TRANSPORT OF TERAHERTZ-WAVE COHERENT SYNCHROTRON RADIATION WITH A FREE-ELECTRON LASER BEAMLINE AT LEBRA

N. Sei#, H. Ogawa, Research Institute of Instrumentation Frontier, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

T. Sakai, K. Hayakawa, T. Tanaka, Y. Hayakawa, K. Nakao, K. Nogami, M. Inagaki, Laboratory for Electron Beam Research and Application, Nihon University, 7-24-1 Narashinodai, Funabashi, 274-8501, Japan

Abstract

Nihon University and National Institute of Advanced Industrial Science and Technology have jointly developed terahertz-wave coherent synchrotron radiation (CSR) at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University. We have already observed intense terahertz-wave radiation from a bending magnet located above an undulator, and confirmed it to be CSR. To avoid a damage caused by ionizing radiation, we worked on transporting the CSR to an experimental room, which was next to the accelerator room across a shield wall, using an infrared free-electron laser beamline. The CSR power of the vertically polarized component was approximately 40 nJ per macropulse at frequencies of 0.09-0.17 THz.

INTRODUCTION

Because an electron beam of a linac in a free-electron laser (FEL) facility must have a short bunch length and a high charge to realize the FEL lasing, it is suitable for generating intense coherent radiation in the terahertz (THz) region. Although there are various THz-wave sources using such an electron beam [1-3], coherent synchrotron radiation (CSR) hardly affects the electron beam [4]. It can be developed without degrading performance of an FEL. Therefore, Nihon University and National Institute of Advanced Industrial Science and Technology have jointly developed intense THz-wave CSR at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University. We have already observed an intense CSR using an S-band linac at LEBRA and reported the performance of the CSR [5]. However, there is high-flux ionizing radiation due to the electron beam loss around a bending magnet in which the intense CSR is generated. When the CSR is used for a sample with a detector near the bending magnet, the ionizing radiation may spoil the sample and the detector. In order to use the CSR in various experiments, it is necessary to transport it to a safe place for ionizing radiation. Then, we transported the CSR to the experimental room, which was next to the accelerator room across a shield wall, using an infrared FEL beamline. We could obtain a CSR beam whose intensity was approximately one-tenth of that around a bending magnet. In this article, the transport of the CSR using the infrared FEL beamline and characteristics of the CSR transported to the experimental room are reported.

FEL BEAMLINE AT LEBRA

An infrared FEL has been developed with the S-band linac at LEBRA [6]. Because the frequency of the buncher and accelerator tubes is 2856 MHz, the electron beam is bunched in 350 ps intervals. The macropulse duration determined by the flat-top pulse width of the 20 MW klystron output power is 20 μs. Then, there are approximately 57 thousand micropulses in a macropulse. The electron-beam energy can be adjusted from 30 to 125 MeV, and the charge in a micropulse is up to approximately 30 pC in full-bunch mode. The electron beam accelerated by the linac is guided to an FEL undulator line by two 45 degree bending magnets. After passing a 2.4 m planar undulator, it is removed from the FEL undulator line by a 45 degree bending magnet and loses its energy in a beam dump. The spontaneous emission of the undulator is accumulated by two metal concave mirrors which are installed in a 6.72 m optical cavity, and it is amplified by an interaction with the electron beam in the undulator. Fundamental FELs oscillate at wavelengths of 1–6 μm. The FEL beam, which is translated through a hole coupling in the upstream mirror, is converted to a parallel beam with 30 mm diameter by aspherical mirrors. Using the infrared FEL beamline which has 4 flat mirrors in the accelerator room, it is transferred to the experimental room.

GENERATION OF CSR

In a normal operation of FEL experiments, the electron bunch is compressed from 3 to 1 ps by a magnetic compressor using the two 45 degree bending magnets at the FEL undulator beamline [7]. However, there is no optical beam port to extract CSR at the downstream 45 degree bending magnet. Then, we used an optical beam port at the second 45 degree bending magnet which was located above the undulator. Although the CSR was emitted along the electron-beam orbit in the bending magnet chamber with the inner height of 24 mm, its solid angle which incident on a transfer pipe (diameter, 20 mm; length, 265 mm) was only 65 mrad. The CSR passed

