

# DEVELOPMENT AND PRESENT STATUS OF PHOTON FACTORY LIGHT SOURCES

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## Abstract

Two synchrotron radiation sources of KEK, Photon Factory storage ring (PF-ring) and Photon Factory Advanced Ring (PF-AR), continued stable user operation for FY2017. At the PF-ring, renewal of the first generation undulator and an upgrade of the injection section are progressing in FY2018. Preparing for the simultaneous top-up injection with the SuperKEKB Factory, a new direct beam transport line from the injector linac to PF-AR was completed at the end of FY2016. As the full energy injection of PF-AR has become possible, beam instability bothering the beam accumulation was solved, and the injection efficiency has been improved significantly. The operational status of both rings and the vacuum design of the reconstructed injection section of PF-AR storage ring will be described.

## PF-RING

### Operational Status

PF-ring is a 2.5 GeV synchrotron radiation (SR) source with a horizontal emittance of 35 nm rad. Main parameters are summarized in Table 1. The operational statistics of recent four years are shown in Table 2.

The operation time of the PF-ring has become shorter than before; it had been over 5000 h in the 2000s [1]. One of the reasons is rising electricity price in Japan after the Great East Japan Earthquake of 2011. At 2014, it hit bottom and then it has recovered at a level of 3500 h to 4000 h. We have worked to increase the user time ratio over 80%.

The failure rate kept a low level about 0.5% every year and the mean time between failures (MTBF) kept a long time. At FY2017, the number of failures recorded the smallest, and the MTBF exceeded 200 hours finally.

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

	PF-ring	PF-AR
Energy (GeV)	2.5	6.5
Circumference (m)	187	377
Emittance (nm rad)	35	293
Harmonic number	312	640
Beam current (mA)	450	60 (Single bunch)
Critical (keV)	4.0	26
No. of insertion devices	12	6

### Two Operation Modes of the PF-ring

Now we have two operation modes, a multi bunch mode, and a hybrid fill mode. Total current is kept at 450 mA for both modes. The hybrid fill mode has an isolated bunch of 50 mA, and 400 mA is distributed into 131 bunches.

For usual multi bunch mode, 450 mA is distributed into 188 bunches, and the filled bunches are divided into four trains. Each bunch train has 47 bunches and spaced by a gap of 31 bunches. In the PF-ring, a longitudinal multi-bunch instability of a quadrupole mode is likely to occur. As our bunch-by-bunch feedback system is only valid for a dipole mode instability, the specific bunch fill pattern was found to avoid the occurrence of the quadrupole mode instability. In FY2017, the quadrupole mode instability was suppressed well and was not observed during the user time.

Table 2: Operational Statistics of the PF-ring

Fiscal year	2014	2015	2016	2017
Operation time (h)	3024	3888	3432	3624
User time (h)	2328	3048	2928	3000
User time ratio (%)	77.0	78.4	85.3	82.8
No. of failures	15	23	18	14
Total downtime (h)	11.4	14.4	17.3	16.6
Failure rate (%)	0.5	0.5	0.6	0.6
MTBF (h)	155	133	163	215
Mean downtime (h)	0.8	0.6	1.0	1.2

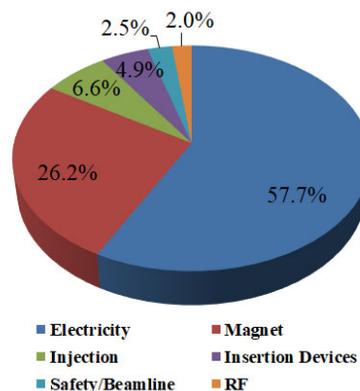


Figure 1: Breakdown of the failure time of PF-ring at FY2017.

### Breakdown of Failures in FY2017

The biggest failure occurred in FY2017 was not a failure of accelerator itself, but a power cut by a ground fault in a transformer substation that supplies power to the PF-ring and the injector linac. Though the power cut was recovered within an hour, it took almost half a day before recovering normal operation of the linac. The time required for recovery of the single electricity failure accounted about 60% of the whole downtime as shown in Fig. 1.

We were having two vacuum troubles of aged accelerator components though they did not affect the downtime.

One was corrosion of the aluminum vacuum duct of the super conducting wiggler (SCW). As the critical energy of

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the SCW radiation is high as 20 keV, there were severe radiation damage and rust on the metal surface in downstream of the SCW. The vacuum leak started at the 2011 Earthquake, and at a small earthquake on October 2016, leak was recurred both in the ring vacuum and the thermal isolation vacuum. The user operation had continued with temporary sealing for years until then, but to prevent any chance of secondary damage, we had interrupted the use of the SCW in December 2016. The recovery work was done during the summer shutdown period of 2017. As we avoided a transport of the SCW, the replacement and vacuum welding of the aluminum beam duct was carried out in the ring tunnel. The SCW has revived from October 2017.

