SIMULATION OF AN X-RAY FEL OSCILLATOR FOR THE MULTI-GEV ERL IN JAPAN

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Abstract

We propose a scheme of velocity bunching in an ERL main linac to operate an X-ray FEL oscillator (X-FELO). The velocity bunching brings significant enhancement of the small-signal gain and an X-FELO at 0.1 nm is possible with a 5-GeV electron beam from the ERL light source planned in Japan. Simulation of the velocity bunching and the X-FELO are presented.

INTRODUCTION

In Japan, a collaboration team of KEK, JAEA, ISSP and other laboratories has organized a research program towards future light sources based on energy-recovery linac (ERL) [1]. The ERL produces an electron beam of small emittance and short bunch duration at high repetition rate, which brings X-ray radiation of high-brilliance and ultra-short pulse duration. Furthermore, the ERL light source can accommodate a FEL oscillator operated in hard X-ray region (X-FELO) to produce X-ray pulses of excellent temporal coherence, which can not be obtained in FELs operated in the SASE mode [2].

Adding to generation of high-brightness and high-repetition electron bunches, the X-FELO requires further technological challenges such as fabrication of perfect crystals for the Bragg mirrors, achievement of tight alignment of the X-ray resonator. The X-FELO, however, delivers unprecedented X-ray pulses, hard X-ray pulses with both spatial and temporal coherence, which will open cutting-edge X-ray science. We are, therefore, planning to build an X-FELO as a part of our future light source facility based on a 5-GeV ERL.

There are two possible configurations to integrate an X-FELO into an ERL light source facility. One is installing an X-FELO in a straight section of the return loop, and the other is adding a single-ended branch for an X-FELO at the downstream of the ERL main linac. In the latter configuration, an electron beam of high-average current is unavailable, but we can accelerate an electron beam of small current $1-10\mu$A which is enough to operate the X-FELO.

In the present paper, we propose a scheme of velocity bunching to obtain FEL gain enough to operate an X-FELO in the 5-GeV ERL, the future light source facility under proposal in Japan. We also present the X-FELO performance calculated by one-dimensional time-dependent FEL code.

VELOCITY BUNCHING FOR X-FELO

In order to operate an X-FELO, the single-pass FEL gain must exceed the round-trip loss of the X-ray oscillator. Assuming typical ERL bunch parameters and the round trip loss of 10-20%, previous studies presented examples of 0.8-1 Å FELs based on 7-10 GeV electron energies [2][3].

Here we suggest that operation of a similar X-FELO with an electron beam of 5 GeV is possible by using velocity bunching at the beginning section of the ERL main linac.

Velocity bunching at an ERL main linac was originally studied to produce ultra-short X-ray pulses from undulator radiation [4]. In the study, it was revealed that a scheme of velocity bunching can generate X-ray pulses of better brilliance than a scheme of magnetic bunching through an ERL return loop. This is because that energy spread of an electron bunch after the bunch compression has a smaller value at the velocity bunching. We also found that incomplete energy-recovery due to phase slip during the velocity bunching and HOM power generated by short electron bunches passing through superconducting cavities are of no matter, because utilization of a short X-ray pulse for pump-probe experiments does not need high repetition operation.

In the velocity bunching for an X-FELO, excessive bunching is useless for two reasons: (1) emittance blowup results in FEL gain degradation, (2) mismatching of Bragg mirror bandwidth and electron bunch length also reduces FEL gain [2]. For a Bragg mirror with a bandwidth $\sigma_M^\omega = 1/(100fs)$, we chose electron bunch length after the compression $\sigma_t = 400fs$ to satisfy the matching condition $2\sigma_M^\omega \sigma_t \gg 1$.

For velocity bunching at a normal conducting linac, solenoid field is applied to the bunching section of linac to compensate emittance growth caused by space charge force and defocusing RF field [5]. For velocity bunching at a superconducting linac, however, solenoid field can not be applied to the linac and emittance compensation by solenoid field is impossible. In the following calculations, we optimize bunch slice motion through the electron gun to the bunching section to minimize the projection emittance after the bunching.

In order to investigate the advantage of velocity bunching for an X-FELO, we calculated emittance and energy spread after the velocity bunching by using a particle tracking code PARMELA [6]. In the simulations, we assume the following configuration of the accelerator, which is similar to the Compact ERL under construction as shown in Fig. 1 [1]: 500 kV DC gun, buncher, 2-cell×3 injector cavities, 3-dipole merger, and accelerator modules of the