---

#Corresponding author. sei.n@aist.go.jp

ISBN 978-3-95450-126-7

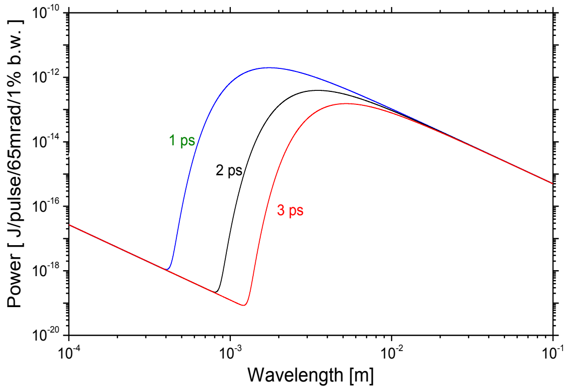

Figure 1: Calculated spectra of CSR emitted in the 45 degree bending magnet at the bunch length of 1. 2 and 3 ps.

through the transfer pipe and was extracted through a quartz window from a vacuum to the atmosphere.

T The bunch length of the electron beam is estimated to be approximately 2 ps at the radiation point of the CSR in the full-bunch mode. As shown in Fig. 1, the calculated CSR spectrum has a maximum for the bunch length of 2 ps at a wavelength of 3 mm. The electron-beam energy is 100 MeV. Then, we used a Schottky D-band diode detector (Millitech Inc., DXP-06) to detect the CSR. To improve injection efficiency for the detector, a pyramidal horn whose opening was 11 and 17 mm in the vertical and horizontal directions was attached to the detector. This detector can measure electromagnetic radiation at frequencies of 0.09-0.17 THz, and the nominal sensitivity of the diode detector is 5 mV / 10 μm for a cw source. We observed an intense THz wave emitted from the quartz window with the diode detector [5]. The measured intensity of the THz wave was proportional to the second power of the electron-bunch charge regardless of the polarization. This experimental result indicated that the intense THz wave was coherent radiation. When a quartz lens with an effective diameter of 46 mm was located 280 mm from the quartz window, the radiation power of the horizontally and vertically polarized components was 23 and 1.8 mW at the frequencies of 0.09–0.17 THz, respectively. The profile of the intense THz wave suggested the reason why the intensity of vertically polarized component was much lower than that of horizontally polarized component. Figure 2 shows two-dimensional mapping of the horizontally and vertically polarized components of the intense THz wave measured at 0.53 m from the quartz window. To improve the spatial resolution, a metal slit (horizontal size, 8mm; vertical size, 4 mm) was attached in front of the pyramidal horn. As shown in Fig. 2, the vertically polarized component of the intense THz wave was distributed over a wide region. It had two peaks at an elevation angle of ±66 mrad from the quartz window and hardly existed on the horizontal plane. The spatial distributions of the intense THz wave were roughly in agreement with those of synchrotron radiation. Therefore, the intense THz wave was identified as CSR.

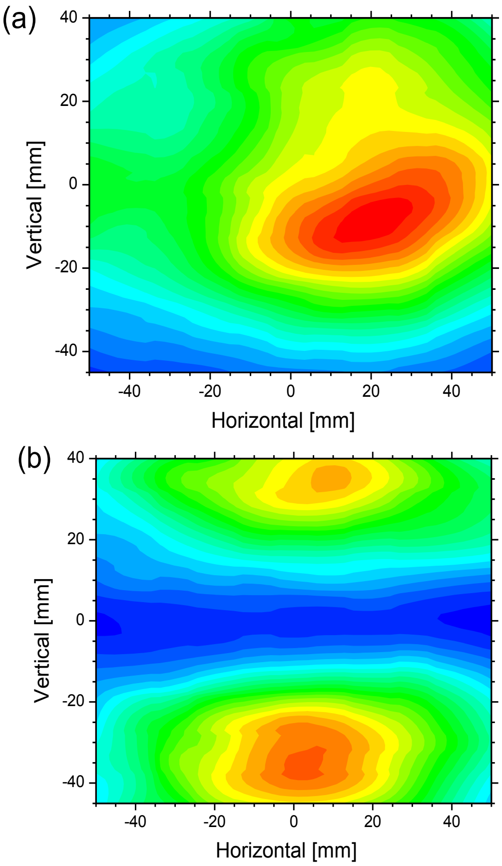

Figure 2: Measured two-dimensional mapping of (a) the horizontally and (b) vertically polarized components of the THz wave power. Red and blue denote high and low intensity, respectively. The data are averaged for a period of the burst mode.

