Development of Pulse Duration Measurement System for Coherent Harmonic Generation Experiments

H. Zen[1], M. Adachi[2,3], S. Tanaka[2] and M. Katoh[2,3]
[1]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*
[2]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585, Japan*
[3]*The Graduate University for Advanced Studies (SOKENDAI), Okazaki 444-8585, Japan*

The Coherent Harmonic Generation (CHG) from relativistic electron beam through the interaction with high power laser is promising way to generate short pulse EUV coherent radiation [1]. However, saturation limits the number of photon in a pulse [2]. In conventional laser, Chirped Pulse Amplification (CPA) technique is commonly used to avoid damage or saturation and to obtain high power laser beam. We proposed utilization of CPA to CHG technique to overcome the saturation problem [3].

We are planning to make proof of principle experiment at the wavelength of 266 nm which corresponds to the 3rd harmonics of Ti-sapphire laser. For the experiment, we need a pulse duration measurement system and an UV pulse compressor.

In this fiscal year, we have designed and developed the pulse duration measurement system. We selected an optical cross correlation as the way to measure the UV pulse duration, since 150-fs Ti-sapphire laser is available in UVSOR for the pump beam of cross correlation. Figure 1 shows the schematic diagram of pulse duration measurement system. Fundamental of Ti-sapphire laser (800 nm) and 266-nm radiation from CHG is focused together to BBO crystal which is optimized for Difference Frequency Generation (DFG). Then, 400-nm radiation is generated from DFG crystal when the fundamental and CHG radiation enter to the crystal at the same time. By measuring the dependence of the 400-nm radiation intensity on the time delay between the two pulses, we can measure the temporal profile of UV light. Figure 2 shows the photo of the developed pulse duration measurement system.

To check the properties of developed system, we generated UV laser beam from 800-nm laser beam (150 fs-FWHM) and 3rd harmonic generation crystals. Figure 3 shows the result of cross correlation measurement of the UV laser beam. The measured pulse duration was 0.8 ps in FWHM. This value is much longer than the expected pulse duration of UV laser beam (around 150 fs). Since we used DFG crystal of 2-mm thickness in this experiment to obtain larger signal, group velocity mismatch of 800-nm and 266-nm light in the crystal causes 0.75-ps slip of those pulses. Therefore, the measured result (0.8 ps, FWHM) indicates the temporal resolution of the developed system. This value is acceptable for the proof of principle experiment, because we will generate 10-100 ps UV radiation and compress it to 1 ps or shorter. Moreover, we are now planning to install thinner crystal (1 mm, 0.5 mm) to obtain better temporal resolution.

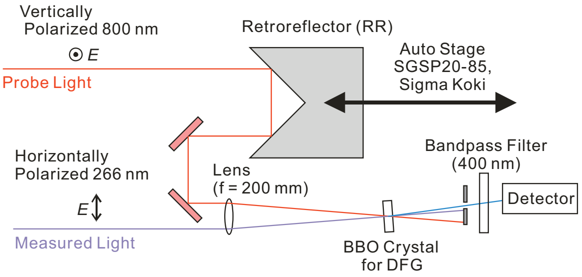

Fig. 1. Schematic drawing of pulse duration measurement system.

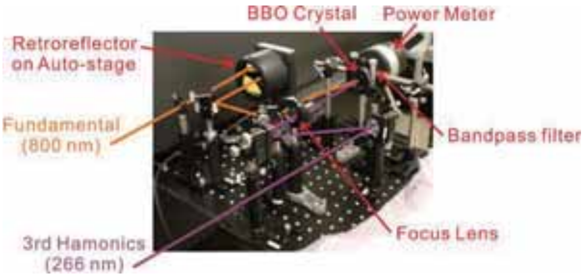

Fig. 2. Photo of the developed pulse duration measurement system.

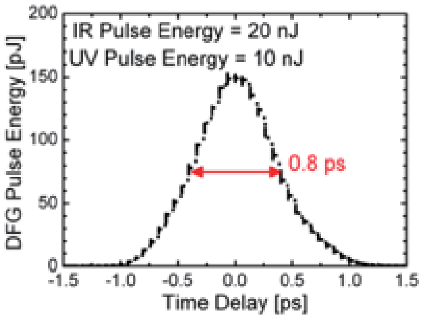

Fig. 3. Result of cross correlation measurement.