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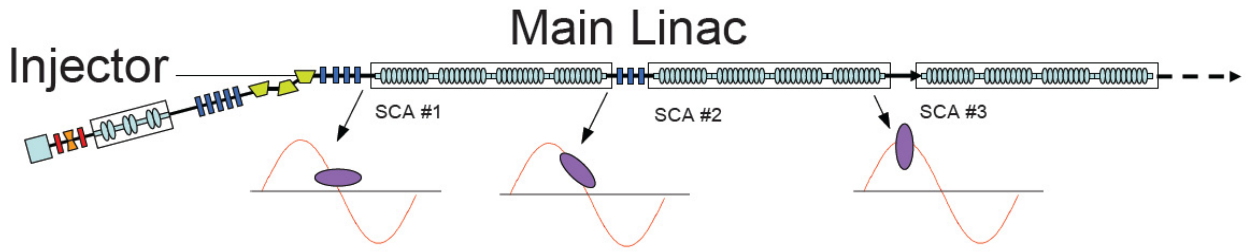

Figure 1: A schematic view of velocity bunching in an ERL main linac. An electron bunch generated from the injector is compressed at the beginning section of the main linac.

main linac. Each module of the main linac accommodates four 9-cell cavities. In the simulation, we made particle tracking up to the SCA #2. Two solenoid magnets and five quadrupole magnets are installed in the injector. Four quadrupole magnets before the main linac and a quadrupole triplet between the main linac modules are used to obtain appropriate beam envelope during the main linac. All these focusing elements and RF parameters of the injector are determined by multi-parameter optimization scheme [7] to minimize the beam emittance at the end of the main linac.

We note a problem of emittance growth due to chromatic aberration, specific to the velocity bunching. An electron bunch has a large energy spread during the velocity bunching and may suffer from chromatic aberration by focusing elements, the triplet in the middle of the linac in our case. The beam envelope in the main linac is controlled by four quadrupole magnets before the linac to minimize the chromatic aberration.

In the velocity bunching, the final bunch length is a function of bunch length, energy and phase at the injection, accelerator gradient and linac length. We inject an electron bunch at 90 degrees ahead of the crest and the injection energy and the accelerator gradient are chosen as 10.9 MeV and 8.5 MV/m, respectively. The velocity bunching is conducted by four cavities of SCA #1 and two cavities of SCA #2 of the main linac and the last two cavities of SCA #2 are used for on-crest acceleration.

Figure 2 shows simulation results of the velocity bunching. Parameters of electron bunch at the end of the main linac are bunch charge 7.7 pC, energy 27.7 MeV, rms bunch length $\sigma_t = 380$ fs, rms energy spread $\sigma_E = 250$ keV, rms normalized emittance $\varepsilon_x = 0.16$ mm-mrad and $\varepsilon_y = 0.13$ mm-mrad. The energy spread 250 keV corresponds to 5×10^{-5} at 5 GeV. For a bunch of 7.7 pC/380 fs, energy spread introduced by RF curvature and longitudinal wake is negligibly small in comparison with the energy spread introduced by velocity bunching.

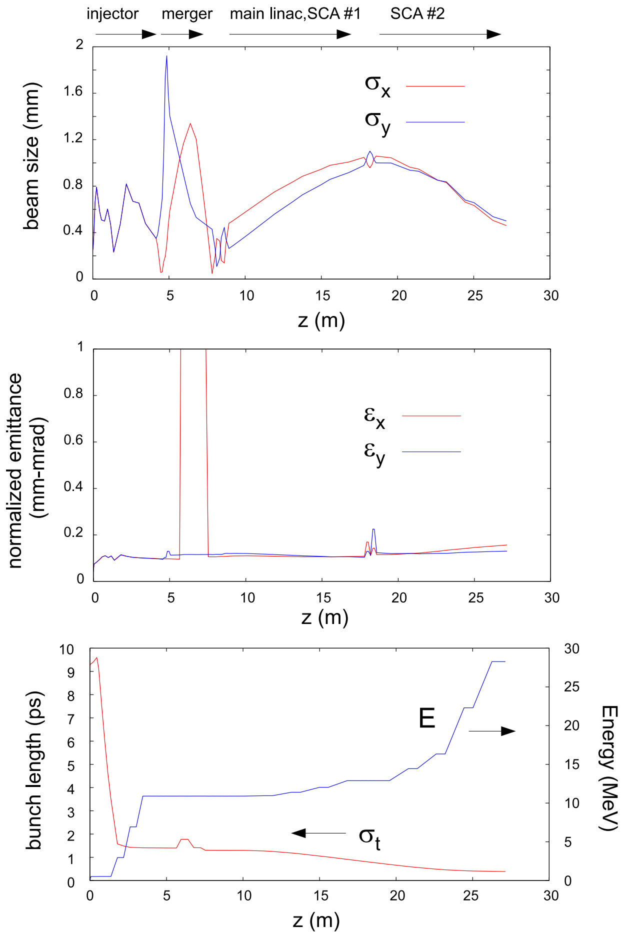

Figure 2: PARMELA simulation from the electron gun to the main linac (SCA #2) for velocity bunching. (upper) transverse beam size, (middle) transverse emittance, (bottom) bunch length and energy.

