X-BAND FEL DRIVER LINAC DESIGN WITH OPTICS LINEARIZATION*

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Abstract

In this paper, a compact hard x-ray FEL design is proposed with a single bunch charge of 250 pC, which is based on all X-band rf acceleration and two-stage bunch compression. It eliminates the need for a harmonic rf linearization section by employing optics linearization in its first-stage bunch compression. Emittance growth in the horizontal plane due to coherent synchrotron radiation (CSR) is investigated and minimized, to be on a similar level with the LCLS. An electron bunch distribution at the linac end is taken as the input for an FEL simulation in GENESIS, with a beam energy of 7 GeV. At an FEL radiation wavelength of 0.15 nm, a saturation length of roughly 40 meters can be achieved by employing an undulator with a period of 1.5 cm. Without tapering, an FEL radiation power above 10 GW is achieved with a photon pulse length of 50 fs, which is LCLS-like performance. The overall length of the accelerator plus undulator is around 250 meters, which is much shorter than the LCLS length of 1230 meters.

OVERVIEW AND ACCELERATOR DESIGN

In this paper, a very compact FEL driver is proposed with an accelerator length less than 200 m. An alternative way to do a linearized bunch compression in a first stage is proposed. The key point is to eliminate the harmonic rf section, and to apply an optics linearization instead, with a specially designed bunch compressor that includes quadrupole and sextupole magnets. Similar schemes have been proposed and studied preliminarily before, either in an analytical manner [1] [2] [3], by numerical simulations [1] [3] [4] [5], or in experimental measurements [3]. The second-order longitudinal dispersion T_{566} of this bunch compressor is precisely controlled and used to compensate the second-order curvature from the main rf acceleration. 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 impact is relatively small. Compared with a four-dipole chicane, this bunch compressor has the opposite sign of the linear longitudinal dispersion R_{56}. The main rf system in the first linac then has to work on the falling slope of the sinusoidal wave, which is the only way to shorten the bunch length; otherwise the bunch length is lengthened. In order to do a normal under-compression in the second stage, and still use longitudinal wakefields to remove the residual chirp in the last linac, one needs to do an over-compression in the first-stage bunch compressor. Over-compression may cause larger transverse emittance growth due to phase smear in the over-compression process, associated with energy change from coherent synchrotron radiation (CSR) in a dispersive region. The optics design of this bunch compressor needs to be investigated and optimized carefully to minimize these impacts.

The accelerator of this FEL driver is sketched in Figure 1. Compared with a similar hard x-ray FEL design based on S-band rf acceleration, this all X-band-based FEL has several potential advantages. One advantage is its compact size at the same final beam energy, due to the higher acceleration gradient provided by X-band rf cavities. In general the accelerator length is only one-fourth or one-third of the S-band-based accelerator. Besides, a shorter wavelength of X-band rf also makes the establishment of energy modulation easier, which then makes it possible to run on an rf phase closer to the crest and so save rf power. Another possible advantage is that it may be easier to manipulate the longitudinal phase space, especially in the second and last linac (for a two-stage bunch compression), mainly due to a much stronger longitudinal wake field of X-band rf. One may also benefit from a smaller CSR-induced emittance growth in bunch compressor two, as a larger energy correlation can be generated in Linac2 and then removed in Linac3, so the strength of the bunch compressor dipoles can be decreased.

NUMERICAL SIMULATION

In this section start-to-end ELEGANT [6] 6-D numerical simulation results are presented. The simulation starts at a beam energy of 50 MeV, where X-band photoinjector simulations show that an RMS bunch length of 160 μm could be achieved along with a normalized transverse emittance of 0.5 μm.rad at a bunch charge of 250 pC, by tuning the drive laser system, bunching system, and subsequent acceleration section [7]. Space-charge effect and velocity bunching are two dominant effects in this section from the production of the electron bunch and its acceleration to a beam energy of 50 MeV. The details on the simulation results of this part are not discussed here.

