Project on the superposition of beamlines for parametric X-ray radiation and coherent transition radiation in the THz region at LEBRA

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Abstract. A new project to develop a terahertz (THz)-wave light source is in progress at the parametric X-ray (PXR) beamline of the Laboratory for Electron Beam Research and Application (LEBRA) at Nihon University. The THz-wave source is based on coherent transition radiation (CTR) emitted from a metal foil inserted downstream from a crystal target that is the PXR radiator. Beryllium or titanium foil is the most promising candidate for a THz-wave radiator. Since the electron linac of LEBRA was developed for a free electron laser (FEL), electron beam with bunch length of 1 ps (rms) can be provided by magnetic bunching at the bending magnet section. Thus, very intense coherent transition radiation (CTR) can be obtained in the frequency region around 1 THz. The results of preliminary experiments for CTR production suggested that sufficiently intense THz-CTR can be obtained using the LEBRA linac. In order to realize a THz-wave source for practical application studies, we have a plan to add the extraction feature for THz waves to the PXR beamline.

1. Introduction

The Laboratory for Electron Beam Research and Application (LEBRA) has been running as a light source facility by Nihon University. The light sources have been conducted using the electron beam from a conventional electron linac. The first light source developed at LEBRA was an infrared free electron laser (FEL) with a wavelength range from 1.3 to 6 µm [1]. The second one was a monochromatic X-ray source based on parametric X-ray radiation (PXR) [2, 3]. Both of these sources were constructed on the dedicated beamline and have selectivity for the photon energy (wavelength) as a feature of the light sources. Usually, the FEL beamline and the PXR beamline are used alternately by the week. Various user studies employing these monochromatic light sources have been conducted since 2004 at LEBRA.

In addition to the light sources, a project to develop new sources in the wavelength region of THz has been started at LEBRA. Terahertz (THz)-wave sources are based on coherent radiation
because of the electron bunch length, estimated to be 1 ps [4]. First, coherent synchrotron radiation (CSR) from a bending magnet (BM) has been applied to the THz-wave source at the FEL beamline [5]. The second 45°-BM of the 90° bending section upstream of the FEL undulator is used as a CSR radiator. Since the magnetic compression of the electron bunches is halfway achieved at the source point, the available THz wave mainly consists of components with frequencies below 0.3 THz. To extract a THz wave to an experimental hall where a person can work, the THz-CSR beam is superposed onto the FEL transport line using a reflector of LiTaO$_3$ crystal. The THz-wave power in the experimental hall will be significantly reduced due to the diffraction loss in the long vacuum duct. Actually, the intensity measured by a D-band wave detector was roughly 100 nJ per macropulse when the macropulse duration of the electron beam was 20 µs.

In addition to the THz-CSR source at the FEL beamline, we are planning to develop THz-wave sources at the PXR beamline. Originally, the design concept of the PXR beamline assumed a target would be inserted against the electron beam for the utilization of the beamline. Thus, coherent transition radiation (CTR) is a promising candidate for a THz radiator at the PXR beamline.

2. LEBRA PXR beamline

The PXR beamline was developed as a dedicated beamline for PXR generation. Figure 1 shows the geometric configuration of the PXR beamline. The PXR generating system is connected to the linac through the 90° bending section. The PXR generator consists of a double crystal system, where the first crystal is the X-ray radiator and the second one is the X-ray reflector for transport, in a large vacuum chamber. The beamline has a transport line penetrating a 2-m-thick shield wall to extract X-rays to the experimental hall. In front of the shield wall, a multipurpose vacuum chamber is connected to both the electron beamline and the X-ray line.

