Light Sources

Observation of Transverse-Longitudinal Coupling Effect at UVSOR-II

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Coherent synchrotron radiation (CSR) emits from the longitudinal dip-structure of radiation wavelength scale. We have demonstrated the measurements of CSR by the technique called 'laser bunch slicing' since 2005 [1] and succeeded in emission of the quasi-monochromatic CSR from the bending magnet using the amplitude-modulated laser pulse [2]. In this paper, the turn-by-turn CSR signal is observed by the Schottky diode detector for terahertz range with a time response of a few hundred pico-second [3]. The detector is prepared with three different frequency range. The UVSOR-II electron storage ring was operated with three electron beam optics, the normal optics, and the two low-alpha optics with different betatron tunes of 3.53 and 3.68. Since the tune is close to the half and third resonances, we refer to the latter two as low-alpha (1/2) and low-alpha (1/3) optics.

Figure 1 shows the CSR signals in two low-alpha optics. With the low alpha (1/2) optics, as shown in Fig.1 (a) - (c), the CSR is intense at every other turns. In the middle and high-frequency ranges, it is intense at the first and third arrivals. At the low-frequency range, it could be observed up to the 11th arrival. Although the CSR at the third and fifth arrivals is intense, that of the first arrival is weak.

In the low-alpha (1/2) optics, the betatron tune is close to a half integer. Thus, the intermittent CSR emission was expected to be related to the betatron motion. To confirm this, we tried the same experiment with the low-alpha (1/3) optics. Because of the limited beam time, CSR was observed only at the middle frequency range. The result is shown in Fig. 1 (d). The CSR is intense at every third arrival, the first and fourth. Weak CSR is also observed at the seventh arrival, despite the absence of CSR at the fifth and sixth.

For normal optics, although the results are not shown here, the CSR at the first arrival was detected by all three detectors.

We have observed the transverse-longitudinal coupling effect in laser bunch slicing by measuring the THz CSR turn by turn with ultra-fast diode detectors. The results were in good agreement with the numerical simulation based on linear beam dynamics theory.

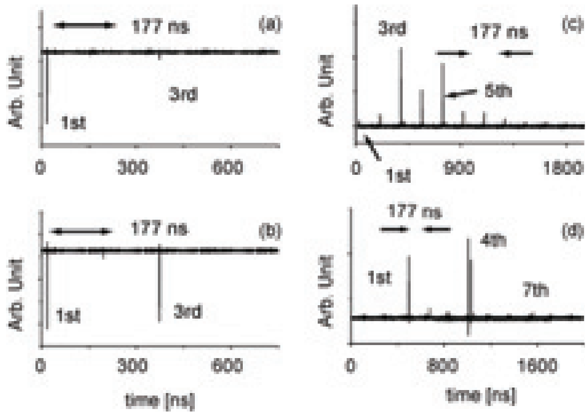

Fig. 1. CSR signals of three diode detectors at the low-alpha optics. Revolution time of the ring is 177 ns. (a), (b), and (c) are with the low-alpha (1/2) optics. Sensitivity ranges are (a) 11.0 - 16.6 cm^{-1}, (b) 7.3 - 11.0 cm^{-1}, and (c) 3.7 - 5.7 cm^{-1}. (d) is with low-alpha (1/3) optics. Sensitivity range is 7.3 - 11.0 cm^{-1}.

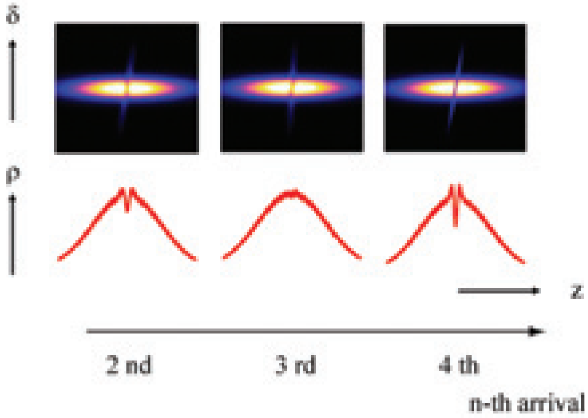

Fig. 2. An example of evolution of fragments and a dip structure in longitudinal phase space (upper) and its corresponding longitudinal density distribution (lower). The horizontal axis is an arrival order after the revolutions

[1] M. Shimada *et al.*, Jpn. J. Appl. Phys. **46** (2007) 7939.
[2] S.Bielawski *et al.*, Nat. Phys. **4** (2008) 390.
[3] M.Shimada *et al.* Phys. Rev. Lett. **103** (2009) 144802.

Measurement of Betatron Oscillation Amplitude Excited by RF Knockout at UVSOR-II

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Abstract

In order to measure the betatron tune, we need to stimulate betatron oscillations. We measured betatoron oscillation amplitudes stimulated by an RF knockout, by using a turn-by-turn beam position measuring technique. The results were compared with simulations. It was found that the non-linear effect of sextupole magnets produces a saturation effect on the betatron oscillation amplitude.

Experimental and Calculation

The electron beam circulating in the UVSOR-II storage ring was stimulated by the RF knockout system. The signals from a beam position monitor were processed by a high-speed digital oscilloscope (5GS/s). The beam position was measured turn by turn.

We simulated the betatron oscillation by transfer matrix calculation. This simulation includes the radiation damping, the kicks by the RF knockout, and the non-linear effect of sextupole magnets.

The kick angle of the RF knockout is based on the simulation using electromagnetic field analysis software, POISSON. Figure 1 shows the cross section of the RF knockout chamber at UVSOR-II and the magnetic field lines. In this case, magnetic field is generated for stimulating horizontal betatron oscillation.

The effect of sextupole magnets was included as using the following expression:

$$x'_{n+1} = x'_n + kx_n^2$$

where x_n is beam position at n-th turn, x'_n is beam angle at n-th turn, and k is a constant proportional to the sextupole field strengths which were determined to make the chromaticity zero.

