OPERATION AND RECENT DEVELOPMENTS OF THE PHOTON FACTORY ADVANCED RING

T. Miyajima*, T. Abe, K. Ebihara, K. Haga, K. Harada, Y. Hori, T. Ieiri, S. Isagawa, T. Kageyama, T. Kasuga, T. Katoh, H. Kawata, M. Kikuchi, Y. Kobayashi, K. Kudo, T. Mitsuhashi, S. Nagahashi, T. T. Nakamura, H. Nakanishi, T. Nogami, T. Obina, Y. Ohsawa, M. Ono, T. Ozaki, H. Sakai, Y. Sakamoto, S. Sakanaka, M. Sato, M. Satoh, T. Shioya, M. Suetake, R. Sugahara, M. Tadano, T. Takahashi, S. Takasaki, Y. Tanimoto, M. Tejima, K. Tsuchiya, T. Uchiyama, A. Ueda, K. Umemori, C. Weixing, N. Yamamoto, S. Yamamoto, and S. Yoshimoto
High Energy Accelerator Research Organization, Tsukuba 305-0801, Japan

Abstract

The Photon Factory Advanced Ring (PF-AR) is a synchrotron light source dedicated to X-ray research. Although the PF-AR is usually operated at a stored beam energy of 6.5 GeV, a 5.0 GeV mode is also available for medical application. In the 6.5 GeV mode, the beam current of 60 mA in a single-bunch and the typical lifetime of 15 hrs at the current have been archived. Single-bunch operation for pulsed X-ray and its relatively high beam energy characterize the PF-AR. However, the high-current in single-bunch causes several problems to be solved, such as the temperature rise of some of the vacuum components, a pressure increase in the ring, and a sudden drop of beam lifetime. In order to avoid these problems, developments of new methods have been continued. In this paper, the status and the recent developments of the PF-AR are presented. It concerns: the successful operation with a two-bunch high-current operation at 5.0 GeV; the vertical beam size control for the medical application; modulating the RF acceleration phase in order to elongate the bunch length; stabilizing temperature in the ring tunnel; the study for medium emittance operation with 160 nm·rad; transferring the RF cavities in order to install a new insertion device; an innovative injection scheme using a pulsed quadrupole magnet.

INTRODUCTION

The AR that was originally constructed as a booster of the TRISTAN electron-positron collider has been parasitically used as an X-ray source [1]. It was converted into a ring dedicated to pulsed X-ray research and renamed PF-AR(Photon Factory Advanced Ring for pulse X-rays) after completion of the Tristan project. Since its performance as a light source was not satisfactory, the PF-AR upgrading project[2] started in 1999. The project was completed in the end of 2001, and commissioning of the upgraded ring was successfully done in the beginning of January, 2002 [3, 4]. After fine tuning of the machine, users' operation started in April. A beam current of 60 mA and a typical beam lifetime of 15 hrs at the current were achieved at 6.5 GeV, and the stability of the orbit was largely improved.

* E-mail address : tsukasa.miyajima@kek.jp

Table 1: Principal parameters of the PF-AR.

Parameter	Value
Beam energy	5.0 - 6.5 GeV
Injection energy	3.0 GeV
Circumference	377.26 m
Harmonic number	640
Horizontal betatron tune	10.15
Vertical betatron tune	10.21
rf frequency	508.58 MHz
Emittance (at 6.5 GeV)	294 nm·rad
Initial stored current (single bunch)	60 mA
Initial stored current (two bunches)	70 mA

In the PF-AR, both the ring tunnel and the experimental halls are housed underground. There are four SR beamlines (BL-NW12, NW02, NE01, NE03) from insertion devices (three in-vacuum-type undulators, one elliptically-polarized multipole wiggler) and a SR beamline (BL-NE05) from a bending magnet. In addition, new beam lines (BL-NW14, NW10) have been constructed in the north-west experimental hall. BL-NW14 is a SR beamline from an insertion device, and BL-NW10 is a SR beamline from a bending magnet. The construction of these beamlines will be finished in August, 2006.

The PF-AR has been operated at beam energies of 6.5 and 5.0 GeV, where the 5.0 GeV operation is arranged for medical applications. The ring usually stores a single-bunch beam of about 60 mA, providing unique pulse X-rays for researches such as the time-resolved X-ray experiments. High beam energy and full-time single-bunch operation characterizes the PF-AR. The principal parameters of the ring are given in Table 1.

TWO-BUNCH OPERATION

The PF-AR is usually operated in the single-bunch mode at 6.5 GeV. Also, the 5.0 GeV operation is arranged for a medical application. Since the medical application monopolizes the PF-AR, we can operate it in a special operation mode and can change the the vertical beam size. Also, since the medical application does not require the

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single-bunch beam, we can store a few bunches in order to increase the beam current and improve issues as shown below.