[1] R. Prazeres *et al.*, Nucl. Inst. Meth. A **304** (1991)72.
[2] T. Tanikawa *et al.*, Appl. Phys. Exp. **3** (2010) 2702.
[3] H. Zen *et al.*, Proc. of FEL2011 (2012) 366.

Development of an Electron Beam Bunch Length Measurement System for the Transmission-type Polarized Electron Source

N. Yamamoto [1], T. Niwa [2] , T. Inagaki [2], M. Hosaka [1], A. Mano [1], Y. Takashima [2,1] ,
T. Konomi [3], M. Adachi [3], M. Katoh [3,1], K. Sakaue [4] and T. Takatomi [5]
[1] Nagoya University Synchrotron Radiation Research Center, Nagoya, Aichi, 464-8603
[2] Graduate School of Engineering, Nagoya University, Nagoya, Aichi, 464-8603
[3] UVSOR Facility, Institute for Molecular Science (IMS), Okazaki, Aichi, 444-8585
[4] Research Institute for Science and Engineering, Waseda University (RISE), Tokyo, 169-8555
[5] High Energy Accelerator Research Organization (KEK), Ibaraki, 305-0801

Spin polarized electron sources are expected as electron sources for next high energy accelerators, such as the International Linear Accelerator (ILC). In the development of the transmission-type spin polarized electron sources, the electron spin polarization of ~90 % and he high beam brightness of ~2 × 10^7 A.cm^{-2}.sr^{-1} were already achieved at Nagoya University [1, 2].

For the next step of the development, the time response of the transmission-type photocathode has to be characterized. Then we designed and manufactured an electron beam bunch length measurement system using a radio frequency (rf) deflecting cavity [3].

The system consisted of a laser injection system using a mode-locked Ti:Sapphire laser, an rf deflecting cavity and a beam profile monitor. The system was modified for 20-keV electron beams, which corresponds to the Lorentz factor β of 0.272. At low energy, the difference between velocities of rf waves and electron beams is important for designing the cavity structure. Concerning beam dynamics, stretching of bunch length due to space charge effect is also non - negligible.

Parameters of the deflecting cavity are shown in Table 1. The deflecting cavity is made of Oxygen-Free Copper and has one cell rectangular structure with six frequency tuners. Electron beams are deflected by magnetic field of TM120 mode in deflecting cavity. The resonance frequency is 2612.9 MHz that is 29 times of beam reputations (90.1 MHz). The longitudinal length was chosen to be 46.81 mm with consideration for beam deflecting efficiency. The deflecting efficiency is maximized when the longitudinal length is equal to the product of the rf half-wavelength and the Lorentz factor β.

Most of cavity designs are made by analytical calculation from Maxwell equations and a 3-D simulation cord ANSYS HFSS are also used for designs of rf input and monitor ports.

The fabrication and assembling of the cavity was made at Equipment Development Center of IMS and Mechanical Engineering Center of KEK. After them, a set of rf measurements was performed with an Agilent N5230A Network Analyzer. The frequency tuning range is 2.9 MHz from 2611.2 to 2614.1 MHz. The loaded and unloaded quality factors are 10,155 and 20,565 respectively and in good agreement with the calculation (only just 4% below). The gradient of magnetic field along with longitudinal direction was also measured by the bead-pull method and confirmed by the HFSS simulation.

The deflecting cavity and beam profile monitor were installed in the downstream of the polarized electron gun at UVSOR. The operation test by using 20-keV CW beams was done and it is demonstrated that the performances of the cavity are enough to deflect the 20-keV beams.

We are preparing the picosecond laser injection system for generation of pulsed electron beams. By using this system consisting of grating dispersion compensators and an 30m photonic crystal fiber, the laser pulse duration can be changed in the range of a few to several tens picoseconds.

In near future, the systematic measurements of the temporal response of electron sources are scheduled and the results will be feed backed for the photocathode developments to realize fast temporal response, highly brightness and highly spin polarized simultaneously.

