3 PF-AR

3-1 Operation Summary

As shown in Fig. 1, the total operation time has remained stable at around 5000 h every year since the full-scale reconstruction of the PF-AR in 2001. The operation statistics for the last 5 years are listed in Table 1. The scheduled machine study has been reduced to every two weeks from every week since FY2008, so the ratio of user operation time to total operation time increased and reached about 90% in FY2008 and FY2009.

The mean time between failures (MTBF) was estimated as the quotient of the scheduled user time divided by the total number of failures. Any troubles which interrupted the user operation by closing the main beam shutters (MBS) of all beamlines were taken into account as failures. The down time included the whole time until the MBS was reopened for the user. The mean down time (MDT) was estimated as the quotient of the total down time divided by the total number of failures.

The failures are classified based on their sources in Table 2. The most frequent failure of the PF-AR is a sudden drop of the beam lifetime caused by dust trapping. A severe beam lifetime drop frequently lasts for tens of minutes and the stored current can be lost in a short time, then the user operation is interrupted for the beam injection. The number of beam dumps caused by the RF system or by the magnet system was kept below 10 in most years. The dust trapping accounted for about 40% to 60% of the total failures. A solution for dust trapping has been a major challenge for us. Details of the experimental investigation of the phenomena and long-term statistics are described in the next section.

The distributed ion pump (DIP) installed at every bending magnet section was thought to be a main source of dust particles. As sufficient total pumping speed was secured by the large number of sputter ion pumps added in the three years from 2006 to 2008, an adequate beam lifetime could be achieved even with the DIPs switched off during user operation. As a result, the

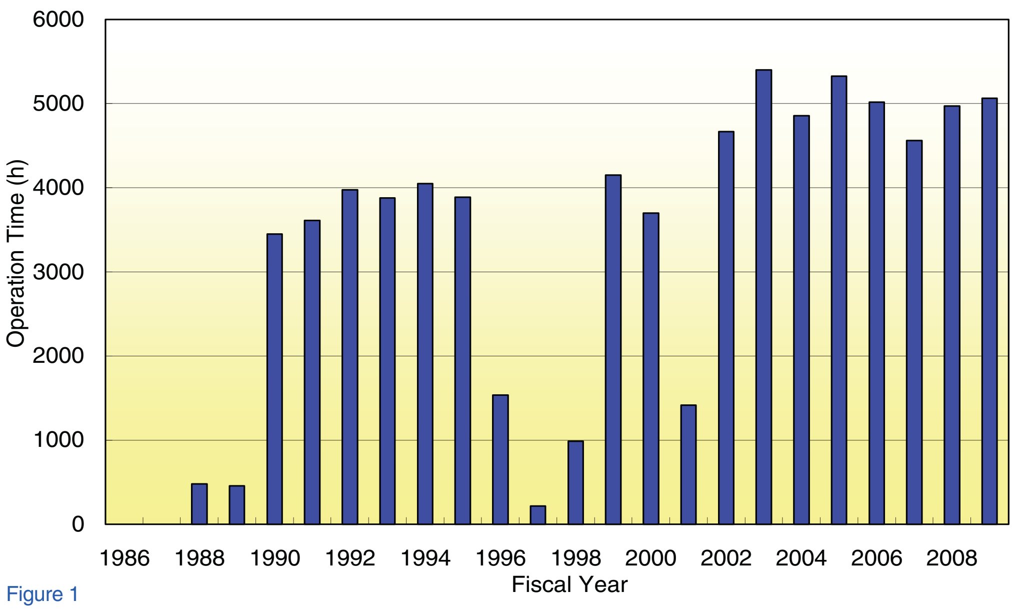

Figure 1
Operation time as a function of fiscal year.

Table 1
The mean time between failures (MTBF) of PF-AR during FY2005 - FY2009.

Fiscal year	2005	2006	2007	2008	2009
Total operation time (h)	5313.0	5016.0	4561.0	4969.0	5063.0
Scheduled user time (h)	4456.0	4032.0	3624.0	4344.0	4392.0
No. of failures	79.0	51.0	60.0	40.0	41.0
Total down time (h)	69.3	55.1	45.2	41.7	91.0
MTBF (h)	56.4	79.1	60.4	108.6	107.1
MDT (h)	0.9	1.1	0.8	1.0	2.2

Table 2
Classification of failures based on the source of the trouble.

