X-RAY FELS BASED ON ERL FACILITIES

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Abstract

The characteristic high repetition rate and the high brightness of electron beams delivered by ERLs have led to a great number of ERL-based proposals for hard x-ray sources including x-ray FELs. FEL oscillators requiring comparatively low peak currents are often proposed for FEL sources in ERLs. However, single-pass FELs in SASE or seeded mode do not seem out of reach when bunch-compression schemes for higher peak currents are utilized. Using the proposed Cornell ERL as an example, we present and discuss oscillator and single-pass FEL schemes which provide high-brightness ultra-short x-ray pulses for experiments.

INTRODUCTION

The high repetition rate and high brightness of the electron beams delivered by ERLs are outstanding features that make 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 stability and heating issues of the focusing and reflective optics might limit the useable repetition rate to the MHz range. Provided that proper bunch compressors are available, the electron beam delivered by ERLs is also 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. Note that energy of the compressed beam is not recovered. In this paper we present and discuss simulation results for both FEL oscillator and high-gain FELs based on the Cornell-ERL.

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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 slice 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. For the seeded hard x-ray simulations, we considered a second pass through the first part of the linac increasing the energy up to 7.8 GeV. In this case a further increase of the horizontal emittance up to 1 mm mrad during the passage through second arc has to be taken into account.

Seeded FEL

As conventional lasers still do not deliver the necessary short wavelengths at the needed peak power level of a few hundred MW, techniques allowing for the production of coherent short wavelengths in the x-ray range are of major interest. A very promising technique is the Echo Enabled Harmonic Generation (EEHG) [4] which is based on the beam echo effect [5]. The manipulation of the energy modulation process is rather complicated. It involves the generation of energy bands in a first undulator-chicane section and a spatial modulation at very high harmonics in the second undulator-chicane section. In this approach bunching of about 9% can be achieved on very high harmonics around 100.

Soft X-rays Combining the EEHG-scheme with the fresh bunch technique [7] (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 a modest increase in the total energy spread can increase the FEL gain length to an intolerable value, preventing effectively the FEL amplification. This problem can be overcome by using by the fresh

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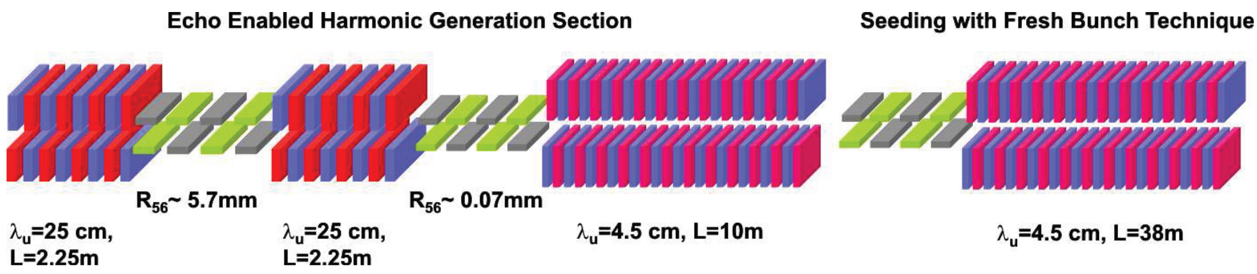

Figure 1: Using the fresh bunch technique [7], a radiator following a regular Echo enabled FEL [4] can deliver high power radiation pulses of soft x-rays. The EEHG part consists of two 2.25 m modulators, each with a period length of 25 cm. The EEHG-radiator has a period length of 4.5 cm and consist of two undulators 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.

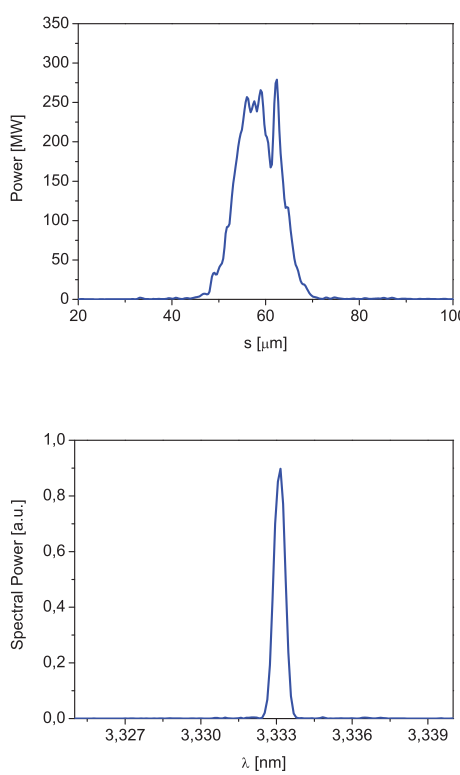

Figure 2: The final output of the combined FEL setup showing the power profile (top) and the spectral distribution (bottom).

bunch technique,in which 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 optimized the EEHG setup for the 80^{th} harmonic of a seed wavelength of 267 nm yielding a radiation wavelength of 3.3 nm. The modulators are seeded with the same wavelength but different pulse durations on the order of a few 10 fs, 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 an $r_{56} = -5.7$ mm; and the second chicane has an $r_{56} = 7 \times 10^{-2}$ mm. The achieved bunching at the entrance of the radiator amounts to 7 %, which is slightly less than maximum theoretical value of 9%. The output after the second radiator is depicted in Fig. 2. 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 presumably less than the rate of the electron bunches kicked into the compressor beamline.