Another vacuum trouble was also corrosion occurred on the copper water cooling tube installed in the septum duct. Figure 2 shows a photo of the inner part of the septum duct. At the left side of this duct, the injection septum magnet is placed. The stored beam travels through the center of the duct in front, and the injection beam comes by penetrating the SUS foil. A copper plate with the water cooling tube is equipped on the inner wall which is irradiated by SR. The septum duct was one of a few components still in use since 1982, the first commissioning of the PF-ring. We assume that a pin hole pierced at a bent part of the tube. The leakage had been first aided using a liquid seal for a while. Now we stopped the water cooling by adding an SR absorber at the upstream, and the inside of the cooling tube is evacuated. We are planning to upgrade the injection section with a renewal of a septum magnet soon.

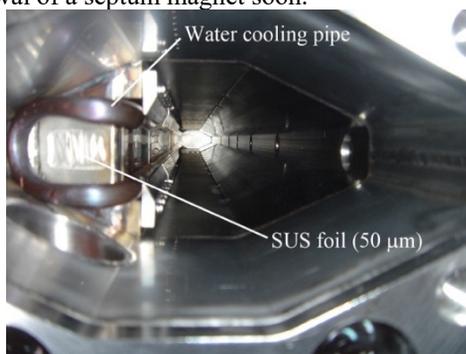


Figure 2: Water cooling copper tube (left) and the SUS foil of 50 μm-thick separating beam-transport and storage ring.

## PF-AR

### Operational Status

PF-AR is a 6.5 GeV SR source exclusively operated in a single bunch mode. Operation statistics of recent four years are summarized in Table 3. In FY2016, because of the construction of the direct beam transport (BT) line, the beam operation stopped from July 2016 to January 2017, and the new BT line and the storage ring were commissioned on February and March 2017. So, the total operation time was short and the user time ratio was low for FY2016. For regular years, the operation time of PF-AR remained at 70% or 80% of that of PF-ring, because its electricity cost two times higher than the PF-ring squeezed the budget.

The full energy injection has become possible by the completion of the direct BT line, the time required for the injection reduced significantly. Beam accumulation at 6.5 GeV is almost instability free unlike the previous 3 GeV injection, and the injection efficiency is also improved by the renewal of the injection section.

As the upgrade of the operation interlock system and radiation survey during the injection with opening the main beam shutter of SR beamlines were also completed, PF-AR has been ready for the top-up injection. After the completion of the pulse-by-pulse switching of the electron guns of the linac, the simultaneous top-up injection will become possible for four storage rings, PF-ring, PF-AR, HER, and LER of the SuperKEKB.

Table 3: Operational Statistics of the PF-AR

Fiscal year	2014	2015	2016	2017
Operation time (h)	2352	3336	1821	2448
User time (h)	1992	2784	1104	2136
User time ratio (%)	84.7	83.5	60.6	87.3
No. of failures	22	18	13	55
Total downtime (h)	37.0	31.0	18.3	24.7
Failure rate (%)	1.9	1.1	1.7	1.2
MTBF (h)	90	155	85	39
Mean downtime (h)	1.7	1.7	1.4	0.4

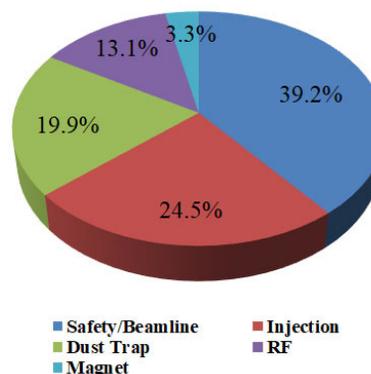


Figure 3: Breakdown of the failure time of PF-AR at FY2017.

### Breakdown of Failures in FY2017

In FY2017, the number of failures significantly increased as shown in Table 3 and Fig. 3. About half of the failures was a sudden beam loss caused by the dust trapping. And beam dump (or loss) caused by an accidental discharge of the injection kicker magnet accounted to 15 times.

The dust trapping in PF-AR has been observed especially just after a large reconstruction. It is expected that its frequency is gradually decreasing as the vacuum scrubbing proceeding.

The accidental discharge of the kicker magnet without any injection trigger was an initial failure of the new injection kicker system. It could be eliminated by switching off the power supply. But it is incompatible with the top-up injection, investigation of causes and noise countermeasures is in progress.

These frequently occurred failures were shortly recovered by re-injection. As the time required for injection has been reduced, the mean downtime was short as 0.4 h. We hope

the operation stability and the MTBF will improve than before thanks to the full energy injection in FY2018.

