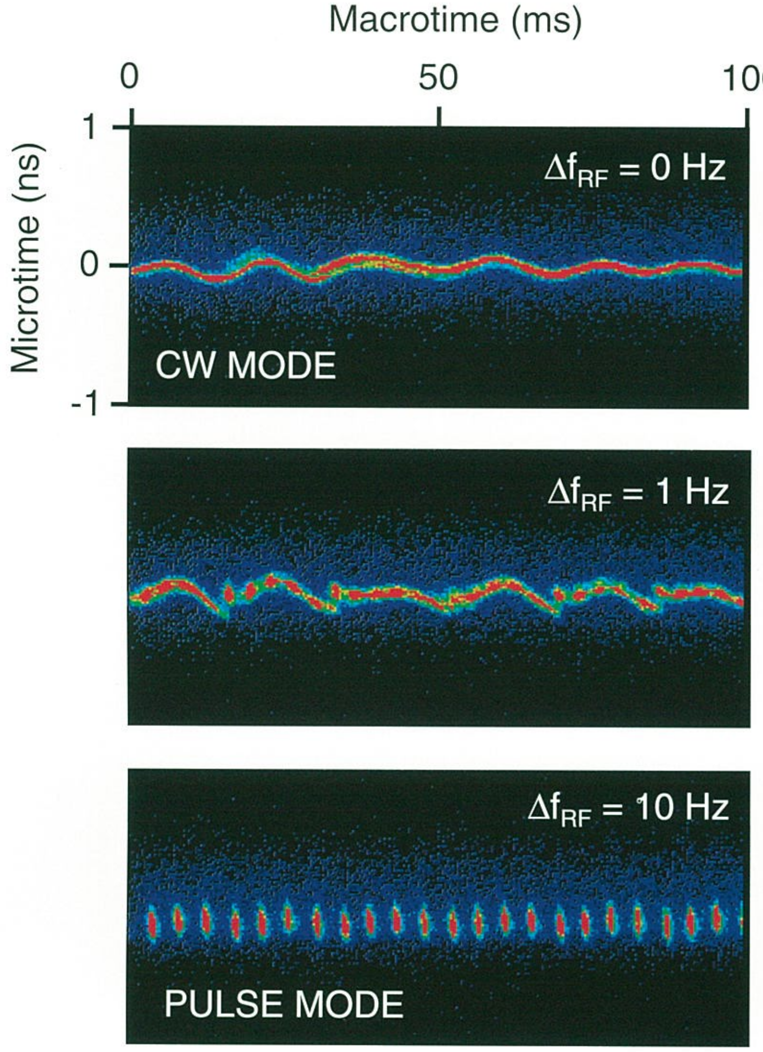

Beam Physics

Development of In-vacuum Undulator for UVSOR

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An upgrade plan is proposed for UVSOR [1]. In this plan, new four straight sections of 1.5 m long will be created. These sections have small vertical betatron function of less than 1m. They are suitable for installing in-vacuum short period undulators [2]. The gap between the magnetic poles can be reduced down to 10 mm without reducing the beam lifetime. To investigate the effects of this type of devices on electron beams and to evaluate the undulator radiation, we have started developing an in-vacuum undulator.

The main parameters of the undulator are shown in Table 1. The minimum gap of the magnetic poles is 10 mm for upgraded lattice. The period length is decided to be 36 mm, which will result in very wide tunability in VUV and soft X-ray region, as shown in Figure 1.

Before the upgrade of the ring, this undulator will be installed in the ring for performance test, at a free space that will be created by removing the super-conducting wiggler. In this case, the minimum gap is limited to be 20 mm because of relatively large betatron function of the present beam optics. As a result, the tunability is limited as shown in Figure 1. However, the fundamental and the third harmonic of the undulator radiation will come to the photon energy range around 100 eV and 300 eV, which are close to L-edge of Si and K-edge of C respectively. After the performance test, some users are planning to use the undulator as a high flux and moderately monochromatic light source.

This fiscal year, only the magnetic pole is being constructed. The remaining parts will be constructed in next fiscal year. The construction of the undulator will be completed in next fiscal year. In March 2002, it will be installed in the ring.

