ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF041

# LOW EMITTANCE LATTICE FOR PF-AR

N. Higashi*, K. Harada, S. Nagahashi, N. Nakamura, T. Obina, R. Takai, H. Takaki
KEK, Ibaraki, Japan
K. Hirano, Hiroshima University, Hiroshima, Japan

*Abstract*

PFAR is a synchrotron-type 6.5 GeV light source in KEK. The user-run was started in 1987, and the lattice is almost the same as the original one. Now we consider the emittance improvement to enlarge the horizontal tune advance in the normal cell. Thanks to this manipulation, the emittance will be improved to about a half of the current value.

## INTRODUCTION

PF-AR is a synchrotron-type 6.5 GeV light source,. Its circumference is 377 m, the emittance is about 300 nmrad, the beam current is about 50 mA with the single-bunch operation. Until 2016, the beam was injected to the ring with 3.0 GeV and accelerated to 6.5 GeV for the user-run. Now a new beam transport line dedicated for 6.5 GeV PF-AR was built, the user-run is operated with the full-energy injection [1]. Compared with the case of 6.5 GeV, the bunch length in the ring is shorter and the damping time is longer, therefore the effect of the beam-instability is more harmful in the case of 3.0 GeV. In addition, since the 6.5 GeV operation is performed using normal conduction cavities with a limited circumference, 6 modules of APS-type 21 multi-cell cavities are required. This made it difficult to avoid the effect of the beam instability due to the HOM excitation. The normal cell of PF-AR is the FODO structure. Therefore we can lower the emittance by increasing the tune-advance per cell. In the past, we have carried out a study on a low-emittance optics that reduced the emittance to about 160 nmrad, which is about half of the current one. However, it was difficult to accumulate large current and operate stably, and some equipments were damaged. Now that the injection energy is 6.5 GeV and the influence of the instability has been considerably improved, it is worth considering again the challenge to the low-emittance optics with considerable carefulness from the viewpoint of the equipment protection. Here, after reviewing the history and the results of the past studies, we will present what we need in the future study.

## PAST LOW EMITTANCE OPTICS

Firstly, the outline of the low emittance optics tried in the past study will be described here.

The beam parameters are summarized in Table 1. The normal cell of PF-AR is the FODO structure composed of QF-B-QD-B. By increasing the phase-advance per cell in the horizontal of the normal cell from 90 degrees to 140 degrees, the emittance is reduced to about 160 nmrad which is about half of the current value. As a result, it is possible to improve the brightness of light by about 2.3 times at 0.1 keV and about 3 times at 1.0 keV or more [2]. The increased current value of the electromagnet can be handled with the existing power supply. The low emittance optics is shown in Fig. 1. The starting point of the optics is the center of the south straight line, where the dispersion function is large because of the optics optimization at the adjacent old injection point. The dynamic aperture at the old injection point is about 65 mm for the current optics and about 25 mm for the low emittance optics, which is almost constant even if the momentum changes in the range of the RF bucket. Compared to the physical aperture, both dynamic aperture is wider than the physical aperture.

Table 1: Parameters of the Ring

| | Present Optics | Past Low Emittance Optics | |
|---|---|---|---|
| Circumference [m] | 377.26 | | |
| Phase advance / cell | | | |
| horizontal degree | 90 | 140 | |
| vertical degree | 90 | 40 | |
| Betatron tune | | | |
| horizontal | 10.14 | 11.84 | |
| vertical | 10.21 | 8.38 | |
| Chromaticity | | | |
| horizontal | -13.60 | -20.67 | |
| vertical | -13.37 | -14.78 | |
| Energy [GeV] | 6.5 | | 3.0 |
| Energy spread $\sigma_E$/E | $1.15 \times 10^{-3}$ | | $5.28 \times 10^{-4}$ |
| Energy loss [MeV/rev] | 6.661 | | 0.302 |
| RF voltage [MV] | 17.4 | | 3.0 |
| Damping time | | | |
| horizontal [msec] | 2.45 | | 24.95 |
| vertical [msec] | 2.46 | | 24.98 |
| longitudinal [msec] | 1.23 | | 12.50 |
| Emittance [nmrad] | 287.59 | 162.60 | 34.7 |
| Momentum compaction | $1.26 \times 10^{-2}$ | $7.50 \times 10^{-3}$ | $7.49 \times 10^{-3}$ |
| Synchrotron tune | 0.054 | 0.043 | 0.028 |
| Bunch length [mm] | 15.94 | 11.81 | 8.61 |
| Bucket height [%] | 0.84 | 1.30 | 1.06 |

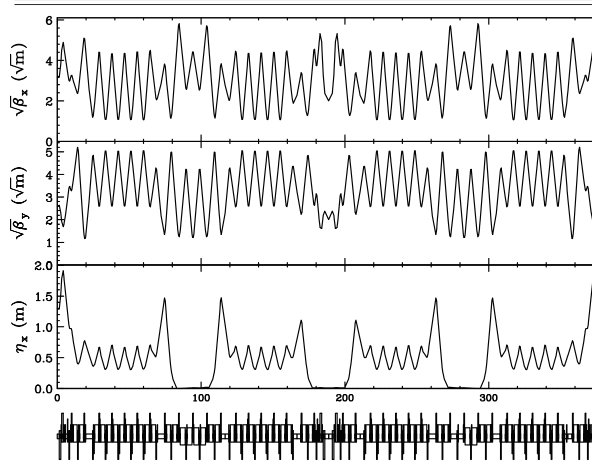


Figure 1: The past low emittance optics of PF-AR.

