Design and Construction of UVSOR-III

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Abstract. A 750 MeV low energy synchrotron light source, UVSOR, has been operational since 1983. To meet the strong demands for brighter light, an upgrade project was performed in 2003, in which the emittance was reduced from 160 nm-rad to 27 nm-rad and four 1.4-m long short straight sections were created. Thereafter, the light source was renamed UVSOR-II. During the ten years after this major upgrade, we have continued upgrading the light source. The top-up injection scheme was introduced and a new 4-m long straight section was created by moving the injection point. In 2012, the bending magnets were replaced with combined function ones to further reduce the emittance. These upgrades resulted in a light source, renamed UVSOR-III, that has an emittance of 17 nm-rad, is equipped with six undulators, and is fully operated in the top-up mode. The commissioning is in progress and user operation will start in August 2012.

1. Introduction
UVSOR is a low energy and compact synchrotron light source. The electron energy produced is 750 MeV and its circumference is 53 m. The first light was generated in 1983. This second generation light source has been operating as one of the major light sources in Japan, providing VUV and soft X-rays to nationwide users. To meet the increasing demands for brighter light, an upgrade project was performed in 2003. By modifying the magnetic lattice, the emittance was reduced from 160 nm-rad to 27 nm-rad and four 1.4-m long short straight sections were created [1, 2]. The upgraded light source was renamed UVSOR-II.

Soon after this first major upgrade, further upgrades were proposed and have been performed. The first one introduced the top-up injection scheme [3]. In this adaptation, the injector and beam transport system were made compatible with full energy injection. In addition, we reinforced the radiation shielding and safety control system. Finally, in 2008, we started the top-up operation. At present, the design and construction of a pulsed sextupole magnet is in progress for realizing a sophisticated injection scheme in which the orbit movement during the injection would be minimized. The details of this operation will be described in a separate paper.

The second stage of the upgrade plan was to move the injection point to obtain a 4-m long straight section. This was performed in 2010. A new optical klystron type undulator was installed in 2011, which would be used for coherent light source developments. The third stage was the replacement of the bending magnets with combined function ones to reduce the emittance to about 17 nm-rad. This was completed in May 2012. The commissioning of the synchrotron is in progress. After successful commissioning, the ring will be renamed UVSOR-III. In this paper, the latter two upgrades toward UVSOR-III are described.
2. Creation of the New Straight Section
The original UVSOR had four 3-m straight sections, whereas UVSOR-II had four 4-m long straight sections and additional four 1.5-m short straight sections. The injection point to the ring was located at one of the 4-m straight sections. Because the septum magnet at the injection point was about 1 m long, there was a dead space that was difficult to use for an insertion device and had been used for testing beam diagnostic devices. By moving the injection point to one of the short straight sections, the 4-m straight section could be fully used for an undulator. In 2010, we added two dipole magnets and two quadrupole magnets in the beam transport line and extended it to a 1.5-m straight section as shown in Fig. 1. In addition, we moved the septum magnet to the new injection point at the straight section.

Figure 1. Creation of a 4-m straight section by moving the injection point. Straight section S1, before (left) and after (right) the reconstruction.

UVSOR has a long history of free electron laser development [4]. It had been conducted by utilizing an undulator normally used for photoemission spectroscopy. We decided to use the new straight section for light source development including a resonator type free electron laser, laser slicing/modulation for coherent terahertz radiation, coherent harmonic generation, and laser Compton scattering [5]. An optical klystron type undulator containing twin helical undulators of APPLE-II type and a buncher magnet in between were constructed and installed. The laser system was reinforced. Two dedicated beamlines were designed and constructed, one to extract coherent terahertz radiation [6] and another to extract free electron laser or coherent harmonic radiation in the range between visible to VUV. After the construction of the new experimental area, the undulator, which had been parasitically used for free electron laser, will be used as an undulator dedicated for the photoemission spectroscopy beamline. At present, the magnetic configuration of the undulator is similar to that of the optical klystron. However, in the near future, it will be modified to that of a normal undulator of variable polarization, which can provide much brighter light to the beamline.