An electron bunch that consists of one million macro particles is then generated internally in ELEGANT, employing an RMS bunch length of 160 μm and a normalized transverse emittance of 0.5 μm.rad. The beam energy is 50 MeV and the single-bunch charge is 250 pC. The un-

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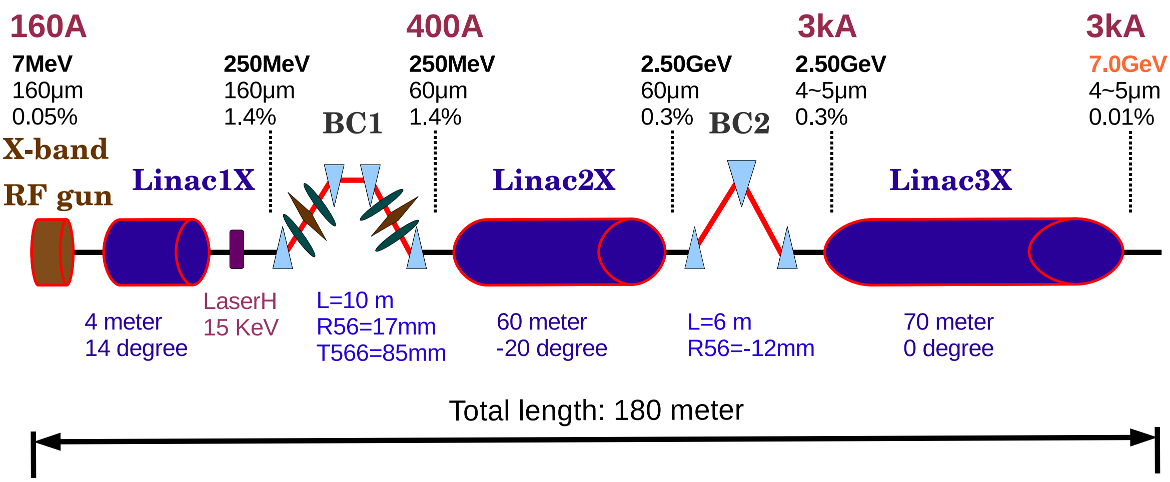

Figure 1: Sketch of an all X-band-based hard x-ray FEL accelerator design.

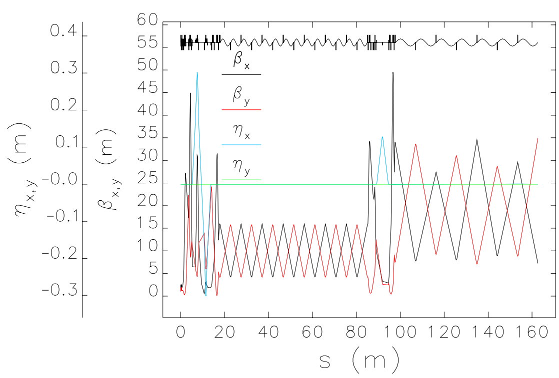

Figure 2: Start-to-end TWISS parameters, a beam energy from 50 MeV to 7 GeV. Black curve denotes horizontal beta function; red curve, vertical beta function; blue curve, horizontal dispersion function; and green curve, horizontal angular dispersion function.

correlated RMS energy spread is 12.5 keV. The distribution in both longitudinal and transverse planes is assumed to be a perfect Gaussian distribution. This electron bunch is transported through a first linac section (Linac1), bunch compressor one, a second linac section (Linac2), bunch compressor two, and a third linac section (Linac3). The start-to-end first order optics is illustrated in Figure 2, from entrance of Linac1 to the end of Linac3. The optics design is performed and optimized in an accelerator design code MAD8 [8] first, then translated into ELEGANT [6] format.

The CSR-induced transverse emittance growth is on a similar level between this X-band-driven FEL and the LCLS. In detail, while the vertical emittance is always preserved at 0.5 μm.rad during the acceleration and bunch compression, the horizontal emittance is increased to 0.55 μm.rad in the core part and 0.8-0.9 μm.rad in the bunch head and tail.

After the two-stage bunch compression, a peak current over 3 kA is achieved in a pulse length of roughly 50 fs. The vertical normalized emittance is preserved at 0.5 μm.rad, and the horizontal normalized emittance is increased by 20% on average. The residual correlated energy spread is removed in Linac3, mainly by the strong X-band rf longitudinal wakefield. The Linac3 runs on-crest with a total length of 70 meters. A final flat energy profile is achieved as shown in Figure 3, as well as the current profile, longitudinally sliced transverse emittance, and energy spread. This final electron beam is injected into the design undulator for a hard x-ray FEL with a radiation wavelength as short as 0.15 nm. The detailed FEL simulation and performance is presented below.

