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BEAM SHAPING FOR HIGH-REPETITION-RATE X-RAY FELS*

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Abstract

Beam shaping at normal-conducting, accelerator-based FELs, such as LCLS, plays an important role for improving lasing performance and for supporting special operating modes, such as the self-seeding scheme. Beam shaping methods include horn-collimation and dechirper manipulation. Applying the beam shaping concept to high-repetition-rate FELs driven by a superconducting linac, such as LCLS-II, beam invasive methods are not preferred due to concerns about high power deposition. We have recently studied a few shaping options for LCLS-II, such as manipulating the beam chirp before compression using corrugated devices, and modifying higher order optics terms in a chicane using octupoles. In this report we will discuss the results.

INTRODUCTION

In LCLS-II x-ray FEL pulses will be generated that have high average brightness at a megahertz-level repetition rate, opening up remarkable, new capabilities for various scientific research fields. The electron beam quality is the most important factor affecting the FEL performance; typically what is required is an electron beam with low emittance and high current. While the (slice) emittance is determined at the gun, high peak current can be achieved by longitudinal compression of the bunch.

For the LCLS-II driven by superconducting linacs, the electron bunch, coming from a very-high-frequency (VHF) gun, has a lower peak current and a lower energy than what is achieved at the present (normal conducting) S-band RF gun of LCLS. To achieve a final peak current at the kA-level, stronger compression is required. However, the achievable peak current is limited by strong nonlinearities in single particle and collective effects in the linacs and bunch compressors. For example, according to the present LCLS-II design, at 100 pC bunch charge, the peak current is about 800 A [1]. For some operating scheme such as the self-seeding mode, electron beam longitudinal phase space distribution is also critical for seeded FEL lasing performance.

Beam shaping schemes typically include electron beam phase space manipulation for achieving higher beam current, lower transverse emittance, and uniform longitudinal phase space. This type of beam phase space manipulation can be realized by direct interaction on the electron beam phase space, or by machine configuration optimization. For example, at the LCLS, beam shaping methods such as horn collimation [2] and emittance spoiling by foil [3, 4] have greatly improved the FEL performance and operating flexibility. Unfortunately, such beam invasive methods are not preferred for high-repetition rate FELs and new schemes have to be developed. We summarize two beam shaping methods for the high-repetition rate FELs in this paper. The LCLS-II machine layout is shown in Fig. 1.

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MANIPULATION OF BEAM CHIRP BEFORE FINAL COMPRESSION

In a technical note [5], manipulation of electron beam high-order time-energy chirp has been studied. The idea is to add a dechirper-like corrugated structure in the low energy region of the LCLS-II linac, where it can function as a passive phase space linearizer and help customize the beam energy chirp before it enters the second bunch compressor. After optimizing the parameters of the system, it is possible to enhance the compression factor in the final bunch compressor and thus to achieve a higher final peak current. Note also that, with this method, the current profile can be shaped to avoid large spikes at the head and tail of the distribution. Details of this scheme can be found in [5], and in Fig. 2 we show one result of the final beam before the undulator with using a 0.25-m long corrugated structure (diameter of the structure is 1 mm). Comparing to standard LCLS-II simulation results, we found that the current horn at the bunch head is suppressed, and the core beam current is improved to above 1 kA.

MANIPULATION OF HIGH ORDER OPTICS TERMS IN COMPRESSOR CHICANE

To shape the beam current profile after compression, besides manipulation of the electron beam chirp as discussed above, one can also modify the high-order (nonlinear) terms of the compressor optics. We investigated a scheme recently reported in [6], where an octupole magnet has been adopted in the chicane for U5666 control. Following the methods in [6], we studied the requirement of the U5666 for a given electron beam at the LCLS-II before final compression, developed an optimization procedure using LiTrack code [7], derived formulas to calculate the corresponding octupole strength from U5666, and verified the solutions by Elegant [8] tracking simulations. We discuss these results in the following subsections.

Required U5666 for Current Horn Suppression

With a known beam longitudinal chirp before compression and the chicane R56, to avoid current spikes, one can solve the required high-order term U5666 following the method developed in [6]. But for the overall machine setup, the system should be optimized with also including the machine parameters such as linac phase and amplitude, harmonic linearizer amplitude and phase, BC1 chicane R56, BC2 chicane R56, etc. LiTrack tracking is fast and can be

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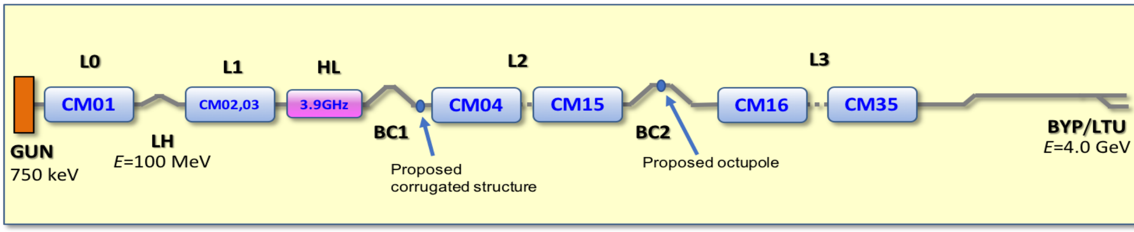

Figure 1: A schematic of the LCLS-II machine layout. The two locations for proposed corrugated structure and octupole are marked in the figure.