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Table 1. Parameters of In-vacuum Undulator

Magnet type	Pure Permanent (Nd-Fe-B)
Remanent Field	1.17 Tesla
Period Length	36 mm
Number of Period	26
Magnetic Length	936 mm
Overall Length	1.4 m
Minimum Gap	10 mm for low-β optics 20 mm for present optics
Max. K-parameter	2.77 for low-β optics 1.15 for present optics
Polarization	linear (horizontal)

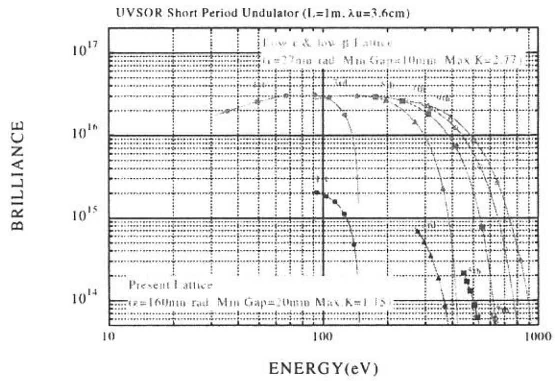

Fig. 1 Brilliance of the in-vacuum undulator for present and upgraded optics, calculated by SPECTRA [3]

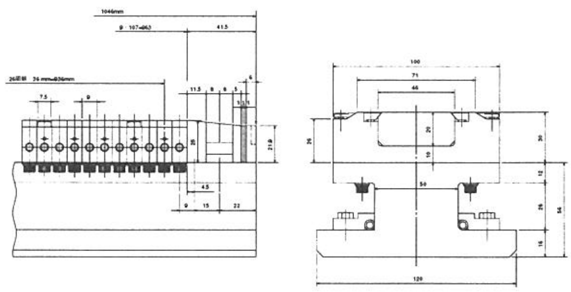

Fig. 2. Magnetic poles of in-vacuum undulator (under construction by Sumitomo Special Metals Co. Ltd.)

An Upgrade Plan for UVSOR

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1. Introduction

In these years, some of the second-generation synchrotron light sources has been or will be upgraded to compete with the third generation light sources [1, 2]. As stimulated by these works, we have started a design study on upgrading UVSOR. The goal is to realize (1) smaller emittance, (2) more straight sections for insertion devices with much smaller budget than that to construct a new ring.

2. Magnetic Lattice

The basic structure of the UVSOR magnetic lattice is double-bend achromat, which has totally eight straight sections between the bending magnets. However, four short straight sections are occupied by quadrupoles and sextupoles, as shown in Fig. 1. We have designed a new lattice, in which, the original DBA cells are modified as shown in Fig. 1. New four free space of 1.5 m are created at the short straight sections. There is no change on the bending magnets. All the quadrupole and sextupole magnets are replaced with combined function type magnets which are capable of producing both quadrupole and sextupole fields. The parameters of the new magnets are shown in Table 2.

Optical functions of the present and new lattice are shown in Fig. 2. The beam parameters are summarized in Table 1. A small emittance of 27 nm-rad can be achieved by making horizontal focussing stronger and by distributing the momentum dispersion in all the straight sections. The vertical betatron function is 1.5 m and 0.5 m at the center of the long and short straight sections respectively, which is optimized for installing narrow gap undulators.

Four families of sextupoles are used to compensate the linear chromaticity and to optimize the dynamic aperture. A tracking simulation has proved that the dynamic aperture is sufficiently large for injection and storage, as shown in Fig. 3.

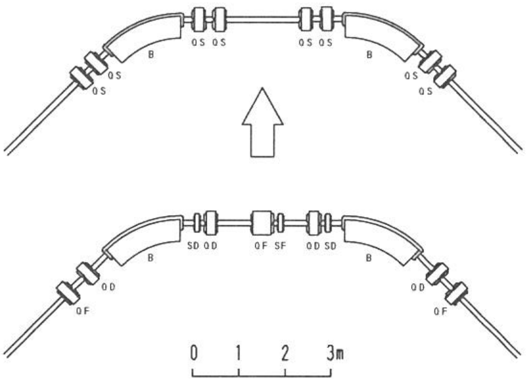

Fig. 1. Lattice modification. The lower is the present configuration and the upper is the upgraded one. One quadrant of the ring is shown. The sextupoles are integrated in the quadrupole magnets in the new lattice.

