# GENERATION OF COHERENT SYNCHROTRON RADIATION FROM JEARI-ERL

R. Hajima*, E.J. Minehara, M. Sawamura, R. Nagai, N. Kikuzawa,
H. Iijima, T. Nishitani
Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan
T. Takahashi
Research Reactor Institute, Kyoto University, Kumatori, Osaka 590-0494, Japan
S. Okuda
Frontier Science Innovation Center, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan

*Abstract*

An electron beam with high-average current and short bunch length can be accelerated by energy-recovery linac. Coherent synchrotron radiation (CSR) from such an electron beam will be a useful light source around millimeter wavelength. We report results from preliminary measurements of CSR emitted from a bending magnet of JAERI-ERL.

## INTRODUCTION

Coherent synchrotron radiation (CSR) is emission of electromagnetic waves from electron bunches whose temporal duration is shorter than the radiation wavelength. The emitted power of CSR is proportional to $\sim N_e^2$ ($N_e$ is the number of electrons in a bunch), while the power of incoherent synchrotron radiation (ISR) is proportional to $N_e$. Thus we can expect that the enhancement of CSR power is $\sim 10^{10}$ for an electron bunch of 1 nC. CSR has been observed at electron linacs[1] and storage rings[2], and applied to many experiments in THz and millimeter wavelength region. Generation of high-power CSR was recently demonstrated by using an energy-recovery linac (ERL) at Thomas Jefferson National Accelerator Facility [3]. Since an ERL can accelerate a high average current beam with short electron bunches, it is an excellent source of CSR. In Japan Atomic Energy Research Institute (JAERI), we have developed an energy-recovery linac for a high-power free-electron laser[4]. In this paper, we present results from preliminary measurements of CSR emitted from a bending magnet of JAERI-ERL.

## EXPERIMENTAL SETUP

An experiment was carried out to characterize the CSR emission from the JAERI Energy-Recovery Linac. We measured CSR from a bending magnet at the middle of the second arc as shown in fig.1. The bending angle and the curvature radius are 60 degrees and 200 mm, respectively. The experimental setup for the CSR measurement is shown in fig.2. CSR emission is extracted through a vacuum window of Kovar glass (4.5 mm thickness) and converted into a parallel beam by spherical mirror M3 (f=1200 mm) to transport the beam to a Martin-Puplett interferometer. The interferometer consists of a fixed mirror (FM), a movable mirror (MM) and two beam splitters (BS1, BS2). The beam splitters are made of wire grids wound from 10$\mu m$ tungsten wire with a spacing of 25 $\mu m$, which also act as polarizer. The incident beam is split by BS1 and the transmission beam goes to a detector (D2) for monitoring the CSR power. The reflected beam from BS1 is split again by BS2 and enters the two spectrometer arms, where the path length difference is controlled by movable mirror (MM). The reflected beams from the two arms are recombined by BS2 and transported to a detector (D1) for the observation of interferogram. Two detectors are identical ones: Si-bolometer operated at liquid helium temperature. The CSR power is large enough, then we bypass the pre-amplifiers of the detectors and the signals are directly input to a lock-in-amplifier, which is synchronized to electron beam macro-pulses. The spatial acceptance of the measurement system is 100 mrad in the horizontal plane and 87 mrad in the vertical plane.

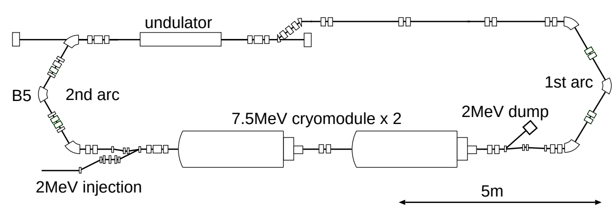


Figure 1: Layout of the JAERI-ERL. Coherent synchrotron radiation from a bending magnet at the 2nd-arc (B5) is observed.

## EXPERIMENTAL RESULTS

The electron beam parameters at the experiment are as follows: electron energy 17 MeV, bunch repetition 10.4125 MHz, macro-pulse length 30 $\mu$s, macro-pulse repetition 10 Hz.