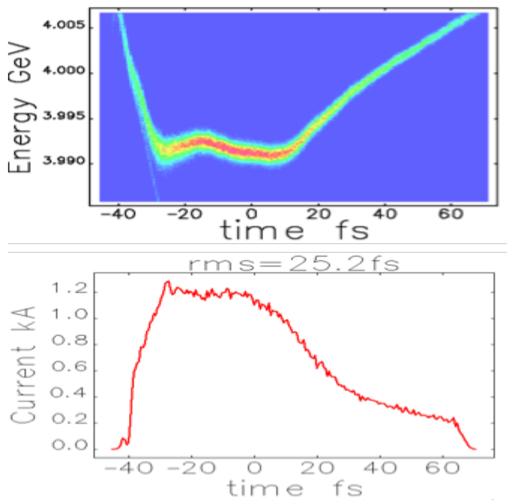

Figure 2: Electron beam phase space and current profile with adding a corrugated structure after BC1, from Elegant simulations. Bunch head is to the left. Same as in the following plots.

combined with multi-objective optimization. We adopted the Non-dominated Sorting Genetic Algorithm (NSGA) in the optimization process for this purpose, with the variables of the linac and chicane parameters. The BC2 chicane is treated as a general compressor in LiTrack with providing two variables: R56 (with fixed T566 = -1.5 R56) and U5666. The optimization target includes higher core current, uniform current shape and small energy spread right after compressor. We show one example of the solutions from LiTrack optimizer with a good current profile in Fig. 3. The optimized machine configuration for this example is summarized in Table 1. We will discuss further in the following subsections using this example.

U5666 and Octupole Strength

Once we know the required U5666 based on LiTrack optimization, we still need to solve the corresponding octupole strength. In this configuration, the octupole is located at the center of a symmetric 4-dipole chicane. In a note by Nosochkov [9] the path length difference through the chicane due to octupole kick is calculated, from which the U5666 from the ocutpole can be derived as:

$$U_{5666} \simeq -\frac{1}{6} K_3 L_0 \theta^4 (L_B + L_D)^4, \qquad (1)$$

Table 1: Main Parameters for Machine Setup with U5666

Parameter	value	unit
Energy out of injector	100	MeV
Bunch charge	100	pC
Final beam energy	4	GeV
L1 phase	-22	deg
L1H phase	-160	deg
BC1 energy	232	MeV
BC1 R56	-60	mm
L2 phase	-25	deg
BC2 energy	1.63	GeV
BC2 R56	-60	mm
BC2 U5666	45	m

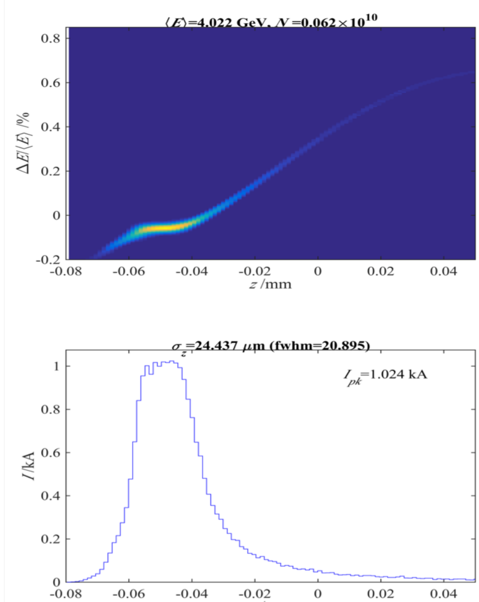

Figure 3: Electron beam phase space and current profile with U5666 = 45 m from LiTrack simulations.

where K_3 is the octupole stength ($K_3 = \frac{B'''}{B\rho}$) , L_0 is the octupole length, θ is the chicane single dipole bending angle, L_B is the chicane dipole straight length, and L_D is the drift length between the first (third) and second (fourth) dipole. For the example in Table.1, the LCLS-II BC2 chicane R56

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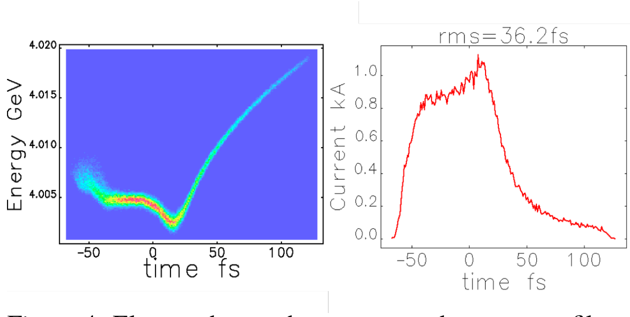

Figure 4: Electron beam phase space and current profile at the undulator entrance with octupole $K_3L_0 = -2700\ m^{-3}$ from Elegant simulations, other parameters are used from Table 1.