Results and Discussion

Figure 2 shows simulated beam position at the beam position monitor turn by turn. After the betatron oscillation is excited very quickly within 7×10^4 turns, the amplitude is decreasing for the following 10^6 turns owing to the radiation damping and amplitude-depended tune shift produced by sextupole magnets. Then the amplitude becomes constant. Figure 3 shows the measured and calculated horizontal betatron oscillation amplitude versus the electric power fed to the RF knockout. As the electric power is increasing, the amplitude is also increasing. However, the amplitude tends to saturates. We think this is due to the non-linear effect of the sextupole magnetic fields. The measurement agrees well with the simulation results when the sextupole effect is included. This result indicates that it is essential to consider the non-linear effects of the sextupole magnets in the design of an RF knockout system.

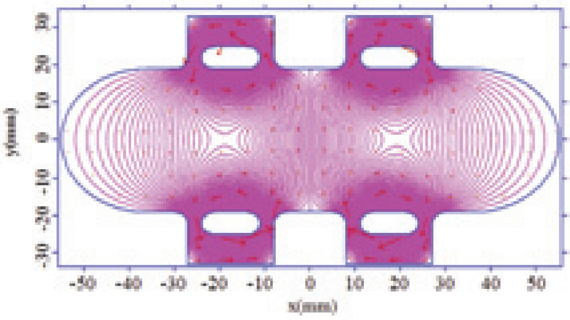

Fig. 1. Form of RF knockout chamber at UVSOR-II and magnetic field lines (magenta lines).

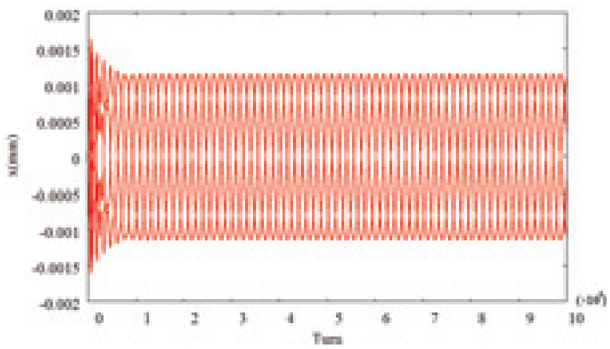

Fig. 2. Simulated horizontal beam position from center of BPM chamber every turn.

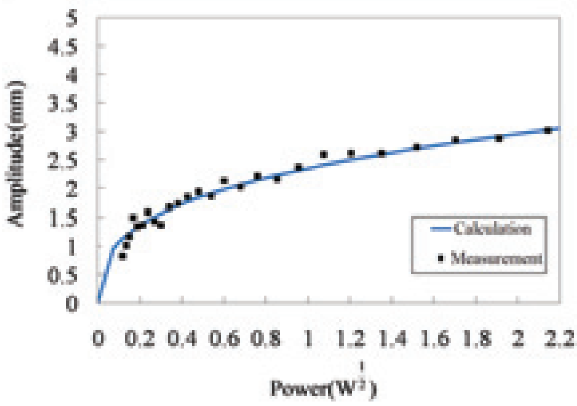

Fig. 3. Measured and calculated horizontal betatron oscillation amplitude to power.

Distribution of Injection Signal for Synchrotron Radiation Beam Lines

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At UVSOR, so-called top-up operation was started in October 2008 [1]. The status of top-up operation at UVSOR is described elsewhere in this report. The test top-up operation has been held every Thursday night. It was revealed that user experiments were affected by beam injection at some beamlines. Especially, the effect was critical at BL6B, with FT-IR spectrometers.

Currently, the injection bump orbit is not closed in normal injection condition, because of the insufficiency of the current sources for the bump magnets. As consequence of bump leakage, large transverse oscillation of the beam occurs at all position of the storage ring.

Sufficient suppression of the oscillation is costly and need time. So we decided to distribute the signals that indicate whether beam injection is under way or not. Beamline users can neglect or stop acquiring data so as to get rid of the effect of beam injection. The signal is simple DC high/low (5V/0V) voltage, generated at the injection control system and distributed through a distribution board. The board is shown in Fig. 1.

At present, beam injection is held every minute, being continued at 1Hz until the beam current exceed the desired beam current, usually 300 mA for multi-bunch mode. We prepared for three types of signals: “short”, “long” and “long with prior notice”. They are described in Fig. 2. The “long” signal includes the whole period including all injection shots. The “Long with prior notice” signal is similar to “long” signal, but it goes high (+5V) several seconds before injection starts. On the other hand, the “short” signal rise up and go down at every shot, with controllable width.

The first application of the injection signal was done at BL3U [2]. The result is shown in Fig. 3. The spectrum has some spike without utilizing signals. The spikes on the spectrum disappear employing the “long” signal, stopping the data acquisition while beam injection is under way.

We have distributed the beam injection signal to desired beamlines. At BL6B, one of the FT-IR spectrometers has upgraded to utilize the beam injection signal [3]. The top-up operation is going to be the standard operation mode at UVSOR in FY2010.

[1] K Hayashi *et al.*, UVSOR Activity Report 2008 (2009) 35.
[2] M. Nagasaka, private communication.
[3] S. Kimura, private communication.

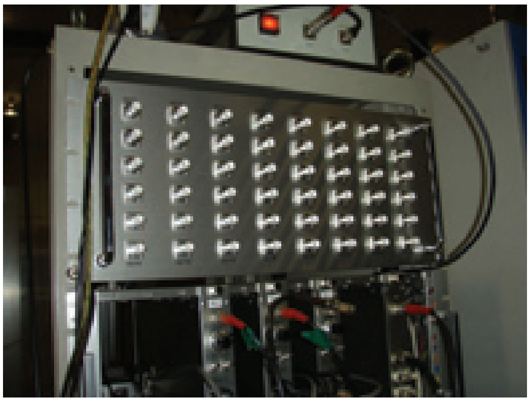

Fig. 1. Distribution board for injection signal.

