4 PF-AR

4-1 Summary of Machine Operation

The operation statistics for FY2003 are summarized in Table 1. The total operation time increased greatly to 5,400 hours from 4,667 hours in FY2002 (Fig. 1). Although failure time was twice as long as that of FY2002, partly due to an accident affecting the RF system described below, the total user time increased by 10%.

The PF-AR was restarted on April 1 after intermission for one month. Immediately after that, we encountered a serious problem with the RF acceleration system on April 3, leading to a postponement of users' run time that was scheduled to start on April 4. The accident is described in detail in the following note. After hard work for restoration which took 10 days, we were able to start users' run on April 15. Although the RF acceleration voltage became lower than before after the accident, an initial beam current of 55 mA was recovered by fine tuning of the RF system.

Table 1 Operation statistics of PF-AR in FY2003.

Operation Time	5400.0 h	
SR Experiment	4122.0 h	76.3%
Beam Development	1002.0 h	18.6%
Failure	177.5 h	3.3%
Miscellaneous	98.0 h	1.8%

After the RF accident, generally speaking, the operation of the PF-AR was stable throughout FY2003. The sudden changes in the beam lifetime which were mentioned in the previous issue of this report continued to occur, however, the frequency of these was greatly reduced. In the first half of FY2003, the PF-AR was regularly injected three times a day. In order to minimize interruption of SR experiments due to injection, the injection frequency was reduced to twice a day from December.

The operation energy for medical application is 5 GeV. At this energy, the RF power is capable of storing beam current of more than 70 mA. However, the wake field excited in the RF cavities limits the beam current to about 60 mA as mentioned in the previous issue. In order to lessen the effect of the wake field, accumulation of two bunches in non-symmetric buckets was attempted. An initial beam current of 70 mA at 5 GeV was achieved in this two-bunch mode as described in the following section. This mode has now been established as a standard operation mode for medical application.

The present value of the emittance (290 nm·rad) is not satisfactory. We have been making efforts to find a stable operating point that gives an optimum emittance of 160 nm·rad, however, we still have several difficulties to overcome to realize low-emittance.

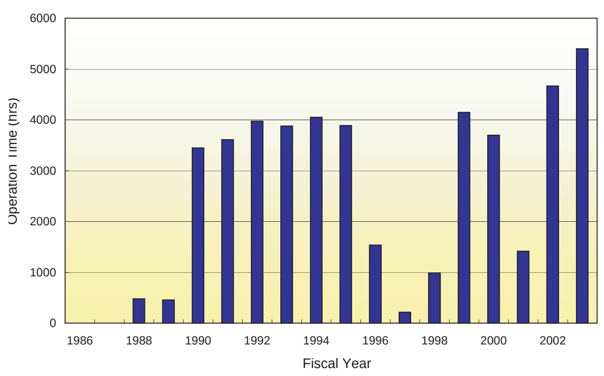


Figure 1
Operation time history of the PF-AR.

Trouble in cavity No. 3

During vacuum scrubbling with the beam, a sudden vacuum leak from the feedthrough for the HOM damper of the #1 RF cavity in the west long straight section occurred on April 3. The cause of the leak was overheating at the feedthrough due to an improper connection between it and the cable to the dummy load that absorbs the HOM power. Although the leak was fixed immediately, we found that the accident had damaged the #3 RF cavity in the same straight section. Since the vacuum pressure around the #1 cavity recovered gradually, we started vacuum scrubbling using the beam. However, an electric discharge in the #3 cavity repeatedly occurred 10-30 min after every beam injection, and the situation did not improve. We finally decided to disconnect the #3 cavity from the RF system. The klystron power amplifier in the west RF system supplied the four RF cavities using a power splitter system that split the RF power equally into four channels. Fortunately, the RF group of the light source division had already developed a key component of a splitter system that can split the RF power equally into three channels. We changed the power splitter and disconnected the detuned #3 cavity on April 14. Tuning of the RF system without the #3 cavity went smoothly and we were able to start users' run on April 15. After the temporary restoration, we have been making every effort to restore the #3 cavity on several occasions, however, our efforts have not paid off as yet. Therefore, we were forced to operate the PF-AR using only five RF cavities (two cavities in the east long straight section and three in the west) throughout FY2003.

