Design of a dedicated beamline for THz coherent synchrotron radiation at UVSOR-III

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Abstract. We report the design of a THz beamline for coherent synchrotron radiation (CSR) at the UVSOR-III very-low-emittance synchrotron radiation light source. The emitted THz-CSR is collected by a three-dimensional “magic mirror,” which is a perfect collecting mirror for bending-magnet radiation with an acceptance angle of 288 mrad (H) \times 80 mrad (V). A quasi-monochromatic THz-CSR with an average flux of 10^4 µW/0.1 % b.w. and a peak power of 120 nJ/pulse/0.1 % b.w. is expected at the beamline.

1. Introduction
Infrared (IR) and terahertz (THz) spectroscopies have now become conventional methods for the measurement of vibration modes and low-energy electronic structures. IR/THz synchrotron radiation (SR) is also used as a light source for spectroscopy and microscopy throughout the world. The reason is that IR/THz-SR is an ideal source, in which the electron beam emittance is smaller than the diffraction limit of light. So far, many advanced types of spectroscopy have been developed such as IR imaging, pressure-dependent and magnetic-field-dependent THz spectroscopy, and so on. [1] However, to realize further advances in spectroscopy, intense tunable light sources must be developed.

One candidate for an intense broadband THz source is coherent synchrotron radiation (CSR). [2] CSR is light with a longer wavelength than the length of the longitudinal fine structure of an electron bunch in an accelerator. The longitudinal fine structure then behaves like one particle with a large charge density. Since the length of the fine structure is similar to the wavelength of THz light, CSR appears in the THz region. The generation of CSR from storage ring has been investigated at several SR facilities, [3, 4, 5] especially using a laser-slicing method at Advanced Light Source, USA. [6] However, only few applications using CSR have so far been performed [7, 8], because of the instability.

At the UVSOR Facility, basic studies on the generation of CSR by the interaction between the electron beam in the storage ring and a pulse laser introduced from outside have been performed so far. Broadband CSR was produced using a bursting mode [9] and a laser slicing...
technique [10, 11]. Quasi-monochromatic CSR was also obtained due to the periodic modulation of electron bunches created by an amplitude-modulated laser pulse. [12, 13] The obtained quasi-monochromatic CSR had $10^4$ times an intensity of “normal” (incoherent) SR. On the other hand, another type of coherent radiation, coherent harmonic generation (CHG), in the vacuum-ultraviolet (VUV) region was also studied using the same periodic modulation of electron bunches. [14, 15, 16]

Since 2008, a research project on the utilization of coherent light sources called Quantum Beam Technology Program has been under way, in which THz-CSR and VUV-CHG are being used for applications. The main purpose of the program is to develop novel types of spectroscopy using intense THz-CSR, such as THz pump-photoemission probe spectroscopy (TPPS) to investigate the change of electronic structure after excitation of low energy electronic and vibrational states and quasiparticles. [17]

At the UVSOR Facility, the first SR was obtained from the old UVSOR-I ring in 1983. In 2003, the emittance of the light source was improved from 160 nm-rad to 27 nm-rad, and four undulators were installed (UVSOR-II). In 2012, the storage ring will be again improved to achieve an emittance of 15 nm-rad (UVSOR-III). The main targets of UVSOR-III are soft x-ray micro-spectroscopy and imaging, high-resolution angle-resolution photoemission spectroscopy in the VUV region, and application of coherent radiations.

In this paper, we report on the beamline dedicated to THz-CSR at UVSOR-III. The acceptance angle of the beamline is 288 mrad (H) × 80 mrad (V), which is larger than that of the previous IR/THz beamline BL6B, in UVSOR-II [215 mrad (H) × 90 mrad (V)]. [18] Although the horizontal acceptance angle of IRENI beamline at Synchrotron Radiation Center in Wisconsin, USA, is the largest [320(h)×25(v) mrad$^2$], [19] our new THz-CSR beamline has the largest solid angle. The emission intensity of THz-CSR is dependent on the emission angle of the bending magnet. To obtain intense light at around 1 THz, the design of the optics employs a three-dimensional “magic mirror” (3D-MM). As a result, the average flux and peak intensity at 1 THz or higher are expected to be $2 \times 10^{18}$ ph/s/0.1 % b.w. and 120 nJ/pulse/0.1 % b.w., respectively.

