CSR

Tunable Narrowband Terahertz CSR from Electron Bunch Interacted with Modulated Laser Pulse

M. Shimada[1], M. Katoh[1], S. Kimura[1], M. Hosaka[2], Y. Takashima[2], S. Bielawski[3], C. Szwaj[3], C. Evain[3], A. Mochihashi[4], T. Hara[5], T. Takahashi[6]
[1]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan*
[2]*Graduate School of Engineering, Nagoya University, Nagoya 464-8603 Japan*
[3]*Université des Sciences et Technologies de Lille, Villeneuve d'Ascq Cedex, France*
[4]*Japan Synchrotron Radiation Research Institute, SPring-8, Sayo-cho Hyogo 679-5198 Japan*
[5]*RIKEN SPring-8 Center, RIKEN Harima Institute, Sayo-cho Hyogo 679-5148 Japan*
[6]*Kyoto University Research Reactor Institute, Kumatori-cho Osaka 590-0494 Japan*

Powerful and tunable narrowband terahertz (THz) light source is expected to open a new field in biology, chemistry, medical sciences and so on. Recently, we have developed a new method to produce monochromatic synchrotron radiation in the terahertz region on storage rings [1]. In this method, a specially tailored electron bunch emits monochromatic radiation in a uniform magnetic field. This is in contrast with the ordinary technique to produce monochromatic radiation by utilizing periodic magnetic fields created by undulators.

At UVSOR-II, we have already succeeded in producing intense broadband THz emission by using the laser slicing technique [2]. In the feasibility study before starting this experiment, we had pointed out the possibility to produce monochromatic radiation by extending this technique. We had predicted that, by creating many dips periodically on an electron bunch, we could produce quasi-monochromatic synchrotron radiation through coherent synchrotron radiation (CSR) mechanism.

To create many dips periodically or, in other words, periodic density modulation, we developed a method to produce amplitude-modulated laser pulses by using a technique called 'chirped pulse beating' (see Fig. 1), in collaboration with a French team [1]. This is a robust technique which fits the accelerator circumstances and is easy to operate.

The amplitude modulated laser pulses are injected to the ring through a laser transport line which was constructed by utilizing a part of the existing optical cavity for free electron laser. The laser pulses interact with electron bunches in an undulator whose fundamental wavelength is tuned to the laser wavelength, 800 nm in this case.

In the undulator, the laser field and the electrons exchange their energy, and an energy modulation is created on the electron bunch. The energy modulation is larger/smaller where the electrons interact with laser field of larger/smaller amplitude. After this interaction the electron bunch proceeds in the ring. Since the higher/lower energy electrons go slow/fast., in other words, the time of flight depends on the energy, the energy modulation is converted to a density modulation. Electrons escape out from strongly modulated parts. Fig. 2 shows a result from numerical simulation on the formation of the density modulation. The period of the density modulation is exactly same as that of the amplitude modulation of the laser pulse.

The density modulated electron bunch emits CSR at the wavelength corresponds to the density modulation period. This can be understood by using a general expression of the power of the CSR;

$$P(\lambda) = P_0(\lambda)(N_e + N_e^2 f(\lambda)),$$

$$f(\lambda) = \left(\int \cos(2\pi z/\lambda) S(z) dz\right)^2$$

where the $P(\lambda)$ is the radiation power at the wavelength λ emitted by an electron bunch, the $P_0(\lambda)$ that emitted by a single electron, the N_e the number of the electrons, the $S(z)$ is the longitudinal density distribution of the electron bunch. If the bunch has a single dip, the $f(\lambda)$ has a value close to unity for the wavelength longer than the dip width. In this case, the CSR spectrum becomes broadband. On the other hand, when sinusoidal density modulation is created on the bunch, then the $f(\lambda)$ has a sharp peak at the wavelength corresponds to the density modulation period.