4-2 Research and Development

Operations of the RF system

The RF system for the PF-AR has been operated using six 11-cell cavities; four in the west straight sections, two in the east. In April 2003, a vacuum fault due to the

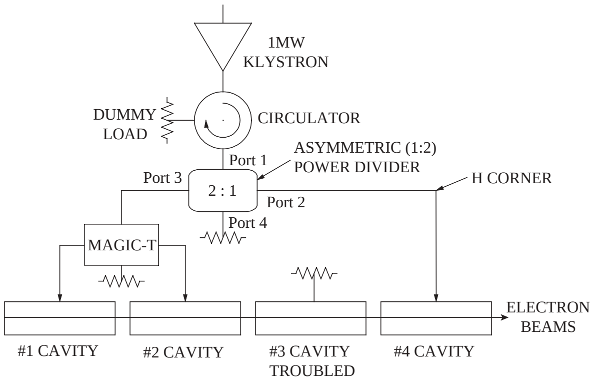


Figure 2
Modified west RF station for driving three cavities.

Figure 3
Installation of an asymmetric power divider into the PF-AR system.

burnout of a HOM-coupler cable occured in one of the cavities (W1: cavity No.1 in the west RF section). Although this fault was quickly rectified, another problem arose in cavity W3. No problems occured under RF-conditioning of up to 190 kW per cavity, but frequent trips occurred at a beam energy of 6.5 GeV. In spite of various efforts to fix this problem, it could not be resolved within the available time constratints, so the W3 cavity was detuned from operations, and the remaining three cavities of the west RF station were driven by a single 1 MW klystron. For this, a unique three-way power distribution technique was used [1], which has been described previously [2].

In RF systems the high RF power is usually divided using several magic-Ts or 3 dB couplers. In such systems the number of cavities is limited to a power of 2 (i.e. 2,4,8...). In our system, however, we have used a combination of an asymmetric (1:2) power divider and a conventional magic-T, as shown in Fig. 2. The asymmetric power divider can divide the input power at 508.6 MHz in a ratio of 1:2, while maintaining the neccessary isolation between the cavity ports. Using this system, five RF cavities were available for user operations. Installation of the asymmetric divider into the PF-AR RF system is shown in Fig. 3. Using the above system, a maximum beam current of 55 mA could be stored comparable to that before the cavity problems. We have been using this modified RF system since April 2003 without any problems at a power level of more than 600 kW. Some problems were also experienced in the RF protection system, including an arc-sensor action at the east klystron. With considerable work, most of the problems were resolved.

In order to make space for new undulators for the ERATO-project, the RF cavities will be re-arranged in the summer of 2004. Two of the cavities in the west section will be moved to the east section and at the same time the faulty cavity will be replaced. After replacement, the inner surfaces of the faulty cavity will be investigated indetail.

Also during FY2003 an RF-phase modulation method for elongating the bunch length was studied, and applied several times during 5 GeV clinical operation time. Bunch-elongations of about 10% were achieved, which, although small, contributed to stable 5 GeV operation. This effect is believed to be due to a reduction in heat-load at some of the tapered transitions within the vacuum chambers.

References

[1] T. Takahashi, H. Nakanishi, S. Sakanaka and K. Umemori, *Proc. of APAC* (2004).
[2] T. Takahashi, S. Sakanaka and M. Izawa, IEEE Trans. on *Nucl. Sci.* **48** (2001) 1592.

Two-bunch high-current operation at 5.0 GeV for medical application

The PF-AR is usually operated in single-bunch mode at a stored beam energy of 6.5 GeV, but a 5.0 GeV mode is also available for medical application. Since there are no other users during this mode a special operation mode can be used, and the vertical beam size varied. Also, since single-bunch operation is not a requirement of the medical application, two-bunch operation can be used in an attempt to increase the beam current and resolve some other issues.

