BEAM DYNAMICS STUDY OF X-BAND LINAC DRIVEN X-RAY FELS*

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Abstract

Several linac driven X-ray Free Electron Lasers (XFELs) are being developed to provide high brightness photon beams with very short, tunable wavelengths. In this paper, three XFEL configurations are proposed that achieve LCLS-like performance using X-band linac drivers. These linacs are more versatile, efficient and compact than ones using S-band or C-band rf technology. For each of the designs, the overall accelerator layout and the shaping of the bunch longitudinal phase space are described briefly.

INTRODUCTION

During the last 40 years, the photon wavelengths from linac driven FELs have been pushed shorter by increasing the electron beam energy and adopting shorter period undulators. Recently, the wavelengths have reached the X-ray range, with FLASH (Free-Electron Laser in Hamburg) [1] and LCLS (Linac Coherent Light Source) [2] successfully providing users with soft and hard X-rays, respectively. FLASH uses a 1.2 GeV L-band (1.3 GHz) superconducting linac driver and can deliver 10-70 fs FWHM long photon pulses in a wavelength range of 44 nm to 4.1 nm. LCLS uses the last third of the SLAC 3 km S-band (2.856 GHz) normal-conducting linac to produce 3.5 GeV to 15 GeV bunches to generate soft and hard X-rays with good spatial coherence at wavelengths from 2.2 nm to 0.12 nm.

Newer XFELs (at SPring8 and PSI) use C-band (5.7 GHz) normal-conducting linac drivers, which can sustain higher acceleration gradients, and hence shorten the linac length, and are more efficient at converting rf energy to bunch energy. The X-band (11.4 GHz) rf technology developed for NLC/GLC offers even higher gradients and efficiencies, and the shorter rf wavelength allows more versatility in longitudinal bunch phase space compression and manipulation. In the following sections, three different configurations of X-band linac driven XFELs are described that operate from 6 to 14 GeV. The first (LOW CHARGE DESIGN) has an electron bunch charge of only 10 pC; the second (OPTICS LINEARIZATION DESIGN) is based on optics linearization of the longitudinal phase space in the first stage bunch compressor and can operate with either a high (250 pC) or low (20 pC) bunch charge; and the third (LCLS INJECTOR DESIGN) is similar to LCLS but uses an X-band linac after the first stage bunch compressor at 250 MeV to achieve a final beam energy up to 14 GeV. Compared with LCLS, these X-band linacs are at least a factor of three shorter.

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LOW CHARGE DESIGN

This 6 GeV hard XFEL design is composed of a compact 150-meter-long X-band injector and linac, plus a 30 m undulator. A sketch of the accelerator layout is illustrated in Fig. 1 (left), and plots of the final beam current profile and longitudinal phase space are shown in Fig. 1 (right). It can operate in the short bunch, low charge regime, which guarantees a small nonlinear energy modulation along the bunch from the X-band acceleration (26 mm rf wavelength). No harmonic RF linearization is needed in either stage of bunch compression. An acceleration gradient of 80 MV/m is assumed, which is achieved routinely in the SLAC NLCTA X-band linac. The effective 'real estate' gradient is about 60 MV/m when components such as quadrupoles are included. In comparison, the S-band RF structures in LCLS are operated at an acceleration gradient of 20 MV/m. For bunch compression, a two stage system is adopted, each using a standard four-dipole chicane. The bunch generated by the X-band photocathode gun is assumed to have a charge of 10 pC, an rms length of 40 μm and a peak current of 30 A. This electron bunch is compressed to a final length of 0.3 μm rms with a peak current of 3 kA. A laser heater is located before the first stage of bunch compression to increase the uncorrelated energy spread, which provides more Landau damping to suppress transverse emittance growth caused by coherent synchrotron radiation.

The longitudinal wakefield in Linac2 can be optimized by tuning Linac2 length, to partially or fully cancel the timing jitter induced bunch length variation, and to generate a flattop electron current profile as shown in Fig. 1 (right). Simulations using GENESIS [4] of such bunches lasing at 0.15 nm in a $\lambda_w = 1.5$ cm period undulator, and other design considerations, can be found in [5].

OPTICS LINEARIZATION DESIGN

For linac based XFELs, a harmonic RF section is typically used before the first stage bunch compression, where the bunch is the longest, to cancel the higher order energy correlation caused by the RF curvature in the main acceleration section. This leaves a nearly linear energy variation along the bunch. For example, FLASH uses third harmonic (3.9 GHz) rf cavities and LCLS has a fourth harmonic (X-band) accelerator structure.

