FREE-ELECTRON LASER OPTIONS FOR THE ENERGY-RECOVERY LINAC LIGHT SOURCE IN JAPAN

R. Hajima*, N. Nishimori, JAEA, Tokai, Naka, Ibaraki 3191195, JAPAN

Abstract

A research program towards a future ERL light source based on an energy-recovery linac (ERL) has been launched in Japan. Possible FEL options in the future ERLs are also under discussion. We investigate an X-ray FEL oscillator, one of the attractive options in a multi-GeV ERL light source, by 1-D time-dependent simulations. The simulation shows that narrow-band FEL lasing in hard X-ray wavelength region is established by Bragg reflectors, and even a single supermode operation is possible by choosing appropriate cavity-length detuning.

INTRODUCTION

Next generation light sources based on an energy-recovery linac (ERL) are under development by Japanese collaboration team consisting of KEK, JAEA, ISSP and other laboratories. A high-brightness electron beam in the ERL light source allows an operation of free-electron laser in addition to providing undulator radiation. We present possible FEL options in the future ERL light sources under development in Japan. A FEL oscillator operated in hard X-ray region (X-FELO) is one of the attractive FEL options because of its excellent temporal coherence which can not be obtained in FELs operated in the SASE mode. One-dimensional time-dependent simulations are conducted to investigate evolution of temporal coherence in the X-FELO, and simulation results are presented.

THE ERL-LS PROJECT IN JAPAN

R&D Status

Accelerator components for the future ERL light sources are under development in the Japanese collaboration team.

For the generation of an electron beam of small emittance and high average current, we decided to adopt a photo cathode DC gun. A 250 kV-50 mA gun has been developed as a prototype of the ERL injector[1]. We obtained the first beam with a small current $\sim 1\mu$A from the gun on Jun. 20, 2008. Extraction of large beam current and measurements of the beam emittance and the bunch length are in preparation. In parallel with the 250 kV-gun testing, we started to construct a 500 kV gun, which will be the injector of the ERL light source.

We are also developing two types of superconducting cavities, one for the injector and the other for the main linac. Both of them are operated at 1.3 GHz and designed for high-average beam current. The injector cavity is a 2-cell structure with coaxial-type input couplers and modified TESLA-type HOM couplers. The main linac cavity is a 9-cell structure similar to the TESLA cavity but has a special design for high-average current operation [2].

The Compact ERL

The Compact ERL, a test facility for the ERL light source, will be constructed to demonstrate all the components relevant to future ERL light sources. In the present design, the Compact ERL is a 60-85 MeV ERL with a 5-10 MeV injector and the beam current is 10-100 mA[3]. The construction site is an old experimental hall of 12-GeV KEK-PS, which has been shut down. In the Compact ERL, X-ray generation via laser Compton scattering and THz generation from coherent synchrotron radiation will be provided for user applications in addition to the study of accelerator physics and technologies. We also have a future plan to reinforce the beam energy up to 200 MeV after successful operation at the initial parameters.

Future X-ray and γ-ray Light Sources

We plan to build a 5-GeV ERL for a X-ray light source as a successor to KEK-PF. The ERL can produce coherent X-rays and femtosecond X-ray pulses in soft X-ray and hard X-ray regions. The community of synchrotron radiation users will receive the full benefit of this ERL light source.

We have also proposed a high-flux γ-ray light source utilizing laser Compton scattering in an ERL[4] [5]. The features of the ERL, high average current, a short electron bunch, small emittance, flexible manipulation of an electron beam, allow the best use of laser Compton scattering for the generation of high-flux γ-rays. In our design, the γ-ray flux from the ERL light source exceeds existing sources based on storage rings by several orders of magnitudes. The high-flux γ-ray source can be used for industrial applications such as nondestructive detection and assay of radionuclides for the management of nuclear wastes[4]. Such an ERL γ-ray source can also be adopted to generate polarized positrons for the International Linear Collider [6].

FEL OPTIONS

A small emittance electron beam generated in an ERL is essentially compatible with free-electron lasers. We have several options of FELs to operate concurrently with the future ERL light sources.

The electron bunches in the X-ray ERL light source have usually small charge 10-100 pC and not suitable for high-gain SASE FELs. However, one can add a separate injector

* hajima.ryoichi@jaea.go.jp

for generating high-charge low-repetition rate bunches and share an ERL linac to drive a SASE FEL. This type of configuration was proposed in 4GLS[7].

In the γ-ray source, a built-in FEL oscillator can be used for the Compton scattering[8]. This option realizes automatic synchronization of laser and electron pulses, and enables one to eliminate an external laser system and a super-cavity. FEL lasing in visible and UV is helpful to generate a γ-ray at a specific energy with a smaller electron energy than a design with an external IR laser.

Recently, an XFEL oscillator (X-FELO) was proposed as an option of future multi-GeV ERLs (Fig.1)[9]. The X-FELO looks an attractive and promising option, because it realizes fully coherent X-ray pulses with wavelength of about 1Å by small modification of the X-ray ERL light source. We investigate lasing behavior of the X-FELO in the following sections.

