OPTICS TUNING AND COMPENSATION IN LCLS-II *

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Abstract

The LCLS-II is a future upgrade of the Linac Coherent Light Source (LCLS) at SLAC. It will include two new Free Electron Lasers (FEL) to generate soft and hard X-ray radiation. The 2.9 km LCLS-II lattice will include 1/3 of the SLAC linac located just upstream of the LCLS-I, a dogleg and bypass line around the LCLS-I, a 2.4° bend section, beam separation and diagnostic regions, and the FEL undulators and dump. The LCLS-I operation shows that occasionally the beam phase space may be significantly mismatched due to focusing errors in the beamline. This requires correction to ensure good beam quality in the undulators. Similarly, the LCLS-II must have lattice correction system with a large tuning range to cancel such errors. Since the different LCLS-II regions are connected using matching sections, the latter can be used for correction of the mismatched lattice functions. In addition, a large tuning capability is required to provide a wide range of focusing conditions at the FEL undulators. The capability of the LCLS-II lattice to compensating focusing errors equivalent to up to 160% of mismatched beta function and to providing matched optics for a large range of undulator quadrupole strengths is evaluated resulting in specifications for the required range of magnet strengths.

INTRODUCTION

The LCLS-II upgrade project will expand the capabilities of the existing Linac Coherent Light Source (LCLS) [1] at SLAC with two new Free Electron Lasers (FEL) to generate soft and hard X-ray radiation (SXR and HXR). These new lines will share ∼1 km of the SLAC linac [2] located just upstream of the existing LCLS-I, as well as dogleg, bypass and 2.4° bend sections. Then the beamline will split into separate HXR and SXR lines each consisting of diagnostic, undulator and dump sections. The LCLS-I experience shows that occasionally the betatron phase space of the electron beam may be significantly mismatched due to focusing errors [3]. The latter may be caused by mismatched optics conditions in the injector, deviation of beam energy, effects of transverse wakefield in the linac, coherent radiation effects in the compressor chicanes and quadrupole field errors [3]. Such a mismatch eventually can develop into emittance growth degrading the beam quality. Consequently, the LCLS-II correction system must be capable of compensating the focusing errors in a sufficiently large range. Since the LCLS-II lattice is divided into several dedicated regions connected to each other using matching sections, the latter can be used for correction of the incoming beta mismatch. Additionally, large tuning capabilities of the matching sections are required for providing a wide range of matched optics at the FEL undulators.

This study was performed for the lattice downstream of the linac. The tuning abilities were determined for the focusing errors equivalent to up to 160% of mismatched beta function and for a factor of 7 in the range of focusing strength in the undulator optics. As a result of the study, the required range of matching quadrupole and corrector strengths for beam energy up to 15 GeV was determined.

CORRECTION OF FOCUSING ERROR

A mismatch of beta functions must be corrected as soon as possible in order to minimize a potential emittance growth $\epsilon = B_{mag}\epsilon_0$ [4], where ϵ_0 is the nominal emittance, and the mismatch parameter B_{mag} [5] can be written as

$$B_{mag} = 1 + \frac{1}{2}\left[\left(\sqrt{w} - \frac{1}{\sqrt{w}}\right)^2 + \left(\alpha_0\sqrt{w} - \frac{\alpha}{\sqrt{w}}\right)^2\right], \quad (1)$$

where $[\alpha_0, \beta_0]$ and $[\alpha, \beta]$ are matched and mismatched betatron functions, respectively, and $w = \beta/\beta_0$. For a given B_{mag} value, there is a range of $[\alpha, \beta]$ satisfying to

$$B_{mag} - \sqrt{B_{mag}^2 - 1} \le w \le B_{mag} + \sqrt{B_{mag}^2 - 1}, \quad (2)$$

where

$$\alpha = \alpha_0 w \pm \sqrt{2wB_{mag} - w^2 - 1}. \quad (3)$$

For example, $B_{mag} = 1.5$ corresponds to a range of mismatched beta functions from $\beta/\beta_0 = 0.38$ to 2.62.

