LONGITUDINAL PHASE-SPACE MEASUREMENTS OF A HIGH-BRIGHTNESS SINGLE-BUNCH BEAM

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Abstract

A measurement system of the longitudinal phase-space distribution of electrons using the combination of an optical transition radiation profile monitor and a streak camera are currently under development at ISIR, Osaka University. The energy spectrum is measured using transition radiation in a preliminary experiment. It is found that the OTR monitor has a higher momentum resolution than the momentum analyzer system usually used.

INTRODUCTION

We are conducting experimental studies on Self-Amplified Spontaneous Emission (SASE) in the infrared region using the L-band linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University [1-3]. The performance of SASE-FEL strongly depends on beam parameters, such as a longitudinal beam profile, bunch charge, the transverse emittance and an energy profile. A correlation between longitudinal positions of electrons in a bunch and their energies has a crucial effect on the temporal evolution of the optical pulse of SASE. Several types of methods are extensively under study to evaluate the longitudinal phase-space profile of the electron beam [4-7]. Among them, a combination of Cherenkov radiation and a streak camera was used in Ref. 5 and a combination of synchrotron radiation and a streak camera in Ref. 7.

In order to measure the electron distribution in the longitudinal phase-space, we use a combination of an optical transition radiation (OTR) monitor and a streak camera together with a bending magnet. Since the bending magnet produces momentum dispersion in the electron beam, electrons diverge in the horizontal direction. The OTR radiator is placed in the lower course of the beam line from the bending magnet and it works as a converter from electrons to photons. The horizontal intensity distribution of photons is proportional to the momentum distribution of electrons, provided that the beam size of the electron beam due to the transverse emittance is negligibly small compared with the momentum distribution. By means of an appropriate optical system, the intensity distribution of photons on the OTR radiator can be focused on the horizontal slit of the streak camera. When the temporal sweep of the camera is turned on, a streak image reproduces the electron distribution on the longitudinal phase-space.

Advantages of using OTR are as follows: (1) the radiator is a simple metallic plate or foil, which produce no vacuum degradation by irradiation, (2) since the emission process is a very rapid phenomenon at a flat surface, the temporal resolution is expected to be high, (3) the number of photons is proportional to the incident electron number without intensity saturation. Furthermore, if a very thin organic film vapour-deposited with metal is used as an OTR radiator, a quasi-non-destructive monitor will be realized [8].

Compared with Cherenkov radiation or synchrotron radiation, on the other hand, the intensity of transition radiation is lower and the photon yield in the visible region is of the order of 10^{-2} photons per incident electron [9]. The L-band linac, however, can produce a high-intensity single-bunch beam typically with charge of 30 nC, so that a detectable number of photons is expected.

We recently began the feasibility study of the longitudinal phase-space monitor with OTR. In this contribution, we will present preliminary experimental results of the energy spectrum measurements with OTR.

PROPERTIES OF TRANSITION RADIATION

Transition radiation is produced by relativistic charged particles when they traverse the boundary surface of two media with different dielectric constants. When a charged particle of the velocity βc, energy γ and charge e passes across a metallic surface in a vacuum, the radiation energy per unit solid angle dΩ and unit frequency dω is given by [10]:

$$\frac{d^2W}{d\omega d\Omega} = R\frac{e^2}{4\pi^2 c}\frac{\sin^2\theta}{\left(1-\beta\cos\theta\right)^2}, \qquad (1)$$

where R is the reflection coefficient of the metal and θ the angle of emitted photons with respect to the electron

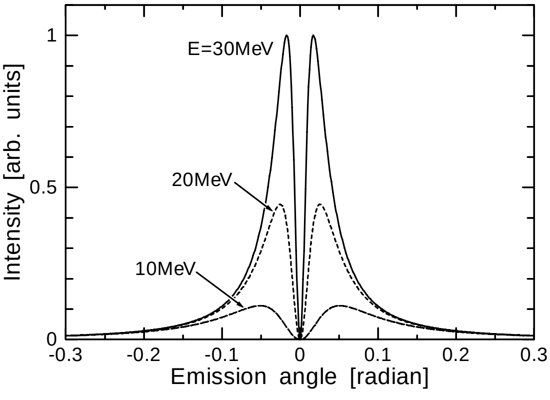

Figure 1: Angular distribution of the transition radiation.

