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Optics Design for a Soft X-ray FEL at the SLAC A-Line *

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SLAC National Accelerator Laboratory, Menlo Park, CA 94025

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LCLS capabilities can be significantly extended with a second undulator aiming at the soft x-ray spectrum (1 – 5 nm). To allow for simultaneous hard and soft x-ray operations, 14 GeV beams at the end of the LCLS accelerator can be intermittently switched into the SLAC A-line (the beam transport line to End Station A) where the second undulator may be located. In this paper, we discuss the A-line optics design for transporting the high-brightness LCLS beams using the existing tunnel. To preserve the high brightness of the LCLS beams, special attention is paid to effects of incoherent and coherent synchrotron radiation. Start-to-end simulations using realistic LCLS beam distributions are carried out.

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Abstract

LCLS capabilities can be significantly extended with a second undulator aiming at the soft x-ray spectrum (1 – 5 nm). To allow for simultaneous hard and soft x-ray operations, 14 GeV beams at the end of the LCLS accelerator can be intermittently switched into the SLAC A-line (the beam transport line to End Station A) where the second undulator may be located. In this paper, we discuss the A-line optics design for transporting the high-brightness LCLS beams using the existing tunnel. To preserve the high brightness of the LCLS beams, special attention is paid to effects of incoherent and coherent synchrotron radiation. Start-to-end simulations using realistic LCLS beam distributions are carried out.

INTRODUCTION

The A-Line, one of the two original beam transport systems at SLAC, was designed to deliver electron beams from the linac to fixed target experiments in the End Station A experimental hall [1]. The A-Line guides the beam through a total bend angle of 24.5 degrees. The first 0.5 degree bend was originally provided by a set of five pulsed magnets and the next 24 degrees were provided by 12 large conventional dipole magnets, each three meters long and bending the beam by 2 degrees. The layout of the A-Line/ESA can be seen in Fig. 1.

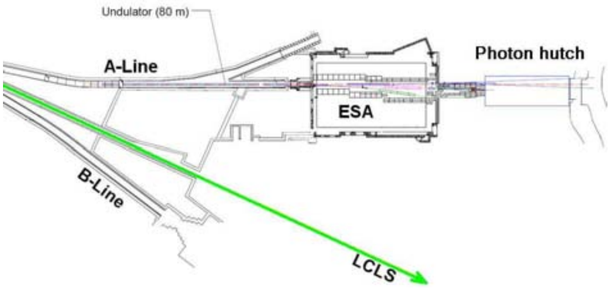

Figure 1: The Layout of the A-Line/ESA

The Linac Coherent Light Source (LCLS) currently under construction at SLAC will operate in Self-Amplified Spontaneous Emission Free Electron Laser (SASE FEL) mode in the x-ray wavelength range of 0.15 - 1.5 nm [2]. To extend the LCLS capabilities, a second undulator aiming at the soft X-ray spectrum (1 – 5 nm) can be located in the A-Line before End Station A (ESA). However, Incoherent and Coherent Synchrotron Radiations (ISR and CSR) in the 24.5 degrees bending section will generate energy spread, which may couple to the transverse (bending) plane and increase the beam emittance, and thus degrade the free electron laser performance. To transport the high-brightness LCLS beam through the existing tunnel while preserving the beam quality, a new lattice for the A-Line was designed. Special attention was paid to ISR and CSR effects. Theoretical estimates and simulation results obtained with the program Elegant [3] are presented.

A-LINE OPTICS DESIGN

The A-Line lattice design criteria are as follows. First, the lattice should not significantly degrade the LCLS electron beam emittances. Secondly, the momentum compaction factor R_{56} should be less than $\sim$10 mm so that electron energy jitter does not become excessive x-ray time jitter. Thirdly, the betatron phase advance should be 120 degrees in the straight section at the center of the two 12 degree bending sections, to allow for beam emittance diagnostics. Finally, the beta function at the end of the bending sections should be matched to the undulator section with a $\sim$10 m average beta value. Based on the criteria listed above and making use of as many existing components as possible, a new A-line lattice was designed using the computer program MAD [4]. The beta functions (β_x and β_y) and the dispersion functions (η_x and η_y) of the lattice are shown in Fig. 2.

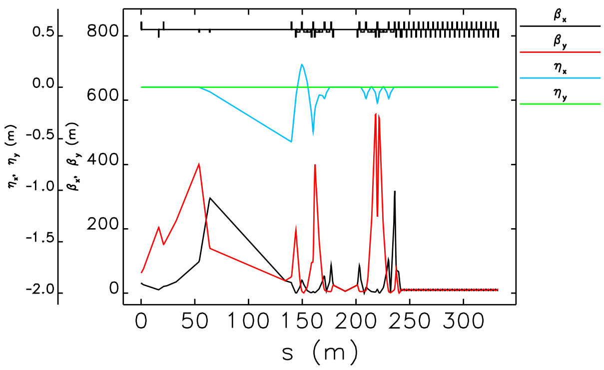

Figure 2: Beta functions and dispersion function of the new A-Line lattice. R_{56}=10 mm.