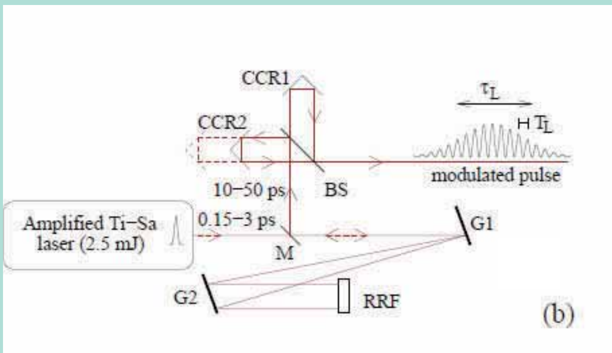

Fig. 1. Principle of Chirped Pulse Beating [1]. A femto-second laser pulse is stretched and separated into two pulses. They are merged with some delay on one pulse.

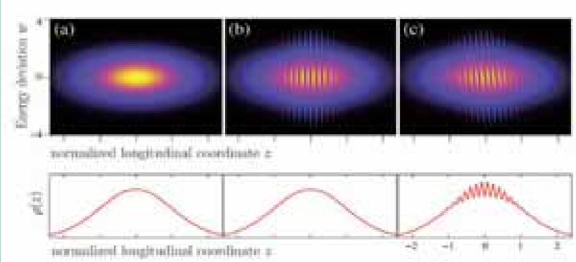

Fig. 2. Evolution of the electron distribution in longitudinal phase-space (upper) and their projection onto the longitudinal coordinate (lower), (a) before the interaction, (b) just after the interaction and (c) after traveling in the ring [1].

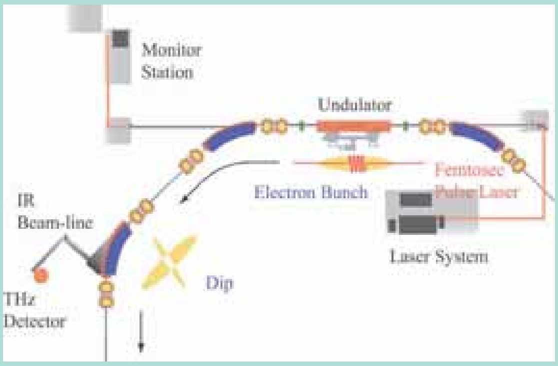

Fig. 3. Laser slicing system at UVSOR-II [2].

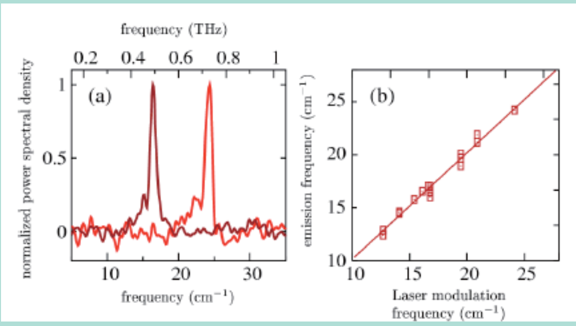

Fig. 4. Typical narrowband THz CSR spectra, and tunability curve [1]. (a) Two THz CSR spectra obtained with modulation frequencies of 16 cm^{-1} and 24cm^{-1}, respectively. (b) Peak frequency of THz CSR versus laser modulation frequency.

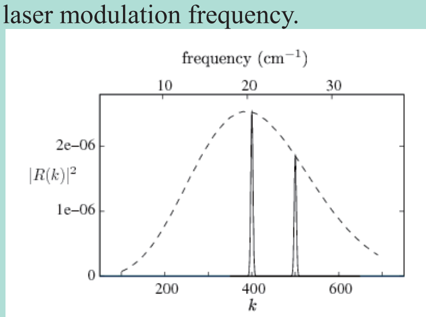

Fig. 5. Calculated CSR intensity versus modulation frequency [1]. The two peaks (full lines) are spectra associated to modulation frequencies of k_m=400 and k_m=500, respectively.