The horizontal and vertical betatron tunes in the 5.0 GeV mode are usually 10.194 and 10.200, with a vertical beam size of about 300 (µ)m. During medical application beamtime the beam size can be varied from 180 (µ)m to 300 (µ)m at any time by changing the betatron tunes. When the betatron tunes approach a coupling resonance, the coupling strength between horizontal and vertical betatron motion increases and the vertical beam size also increases. Four modes have been set for the vertical beam size corresponding to sizes of 180, 230, 270 and 300 (µ)m (mode-180, mode-230, mode-270 and mode-300). The betatron tunes for each beam size are shown on the tune diagram in Fig. 4, and a screenshot of the control panel for changing the vertical beam size is shown in Fig. 5.

In the 5.0 GeV operation mode there were several problems to be solved, including the temperature rise of some of the vacuum components, a pressure increase in the ring, and a sudden drop in lifetime. The temperature rise during 5.0 GeV operation for some vacuum compo-

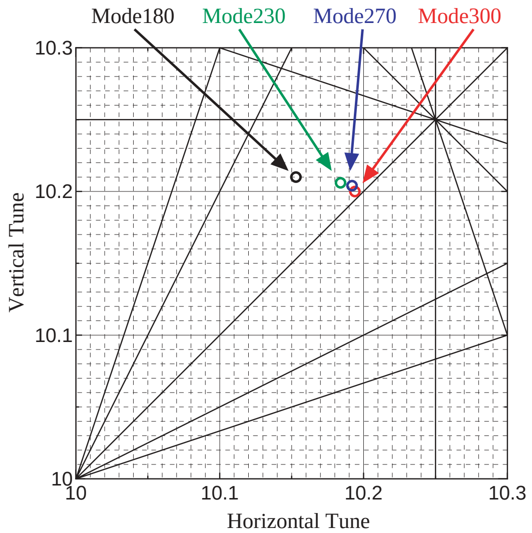


Figure 4
Tune diagram near the coupling resonance.

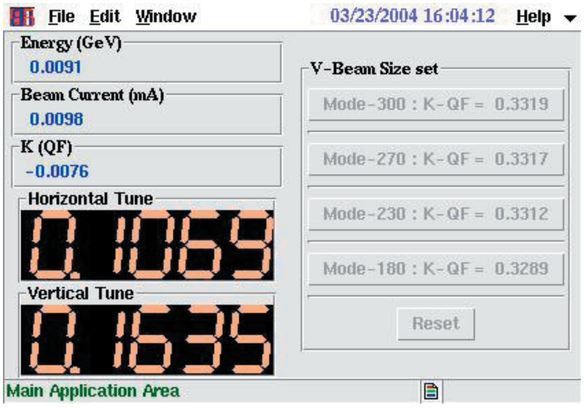


Figure 5
The control panel of the vertical beam size for the medical application.

nents was considerably greater than during 6.5 GeV, and this is thought to be due to the shortened bunch length at 5.0 GeV. By modulating the RF acceleration phase at twice the synchrotron frequency it was possible to elongate the bunches by 10%, reducing the temperature rise effect.

Since November 2003 a new method for avoiding these issues and increasing beam current has been attempted: 2-bunch injection. Since the temperature rise in the vacuum components depends on the beam current-per-bunch, 2-bunch injection is effective in reducing this effect, since current-per-bunch can be reduced while maintaining the same total stored current.

In order to acheive 2-bunch injection it was necessary to improve the beam feedback system. The transverse feedback system is used during injection to suppress beam instabilities, but this system was until then only able to operate in single-bunch mode. Without the feedback system maximum beam current was limited to 10 mA, but after modification a beam current of 70 mA could be stored. Use of 2-bunch mode also reduced the temperature of the vacuum components, and sudden drops in lifetime were not observed. Fig. 6 shows beam current and beam lifetime for 5.0 GeV medical application with single-bunch and 2-bunch operation, and the temperature of the vacuum components is shown in Fig. 7.