![Figure 1. Schematic top view of the LEBRA-PXR beamline. The promising THz-wave sources based on CTR or CER are also indicated downstream from the PXR radiator on the electron beamline.](image)

The LEBRA linac usually provides a 100-MeV electron beam for PXR production. The typical macropulse of the electron beam has an intensity from 100 to 135 mA, depending on the condition of the electron gun. Since the average beam current is limited to 5 µA because of legal regulations for radiation safety, the linac is ordinarily operated in the macropulse condition of 5-µs duration and 5-pps repetition rate.
The PXR source has provided X-rays from 4 to 34 keV employing a Si(111) or Si(220) plane as an X-ray radiator. Typical parameters of the LEBRA-PXR beamline are listed in table 1. The main application of the LEBRA-PXR source is X-ray imaging effectively using energy-selective monochromaticity and/or the spatial coherence of PXR. In particular, diffraction-enhanced imaging (DEI) that can give a phase contrast or contrast based on small-angle scattering is the most characteristic application of PXR.

**Table 1.** Typical parameters of the linac and the PXR source of LEBRA.

| Parameter                                      | Value                               |
|------------------------------------------------|-------------------------------------|
| Electron energy                                | 100 MeV (typ.)                      |
| Accelerating frequency                         | 2856 MHz (S-band)                   |
| Macropulse beam current                        | 70 – 135 mA (typ.)                  |
| Macropulse duration                            | 4 – 5 µs (typ.)                     |
| Macropulse repetition rate                     | 5 pps                               |
| Average beam current                           | 1 – 3.5 µA                          |
| electron bunch length                          | 1 – 3 ps (rms)                      |
| bunch charge                                   | 25 – 47 pC                          |
| Beam size on the target                        | 0.5 – 2 mm in dia. (FWHM)           |
| PXR energy range                               | Si(111) target: 4.0 – 20.5 keV      |
|                                                | Si(220) target: 6.5 – 34 keV        |
| Irradiation field at the X-ray exit            | 100 mm in diameter                  |
| Total X-ray photon rate                        | ~10^7 /s @17.5 keV                  |

3. **THz-wave sources at the PXR beamline**

The PXR beamline is equipped with two target-insertion devices to monitor the beam profile. One is installed between the 90° bending section and the PXR generator. The other one is installed downstream from the PXR chamber. Since the magnetic compression for electron bunches is fully achieved at these points, a metal foil inserted using the insertion device could be a THz-wave source based on transition radiation having frequency components higher than those of the existing wave source in the FEL beamline. The most downstream bending magnet of the PXR beamline is also a candidate for a THz-wave radiator.

3.1. **Coherent transition radiation**

In principle, it is possible to adopt the upstream metal foil target and the crystal target for PXR as a CTR radiator. These targets, however, are more than ~4.8 m away from the entrance of the through-hole penetrating the shield wall. Because of the diffraction effect, it is difficult to guide the THz-wave beam to the PXR transport line without a considerable intensity reduction. Thus, the downstream target is the most preferable CTR source on the PXR beamline. Since the backward CTR beam can be extracted from the view window just above the target, it is possible to effectively transport the THz-wave beam in the atmosphere without serious diffraction loss by using a focusing mirror system.

In the case of forward CTR, the light beam reaching the multipurpose chamber will be treated by using mirrors in the vacuum. However, the duct aperture between the target and the multipurpose chamber is not sufficient. Therefore, the diffraction loss cannot be ignored, especially for the lower-frequency components.
3.2. Coherent edge radiation
When a relativistic electron crosses the boundary of a magnetic field, electromagnetic radiation, referred to as edge radiation, is emitted. In the THz region, coherent edge radiation (CER) from an electron bunch has substantial intensity, and its characteristics are very similar to those of transition radiation [6]. On the LEBRA-PXR beamline, the entrance of the last BM can be a THz-CER source in addition to THz-CSR from the bending section. Since the CER source is pointlike, it will be easier to prepare a beam-shaping optical system than in the case of CSR. The distance between the CTR target and the entrance of the BM is estimated to be 400 mm. This value suggests that the shadow effect of the CTR target will considerably suppress CER having longer wavelengths than 1 mm when the electron beam energy is 100 MeV [7, 8]. Thus, CER without the CTR target is more practical for a THz-wave source emitted in the forward direction from the electron beam.

