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START TO END SIMULATION STUDY FOR OSCILLATOR-AMPLIFIER FREE-ELECTRON LASER

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Abstract

External seeding techniques like high-gain harmonic generation (HGHG) and echo-enabled harmonic generation (EEHG) have been proposed and proven to be able to generate fully coherent radiation in the EUV and X-ray range. A big challenge is to combine the advantages of seeding schemes with high repetition rates. For seeding at a high repetition rate, an optical resonator scheme has been introduced to recirculate the radiation in the modulator to seed the high repetition rate electron bunches. Earlier studies have shown that a resonator-like modulator combined with an amplifier in high gain harmonic generation (HGHG) configuration can be used to generate radiation whose wavelength can reach the water window region. This scheme overcomes the limitation of requiring high repetition rate seed laser systems. In this contribution, we present start-to-end simulation results of this oscillator-amplifier FEL scheme.

INTRODUCTION

For over ten years, SASE FELs [1] have been delivering radiation to users in XUV and X-ray wavelength range. However, SASE suffers from poor longitudinal coherence and large shot-to-shot fluctuations due to the stochastic behavior of the start-up process. To overcome these limitations, several external seeding techniques like high-gain harmonic generation (HGHG) [2] and echo-enabled harmonic generation (EEHG) [3, 4] have been proposed and proven to be able to generate fully coherent radiation in the EUV and X-ray range. The continuous wave (CW) machines with superconducting accelerator technology can deliver a million pulses per second. However, the repetition rate of current laser systems with sufficient power to modulate the electron beam is limited to the kilohertz range.

For seeding at a high repetition rate, an optical resonator scheme has been introduced to recirculate the radiation in the modulator to seed the high repetition rate electron bunches. Earlier studies have shown that a resonator-like modulator combined with an amplifier in an HGHG configuration can be used to generate radiation whose wavelength can reach the water window region [5, 6]. This scheme overcomes the limitation of requiring high repetition rate seed laser systems. The usage of the oscillator-amplifier setup for a seeded FEL is a promising approach to reach short wavelengths at the high repetition rates based on superconducting linear accelerators. In this contribution, start-to-end simulation with a more realistic electron beam is conducted for this scheme.

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THE LAYOUT

High-Gain Harmonic Generation has been proposed and proven to be able to generate fully coherent radiation in a single pass. In this process, the electron beam achieves an energy modulation in a modulator. The energy modulation is converted into a density modulation in a dispersive section. Finally, the electron beam which has sufficient bunching in the desired harmonic of the seed laser will generate fully coherent FEL radiation in the amplifier.

The layout of oscillator-based HGHG is shown in Fig. 1. Different from a regular single-pass HGHG, this scheme has an optical cavity which consists of simple transportation mirrors and focusing mirrors. In addition, the intra-cavity modulator is longer to achieve higher gain and compensate the losses in the cavity. The power of the radiation is amplified by its interaction with the electron bunch in the intra-cavity modulator, and the optical field is stored in the cavity to seed the next electron bunch. The modulated electron beam is guided to the following dispersion section to achieve sufficient bunching in the desired harmonic of the seed laser. Finally, it generates radiation at a harmonic of the modulator wavelength in the amplifier.

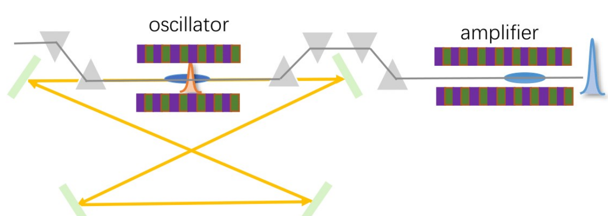

Figure 1: A possible design for the implementation of an HGHG seeded Oscillator-Amplifier.