It is planned in the future to optimise 2-bunch injection to achieve stored currents of over 80 mA.

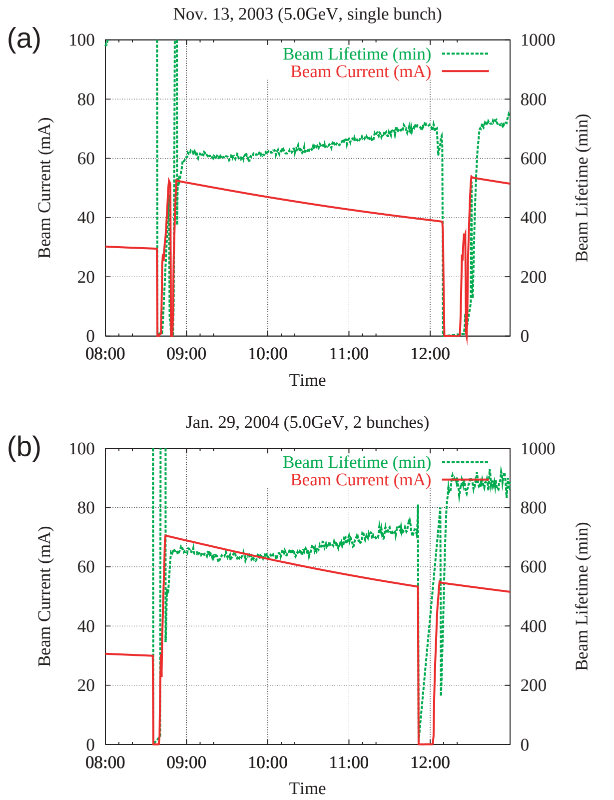


Figure 6
The beam current and the beam lifetime during the medical application for (a) single bunch and (b) 2-bunch operation.

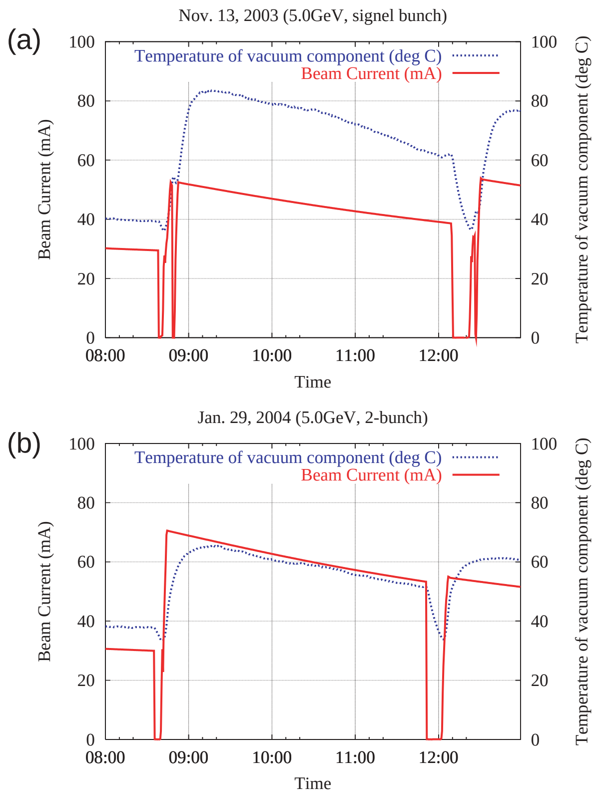


Figure 7
The beam current and the temperature of the vacuum components adjacent to a RF cavity for (a) single bunch and (b) 2-bunch operation.

Medium emittance operation

The PF-AR is currently operated at an emittance of 290 n·mrad under 90º optics in user operation. At the operating point with horizontal and vertical tunes of 10.15 and 10.21, the maximum beam current reaches over 60 mA in single bunch mode and operation is quite stable.