The horizontal and the vertical betatron tunes in the 5.0 GeV operation mode are usually 10.194 and 10.200, and the vertical beam size is about 300 μm. For the medical application, we control the vertical beam size from 180 μm to 300 μm by changing the betatron tunes at any time. When the betatron tunes approach a coupling resonance, the vertical beam size expands. We have prepared four sets of operating points that correspond to the vertical beam sizes of 180, 230, 270 and 300 μm. The betatron tunes for each beam size on the tune diagram near the coupling resonance are shown in Figure 1.

In the 5.0 GeV operation mode, we had some issues to be solve: the rise in temperature of some vacuum components, the increase of the pressure in the ring and the sudden drop of lifetime. The temperature rise at some vacuum components during the 5.0 GeV operation was considerably larger than that during the 6.5 GeV operation. The phenomena seem to relate to the fact that the bunch length at 5.0 GeV is somewhat shorter than that at 6.5 GeV. We have therefore tried to elongate the bunch length by modulating the rf acceleration phase at the second harmonic of the synchrotron frequency. It was successfully elongated about 10% and the phenomena have been improved.

Since November 2003, we tried another method to avoid these issues and increase the beam current. It is 2-bunch operation. Since the temperature rise at some vacuum components depends on the beam current per bunch, its decrease is efficient to lighten the phenomena. In 2-bunch operation, we can decrease the beam current per bunch without decreasing the total beam current.

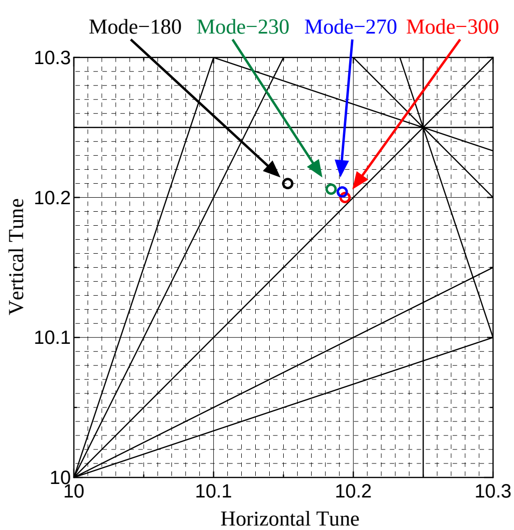

Figure 1: Tune diagram near the coupling resonance. For the medical application, we can change the operating point to following 4 modes, Mode-180, Mode-230, Mode-270, and Mode-300. These modes correspond to the vertical beam size.

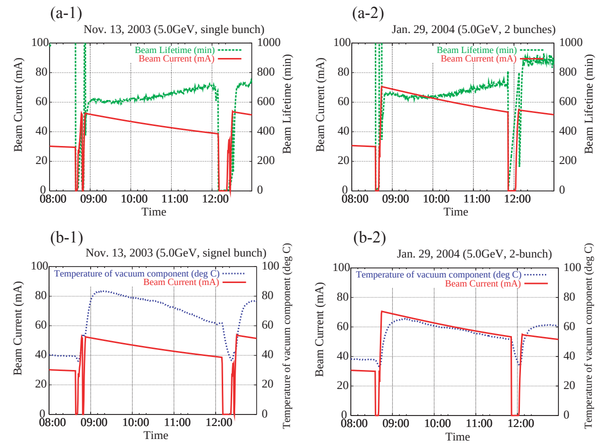

Figure 2: The beam current and the beam lifetime during the medical application for (a-1) single bunch and (a-2) 2-bunch operation. And the beam current and the temperature of the vacuum components adjacent to an RF cavity for (b-1) single bunch and (b-2) 2-bunch operation.

In order to achieve the 2-bunch injection, we improved the beam feedback system. The transverse feedback system has been used during the injection in order to suppress the beam instability at the injection energy of 3.0 GeV. However, the feedback system could function only in the single bunch operation. Without the feedback system, the beam instability limited the maximum beam current at about 10 mA. By improving the system so as to be able to stabilize 2-bunches, the beam current of 70 mA has been achieved. The temperature of the vacuum components dropped, and the sudden decrease of lifetime never occurred. The beam current and the beam lifetime during the medical application for single bunch and 2-bunch operation are shown in Figure 2-(a). Also, the temperature of the vacuum components is shown in Figure 2-(b).

In the future, we will optimize the 2-bunch operation to achieve the beam current over 80mA.