The LCLS-II lattice is composed of several dedicated regions connected to each other with 9 matching sections. An example of the HXR lattice downstream of the linac is shown in Fig. 1. The arrows in Fig. 1 show the locations of the matching sections in the regions of the dogleg, bypass, LTU, diagnostic, undulator and main dump. The SXR beamline has similar structure.

The strategy used to study the correction of focusing errors is as follows:

- Consider 3 cases of incoming B_{mag} values in x/y planes: $[1.5/0]$, $[0/1.5]$ and $[1.5/1.5]$.
- Generate a full range of incoming mismatched $[\alpha, \beta]$ conditions based on Eqn. 2 and 3.
- Aim at full correction within one matching section.
- Assume individual power supplies (PS) for matching quadrupoles.
- Use bipolar magnets if needed.

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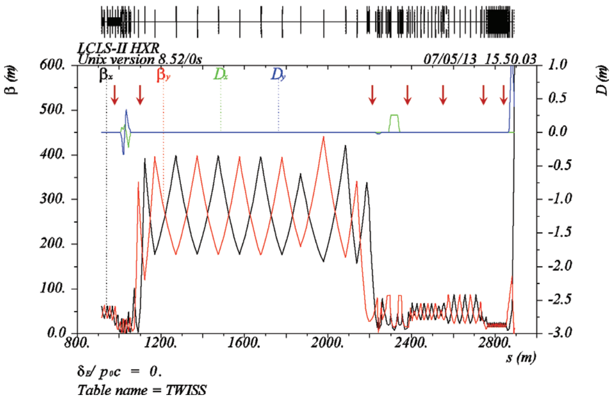

Figure 1: LCLS-II HXR lattice downstream of the linac. The arrows indicate matching sections.

- Optimize the number of matching quadrupoles to satisfy the tuning range and to obtain acceptable optics and quadrupole strengths.
- In case of a mismatch, calculate the residual B_{mag}.
- Determine the required matching quadrupole strengths at 15 GeV.

Most of the LCLS-II matching sections are located in dispersion free regions. Therefore, a minimum of 4 quadrupoles is needed to match α and β in x, y planes. However, the tuning range of 4 quadrupoles may be limited. Some of the LCLS-II matching sections already have more than 4 quadrupoles available which improve the tuning capability. These are the sections upstream of the dogleg, LTU, and HXR diagnostic regions. The matching sections upstream of the SXR diagnostic, HXR/SXR undulator and dump nominally use 4 or 3 (at dump) quadrupoles. They require using 1 or 2 more quadrupoles to satisfy the tuning range.

A special case is the SXR LTU diagnostic matching section downstream of the separation septum where vertical dispersion η_y is not zero. Lattice functions in this region are shown in Fig. 2. In this case, the quadrupoles correcting large incoming B_{mag} affect both the beta functions and dispersion. Two more quadrupoles may help with correction of the $\eta_y, \eta_{y'}$. However, quadrupoles are typically not as efficient in controlling dispersion as dipoles. In this case, 6 quadrupoles and 4 vertical dipole correctors were found necessary. In addition to correcting dispersion, the dipole correctors also cancel vertical orbit they generate. The latter is typically within a few mm. In rare cases, it was limited to 10 mm. The resulting range of quadrupole strengths in this matching section at 15 GeV for various $[\alpha, \beta]$ conditions in Eqn. 2 and 3 is shown in Fig. 3. Similar calculations were performed for all other matching sections.