SIMULATIONS

Start-to-end simulation is carried out for this oscillator-amplifier scheme. ASTRA is used to track the particles from the gun to the end of the injector, which considers longitudinal space charge and microbunching instability effects. ELEGANT is utilized to track the particles in the linac and bunch compressors, which considers the coherent

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synchrotron radiation (CSR) and incoherent synchrotron radiation (ISR) effects. For the external seeding schemes, FEL will get beneficial performances when the electron beam has a smoother longitudinal phase space. In our case, we use the electron beam which has a flat top current distribution based on a longitudinal phase space shaping technique [7]. The parameters of the electron beam are presented in Table 1 and the longitudinal phase space and corresponding current, energy spread, emittance distribution are shown in Fig. 2.

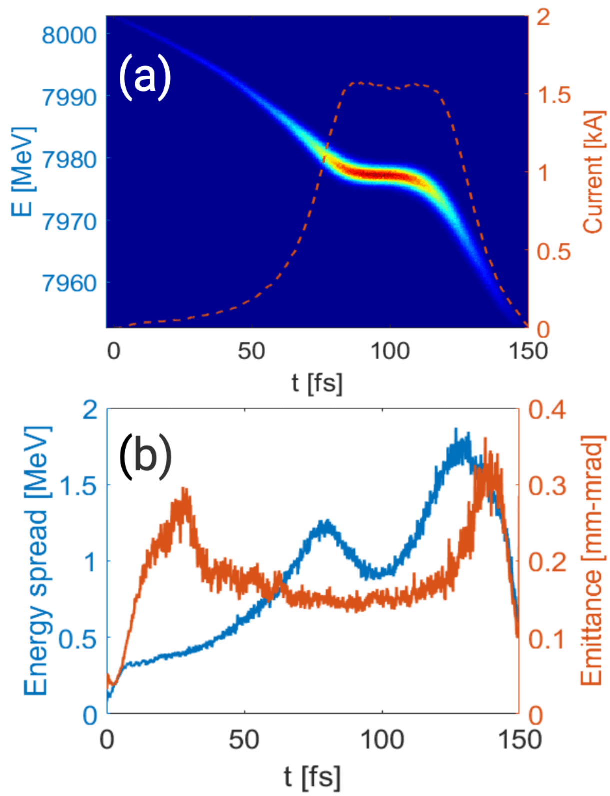

Figure 2: (a) Longitudinal phase space of the electron beam and corresponding current distribution at the end of the Linac. (b) The energy spread (blue line) and emittance (orange) distribution of the electron beam.

The FEL simulations are performed with Genesis 1.3 [8] and the optical field manipulation is done with ocelot [9], which accounts for the slippage, reflectivity and focusing. Some parameters for simulation are presented in Table 1. In this case, the oscillator starts from shot noise which means there is no need of the seed laser. The complete process can be divided into two phases namely the "build-up regime" and the "steady-state regime". The net gain per pass in the build-up regime needs to be positive to build up the peak power required for seeding. For the steady-state regime, the net gain needs to go back zero to keep the balance between the power gain and the oscillator power loss. For a transition from positive gain to zero net gain, the gain has to be reduced. Several different methods to control the power gain were discussed in Ref [10]. In this contribution, we control the net gain by adjusting the total reflectivity of the cavity. In

Table 1: Simulation Parameters

Electron beam	
Energy	8 GeV
Uncorrelated energy spread	0.9 MeV
Peak current	1500 A
Emittance	0.2 mm·mrad
Charge	100 pC
Bunch length	150 fs
Intra-cavity modulator	
Modulator length	12 m
period length	80 mm
K value	12.7
Amplifier	
Amplifier length	28 m
period length	50 mm
K value	4.7

the build-up regime, the reflectivity is high enough to build up the desired peak power for seeding. To reduce the net gain in the modulator, we reduce the total reflectivity in the cavity for the simulation.