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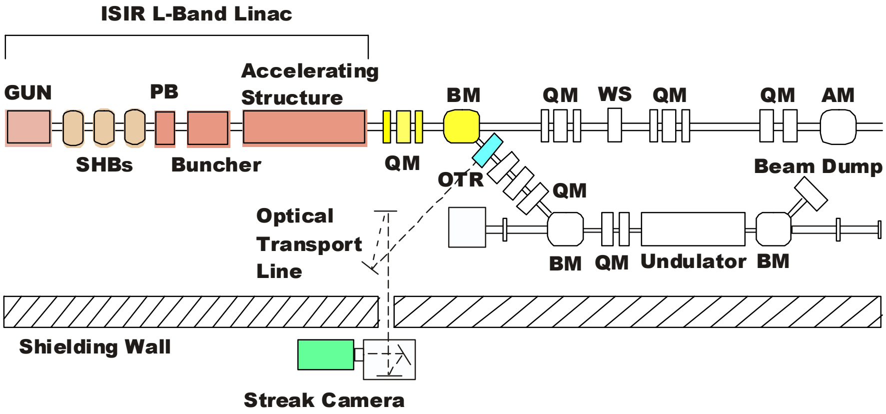

Figure 2: Schematic layout of the ISIR L-band Linac and FEL beam line. GUN: Electron gun, SHBs: Sub-harmonic Bunchers, BM: Bending magnet, QM: Q-magnet, AM: Analyser magnet, WS: Wire Scanner Monitor.

beam axis for the forward radiation and the direction of specular reflection for the backward. The angular distributions of the emitted radiation for electron energies obtained with our linac are shown in Figure 1. The emission angle of the maximum intensity is expressed by

$$\theta \cong \frac{1}{\gamma}. \qquad (2)$$

The peak intensity of transition radiation for 10 MeV energy is one-tenth of that for 30 MeV, and the emission angle for 10 MeV increases three times wider than that for 30 MeV. We, therefore, have to broaden the acceptance angle of the photon detection system in order to make use of the transition radiation as a longitudinal phase space monitor for lower energy electrons.

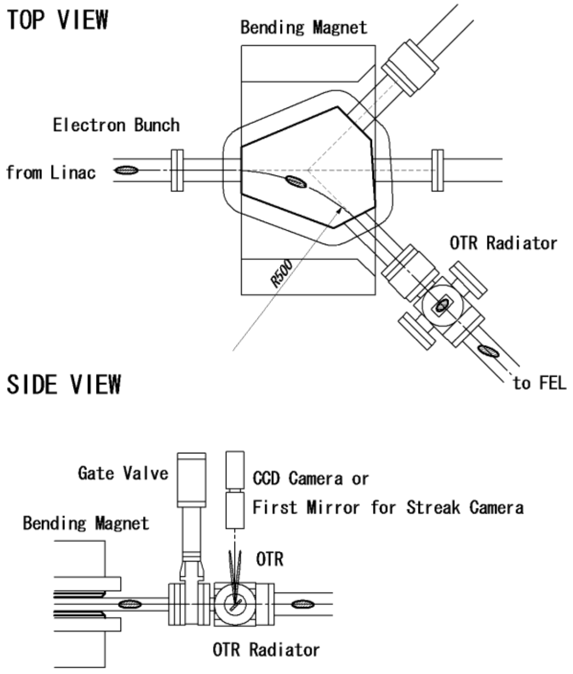

Figure 3: Configuration of the OTR radiator.