Hard X-rays Replacing the first radiator of the above combined setup with an FEL oscillator (see Fig. 3), allows us to aim for hard X-rays. In spite of the poor reflectivity of the mirrors in the soft x-ray range, it is safe to assume that the generated power in the oscillator is high enough to fill the resonator gradually. This is due to the significant bunching on higher harmonics generated in the EEHG-modulator system. Once the resonator is filled sufficiently, one can switch off the seed laser, allowing an undisturbed bunch to be energy-modulated in the FEL oscillator on a wavelength in the soft x-ray range. The following chicane can then convert the energy modulation to a bunching on higher harmonics. The second radiator tuned to this harmonic delivers radiation in the hard x-ray range.

In this scheme, it is crucial to keep the power level in the oscillator constant after the filling. Therefore, the resonator has to be filled with as much radiation as necessary to ensure that the undisturbed electrons modulated in the oscillator will emit enough power to replace the losses in the actual pass. To do so, the layout of the oscillator- i.e undulator length and the position of the mirrors- and the number of the passes have to be chosen in dependency of the mirror-reflectivity and induced bunching.

In order to study the radiation properties of such a scheme, we optimized the EEHG modulator system for

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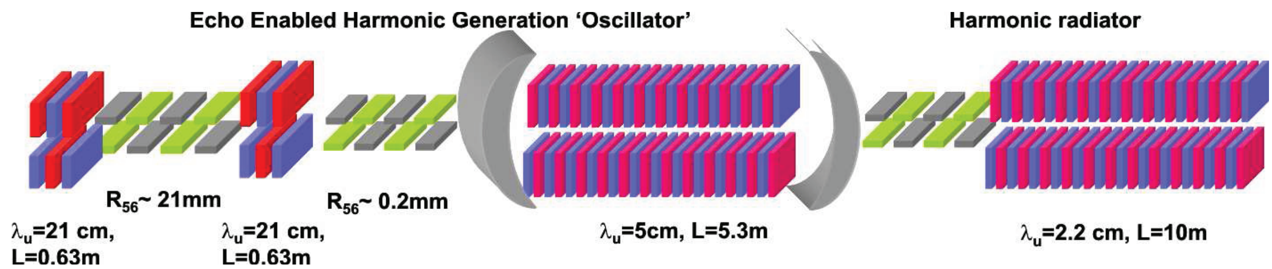

Figure 3: Using an oscillator as radiator following a regular Echo enabled modulation system [4] high power radiation can be delivered in hard x-rays range. The EEHG part consists of two 0.63 m modulators, each with a period length of 21 cm. The oscillator has a period length of 5 cm and is tuned to 2 nm. The second radiator consists of 5 undulators, each 3.52 m long with a period length of 2.2 cm.

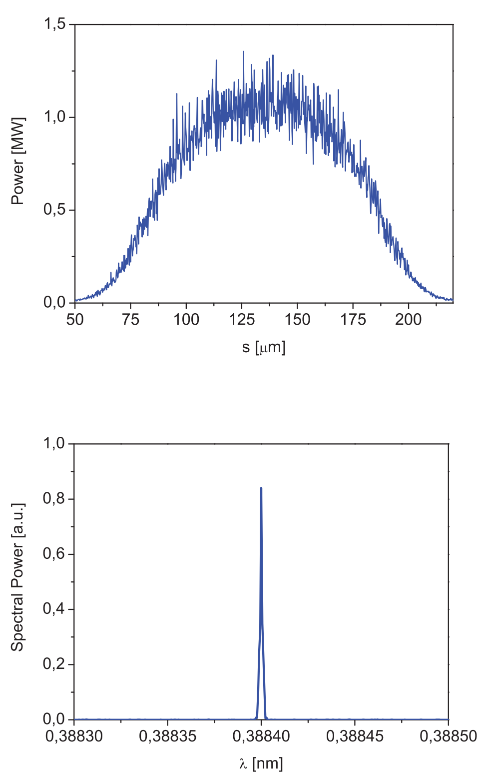

Figure 4: Output of the harmonic radiator of the combined FEL setup showing the power profile (top) and the spectral distribution (bottom).

the 103rd harmonic of a seed wavelength of 200 nm yielding a radiation wavelength of 1.94 nm. The modulators are seeded with the same wavelength and the seed pulse is as long as the electron bunch. The imprinted energy modulation is 3.6 MeV in the first modulator and 0.5 MeV in the second. The first EEHG-chicane has an $r_{56} = -21$ mm, and the second chicane has an $r_{56} = 0.2$ mm. The achieved bunching at the entrance of the oscillator amounts to 3.5 %. The total reflectivity of the mirror system is assumed to be about 7.5%. The output after the harmonic radiator is depicted in Fig. 4. The final radiator delivers radiation pulses with a duration of 110 fs rms. The number of photons per pulse is 7×10^8 in a relative bandwidth of 2×10^{-4}, resulting in a peak brightness of 1.2×10^{28} photons/(s mrad^2 mm^2 (0.1% bw)).