Table 1. Main Parameters of UVSOR

	Present	Upgraded
Circumference	53.2 m	
Lattice Type	DBA	extended DB(A)
Number of Cells	4	4
Straight Sections	3m x 4	4m x 4, 1.5m x 4
Beam Energy	750 MeV	
Emittance	165 nm-rad	27.4 nm-rad
Energy Spread	4.2×10^{-4}	
Betatron Tunes	(3.16, 1.44)	(3.75, 3.20)
Nat. Chromaticity	(-3.4, -2.5)	(-8.1, -7.3)
XY Coupling	~10%	
Mom. Comp. Factor	0.026	0.028
RF Frequency	90.115 MHz	
Harmonic Number	16	
RF Voltage	46 kV	>80 kV
RF Bucket Height	0.74 %	>1.1 %
Max. Beam Current	250 mA	> 250 mA
Beam Lifetime (200mA)	~6 hr	> 6hr

Table 2. Parameters of focusing magnets

Core Length	0.2 m
Bore Diameter	94 mm
Maximum Quadrupole Field	15 T/m
Maximum Sextupole Field	35 T/m^2

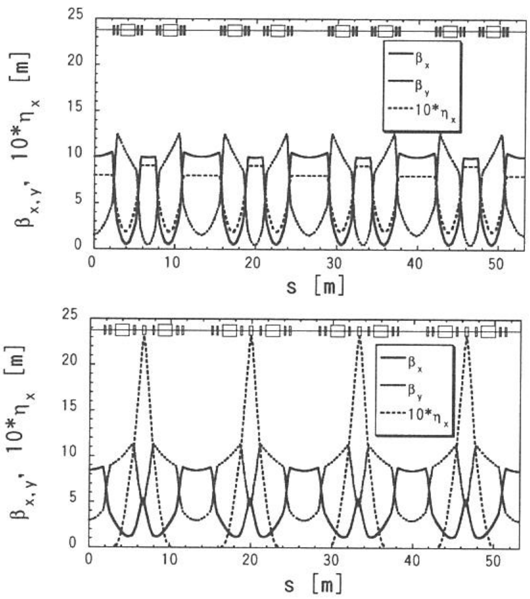

Fig.2. Optical functions of present (lower) and upgraded (upper) lattice.

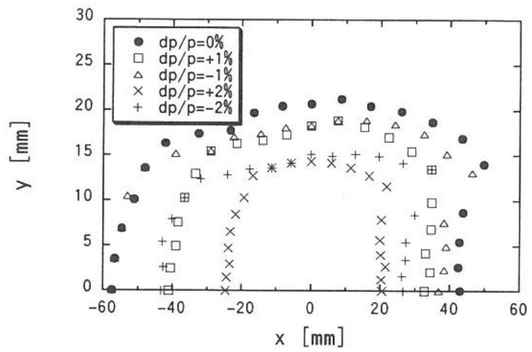

Fig. 3. Dynamic aperture calculated at the center of the long straight section of the new lattice. The results for momentum deviation within 2% are shown. A computer code SAD [3] is used for the simulation.

The reduced emittance will cause strong Touschek effect, which will dominantly limit the beam lifetime. This problem can be solved by increasing the RF accelerating voltage and by utilize the existing third harmonic RF cavity [4] in bunch lengthening mode.

3. Synchrotron Radiation Spectra

On the new lattice, totally six straight sections will be available for insertion devices. The existing undulators will cover the energy range from 10 to 100 eV with higher brilliance by one order of magnitude, as shown in Fig. 4. The small betatron function enables installation of in-vacuum and short period undulators. Their magnetic gap can be as small as 10 mm without reducing the lifetime. They can cover the energy range up to 500 eV and more, as shown in Fig. 4.

