R_{56}$ created by these chicanes is small (few hundred $\mu \mathrm{m}$ ) and is of negative sign; the latter is used to compensate the positive $R_{56}$ from the dogleg dipoles to mitigate effects of micro-bunching instability [2]. However, there is a strong interest in positive $R_{56}$ adjustment for other beam applications. Below we propose an option for $R_{56}$ tuning in the SXR LTU dogleg using dipole steering correctors. It provides capability for both positive and negative $R_{56}$ adjustments, however in a small range.
As follows from Eq. (2), the change of $R_{56}$ requires changing the bending angles and/or dispersion at the dipoles. Since these parameters at the two main dogleg dipoles are fixed, an alternative is to introduce additional dipole field, for example, through steering correctors or offset quadrupoles. For the SXR LTU dogleg, we propose to use horizontal steering correctors in this area, schematically shown in Figure 18. The correctors create not only the desired horizontal dispersion but also an unwanted orbit. After the dogleg, both the corrector orbit and dispersion must be cancelled, thus forming a closed bump. A minimum of five correctors is required to satisfy five conditions: achieve desired value of $R_{56}$ and cancel the spatial and angular orbit and dispersion.

According to Eq. (2), the change of $R_{56}$ in this corrector scheme is due to change of dispersion at the dogleg dipoles $(\Delta \eta \theta)$ and due to dispersion and bending angles of correctors $\left(\eta \theta_{c}\right)$, where the bump orbit and $\Delta \eta$ are linearly proportional to corrector strengths. By design, the maximum field of the dogleg correctors (20 $\mathrm{G} \cdot \mathrm{m}$ ) is much lower than the nominal field of the dogleg dipoles ( $2486 \mathrm{G} \cdot \mathrm{m}$ at 4 GeV ), therefore the created $R_{56}$ appear to be dominated by the change of dispersion at the main dipoles $(\Delta \eta \theta)$. Consequently, at least one dogleg dipole should be inside the corrector bump for maximum effect. In this case, the created $R_{56}$ linearly scales with the corrector strengths and the bump orbit.
Various 5-corrector combinations are possible using the available correctors in Figure 18. Below we present two bump configurations which provide the maximum $R_{56}$ range. Optics calculations are done using MAD and elegant, and the data fitting is performed using MS Excel.


Figure 18: Plan view layout of the SXR LTU dogleg, where horizontal correctors are schematically depicted by black boxes, dipoles are shown in blue color, and quadrupoles are in red. BX31B and BX32B are the two main dogleg dipoles. The kickers BYKIK1,2 are nominally off. The $X, Z$ coordinates are relative to the beginning of the LCLS-II Spreader.

### 8.1 SXR LTU Corrector Bump-1

The bump-1 scheme uses the following correctors: XCDL11, XCDL13, XCDL15, XCDL17, XCDL19 (see Figure 18), where the first dogleg dipole BX31B is inside the bump. The bump orbit and the dogleg optics functions corresponding to maximum corrector strength are shown in Figure 19. In the bump, the first corrector XCDL11 initiates the orbit, while the other four correctors serve to cancel both the orbit and dispersion. The corresponding peak orbit is 6.3 mm ; it scales linearly with the corrector strengths. The dogleg periodic beta functions are practically unaffected by the very weak corrector focusing. The achieved range of $R_{56}$ is from $-330 \mu \mathrm{~m}$ to $+322 \mu \mathrm{~m}$ at 4 GeV , limited by the $\pm 20 \mathrm{G} \cdot \mathrm{m}$ maximum corrector field. The $R_{56}$ from the bump scales linearly with the bump orbit as shown in Figure 20.


Figure 19: Dogleg orbit (left) and optics functions (right) at maximum corrector strength in bump-1 corresponding to $R_{56}=+322 \mu \mathrm{~m}$ at $\mathbf{4} \mathbf{G e V}$.


Figure 20: Peak horizontal orbit in bump-1 versus the bump $R_{56}$. The line and the equation represent the data fit.

