FELS AS X-RAY SOURCES IN ERL FACILITIES*

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Abstract

Hard x-ray Energy Recovery Linacs (ERLs) operate with high-brightness electron beams, matching the requirements for x-ray FELs in terms of emittance and energy spread. We have analyzed in how far it is feasible to include x-ray FELs in ERL facilities. x-ray FEL oscillators require comparatively low peak currents and are therefore good candidates for FEL sources in ERLs. However, high-gain FELs do not seem out of reach when bunch-compression schemes for higher peak currents are utilized. Using the proposed Cornell ERL as an example, different FEL concepts are discussed and their suitability as x-ray sources are analyzed.

INTRODUCTION

In addition to the characteristic high repetition rate in the GHz range, the high brightness of the electron beam delivered by ERLs is an outstanding feature that makes ERL-based facilities desirable drivers for x-ray FELs.

Generally, FEL oscillators requiring low peak current and taking advantage of both high repetition rate and high brightness are favored in ERL based facilities. However for hard x-rays the stability and temperature issues of the focusing and reflective optics can limit the useable repetition rate to the MHz range, thus reducing the benefits of an ERL. Further, provided that proper bunch compressors are available, the electron beam delivered by ERLs is suitable for high-gain single-pass FELs in the x-ray range, due to the small emittance and energy spread.

Cornell University plans to build an ERL-based x-ray lightsource [1]. Recently, a suitable bunch compressor scheme was discussed for this ERL [1, 2]. The facility is designed for bunches of 77 pC charge and 2 ps duration with a repetition rate of 1.3 GHz. The linac is divided into two parts arranged around a turnaround arc. It delivers electron bunches with an energy of 5 GeV, normalized transverse emittances of 0.3 mm mrad and relative energy spread of 2×10^{-4}. Using the second order time of flight terms in the turnaround arc, a simple four dipole chicane compressor, located after the second part of the linac, can be used to generate short bunches in the 100 fs range [2]. While the uncompressed beam delivered by the Cornell ERL is an excellent driver for an FEL-oscillator in the hard x-ray regime, the compressed beam can drive high-gain FELs. In this paper we present and discuss simulation results for both FEL oscillator and high-gain FELs based on the Cornell-ERL.

SINGLE-PASS FEL SCHEMES

For the simulation studies presented here, we chose a moderate bunch compression factor of 10, reducing the rms bunch duration from 2 ps to 200 fs while increasing the bunch peak current to 230 A. Taking into account collective and stochastic effects such as coherent and incoherent synchrotron radiation, we use the code *Bmad* [3] to track the electrons from the injector through the first linac section, the turnaround arc, the second linc section and finally through a four dipole chicane. The relative energy spread at the exit of the chicane amounts to 6.4×10^{-5}. The horizontal emittance is increased from 0.3 to 0.6 mm mrad mainly due to the incoherent synchrotron radiation while the vertical emittance remains 0.3 mm mrad.

Seeded FEL

Combining the Echo Enabled Harmonic Generation (EEHG) scheme [4] with the fresh bunch technique [5] (see Fig. 1), an FEL setup is built where the compressed ERL bunch can drive a seeded single pass FEL in the soft x-ray regime. The EEHG scheme utilizes two modulators and two chicanes to generate significant bunching on very high harmonics with a modest increase in the total energy spread. The following radiator, in resonance to a specific harmonic, generates and amplifies high power radiation. However, for very high harmonics and low peak currents, even the modest increase in the total energy spread can increase the FEL gain length to an intolerable value, preventing effectively the FEL amplification. The fresh bunch technique offers a possibility to overcome this problem. In this approach the seeding pulse is significantly shorter than the electron bunch. As a result, the harmonic generation process, and with it the enlargement of the energy spread applies only to a fraction of the bunch. After passing through the EEHG part the resulting radiation is shifted – via a simple magnetic chicane – to a 'fresh' part of the bunch which was not affected by the EEHG process.