Table 1. Parameters of the RF cavity

Size	
Width	121.01 mm
Height	129.98 mm
Longitudinal length	46.81 mm
Resonance mode	TM120
Resonance frequency	2612.9 MHz
Quality factor (Loaded)	10,155
Quality factor(Unloaded)	20,565
Input coupling factor	1.02
Magnetic field at 1 W	1.57 G (Max.)

[1] N. Yamamoto, T. Nakanishi *et al.*, J. Appl. Phys. **103** (2008) 064905.

[2] X.G. Jin, N. Yamamoto *et al.*, Appl. Phys. Ex. **1** (2008) 045002.

[3] T. Niwa, N. Yamamoto *et al.*, Proc. of the 9th Annual Meeting of PASJ, pp. (2012) 1100.

Pulsed Sextupole Injection in UVSOR-III

Y. Hida[1], H. Zen[2], T. Konomi[3,4], N. Yamamoto[5], M. Adachi[3,4], M. Hosaka[5], K. Hayashi[3],
J. Yamazaki[3], Y. Takashima[1] and M. Katoh[3,4]
[1]*Graduate School of Engineering, Nagoya University, Nagoya, Aichi, 464-8603, Japan*
[2]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*
[3]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585, Japan*
[4]*The Graduate University for Advanced Studies (SOKENDAI), Okazaki 444-8585, Japan*
[5]*Nagoya University Synchrotron Radiation Research Center, Nagoya, Aichi, 464-8603, Japan*

Since 2010, the top-up injection of electron beam to storage ring has been started to keep the beam current almost constant during user experiments in UVSOR [1]. For the electron beam injection, we essentially require kicking the electron beam in horizontal direction and the kick induces betatron oscillation of electron beam. This oscillation disturbs user experiments and causes undesired spikes in measured data. To prevent this effect, beamline users are required to stop their measurement for ten seconds during the injection and for five seconds after the injection.

A new injection scheme called as pulsed multipole injection has been developed in KEK [2, 3]. We decided to introduce this scheme with pulsed sextupole magnet (PSM) to UVSOR to increase the efficiency of user experiments. Based on the numerical experiments, the PSM has been designed as Fig. 1 and fabricated as Fig. 2(a). The magnet was made of 0.2-mm-thick laminated silicon steel sheets to reduce eddy current effects. The coil is formed by a one-turn cupper bar with a diameter of 5 mm. Figure 2(b) shows the photo of PSM after installation to the UVSOR-III storage ring. The main specification of the designed PSM and its power supplies are summarized in Table 1.

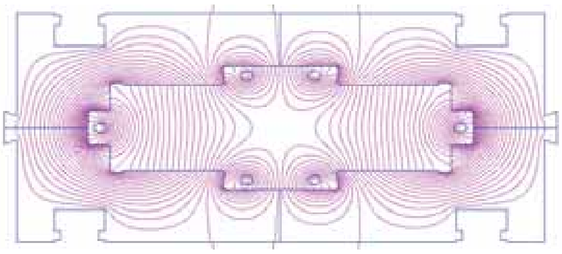

Fig. 1. Geometry of designed sextupole magnet and magnetic flux lines calculated by Poisson.

(a) (b)

Fig. 2. Photo of the manufactured sextupole magnet (a). Photo of the sextupole magnet after installation to the storage ring (b).

Table 1. Specification of the sextupole magnet.

Sextupole Magnet	
Core Length	240 mm
Vertical Gap	45 mm
Horizontal Gap	136 mm
Inductance	2.15 μH
Power Supply	
Peak Excitation Current	2200 A
Pulse Width	1.3 μs

We have performed test experiments of electron beam injection with PSM. After optimization of horizontal and vertical tune of the UVSOR-III storage ring, we achieved maximum injection efficiency of 23% and electron beam injection up to 300 mA in multi-bunch filling (12 bunches in 16 RF buckets). We have already observed the drastic suppression of horizontal electron beam movement with PSM injection.

For further improvement of injection efficiency, the maximum excitation current will be increased and place of PSM will be moved.

[1] H. Zen *et al.*, Proc. of IPAC10 (2010) 2576.
[2] K. Harada *et al.*, Phys. Rev. ST Accel. Beams **10** (2007) 123501.
[3] H. Takagi *et al.*, Phys. Rev. ST Accel. Beams **13** (2010) 020705.

