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Operational Status of PF-Ring and PF-AR after the Earthquake

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Abstract. In 2011, two SR sources of KEK, PF-ring and PF-AR, needed to change the operation schedule because of the unprecedented earthquake on March 11. Though the injector linac and the storage rings suffered a serious damage, temporary recovery was accomplished quickly and the trial operation started in May. The regular user operation could be resumed in October 2011. In the restoration work after the earthquake, some old vacuum components were removed from PF-ring. This work fortunately brought an effect of settling the quadrupole-mode longitudinal instability. For the top-up injection of PF-ring, the pulsed sextupole magnet has been used instead of the conventional kicker magnets since 2011. The hybrid-fill mode in place of the single-bunch mode has become available. Recently, the 10-Hz orbit switching for the tandem circularly polarized undulators has been developed for the user operation.

1. Introduction

KEK manages two synchrotron radiation (SR) sources, namely, Photon Factory storage ring (PF-ring) and Photon Factory advanced ring (PF-AR). Principal parameters of these rings are listed in Table 1.

PF-ring reached the 30th anniversary since it started to serve SR for users in 1982. By the full reconstruction of the normal cell sections in 1997, its emittance was improved to 35 nm•rad. Additional straight sections were created and existing straight sections were largely extended in 2005. In-vacuum short-period undulators to deliver hard X-rays have been developed for the additional straight sections. The renewal of VUV/SX undulators has been promoted by making use of the extended straight sections. Firstly, tandem circularly-polarized undulators were installed in one of the longest straight sections, and fast polarization switching system is being developed.

Based on the multi-energy acceleration scheme, the KEK injector linac (Linac) realized simultaneous injection for PF-ring and the two main rings of KEKB [1]. The full-time top-up injection of PF-ring started in 2009, and a new injection scheme using the pulsed sextupole magnet [2] was put to practical use in 2011.
The notable features of PF-AR are the high critical energy and the full-time single-bunch operation. Additional four beam lines have been built with four in-vacuum undulators in this decade. Some hard X-ray activities have been transferred from PF-ring. Time-resolved X-ray structural analysis is one of the outstanding activities in PF-AR [3].

At the great east Japan earthquake on March 11, 2011, the most serious damage was a fall of quadrupole magnets in Linac. Consequently, some beam ducts were fractured, and most of the 600-m Linac was exposed to the air. At PF-ring, one of the vacuum bellows was broken and half of the ring was exposed to the air. The details on the earthquake damages and the results of the magnet level survey were reported previously [4]. Temporary recovery of the beam duct was accomplished quickly, and trial operation started in the middle of May. The user time scheduled from May to July was cancelled, and was resumed in October 2011.

| 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 (injected at 3) |
| Emittance (nm rad)             | 35      | 293     |
| Beam current (mA)              | 450 (top-up) | 60      |
| Beam lifetime (h)              | 22      | 22      |
| Critical energy (keV)          | 4.0     | 26      |
| No. of insertion devices       | 11 (3 in-vacuum) | 6 (5 in-vacuum) |

2. Operational status after the earthquake
Operational statistics of the fiscal year 2011 are summarized in Table 2 with those of the previous two years. The biggest influence of the great earthquake was that the scheduled user time decreased by about 30% in comparison with the previous year. The failures recorded in the regular user operation slightly increased at PF-ring, but the mean time between failures (MTBF) maintained a good standard of more than 150 hours. The MTBF of PF-AR is inferior to PF-ring. The most frequent failure that accounts for half of all failures is the sudden drop of the beam lifetime attributable to the dust trapping [5].

Even in the latter half of FY2011, from October 2011 to March 2012, frequent aftershocks continued in east Japan. Sometimes the beam was dumped by the quake, and sometimes we stopped the beam operation and made a patrol in the ring tunnel according to the KEK’s safety rule. The number of failures caused by the earthquakes amounted to four or five in FY2011.

Additional troubles thought to be the influence of the earthquakes still continue even in the new fiscal year from April 2012. PF-ring is driven by four RF cavities, and four 250-kW circulators are installed in the waveguide circuits for the RF cavities. Three of four circulators suffered water leak troubles during one year after the earthquake. At the high voltage cabinet of the klystron power supply shown in Figure 1, the ceramic insulators cracked frequently by the aftershocks.
Table 2. Operational statistics of PF-ring and PF-AR

|                      | PF-ring     |           | PF-AR      |           |
|----------------------|-------------|-----------|------------|-----------|
| Fiscal year          | 2009        | 2010      | 2011       | 2009      | 2010      | 2011      |
| Total operation time (h) | 4976        | 5064      | 4728       | 5063      | 4608      | 4080      |
| Scheduled user time (h) | 4008        | 4080      | 2832       | 4392      | 4032      | 2904      |
| Number of failures   | 24          | 18        | 18         | 41        | 74        | 49        |
| Total failure time (h) | 42.7        | 29.2      | 14.9       | 91.0      | 73.7      | 38.9      |
| Mean time between failures (h) | 167.0       | 226.7     | 157.3      | 107.1     | 54.5      | 59.3      |
| Mean down time (h)   | 1.8         | 1.6       | 0.8        | 2.2       | 1.0       | 0.8       |