In order to study the radiation properties of such a combined scheme, we optimize the EEHG setup for the 80th harmonic of a seed wavelength of 267 nm. The modulators are seeded with the same wavelength but different pulse durations on the order of a few 10 fs, thus much shorter than the electron bunch duration. The imprinted energy modulation is 1.7 MeV in the first modulator and 0.625 MeV in the second. The first EEHG-chicane has a $r_{56} = -5.7$ mm; the value for the second chicane is $\mathrm{r}_{56} = 7 \times 10^{-2}$ mm. The achieved bunching at the entrance of the radiator amounts to 7 %, which is slightly less than maximum theoretical value of 9%. Figure 2 shows the output of the EEHG part

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Figure 1: Using the fresh bunch technique [4], a radiator following a regular Echo enabled FEL [5] can deliver high power radiation pulses of soft x-rays. The EEHG part consists of two 2.25 m modulators, each with a period length of 25 cm. The EEHG-radiator has a period length of 4.5 cm and consist of two undlators each 4.5 m long.The second radiator consists of 8 undulators, each 4.5 m long with a period length of 4.5 cm.

of the 'combined FEL setup'. The output after the second radiator is depicted in Fig. 3. The final radiator delivers radiation pulses with a duration of 18 fs. The number of photons per pulse is 1.7×10^{11} in a relative bandwidth of 2×10^{-4}. Note that the repetition rate of this setup is determined by the repetition rate of the seed laser which is much less than the rate of the ERL.

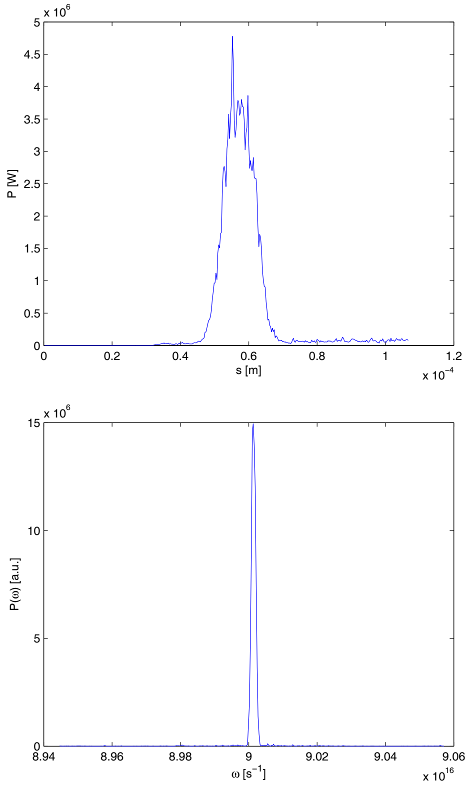

Figure 2: Output of the EEHG part of the combined FEL setup showing the power profile (top) and the spectral distribution (bottom).

SASE FEL

Cornell ERL can drive a SASE-FEL in hard x-ray regime by utilizing a modified current enhancement technique [6]. Using a 800 nm laser seed and a chicane with an $r_{56} = -0.94$ mm, we achieve a moderate current enhancement of a factor of 3. This is enough to achieve saturation for a 0.45 nm x-ray pulse in 48 m using delta undulators [7] with a period length of 2.2 cm. The output power of the SASE-FEL is shown in Fig. 5. The output pulse has an rms duration of 74 fs, consisting of 1.2×10^{10} photons per pulse emitted in a relative bandwidth of 10^{-3}.

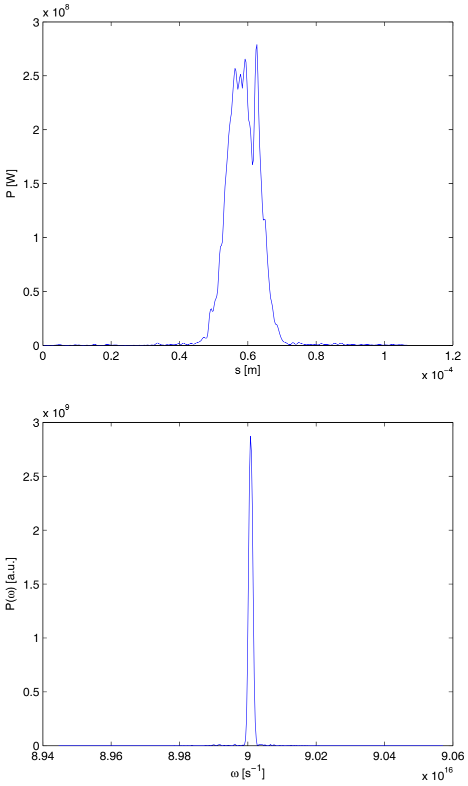

Figure 3: The final output of the combined FEL setup showing the power profile (top) and the spectral distribution (bottom).