SASE FEL

The Cornell ERL can drive a SASE-FEL in the hard x-ray regime by utilizing a modified current enhancement technique [8] (see Fig. 5). 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 sufficient to achieve saturation for a 0.45 nm x-ray pulse in a 48 m long undulator line consisting of delta undulators [9] with a period length of 2.2 cm. The output power of the SASE-FEL is shown in Fig. 6. 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}.

FEL OSCILLATOR

Due to the very narrow bandwidth, 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 [10, 11, 12, 13]. 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 a few MHz. In addition to the narrow bandwidth, the transverse emittance and the duration of the emitting electron beam are key parameters for achieving a 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 [13]. Using the 1D code developed in [13], we simulate the saturation power as a function of emittance and bunch duration. The simulation results are shown in Fig.7.

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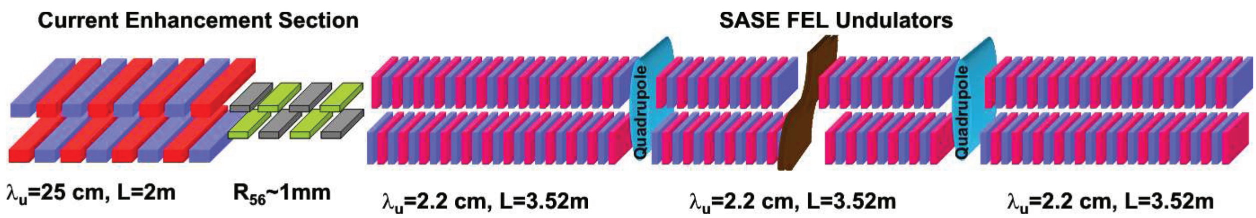

Figure 5: A SASE FEL setup for an ERL consisting of a current enhancement section and an undulator section. The current enhancement part consists of a 2 m long undulator with a period length of 25 cm and a chicane with an r_{56} of about 1 mm. The SASE FEL section consists of 12 undulators, each 3.52 m long with a period length of 2.2 cm.

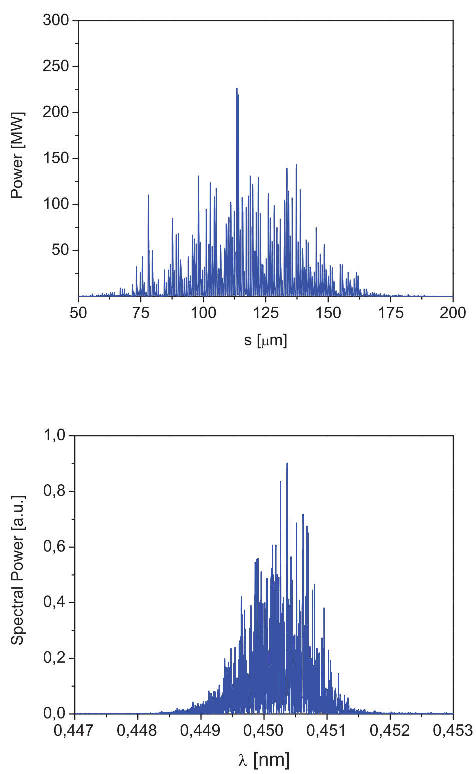

Figure 6: Output power of an ERL driven SASE-FEL utilizing the current enhancement scheme showing the power profile (top) and the spectral distribution (bottom).

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 the soft and hard x-ray regime, as well as for SASE FELs and oscillators in hard x-ray regime.

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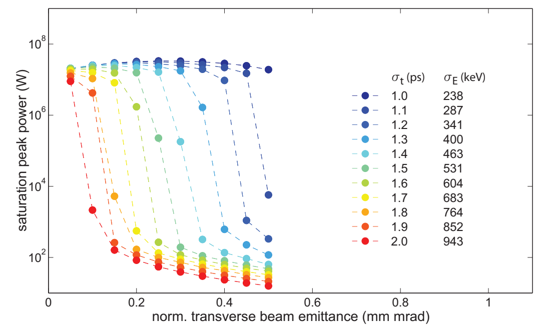

Figure 7: Calculated intra-cavity power of a hard x-ray FEL Oscillator driven by the Cornell ERL. Shown is the saturation peak power as a function of transverse beam emittance and bunch duration. A bunch charge of 25 pC is assumed, the undulator has 3000 periods with a period length of 15 mm. The radiation wavelength is 0.103 nm. We assume spectral losses on the order of 15% per roundtrip, including 4% out-coupled power.

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