The experimental setup is illustrated in Fig. 3. The CSR was observed at the second bending magnet from the undulator section where the interaction between the electron bunch and the laser pulse took place. The THz spectrum is measured by the Martin-Puplett interferometer at the beam-line BL6B. We succeeded in observing the narrowband THz CSR as shown in Fig. 4(a). It was also confirmed that the larger number of the modulation gave the narrower line width.

Another important feature of this new technique, the 'tunability', was also successfully demonstrated. Just by adjusting the position of a retro-reflector, which is a component of 'chirped pulse beating' optical systems, we could change the modulation period. The radiation wavelength was found to exactly same as the modulation period as shown in Fig. 4(b). A detectable peak was in the 12-25 cm^{-1} range.

Intensity of THz CSR for given laser peak power and for the present experimental setup can be estimated analytically as a function of the modulation frequency. The result is bell shaped with the peak around 20 cm^{-1} as shown in Fig. 5 and qualitatively explains well the experimental results.

Acknowledgement

This work was supported by the Joint Studies Program (2005–2007) of the Institute for Molecular Science and the JSPS Fellowship Program for Research in Japan (grant S06215), by Grants-in-Aid for Scientific Research B15360038 and B15360039 from JSPS and by the research foundation for Opt-Science and Technology. CERLA is supported by the French Minist`ere charg´e de la Recherche, the R´egion Nord-Pas de Calais and FEDER.

[1] S. Bielawski, C. Evain, T. Hara, M. Hosaka, M. Katoh, S. Kimura, A. Mochihashi, M. Shimada, C. Szwaj, T. Takahashi, Y. Takashima (in alphabetic order), Nature Physics **4** (2008) 390.

[2] M. Shimada, M. Katoh, S. Kimura, A. Mochihashi, M. Hosaka, Y. Takashima, T. Hara, T. Takahashi, Jpn. J. Appl. Phys. **46** (2007) 7939.

[3] Y. Takashima, M. Katoh, M. Hosaka, A. Mochihashi, UVSOR Activity Report 2002 (2003) 56.

[4] Y. Takashima, M. Katoh, M. Hosaka, A. Mochihashi, S. Kimura, T. Takahashi, Jpn. J. Appl. Phys. **44** (2005) L1131.

Undulator

Independent Tuning of Variable Polarization Undulator U7

K. Hayashi, M. Katoh, J. Yamazaki, A. Mochihashi, M. Shimada
UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan

Outline of U7

The variable polarization undulator, U7, was introduced in summer 2006 (Fig.1). It is a 3m Apple-II type undulator. It is the 4th undulator operational at UVSOR.

Fig. 1. Variable polarization U7 undulator.

All undulators of UVSOR can be controlled via Ethernet from beamlines. They have several steering magnets to cancel the closed orbit distortion (COD) caused by pole gap change. U7 has four correction magnets (two horizontal/vertical steerings and two quadrupoles) at the ends of the undulator. The controller commands DC power supply to provide feedforward current for steering magnets, referring both of the pole gap and the correction table in period less than one second.

Method of COD correction

We first prepared the correction table for the local quadrupole magnets to cancel the betatron tune shift caused by gap change based on measurements. Then, we prepared the correction table for the steering magnets to compensate the COD due to gap change [1].

As the first step, COD due to the gap change was measured by beam position monitors (BPM). Next, COD caused by the excitation of the steering magnets was measured. Then the currents of the steering magnets were determined so as to minimize the COD. We used least-square method, that is to find local minimum of S given below;

$$S = \sum_{i=1}^{N_{BPM}} \begin{Bmatrix} (x_i + u_i^H I_H)^2 \\ (y_i + v_i^V I_v)^2 \end{Bmatrix}$$

where u_i^H, I_H and x_i represent horizontal COD at i-th BPM caused by the excitation of horizontal steering magnets at unit current, excitation current of horizontal steering magnets and horizontal COD of i-th BPM caused by gap change, respectively.

