RECENT DEVELOPMENT OF PF RING AND PF-AR

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Abstract

Two synchrotron light sources, namely the Photon Factory storage ring (PF-ring) and the Photon Factory Advanced Ring (PF-AR), are operating at the High Energy Accelerator Research Organization (KEK). In 2011, despite severe damage caused by the 3/11 Great East Japan Earthquake, operation of the rings was restored within three months, and some new operation modes were later established. Further improvements at both rings are also planned in the near future.

INTRODUCTION

Two electron storage rings are currently dedicated to Synchrotron Radiation (SR) research at KEK, and have been meeting a wide variety of needs of SR users since the 1980s. Principal parameters of the PF-ring and PF-AR are listed in Table 1. Top-up injection with a pulsed sextuple magnet was established in 2009 at the PF-ring [1], while energy ramp-up after injection is necessary at the PF-AR under the current injector configuration and beam refill is scheduled twice a day.

Table 1: Principal Parameters of PF-ring and PF-AR

	PF-ring	PF-AR
Circumference (m)	187	377
Beam energy (GeV)	2.5	6.5 (inject. 3.0)
Beam current (mA)	450 (top-up)	60 - 40 (decay)
Emittance (nm.rad)	35	293
Beam lifetime (hours)	22	22
Bunches / rf buckets	252/312	1/640 (single-bunch)

On 11 March 2011, the Great East Japan Earthquake severely damaged accelerators and buildings in KEK [2]. Despite the limited supply of electricity, the damaged accelerator components were quickly repaired through joint efforts by KEK staff and cooperating companies. The PF-ring and the PF-AR, as well as the injector linac, were successfully recommissioned in May. After the scheduled shutdown for three months, routine user operation resumed in September.

PF-RING

Operational Status

In 2012, the PF-ring is celebrating its 30th anniversary. Since its commencement, continuous improvements, including several major upgrades, have progressively enhanced the performance of the accelerator, and now the PF-ring provides stable and quality SR for over 3,000 users per year.

Table 2 summarizes the operational statistics of the PF-ring over the past three years. In 2011, the total user time decreased because of the recovery work after the earthquake and the following recommissioning of the machine. About one third of the total failure time was owing to frequent aftershocks and occasional earthquakes. Nevertheless, the mean time between failures (MTBF) remained satisfactorily long.

Table 2: Operational Statistics of PF-ring

Fiscal year	2009	2010	2011
Total operation time (h)	4976	5064	4728
Total user time (h)	3965	4051	2817
Number of failures	24	18	18
Total failure time (h)	42.7	29.2	14.9
Mean time between failures (h)	167.0	226.7	157.3

Developments

Hybrid Mode

The PF-ring had long had two optional modes of operation, i.e., 3-GeV and single-bunch modes. The 3-GeV mode was suspended in 2010, mainly because the majority of our user community preferred the 2.5-GeV top-up operation which had started in the previous year.

In February 2012, the single-bunch mode was replaced by the hybrid mode [3], aiming to satisfy simultaneously both multi-bunch users who need high average flux and single-bunch users who need pulsed high peak intensity. Figure 1 shows the bunch fill pattern in the hybrid mode. The beam consists of a continuous multi-bunch part (3.1 mA/bunch × 130 bunches) and one single-bunch part (50 mA/bunch) in the middle of the 364-ns gap.

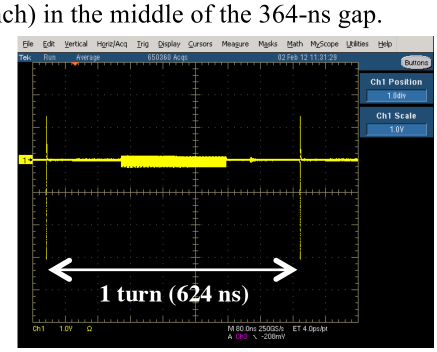

Figure 1: Bunch fill pattern in the hybrid mode.

The hybrid mode was realized by developing a fill pattern control system (combination of bunch current

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measurement and injection bucket selection) and by establishing transverse and longitudinal bunch-by-bunch feedback systems to suppress beam instabilities. Temperatures of high impedance vacuum components, such as ceramic tubes and old types of bellows, were carefully monitored. It was observed that the temperatures were slightly higher than those in the single-bunch mode, but remained within a permissible level. After several preparatory studies, a practical run was conducted for six days in February 2012 without any fundamental problems.