2. Front end

Figure 1 shows the form factor of the THz emission from the electron bunch modulated by pulse laser as a function of the horizontal emission angle from the straight section. The form factor corresponds to the efficiency of the evolution of CSR. THz-CSR below 3 THz ($\sim$100 cm$^{-1}$ $\sim$12 meV) is generated from 10 degrees. The form factor of the 3 THz emission, however, is very small. An emission with a frequency lower than 2 THz is therefore mainly used in this beamline. Above 15 degrees, the intensity of THz-CSR below 2 THz ($\sim$67 cm$^{-1}$ $\sim$8 meV) rapidly increases. According to the geometrical conditions, the first mirror can be located at a maximum of 34 degrees. Because the maximum width of the first mirror was limited to 300 mm, the acceptance angle was set at 17.5–34 degrees (total 288 mrad) in the horizontal direction. The vertical angle was set at ±40 mrad to collect the widely expanded THz-CSR.

A top view of the THz beamline is shown in Fig. 2. The emitted THz light is collected by a 3D-MM (M0) of the same type as those already successfully installed at BL43IR in SPring-8 [20] and BL6B in UVSOR-II [18]. The 3D-MM was installed in the bending-magnet chamber and is controlled by a 5-axis pulse motor stage (x, z translation; $\theta_x$, $\theta_y$, $\theta_z$ rotation). To extract the emission at 34 degrees, the 3D-MM is located at the short distance of 55 mm from the electron orbit. The 3D-MM is made of aluminum and was fabricated by an NC length milling machine at the Equipment Development Center of Institute for Molecular Science. The surface roughness is less than $\pm$1 $\mu$m, which is comparable to the visible wavelength but much smaller than the wavelength of THz light. Visible light is scattered by the surface of the 3D-MM, but THz light can be focused. To eliminate the heat load from the SR, we employed a copper rod
(6 mm in diameter) with water cooling on the emission plane because the power from the SR is concentrated in the emission plane. The 3D-MM, which is located 880 mm from the center of the source, reflects the THz-CSR to the focal point (F0) on the outside of the bending-magnet chamber, as shown in Fig. 2 (1200 mm from M0). The THz-CSR collected by the 3D-MM

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Frequency-dependent form factor of THz-CSR as a function of the horizontal angle of the bending magnet from the straight section (a) and the schematic layout of the emission angle of the bending-magnet radiation (b). The interaction between the electron bunch and pulse laser light occurs in the upstream undulator.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Schematic top view of the beam extraction part of the THz-CSR beamline, BL1B, at UVSOR-III. The three-dimensional magic mirror (3D-MM, M0) and a plane mirror (M1) are located in the bending-magnet chamber. A parabolic mirror (M2) is installed to form a parallel beam. The straight section (BL1U) is used for coherent harmonic generation (CHG) in the VUV region.}
\end{figure}
is intercepted by a plane mirror (M1) located in the bending-magnet chamber and guided to the beamline. The focal point (F1) is located on the outside of the bending-magnet chamber through a tapered z-cut quartz window (24 mm in diameter and 5 mm thickness at the center). After F1, the light is formed into a parallel beam by a parabolic mirror (M1) and guided to the outside of the radiation shielding wall.

A new vacuum chamber containing the bending magnet as well as the 3D-MM and M1 plane mirrors was installed in the spring of 2011. In the beamline, a Martin-Puplett type Fourier transform interferometer (FARIS-1, JASCO ltd.) will be installed to check the spectral features of the THz-CSR. Installation of all components of the THz beamline will be completed by December 2011.

3. Photon flux

The calculated photon flux spectrum of THz-CSR compared with "normal" SRs at BL1B and the old BL6B is shown in Fig. 3. Quasi-monochromatic CSR is obtained using the periodic modulation of electron bunches created by an amplitude-modulated laser. The bandwidth is about 0.1 % of the frequency. The frequency of the light can be scanned by changing the periodicity of the amplitude-modulated laser. The CSR spectrum intensity in Fig. 3 is the trace of the peak photon flux of the quasi-monochromatic CSR. The CSR spectrum has a peak at about 1 THz and the intensity below 3 THz is superior to that of normal SR. The expected average flux and peak power at 1 THz are about $2 \times 10^{17}$ ph/s/0.1 % b.w. (=104 $\mu$W/0.1 % b.w.) and 120 nJ/pulse/0.1 % b.w., because the repetition rate of the pulse laser for modulation is 1 kHz.

![Figure 3](image_url)

**Figure 3.** Calculated spectrum of the photon flux of THz-CSR at BL1B of UVSOR-III in comparison with the normal SRs emitted at BL1B and BL6B of UVSOR-III.
4. Conclusion
We have designed a beamline for coherent synchrotron radiation in the terahertz region (THz-CSR). An acceptance angle of 288 mrad(H) × 80 mrad(V) was set at a bending radius of 17.5–34 mrad due to the form factor of the CSR. The average flux and peak power at 1 THz or higher are expected to be about 104 µW/0.1 % b.w. and 120 nJ/pulse/0.1 % b.w., respectively.

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