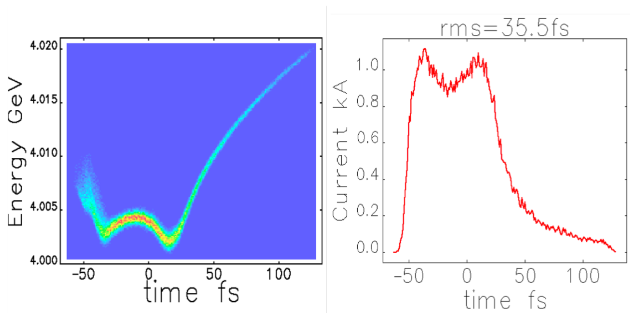

Figure 5: Electron beam phase space and current profile at the undulator entrance with octupole $K_3L_0 = -2200\ m^{-3}$ from Elegant simulations, other parameters are used from Table 1.

is -60 mm, $L_B = 0.549$m, $L_D = 9.86$m, and $\theta = 0.0541$rad, so Eq. (1) can be written as:

$$U_{5666} \simeq -0.0167 K_3 L_0 \tag{2}$$

According to the LCLS-II BC2 chicane vacuum chamber size (full horizontal width 50 mm), with assuming the maximum allowed octupole pole-tip field B = 5 kG and octupole length $L_0 = 0.2$ m, at an energy of 1.6 GeV, the maximum achievable $K_3L_0 = 7195m^{-3}$, which corresponds to a maximum achievable U5666 of 120 m from Eq. (2).

Elegant Tracking

We use Elegant code [8] to verify the solution that was found from LiTrack optimizer, and check transverse effects such as emittance growth. The machine configuration is set up using the same parameters as listed in Table 1 and the octupole strength is calculated using Eq. (2), which is $K_3L_0 = -2700m^{-3}$ here. The final phase space and current profile at the undulator entrance are shown in Fig. 4.

We see from Fig. 4 that the core part current profile has a small ramp. We can tweak the strength of the octupole to correct it. With reducing the K_3L_0 to be $-2200\ m^{-3}$, we have a more balanced current shape, as shown in Fig. 5.

One major concern about using an octupole is the emittance growth. The octupole at the center of the chicane will mainly modify the bunch head and tail, increasing the

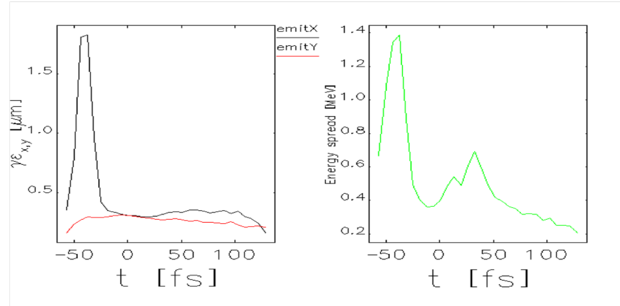

Figure 6: Electron beam sliced emittance and energy spread at the undulator entrance with octupole $K_3L_0 = -2200\ m^{-3}$ from Elegant simulations, other parameters are used from Table 1.

head/tail emittance and mismatch. We checked the slice emittance and energy spread for the case with $K_3L_0 = -2200\ m^{-3}$, and show the results in Fig. 6. We see the slice emittance and energy spread at the core part in the bunch center are preserved, with head and tail showing emittance and energy spread growth. We also observed an obvious mismatching at the bunch head and tail. If we send this beam to undulator, only the core part of the bunch will lase efficiently. So this method actually provides a way for x-ray pulse length control, similar to the slotted foil scheme that selectively spoils the beam emittance.

Due to emittance growth at the bunch head and tail, it might cause particle loss along the downstream beamline. A small fraction of particle loss is typically fine for a copper-linac based FEL facility, since the average beam power is low, but it could cause damage and radiation protection issues for a high-repetition rate, superconducting linac with average beam power up to a few hundred kilowatts. With our present setup, we see about 6% particle loss at the halo collimators in the bypass beamline section. Reduction of particle loss needs further study.

DISCUSSION

Electron beam shaping is helpful to improve the FEL lasing performance and increase the operating flexibility of an x-ray FEL. Such shaping at the LCLS copper-linac based accelerator has been very successful. However, in a superconducting linac with high average power, invasive methods should be avoided. In this paper we investigated two schemes: modifying the beam chirp with a corrugated structure or the chicane higher order optics terms using an octupole. Both methods showed improvement on the current profile and beam phase space. The octupole method induces emittance growth on the bunch head and tail, resulting in particle loss in downstream collimator sections; these needs further investigation. Note this also provides a new way of controlling the lasing part along the electron bunch hence generating shorter x-ray pulse. These methods can also be applied in the copper-linac based FELs, where particle loss should not be a problem.

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