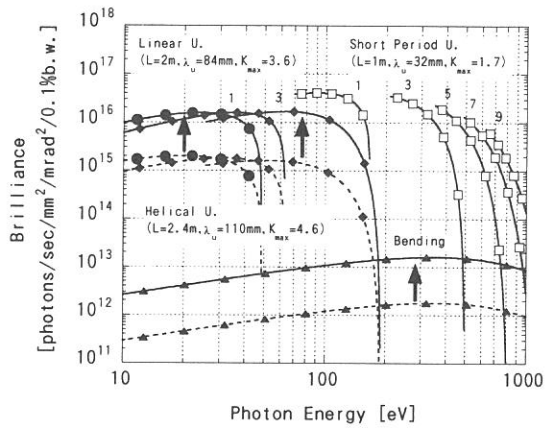

Fig.4. Synchrotron Radiation Spectra from the existing linear (black diamonds), helical (black circles) undulators, the bending magnet (black triangles) and an example of future short period undulator (white squares). The dashed lines are for the present lattice. The increase of the brilliance, as the result of lower emittance, is indicated with arrows. A computer code, SPECTRA [5] is used for the calculation. The beam current is 200 mA and the XY coupling is 10%. The undulator parameters are shown in the figure.

4. Summary

We have designed a new lattice for UVSOR, which has smaller emittance and more straight sections. The emittance will be 27 nm-rad, which is close to those of the third generation light sources. Totally six insertion devices can be installed. The small vertical betatron function at the straight sections enables us to install small gap and short period devices, which will cover much shorter wavelength than the existing undulators.

By introducing the new lattice as well as by replacing old accelerator components, the UVSOR will be converted to a high brilliance synchrotron light source in VUV and soft X rays, which can compete with the third generation light sources in next decade.

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A New Method for Monitoring Bunch Length

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We have developed a new method to measure bunch length by the detection of the synchronous phase shift on the UVSOR storage ring. Conventionally bunch length is measured by using optical methods in which a longitudinal profile of bunch is evaluated from synchrotron radiation. For example, a dual-sweep streak camera can provide a lot of information about electron distribution in a bunch over a wide dynamic range, but it takes at least several minutes to evaluate one numerical result and an instantaneous resolution is limited. In our new method, a longitudinal profile of the bunch is picked up using an electrode and bunch length is obtained through synchronous phase information. Although information available is limited, a continuous observation is possible using the method.

The principle of the methods is based on the bunch length dependence of the loss factor of beam bunch. The loss factor is a parameter used to characterize an energy loss of the electron beam due to the interaction with the vacuum chamber impedance and is defined by

$$k = \frac{\Delta E}{e^2 N_b^2}, \tag{1}$$

where ΔE, e and N_b are the energy loss per tune for an electron bunch, the electron charge and the total number of electron in the bunch, respectively. Assuming that the bunch distribution is Gaussian with RMS bunch length σ_τ, the loss factor can be expressed as

$$k = \frac{\pi I_0^2}{e^2 N_b^2} \int_{-\infty}^{\infty} Z_{res}(\omega) e^{-\omega^2 \sigma_\tau^2} d\omega, \tag{2}$$

where I_0 and $Z_{res}(\omega)$ is the total bunch current and the resistive part of the longitudinal coupling impedance at the frequency of ω. With Eq. (2), one can get for example

$$k \propto \begin{cases} \sigma_\tau^{-1} & \text{for } Z_{res} \text{ is constant} \\ \sigma_\tau^{-2} & \text{for } Z_{res} \propto \omega \end{cases} . \tag{3}$$

Thus the loss factor depends strongly on the bunch length.

In order to obtain a scaling law between the loss factor and the bunch length in the UVSOR storage ring, simultaneous measurements between the loss factor and the bunch length have been performed. In the UVSOR storage ring, the most efficient way to lengthen the electron bunch is by using FEL-induced bunch heating [1]. A visible wavelength of 520 nm for the FEL oscillation was chosen because the FEL gain at the wavelength is rather high, and then the phase shift would be measured over a wide range of the bunch length. Since the energy loss of the electron bunch is compensated by the rf cavity field, the loss factor can be deduced from the synchronous phase shift $\Delta\phi$ as

$$k = \frac{V_{rf} \left| \sin(\phi_{s0} + \Delta\phi) - \sin\phi_{s0} \right|}{e N_b} \tag{4}$$

where ϕ_{s0} corresponds to the synchronous phase for a zero beam current and V_{rf} the peak accelerating voltage in the rf cavity. The setup for the synchronous phase detection is shown in Fig. 1. In order to obtain the beam