The rise-time of the measurement system was 1.3 ns, so that we could not distinguish individual micropulse in the full-bunch mode. As shown in Fig. 3, the CSR was observed as a cw in the macropulse of the electron beam. Because the width of the macropulse was 20 μs, the CSR power per macropulse was evaluated to be approximately 0.4 μJ in the frequencies of 0.09-0.17 THz. The characteristics of the CSR around the bending magnet were reported in ref. 5 in detail.

TRANSPORT OF THE CSR BEAM

In order to apply the intense CSR to various experiments, it is necessary to transport it to the experimental room where radiations generated by the electron beam are shielded. Because the route which connects the experimental room with the accelerator room was limited, we planed using the infrared FEL beamline for the transportation of the CSR beam. The infrared FEL beamline was 1.8 m away from the quartz window which extracts the CSR beam. As shown in Fig. 4, an angle

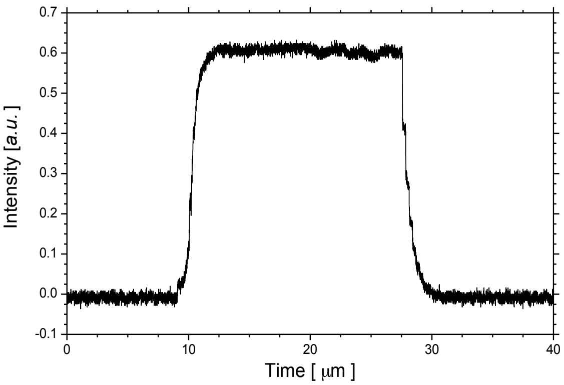

Figure 3: Typical power evolution of the CSR in the full-bunch mode. This was measured by the D-band diode detector at 1.44 m from the quartz window with using a quartz lens, which was located at 0.99 m from the quartz window. The effective diameter and focal length of the quartz lens were 46 and 500 mm, respectively.

between the CSR beam and the infrared FEL beam was 135 degree. Then, we used two plane mirrors to insert the CSR beam into the infrared FEL beamline. One of the plane mirrors was attached to an actuator which was inserted in a vacuum mirror chamber, and it could be pulled out from the infrared FEL pass by a remote control when the FEL was used. In the infrared FEL beamline, the FEL was transported as a parallel beam. To convert the CSR to a parallel beam, a convex polymethylpentene lens, whose focal length was 800 mm, was inserted at the position 800 mm away from the CSR source. The vacuum chamber which stored the mirror actuator had a quartz window (diameter, 89 mm) to enter the CSR beam from the air.

The transported CSR beam was extracted from a sapphire window which was attached to the uppermost stream mirror chamber in the experimental room. This mirror chamber also had a mirror actuator, and the CSR beam passed through the window when the mirror was pulled out from the FEL pass. When the CSR beam focused by a parabolic mirror whose effective diameter was 50 mm, measured power was 0.13 and 0.32 mW for the horizontally and vertically polarized components, respectively. It is noted that the CSR power transported to the experimental room was much lower than that around the bending magnet. This reason is that the CSR was lost between the bending magnetic chamber and the mirror chamber in the air due to large divergence of the CSR beam. Then, we inserted a square aluminum pipe whose side was 36 mm between the convex polymethylpentene lens and the plane mirror. The CSR power increased approximately five times by the aluminum pipe. Because the CSR beam was transported to the experimental room with being reflected by circle plane mirrors in the horizontal plane, the transportation efficiency of horizontally polarized component was much lower than that of the vertically polarized component. However, the CSR power of the vertically polarized component per macropulse was approximately 40 nJ at the frequencies of 0.09-0.17 THz. This CSR power was strong enough to conduct THz imaging or spectroscopic analysis with a pyrometer. We observed a profile of the vertically polarized component of the CSR beam with using the D-band diode detector at a focal position of the parabolic