Fiscal year	2005	2006	2007	2008	2009
RF	12	10	1	4	8
Magnet	4	1	1	2	2
Injection	4	3	8	9	1
Vacuum	2	6	2	0	2
Dust trapping	37	24	39	15	16
Insertion devices	0	1	0	0	0
Control/ monitor	4	0	1	1	1
Cooling water	5	1	0	3	4
Safety/ beamline	9	4	5	5	7
Earthquake	2	0	1	0	0
Electricity	0	1	2	1	0
Total	79	51	60	40	41

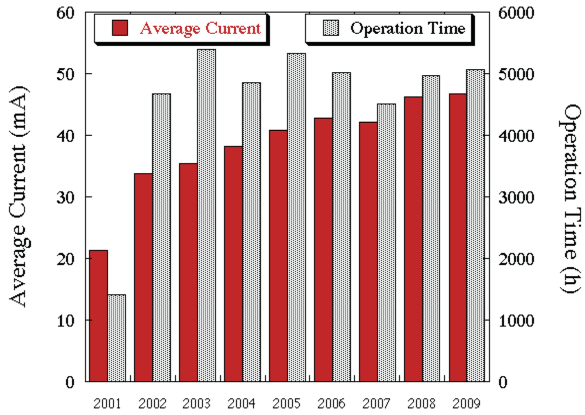

Figure 3
Improvement of average current after the full-scale reconstruction in 2001.

number of failures caused by dust trapping was remarkably reduced in FY2008 and FY2009. The total number of failures was also reduced and the MTBF exceeded 100 h in the last two years.

In FY2009, vacuum leaks of the beam duct occurred twice in the year. The first one occurred at an inferior brazing of a synchrotron radiation (SR) absorber of OFHC copper and the other was caused by thermal damage of a shield bellows irradiated by an abnormally deviated SR. Restoration of the vacuum needed tens of hours of work. This was the reason why the MDT of FY2009 was about twice as long as that of the other years.

As shown in Fig. 2, the averaged dynamic vacuum pressure, Pav/I [Pa/A], is increasing gradually and the beam lifetime, which is mainly limited by residual gas scattering, is still increasing. Though the initial stored current has been fixed at 60 mA since 2004, the average current during the total operation time has slightly increased year by year as shown in Fig. 3.

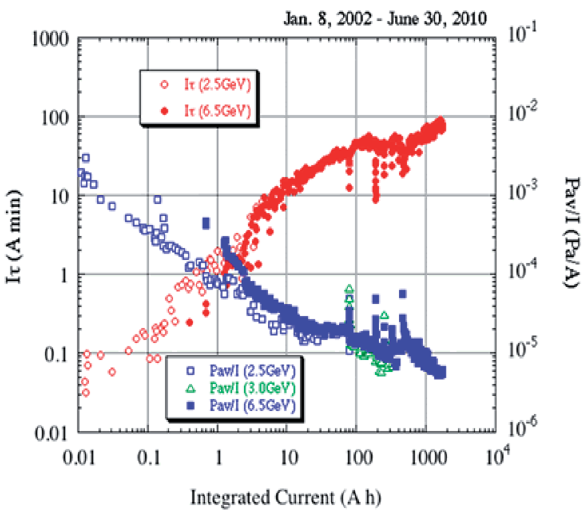

Figure 2
Improvement of beam lifetime and vacuum pressure.

3-2 Dust-Trapping Research

Stored beams in electron storage rings are susceptible to trapping of positively charged and micron-sized particles. This phenomenon, called “dust trapping,” can significantly reduce the beam lifetime. In many cases, it ceases momentarily, but occasionally it lasts for tens of minutes, whereby the experiments utilizing accelerator beams are severely disrupted. At the PF-AR, this phenomenon has been the most serious problem for many years. Figure 4 shows a statistical chart of the lifetime drop events since the major upgrade of the storage ring in 2001. For the first several years, the occurrence frequencies of all types of lifetime drops tended to reduce, but thereafter they have remained at a certain level.

Successive investigations during user operations suggested that dust particles were often generated by electric discharges at distributed ion pumps (DIPs), to which a DC high voltage is applied, and at discharge-prone vacuum chambers such as in-vacuum insertion devices, in which discharge can be generated by beam-induced fields. Based on the results of these investigations, we started to take measures against dust sources in 2006: 1) we installed additional 61 sputter ion pumps for substitutional use of all 56 DIPs, 2) we attempted twice to condition the beam-induced discharge sources by storing 25% higher current beams prior to user operation for eight hours each. As a result, the frequency of long-lasting drops reduced to 30% [1].