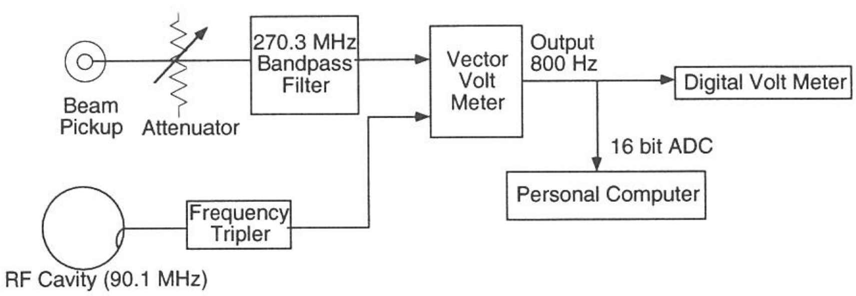

Fig. 1 Setup for the synchronous phase detection.

phase with high resolution, a frequency of 270 MHz which correspond to the 3rd harmonics of the rf frequency has been chosen for the measurement. In the system, the phase information of the bunch can be recorded at a rate of 800 Hz. At the same time, longitudinal bunch profiles have been taken by using a dual-sweep streak camera. The bunch length has been varied up to 400 ps (RMS) with a higher beam current from the natural bunch length of 115 ps.

The loss factors are deduced from the measured phase shift using Eq. (4) and are plotted as a function of the bunch length in Fig. 2. As seen in the figure, the relation between the loss factor and the bunch length does not completely obey the simple scaling law as in the SPEAR storage ring [2]. It is probably due to the resistive-wall impedance, which plays an important role at the low frequency region. Accordingly we introduce offsets for both the bunch length and the loss factor and perform a fitting with these parameters. The result of fitting is shown as a solid line in Fig. 2 and the fit is apparently good. The relation between the loss factor and the bunch length is written using the fitting parameters as

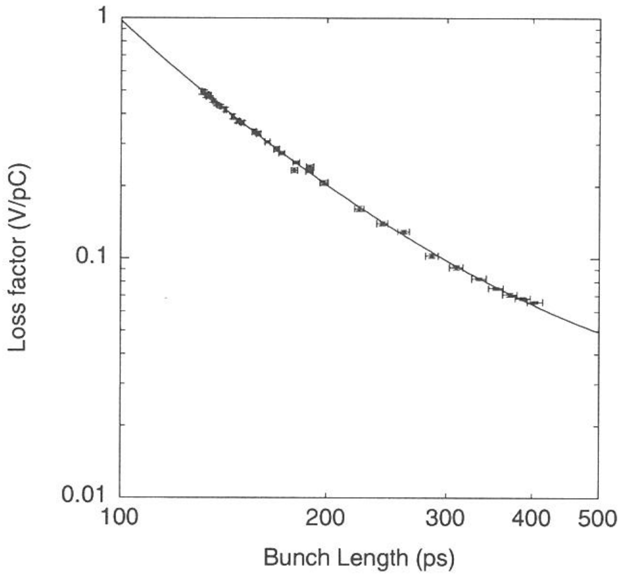

Fig. 2 Dependence of the loss factor on the bunch length. The solid line is the result of the fitting given in Eq. (5).

$$(k-0.0234)=3180(\sigma_\tau-28.9)^{-1.90} \qquad (5)$$

where the loss factor k and the bunch length σ_τ are measured in units of [V/pC] and [ps], respectively. In the UVSOR storage ring the resistive part of the longitudinal coupling impedance is seemed to depends linearly on the frequency (see Eq. (3)). With the scaling low given in Eq. (5), we can deduce the bunch length from the information of the synchronous phase shift. In our present system shown in Fig. 2, we can detect the phase shift at the rate of 800 Hz that is the sampling rate of the vector volt meter used in the system. This allows measuring the variation of bunch length continuously within the rate. The new method for monitoring bunch length has already been used for experiments on the bunch lengthening associated with the FEL power variation [3].

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Study for pump and prove experiment using the UVSOR-FEL

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Storage ring free electron lasers (SRFELs) have potentially advantages for pump and prove (two-color) experiments because of spectral tunability and natural synchronism between synchrotron radiation (SR). However, in a practical operation of the SRFEL extreme stable lasing and higher out-coupled power are crucial for the pump prove experiment. Performance of the UVSOR-FEL has been steadily improved by installation of sturdy cavity-mirror chambers employing simple structure and heavy bases against mechanical vibrations [1], and development of a longitudinal feedback system for stable FEL oscillation [2]. At present, we are planning a pump and prove experiment to investigate dynamics of highly excited state of atomic Xe. A shown in Fig. 1, the target Xe is excited to the $5p^5(^2P1/2)4f'[5/2]_2$ autoionization resonance via the $5p^5(^2P3/2)5d[5/2]_1$ intermediate state by using a sequential two-color photoreaction with SR (119 nm) and the FEL (570 nm). Photoelectron energy spectra emitted from the resonance state will be measured. According to an estimation of the photoelectron rate, an FEL average-power of 50 mW would be at least required.