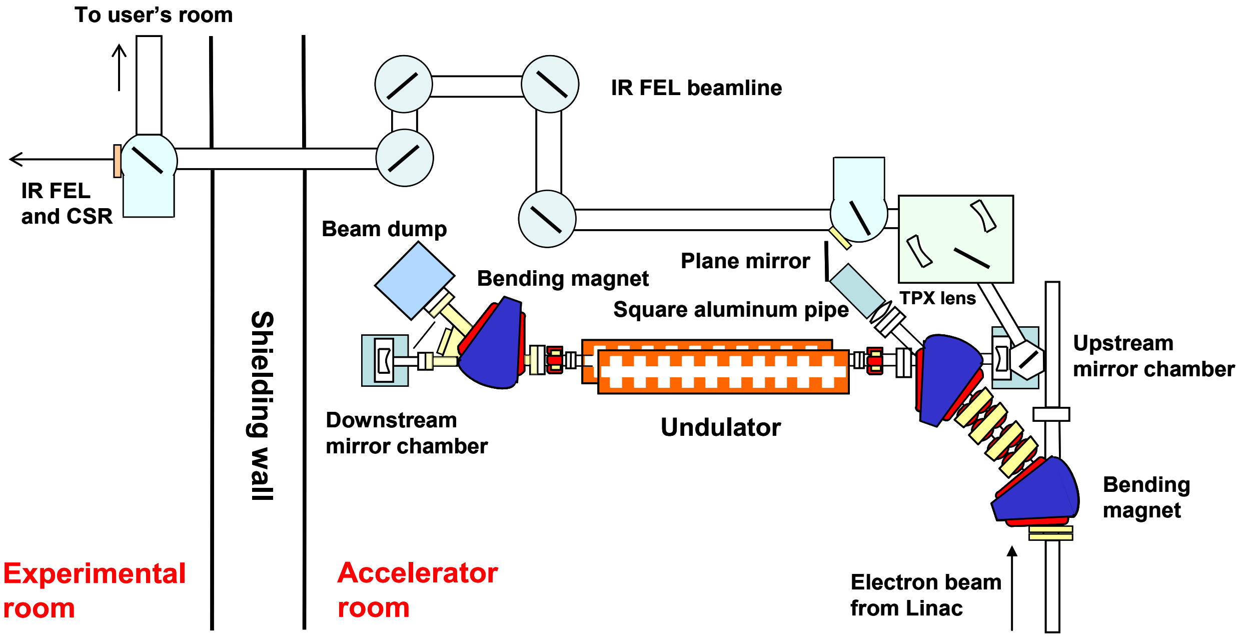

Figure 4: Schematic layout of the transportation of the infrared FEL and CSR beam.

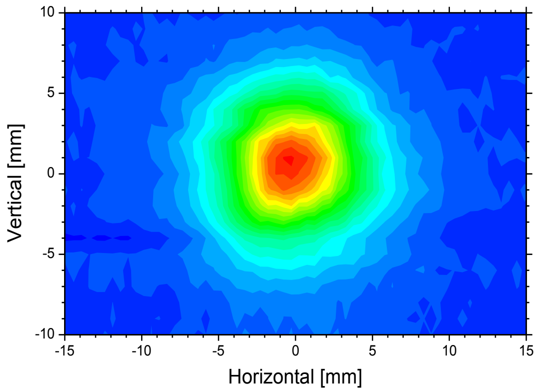

Figure 5: Measured profile of the vertically polarized component of the transported CSR beam with using the D-band diode detector at a focal position of the parabolic mirror.

mirror. As shown in Fig. 5, the transported CSR was a Gaussian beam. It is noted that the CSR lose its spatial coherency by the beam transportation.

CONCLUSIONS

We achieved the transportation of the CSR beam from the accelerator room to the experimental room at LEBRA. The CSR power of the vertically polarized component was higher than that of horizontally polarized component, and it was approximately 40 nJ per macropulse at the frequencies of 0.09-0.17 THz. We have undertaken experiments in which the transported CSR beam is applied.

The bunch length of the electron beam is minimized in the FEL undulator line. Therefore, the CSR power emitted from the downstream 45 degree bending magnet is higher than that emitted from the second 45 degree bending magnet above the undulator. We will develop the new THz wave source at the downstream 45 degree bending magnet.

ACKNOWLEDGEMENTS

This work was supported by Japan Society for the Promotion of Science KAKENHI 23656596. Moreover, this work has been supported in part under the Visiting Researcher's Program of the Research Reactor Institute, Kyoto University.

REFERENCES

[1] Y. Shibata *et al.*, Pyhs. Rev. A **44** (1991) R3449.
[2] Y. Shibata *et al.*, Pyhs. Rev. A **44** (1992) R8340.
[3] Y. Shibata *et al.*: Pyhs. Rev. E **52** 6787.
[4] G. L. Carr *et al.*, Nucl. Inst. and Meth. A **463** (2001) 387.
[5] N. Sei *et al.*, J. Phys. D: Appl. Phys. **46** (2013) 045104.
[6] Y. Hayakawa *et al*, Nucl. Inst. and Meth. A **483** (2002) 29.
[7] T. Tanaka *et al*, Nucl. Inst. and Meth. A **528** (2004) 486.