FEL SIMULATION

FEL performance is preliminarily studied, with the GENESIS simulation results presented in this section. In the following parts, we show a concrete example of FEL lasing at 0.15-nm wavelength, which is the same as achieved at LCLS. The undulator is designed to have a shorter period $\lambda_w = 1.5$ cm than the LCLS value of 3 cm, as the beam energy of 7 GeV is lower than the LCLS beam energy of 14 GeV. The undulator strength K is chosen so that the resonant FEL wavelength is $\lambda_r = 0.15$ nm according to Eq. 64 for $\theta = 0$ and $E = 7$ GeV. The electron bunch distribution generated from the ELEGANT simulation is then fed into an undulator system, and the associated FEL performance is simulated and evaluated within the code GENESIS [9]. The electron bunch transverse profile is matched into the undulator beamline where the average beta function is roughly 20 meters. No undulator tapering is adopted here to further

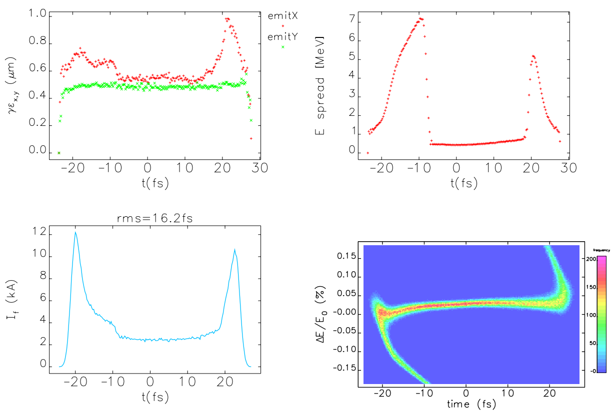

Figure 3: Beam properties at the end of Linac3, which is also the entrance of the undulator. Left top: longitudinally sliced emittance; left bottom: current profile along longitudinal direction; right top: longitudinally sliced energy spread; right bottom: longitudinal phase space.

increase the FEL saturation power.

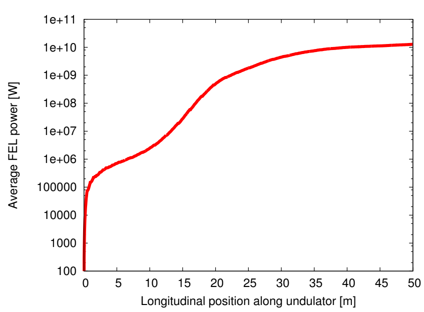

Figure 4: FEL power evolution along the undulator.

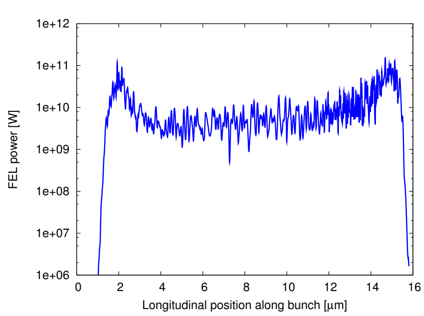

Figure 5: FEL power temporal profile at 40-m undulator.

Given a high peak current of 3 kA, plus a small sliced transverse emittance and energy spread, within a 40-m-long undulator the FEL radiation power can saturate at an average power of $P_{sat} \sim 10$ GW as shown in Figure 4. In comparison, LCLS achieves roughly 6 GW in 60 meters without tapering. An overall undulator length of 50 m is chosen to guarantee saturation. The temporal and spectrum profile of the FEL at 40 m of undulator is shown in Figure 5 and Figure 6, respectively.

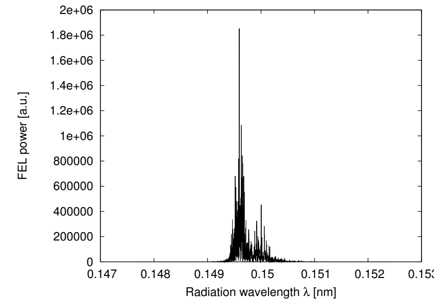

Figure 6: FEL power spectrum at 40-m undulator.

CONCLUSION

Start-to-end optics design and 6-D macro particle simulations are presented for an electron beam energy from 50 MeV to 7 GeV. The electron bunch is successfully compressed to a peak current above 3 kA, while its brightness is well preserved in both the transverse and longitudinal planes. The CSR-induced transverse emittance growth is at a similar level in both this X-band-driven FEL and the LCLS. This all X-band rf-based hard x-ray FEL could achieve LCLS-like performance in a shorter overall length of 250 meters.

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