3. Magnetic Lattice of UVSOR-III
The original UVSOR (UVSOR-I) lattice consisted of four double-bend achromat cells. For UVSOR-II, the triplet of the quadrupole magnets between the two dipole magnets were replaced with a pair of doublets, to create a short 1.4-m long straight section. To reduce the emittance, the horizontal betatron phase advance of the cells was increased and, in addition, the dispersion function was distributed to all straight sections. To create as much space for the straight sections as possible, the sextupole field was integrated in the quadrupole magnets [1, 2].

The lattice of UVSOR-III is basically the same as that of UVSOR-II. However, to further reduce the emittance, the dipole magnets were replaced with combined function magnets. They have a taper-shaped pole face to create a horizontal defocusing quadrupole field as well as a dipole field. The lattice
functions and main parameters of UVSOR-I, II, and III are summarized in Fig. 2 and Table 1. The main parameters of the dipole magnets are shown in Table 2. When introducing the combined function magnets, the damping partition numbers are changed and the horizontal emittance is reduced. In addition, the ring can be operated without one family of the defocusing quadrupole magnets. In future, these will be removed when more spaces are required in the ring. After replacing the dipole magnets in the storage ring, there are no magnets remaining that have been in use since the initial light was generated in 1983. We had observed water leakage from a few of those old magnets; therefore, the storage ring operation will be more reliable in the next decade.

![Figure 2. Optics of UVSOR-I, II, and III (from left to right). The betatron functions in the horizontal and vertical plane (solid and dashed line) and the dispersion function (chain line).](image)

**Table 1.** Main parameters of UVSOR-I, II, and III

|                | I          | II         | III        |
|----------------|------------|------------|------------|
| Operation Energy | 750 MeV   | 750 MeV    | 750 MeV    |
| Injection Energy | 600 MeV   | 600 MeV    | 750 MeV    |
| Average Beam Current | ~200 mA (decay) | ~200 mA (decay) | 300 mA (top-up) |
| Circumference   | 53.2 m    | 53.2 m    | 53.2 m    |
| Number of Superperiods | 4        | 4         | 4         |
| Straight Section for I.D. | 3 m × 3  | 4 m × 3, 1.5 m × 2 | 4 m × 4, 1.5 m × 2 |
| Emittance       | 160 nm-rad | 27.4 nm-rad | 16.9 nm-rad |
| Energy Spread   | $4.2 \times 10^{-4}$ | $4.2 \times 10^{-4}$ | $5.4 \times 10^{-4}$ |
| Betatron Tunes  | (3.16, 1.44) | (3.75, 3.20) | (3.60, 3.20) |

**Table 2.** Main parameters of dipole magnets

|                          | New       | Old       |
|--------------------------|-----------|-----------|
| Bending Radius           | 2.2 m     | 2.2 m     |
| Magnetic Length          | 1.728 m   | 1.728 m   |
| Pole Gap at the center   | 55.2 mm   | 48.0 mm   |
| Bending Angle            | 45°       | 45°       |
| Field Index (n)          | 3.36      | 0         |
| Quadrupole field (K1)    | $-1.2$ m$^{-1}$ | 0 m$^{-1}$ |
| Sextupole field (K2)$^*$ | $-2.43 \times 2$ m$^{-1}$ | 0 m$^{-2}$ |

$^*$ The sextupole field was created on the shaped edge of the
4. New In-vacuum Undulator
As a part of the upgrade program, an in-vacuum undulator was installed at a 1.5-m straight section, which is the last section reserved for insertion devices. As a result, UVSOR-III is now equipped with six undulators, of which three are in-vacuum type producing soft X-rays, two are variable polarization type producing VUV, and the last is the optical klystron previously described.

The in-vacuum undulator installed this year has a period length of 38 mm. The mechanical limit of the pole gap is 8 mm; however, in actual operation, it would be around 10 mm. The soft X-rays from this device will be provided to a STXM beamline, which is also in construction as part of the upgrade program.

5. SUMMARY
The upgrade project to UVSOR-III is almost complete and commissioning of the synchrotron is now in progress. The storage of the electron beam was successful. The beam injection efficiency is currently around 50 %, which should be improved to around 80 % as UVSOR-II. The vacuum conditioning and beamline conditioning will be completed in July 2012. The beam lifetime of UVSOR-II was around 3 hours at the beam current of 300 mA. It is expected that the beam lifetime of UVSOR-III will be slightly shorter than that of UVSOR-II due to the stronger Touschek effect. Thus, the top-up operation will be indispensable. UVSOR-III will be available to users in August 2012.

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