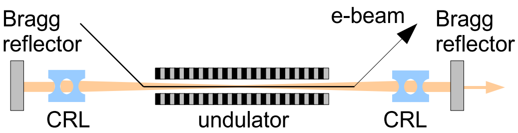

Figure 1: An XFEL oscillator with Bragg reflectors and compound refractive lenses (CRL) installed at a multi-GeV ERL.

1-D TIME DEPENDENT SIMULATIONS OF X-FELO

We employ a 1-D time-dependent FEL simulation code for analysis of the X-FELO. 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.

It is also known that the longitudinal mode structure of FEL oscillators is a function of cavity-length detuning and slippage length. Thus, analysis of the X-FELO requires a time-dependent simulation to deal with the whole bunch length, in stead of a bunch-slice simulation popular in SASE FELs.

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 [10][11].

The special feature of the X-FELO, a narrow-band mirror of Bragg reflector, is implemented as frequency filtering of a FEL pulse every round trip. The temporal profile of a FEL pulse at the undulator exit is converted into the frequency domain by fast Fourier transformation (FFT), and a frequency filter corresponding to the Bragg reflectors is applied. The filtered FEL pulse is then converted back to the time domain by FFT. In this procedure, reflecting at a pair of Bragg reflectors is simulated by single filter, and phase shifts caused by the focusing elements and the reflectors are ignored.

We have chosen simulation parameters similar to Kim's paper[9]: FEL wavelength $\lambda = 1$ Å, electron beam energy $E = 7$ GeV, bunch charge $Q = 19$ pC, undulator parameter $K = 1.414$, undulator pitch $\lambda_U = 1.88$ cm, the number of undulator period $N_U = 3000$, small signal gain $G = 27\%$. The temporal profile of an electron bunch is assumed to be triangular 2 ps (FWHM). In the simulations, the number of macro particles is 768k.

The narrow-band Bragg reflectors made of high-quality single crystals are assumed to have a rectangular-shaped bandwidth of 12 meV (full width), and round trip loss within the bandwidth is 10%. Simulations with virtual mirrors of full-band reflection (round trip loss of 10%) are conducted for comparison.

Figure 2 shows evolution of intracavity FEL pulse energy from shot noise to saturation. We plot results with the Bragg reflectors and the full-band virtual reflectors. Lasing with the Bragg reflectors requires longer start-up than the full-band reflectors. This is because that the spontaneous emission has much broader spectrum than the reflector's bandwidth and the longer start-up period is necessary to build up a FEL pulse matched to the bandwidth. In the exponential growth regime, both results show similar gain.

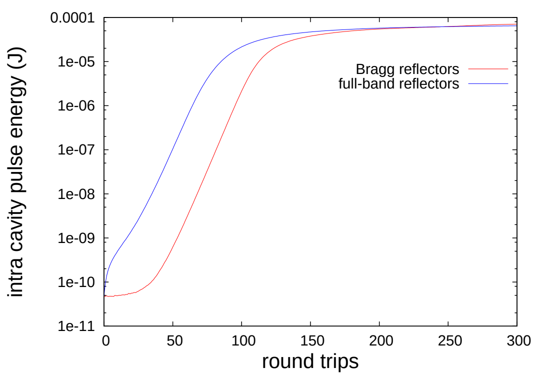

Figure 2: FEL pulse evolution for two types of optical cavities with Bragg reflectors and full-band virtual reflectors

In Fig.3 and 4, we plot temporal profile of saturated FEL pulses for the Bragg reflectors and the full-band reflectors, respectively. In the optical cavity with Bragg reflectors, the saturated FEL pulse has a temporal profile with several peaks. The spectral width is reduced by the Bragg reflectors, but the pulse is not single supermode.

The FEL pulse for the full-band reflectors in Fig.4 has a number of spikes with $\sim$10 fs intervals. The coherent length is somewhat longer than the slippage distance (1 fs), because a relatively large round-trip loss, 10%, allows coherence buildup over many round trips. We have confirmed the coherent length becomes equal to the slippage distance for an optical cavity with a smaller loss (1%).

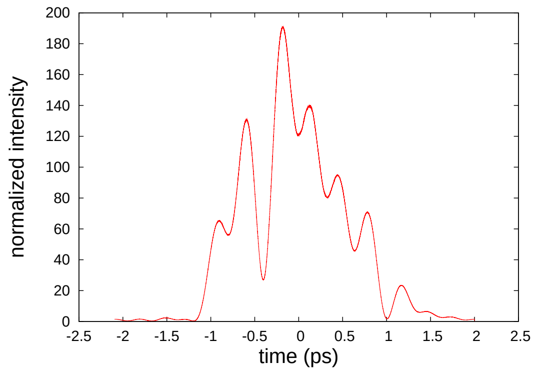

Figure 3: Temporal profile of a saturated FEL pulse with Bragg reflectors. ($dL = 0$)

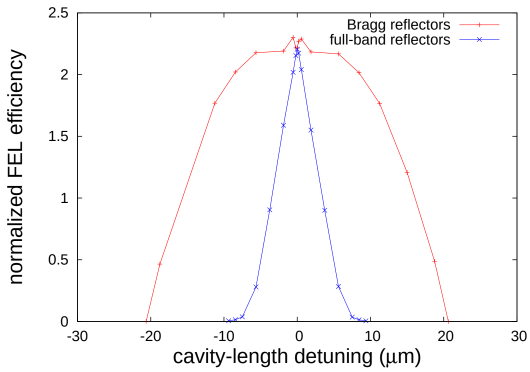

Figure 5: Cavity-length detuning curves for two types of reflectors.