At PF-ring, the vacuum trouble attributed to the heating-up of the RF shielded gate valves occurred in the trial operation just after the earthquake. The color of the elastomer O-ring and the valve disc were changed due to heating as shown in Figure 2. We removed all of the same-type gate valves from the storage ring during the maintenance period in 2011. After the removal of these gate valves, the quadrupole-mode longitudinal instability became very weak. The insufficient RF shield presumably made them high impedance sources. Now, we can suppress the quadrupole-mode longitudinal instability by controlling the length of the bunch train. It was observed that the coupled instability grew in the latter half of the bunch train. The partial filling pattern made of one batch of 250 bunches is divided into four batches of 63 bunches each. The dipole-mode longitudinal instability can be completely suppressed by the digital feedback system using “integrated General-purpose signal processors (iGp)”. As the quadrupole-mode instability was settled, the effective brightness of SR beams has been stably improved especially from the undulators located at the section that has a finite dispersion function.

3. Recent developments and future plans

3.1. Hybrid filling mode

Presently at PF-ring, it is possible to keep an arbitrary bunch filling pattern using the bunch current control system developed for the top-up operation. From February 2012, the single-bunch mode was replaced by the hybrid mode, aiming to satisfy simultaneously both multi-bunch users and single-bunch users. 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 center of the 364-ns gap. Figure 3 shows a streak camera image of the hybrid fill. Using a timing gate to protect the circuits from an excessive single-bunch signal, the bunch feedback systems well suppressed the coupled-bunch instabilities of the multi-bunch part in both longitudinal and transverse direction. And no instabilities were observed at the single-bunch part without the bunch feedback.

![Streak camera image of the hybrid fill mode.](image)

3.2. 10-Hz polarization switching

The beam line BL-16 of PF-ring 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 longest 9-m straight-sections [6].
The horizontal direction of the SR from each polarized undulator is alternately tilted by up to 0.3 mrad. This alternating local bump is formed by five identical AC steering magnets. The feed-forward correction using four fast steering magnets can restrain the vertical and horizontal orbit distortions at the outside of the local bump within 3 $\mu$m, as small as less than 10% of the vertical beam size. The polarization switching at a frequency of 10 Hz is being supplied for the user experiment from January 2012.

3.3. Development of in-vacuum undulators
In 2013, a short gap undulator SGU15 will be installed at PF-ring. It is the fourth in-vacuum undulator installed at one of the four short straight sections. These 1.4-m straight sections were created at the straight section upgrade in 2005, and the vertical betatron function is designed to be as small as 0.4 m suitable for the magnetic gap below 4 mm. The last SGU has a magnetic length of 500 mm and a periodic length of 17.6 mm, and delivers a broad range of hard X-rays by utilizing up to the 9th harmonic of radiation, including even numbered harmonics as well.

![Figure 4](image.png)

**Figure 4.** Injection plans of PF-AR to realize simultaneous injection with KEKB and PF-ring.

3.4. New injection scheme for PF-AR
Linac provides the electron or positron beam to the four storage rings, namely, PF-ring, PF-AR and KEKB LER/HER. At present, simultaneous continuous injection to the three rings, PF-ring (2.5 GeV) and KEKB LER(3.5 GeV)/HER(8 GeV), has been already realized, while the injection to PF-AR (injected at 3 GeV) is exclusive because it uses the common beam transport (BT) line with 8-GeV HER as shown by the blue line in Figure 4. In the upcoming Super KEKB project, estimated beam lifetime is as short as ten minutes, so the realization of the simultaneous injection to PF-AR is mandatory no later than the start of the physics run at the Super KEKB in 2015.

In April 2012, a new plan to build a direct BT tunnel from Linac to PF-AR, as shown by the red line in Figure 4, has been approved. Two injection plans are under discussion: (1) to inject 4-GeV positron beams provided for the Super KEKB LER, (2) to inject full-energy 6.5-GeV electron beams using the new direct BT line. The second plan enables the top-up injection and is much more favorable to the SR user. In order to realize the full energy injection, replacement of the pulsed bending magnet at the end section of Linac and movement of the injection section of AR ring are necessary. We are studying the feasibility of these plans in the intervals between user operations.

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