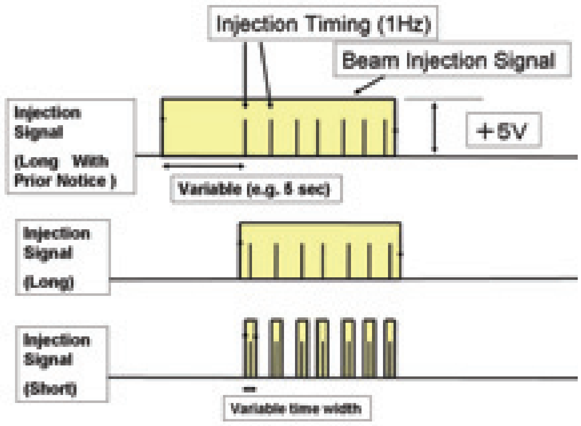

Fig. 2. Scheme of beam injection signals.

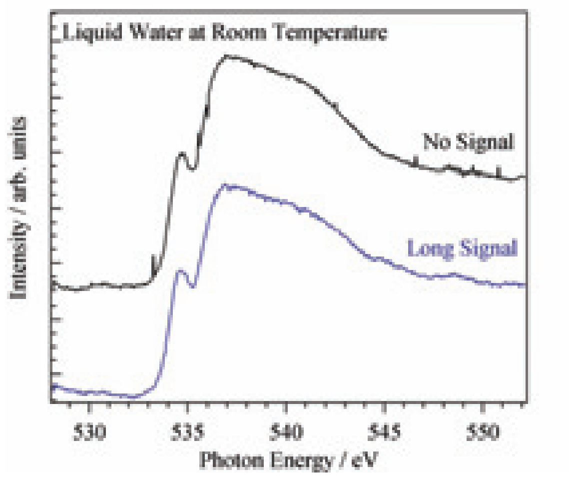

Fig. 3. Result of first application of beam injection signal (O K-edge X-ray absorption spectrum for liquid water).

Development of Turn-by-Turn BPM System at UVSOR-II

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Abstract

Recently, top up operation that keeps beam current constant began in the UVSOR storage ring. This operation temporally affects the beam orbit during beam injection. Therefore, a system that can measure the temporal orbit change was required to improve the operation. We have developed a TBT (Turn By Turn) BPM system and succeeded in measuring a bump orbit of a stored beam and an injection beam orbit by using this system for the first time at UVSOR-II.

TBT BPM system

The TBT BPM system consists of a high sampling rate digital oscilloscope (5 GHz/s), a high frequency amplifier and a waveform processing circuit between a BPM electrode and the oscilloscope. The direct signal from the electrode was found to be too fast to measure the signal peak voltage precisely under a limited sampling rate of the oscilloscope. Therefore we have developed a simple waveform processing circuit to make the pulse duration longer and broaden the signal peak. The diagram is shown in Fig. 1. We estimated the relative accuracy of the system via a repetitive measurement of a stable stored beam orbit. Figure 2 shows histograms of distribution of measured deviation from the averaged beam position. Standard deviations of 10 μm in horizontal and 50 μm in vertical have been obtained.

Measurements

We measured a bump orbit of the stored beam and an injection beam orbit using the TBT system. For the measurement, we used B1U BPM and set the oscilloscope low pass filter at 200 MHz.

Figure 3 shows the horizontal bump orbit measured using the system and a calculated one. The maximum value of the amplitude was 18 mm at the BPM. As shown in the figure, measured orbit agreed very well with the numerical result.

Figure 4 shows an injection beam orbit. The initial amplitude of the betatron oscillation was 20.1 mm. The oscillation was damped with a time scale of milliseconds. A vibration with a periodicity of about 20 kHz is accompanied with it.

Conclusion

We have developed a TBT BPM system which was composed of commercial products like the high frequency amplifier, the wave processing circuit and the digital oscilloscope. We confirmed the performance of this system. The measuring accuracy of tens of microns in both horizontal and vertical direction is sufficient for TBT measurement. A bump orbit of a stored beam and an injected beam orbit were measured for the first time at UVSOR-II and the effectiveness of the system was demonstrated. The TBT system will be used for reducing the injection effect for user experiments.

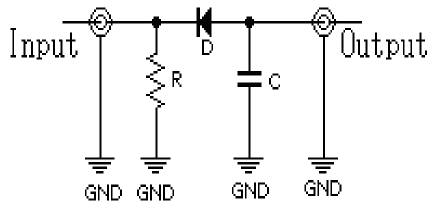

Fig. 1. Diagram of waveform processing circuit.

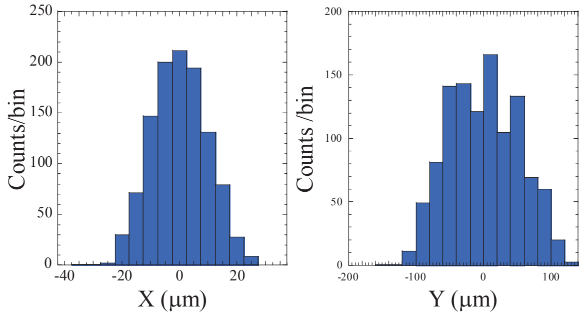

Fig. 2. Accuracy of this system (left shows horizontal right shows vertical).

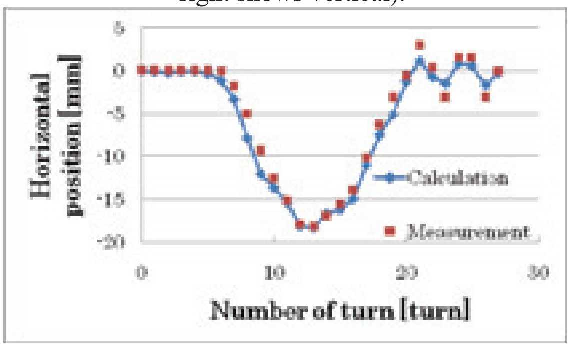

Fig. 3. Measured bump orbit compared with numerical one.