Light Source

Saturation of the Laser-Induced Narrowband Coherent Synchrotron Radiation Process

M. Hosaka[1], N. Yamamoto[1], Y. Takashima[1,2], C. Szwaj[3], M. Le Parquier[3], C. Evain[3],
S. Bielawski[3], M. Adachi[4], H. Zen[4], T. Tanikawa[4], S. Kimura[4], M. Katoh[4], M. Shimada[5]
and T. Takahashi[6]

[1]Nagoya University Synchrotron Radiation Research Center, Nagoya 464-8603, Japan
[2]Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan
[3]Universit´e des Sciences et Technologies de Lille, F-59655 Villeneuve d'Ascq Cedex, France
[4]UVSOR, Institute for Molecular Science, Myodaiji-cho, Okazaki 444-8585, Japan
[5]High Energy Accelerator Research Organization, KEK, Tsukuba, 305-0801, Japan
[6]Research Reactor Institute, Kyoto University, 590-0494, Japan

In a bending magnet, a relativistic electron bunch can radiate narrowband terahertz coherent synchrotron radiation when its longitudinal distribution is sinusoidally modulated. We have already demonstrated this by creating the modulation using interaction between an electron beam and a laser pulse containing a sinusoidal amplitude modulation. We have also demonstrated that the emitted power increases with the beam current and the laser power and the scaling is quadratic. However, when the laser power is arbitrarily increased, a departure to this quadratic increase with laser power is also expected, eventually leading to a decrease of emitted power with laser.

In order to observe the saturation phenomenon in the long pulse regime, we used higher energy pulses (by means of a new amplifier), and realized a pulse-shaper able to provide modulated pulses with adjustable duration and modulation period. The experiment is performed with an electron energy of 600 MeV and a laser pulse modulation period of 2.38 ps (i.e., a terahertz emission spectroscopic wavenumber of 14 cm-1), near the maximum efficiency of the system. In the present conditions, departures from quadratic scaling are typically observed, as is shown in Fig. 1. Near maximum laser pulse duration available from the pulse shaper (191 ps FWHM), only a slight (though noticeable) departure from quadratic scaling is observed [Fig. 1 (b)]. However, when the laser pulses are further compressed [down to 28.5 ps FWHM in Fig. 1(c)], a strong saturation effect is observed, leading to the appearance of a maximum.

In order to analyze the process in detail, we use the theoretical approach introduced in the framework of laser-induced CSR. We have calculated an integrated form factor of the CSR as a function of modulation energy. We have also estimated the modulated energy as a function of laser energy and pulse duration. The calculated result is compared with the experimental one. Although not shown here, the theoretical values of the integrated form factor is consistent with the experiment [2]. Future extensions of this work concern studies of the consequences of this saturation effect in various situations. This may be important in order to compare the ultimate limits due to saturation effects (in particular in THz pulse energy and peak power) due to the saturation effect, in the cases of slicing, and modulated pulse based strategies.

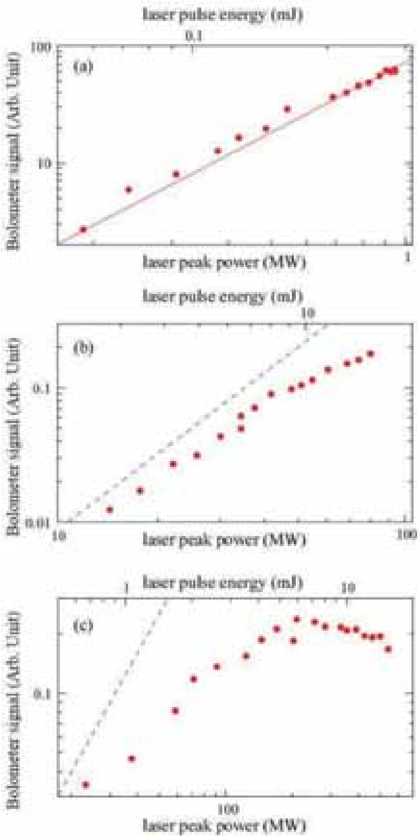

Fig. 1. Typical scalings of terahertz signal versus laser power, for three power ranges. (a): reference quasi-quadratic behavior that was already observed at low power, with a 2 mJ amplifier and 300 ps long pulses.