Since the ring was designed as a booster synchrotron, the circumference is small for a 6.5 GeV light source. Consequently, the minimum practical emittance is limited to 160 n·mrad under 140º optics. In order to realize this value for user operation, machine studies of the medium emittance optics were started in April 2003. During these studies, the injection parameters, betatron tunes and the corrector magnets for the closed orbit distortion were adjusted. As a result of the adjustments, electrons could be stored in the medium emittance optics with horizontal and vertical tunes of 11.57 and 8.24. Fig. 8 shows the optical functions of these optics. However, there are some issues during injection: temperature rise at some of the vacuum components, unstable injection, a limited of beam current of 30 mA, and a short beam lifetime.

The temperature of some of the vacuum components reached about 100°C during injection of the medium-emittance optics, considerably higher than for normal emittance operation. This is believed to be due to the shorter bunch length at medium-emittance. In order to elongate the bunch length, it is planned to optimize the RF acceleration voltage or modulate the RF acceleration phase at twice the synchrotron frequency.

It used to be the case that the acceleration cycle during which the magnets were ramped up to 6.5 GeV and then down to 3 GeV caused injection instability and the inability to store a beam.This was believed to be due to the hysteresis of the magnets resulting in differences in magnetic field before and after the acceleration cycle. After introducing a new method for standardising the magnets, injection after the acceleration cycle has become more stable.

A limitation in beam current was observed at around 30 mA, believed to be due to beam instabilities related to higher-order modes of the RF cavity. In order to avoid this operating points free from instability will be searched for.

It is planned in the future to tune the accleration up to 6.5 GeV and 2-bunch injection in order to increase beam current. To increase the beam lifetime, the optical function will also be optimised.

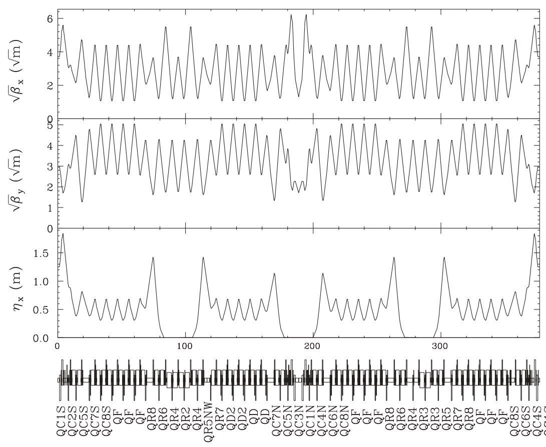


Figure 8
Optical function in the PF-AR under the medium emittance optics.

An innovative injection scheme using a pulsed quadrupole magnet

An innovative injection scheme has been proposed which uses a pulsed quadrupole magnet and allows the stored beam to be fixed on a central orbit even during beam injection without using a pulsed bump.

In electron storage rings, beam injection must be carried out without loss of the stored beam. This is usually achieved with the conventional method of a pulsed bump with several dipole kickers. This method is adopted in every electron storage ring since it is not difficult to implement. However it has the drawback that a slight oscillation of the stored beam is caused by the pulsed bump. This oscillation can become a serious problem during the top-up injection which has recently begun at several synchrotron light sources. A new injection method or system is hoped for to prevent the oscillation.

In general, oscillation of the injected beam is non-linear due to the large amplitude of oscillation. For simplicity however, the oscillation can be assumed to be linear, and describable by its amplitude and momentum (divergence angle) component. To achieve successful injection, the magnitude of the oscillation must be reduced instantaneously. Since the momentum kick applied to the beam by a quadrupole magnet is proportional to the amplitude, the magnitude can be effectively reduced by choosing the phase between the injection point and the magnet location. A quadrupole has zero field strength at the magnetic pole centre, so when the stored beam passes through the centre no oscillation is generated since the beam receives no momentum kick, making the pulsed quadrupole magnet more suitable than a pulsed dipole kicker.