The first test experiment to provide the FEL and SR into a Xe target chamber was carried out at an SR beam line of BL7B in November 2000. In order to increase the out-coupled power, a multilayer of Ta_5O_2/SiO_2 with large transmission 1100 ppm were used as the optical cavity mirrors. In addition, an FEL transport system to the BL7B was newly developed. A schematic figure is shown in Fig. 2. The transport path-length of the FEL is longer than the SR path-length by just a half circumference of the storage ring to synchronize the FEL with SR.

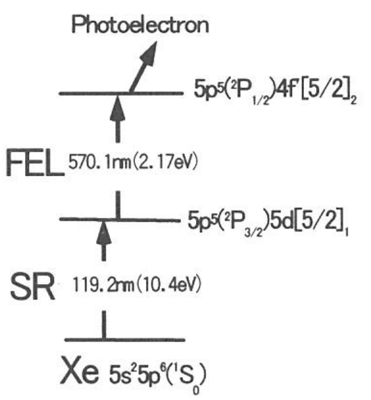

Fig. 1 Energy diagram of the Pump & prove experiment.

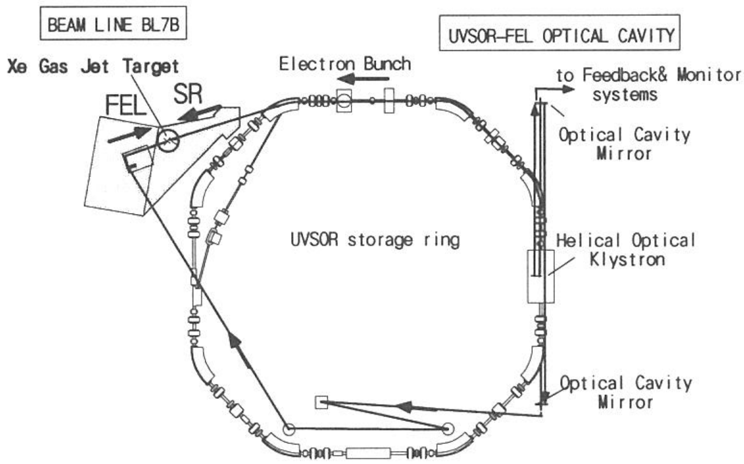

Fig.2 The FEL and SR transport system

Synchronism between the FEL and SR at the Xe target position was roughly measured by a photo diode. A result after a preliminary adjustment of the FEL path-length is shown in Fig. 3. Arrival time of the FEL pulse at the target position was successfully adjusted within an accuracy of 1 ns (in the actual experiment, the path length will be precisely adjusted by detecting of the photoelectron event rate).

The longitudinal feedback system of the UVSOR-FEL detects temporal deviation between an electron bunch and an FEL micropulse by measuring higher harmonics of those signals in the frequency domain, and regulates the accelerating rf frequency of the storage ring to reduce the temporal deviation [2]. The synchronism between the electron bunch and the FEL micropulse is able to be held with high accuracy, and as a result CW lasing is maintained with small power fluctuation for long time. However we have experienced that the FEL power sometimes drops because of a transverse mode change due to probably thermal deformation of the optical cavity. Consequently we has to change manually the transverse axes of the cavity mirrors several times in an hour. In addition, the FEL wavelength drifts slowly (a rate of approximately 0.1 nm/hour), we changes the optical-klystron gap by about 10 μm.