We separate the lattice into four sections, that we denote as the transport, bending, matching and undulator sections. The transport section includes all the elements upstream

*Email: genghp@slac.stanford.edu. Visiting SLAC from University of Science and Technology of China of the first of the twelve conventional dipoles. It transports the beam from the Linac to the Beam Switch Yard (BSY) and bends the beam by 0.5 degrees to the A-Line. The bending section includes the twelve conventional dipoles and quadrupoles between them. It bends the beam by a total angle of 24 degrees, while rematching the dispersion function to zero at the end. A long dispersion-free straight section at the center of the bending section is reserved for beam emittance diagnostics. The matching section includes all elements from the end of the last of the twelve conventional dipoles to the beginning of the first undulator. It matches the Twiss parameters from the end of the bending section to the ones in the undulator. The undulator section extends from the beginning of the undulator to the beginning of ESA, and is composed of standard FODO cells. The average beta functions in the undulator section are ∼10 m. The new lattice has the following features:

1. It is achromatic, with R56 tunable from 6 mm to 10 mm by simply adjusting the quadrupole strengths in the bending section.
2. It has a 20 m straight section, with 120 degrees of phase advance in both planes, that is reserved for beam emittance diagnostics.
3. It uses all 12 existing 3-m-long dipoles and most existing quadrupoles and fits into the A-Line tunnel.
4. It has an 80 m straight section reserved for the undulator before End Station A.

ISR/CSR STUDY

Transverse emittance dilution will occur if significant energy spread is generated in a dispersive section. Energy spread is mainly generated by incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR). The normalized emittance growth due to ISR in a transport line can be estimated by

$$\Delta(\gamma\epsilon_x) = 4 \times 10^{-8} E(\mathrm{GeV})^6 \cdot I_5, \tag{1}$$

where I_5 is defined as

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds; \tag{2}$$

here, ρ is the bending radius and $\mathcal{H}$ is the well known curly $\mathcal{H}$-function, defined as:

$$\mathcal{H} = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2, \tag{3}$$

with γ_x and α_x the usual Twiss parameters, and η_x' is the derivative of dispersion function along the beam trajectory. For the 13.6 GeV LCLS beam and the lattice shown in Fig. 2, the normalized emittance growth due to ISR is about 0.15 μm.

For very short electron bunches, coherent synchrotron radiation can dilute the transverse emittance (in the bending plane) by generating coherent energy spread in the dipoles.

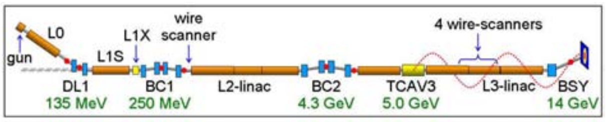

Figure 3: The Layout of the LCLS accelerator and the beam energy along the linac.

Table 1: Accelerator parameters used for generating over-compressed LCLS beams. Linac-1x is the x-band accelerator following Linac-1. MCF stands for Momentum Compaction Factor.

Parameter	Symbol	250 pC	20 pC	Unit
L1 rf phase	ϕ_{rf1}	-25.5	-22	degree
L1x rf phase	ϕ_{rf1}	−160	−160	degree
BC1 MCF	R_{56}	−45.5	−45.5	mm
L2 rf phase	ϕ_{rf2}	−41.7	−37.5	degree
BC2 MCF	R_{56}	−24.7	−24.7	mm
L3 rf phase	ϕ_{rf3}	0	0	degree
A-Line MCF	R_{56}	+6	+10	mm

In this case, however, the energy spread is correlated along the bunch unlike the case of ISR. Assuming a gaussian bunch, the free-space CSR-induced relative energy spread in a dipole under steady-state conditions is [5]:

$$\sigma_\delta = 0.22 \frac{N_e r_e L_B}{\gamma \rho^{2/3} {\sigma_z}^{4/3}}, \tag{4}$$

where r_e is the classical electron radius and γ the Lorentz energy factor, σ_z the rms bunch length, L_B the dipole length, ρ the bend radius and N_e the number of electrons per bunch. In the A-Line, with ρ= 86 m, L_B = 3 m, the CSR induced energy spread for a 250 pC, 13.6 GeV beam with bunch length σ_z = 10 μm is about 3×10^{-4}. The CSR effect on emittance growth in a bend is usually more complicated and requires detailed particle tracking with computer codes such as Elegant [3].