In order to confirm the operation of this new injection scheme in a real machine, a pulsed magnet system has been developed for the PF-AR [1] with the design goal

Table 2 Principal parameters of the pulsed quadrupole magnet.

Length [mm]	300
Vertical bore [mm]	36
Horizontal bore [mm]	102
Turn number of coil [turns]	1
Voltage (max) [kV]	20 (40)
Field gradient (max) [T/m]	3 (6)
Peak current (max) [A]	2000 (4000)
Inductance [μH]	1.8
Pulse width [μs]	2.4
Thickness of silicon steel [μm]	150

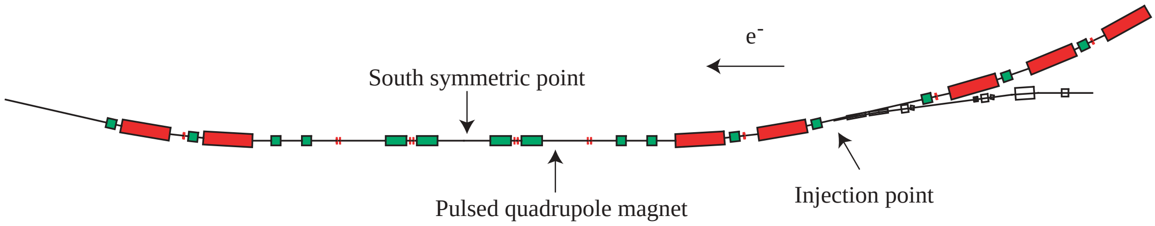


Figure 9
Principal parameters of the pulsed quadrupole magnet.

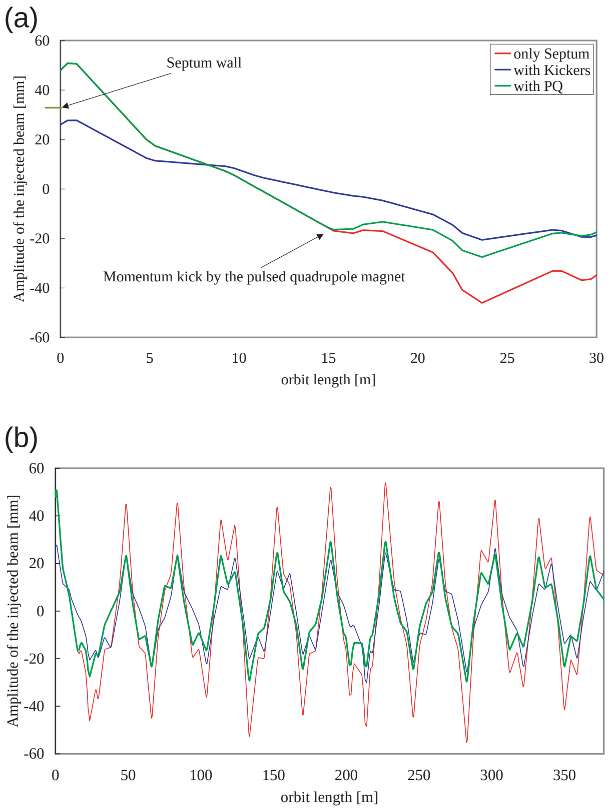


Figure 10
Oscillations of the injected beam: beam amplitude near the injection point (a), and over the entire first turn (b). The red line labelled "only Septum" shows the orbit of the injected beam with only a septum magnet, and the blue line labelled "with Kickers" the orbit in the present system with both septum and kicker magnets. This is the effective orbit after reduction of the amplitude by the local bump of the stored beam. With the present system, the height of the local bump is 22 mm, and by adding this value the initial point of the orbit is at the outside wall of the septum magnet. The green line labelled "with PQ" line shows the orbit of the new system with septum magnets and pulsed quadrupole magnet.

that the oscillation of the injected beam be the same as that with the present injection system. At present the amplitude of the injected beam is about ± 50 mm without exciting the dipole kickers, and reduced to ± 25 mm by the pulsed bump of the stored beam. The parameters of the pulsed quadrupole magnet are given in Table 2, and the lattice configuration shown in Fig. 9. Fig. 10 shows the oscillation of the injected beam, and a photograph of the magnet is shown in Fig. 11.