Result of COD correction

The result of COD correction is shown in Fig. 2 as to horizontal COD in horizontal polarization mode for example. COD without correction caused by gap change from 100mm to 24mm is larger than 100 microns, while smaller than 10 microns with correction. At present, horizontal polarization mode (gap 24mm-200mm) and vertical polarization mode (gap 35mm-200mm) are opened for users. In vertical mode, short gap (smaller than 35mm) causes beam life shortening, which should be improved by introducing more sophisticated correction for non-linear effects.

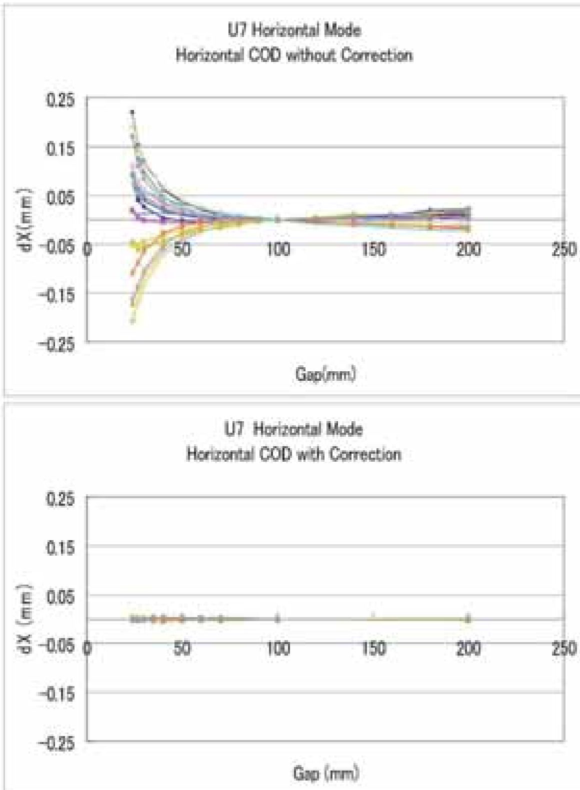

Fig. 2. COD without(up) and with(down) correction

Polarization change is also allowed at fixed gap, 100mm. The COD during the polarization change was successfully corrected to be less than 10 microns.

[1] K. Hayashi *et al.*, UVSOR Activity Report 2003 (2002) 51.

Lasing below 200 nm at the UVSOR-II FEL

M. Hosaka[1], M. Koike[1], N. Yamamoto[1], Y. Takashima[1], M. Katoh[2], M. Shimada[2], J, Yamazaki[2], A. Mochihashi[2,3]
[1]*Graduate School of Engineering, Nagoya University, Nagoya 464-8603 Japan*
[2]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan*
[3]*RIKEN SPring-8 Center, RIKEN Harima Institute, Sayo Hyogo 679-5148 Japan*

The UVSOR-II FEL has been recognized as a useful tool for application experiments because of its high out-coupled average power in the deep UV region down to 215 nm. This fiscal year, application experiments, irradiation on bio-molecules and time resolve experiments on a scintillator have been performed. In the irradiation experiment, average power of 100 mW could be maintained and in the time resolved experiment, FEL of wavelengths of 215 nm and 240 nm was employed. In order to promote application experiments more extensively, FEL lasing in shorter wavelength below 200 nm is required.

The shortest wavelength attained in storage ring FELs is 176.4 nm at Elettra, Italy [1]. They employed fluoride multilayers for resonator mirrors and in-vacuum diagnostic system. At the UVSOR-II FEL, on the other side, attainable wavelength is limited by diagnostic system (out-of vacuum) now and therefore we decided to demonstrate an FEL lasing just below 200 nm.

