AN INJECTOR FOR THE PROPOSED BERKELEY ULTRAFAST X-RAY LIGHT SOURCE*

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Abstract

Berkeley Lab has proposed to build a recirculating linac based x-ray source for ultra-fast dynamic studies [1]. This machine requires a flat electron beam with a small vertical emittance and large x/y emittance ratio to allow for compression of spontaneous undulator emission of soft and hard x-ray pulses, and a low-emittance, round electron beam for coherent emission of soft x-rays via the FEL process based on cascaded harmonic generation [2]. We propose an injector system consisting of two high gradient high repetition rate photocathode guns [3] (one for each application), a ~120 MeV superconducting linear accelerator, a 3rd harmonic cavity for linearization of the longitudinal phase space, and a bunch compressor. We present details of the design and the results of particle tracking studies using several computer codes.

INTRODUCTION

The proposed Linac-based Ultra-fast X-ray source ('LUX') facility [1] requires a high-brightness, high duty factor, and highly reliable electron beam injector to produce both hard x-rays by spontaneous emission in undulators and wigglers and soft x-rays in cascaded harmonic generation free-electron lasers. Two rf photoinjector guns produce electron beams with very different emittance profiles, albeit with similar brightness, for the different x-ray production modes. The parameters for the injector are listed in Table 1.

Energy at rf gun exit	~ 10	MeV
Energy at compressor entrance	~ 120	MeV
Bunch charge	1-3	nC
Flat beam injector (1 nC):		
Horizontal emittance	~ 20	mm-mrad
Vertical emittance	< 0.4	mm-mrad
Total emittance	< 3	mm-mrad
Round beam injector (1 nC):		
Emittance	< 2	mm-mrad
Uncorrelated energy spread	± 15	keV
Correlated energy chirp	± 600	keV
Bunch length at compressor entrance	~ 20	ps
Bunch length at compressor exit	2	ps
Repetition rate	~ 10+	kHz

Table 1: LUX photoinjector parameters.

The dual-gun injector complex is shown schematically in Figure 1. Two rf photoinjector guns [3] provide time-interleaved beams at the 10kHz repetition rate. One gun utilizes a magnetized cathode configuration for flat beam production [4], while the other gun produces a typical 'round' beam from an unmagnetized cathode. The beams from the two guns are both injected into the super-conducting linac and from there follow an identical beamline. The magnetized beam follows a linear trajectory to the linac, while the unmagnetized beam is transferred via an achromat transfer line from a gun situated off-axis.

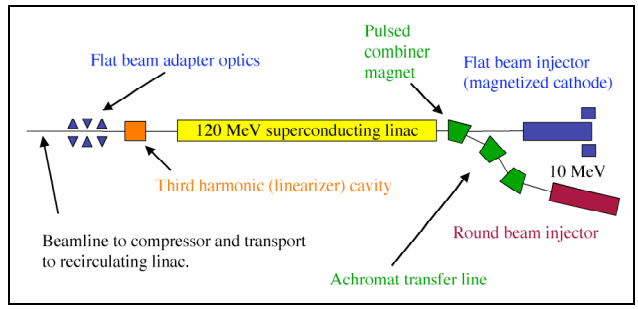

Figure 1: LUX dual-gun injector complex.

Following the linac, a 3rd harmonic (3.9GHz) cavity (3HC) acts to linearize the longitudinal phase space of the beam, and to impose the requisite correlated energy chirp prior to injection to the compressor beamline and transfer to the main recirculating linac of LUX. Between the 3HC and the compressor is the 'Adapter' beamline of skew quadrupoles followed by normal quadrupoles. The skew quadrupole lattice removes the angular momentum carried by the magnetized ('flat') beam, producing a beam with large (~50) ratio between horizontal and vertical emittance. The normal quadrupoles then match the beam to the compressor.

BEAMLINE OPTIMIZATION

We have optimized the generation, transport, acceleration, and manipulation of the electron beams using the 2.5D particle tracking code *Astra* [5]. Optimization seeks to find beamline parameters that simultaneously produce both sets of beams ('flat', 'round') which satisfy the performance requirements (Table 1). Considerable effort has been spent on studying emittance compensation [6] for beams carrying significant canonical angular momentum. The evolution of the magnetized beam is shown in Figure 2, and that of the unmagnetized beam in Figure 3. Figure 2 shows the evolution of several various normalized RMS 'emittances' projected over the full 20ps bunch length: the total 4D emittance (ϵ_{4D}); the usual radial emittance (ϵ); and the two uncoupled, normal mode

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emittances (ε_{drift}, $\varepsilon_{cyclotron}$). For eventual application of the flat beam where an ultra-low vertical emittance is required, the cyclotron emittance is minimized. For quasi-laminar beams, the circular (normal) mode emittances are related to the radial emittance and canonical angular momentum ($M=xp_y-yp_x$) via

$$2\varepsilon_{\pm} = \pm\langle M\rangle + \sqrt{(2\varepsilon_r)^2 + \langle M^2\rangle}\,. \qquad (1)$$

The drift and cyclotron (i.e. circular modes) emittances correspond to the (+) and (-) angular momentum modes in Equation (1).

