SIMULATION OF AN X-BAND HARD X-RAY FEL WITH LCLS INJECTOR*

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Abstract

In this paper, the accelerator design and start-to-end 3D macro particle simulation (using ELEGANT and GENESIS) of an X-band rf-driven hard x-ray FEL with LCLS injector is briefly discussed. A preliminary design and LiTrack 1D simulation studies were presented earlier [1]. In numerical simulations this X-band rf-driven hard x-ray FEL achieves/exceeds LCLS-like performance in a much shorter overall length of 350 m, compared with 1200 m in the LCLS. One key feature of this design is that it may achieve a higher final beam current of 5 kA plus a uniform energy profile, mainly due to the employment of stronger longitudinal wakefields in the last X-band rf linac [2].

OVERVIEW AND ACCELERATOR DESIGN

LCLS is the world's first hard x-ray FEL in routine operation, providing soft and hard x-rays to its users with good spatial coherence at wavelengths from 2.2 nm to 0.12 nm by varying the bunch energy from 3.5 GeV to 15 GeV [3]. Design and beam dynamic studies are performed for several X-band rf-driven hard x-ray FEL drivers [4]. A low-charge hard x-ray FEL design [5] employs the entire X-band photoinjector and rf linac, which are optimized for a very low bunch charge of 10 pC and an average SASE FEL power of over 10 GW in a pulse length of 5 fs (start-to-end simulation in a short undulator length of 20 m). Thanks to the small 3D emittance associated with the low bunch charge (short initial bunch length from photoinjector, etc.), a linear bunch compression is achieved in two stages of bunch compressors without the assistance of harmonic rf linearization.

A second hard x-ray FEL design also features the entire X-band photoinjector and rf linac, but is dedicated for a normal bunch charge of 250 pC [6]. The longitudinal phase space linearization is done in its first-stage bunch compression with a specially designed bunch compressor composed of dipole, quadrupole, and sextupole magnets. From the start-to-end simulation using computer codes ASTRA [7], ELEGANT [8], and GENESIS [9], it is shown that this FEL achieves an average SASE FEL power of over 30 GW in a pulse length of 50 fs.

Both of these two hard X-ray FEL designs described above achieve a shorter SASE FEL saturation length due to a shorter undulator period and a weaker undulator field. It is also noted that the low-charge hard x-ray FEL design [5] achieves a better final beam quality than the LCLS case.

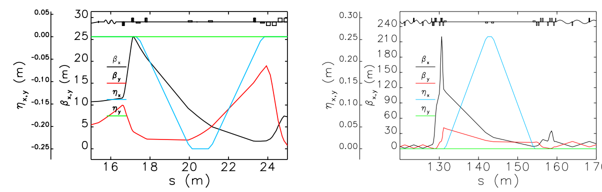

Figure 2: Beta functions and dispersion functions in the bunch compressors. Left: bunch compressor one, which is exactly the same as LCLS BC1; right: bunch compressor two, which is similar to LCLS BC2.

Analytical and numerical simulation studies show that the tolerance (charge and timing jitter, transverse misalignment) is acceptable for both of the above two hard X-ray FEL designs [5], [6].

A sketch of this compact (300 m) hard x-ray FEL driver using X-band accelerators plus an LCLS injector is shown in Figure 1. As previously mentioned, it employs an LCLS injector, which means that to the end of BC1 it is exactly the same as the LCLS. The only difference is that the S-band rf in Linac2 and Linac3 is replaced by an X-band rf. The BC2 design is similar to LCLS, at a beam energy of 4.3 GeV. For a bunch charge of 250 pC, the initial RMS bunch length is 690 μm from the S-band photoinjector. It is compressed to a final RMS length of either 6 μm (3-kA peak current) or 4 μm (5-kA peak current).

OPTICS DESIGN

The optics design of the linac, the bunch compressors, and the matching sections are done in MAD8 [10] and then converted to ELEGANT [8]. The TWISS parameters of bunch compressors one (BC1) and two (BC2), shown in Figure 2, are similar to the LCLS BC1 and BC2 (transverse phase-space matching to minimize CSR induced transverse emittance growth). The start-to-end TWISS parameters of the overall accelerator are shown in Figure 3. An average beta function of 10 meters and 20 meters are employed in Linac2X and Linac3X, respectively, to minimize both dispersive and wakefield-induced transverse emittance dilutions.

* Work at Argonne is supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357. Work also supported by the U.S. Department of Energy under Contract DE-AC02-76SF00515.