The lasing experiment was made at electron beam energies of 600 MeV and 750 MeV. Multilayers of Al_2O_5/SiO_2 were employed for the cavity mirrors. The mirrors were designed to maximize reflectivity at 198 nm. The numbers of layers for the front and backward cavity mirrors are 41 and 51, respectively. In order to obtain high out-coupled power from the backward mirror, smaller number of layer was chosen for it. Calculated round trip reflectivity using the optical constant of Al_2O_5 and SiO_2 is 99.1 %. After degassing the mirror with synchrotron radiation from an optical klystron, the reflectivity was measured using cavity ring-down technique. The measured round-trip reflectivity was 98.5%. We suppose that the value is smaller than calculated one due to mirror degradation in the process of the degassing. The first lasing experiment was made with 600 MeV electron beam of 100 mA/2bunch. The shortest wavelength spectrum in the experiment is shown in figure 1. As seen in the figure, the shortest wavelength attained with the mirrors was 199.3 nm although the designed value was 198 nm. We suppose that the wavelength of maximum reflectivity of the mirrors was shifted toward longer wavelength due to the mirror degradation after irradiation of synchrotron radiation, which is often observed in other FEL experiments at UVSOR-II. The measured threshold beam current for the lasing was 28.9 mA/2bunch, which is almost consistent with the FEL gain calculation.

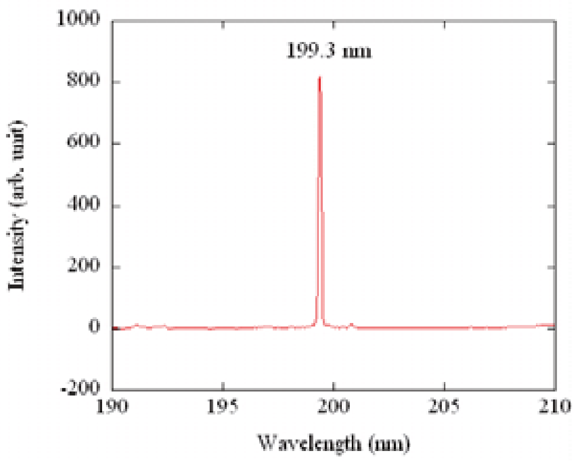

Fig. 1. Measured spectra of the FEL lasing at 199.3 nm. The gap length of the U5 optical klystron was 44.8 mm.

After lasing with 600 MeV electron beam, we raised it up to 750 MeV, which is favorable for a high power FEL operation [2]. An FEL lasing was obtained; however, the shortest wavelength was not shorter than 200 nm anymore. The out-coupled power around 202 nm was 18 mW at a beam current of 90 mA/2bunch. Since the aim of this experiment is to examine a lasing below 200nm, we did not store high beam current in the storage ring. However for users' applications, we will increase the beam current (~ 200 mA/2bunch), and higher out-coupled FEL power will be is obtained.

In conclusion, we have succeeded in an FEL lasing below 200 nm and found no technological barrier for the lasing. Further shortening of the lasing wavelength, a VUV diagnostic system and cavity mirror for the shorter wavelength is necessary. According to a gain estimation, an FEL lasing is possible at UVSOR-II with more than 96 % round trip reflectivity cavity mirrors.

[1] F. Curbis *et al.*, Proceeding of the 27th FEL conference (2005) 473.
[2] M. Hosaka *et al.*, UVSOR Activity Report 2006 (2007).

Full-Energy Injection in UVSOR-II

M. Katoh[1], K. Hayashi[1], J. Yamazaki[1], M. Shimada[1], A. Mochihashi[2]
[1]UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan
[2]Japan Synchrotron Radiation Research Institute, SPring-8, Sayo, Hyogo 679-5198 Japan