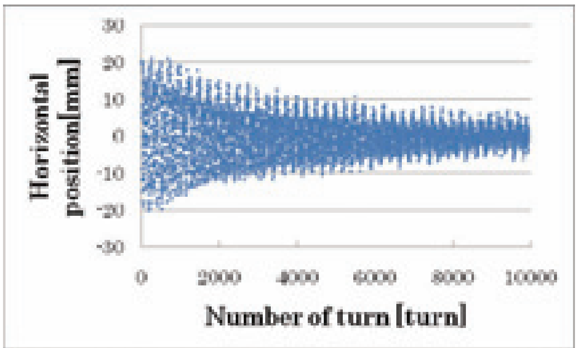

Fig. 4. Injection beam orbit measured by TBT system.

Stabilization of the Electric Septum of UVSOR-II Injector

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Introduction

Top-up test runs was started in 2008. As the results of the test runs, the stored beam current was kept almost constant at 300 mA (see Fig. 1). The electron beam is injected for about 10 second every one minute with the repetition rate, 1 Hz. As shown in Fig. 1, sometimes stored beam current gets smaller than 300 mA even with top-up injection. The beam current reduction is due to reduction of injected beam charge caused by reduction of accelerated beam charge in the UVSOR-II injector. For keeping the constant beam current, operational condition of the injector should be stabilized. From long operational experience, we have recognized that the voltage fluctuation of the electric septum equipped in the injector is the most significant source of the fluctuation of the accelerated charge. In this fiscal year, we introduced a computer based control system to stabilize the septum voltage.

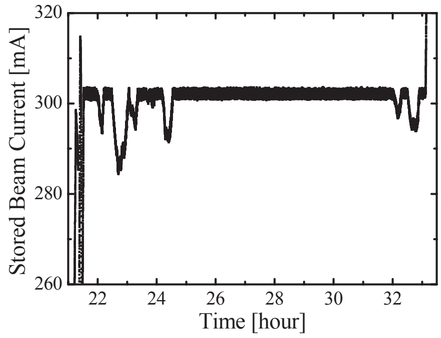

Fig. 1. Time trend of the stored beam current in the UVSOR-II storage ring.

Computer Based Stabilization System

Schematic drawing of the computer based stabilization loop is shown in Fig. 2. The pulsed voltage waveforms of the electric septum are measured by an oscilloscope and the waveform data are sent to the control PC. From the waveform and its time trend, the set value of a high voltage power supply for the septum is determined based on PID

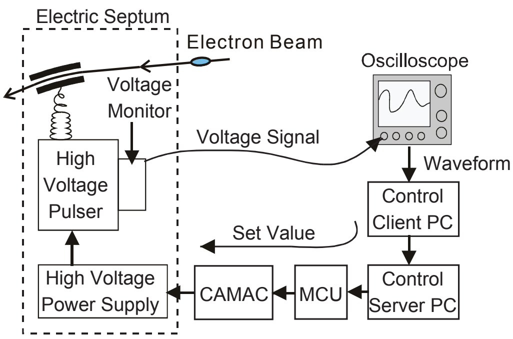

Fig. 2. Schematic drawing of the computer based stabilization loop.

algorithm by a control client PC. The PID determination of the set value is done by a program developed on LabView (shown in Fig. 3). The set value is sent to the power supply via a server PC, multi-control unit (MCU) and CAMAC modules.

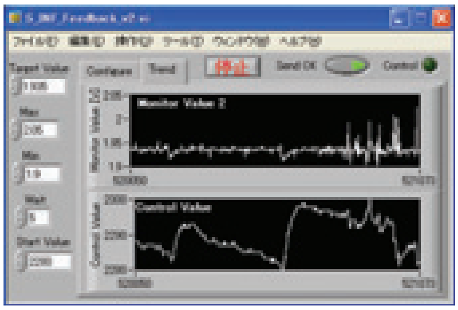

Fig. 3. The program for determining the set value of the electric septum used for the UVSOR-II injector.

Results

Demonstration experiment to check the effect of the developed system was carried out and the result is shown in Fig. 4. With the system, the septum voltage was kept constant and the accelerated charge in the injector is not so much fluctuated. While the stabilization system was turned off, the septum voltage gradually increased and the accelerated charge rapidly decreased. It was found that the stabilization system was really effective to compensate the fluctuation of septum voltage. The stabilization system is now usually used during user operation. And then we found another source of fluctuation, fluctuation of klystron output power which is used for driving a 15 MeV linac in the injector. The klystron fluctuation will be stabilized near future.

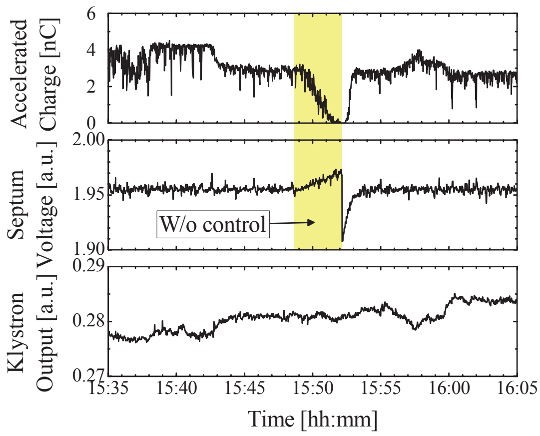

Fig. 4. Time trend of the accelerated charge in the UVSOR-II injector (top), peak voltage of the electric septum (middle) and output power for the accelerator tube (bottom) with and without the stabilization.