Fast Polarization Switching

The SR beam line BL-16 was specially reconstructed to promote precise measurements of materials that have photon helicity dependence by utilizing a lock-in technique. In order to deliver fast polarization switching SR, installation of two tandem APPLE-II type undulators, ID16-1 and ID16-2, was completed in 2010 in one of the two longest straight-sections (9 m) of the PF-ring.

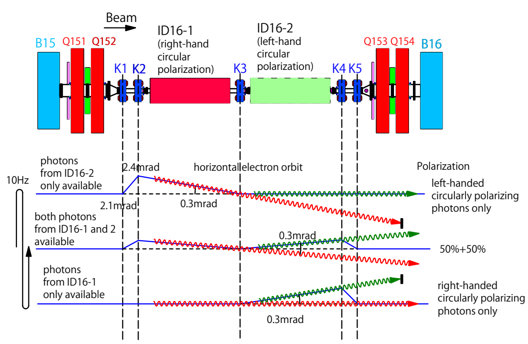

Figure 2: Fast polarization switching mechanism.

The mechanism of the fast polarization switching system [4] is illustrated in Fig. 2. Two undulators are set to radiate SR polarized oppositely to each other, and the horizontal direction of the SR from each undulator is alternately tilted by up to 0.3 mrad, enough to be separated off. This alternating local bump is formed by the five identical kicker magnets K1-K5. Unwanted distortion of the beam orbit in the whole ring is supposed to be suppressed by a feed-forward control system using correction magnets and beam position monitors surrounding the undulators [5, 6].

After several machine developments, a preliminary run with polarization switching at a frequency of 10 Hz was conducted during user time in January 2012. It was confirmed that the horizontal orbit distortion was restrained within 2 μm (less than 1% of the beam size), and no significant influence on SR stability at other beam lines was observed. We expect that fast polarization switching will shortly become available as a regular operation at the PF-ring.

Suppression of Longitudinal Quadrupole Oscillation

The multi-bunch beam of the PF-ring intrinsically has longitudinal coupled-bunch instabilities. The dipole mode of the synchrotron oscillation (center-of-mass oscillation) can be completely suppressed by the bunch-by-bunch feedback system [7]. The quadrupole-mode oscillation (bunch-length oscillation) had been mitigated by prolonging the bunch length intentionally by means of rf phase modulation [8]. This stabilization, however, caused deterioration in brilliance of SR particularly from insertion devices located at energy dispersive points. Therefore, we decided to utilize the longitudinal feedback system instead of the rf phase modulation.

In the post-earthquake run, the quadrupole oscillation disappeared at a regular stored current of 450 mA. This improvement could be attributed to the removal of three sector gate valves that were damaged by the earthquake. These gate valves employed an Ethylene Propylene Diene Monomer (EPDM) rubber seal, which had a high tolerance to radiation but its heat resistance was not high enough (Fig. 3). The insufficient rf shielding presumably made the gate valves act as high impedance sources. The removal of these gate valves also mitigated the beam instabilities in the hybrid mode.

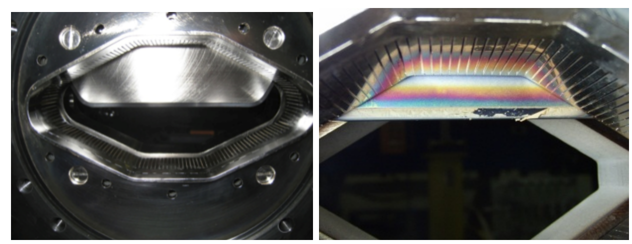

Figure 3: Normal (left) and damaged (right) gate valves.

The quadrupole-mode oscillation, however, still occurred when the current decayed below 320 mA. We found recently that the instability grew in the latter half of the continuous 250 bunches, and experimentally confirmed that decreasing the number of bunches in one batch could improve this problem. Figure 4 shows the improved bunch fill pattern that could suppress the quadrupole-mode oscillation down to 270 mA. One batch of 250 bunches was divided into four batches of 63 bunches each.

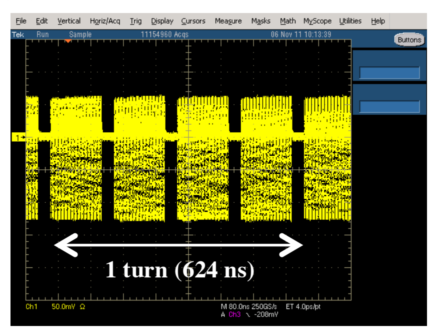

Figure 4: Improved fill pattern in the multi-bunch mode.