In the previous report [1] we have mentioned replacement of power supplies for electromagnets of the booster synchrotron in UVSOR; aiming at the full-energy injection operation. Before the replacement, the maximum acceleration beam energy with the booster was restricted up to 600 MeV because of specifications of the power supplies for the electromagnet; after the beam injection we had to accelerate the beam up to 750 MeV in the storage ring for users operation. Such operation was not suitable for stabilization of the beam position in the storage ring, and moreover, it could become critical problem for 'top-up' operation which we are planning to do in the future. After the replacement and basic tuning of the power supplies for 600 MeV operation mode, we continued development of the operating condition for getting full-energy injection mode. In the development we settled the 750 MeV operating point of the booster on the extension of the 600 MeV operation; without changing beam optics. Figure 1 shows output patterns of the power supplies for the 750/600 MeV operations. The main power supply ('Main Coil' in the figure) supplies all of the magnets; bending, QF and QD magnets. Additional power supplies ('Sub Coil QF' and 'Sub Coil QD') are also used to control the quadrupole fields. During the additional acceleration the QF and QD magnets saturate because of the main power supply, so the QF and QD output had to decrease in the acceleration process. That means slight change in the beam optics, but we didn't have any serious problems in the operation. Because of the change in the operation pattern, a repetition rate of the booster in the 750 MeV operation is settled at 1Hz while the repetition in the 600 MeV is usually ~3 Hz. To compensate the additional beam loading and keep enough beam intensity in the booster, we have adopted a pattern operation for RF accelerating voltage. To transport the 750MeV beam from the booster to the storage ring, we have also replaced a power supply for bending magnets in the beam transport line at the end of FY2006.

After the upgrade of the beam transport line, soon we succeeded the full energy injection [2]. Figure 2 shows typical operation pattern of the booster synchrotron in 750 MeV operation. The beam current circulating in the booster was measured by an AC-CT via an linear wave detector for RF frequency (90.1 MHz) component; in the figure the beam current seems to change because of the change in the bunch length during the acceleration. At present, the extraction beam current from the booster to the storage ring is almost the same as that in the 600 MeV operation; typically it takes 3 times longer injection time to get the same beam current in the storage ring. In the daily users operation, however, we re-inject the beam upon the remaining beam in the full-energy injection operation; that shortens the time for the injection up to almost the same as that in the 600 MeV operation actually.

Now we are planning to perform 'top-up' operation in UVSOR near the future. The development the top-up systems including hardware and control systems are under way. Upgrade of radiation safety to cope with the continuous injection is also planning.

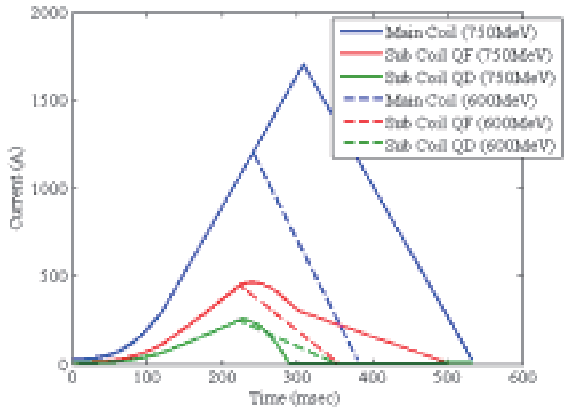

Fig. 1. The operation pattern of power sources for electromagnets in the booster. 750/600 MeV patterns are shown.

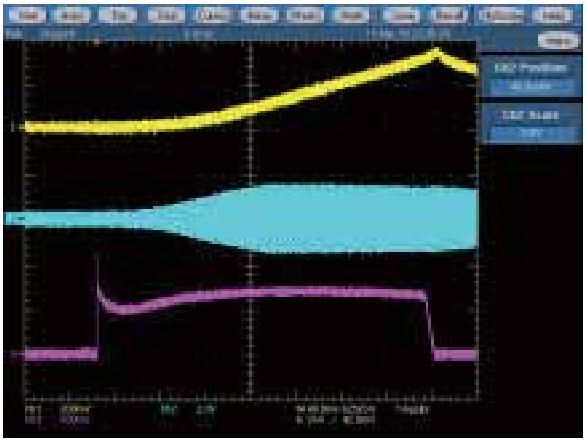

Fig. 2. A typical operating condition of the booster; magenta: beam current from AC-CT, yellow: output of the main power source, cyan: RF voltage from pick-up electrode in the RF cavity. The beam is accelerated up to 750 MeV at the top of the main power source output.