Single-Bunch Top-Up Operation and Single-bunch Injection at UVSOR-II

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Introduction

The Single-Bunch (SB) top-up operation is strongly required at UVSOR-II, because of quite short beam lifetime with the operational mode. For the usual SB operation, we used to inject four bunches and undesired three bunches were eliminated by an RF Knock Out (RF-KO) [1]. With that injection scheme, electron loss in the storage ring is large and radiation is high. High radiation environment is not good for top-up operation. The best way to reduce the radiation is inject single electron bunch into the storage ring i.e. no bunch elimination in the storage ring. In fiscal year 2009, we achieved single-bunch injection and single-bunch top-up operation by only modifying electron gun and trigger system for the gun.

Single-Bunch Injection

A schematic drawing of the UVSOR-II injector is shown in the Fig. 1. For multi-bunch injection, electron bunch train with the energy of 15 MeV and the macro-pulse duration of 1.4 μs is generated by the 70 keV DC Gun and Accelerator Tube. A part of bunch train is injected to the booster synchrotron and accelerated up to 750 MeV.

Since the frequency of the acceleration cavity of booster synchrotron is about 90 MHz, i.e. the bucket length is about 11 ns, single-bunch circulation and acceleration in the booster synchrotron could be accomplished if we could generate short pulse train (pulse duration of 5 ns) at the Linac. The DC Gun has already equipped a grid-pulser for short pulse generation. The electron bunch waveform which is generated by the short pulse grid pulser is shown in Fig. 2. We succeeded to generate 5 ns pulse trains.

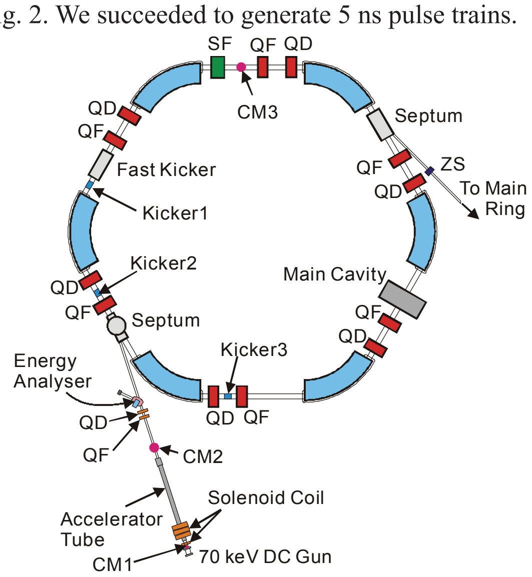

Fig. 1. Schematic drawing of UVSOR-II injector.

For stable injection of the electron to a certain bucket, firing timing of the gun is generated from 90 MHz RF signal and 1 Hz trigger signal. Test injection and purity measurement was done. The result is shown in Fig. 3. It was confirmed that the bunch purity more than 500 was achieved by only the single-bunch injection.

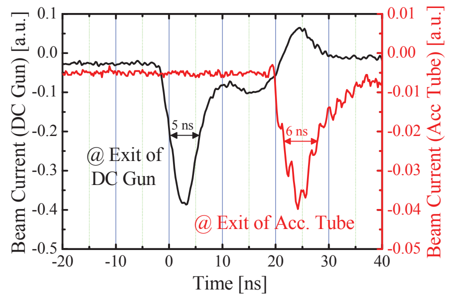

Fig. 2. Short bunch train generated by the Linac.

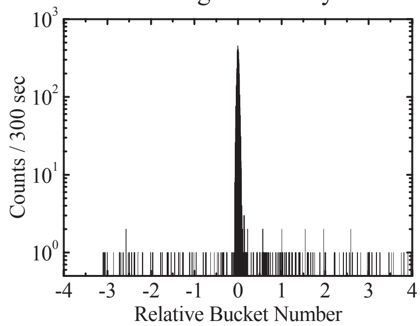

Fig. 3. Result of test injection.

Single-Bunch Top-up Operation

Single-bunch top-up operation was done during single-bunch user operation. The beam current was kept at 53 mA for 12 hours as shown in Fig. 4. Single bunch users were really satisfied with constant and high beam current.

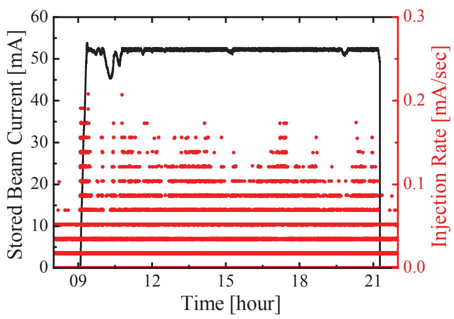

Fig. 4. Time trend of the stored beam current and injection rate during the single-bunch top-up operation in 16 Sep. 2009.

[1] A. Mochihashi *et al.*, UVSOR Activity Report **30** (2003) 39.

Upgrade of the Ti:sapphire Laser System at UVSOR-II

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UVSOR-II is equipped with the Ti:sapphire laser system which delivers intense laser pulses into the storage ring and to beamlines in synchronized with the RF frequency of the ring, and is utilized in user experiments and light source developments such as coherent synchrotron radiation (CSR) in THz region [1,2] and coherent harmonic generation (CHG) in VUV region [3].

CSR and CHG are coherent light sources obtained from the electron bunch at the bending and undulator magnets in the ring. Though the synchrotron radiation, in usual, obtained at the storage ring are incoherent in the wavelength region shorter than the electron bunch length, around 30 mm at UVSOR-II, such coherent radiations are obtained from the electron bunch by using the electron-laser interaction in the magnetic field of the undulator U5. In the previous studies, we have succeeded to generate broadband and monochromatic THz-CSR [1,2] and VUV-CHG [3].

The five-year plan supported by Quantum Beam Technology program of JST and MEXT has been started from FY2008, in which we aim to the user application using these coherent lights. For the user application, we plan to upgrade characteristics of the light sources. One of them is enhancement of the radiation power, which will be accomplished by enhancing the laser energy. We have installed a 10-Hz 50-mJ/pulse laser amplifier at FY2008 and a 1-kHz 10-mJ/pulse laser amplifier at FY2009.