In this XFEL driver design, an alternative way to linearize the bunch compression in the first stage is employed. It eliminates the harmonic RF section, which would be difficult with an X-band injector, and uses optics linearization instead with a specially designed bunch compressor that

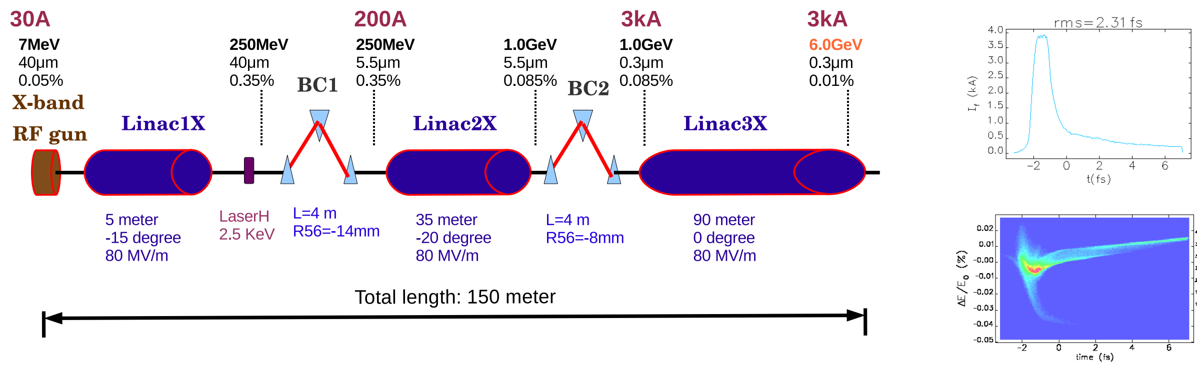

Figure 1: Left: sketch of a compact (150 m) XFEL driver using all X-band accelerators including an X-band photocathode gun [3]. An acceleration gradient of 80 MV/m is assumed in the X-band accelerator structures, and a two stage bunch compression system is adopted with relatively weak dipole magnets to suppress ISR (incoherent synchrotron radiation) and CSR (coherent synchrotron radiation) effects. Right: ELEGANT simulations of the final bunch current and energy profile at the end of the accelerator (undulator entrance).

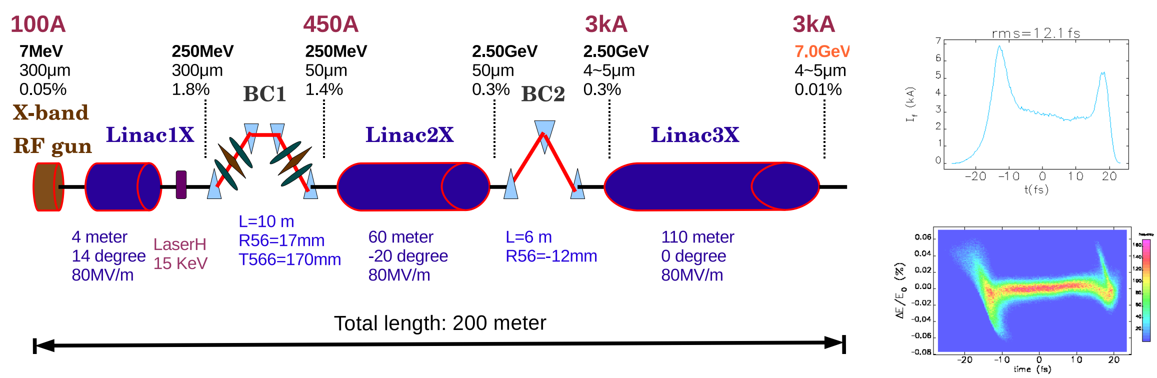

Figure 2: Left: sketch of an all X-band, hard X-ray FEL driver with optics linearization in the first stage bunch compressor. Right: ELEGANT simulations of the final bunch current and energy profile at the end of the accelerator.

includes quadrupole and sextupole magnets. The second order longitudinal dispersion T_{566} of this bunch compressor is used to compensate the second order curvature from the rf acceleration. The third order longitudinal dispersion U_{5666} can also be tuned to cancel the third order rf curvature, however, in most cases this is not necessary as its effect is relatively small.

An all X-band, 200-meter-long, XFEL driver using this linearization scheme is shown in Fig. 2 together with plots of the resulting bunch longitudinal phase space and the final beam current profile. Two stages of bunch compression are used to preserve the beam brightness and to allow timing jitter cancellation using the effect of the strong longitudinal wakefield. With this optics linearization scheme, the bunch needs to be overcompressed in the first stage compressor (unlike in LCLS), and under compressed in the second (like in LCLS). The two stage bunch compression also makes the compression ratio smaller in each stage, and a compression ratio less than 10 is preferred to achieve good linearity during compression. The optics for this design was computed and optimized using the code MAD8 [6], then translated for use with the ELEGANT [7] code. A start-to-end (6 MeV to 7 GeV) 6-D simulation was performed in ELEGANT with all the collective effects included, although with perfect alignment of all of the beam elements. This was followed by an FEL lasing simulation of 1.5 Angstrom (8 keV) photons in a $\lambda_w = 1.5$ cm undulator using the GENESIS [4] code. With 250 pC bunchs from the injector, a similar lasing performance (photons per electron in the undulator) as that at LCLS for the same injector bunch charge was achieved. However, the pulse length is about a third shorter than that at LCLS as 40% of the charge is collimated in the first stage bunch compression at 250 MeV. The collimation is necessary to preserve a small slice transverse emittance by removing the electrons in the head and tail of the bunch, which are heavily affected by CSR effect during the over compression process. Examples of lasing simulation results for this and the low charge design are shown in Fig. 3. A detailed description of this design can be found in [8].

