# DESIGN AND PERFORMANCE OF LINAC AND RECIRCULATION OPTICS FOR THE X-RAY FREE ELECTRON LASER OSCILLATOR*

M. Borland † ANL, Argonne, IL 60439, USA

*Abstract*

The X-ray Free Electron Laser Oscillator (XFEL-O) [1] is a concept for a high-brightness fourth-generation x-ray source with full spatial and temporal coherence. It is based on a cw electron source and superconducting linac. In order to reduce cost and increase versatility, a recirculating linac configuration is being entertained. In this paper, we present an optics design for the four-pass linac and the three recirculation systems. The design goals are preservation of the beam emittance and energy spread, as well as minimal cost and complexity. We also present the results of tracking studies that show the expected performance.

## INTRODUCTION

The XFEL-O concept offers a number of advantages over other x-ray light sources [1]. The spectrum is orders of magnitude narrower than that offered by a high-gain FEL based on the self-amplified spontaneous emission (SASE) process. Unlike a SASE FEL, the XFEL-O would offer stable pulsed x-ray output. Depending on the repetition rate, the average brightness will be six or more orders of magnitude higher than the typical average brightness of a high-energy $3^{rd}$-generation storage ring.

The XFEL-O requires a high-quality, low-charge electron beam like that needed for energy recovery linac (ERL) light sources in high-coherence mode [2]: 20 pC/bunch, 0.1 $\mu$m normalized emittance, and 2- to 3-ps rms bunch duration. The repetition rate is only a few MHz, so energy recovery is not required. One possible cost-effective configuration [3] for the XFEL-O is a multipass linac.

This paper presents an optics design for such a linac, using a race-track configuration with vertically stacked arcs. Our assumptions are that the beam is delivered from a superconducting linac injector at an energy of 550 MeV [4], and that we wish to accelerate to 10 GeV in four passes through a second superconducting linac. Our design includes many modules. Although space does not permit discussion of all of these, we list them nonetheless: (1) Horizontal injection system to bring the beam into the linac. (2) Multipass linac optics for a 2362.5-MeV/pass superconducting linac. The layout and optics concept are very similar to those used in [5], and will not be covered here. (3) Vertical energy separation and combination systems. (4) 180-degree arcs based on theoretical minimum emittance (TME) cells. (5) Relay optics to transport beam between the arcs. (6) Optics for x-y emittance exchange between the arcs. (7) Vertical extraction system to deliver 10-GeV beam to the undulator.

The program `elegant` [6] was used for all matching, which included floor coordinate constraints, optics constraints, and minimization of emittance growth.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

† borland@aps.anl.gov

## INJECTION SYSTEM

Beam is brought into the linac via a horizontal dogleg, which starts with a 15.5° bend toward the linac. To complete the dogleg, one or more opposite bends totaling 15.5° will be needed. The final horizontal dipole will be seen by all the beams, as it must be downstream of the vertical combiner magnet. For the high-energy beams, the final horizontal dipole is part of a three-magnet chicane, which is achromatic provided rectangular dipoles are used. The middle chicane dipole is a septum magnet with opposite polarity on the two sides of the septum, to bend the incoming beam appropriately. The field seen by the incoming beam is about 1.85 T (seven times the field seen by the other beams), resulting in a 15.5° total bend from the septum and the final chicane dipole. The large angle allows good separation from the vertical combiner system. Figure 1 shows the optical functions for the injection system.

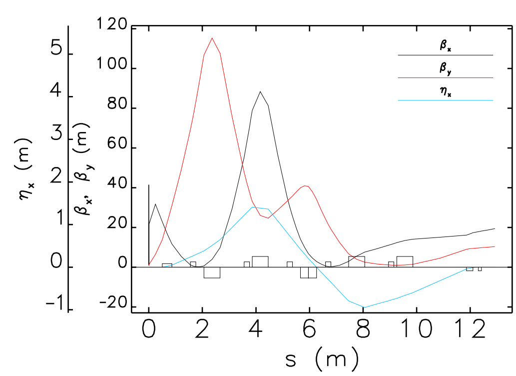


Figure 1: Optics of the injection dogleg.

## VERTICAL SEPARATORS AND COMBINERS

Beam from the linac must be separated vertically by energy and fed into three arcs. This is accomplished using vertical doglegs that share a common initial dipole, which bends the first-pass beam by 3.75°. Keeping the angle small reduces emittance growth due to quantum excitation, but a larger angle avoids collisions of elements in the three separator beamlines. Each separator has five quadrupoles and five sextupoles between the dipoles. The vertical separation of the beams at location of the first quadrupole in the separators is about 7.5 cm, indicating that a multi-axis magnet design is likely needed. Alternatively, the magnets could be longitudinally offset in the beamlines.

Following the second dipole are six additional quadrupoles, which are used to match the lattice into the arcs. Even with the large number of quadrupoles, matching proved challenging, particularly keeping the maximum beta functions under 300 m. The vertical combiners are very similar to the separators, but required additional quadrupoles between the dipoles.