Following measurement of the field, the pulsed quadrupole magnet will be installed in the ring.

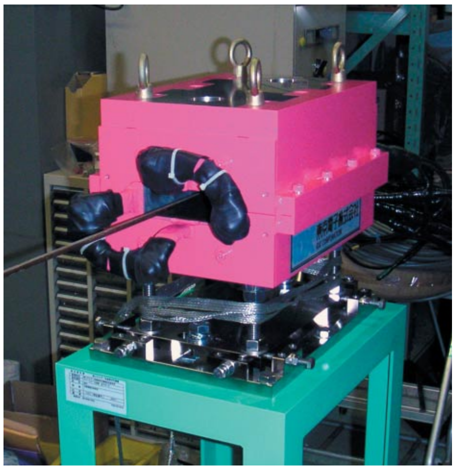


Figure 11
The pulsed quadrupole magnet.

Reference

[1] K. Harada, Y. Kobayashi, T. Miyajima, S. Nagahashi, "PF-AR Injection System With Pulsed Quadrupole Magnet", *Proc. of APAC* (2004).

New orbit feedback scheme beneficial for ID beamlines

The eigen-vector method with constraint condition is a new COD (closed orbit distortion) correction method that enables us to combine the local orbit correction at the insertion devices with global COD correction. In general, it is difficult to realize the global orbit feedback and local orbit feedback simultaneously due to the interference between the two feedback loops. For example, if two orbit feedback systems are operating independently, it may happen that both of the systems try to correct the same orbit distortion at the same time. In order to avoid such interference, the local orbit corrections are integrated into the global orbit correction as a constraint condition using Lagrange's undetermined multiplier method [1,2]. In order to apply this method, we only use the new contrived response matrix for the global COD correction where the local correction is involved and carried out simultaneously. We have tested this correction scheme at the PF-AR. Because there is no real-time fast orbit feedback system at PF-AR, we use the slow orbit correction system which takes more than 10 seconds to carry out each COD correction procedure.

The constraint conditions are applied to six BPMs (beam position monitors) placed on both sides of the three insertion devices ID-NW12, ID-NW2 and ID-NE1.

There are 79 (vertical) steering magnets and 84 BPMs. Numbering BPMs from the south symmetrical point, the numbers of the six BPMs under constraint conditions are No. 25, No. 26 (for NW12), No. 36, No. 37 (for NW2), No. 41 and No. 42 (for NE1). In the machine study, we generate a vertical COD using one vertical steering magnet and then correct it using the other ones.

Fig. 12 shows the RMS values of the residual COD after six correction iterations with the new and the ordinary method. The residual CODs at the constrained six BPMs are as small as 10 µm, about the same as the resolution of the BPMs. On the other hand, for most of the cases, there is no large difference seen between the new and ordinary methods in the RMS CODs of all the 84 BPMs. The RMS value of the kick angles of the steering magnets is larger by 25% with the new method than with the ordinary method.

In a few cases, however, the performance using the new COD correction method shows deterioration in the RMS CODs of all the 84 BPMs. Especially when the source of the COD is very close to the constraint point, the COD after correction is still large near the steering magnet used for the COD source. Because we exclude one steering magnet of the COD source from the correctors, the corrector interval becomes large. Fig. 13 shows the case where the COD is generated by the vertical steering magnet of ZVNW06 that is next to ID-NW2 (constraint point). The COD has a large amplitude near the COD source although both the COD and the divergence angle in all of the three insertion devices are well corrected with the new method. If we have another steering magnet in this section or we do not use the steering magnet as the COD source, the COD at all the BPMs can easily be corrected for all the cases.