In order to experimentally demonstrate the hypothesis that these two kinds of electric discharges can produce harmful dust particles, we installed in the PF-AR a new vacuum device that intentionally generates electric discharges. Figure 5 shows an example of the intentional discharges in the device. In the experiments using this device, the dust trapping was reproducibly demonstrated with two kinds of intentional discharges [2]. Figure 6 is an example of the experimental data that shows sudden decreases in the beam lifetime were repeatedly induced because of the electric discharges.

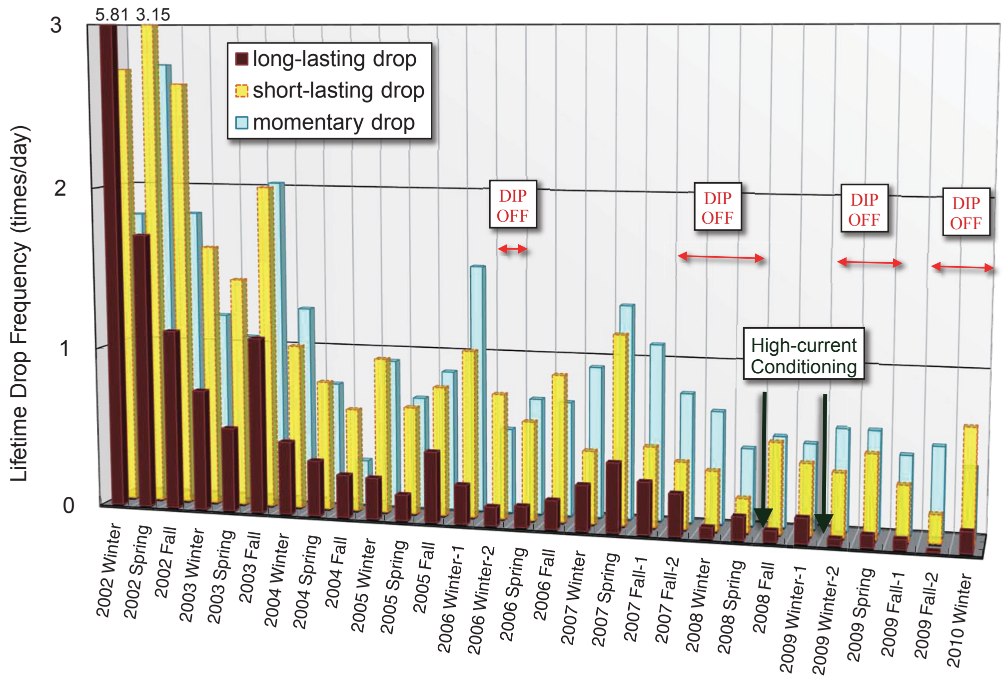

Figure 4
Statistical chart of lifetime drop frequencies since 2002. We categorized the lifetime drops into three patterns according to their duration.

In one experiment, we incidentally succeeded in visually observing the dust-trapping phenomenon; a trapped dust particle was captured by two video cameras, and appeared as a luminous body that resembled a shooting star. This was the first direct observation of a dust particle trapped by an electron beam [2]. By analyzing the recorded movies, we found some useful information about the trapped dust particle: it moved along the electron beam orbit with a speed of 10 m/s or more, and its temperature might reach 1200 K or higher. For further investigation, we improved the sensitivity of the video cameras by about three orders of magnitude. As a result, we could observe trapped particles more frequently, and found that they behaved differently in different conditions. Some details of these observations can be found in a related article in the highlights section of this report.

In a dust-trapping theory, a high-energy electron beam deposits ionization energy on a trapped dust particle [3]. As a result, the dust particle acquires high positive charge and reaches a high temperature of 1000 K or more. At higher temperatures, the dust can be cooled by heat radiation, and this is the most likely reason why the dust particles could be visually observed by video cameras.

Dust particles of thermally stable materials, which have high melting points and low vapor pressures, can reach thermal equilibrium between heating by energy deposition from the beam and cooling by heat radiation. Such particles can be stably trapped by electron beams, and cause lasting drops in the beam lifetime. Possible materials in accelerator vacuum components are titanium, silica, alumina, and so on.

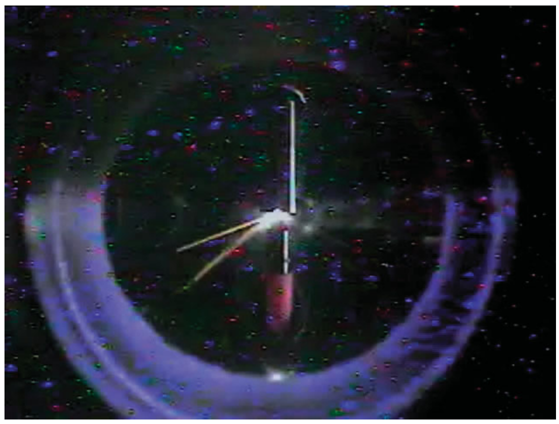

Figure 5
Example of the electric discharges. The spark is generated by applying a DC high voltage to the lower electrode.