[1] M. Katoh,UVSOR Activity Report 2006 (2007) 8.
[2] K. Hayashi *et. al.*, The 21st Jpn. Soc. on Syn. Rad. Res. Conf. (Kusatsu, 2008) 14P004.

Spectrum Measurement of Terahertz Synchrotron Radiation by Laser Bunch Slicing at UVSOR-II Electron Storage Ring

M. Shimada[1], M. Katoh[1], S. Kimura[1], M. Hosaka[2], Y. Takashima[2], N. Yamamoto[2], A. Mochihashi[3], T. Hara[4], T. Takahashi[5]

[1]UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan
[2]Graduate School of Engineering, Nagoya University, Nagoya 464-8603 Japan
[3]Japan Synchrotron Radiation Research Institute, SPring-8, Sayo Hyogo 679-5198 Japan
[4]RIKEN SPring-8, Sayo Hyogo 679-5148 Japan
[5]Kyoto University Research Reactor Institute, Sen-nan Osaka 590-0494 Japan

Laser bunch slicing is a technique for producing intense coherent synchrotron radiation (CSR) in terahertz region by formation of a sub-millimeter dip on electron bunches. The intensity of CSR is enhanced at the wavelength longer than the longitudinal size of the dip. We have already been successful in observation of THz CSR signal train synchronized with the 1kHz laser trigger signal [1]. The intensity of the THz CSR is 10^4 – 10^5 times larger than that of the normal SR and proportional to square of the peak current of the electron beam.

The experimental setup is shown in Fig.1. A Ti:Sa laser pulse with sub-pico sec duration propagating from the upstream of an undulator interacts with an electron bunch under a resonance condition. Then the electron changes its energy and its orbit after the bending magnet. This is a process of dip formation. Fig. 2 shows a schematic of the dip formation with various pulse durations. From the numerical results, you can see that a laser with shorter pulse duration makes a sharper dip. It means that the high frequency component of the THz CSR is enhanced with the shorter laser pulse duration.

THz CSR is gathered with large acceptance 215 mrad x 80 mrad at beamline BL6B installing a magic mirror [2]. A Martin-Puplett interferometer is placed in front of the bolometer for spectrum measurement. A gated integrator is used for reducing the background noise.

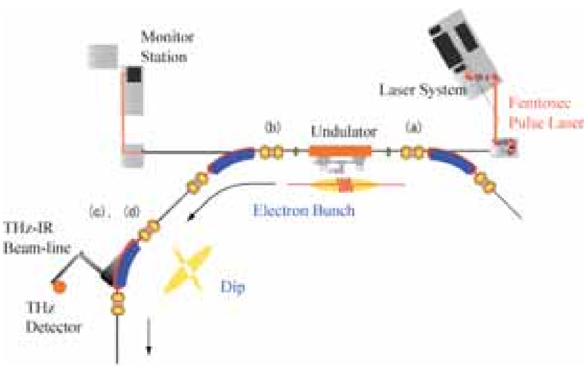

Fig. 1. Schematic of laser bunch slicing system in UVSOR-II

The experimental results of THz CSR spectra are shown in Fig.3. We demonstrated that the THz CSR spectrum depends on the laser pulse duration. High-frequency component of the THz CSR is more intense in the case of shorter laser pulse duration. This result is well explained by the numerical simulation.

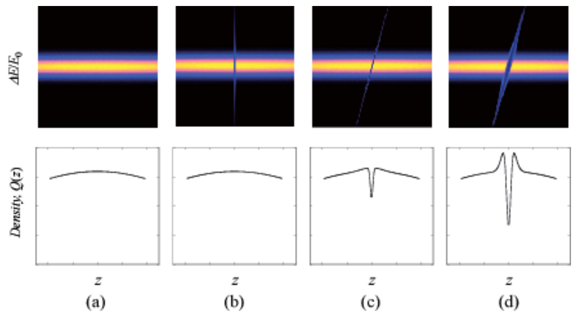

Fig. 2. Numerical simulations of longitudinal phase space (upper) and electron bunch density distribution (lower) in dip formation process. (a) : Before laser interaction, (b) : just after laser interaction, (c) : after passing through bending magnets, (d) : same as (c) but with longer laser pulse duration.