In this machine study, the new orbit correction method has been successfully demonstrated. The RMS COD of the constraint six BPMs at the three insertion devices is suppressed to about 10 µm, about the resolution of the BPMs. On the other hand, there is almost no large difference in the RMS COD of all the 84 BPMs between the new and ordinary methods.

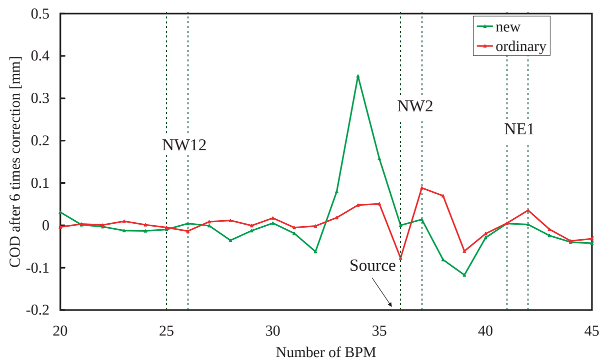
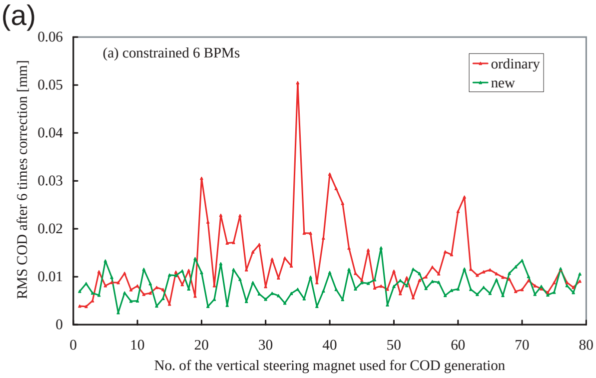


Figure 13
COD pattern of case where the RMS COD is deteriorated. The green line ("new") shows the residual COD after six times correction with new method with constraint conditions and the red one ("ordinary") that with ordinary method without constraint conditions. The positions of six BPMs under constraint conditions (No. 25, 26, 36, 37, 41 and 42) are shown as the vertical dotted line. The source of the COD is the vertical steering magnet of ZVNW06 (shown as "Source" in the figure) that is placed between BPMs of No. 35 and No. 36. If we have a steering magnet (for the corrector) between BPMs of No. 34 and No. 36, the residual COD becomes much smaller.

(a)



(b)

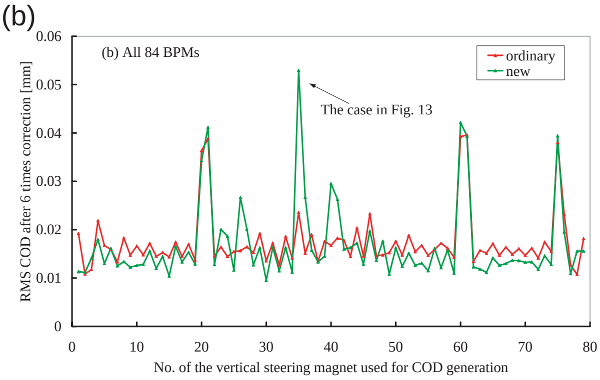


Figure 12
The RMS of the residual COD after 6 correction.
(a) The residual CODs at the constrained six BPMs at the insertion devices are as small as 10 µm, about the resolution of the BPMs.
(b) On the other hand, there is no large difference between the new and ordinary methods in the RMD CODs of all 84 BPMs.

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[1] M. Satoh, Y. Kamiya and N. Nakamura, “New COD Correction Method for Orbit Feedback”, *Proc. of EPAC.* (1998) 1723.

[2] M. Satoh, N. Nakamura and Y. Kamiya, “Error Analysis of a New COD Correction Method Uniting Global and Local Feedbacks”, *Proc. of PAC.* (1999) 1174.