FEL OSCILLATOR

Due to the very narrow bandwidth, the hard x-ray FEL oscillators are complementary to hard x-ray SASE FELs. FEL oscillators operating in the hard x-ray regime were proposed and analyzed in various references [8, 9, 10, 11]. The cavity resonator of such an FEL is composed of high-reflectivity, narrow-bandwidth Bragg mirrors of sapphire or diamond crystals. The resonator dimensions ensure a pulse round-trip rate on the order of few MHz. In addition to the narrow bandwidth, the transverse emittance and the

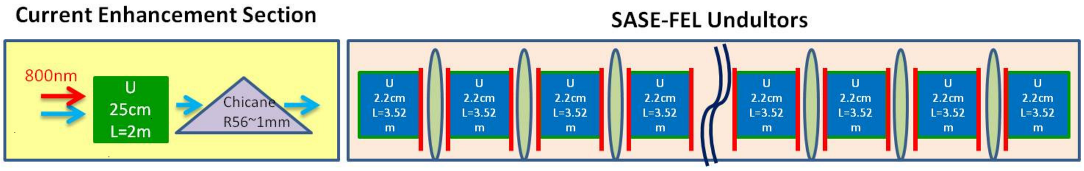

Figure 4: A SASE FEL setup for an ERL consisting of a current enhancement section and an undulator section.

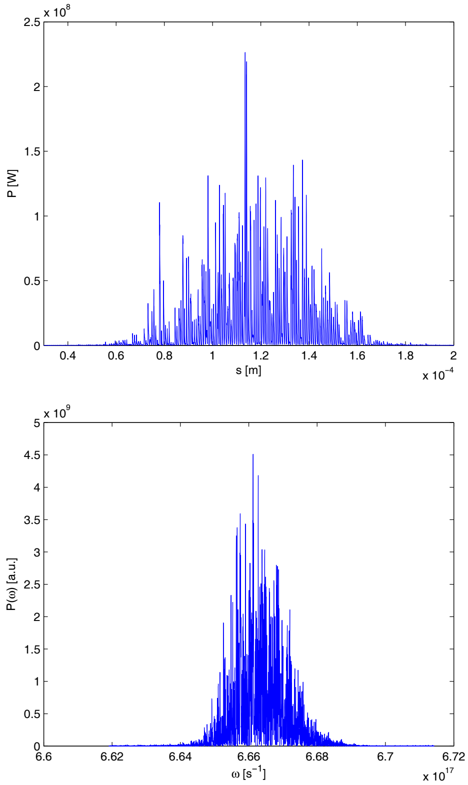

Figure 5: Output power of the an ERL driven SASE-FEL ultilizing the current enhancement scheme showning the power profile (top) and the spectral distribution (bottom).

duration of the emitting electron beam are the key parameters for high peak brilliance in an x-ray FEL oscillator. We study the the impact of these parameters on an oscillator within the Cornell ERL by following up on the work presented in [11]. Using the 1D code developed in [11], we simulate the saturation power as a function of emittance and bunch duration. The simulation results are shown in Fig. 6.

CONCLUSION

We have presented and discussed simulation results for both FEL oscillator and high-gain FELs based on the Cornell-ERL. Our simulations verify that the Cornell ERL is a suitable driver for seeded FELs in soft x-ray regime, as well as for SASE FELs and oscillators in hard x-ray regime.

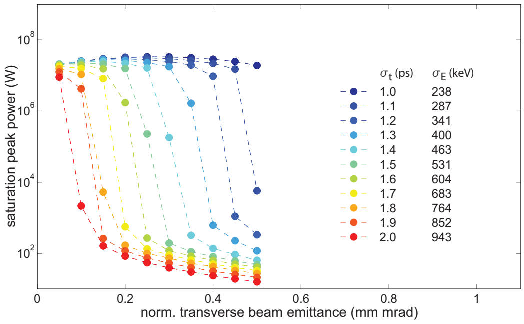

Figure 6: Calculated intra-cavity power of a hard x-ray FEL Oscillator driven by the Cornell ERL. Shown is the saturation power as a function of transverse beam emittance and bunch duration. A bunch charge of 25 pC is assumed, undulator has 3000 periods with a period length of 15 mm. The radiation wavelength is 0.103 nm. We assume spectral losses on the order of 15% per roundtrip, including a 4% out-coupled power.

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