[1] S. Bielawski, *et al.,* Nature Physics **4** (2008) 390.
[2] M. Hosaka *et al.,* Phys. Rev. ST Accel Beams **16** (2013) 020701.

Light Source

Design and Performance Test of a Buncher Magnet for a New Optical Klystron at UVSOR-III

Y. Uematsu[1], M. Hosaka[2], S. Sekita[1], Y. Asano[1], N. Yamamoto[2]
Y. Takashima[1,2], M. Adachi[3], H. Zen[3], S. Tanaka[3], T. Konomi[3] and M. Katoh[3]
[1]*Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan*
[2]*Nagoya University Synchrotron Radiation Research Center, Nagoya 464-8603, Japan*
[3]*UVSOR, Institute for Molecular Science, Myodaiji-cho, Okazaki 444-8585, Japan*

New coherent sources using a relativistic electron beam are being developed at UVSOR-III storage ring. An optical klystron consists of two undualtors separated by a buncher magnet plays an important role for the sources, especially for the coherent harmonic generation. We adapted apple-II type undulators made of permanent magnets and an electromagnet buncher magnet with 3 poles for the optical klystron. The buncher was designed under the conditions that it should be sufficiently compact to be installed in a limited space between the two undulators (the length along the propagation direction of the electron beam should be less than 400 mm) and the magnetic field is sufficient strong: $R56 > 70$ µm, with vanishing first and second field integrals. Taking into account the cost, we have adapted indirect cooling for the coils and therefore the maximum current density is limited around 4 A/mm. The numerical magnetic field calculation was performed with Radia code [1] and optimization of the magnetic field was carried out. Figure 1 shows 3-D drawings of the buncher created by Radia. The shape of the field poles is specially designed in order to increase magnetic field around the electron beam path. After the designed work, the buncher was fabricated. Magnetic field of the constructed buncher was measured and the result is very consistent with the simulation calculation using Radia [3]. The bucher was installed between the two undulators already installed at UVSOR-III 1S. It can be said that then construction of the optical klystron was finally completed.

The performance test of the buncher was carried by observing spontaneous radiation from the optical klystron. Since the spontaneous spectrum as a result of interference between two undulators, is sensitive to the buncher magnetic field, we can characterize the buncher by analyzing the spontaneous spectra. The experiment was made with the electron energy of 600 MeV and the fundamental wavelength of the undulators of 800 nm. Figure 2 shows examples of measured spectra changing excitation current of the buncher. Calculated spectra using spectra [3] are also plotted in the figure. The agreement between measured and calculated spectra reveals that the performance of the bucher is as designed.

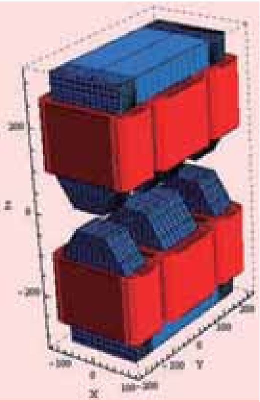

Fig. 1. 3-d drawing of the designed bucher.

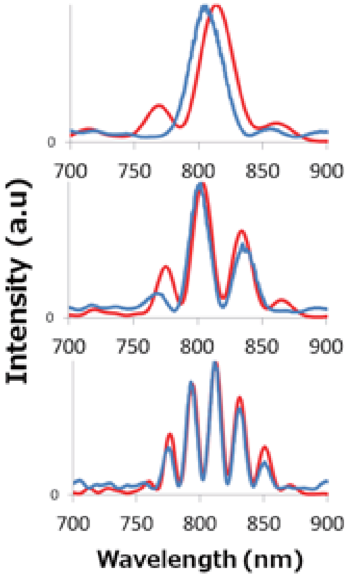

Fig. 2. Measured (blue) and calculated (red) spectra of spontaneous radiation from optical klystron.

Soon we are going to make an experiment on coherent harmonic generation using the optical klystron.