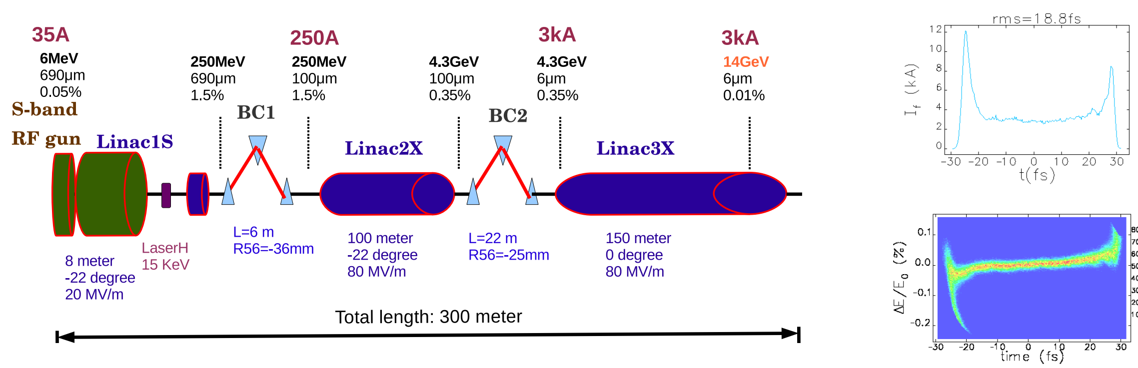

Figure 4: Left: Sketch of an XFEL driver using an LCLS injector through the first compressor, followed by an X-band linac. Right: ELEGANT simulations of the final bunch current and energy profile at the accelerator end.

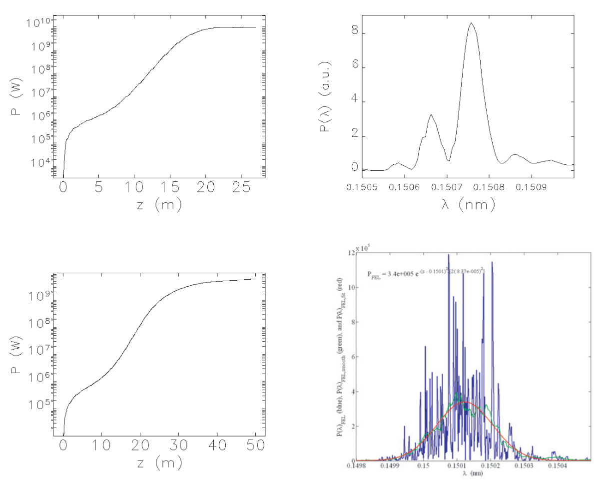

Figure 3: Left: X-ray power along the undulator. Right: X-ray power spectrum 20 m (top) and 30 m (bottom) into the undulator. Top: case 'LOW CHARGE DESIGN'. Bottom: case 'OPTICS LINEARIZATION DESIGN'.

LCLS INJECTOR DESIGN

The XFEL driver layout, bunch phase space and current profile for this design are shown in Fig. 4. The driver has a LCLS-like injector followed by an X-band linac after the first bunch compressor at 250 MeV. The injector includes an S-band photoinjector and linac, an X-band 'linearizer' structure, a laser heater and a four dipole chicane.

After the injector, the beam is accelerated -22 degrees off crest to 4.3 GeV in an X-band linac, then compressed in the second stage bunch compressor, which consists of a four dipole chicane. In the third linac, which is also X-band, the electron beam energy is increased to 14 GeV and the residual correlated energy spread is removed mainly by the strong longitudinal X-band accelerator structure wakefield. The resulting electron beam has a similar or better quality than that from LCLS simulations. The total length of the accelerator is roughly 300 meters, including the LCLS style injector. Employing an LCLS like undulator with $\lambda_w = 3$ cm, FEL saturation can be achieved within 60 meters at a photon wavelength of 1.5 Angstrom.

Based on these ELEGANT and GENESIS simulations, this 300 m driver can generate the same XFEL performance as the 1000 m long S-band linac driver for LCLS. It also may provide a wider FEL operation range (i.e., double the final peak current to 6 kA) and much more flexibility in longitudinal phase space manipulation. The detailed design considerations and simulation results can be found in [9].

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