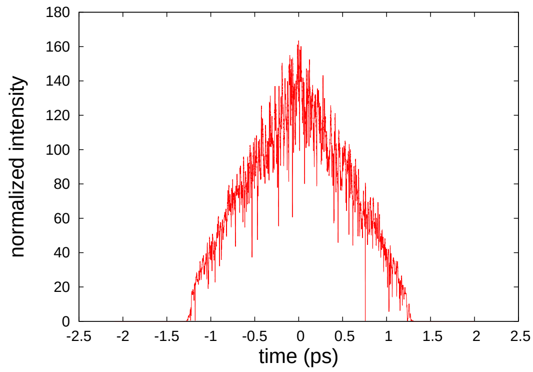

Figure 4: Temporal profile of a saturated FEL pulse with full-band virtual reflectors. ($dL = 0$)

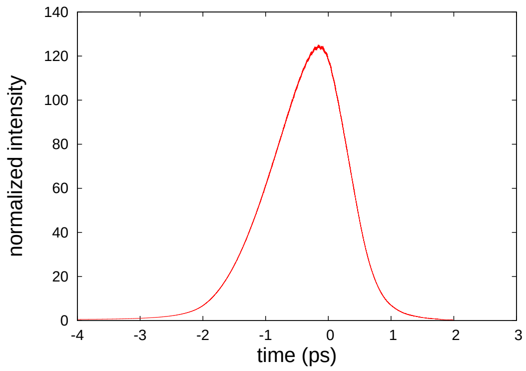

Figure 6: Temporal profile of a saturated FEL pulse with Bragg reflectors. ($dL = -5.6\mu$m)

So far, all the above simulations have been made with assuming the perfect synchronization of the optical pulses and the electron bunches, that is zero detuning of the cavity length, $dL = 0$. Here, we show simulation results with finite cavity-length detuning. Figure 5 shows calculated detuning curves for the full-band and the Bragg reflectors. The vertical axis is normalized FEL efficiency, $4\pi N_U \eta$. In a saturated FEL oscillator, the sum of power extracted from the cavity and power dissipated in the cavity is given by $P_{ext} + P_{dis} = \eta P_{beam}$, where η is the FEL conversion efficiency and P_{beam} is the electron beam power. Assuming $P_{ext}/P_{dis} = 1/2$, we obtain the number of photons per extracted pulse as 1.3×10^9. The detuning width for the Bragg reflectors, $\pm 21\mu$m, is almost consistent with a theoretical value predicted from the gain threshold of the lowest supermode[9].

In FEL oscillators, the number of lasing supermodes can be controlled by cavity-length detuning, because the gain of higher-order modes decreases more rapidly with cavity-length detuning in comparison with the lowest mode. We show a simulation result for a cavity-length detuning $dL = -5.6\mu$m in Fig.6. The FEL pulse is of single supermode with $\tau = 0.77$ ps (rms), $\sigma_\omega \simeq 1/2\tau = 2.6$ meV. The obtained spectral width agrees with the theory[9].

SUMMARY

We have presented the status of the ERL project in Japan and possible FEL options in future ERL light sources. Simulations of an X-FELO have been also conducted and the temporal coherence in saturated FEL pulses has been discussed.

REFERENCES

[1] N. Nishimori et al., Proc. ERL-07, to be published.

[2] S. Sakanaka et al., Proc. EPAC-08, pp. 205–207.

[3] R. Hajima et al. Ed., "Design Study of the Compact ERL", KEK Report 2007-7 / JAEA-Research 2008-032 (2008).

[4] R. Hajima et al., J. Nucl. Sci. Tech. **45**, (2008) 441–451.

[5] R. Hajima et al., Proc. 8th International Topical Meeting on Nuclear Applications and Utilization of Accelerators (AccApp-07), pp.182–188 (2007).

[6] T. Omori, "Ring / ERL Compton e+ Source for ILC", PosiPol-2008, Jun. 16, 2008, Hiroshima, Japan.

[7] 4GLS Conceptual Design Report, CCRLC 2006-4-12 (2006).

[8] V.N. Litvinenko et al., Phys. Rev. Lett. **78** (1997) 4569–4572.

[9] K-J. Kim et al., Phys. Rev. Lett. **100** (2008) 244802.

[10] R. Nagai et al., Nucl. Instrum. Meth. **A483** (2002) 129–133.

[11] R. Hajima, R. Nagai, Phys. Rev. Lett. **91** (2003) 024801.