Figure 1 shows a schematic drawing of the laser system. Their specifications are summarized in Table 1. The laser system consists of the oscillator Mira-900/COHERENT, the regenerative amplifier Legend-HE/COHERENT, the multi-pass amplifier Hidra-50/COHERENT, the multi-pass amplifier Legend-Cryo/COHERENT and is equipped with a Michelson interferometer (MIF) which provides envelope modulation with an arbitrary frequency to a uncompressed laser pulse to generate monochromatic CSR [1]. The modulation frequency is changed by an optical delay length of a splitted laser pulse inside the MIF [1], and a pulse compressor which compressed the stretched laser pulse from 130 fs (minimum) to tens of ps. In usual, these intense laser pulses are transported by using several mirrors (laser travels in air). Recently, we have installed an optical fiber which realizes stable transportation of the oscillator laser pulses from oscillator MIRA to the beamlines BL6B and is utilized as the probe pulse in the THz-CSR field measurement experiment [4].

In the near future, we will generate high power CHG and CSR by using these upgraded laser pulses.

Fig. 1. A schematic drawing of the Ti:sapphire laser system.

Table 1. Specifications of the laser system. [5]

	Legend	Hidra	Legend -Cryo
Repetition Rate	1 kHz	10 Hz	1 kHz
Max. Pulse Energy	2.5 mJ	50 mJ	10 mJ
Center Wavelength	800 nm	800 nm	800 nm
Min. Pulse Duration	130 fs	130 fs	130 fs

[1] S. Bielawski *et al.*, Nature Physics **4** (2009) 390.
[2] M. Shimada *et al.*, Jpn. J. Appl. Phys. **46** (2007) 7939.
[3] T. Tanikawa *et al.*, in this report.
[4] I. Katayama *et al.*, in this report.
[5] http://www.coherent.co.jp

Feasibility Study of Ultra-Short Gamma Ray Pulse Generation by Laser Compton Scattering in an Electron Storage Ring

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The collision of laser photons with free relativistic electrons results in laser Compton scattered (LCS [1]) gamma rays. The scattered gamma rays are intense, quasi-monochromatic, tunable in energy, narrow in angular spread, and highly polarized. They are useful for applications such as nuclear physics, generation of polarized positrons, nondestructive inspection, and electron beam diagnosis. We aim to generate ultra-short gamma ray pulses with sub-picosecond width through laser Compton scattering technology, and explore the applications. The size of an electron bunch circulating in a storage ring is a few centimeters in the longitudinal direction, a few hundreds of microns in the horizontal direction, and a few tens of microns in the vertical direction. Therefore, the ultra-short gamma ray pulses may be generated by injecting femtosecond laser pulses from the perpendicular direction into the electron beams, because the interaction time between the electron beams and the laser will be shortened.

We carried out the head-on collision experiment because it was much easier to realize the collision between the laser and the electron bunch. For the 90-degree collision, it is necessary to adjust the timing in the picosecond range. An existing optical port for FEL at was used for the head-on collision experiment. The laser and detector system used in this experiment can be applied to the 90-degree collision experiment. The pulse width, the pulse energy, and frequency of the laser were 55 fs (rms), 2.0 mJ, and 1 kHz, respectively. The laser was 10 mm in diameter, which made aligning the laser beam and the electron beam easy. The power of the laser at the collision point was estimated at 0.25 W from the attenuation at the mirrors. The LCS gamma rays are detected by a NaI scintillator. In front of the detector, a collimator is placed to restrict the angular acceptance. The collimator is a lead block 10 cm thick with a hole 5 mm in diameter. For energy calibration of the detector, ^{137}Cs and ^{60}Co are used. A gate signal synchronized with the laser injection is sent to the MCA. The noise from bremsstrahlung gamma rays is reduced to 1/20. By adjusting the laser timing, the laser and electron can be collided at an arbitrary place in the straight section. We set the collision point 7.6 m from the detector. The beam current was around 1 mA, much lower than the normal operating condition, to avoid pile-up in the detector. The maximum energy and intensity of the LCS gamma rays under the experimental conditions are 13.1 MeV and 460 photons s^{-1} mA^{-1}, respectively.

Figure 1 shows the measured spectra. We compared the measured and calculated gamma ray spectra. The response of the scintillator detector was calculated by the EGS5 code [2]. Curves in Fig. 1 show the calculated spectra. The measured spectral shapes agree well with the calculation when the intensity of the calculated spectra is multiplied by 0.73, while the spectral shape measured with the collimator does not agree well with the calculation. This disagreement is presumably due to the misalignment of the collimator. If the collimator is assumed to be shifted by 1.7 mm in the horizontal direction, the measured spectrum agrees well with the calculation.

In the near future, we will carry out a 90-degree collision experiment using another view port for vertical injection.

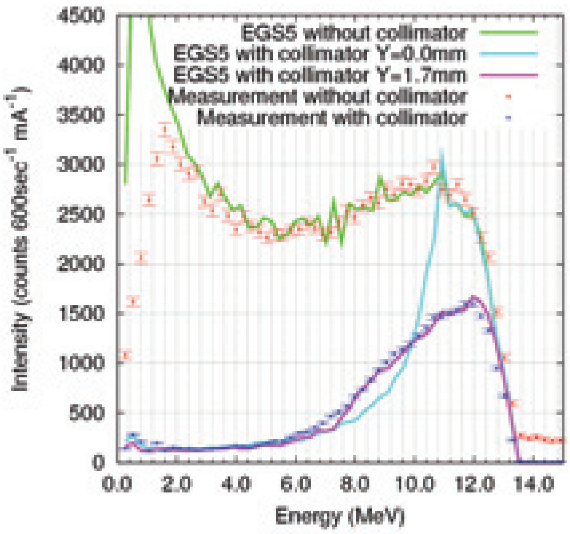

Fig. 1. Measured spectra of the LCS gamma rays. Red points are measured without collimator; blue ones are with collimator. Error bars are 1σ of statistical error.

[1] J. Stepanek, Nucl. Instr. and Meth. A **412** (1998) 174.