4. Observation of CTR at the PXR beamline
The intensity of transition radiation depends on the plasma frequency $\omega_p$ of the target material and the incident electron energy $E$. The spectral intensity $I_{TR}(\omega)$ in the bandwidth $\Delta\omega$ at the frequency $\omega$ within the radiation cone from a single electron is written as [9],

$$I_{TR}(\omega) = \frac{\alpha}{\pi} \left( 1 + \frac{2 \omega^2 m^2 c^4}{\omega_p^2 E^2} \right) \ln \left( 1 + \frac{\omega_p^2 E^2}{\omega^2 m^2 c^4} \right) - 2 \frac{\Delta\omega}{\omega},$$  \hspace{1cm} (1)

where $c$, $\alpha$, and $m$ are the speed of light, the fine-structure constant, and the electron rest mass, respectively. When $N$ electrons longitudinally form a bunch, the CTR intensity becomes

$$I_{CTR}(\omega) = N \left[ 1 + (N - 1) f(\omega) \right] I_{TR}(\omega).$$  \hspace{1cm} (2)

Here, $f(\omega)$ is the longitudinal bunch form factor defined by

$$f(\omega) = \left| \int F(z) e^{i\pi z} \, dz \right|^2,$$  \hspace{1cm} (3)

where $F(z)$ is the normalized distribution of the electron bunch along the longitudinal direction [10, 11]. According to eq. (1), materials having higher plasma frequencies are suitable for CTR generation in the THz region when the electron energy is higher than several tens of MeV. With respect to electron beam-loss and background radiation, however, it is desirable to use a thin target of light materials. Taking heat resistance into account, light metals such as beryllium and titanium are expected to serve as materials for the CTR target.

To investigate the characteristics of THz-CTR, a preliminary observation for backward CTR extracted from a view window was carried out in the accelerator room using a 100-MeV electron beam from the linac. The experimental setup is explained in figure 2. A 50-µm-thick Ti foil was used for the CTR target mounted on the insertion device, and the Si crystal for PXR production was retracted from the electron beam axis. According to eq. (2, 3), the CTR intensity strongly depends on the electron bunch length and is almost proportional to $N^2$ when the bunch length is comparable to the wavelength [12]. Using magnetic bunch compression at the 90° bending section, the rms bunch length shorter than 1 ps can be achieved at the PXR beamline as same as the FEL beamline. Figure 3 shows the CTR pulse-energy measured by a pyroelectric detector (Gentec-EO THZ5I-MT-BNC) as a function of the electron-macropulse charge. Here, the bunch length might change depending on the macropulse charge because of the variation of the beam loading at acceleration tube. The CTR intensity, however, seems to obey $N^2$ law and this behaviour suggests that the radiation is enhanced by the coherent effect.
The spectrum of THz-CTR was obtained using a Martin-Puplett interferometer and the typical result is shown in figure 4 [13]. Since the THz-wave was too intense for the pyroelectric detector, black polyethylene films were used as an absorber just in front of the detector. Although the structure corresponding to the interference due to the reflected waves from the absorber is found in the spectrum, it can be seen that it has frequency components from 0.1 to 2 THz higher than those of CSR extracted from the FEL beamline.

The measurement using a calibrated thermal sensor (Ophir 3A-P-THz) was carried out to evaluate the absolute power obtained from the THz-CTR source. Since the electron bunch length is highly sensitive to the RF phase fluctuation of the linac, the pulse-to-pulse stability of the CTR output is relatively poor. The sensor used in the experiment, however, has a long response time, 2.5 s. Thus, the output signal was averaged as shown in figure 5. When the current, the duration, and the repetition rate of the electron macropulse are approximately 70 mA, 5 µs and 5 pps, respectively, the average power of the THz wave was approximately 4.6 mW, corresponding to 0.9 mJ per macropulse. This result suggests that the LEBRA THz-CTR source could be one of the most intense THz-wave sources based on accelerators, except for THz-FELs. Further research on CTR and CER at the PXR beamline will be reported in our next publication to be prepare.
5. Superposing the THz-CTR beam on the PXR beam