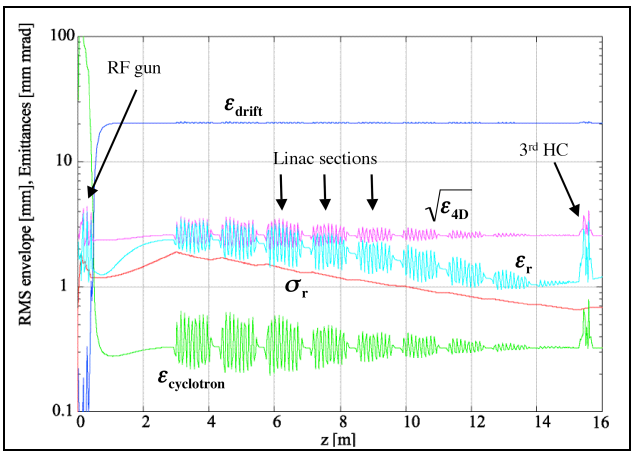

Figure 2: RMS spot and normalized emittance evolution from the cathode (z = 0m) to the entrance of the Adapter (z = 16m) for the magnetized ('flat') beam.

Until the symmetry of the beamline is broken in the skew-quadrupole Adapter lattice, the canonical angular momentum of the beam is conserved. Hence, emittance compensation in this beamline can be monitored by observing the evolution of the radial emittance. Figure 2 illustrates that compensation of the cyclotron emittance through the linac tracks along with the radial emittance. The total 4D emittance (conserved for linear forces) remains essentially constant along this entire portion of the beamline, and at ~2.5 mm-mrad meets the injector specifications with some overhead.

The evolution of the unmagnetized beam up to the Adapter lattice is shown in Figure 3. The gun-to-linac drift length has been increased from 3m to 5m to match the phase of the emittance oscillation. In so doing, the radial emittance is compensated at the linac exit, also with some overhead compared to specifications.

FLAT BEAM ADAPTER OPTICS

Following the 3rd harmonic cavity is the Adapter lattice consisting of 3 skew quadrupoles. The spacing and excitation strength of the skew quadrupoles are determined [7] to cancel the correlations induced by the canonical angular momentum and decouple the horizontal and vertical phase spaces. When this is done properly, the residual angular momentum is removed and, most importantly, the drift and cyclotron emittances are mapped to the horizontal and vertical, producing a flat beam. The evolution of the horizontal and vertical beam emittances and spot sizes are shown in Figure 4.

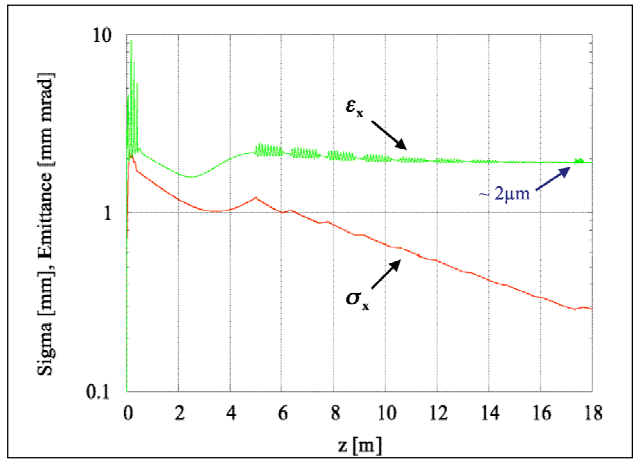

Figure 3: RMS spot and normalized emittance evolution from the cathode to the entrance of the Adapter for the unmagnetized ('round') beam.

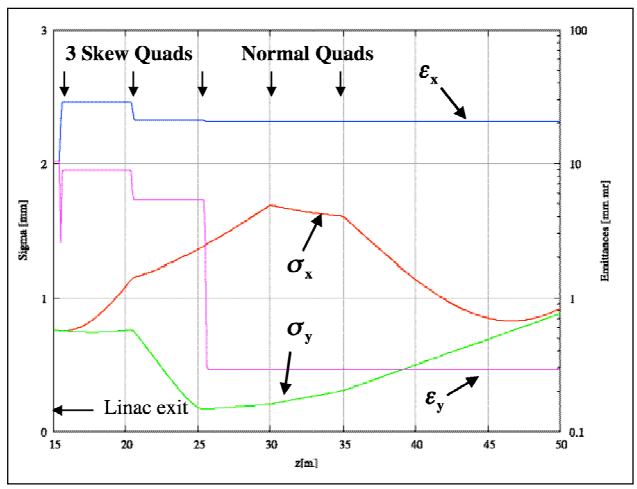

Figure 4: Horizontal and vertical RMS spot size and normalized emittance evolution in the Adapter.