Figure 3 shows results of interferogram measurement, where the horizontal axis is the movable mirror position and the vertical axis is the detector signal. We can see that the signal from the reference detector (D1) has periodical drift during the data acquisition of 5 minutes. The source of the drift was not clear in the experiment, but later found to

* hajima@popsvr.tokai.jaeri.go.jp

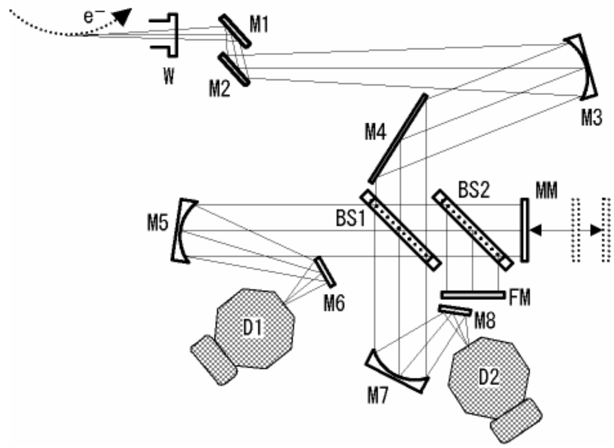


Figure 2: Experimental setup. W: vacuum window, M1, M2, M4, M6, M8: flat mirrors, M3: spherical mirror (f=1200mm), M5: spherical mirror (f=250mm), M7: spherical mirror (f=306mm), FM: fixed mirror, MM: movable mirror, BS1, BS2: beam splitters, D1, D2: Si bolometers.

be the oscillation of beam trajectory due to an un-grounded beam deflector installed at the injector. The raw signal from the interferometer is also disturbed by this beam oscillation as shown in fig.3. The interferogram, however, can be reconstructed after normalization of the raw signal by the reference signal as shown in fig.3.

Figure 4 shows a CSR spectrum obtained from the Fourier transformation of the normalized interferogram. The spectrum has a peak around $1cm^{-1}$ and shows agreement with a spectrum calculated for a Gaussian bunch (FWHM=9 ps). In this experiment, bunch charge is monitored by a current transformer installed at the merger exit and found to be 0.35 nC. In the CSR spectrum, we can see a periodic modulation, which has a period of $\sim 1cm^{-1}$. The modulation is considered as a result of interference of the CSR at the vacuum window, which has parallel surfaces of 4.5 mm thickness.

Next, the beam transport parameters such as acceleration phase in the main linac were tuned to make the CSR power maximum. Figure 5 is a CSR spectrum after the tuning of the beam transport, where bunch charge is 0.27 nC. The interference at the vacuum window is seen again. The CSR shows a larger power than the previous measurement in spite of the bunch charge decreasing. The peak of the CSR spectrum also shifts to the shorter wavelength from the previous measurement. These results suggest that the bunch length for fig.5 is shorter than the bunch for fig.4. We plot a calculated spectrum for a Gaussian bunch (FWHM=5 ps) in fig.5. It should be noted that the CSR spectrum does not reflect a bunch length directly and may be affected by fine structure inside a bunch such as a steep leading edge. The estimation of a bunch length, therefore, requires more precise measurement of the CSR spectrum including shorter wavelength.

The absolute CSR power is calibrated by using a high-pressure mercury-vapor lamp of 100 W, which is equivalent to a black body of 4000 K. The CSR power at the peak in fig.5 (wavenumber=$2.4cm^{-1}$) is found to be $2 \times 10^{-5} W/cm^{-1}$. The CSR power will be $6 \times 10^{-4} W/cm^{-1}$ for 1-ms macro-pulses at 10 Hz repetition, which is maximum beam power available at the JAERI-ERL.