EXPERIMENTAL SETUP

Figure 2 shows a schematic layout of the L-band linac. The linac is equipped with a three-stage sub-harmonic buncher (SHB) system composed of two 1/12 and one 1/6 SHBs in order to produce an intense single-bunch beam with charge up to 91 nC/bunch. For single-bunch operation, the electron beam with a peak current up to 28 A (typically 18 A in our experiments) and a duration of 5 ns is injected from a thermionic gun (EIMAC, YU-156) into the SHB system. After being compressed to a single-bunch, the electron beam is accelerated to 10 – 30 MeV in the 1.3 GHz accelerating tube. The electron beam is transported via an achromatic beam transport line to the wiggler for the FEL system.

The OTR radiator, which converts electrons to photons, is placed at a position 320 mm downstream from the first bending magnet as shown in Figure 3. The screen is an aluminium plate having sizes of $55 \times 40 \times 1.6$ mm^3, and it is tilted vertically by an angle of 45° with respect to the

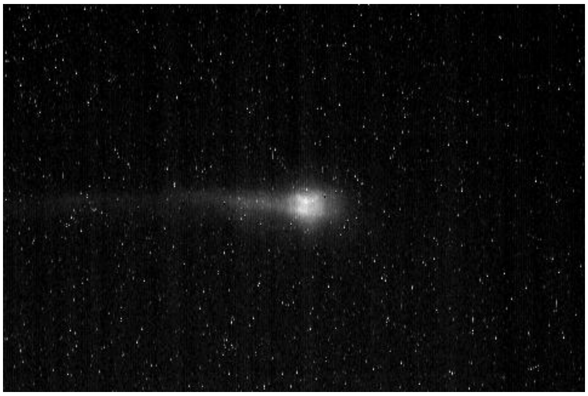

Figure 4: The OTR image of the beam profile measured using a CCD camera. The horizontal direction is the bending orbital plane of the electron beam. Left side of the image is lower momentum one.

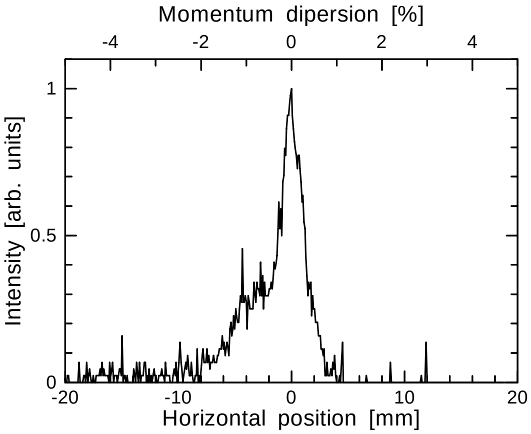

Figure 5: Momentum profile of the electron bunch obtained by integrating the OTR image in a vertical.

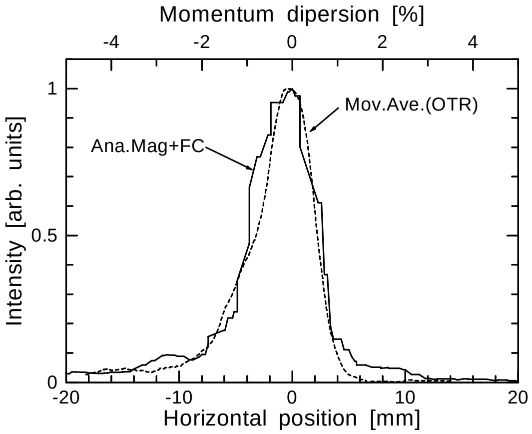

Figure 6: Momentum profiles of the electron bunch. The solid line is the momentum profile measured with an analyzer magnet and a faraday-cup current monitor. The dashed line is the profile obtained by moving average of the OTR profile within a ± 0.5 % width.

bending orbital plane, so that backward transition radiation is emitted in the vertical plane. The first mirror of the optical transport system is a concave mirror and it is placed the focal length away from center of the radiator, so that OTR image on the radiator, which diverges in the horizontal direction, is mostly included in the depth of field of the first mirror.