[2] H. Hirayama *et al.*, SLAC-R-730 (2005).

Top-Up Operation of the UVSOR-II Free Electron Laser

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Introduction

At the UVSOR-II, a free electron laser (FEL) has been developed. The FEL has various good features such as intense, monochromatic, short pulse duration, variable polarization and wavelength tunability. However, the long term stability of the FEL is really poor because of the time varying nature of stored electron beam current. There are two main effects of the time varying beam current. One is the variation of heat load on the resonator mirror and resulting deformation of the mirror. This effect is quite rapid as shown in Fig. 1. To compensate the deformation, frequent mirror adjustments are required for maintaining the laser power. The other is the variation of the laser gain. As shown in Fig. 2, the laser power gradually decreased as the beam current decreased.

Keeping the stored beam current by top-up operation of the storage ring is a solution for those problems. In this fiscal year, we demonstrated FEL lasing during top-up operation of the storage ring.

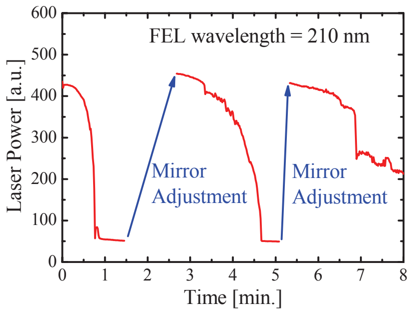

Fig. 1. Laser power decrease due to rapid heat load variation on the resonant cavity.

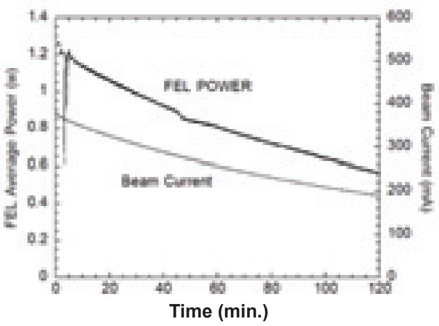

Fig. 2. Laser power decrease due to FEL gain decrease caused by beam current decrease [1].

Demonstration of FEL Top-Up Operation

The FEL lasing during top-up operation was demonstrated. The main operational parameters are listed in Table 1. As the result of top-up operation, we succeeded in keeping the stored beam current and FEL power as shown in Fig. 3. The FEL power was kept around 110 mW more than one and half hour.

During this FEL top-up demonstration, VUV irradiation experiments were carried out by user group of Yokohama National University.

Table 1. Main operational parameters

Electron Beam	Beam Energy	750 MeV
	Beam Current	130 mA/2-bunch
	Emittance	27 nm-rad
	Energy Spread	4.2×10^{-4}
	Bunch Length	108 ps
Optical Klystron	Period Length	110 mm
	Num. of Period	9 + 9
	Num. of Disp.	95
	Polarization	Helical
	Gap	43.9 mm
FEL	Cavity Length	~13.3 m
	Pulse Rate	11.26 MHz
	Wavelength	215 nm

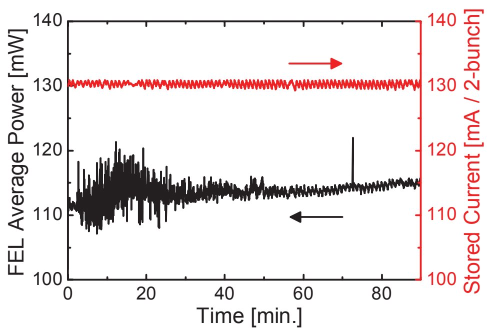

Fig. 3. Time trend of the FEL average power and stored beam current during a FEL top-up operation.

[1] M. Hosaka *et al.*, UVSOR Activity Report **29** (2002) 45.

Coherent Harmonic Generation in VUV Region at UVSOR-II

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Introduction

At the UVSOR-II, electron storage ring, coherent light source developments based on laser seeding techniques are in progress. In the previous results, generation of deep ultra-violet (UV) coherent harmonic (CH) with variable polarization by using a femto-second laser and an optical klystron (OK) has been demonstrated[1, 2].

Based on the successful results, the coherent harmonic generation (CHG) in a shorter wavelength region has been aimed. For the purpose to measure it, a vacuum ultra-violet (VUV) spectrometer has been constructed. In this experiment, the spectra of CH in VUV region have been successfully observed[3].

Design and Construction of VUV Spectral Measurement System

At the UVSOR-II, the spectral measurement of CHG has been performed by utilizing a spectrometer for visible and deep UV light (C5904, Hamamatsu Photonics). In order to measure VUV CH, the new VUV spectral measurement system has been constructed.

Figure 1 illustrates configuration of the new one, which is directly connected to the storage ring at downstream of OK. The VUV spectrometer covers the wavelength range of 50-300 nm limited by a concave replica grating (2400 grooves/mm, Pt coated, 4.5 of F number). It is Seya-Namioka configuration of 64 degree of input-output angle and compatible with an ultra-high vacuum environment. An electron multiplier tube is used as the photo detector, whose wavelength range is below 200 nm.

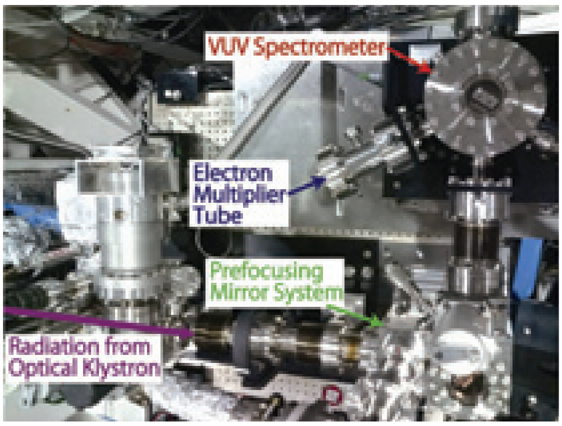

Fig. 1. Photo of VUV spectral measurement system.