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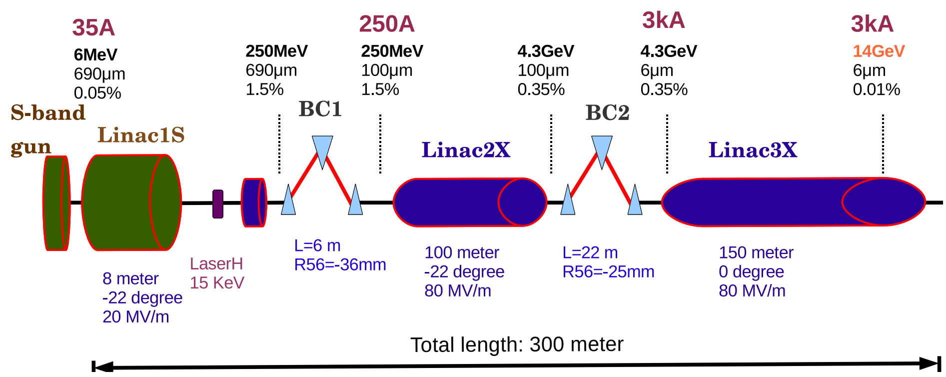

Figure 1: Sketch of a compact (300 m) hard x-ray FEL driver using X-band accelerators plus LCLS injector (up to the end of BC1). An average 'real estate' acceleration gradient of 60 MV/m is assumed in the X-band accelerator structures. The linac for the hard x-ray FEL achieves a final electron bunch energy of 14 GeV (same as the LCLS case) with a peak current between 3 kA and 5 kA (by tuning rf phase and then the bunch compression ratio). A final pulse duration length of 40-60 fs is achieved with a bunch charge of 250 pC. The sliced energy spread is between $0.01\% - 0.02\%$, and the sliced normalized transverse emittance is below 0.6 μm.

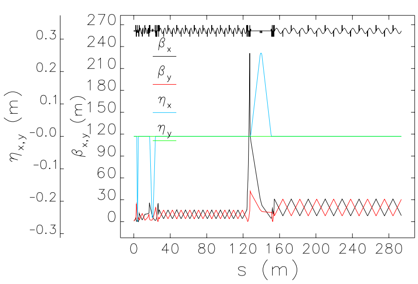

Figure 3: Beta functions and dispersion functions of the overall accelerator, from Linac1S (in Fig. 1) to the end of Linac3X (in Fig. 1) with a final beam energy of 14 GeV.

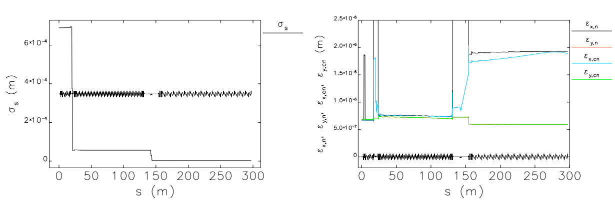

Figure 4: Left: RMS bunch length evolution along the linac, from ELEGANT simulation; right: projected and linear dispersion subtracted emittance evolution along the linac, from ELEGANT simulation.

ELEGANT SIMULATION

The beam dynamics simulation in the photoinjector is performed in ASTRA [7], and then a dumped beam is taken as the initial beam in the ELEGANT simulation. First-, second-, and third-order optics effects are included in the ELEGANT simulation, as well as all the collective effects, such as space-charge effect, incoherent and coherent synchrotron radiation, and transverse and longitudinal wakefields.

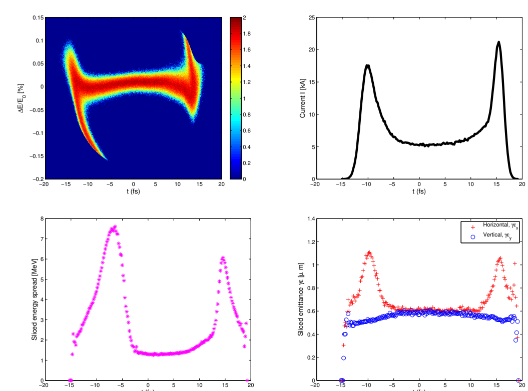

Figure 5: Electron beam properties at the end of Linac3X of this X-band-driven FEL driver, from ELEGANT simulation. Left top: longitudinal phase space; left bottom: longitudinally sliced energy spread; right top: current profile; right bottom: longitudinally sliced emittance.

The RMS bunch length and transverse emittance evolution along the accelerator are shown in Figure 4. Bunch compression ratios of 7 and 15 are achieved in a first- and second-stage bunch compressor. The final RMS bunch length is around 6-7 μm with a peak current over 3 kA. In the vertical plane the emittance is almost preserved. The horizontal emittance growth is mainly contributed from the coherent synchrotron radiation effects in the bunch compressors. Bunch compression ratios of 14 and 10 (for 5-kA final beam current case) could be achieved in a first- and second-stage bunch compression, respectively. The final beam current can be pushed to above 5 kA. The higher peak current at two ends (double horn) is due to compression with larger energy correlation (chirp) from longitudinal wakefields in Linac2X. There is a similar effect in the LCLS case.