We found that the vertical doglegs produced unacceptable emittance growth for 3-ps rms bunch duration, which has double the energy spread compared to 2 ps rms. To eliminate this, we inserted sextupoles into all doglegs. The sextupole positions and strengths were optimized by minimizing the emittance growth as determined by tracking.

## RECIRCULATION ARCS

The heights of the three recirculation arcs relative to the linac are 3.4 m, 1.9 m, and 1.3 m. Informed by previous studies [7, 8] that showed isochronousity and coherent synchrotron radiation (CSR) cancellation properties were not needed for ERL arcs with these beam parameters, we decided to use TME cells in order to make a compact, emittance-preserving system. Since we have no beamlines in the arcs, we only need dispersion suppression at the end of the arcs.

The geometric emittance growth per pass scales like $\gamma^5/(f^2 N_d^3 R)$, where $\gamma$ is the relativistic factor, $f$ is the dipole filling fraction, $N_d$ is the number of dipoles, and $R$ is the mean bending radius. Hence, we want a large radius and an increasing number of cells for the higher-energy arcs. Our design has a 100-m average bending radius with 16, 32, or 64 cells per 180° of bending, with the higher numbers of cells of course corresponding to the higher energies. Dispersion suppression uses half-length, half-angle dipoles. Although the arcs are designed to stack vertically, a horizontal offset might actually be desirable to aid installation and maintenance.

Growth in the momentum spread is negligible, while the horizontal emittance grows by about 50%. Increasing $N_d$ in the lower-energy arcs or increasing $R$ are options to further reduce emittance growth.

## STRAIGHT SECTION OPTICS

We transport the beam from one 180° arc to the next using triplet-based relay optics. In addition to the triplet cells, we must match from the arc to the triplet cells and back. We also included a rotation system to optionally exchange the x and y emittances. This is desirable because the arcs produce only horizontal-plane emittance growth. Exchanging the emittance between the arcs should give final x and y emittances that are nearly the same.

The rotation system requires a transport matrix of the form

$$R_r = \begin{bmatrix} 0 & 0 & R_{13} & R_{14} \\ 0 & 0 & R_{23} & R_{24} \\ R_{31} & R_{32} & 0 & 0 \\ R_{41} & R_{42} & 0 & 0 \end{bmatrix}. \quad (1)$$

We'd like to integrate the rotation system into the relay optics in such a way that the rotation can be switched on and off as needed. The relay cells focus to a waist in both planes midway between each pair of triplets, with (we assume) $\beta_x = \beta_y$. If the rotation system begins at one waist location and ends at the next, then a very convenient arrangement is to have the transfer matrix of the rotation system be

$$R_r = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (2)$$

In this case, the transverse emittances are exchanged but the beam remains matched to the relay optics. To disable the rotation, we turn off the skew quadrupoles and adjust the other magnets to match the relay optics. This is accommodated by embedding a triplet in the rotation system.

We started by matching with skew quadrupoles only to satisfy Eq. (1), which required four magnets. We found a solution satisfying Eq. (2) with seven additional quadrupoles, including a centered triplet. Having obtained this solution, we then created a triplet cell with the same length and the same spacing for the triplet quadrupoles.

As a test, we assembled the rotation module between triplet cells and tracked a matched beam. As expected (Figure 2), we see the two planes exchange emittance and continue to propagate with matched optics.

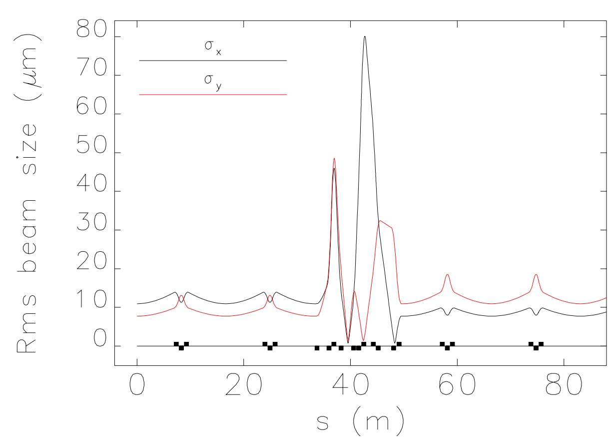


Figure 2: Test of the rotation system and triplet relay optics.

## TRACKING RESULTS

To verify the matching, we computed the Twiss parameters for the entire system, as shown in Figure 3. Although the maximum beta functions are larger than we'd like, it was difficult to do better due to the many constraints in the dogleg matching. The beam sizes are not large, since the emittances are very low.