The source points of CTR and CER are not visible directly from the experimental hall through the PXR transport duct and are at least 4.5 m away from the exit window. An optical mirror system is therefore necessary to extract the THz-wave to the experimental hall for application studies. Since these THz-wave sources are more than 2 m distant from the PXR radiator, it is supposed that the insertion of the PXR target would not seriously affect THz-wave generation with respect to the shadow effect. After passing through the PXR target, the electron beam divergence should grow up to the order of 10 mrad resulted from the multiple scattering in the target crystal. The permanent quadrupole (Q)-magnets in the PXR generator chamber, however, can suppress the extreme increase in the transverse beam size [2]. In addition, the longitudinal structure of the electron bunch should be almost preserved across the thin crystal target. This means that the insertion of the PXR target does not disturb the scheme of coherent radiation. Thus, it is desirable to introduce a system that enables the simultaneous use of the PXR beam and the THz-wave beam. For this purpose, we are planning to utilize the multipurpose chamber downstream from the last BM of the PXR beamline, as shown in figure 1.

Figure 6. Schematic drawing of the system superposing the backward CTR beam onto the PXR beam. The CTR beam is temporarily extracted to the atmosphere and reenters the vacuum via the chamber roof.

Figure 6 schematically shows the transport of the backward CTR beam from the target inserted into the electron beamline. The THz-CTR beam will be extracted to the atmosphere through the optical view window and will be collimated and/or shaped using a curved mirror. The THz-CTR beam will then be transported toward the roof of the chamber through the air and reenter the vacuum through the other view window. A thin plane mirror made of beryllium
will be used to superpose the THz-wave beam on the X-ray beam because of high transmittance of X-rays. The beryllium mirror has to be retractive for the usual mode of the PXR application.

In the case of the forward direction, CER from the BM entrance will be utilized as the THz-wave source. The CTR target upstream of the BM should be retracted from the electron beam axis to avoid the reduction in CER intensity due to the shadow effect. The CER beam, upon reaching the multipurpose chamber, will be collimated by a parabolic mirror focused on the CER source point. Another beryllium mirror will be used for the superposition of the THz wave and of X-rays, as in the case of backward CTR. The scheme of the coupled mirrors in the chamber is shown in figure 7.

The superposing system in the multipurpose chamber should alternate between the backward CTR and the forward CER. A switchable retracting system for the mirrors is currently in the design stage.

6. Application of the superposing beam
X-ray imaging, including advanced techniques such as DEI, has been the main application of the LEBRA-PXR source. Similarly, non-destructive imaging is one of the most popular applications of THz waves. Therefore, simultaneous imaging of THz waves and X-rays seems to be a prospective application of the superposing beam extracted to the experimental hall. The THz-wave beam can be easily separated from the X-ray beam using a thin beryllium mirror or Al-coated-polyimide mirror, as shown in figure 8. THz waves are sensitive to the molecular state in a sample, in contrast with monochromatic X-rays that can detect the kinds of elements [14]. Simultaneous imaging may be a powerful tool for material science and biology.

Using a short pulse of THz-CTR corresponding to a one-cycle or a half-cycle wave, pump-probe spectroscopy is another interesting application of the superposing beam. The timing of the THz-wave pulse to the X-ray pulse is adjustable by optical path length. Collaboration with...
XAFS (X-ray absorption fine structure) analysis, which is another successful application of PXR, is attractive as a unique application [15].

7. Summary
The development of a THz-wave source at the LEBRA-PXR beamline is in progress, and a preliminary observation of THz-CTR from the Ti foil target was carried out using a 100-MeV electron beam of the PXR beamline. The obtained spectrum of THz-CTR had frequency components from 0.1 to 2 THz and the available power was close to 5 mW. This result suggests that the CTR source has sufficient performance to serve as a practical THz-wave source.

To provide the THz-wave beam to application studies, it is planned that the THz-CTR beam or the THz-CER beam will be transported through the X-ray beamline by the superposition of the THz-wave beam onto the PXR beam. The new system is expected to allow users to simultaneously utilize THz-wave and X-rays in the experiment hall where radiation safety is guaranteed.

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