AIR TEMPERATURE STABILIZATION IN RING TUNNEL

In the PF-AR, it has been empirically known that machine condition is strongly affected by the temperatures in the ring-tunnel, although the reason is unclear. One example is a beamloss during ramping. When it was severe, adjustment of the machine parameters related to the operating point and RF systems did not help to improve the situation. Only solution, at that time, was to change the set values of the ring-tunnel temperature.

Air-conditioning for the PF-AR tunnel is controlled separately at four areas, north, east, south and west. Temperature is controlled around 24 °C. The temperature monitoring system was reinforced to investigate the temperature stability in the ring-tunnel. In the results, some behaviours were observed: 1) poor stability of temperature, 2) higher temperature in south and west areas, 3) over-cooling during short shutdown or low energy operation. Main sources of problems were turned out to be malfunction of controllers and aging components.

In order to stabilize the temperature, we renewed temperature controllers and optimized the set value of the tunnel temperature. The temperature condition in the PF-AR tunnel has much improved after that and the beamloss during the ramping have disappeared.

MEDIUM EMITTANCE OPERATION

At present the PF-AR is operated at an emittance of 290 nm·rad under 90-degrees optics in user operation. In this operating point the horizontal and vertical tunes are 10.15 and 10.21, the maximum beam current exceeds 60 mA in the single bunch mode, and the operation is quite stable.

Since the ring was designed as a booster synchrotron, the circumference is small as a 6.5 GeV light source. Consequently, the minimum practicable emittance is limited to 160 nm·rad under 140-degrees optics. In order to achieve the value for user operation, machine studies of the medium emittance optics have started in April 2003. In the machine study, we adjusted the injection parameters, the betatron tunes and the corrector magnets for the closed orbit distortion. As a result of the adjustments, electron could be stored at the medium emittance optics of which the horizontal and vertical tunes are 11.57 and 8.24. Figure 3 shows the optical functions of it. However, in the injection there are some issues: the rise in temperature of some vacuum components, the unstable injection, the limit of beam current at 30 mA and the short beam lifetime.

The temperature of some vacuum components reached about 100 °C during the injection. The temperature rise during the medium emittance operation was considerably lager than that during the normal emittance operation. The phenomena seem to relate to a fact that the bunch length at the medium emittance operation is somewhat shorter than that at the normal emittance operation. In order to elongate the bunch length, we will optimize the rf acceleration voltage or modulate the rf acceleration phase at the second harmonic of the synchrotron frequency.

The limitation of the stored beam current was observed at about 30 mA. It seems that the limitation is caused by the beam instabilities, which relate to the higher order modes of the RF cavities. In order to avoid such instabilities, we have to find and optimize operating point completely free from them.

In the future, we will try to tune the acceleration to 6.5 GeV and 2-bunch injection in order to increase the beam current further under the medium emittance optics. Also, in order to increase the beam lifetime, we will optimize the optical function.

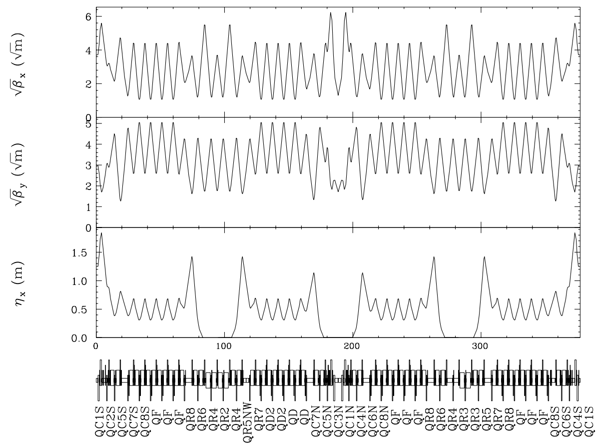

Figure 3: Optical functions in the PF-AR under the medium emittance optics.

TRANSFERRING RF CAVITIES

A new insertion device for the new beamline BL-NW14 will be installed in the west long straight section. However, in this section, there were four RF cavities. No space was there for the new insertion device. In order to make a space for new insertion device, the RF cavities were re-arranged in the summer of 2004 [5]. Two of the cavities in the west section were transferred to the east section.

DEVELOPMENT OF NEW INJECTION SCHEME

A new injection system with a single pulsed quadrupole (PQ) magnet without pulsed local bump made by dipole kickers has been developed in the PF-AR [6]. With this magnet, the oscillation amplitude of the injected beam can be reduced to about a half of that only with septum magnets and the reduced amplitude is almost the same as the case of the usual injection with the pulsed bump. The PQ-magnet was installed in the short straight section near the south symmetric point of the PF-AR in summer of 2004. And we succeeded in injecting beam to the storage ring during the machine study in in autumn, 2004.

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