At first we have used a CCD camera, instead of the streak camera, for directly observing the OTR image. The camera (TAKEX, FC300M) is a progressive shutter camera and works with 659(H) × 494(V) pixels in 1/3 inch. A macro lens (Canon, J6X11) with a lens aperture of 40 mm was used for focusing. The camera was placed at a distance of 210 mm from the OTR radiator. In this configuration, an acceptance angle is approximately ± 0.1 radians, which is sufficient to capture the radiation emitted by the 20 – 30 MeV electrons.

EXPERIMENTAL RESULTS

An experiment is conducted with a single-bunch electron beam of 26.6 MeV energy. The normalized emittances are 165 π mm mrad in the horizontal direction and 160 π mm mrad in the vertical direction. A measured OTR image is shown in Figure 4. The horizontal and the vertical scales are 0.085 mm/pixel. Figure 5 shows the momentum profile of the electron bunch obtained by integrating the image in a vertical. Since dispersion function η is 0.4 m at the position of the OTR radiator, momentum resolution of the measurement system is estimated to be 0.02 %/pixel. Using the resolution, the momentum spread of the OTR profile was evaluated to be 0.4 % (full-width half-maximum). Figure 6 shows a momentum profile measured with a momentum analyzer magnet and a faraday-cup current monitor. The spectrum width of the profile is 1.6 %. The dashed line in Figure 6 shows the profile obtained by moving average of the OTR profile within a ± 0.5 % width. Since the both profiles have a similar width, the resolution of the analyzer magnet slit is estimated approximately to be 1 %. It turns out that the OTR monitor has a higher momentum resolution than the momentum analyzer system usually used.

SUMMARY

In order to measure the longitudinal phase-space profile of the electron beam, we are developing the measurement system consisted of an OTR radiator, a bending magnet and a streak camera. As a preliminary experiment, the momentum spectrum is obtained from the OTR profile, and the momentum resolution of the new system is evaluated. We are now preparing for the longitudinal phase-space measurement experiments.

ACKNOWLEDGEMENTS

The authors express their sincere thanks to Mr. T. Yamamoto for his technical contribution and Mr. S. Suemine for his support of linac operation. This research is partially supported by Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (C), 18540273, 2006.

REFERENCES

[1] R. Kato et al, Nucl. Instr. and Meth. in Phys. Res. A 445 (2000) 164.

[2] R. Kato et al, Nucl. Instr. and Meth. in Phys. Res. A 475 (2001) 334.

[3] R. Kato et al, Nucl. Instr. and Meth. in Phys. Res. A 483 (2002) 46.

[4] A. Doria et al., Nucl. Instr. and Meth. in Phys. Res. A 475, (2001) 296.

[5] J. Rönsch et al, “Longitudinal Phase Space Studies at PITZ”, FEL’05, Stanford, August 2005, p.552, http://www.jacow.org.

[6] H. Loos et al, “Experimental Studies of Temporal Electron Beam Shaping at the DUV-FEL Accelerator”, FEL’05, Stanford, August 2005, p.632, http://www.jacow.org.

[7] S. Zhang et al, “Temporal Characterization of Electron Beam Bunches with a Fast Streak Camera at the JLab FEL Facility”, FEL’05, Stanford, August 2005, p.640, http://www.jacow.org.

[8] T. Asaka et al, "Development of the quasi-non-destructive beam screen monitor", 27th Linear Accelerator Meeting in Japan, (2002).

[9] L. Wartski et al, IEEE. Trans. Nucl. Sci. NS-20 (1973) 544.

[10] M. Jablonka et al, “Beam Diagnostics Using Transition Radiation Produced By A 100 MeV Electron Beam”, PAC’91, San Francisco, May 1991, p.1534.