A-line simulations including CSR and ISR effects are carried out using both nominal (under-compressed) and over-compressed LCLS beams. The LCLS accelerator layout is shown in Fig. 3. The beam has an energy of 135 MeV at the end of the injector, and then it is accelerated to 250 MeV, 4.3 GeV and 13.6GeV in Linac-1, Linac-2 and Linac-3, respectively. For the nominal LCLS beam, the bunch is compressed in the Second Bunch Compressor (BC2) to its final bunch length with a few kA peak current and then accelerated to 13.6 GeV Linac-3. Such a short bunch, when transported through the large bending angles in the A-Line, will generate strong CSR and blow up the beam emittance. To mitigate the CSR effects, we here propose to use the A-Line as the final bunch compressor to reach the peak currents required for the soft x-ray FEL. In this way the average bunch length in the A-Line is longer than for the nominal case and will thus have much reduced CSR effects. An over-compressed LCLS beam in BC2 is required to generate the right sign of chirp to use the

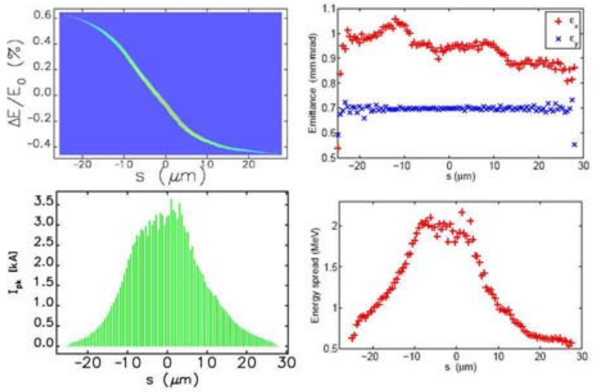

Figure 4: Longitudinal phase space (top left, red corresponds to higher beam intensity), peak current (bottom left), slice emittance (top right) and slice energy spread (bottom right) of the over-compressed 250 pC LCLS beam after passing through the A-Line. Beam head is to the left. Accelerator parameters for generating these beams are given in Table 1.

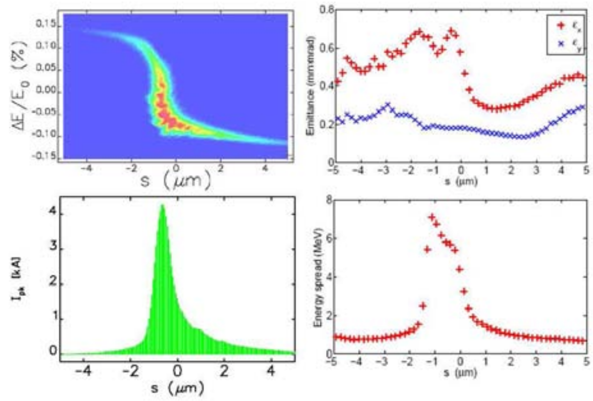

Figure 5: Longitudinal phase space (top left, red corresponds to higher beam intensity), peak current (bottom left), slice emittance (top right) and slice energy spread (bottom right) of the over-compressed 20 pC LCLS beam after passing through the A-Line. Beam head is to the left. Accelerator parameters for generating these beams are given in Table 1.

A-Line for this purpose. In principle, an over-compressed beam after BC2 could be obtained either by increasing the rf phase of Linac-2 or by increasing the strength of BC2. In our simulation, we have kept the BC2 strength at its nominal value while changing the phase of Linac-2 because the linac phase can be adjusted quickly and because it can even vary from pulse to pulse, and thus need not interfere with the normal (hard X-ray) LCLS operation.The accelerator parameters used for generating such an over-compressed beam are shown in Table 1, for both 250 pC (nominal LCLS) and 20 pC of bunch charge. 20 pC is interesting as it may provide $\sim$ fs bunch with a single longitudinal coherent x-ray spike [6]. For the 250 pC beam, the rf phases of Linac-1 and Linac-2 are adjusted from the nominal -22, -37 degrees to -25.5 and -41.7 degrees, respectively, and the momentum compaction factor of the A-Line is 6 mm. For the 20 pC beam, only rf phase of Linac-2 is adjusted to -37.5 degrees, and the momentum compaction factor of the A-Line is 10 mm. The other parameters of the accelerator are kept the same as in the nominal LCLS setup.

The longitudinal phase space, peak current, slice emittance and slice energy spread of the over-compressed 250 pC and 20 pC beam after passing through the A-Line, is shown in Fig. 4 and Fig. 5, respectively. For the 250 pC beam, the energy spread is $\sim 10^{-3}$ and almost linearly correlated along the bunch. This correlated spread gives a special characteristic feature of the FEL radiation as discussed in [7]. The current has a Gaussian-like shape with a peak current of 3.5 kA. The slice emittance is $\sim$1 μm·rad in the x-plane and 0.7 μm·rad in the y-plane (in the beam core). For the 20pC beam, since the charge is lower, the beam current can go as high as 4.5 kA without CSR severely destroying the beam emittance. The shapes of the longitudinal phase space and the current are similar to the ones for 250 pC beam, but at a much shorter bunch length. The core emittance is $\sim$0.7 μm·rad in the x-plane and 0.2 μm·rad in the y-plane. Notice the structure in the phase space plot, which could be due to CSR; it, however, does not seem to degrade the FEL performance [7].

CONCLUSIONS

A new lattice has been designed for the A-Line, one that will allow soft X-rays to be generated concurrently with the nominal (hard X-ray) LCLS operation. Our proposed design uses mostly existing hardware, includes an emittance diagnostic section, and uses the A-line as the final compressor to mitigate CSR effects and preserve the beam brightness.

ACKNOWLEDGEMENTS

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