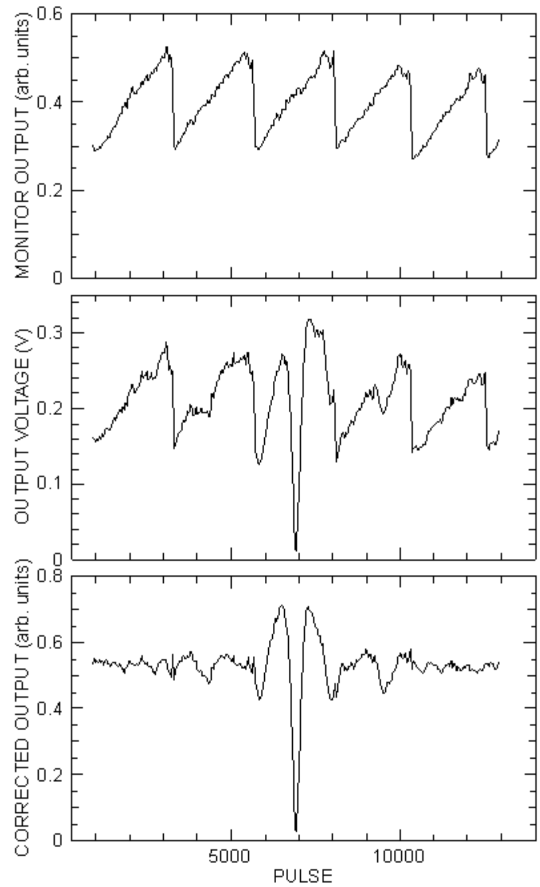


Figure 3: (Top) Reference signal from a detector D2. (Middle) Obtained interferogram with scanning the movable mirror. The horizontal axis is the movable mirror position ($1\mu$m/pulse). (Bottom) Interferogram normalized by reference signal.

## CSR WITH FEL OSCILLATION

Micro-bunching with a period of laser wavelength is formed in an electron bunch, when FEL oscillation takes place. This micro-bunching may change the CSR spectrum at the down stream of the FEL undulator. We plan to investigate this spectrum change due to the FEL oscillation.

When beam transport from the undulator to the CSR observation point is isochronous, micro-bunching generated by FEL oscillation is preserved and results in the enhancement of CSR spectrum at the same frequency as the FEL oscillation. The present experimental setup at JAERI-ERL, however, does not satisfy this isochronous condition.

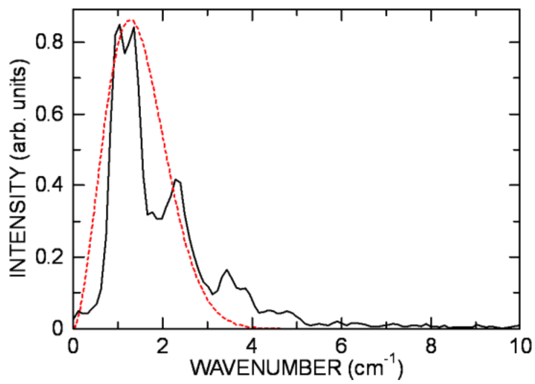


Figure 4: Frequency spectrum of CSR obtained from the interferogram shown in fig.3. The dashed red line is spectrum calculated for a Gaussian bunch (FWHM=9ps).

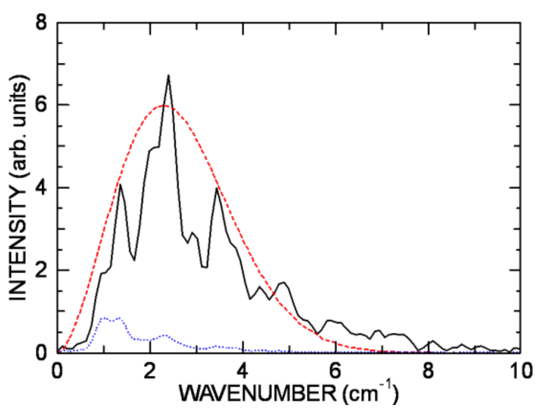


Figure 5: Frequency spectrum of CSR after the tuning of beam optics. The dashed red line is spectrum calculated for a Gaussian bunch (FWHM=5ps). The dotted blue line is the CSR spectrum shown in fig.4 in the same scale.