ISBN 978-3-95450-138-0

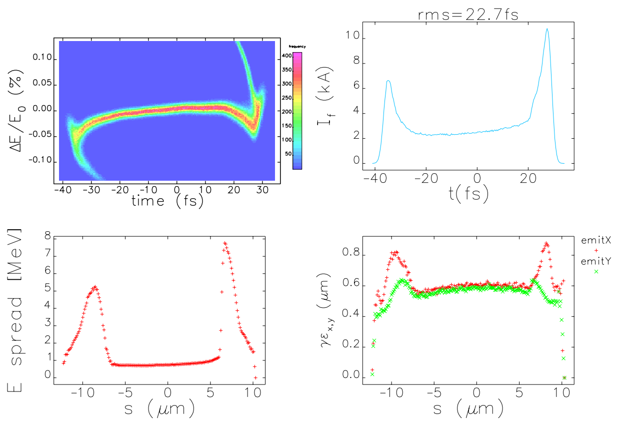

Figure 6: Electron beam properties at the end of LCLS Linac3, from ELEGANT simulation. Left top: longitudinal phase space; left bottom: longitudinally sliced energy spread; right top: current profile; right bottom: longitudinally sliced emittance.

Electron beam properties at the end of Linac3X of this X-band driven FEL driver are shown in Figure 5 from ELEGANT simulation, including longitudinal phase space, longitudinally sliced energy spread, current profile and longitudinally sliced emittance. A normalized transverse emittance of 0.6 μm is preserved at the core part of the electron bunch, with a pulse duration length of 40 fs. A peak current of 5 kA and a longitudinally sliced relative energy spread less than 2×10^{-4} is achieved. The residual correlated energy offset established in Linac1 and Linac2X is removed in Linac3X with the help of a strong X-band rf longitudinal wakefield, and a flat final energy profile is achieved at a final beam energy of 14 GeV.

A similar plot is shown in Figure 6 for the LCLS case. It is observed that the final beam current is over 5 kA in this X-band-driven FEL (3 kA for LCLS), and the sliced transverse emittance is similar for LCLS. A normalized transverse emittance of 0.5-0.6 μm is preserved at the core part of the electron bunch, with a pulse duration length of 70 fs. A peak current of 3 kA and a longitudinally sliced relative energy spread around 1×10^{-4} is achieved. The residual correlated energy offset established in Linac1 and Linac2 is removed in Linac3 with the help of an S-band rf longitudinal wakefield, and a flat final energy profile is achieved at a final beam energy of 14 GeV.

GENESIS SIMULATION

The electron bunch distribution generated from ELEGANT simulation is then fed into an undulator system, and the associated FEL performance is simulated and evaluated within the code GENESIS [9]. The same undulator setup is adopted for both this X-band-driven FEL and the LCLS, which is described below. An ideal undulator is designed to have a short period of $\lambda_w = 1.5$ cm, and the undulator strength K is chosen to tune the resonant FEL wavelength of $\lambda_r = 0.15$ nm, given the centroid energy of the electron bunch chosen at 14 GeV. No nonlinear magnetic field is in-

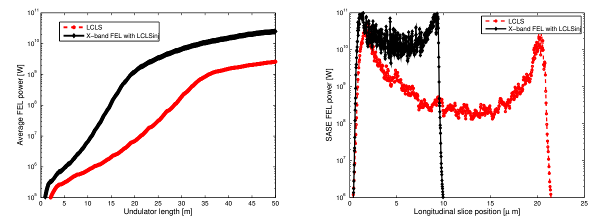

Figure 7: Left: FEL power evolution along the undulator; right: FEL power temporal profile at 50 m into the undulator. Red: LCLS case; black: the X-band-driven FEL.

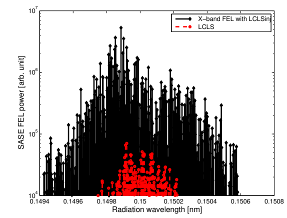

Figure 8: FEL power spectrum at 50 m into the undulator. Red: LCLS case; black: the X-band-driven FEL driver.

cluded for the undulator model. No undulator tapering is adopted.

A comparison of the simulated FEL performance is shown in Figure 7 and Figure 8. As expected, this X-band-driven FEL achieves a shorter FEL gain length, a higher saturation power, and a higher FEL power at the same undulator length (benefiting from a higher peak current of 5 kA) as the LCLS case.

ACKNOWLEDGMENT

The author would like to thank C. Adolphsen, J. Wu, M. Woodley, A. Chao, Z. Huang, Y. Ding, and C. Limborg-Deprey for helpful discussions. The idea for this design is initially from C. Adolphsen et al. [1] and T. Raubenheimer. T. Raubenheimer proposed the push for higher peak current by employing stronger X-band wakefields [2]. Most of the work was done at SLAC. The paper was written at ANL.

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