[1] O. Chubar, P. Elleaume, J. Chavanne, J. Synchrotron Rad. **5** (1998) 481.
[2] Y. Uematsu, Master's Thesis, Nagoya University (2013).
[3] T. Tanaka and H. Kitamura, J. Synchrotron Radiant. **8** (2001) 1221.

Combined-Function Bending Magnets for UVSOR-III

K. Hayashi, M. Adachi, T. Konomi, J. Yamazaki and M. Katoh
UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585, Japan

In the first major upgrade, from UVSOR to UVSOR-II, in 2003, most of the storage ring magnets were replaced, but the bending (dipole) magnets were left untouched for later upgrade. In the next major upgrade, to UVSOR-III, in 2012, all eight bending magnets were replaced with newly designed combined-function ones to reduce emittance from 27 to 17 nm-rad.

The parameters of the new and old bending magnets are listed in Table 1. The quadrupole component of the magnetic field is achieved by adjusting the cross-sectional shape of the pole. The sextupole component is generated by adjusting the longitudinal end-shape of the pole. The mass of the new magnets was reduced, but a sufficient good-field region (<0.1%) of ±3 cm was retained.

Table 1. Design parameters of bending magnets.

	New	Old
Bending radius (m)	2.2	2.2
Bending angle	45°	45°
K1 (m^{-1}) (quadrupole)	–1.2	0
K2 (m^{-2}) (sextupole)	–2.43 (×2)	0
Good field region (cm)	±3	±5
Pole width (cm)	14	18
Gap at center (cm)	5.5	4.8
Mass (metric ton)	3.3	4.3
Material	SUY1	S10C

The pole shape is shown in Figs. 1 and 2. To generate the quadrupole defocusing magnetic field as well as the dipole magnetic field, the pole face is taper-shaped. The sextupole magnetic field component is achieved by shaping the end section of the bending magnets like a paraboloid so that the effective magnetic-field length varies according to the horizontal orbit position of the electrons.

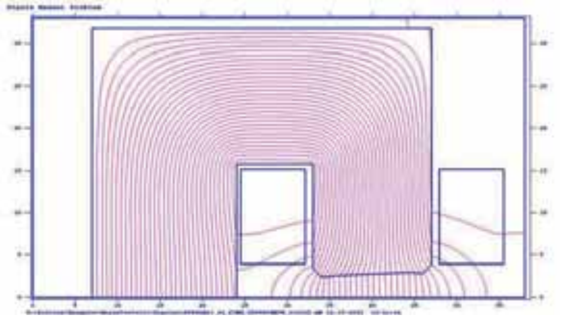

Fig. 1. Cross-sectional view of combined-function bending magnets (upper half is shown).

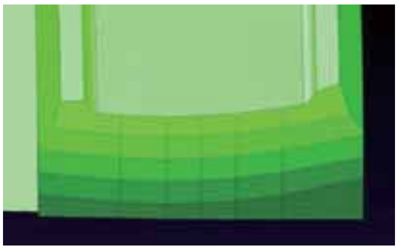

Fig. 2. End-shape of the new bending magnet.

The shape details were investigated by using the 2D calculation code Poisson for cross-sectional shape and the 3D calculation code Opera for longitudinal end-shape. The magnets (Fig. 3) were made by NEC TOKIN Corporation, Japan.

Fig. 3. A new bending magnet (lower half is shown).

The measured magnetic field-strength distribution is shown in Fig. 4. For unknown reasons the quadrupole field strength, which is represented by the gradient of the graph, is about 3% smaller than the design value. The good field region was about ±3 cm. The effective magnetic length was within 1 mm of the design value, 1.728 m.

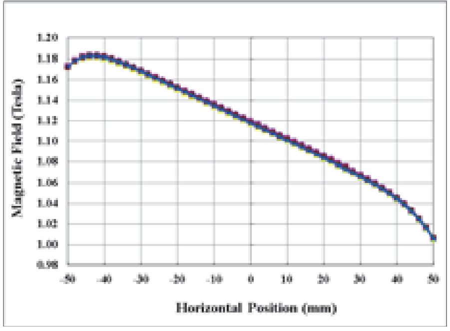

Fig. 4. Horizontal distribution of magnetic field.

The new bending magnets were installed in the UVSOR storage ring in April 2012 and have been operational since August.