Most LCLS-II matching sections provide exact compensation of the studied mismatch of $B_{mag} = 1.5$ for all combinations of incoming $[\alpha, \beta]$. Minor exceptions are the HXR diagnostic matching section, where in a few cases a residual $B_{mag} < 1.06$ was observed, and dump sections where in a few cases horizontal beta function at the dump grew large (up to 5 km in HXR). In case of occasional very large

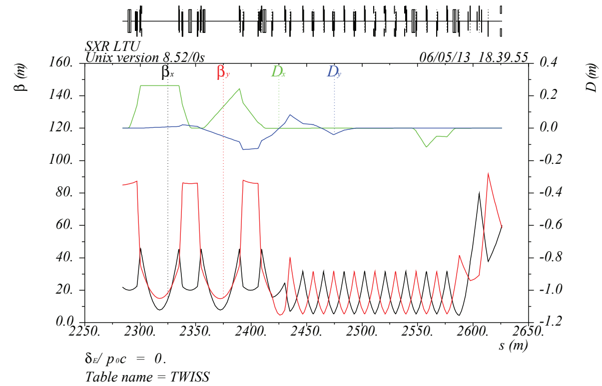

Figure 2: SXR LTU lattice.

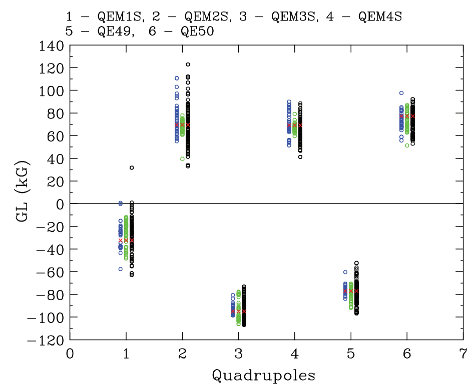

Figure 3: Range of quadrupole strengths in the SXR LTU diagnostic matching section at 15 GeV for B_{mag}=1.5/0 (blue), 0/1.5 (green) and 1.5/1.5 (black).

$B_{mag} > 1.5$ exceeding the tuning range of one matching section, the compensation could be divided between two or more sections. The maximum integrated quadrupole and corrector strengths at 15 GeV sufficient for correction of the studied focusing errors are listed in Table 1.

TUNING OF UNDULATOR OPTICS

The FEL operation requires a capability for large variation of focusing in the undulator cells. This includes variation of integral field $GL^{(u)}$ in the undulator quadrupoles from 25 kG to 60 kG and variation of beam energy from 4.5 to 13.5 GeV. Combining these two ranges results in variation of undulator quadrupole focusing strength $KL^{(u)}$ from 0.0555 to 0.3997 m^{-1} corresponding to a range of undulator cell phase advance from 14° to 123°. Maintaining periodic undulator beta functions under these conditions requires adequate tuning capabilities of the matching sections upstream and downstream of the undulator.

The tuning range for the matching quadrupole strengths was determined in optics simulations. Fig. 4 shows the range of

$$KL^{(u)} = \frac{GL^{(u)}}{B\rho} \propto \frac{GL^{(u)}}{E} \tag{4}$$

as a function of beam energy E, where $B\rho$ is magnetic rigidity, and the dash lines correspond to different values

Table 1: Specification for maximum strength and type of power supply in the HXR and SXR matching quadrupoles and SXR vertical dipole correctors. B - bipolar, U - unipolar.

Name	GL (kG)	PS	Name	GL (kG)	PS
Q19801	40	U	QEM3S	110	B
Q19901	-40	U	QEM4S	90	B
Q20201	40	U	QE49	-100	U
Q20301	-40	U	QE50	100	U
Q20401	50	U	QHXX26	60	B
Q20501	-50	U	QHXX32	60	B
Q20601	80	U	QHXX37	60	B
Q20701	-95	U	QHXX38	60	B
QL1P	70	U	QHXX41	60	B
QL2P	-35	U	QHXX43	60	B
QL3P	25	U	QSXX14	60	B
QL4P	-10	U	QSXX20	60	B
QBP31	10	U	QSXX25	60	B
QBP32	-15	U	QSXX26	60	B
QBP33	10	U	QSXX29	60	B
QBP34	10	U	QSXX31	60	B
QHM1	90	B	QHXH64	60	B
QHM2	80	B	QUE1H	80	B
QHM3	50	B	QUE2H	80	B
QHM4	50	B	QDMP1H	-36	U
QDL47	80	B	QDMP2H	-36	U
QDL48	80	B	QSXH47	60	B
QEM1H	90	B	QUE1S	80	B
QEM2H	90	B	QUE2S	80	B
QEM3H	90	B	QDMP1S	-36	U
QEM1S	90	B	QDMP2S	-36	U
QEM2S	130	B			
Name	**BL (Gm)**	**PS**	**Name**	**BL (Gm)**	**PS**
YCDL52	200	B	YCE51	200	B
YCEM1S	500	B	YCE53	200	B