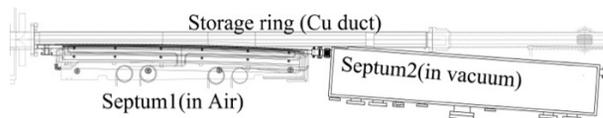


Figure 4: Arrangement of the injection section, two pulsed septum magnets and the copper beam duct adjacent to the septum.

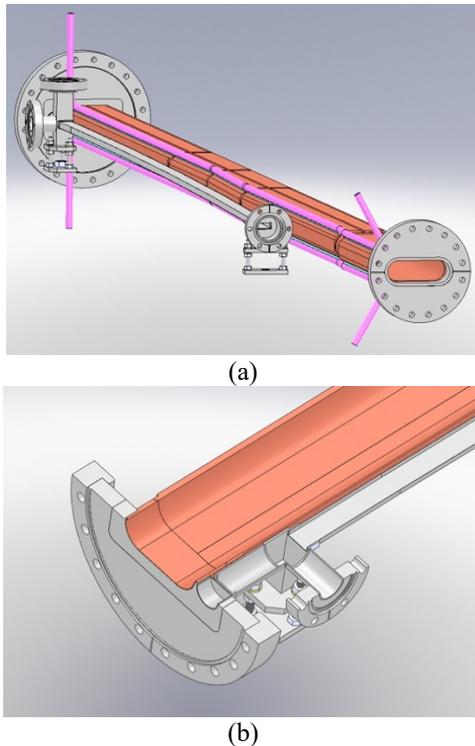


Figure 5: (a) Arrangement of vacuum ducts at the injection section. (b) A cross-sectional view at the injection point. The vacuum of the BT line was separated from the storage ring vacuum by an air gap. (By courtesy of TAIYO EB tech Co., Ltd.)

### Design of the New Injection Section

Along with the construction of the direct BT line, the injection point to the PF-AR storage ring has been changed. The new injection section was designed with three kicker magnets and a DC septum and two pulsed septum magnets. [2, 3, 4]

The arrangement of the two pulsed septum magnets is shown in Fig. 4. Each septum has a magnetic length of 1.5 m and a bending angle of 3 degrees. The upstream septum (Septum2) was installed in a vacuum, on the other hand, the downstream one (Septum1) was installed in the air.

The beam duct passing through the Septum1 was made by 0.3mm-thick SUS plates using laser beam welding and had a rectangular cross section of 20 mm width x 9.5 mm height as shown in Fig. 5(a).

The vacuum duct of the storage ring contact with the Septum1 was made of OFHC copper. For PF-AR, we had

a stock of extruded OFHC copper blank tubes as the quadrupole beam duct, the racetrack cross-section of 90 mm by 38 mm inner measurement. The septum wall approached closest to 30 mm from the stored beam orbit. The copper duct was fabricated by cutting the blank tube and assembled by electron beam welding.

A cross-sectional view at the end of the Septum1 is shown in Fig. 6. The kicker bump height was designed as 23 mm, and the separation of the kicker-bumped beam and the injection beam is designed as 15 mm.

By a field measurement on the bench, the delay and decay of the magnetic field due to an insertion of the SUS duct were confirmed to small enough [4], and the power could be supplied at the specified maximum repetition rate of 12.5 Hz. When installed in the accelerator, it was not able to raise the repetition rate of the Septum1 to the specific rate. The possible rate has been recovered by insulating a ground loop penetrating the Septum1. An extra power dissipation around the Septum1 magnet seemed to extend a required time to recharge the power supply. Similar study on the ground loop around the septum was reported by TPS group recently [5].

As described before [2], the injection efficiency of 84% to 88% was achieved through the commissioning.

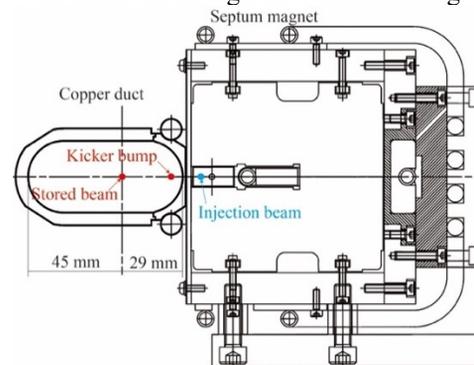


Figure 6: Cross-sectional view at the end of the Septum1.

## SUMMARY

The operational status of the SR sources of KEK, PF-ring and PF-AR, was summarized. We were challenged to ensure the operation time but has kept a stable operation with a low failure rate. By the completion of the direct BT line of PF-AR enabling a full energy injection, the two SR rings are ready for simultaneous top-up injection with the SuperKEKB storage rings.

## ACKNOWLEDGEMENTS

The authors would like to thank M. Etoh and T. Nishino of TAIYO EB tech Co., Ltd. for their contribution to the beam duct production and permission to use the drawings.

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