The return arc of JAERI-ERL is equipped with two families of quadrupole magnets, which vary the momentum compaction in the arc. Figure 6 shows betatron and momentum dispersion functions through the return arc, where the quadrupole parameters are chosen so that whole the arc is isochronous. The beam transport from the undulator to the CSR observation point at the middle of the arc satisfies $R_{56} = 0$ due to the symmetric property of the dispersion function. This does not conclude isochronous beam transport, however. This is because the beam transport is not achromatic at the CSR observation point and there are non-zero terms in the transport matrix: $R_{51} \neq 0$, $R_{52} \neq 0$, which broke the micro-bunching. In the beam transport shown in fig. 6, we can find $R_{51} = 0.12$ and $R_{52} = 3.6$cm from the undulator to the CSR observation point, which are large enough to destroy the FEL micro-bunching of $\lambda = 20\mu$m.

The achromatic condition can be established at the CSR observation point, if the dispersion function is tuned as shown in fig.7. In this quadrupole setting, we find $R_{56} = -4.9$cm from the undulator to the CSR observation point. This non-zero $R_{56}$ destroys the FEL micro-bunching of $\lambda = 20\mu$m, if the correlated energy spread in the micro-bunching is $\Delta E/E > 4 \times 10^{-4}$.

From the above consideration, the enhancement of CSR power due to the FEL micro-bunching is hardly expected in the present experimental configuration. However, there is another effect of the FEL oscillation upon the CSR emission. In superradiant FEL oscillation, a FEL pulse shorter than an electron bunch length is generated [5]. This type of FEL oscillation introduces non-uniform energy spread along the longitudinal direction in an electron bunch. The combination of this energy spread and the momentum compaction in the arc causes electron bunch deformation in its temporal profile, which alters the CSR spectrum.

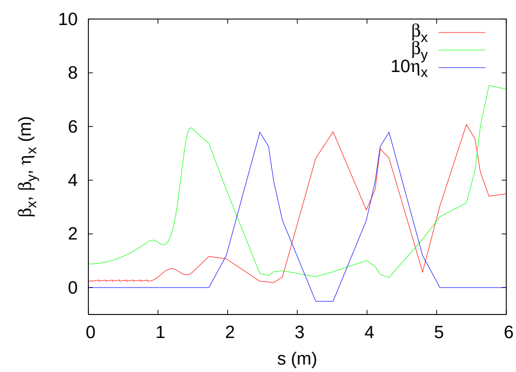


Figure 6: Betatron and dispersion functions from the FEL undulator to the arc exit. The dispersion function is tuned to establish isochronous property at the arc exit.

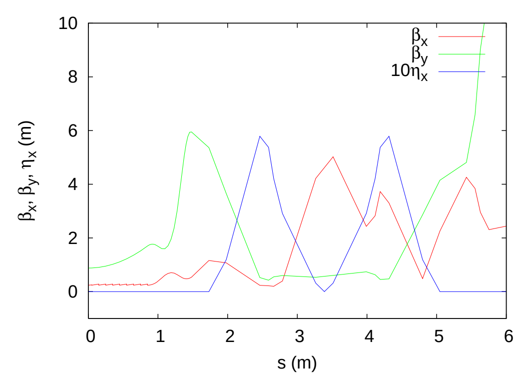


Figure 7: Betatron and dispersion functions from the FEL undulator to the arc exit. The dispersion function is tuned to establish achromatic property at the middle of the arc.

## CONCLUSIONS

We have presented results of preliminary measurements of CSR emission from a bending magnet of JAERI-ERL. CSR power spectra have been obtained from a Martin-Puplett interferometer. The CSR power spectra significantly depend on beam transport parameters such as accelerating phase. When the transport parameters are tuned to maximize the CSR power, the CSR spectrum shows a peak power of $2 \times 10^{-5} W/cm^{-1}$ at $2.4 cm^{-1}$. We have also discussed possible enhancement of the CSR power due to FEL oscillation. From beam optics consideration, power spectrum enhancement at the FEL wavelength is hard to observe in the current experimental setup. However, the CSR power spectrum can be enhanced by non-uniform energy spread as a result of superradiant FEL oscillation.

## REFERENCES


[1] T. Nakazato et al., Phys. Rev. Lett. 63, 1245 (1989).

[2] A. Andersson et al., Opt. Eng. 39, 3099 (2000).

[3] G.L. Carr et al., Nature 420, 153 (2002).

[4] R. Hajima et al., Nucl. Instrum. Meth. A507, 115 (2003).

[5] R. Hajima et al., Nucl. Instr. and Meth. A483, 113 (2002).