One calculation indicates that the energy deposition on a dust particle is proportional to the flux (current density) of an electron beam [3]. High-flux beams can evaporate the trapped dust particles immediately. This theory supports empirical observations in many storage rings. Lasting lifetime drops are seldom observed in high-current accelerators such as the KEKB HER and in low-emittance accelerators such as the SPring-8. On the other hand, they can often be observed in relatively low-current and high-emittance accelerators such as the PF-AR. As for the PF-ring, since we usually store electron beams of more than 300 mA in multi-bunch mode, the lasting lifetime drops seldom occur. In single-bunch mode, however, we store electron beams of as low as 50 mA, and therefore, the lasting lifetime drops can be observed, especially after renewal of the DIPs.

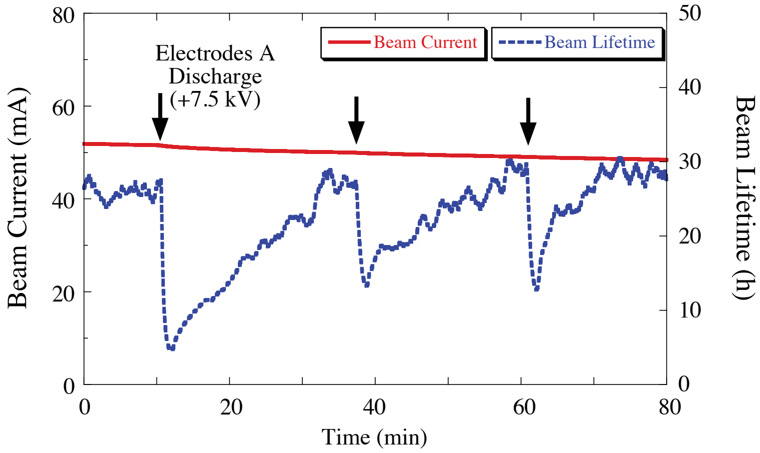

Figure 6
Experimental data showing that sudden lifetime drops were repeatedly induced by intentional electric discharges at the times indicated by the arrows.

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3-3 Update of QF Magnet Power Supply

We updated the power supply for the main focusing quadrupole (QF) in the summer of 2009. The power supplies for the QF and defocusing quadrupole (QD) were fabricated as a pair about 27 years ago, but recently we had experienced some troubles in the QF and judged that it needed to be updated. We fabricated a new QF power supply and replaced the old QF with the new QF. The photograph shows the new QF on the right and the QD on the left.

Figure 7
The new QF is shown on the right.

The principal circuit consists of a thyristor pre-regulator and transistor regulator. The load is 12 quadrupole magnets which are powered in series. The resistance and inductance of the load are 89 mΩ and 70 mH, respectively. The maximum current and voltage are 1340 A and 170 V, respectively. The specification for current stability is better than 50 ppm in 8 hours, and the specification for current ripple is better than 10 ppm.

The design is based on the KEKB magnet power supply design philosophy. In the current regulation controller, the output current, which is measured by a high-precision DCCT, is compared with a current reference. The reference source is a 16-bit DAC with 9.5 V DC full-scale. The purpose is to compensate the long-term variation of circuit elements up to 10 V. The calibration constant is stored in PROM in a board. The load resistor of the DCCT, the DAC and the current-error amplifier are built into a box with a temperature-regulated environment. Temperature regulation is accomplished by cooling the inside with a Peltier device or heating the inside. The temperature is maintained within ±0.5$°C$ at 25$°C$ The differential voltage between the DAC and DCCT is sent to the transistor bank in order to stabilize the output current.

The interface board communicates with the central computers via ARCNET. The current pattern of acceleration, which is a collection of 16-bit digital data, is remotely set in a RAM from the central computers. In the acceleration, the data in the RAM is counted up according to the internal clock in the board, and the output of the DAC is used as a current reference of the power supply. The status and fault-status signal are sent to an IOC module in a VME crate, which is connected to the computer system using EPICS.

In the PF-AR, 28 power supplies for the quadrupole magnets are in operation. The circuits were all of a similar design. We plan to update the old 25 power supplies in the future.