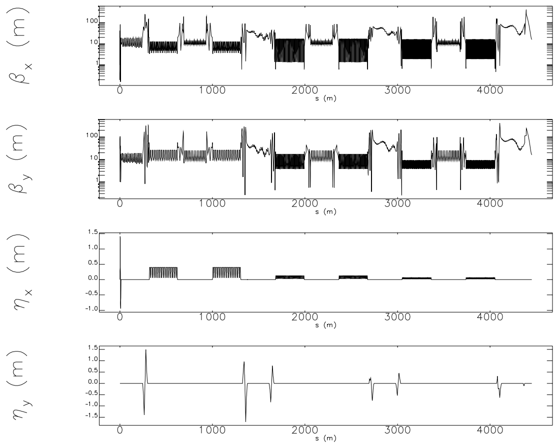


Figure 3: Optics of entire system, with x-y rotators off.

Using the parallel version of `elegant` [9], we performed tracking through the entire system. We started with the x-y rotators turned off and no synchrotron radiation effects, which gave excellent emittance preservation in both planes. We next turned on the x-y rotators, and found to our surprise that these did not allow us to swap the emittances between the planes. This was found to result from using a 3-ps rms bunch duration, which gives a 0.04% rms momentum spread. Dropping the bunch duration to 2 ps rms largely solved the problem. We next added synchrotron radiation effects, including quantum excitation. As Figure 4 shows, the emittance growth is about 25% in each plane.

We also tracked with CSR effects, assuming bunch charge of 20 pC, 40 pC, and 80 pC. Figure 5 shows the effect in the horizontal plane. Effects are similarly negligible in the vertical plane. The rms energy spread decreases slightly as a result of CSR effects, which results from a combination of the CSR "wake" shape and the time/energy profile of the bunch from the linac [10]

## CONCLUSION

We've developed a realistic optics solution for a four-pass linac and recirculation system, including injection, vertical separation and combination, TME-based turn-around arcs, x-y rotation, and extraction. Preservation of the emittance in the separators and combiners required use of sextupoles. Emittance exchange between the x and y planes was used to equalize emittance growth in the two planes, but requires low energy spread and thus a 2-ps rms bunch duration. Emittance growth is about 25% in both planes, with little effect from CSR for up to 80 pC/bunch. The system involves a very large number of magnets: ∼250 bending magnets, ∼1200 quadrupoles, and ∼1100 sextupoles. It seems likely that a two-pass linac will be more economical, because the higher-energy passes involve a large number of arc magnets for emittance preservation.

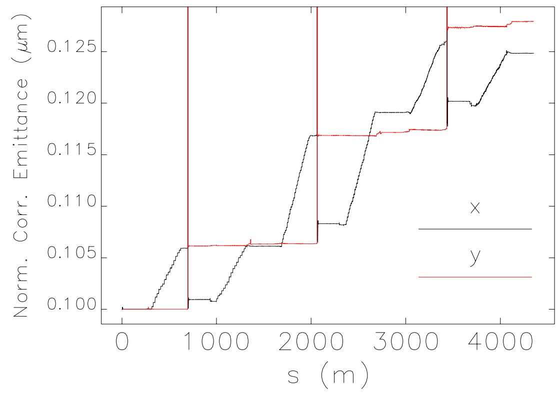


Figure 4: Evolution of the emittance in the presence of synchrotron radiation. Off-scale spikes indicate the locations of the x-y rotators.

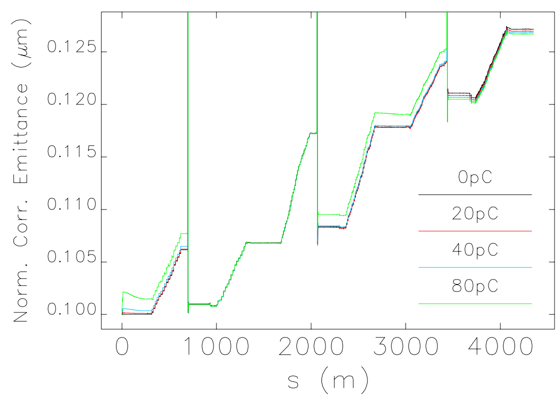


Figure 5: Evolution of horizontal emittance in the presence of CSR for four bunch-charge levels.

## REFERENCES

[1] K. J. Kim *et al.*, Phys. Rev. Lett. **100**, 244802 (2008).

[2] G. Hoffstaetter, FLS 2006 Workshop, DESY.

[3] K. J. Kim, private communication, 2008.

[4] P. N. Ostroumov *et al.*, Proc. Linac 2008, TUP117, to be published.

[5] M. Borland *et al.*, Proc. PAC 2007, 1121-1123 (2007).

[6] M. Borland, APS LS-287, September 2000.

[7] M. Borland *et al.*, Proc. Linac 2008, TUP023, to be published.

[8] M. Borland, Proc. Linac 2008, TUP024, to be published.

[9] Y. Wang *et al.*, Proc. PAC 2007, 3444-3446 (2007).

[10] M. Borland *et al.*, Proc. AccApp07, 196-203 (2007).