SIMULATIONS OF X-FELO

FEL Gain Estimation

Before conducting numerical simulations of an X-FELO, small-signal gain is estimated by analytical formula. We fix the electron energy at 5 GeV, the undulator $a_w = 0.59$, $\lambda_w = 1.43$ cm, $N_w = 3000$, and X-ray and electron beam envelopes $Z_R = \beta^* = 10m$, then FEL gain is calculated for two cases: (1) electron beam without bunch compression, bunch charge of 20 pC, rms bunch length of 2 ps, rms energy spread of 1×10^{-4}, (2) electron beam with velocity bunching, 7.7 pC, 380 fs, 5×10^{-5}.

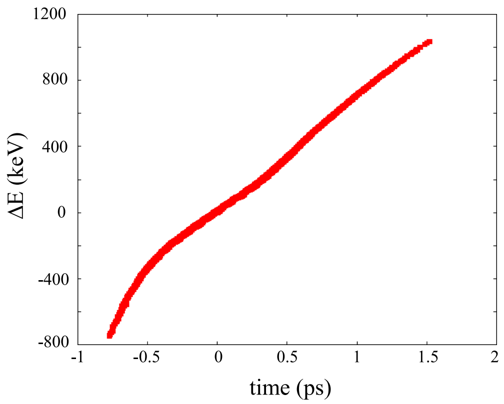

Figure 3: Longitudinal phase plot at the end of SCA #2.

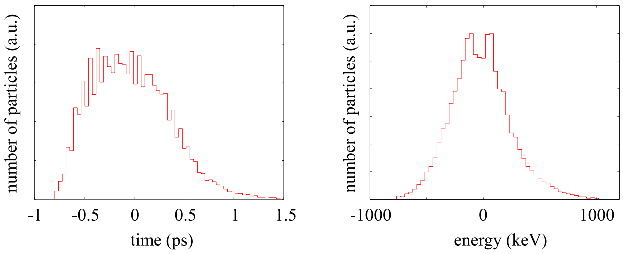

Figure 4: Temporal profile and energy spectrum of an electron bunch at the end of SCA #2.

In Fig. 5, small-signal gain is plotted as a function of normalized emittance. It shows that significant enhancement of FEL gain is expected by velocity bunching even if some amount of emittance growth occurs during the bunching.

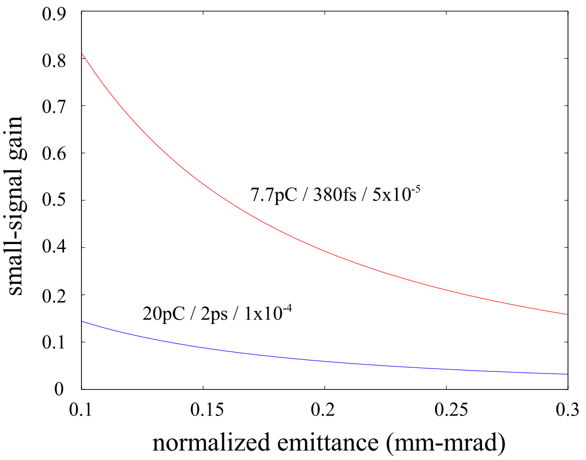

Figure 5: Small-signal FEL gain estimated from analytical formula. Gain without velocity bunching (20 pC, 2 ps, $\sigma_E/E = 10^{-4}$) and gain with velocity bunching (7.7 pC, 380 fs, $\sigma_E/E = 5 \times 10^{-5}$) are plotted.

Model of Bragg Mirrors

In the FEL simulations, Bragg mirrors in an X-FELO are implemented as frequency filtering of an X-ray pulse every round trip. The temporal profile of an X-ray pulse at the undulator exit is converted into the frequency domain by fast Fourier transformation (FFT), and a frequency filter corresponding to the Bragg mirrors is applied. The filtered pulse is then converted back to the time domain by FFT. We use a model of Bragg mirrors as shown in Fig. 6, where reflectivity and phase shift are determined from the Darwin curve including absorption depending on X-ray energy [8].

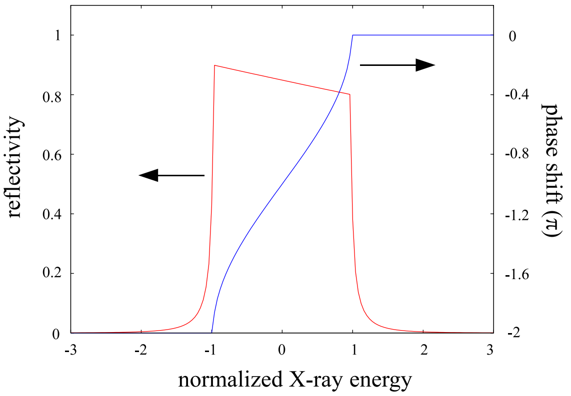

Figure 6: Model of Bragg mirrors: Reflectivity and phase shift are plotted for a cavity rond trip.