LONGITUDINAL DYNAMICS AND BUNCH COMPRESSION

Manipulation of the longitudinal phase space is another essential duty of the injector. To offset intense space-charge forces at low energy, the beam is generated at the cathode with a bunch length ~20 ps. The launch phase and cell-to-cell phasing in the rf guns are adjusted to produce a low emittance beam with small uncorrelated energy spread. The linac produces a nonlinear correlation over the bunch length, which is removed with the 3rd harmonic cavity. The evolution of the longitudinal phase space from the 1st rf gun cell to the gun exit to the linac exit and the 3rd harmonic cavity exit is shown in Figure 5. As shown, the longitudinal phase space at the entrance to the compressor has an uncorrelated energy spread within specifications.

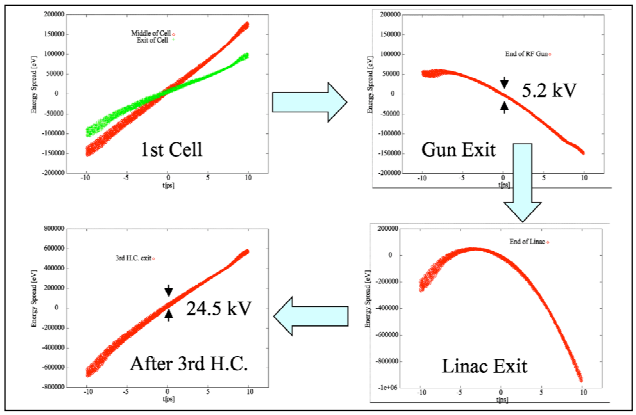

Figure 5: Development of longitudinal phase space from the rf gun to the compressor entrance.

After the flat beam adapter the electron beam executes a 180° turn before it merges the recirculating linac in the bending magnet of the injection chicane (see Figure 6). We use this 180° turn to compress the electron bunch from ~20-30 ps to approximately 2 ps. The design is largely affected by considerations regarding detrimental effects of CSR (coherent synchrotron radiation). Following [8] we split the actual bunch compressor into two parts and separate them by $-I$ transport lines. The idea is to use the CSR in the downstream bunch compressor to compensate for the CSR induced excitation of the horizontal emittance in the upstream bunch compressor. This will give us only a limited success because of the difference in bunch lengths in the upstream and downstream bunch compressors. Therefore to improve compensation we choose bending radii for bend magnets in the downstream compressor to be 1.5 times larger than in the upstream compressor.

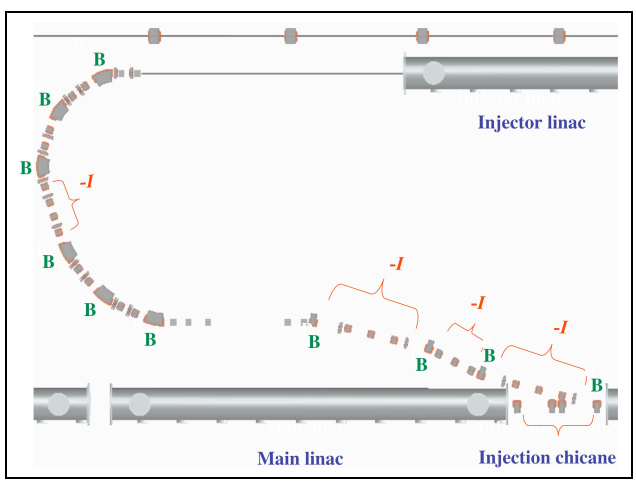

Figure 6: Compressor beamline.

The effect of CSR on horizontal emittance is strongest in the final bend. This is because of the large beta-function in the recirculating linac at the injection point. Compensation of CSR in this magnet requires more complicated arrangements for injection than just a bend. We found that we can have a fairly effective compensation using four bend magnets and separate them by $-I$ transport matrix. In this setting, the two upstream bends have the opposite polarity to the two downstream bends. An additional benefit is that the overall arrangement is achromatic.

To analyze this design we performed particle tracking through the entire bunch compressor and injection lattice using *elegant* [9]. An initial particle distribution was loaded that is uniform both transversely and longitudinally. Tracking through the compressor beamline shows a relative horizontal emittance gain less than 25%, with no discernable increase in energy spread.

CONCLUSIONS

We have produced an injector design for LUX that exceeds performance specifications. There are still several areas that need additional study. We must predict any emittance growth in the low energy achromat line, as well as incorporate its optics into the general emittance compensation scheme for the unmagnetized beam. The Adapter beamline has been optimized for the production of low vertical emittance flat beams using a simple skew quadrupole triplet configuration. This beamline must perform this duty while also matching both the flat and round beam into the compressor. A more complicated beamline may be required to perform this job, and must be studied further.

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