Future Plans

In 2013, the in-vacuum undulator SGU15 will be newly installed in the last remaining free straight-section of the PF-ring. The periodic length of the magnet array is 17.6 mm, and the undulator delivers a broad range of hard X-rays by utilizing up to the 9th harmonic of radiation, including even numbered harmonics as well (Fig. 5). Fine structures of spatially inhomogeneous materials, such as industrial materials and biological samples, will be investigated at BL-15.

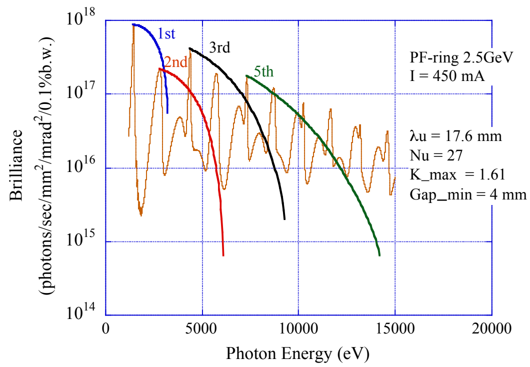

Figure 5: Brilliance spectrum of SGU15.

From 2013 to 2014, three undulators will be upgraded for BL-2, BL-13 and BL-28. These new undulators are to be optimized to enhance photoelectron spectroscopy studies at vacuum ultra-violet and soft X-ray beam lines.

PF-AR

Originally constructed as the TRISNTAN Accumulator Ring (AR) in 1983, the PF-AR became a dedicated light source in 1996 and underwent a major upgrade in 2001. The PF-AR is operating exclusively in a single-bunch mode at 6.5 GeV to deliver pulsed hard X-rays.

Six insertion devices (IDs) including the world's first in-vacuum undulator ID-NE3 are being fully utilized at the PF-AR. Their control systems have been improved in response to users' demands, and now the magnetic array gaps of all the IDs can be changed without disturbing the standard beam orbit.

Operational Status

Table 3 summarizes the operational statistics of the PF-AR over the past three years. Also at the PF-AR, the total user time decreased in 2011 because of the earthquake.

Table 3: Operational Statistics of PF-AR

Fiscal year	2009	2010	2011
Total operation time (h)	5063	4608	4080
Total user time (h)	4301	3958	2865
Number of failures	41	74	50
Total failure time (h)	91.0	73.7	38.9
Mean time between failures (h)	107.1	54.5	58.1

The primary cause of failures (about 30% of the total failure time) in 2011 was related to magnet troubles. The PF-AR has many superannuated components such as magnet power supplies and rf systems, and we have been renewing them step by step. The secondary cause of failures was a sudden decrease in the beam lifetime, which often involved an extra beam refill. This phenomenon is known to be caused by dust particles trapped in the electron beam. Continuous research on dust trapping at the PF-AR [9] has indicated that the PF-AR's beam flux is not intense enough to vaporize some trapped dust particles. The most effective measure to avoid the dust trapping at the PF-AR is to store positron beams.

Future Plans

We are planning to upgrade the beam transport line from the injector linac to the PF-AR. The linac provides electron or positron beams to four storage rings, namely the PF-ring, the PF-AR, and the KEKB LER/HER. Currently, the linac can deliver the beams simultaneously to the PF-ring and the KEKB LER/HER by pulse-by-pulse switching, while the beam injection to the PF-AR is exclusive and takes about 15 minutes. In the KEKB's upcoming SuperKEKB project, estimated beam lifetime is as short as ten minutes, within which the beams will be greatly diminished.

In order to solve this problem, the beam transport line of the PF-AR needs to be upgraded no later than the start of the physics run at the SuperKEKB in 2015. We have already decided to construct a new tunnel for the beam transport line. So far, two candidates have been proposed: 1) The least troublesome way is to inject 4-GeV positron beams, which are the same for the SuperKEKB LER. 2) The most favorable way is to inject 6.5-GeV electron beams, by which top-up injection will be enabled and beam instabilities after injection are expected to be mitigated. The second candidate, however, requires entire rearrangement of the magnets in the transport line and replacement of vacuum chambers for the kicker and septum magnets in the ring.

SUMMARY

Though both the PF-ring and the PF-AR are old machines, we have progressively employed innovative technologies to enhance their performance. For example, top-up injection with a pulsed sextuple magnet was developed at the PF-ring. As recent remarkable achievements, two new operation modes, i.e., hybrid mode and fast polarization switching, were added to the PF-ring's routine operations.

We will continue to work on maintaining stable operation of the machines, which is also important for us to pursue the R&D for the Energy Recovery Linac (ERL)-based future light source at KEK.

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