1D Time-Dependent FEL Simulation

We employ a 1-D time-dependent FEL simulation code for analysis of the X-FELO [3]. A 3-D FEL simulation is inevitable to study high-gain SASE FELs, because transverse profile of the optical field is affected by electron beam, that is optical guiding or gain focusing. In FEL oscillators operated in the low-gain regime, the transverse profile of the optical field is determined by cavity geometry, and 1-D simulations give good approximation.

The simulation code used here was originally developed for an infrared FEL oscillator, which has been benchmarked by a series of experiments at the JAERI-FEL: single super-mode, limit cycle, chaotic spiking and few-cycle pulse generation [9][10].

Parameters used in the X-FELO simulation are FEL wavelength $\lambda = 1$ Å, electron beam energy $E = 5$ GeV, bunch charge $Q = 7.7$ pC, undulator parameter $a_w = 0.59$, undulator pitch $\lambda_w = 1.43$ cm, the number of undulator period $N_w = 3000$, small signal gain $G = 40\%$, bandwidth of the Bragg mirrors 12 meV, round trip loss 10%. Temporal profile of an electron bunch is assumed to be triangular 940 fs (FWHM) and the number of macro particles is 360k. Cavity length detuning is applied to compensate group velocity delay of X-ray FEL pulse due to the dispersion of the Bragg mirrors.

Figure 7 shows evolution of an X-ray FEL pulse from shot noise to saturation. Saturation is obtained after 200 round trips. Assuming the ratio of X-ray power extracted from the Bragg mirror and dissipated in the resonator $P_{ext}/P_{dis} = 1/2$, we find the number of X-ray photons per extracted pulse becomes 7×10^8.

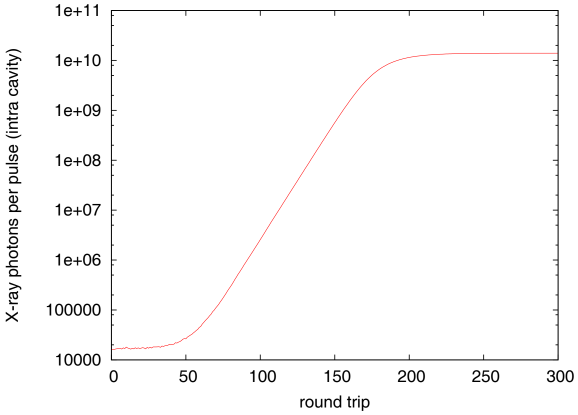

Figure 7: X-ray pulse evolution in the X-FELO.

Figure 8 shows temporal profile of an X-ray FEL pulse after the saturation. The pulse has a smooth Gaussian-like profile and the pulse width is 1.2 ps (FWHM).

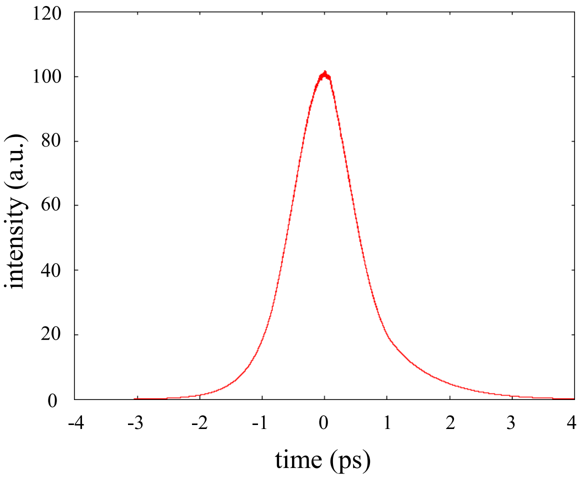

Figure 8: Temporal profile of a saturated FEL pulse. The temporal duration is 1.2 ps (FWHM).

SUMMARY

We have proposed a scheme of velocity bunching at the beginning section of an ERL main linac for an X-FELO. The velocity bunching is effective to obtain FEL gain large enough to operate an X-FELO in 1 Å wavelength region with relatively low energy electrons, 5 GeV. From analytical estimation, small-signal FEL gain of 30-40% is available at a 5-GeV ERL with velocity bunching.

The performance of an X-FELO at 1 Å wavelength driven by 5-GeV ERL equipped with velocity bunching is evaluated by electron beam simulations using PARMELA and FEL simulations. The simulations show that an X-ray pulse extracted from the X-FELO has 7×10^8 photons per pulse and Gaussian-like smooth temporal shape of 1.2 ps (FWHM).

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