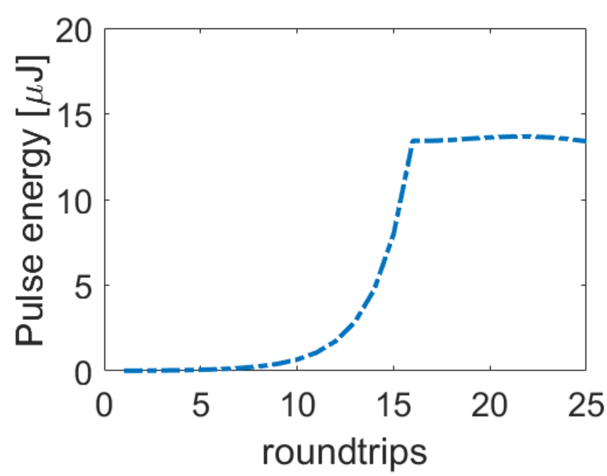

Figure 3: Pulse energy evolution at the end of the intra-cavity modulator.

In this case we use the simulation parameters summarized in Table 1 and the intra-cavity modulator is resonant at 13.5 nm wavelength. As shown in Fig. 3, 15 passes are required in the build-up regime to reach an energy modulation of 7.5 with reflectivity of 6%. After traveling through a dispersion section, the electron beam has 4% bunching at 11th harmonic of the resonant wavelength, which is sufficient for initiating coherent radiation in the amplifier. From the 15th pass and onwards, the total reflectivity is reduced to 3.5% to keep the zero net gain.

After the whole system enters the steady-state region, the stabilities in frequency domain and time domain for the final FEL radiation are shown in Fig. 4. The power profiles

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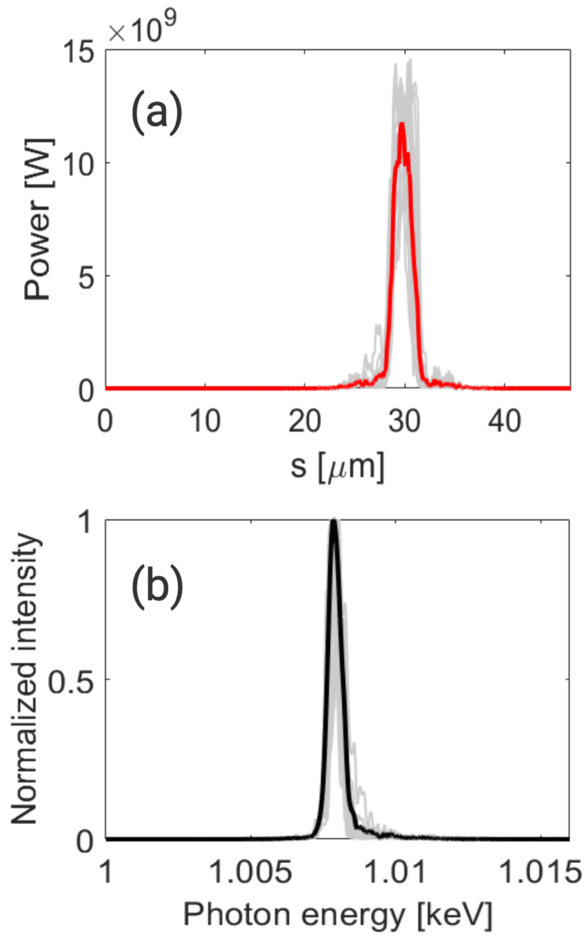

Figure 4: (a) Output power profiles at the end of the amplifier (Grey lines represent 15th-25th passes and red line represents the average power profile.). (b) Output spectra profiles at the end of the amplifier (Grey lines represent 15th-25th passes and black line represents the average spectra profile.).

from the 15th to the 25th pass are shown in Fig. 4a and the spectrum profiles for the same passes are shown in Fig. 4b. As we can see, the peak power of soft X-rays with photon energy of 1 keV is close to 15 GW and the calculated FWHM bandwidth of the average spectrum is 3.9×10^{-4}.

OUTLOOK

In this contribution, we presented start-to-end simulation results of the oscillator-amplifier scheme for seeding at high repetition rates. The simulation results show that high power, fully coherent soft X-rays with photon energy of 1 keV can be achieved by this scheme. Further studies have to be performed on the material for the mirrors and focal properties of the optical components. In addition, we need to design an optical cavity in detail.

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