We are very grateful to Dr. Y. Shoji of New SUBARU for his kind collaboration.

Turn-By-Turn BPM for UVSOR-III

K. Hayashi[1], T. Toyoda[2], M. Adachi[1], T. Konomi[1], J. Yamazaki[1] and M. Katoh[1]
[1]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585, Japan*
[2]*Instrument Development Center, Institute for Molecular Science, Okazaki 444-8585, Japan*

A major upgrade of the electron storage ring at the UVSOR facility started in April 2012. To help in the commissioning procedure we have developed a turn-by-turn Beam Position Monitor (BPM) system, which consists of a signal-switching circuit, a digital oscilloscope, and software [1].

The UVSOR-III storage ring has 24 BPMs, each of which consists of four button electrodes (Fig. 1). We use a commercial signal-processing system (Bergoz Co.) for regular operation.

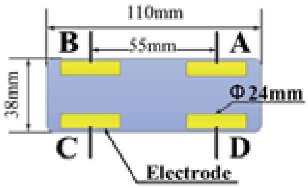

Fig. 1. Layout of BPM electrodes.

At commissioning— especially before the success of the beam storage is confirmed—we need to find out such things as the number of turns the beam has made and where the beam has been lost. Most of these things can be determined by using a turn-by-turn BPM system, but such a system is not necessary for daily operation. We therefore decided to construct a turn-by-turn BPM system, as follows:

- •The system was constructed as cheaply and simply as possible.
- •We used an existing digital oscilloscope for waveform observation and recording.
- •We used existing RF cables that were normally used to connect the BPM heads and the Bergoz signal processing system.
- •We set up the oscilloscope in the ring and controlled it via a LAN.
- •We developed a signal-switching box that could be controlled via the LAN.

Fig. 2 is a block diagram of the system.

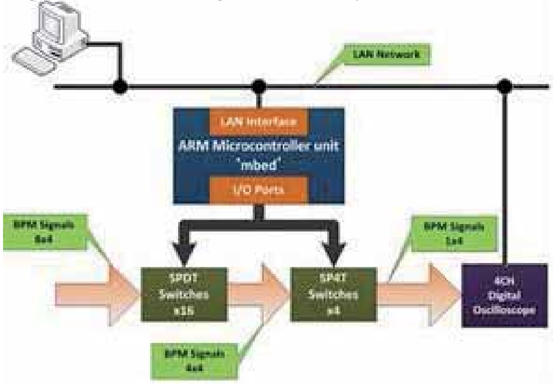

Fig. 2. Block diagram of the BPM system.

The signal-switching box is shown in Fig. 3. Because the BPM signal is a weak (tens of mVs to sub-mV) high-speed pulse (a 100-ps bunch length corresponds to a frequency region of several GHz), we use coaxial switches (Teledyne Coax Switches) to switch signals at low attenuation.

We use a digital oscilloscope (5-GHz sampling frequency, 1-GHz analog signal band) to record four signals from one BPM head; the heads are selected one by one. The data are analyzed off-line.

Fig. 3. BPM switching box.

We control the coaxial switches with an "mbed" microcontroller (NXP Semiconductors), which can be controlled remotely through the LAN. The control application for the BPM system was constructed in HTML (and CSS), which implements a JavaScript library that can handle I/O ports. When we access the mbed from the web browser, the mbed responds as an HTTP server and a control application is displayed in the web browser.

An example of the injection beam trajectory is shown in Fig. 4. By using this system, we have been able to determine not only the orbit but also the betatron tune. At commissioning, the system was very powerful in achieving beam storage.

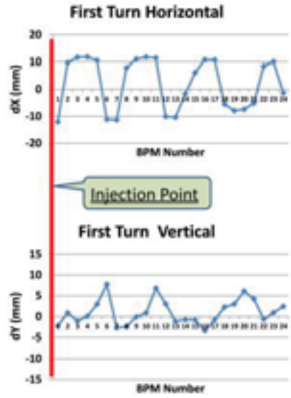

Fig. 4. Example of an injection orbit.

[1] T. Toyoda, K. Hayashi and M. Katoh, Proc. IBIC2012 (2012) MOPA28.