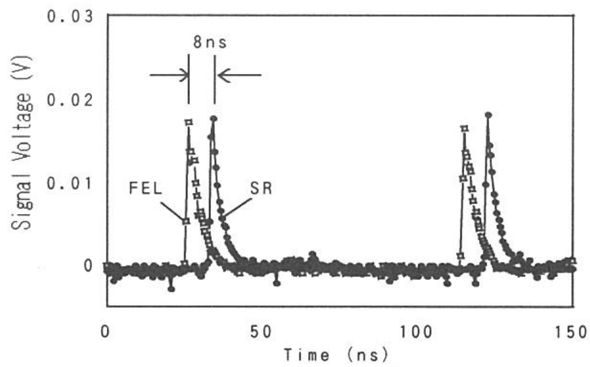

Fig. 3 Measurement of synchronism between SR and the FEL signals by a photodiode whose response time of about 1 ns. The photodiode detected SR and the FEL at a downstream position located 1.2 m from the Xe target position along the SR beam axis. Therefore arrival time of SR and the FEL at the photodiode has to be shifted by 8 ns.

The performance of the UVSOR-FEL is briefed in Table 1. The FEL property attained roughly the required power and the stability. At the moment, the photoelectron from the resonance state was not clearly observed in the experiment because of high background event rate due to SR scattering in the target chamber. The chamber and the detector system are being improved to suppress the background efficiently. On the other hand further developments of the UVSOR-FEL is discussed to reduce the power degradation and the drift of the wavelength.

Table 1 Attained performance of the UVSOR-FEL

Wavelength	570.1 nm
Line width (σ)	0.1 nm
Optical pulse width(σ)	~10 ps
Tunable range	10～20 nm
FEL out-coupled power (100mA/2bunch)	150 mW(=13nJ/pulse)
at BL7B (including transport loss)	100 mW
FEL power fluctuation	～5 %
Time jitter between SR and FEL (σ)	～30 ps (with the feedback)
Repetition rate	11.26 MHz (2 bunch operation)
Electron beam lifetime	100～150 min

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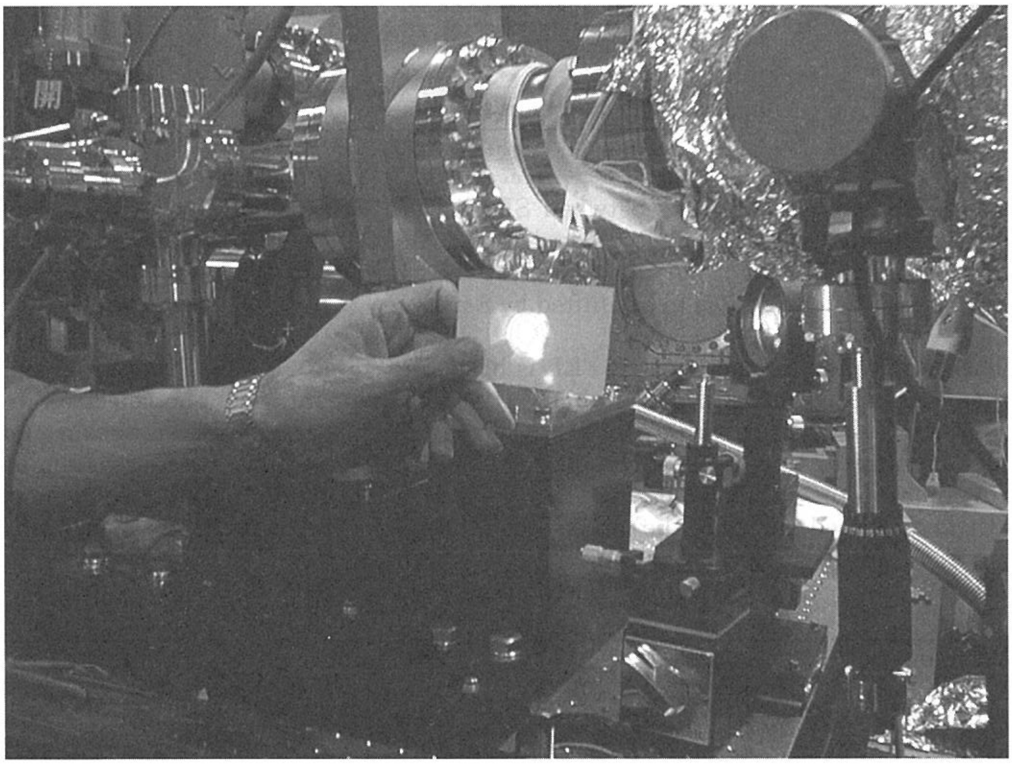
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