Experimental Parameters

Table 1 shows parameters of the electron beam, the OK and Ti: Sapphire laser in this experiment.

Table 1. Experimental parameters.

Electron Beam	Beam Energy	600 MeV
	Beam Current	20 mA/1-bunch
	Emittance	18 nm-rad
	Energy Spread	3.4×10^{-4}
	Bunch Length	114 ps
Optical Klystron	Period Length	110 mm
	Number of Periods	9 + 9
	Number of Dispersion	45
Ti: Sapphire Laser	Central Wavelength	801 nm
	Pulse Energy	2.05 mJ
	Pulse Duration	1.3 ps

Experimental Results

The CHG up to 9th order (89 nm) has been observed. In Fig. 2 the spectrum of the 5th harmonic of SE (Spontaneous Emission) and CH are shown. The data clearly demonstrate a bandwidth of CH becomes much narrower than that of SE.

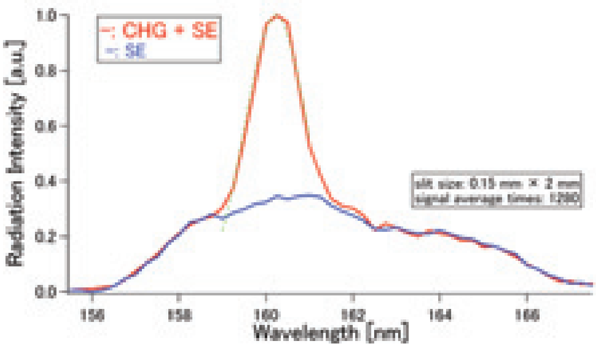

Fig. 2. Spectra of SE (blue line) and CH (red line) at the 5th harmonic.

[1] M. Labat, *et.al.*, The European Physical Journal D, **44**, Number1 (2007) 187-200.
[2] M. Labat, *et.al.,* Proceedings of FEL 08, Korea, 2008.
[3] T. Tanikawa, *et.al.,* Proceedings of FEL 09, England, 2009.

Electric Field Detection of Coherent Synchrotron Radiation

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Coherent terahertz synchrotron radiation (CSR) is a very promising light source for nonlinear terahertz spectroscopy because it may potentially have ultrahigh power and it can be combined with the normal synchrotron radiation. We recently demonstrated generation of CSR by applying the laser bunch slicing technique [1], which is first invented for X-ray generation. However the detection of the electric field of CSR from laser bunch slicing has not been realized until now because the laser and the measurement port are far separated (20 m in the case of UVSOR). In this work, we show that the use of the seed oscillator for probe and 24 m optical fiber for delivering it to the measurement port are useful and robust techniques to observe the electric field of the CSR. These techniques can be applied to the far-infrared spectroscopy using CSR and non-destructive characterization of the electron bunches with longitudinal density modulations [2].

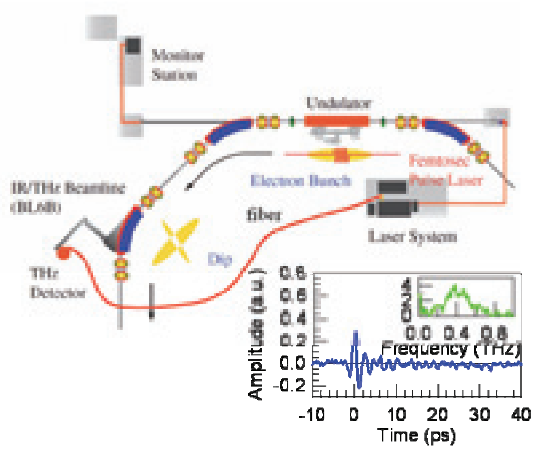

Fig. 1. Experimental setup for the electron bunch slicing. Whole laser setup is synchronized with the RF frequency. We used the seed oscillator for probing the electric field of coherent synchrotron radiation.

Figure 1 shows the setup for the CSR measurement. Probe pulse for terahertz detection is divided from the seed oscillator and is coupled to the large mode-area photonic-crystal optical fiber that delivers the pulses to the detection port. Positive chirping due to the long fiber is compensated by a compressor. The pulse duration after the compressor is about 180 fs. The probe goes through the optical stage with a long delay-line and is focused on the electro-optic crystal (ZnTe). The polarization rotation due to the CSR electric field is detected with electro-optic sampling method.

The rest of the seed oscillator is amplified and is sent to the storage ring. The laser pulse interacts with the electron bunch at the undulator. The spacial and temporal overlaps are confirmed by monitoring the undulator radiation and the laser at the monitor station. As the result of the laser-electron interaction, a part of the electron bunch is strongly energy-modulated and a dip is created on the bunch as it passes through two bending magnets.

The inset of Fig. 1 shows the detected electric field of the CSR waveform. This waveform can be obtained repeatedly, that means the CSR is very stable and is not from the chaotic CSR The oscillation of the terahertz field is detected with the period of 2.5 ps. In the inset of Fig. 1 we also show the Fourier transformation that indicates the peak frequency is about 0.4 THz. This spectrum is in good agreement with the FTFIR measurement of the same radiation at the same port as is reported in the reference [1,3].

In summary, we have demonstrated that the CSR generated with the laser bunch slicing technique has a phase-locked waveform. The use of the electro-optic sampling method and the 24 m long fiber enables us to realize a robust technique for electric field detection even if the distance between the laser and the detection port is far. The use of seed oscillator for probe also has strong advantage since we can choose the nearest pulse to the CSR for detection within the 11 ns range (90 MHz). Therefore, the technique we used in this study is promising for detecting the electric field of novel coherent synchrotron radiations.

[1] M. Shimada *et al.,* Jpn. J. Appl. Phys. **46** (2007) 7939-7944.
[2] S. Bielawski *et al.,* Nat. Phys. **4** (2008) 390-393.
[3] M. Shimada *et al.*, Phys. Rev. Lett. **103** (2009) 144802.