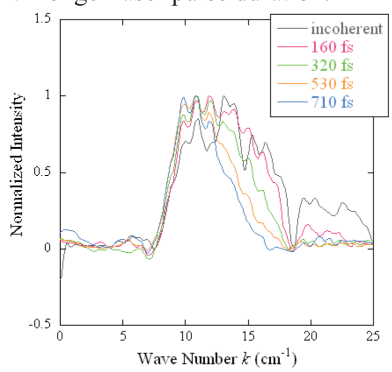

Fig. 3. Spectra of THz CSR obtained with various laser pulse durations, 160 (red), 320 (green), 530 (orange), and 710 fs (blue). For comparison, the spectrum of the normal SR obtained with the same system is also plotted but the intensity is normalized.

[1] M. Shimada *et al.*, UVSOR Activity Report 2006 (2007) 34.
[2] S. Kimura *et al.*, Infrared Phys. Technol. **49** (2006) 147.

Radiation

Radiation Monitoring around Accelerator Using Nuclear Emulsion

Y. Taira, K. Morishima, K. Hamada, T. Nakano

F-lab, Department of Science, Nagoya University, Nagoya 464-8602, Japan

Nuclear Emulsion is a radiation detector, originally used for cosmic ray experiment, and high energy elementary particle experiment.

The structure of Nuclear Emulsion is that 45 micron emulsions applied both faces of 200 micron TAC bases. This type of Nuclear Emulsion is called “OPERA film”.

Tracks of Charged particles in Emulsion read as 3-D information, which consists of position, angle and depth of tracks. The resolution of track is 0.05 micron for position and 0.3 mrad for angle. And scanning of tracks is done automatically, which speed is 5 min/cm^2 [1].

To monitor radiations of scattering around UVSOR Storage Ring, We set up detectors during operation (Fig. 1: circled red ring). The structure of the detector is 20 emulsions, 24*24 mm^2, stacked and vacuum-sealed in laminated sheet. Emulsions can measure angle, position, momentum, flux and particle ID (electron or gamma ray) of arrived radiations.

The angle distribution of the detector is Fig. 2. Electrons (include from gamma ray) arrived from right side to the detector. We checked blue print, confirmed electrons arrived from quadruple magnet and bending magnet. The structure of angle distribution is due to the matter of magnets.

Momentum is calculated from multiple electromagnetic scattering. Scattering is inversely proportional to momentum.

From this experiment, Nuclear Emulsion is very useful to measure leak radiations emitted from accelerator during operation.

Radiation monitoring using Nuclear Emulsion has a great possibility to expand. For example, first the detector for gamma ray CT. Second, monitor neutron at Heavy ion accelerators (RIKEN), Nuclear reactors and heavy particle cancer treatment facilities.

Fig. 1. Set up backward from quadruple and bending magnet.

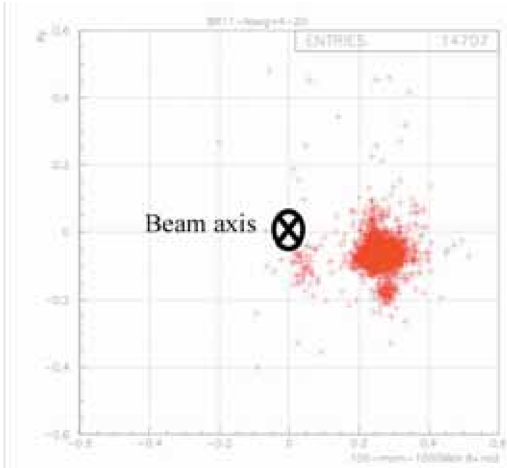

Fig. 2. Angle distribution of electrons that momentum more than 100 MeV/c.

[1] T. Nakano, *Proceedings of International Euro Physics Conference on High Energy Physics (Budapest, Hungary, 2001)* 1218.