of $GL^{(u)}$.

In order to determine the full tuning range for the matching quadrupoles, it is sufficient to match the optics at the conditions corresponding to the boundaries of the area in Fig. 4, indicated by red lines. This can be verified by sampling a horizontal line across the shown area where $KL^{(u)}$ is constant with energy. Along this line the undulator optics is not changed, therefore the matching section optics

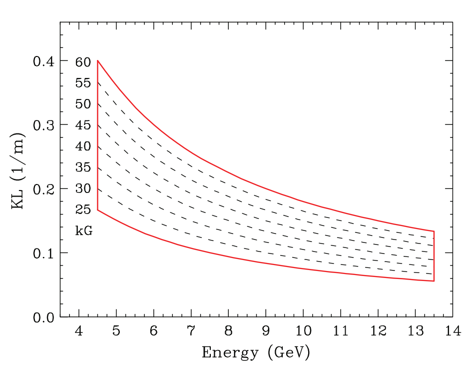

Figure 4: Undulator quadrupole focusing strength $KL^{(u)}$ for a range of $GL^{(u)}$ from 25 to 60 kG and energy from 4.5 to 13.5 GeV.

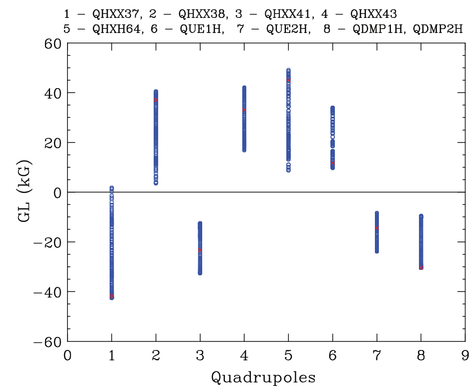

Figure 5: Range of quadrupole strengths in the matching sections upstream and downstream of the HXR undulator.

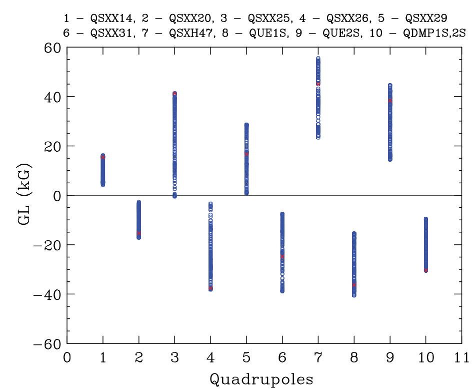

Figure 6: Range of quadrupole strengths in the matching sections upstream and downstream of the SXR undulator.

stays the same and the matching quadrupole $KL^{(m)}$ are constant. As a result, the field strengths $GL^{(m)}$ of the matching quadrupoles along this line are only proportional to energy and their range is determined by the lower and upper energy values, i.e. at the red line in Fig. 4.

Figures 5 and 6 show the range of the matching quadrupole strengths obtained in the simulations. The required maximum strengths are within the specifications in Table 1.

CONCLUSION

The matching sections in the LCLS-II were optimized to have sufficient capability for compensating large focusing errors corresponding to at least $B_{mag} = 1.5$ at a beam energy of 15 GeV. The resulting range for the matching quadrupole strengths also satisfies the undulator optics tuning in the range of beam energy from 4.5 to 13.5 GeV and undulator quadrupole field from 25 to 60 kG.

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