The corrector's integrated field BL versus the bump $R_{56}$ at 4 GeV are shown in Figure 21. The dependence is linear, as expected, and the corresponding fit is provided below, where BL is in $\mathrm{G} \cdot \mathrm{m}$ and $R_{56}$ in $\mu \mathrm{m}$ :
$\mathrm{BL}($ XCDL11 $)=-2.0445 \mathrm{e}-2 \mathrm{R}_{56}-0.09636$
$\operatorname{BL}(X C D L 13)=-3.1549 \mathrm{e}-4 \mathrm{R}_{56}-0.09281$
$\mathrm{BL}($ XCDL15 $)=+4.0909 \mathrm{e}-2 \mathrm{R}_{56}+0.12472$
$\operatorname{BL}($ XCDL17 $)=-3.3651 \mathrm{e}-4 \mathrm{R}_{56}+0.00186$
$\mathrm{BL}(\mathrm{XCDL19})=+6.1349 \mathrm{e}-2 \mathrm{R}_{56}+0.22168$

One can notice in Figure 21 that two correctors (XCDL13 and XCDL17) have negligible strengths. This is because of the $90^{\circ}$ periodic FODO optics of the dogleg (see Figure 19) where all five correctors are positioned periodically, separated from each other by $90^{\circ}$ in phase. For this reason, the orbit and dispersion created by the first corrector XCDL11 are most effectively corrected by the XCDL15 and XCDL19 correctors located in phase with the XCDL11 ( $180^{\circ}$ and $360^{\circ}$ away), while the XCDL13 and XCDL17 are in orthogonal phase $\left(90^{\circ}\right.$ and $\left.270^{\circ}\right)$ and, hence, serve only as a minor orthogonal tweak to the correction.


Figure 21: Strengths of bump-1 horizontal correctors versus the bump $R_{56}$ at 4 GeV . The lines represent linear fit of the data points.

### 8.2 SXR LTU Corrector Bump-2

The following correctors are used in the bump-2 scheme: XCDL15, XCDL17, XCDL19, XCDL22, XCVB2B. In this case, the second dogleg dipole BX32B is inside the bump. The bump orbit and the dogleg optics functions at maximum corrector strength are shown in Figure 22. In the bump, the first corrector XCDL15 initiates the orbit, while the other four correctors serve to cancel both the orbit and dispersion perturbation. The bump-2 has an advantage of a lower maximum bump orbit of 3.9 mm compared to 6.3 mm with the bump-1. It is therefore better in terms of BSC and smaller effects of non-linear field errors. Similar to bump-1, the beta functions are practically unaffected by the weak corrector focusing. The achieved range of $R_{56}$ in bump-2 is from $-298 \mu \mathrm{~m}$ to $+293 \mu \mathrm{~m}$ at 4 GeV which is about $9 \%$ smaller compared to bump-1. The $R_{56}$ depends linearly on the bump amplitude as seen in Figure 23.


Figure 22: Dogleg orbit (left) and optics functions (right) at maximum corrector strength in bump-2 corresponding to $R_{56}=+293 \mu \mathrm{~m}$ at 4 GeV .


Figure 23: Peak horizontal orbit in bump-2 versus the bump $R_{56}$. The line and the equation represent the data fit.

The corrector's integrated field BL versus the bump $R_{56}$ at 4 GeV are shown in Figure 24. The corresponding linear fit is provided below, where BL is in $\mathrm{G} \cdot \mathrm{m}$ and $R_{56}$ in $\mu \mathrm{m}$ :

```
BL(XCDL15) = + 4.1273e-2 R }56+0.1079
BL(XCDL17) }=+6.9936\textrm{e}-4\mp@subsup{\textrm{R}}{56}{}+0.0074
BL(XCDL19) }=+6.7733\textrm{e}-2\mp@subsup{\textrm{R}}{56}{}+0.1800
BL(XCDL22) = - 2.1499e-2 R R56 -0.05305
BL}(XCVB2B)=+6.6436e-2 R R56 + 0.18078
```



Figure 24: Strengths of bump-2 horizontal correctors versus the bump $R_{56}$ at $\mathbf{4} \mathbf{G e V}$. The lines represent linear fit of the data points.

Unlike in bump-1, the last corrector in bump-2 is not in periodic $90^{\circ}$ sequence with the other correctors. For this reason, four correctors are actively used in this bump while one corrector (XCDL17) located $90^{\circ}$ away from the first corrector (XCDL15) serves only as a minor orthogonal tweak to the correction.

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