* nao.higashi@kek.jp

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF041

## PAST LOW EMITTANCE STUDY

The low emittance study oF PF-AR was tried for the first time in January 2003, and in that April a systematic study was started in earnest.

In the study on April 2, 2003, after about half a day adjustment, there are no difficulties to accumulate several mA, though the current could not be increased any more in spite of the continuous injection. After that, the recipe against the beam-instability (the adjustment of the RF voltage, the betatron tune, the octupole electromagnets, the bunch-by-bunch feedback and the chromatic aberration measurement / correction taking into consideration the head-tail instability) were carried out, then we succeeded in accumulating up to about 27 mA on the first day. After that, although we searched for the parameters that enabled the accumulation of 50 mA, which is the operating current, making various adjustments repeatedly, those could not be established.

On April 3, the various adjustments were continued, however the injection rate in the state of the accumulation was poor, the optimum parameters could not be established with good reproducibility and stability. Because of the long-running of the bunch-by-bunch feedback with high output, there occurred some troubles with three of the four RF amplifiers for the stripline kicker. And at around 5 pm, due to the RF trouble it became difficult to operate PF-AR any further. This was because there was a contact failure in the output cable of the HOM coupler of the RF cavity #1 on the west straight line, which was burned out and the vacuum leak was occurred [3]. It was presumed that more power than usual operation flowed from the HOM coupler to the dummy load due to the long accumulation study with the short bunch length in 3.0 GeV operation.

Because of the above troubles, the start of the user-run start was postponed and the recovery operation of the RF was conducted. After that, the vacuuming and the aging were progressed smoothly, however when the beam commissioning was started, a discharge trouble happened at the west RF #3 cavity, and it had never been improved with the continuous aging. In response to this, the West RF cavity #3 was detuned and the waveguide was separated from the klystron, and the user-run was resumed with 3 cavities in the west on April 14.

After this trouble, we conducted two studies in October 2003 and June 2004 in order to establish the optimum injection parameters taking into account for an acceleration / deceleration loop between 3.0 GeV and 6.5 GeV, however the reproducibility and the stability was poor as the same with in the former study, and the accumulated current had never achieved 30 mA. To make matters worse, the beam of 3.4 GeV in the acceleration step was lost and had never achieved 6.5 GeV.

In the summer of 2004, remodeling was carried out to change the cavity configuration and add the insertion device (ID) in the west straight section. The cavity configuration was changed from 4 cavities in west and 2 cavities in east to 2 in west and 4 in east. And the ID was placed at the vacant space used for the cavities. In this process, the West RF cavity #3 was taken away and the backup cavities were placed at the east straight section [4].

In October and December 2004 after the RF restoration was completed, beam studies were resumed to search the optimum injection parameters, however these ended with lack of reproducibility and stability.

Since 2005, the establishment of the stability and the reproductivity of the injection became the first priority for the study including the stability of the air-conditioning and cooling water. The most difficult point in the operation of PF-AR was the lack of completely established parameters, which was a salient problem with the low emittance optics. At that time, this problem was recognized even at the usual injection, and various parameters were always adjusted for the stable operation.

While the low emittance optics study has not been conducted since 2005, the stability of the cooling water and the air-conditioning has been established to some extent thanks to the beam studies and adjustments. Now the number of the stagnation of the injection is decreasing.

## TRY LOW EMITTANCE OPTICS AGAIN

There have been some changes in PF-AR from 2003 and 2004 to the present. Among them, what work as advantages for the low emittance optics are

1. the full-energy injection with 6.5 GeV
2. the protection of the RF amplifiers for the stripline kicker
3. the monitoring of the temperature of the HOM damper cables.

1 means the construction of the direct beam transport line dedicated for PF-AR in 2017 and this enables the full-energy injection of 6.5 GeV, same as the ring energy. As a result, the damping time got about 1/10 compared with the case of the injection of 3.0 GeV, and the various instabilities are expected to be suppressed (Table 1). However, it needs more attention that the energy loss during the injection will be more severe in the case of 6.5 GeV injection.

2 indicates the new circuit protection after the accident occurred in the low emittance optics study in 2003. Originally the bunch-by-bunch feedback is intended to suppress the instability at 3.0 GeV injection and its effect seems to be small at 6.5 GeV, however the possibility of the accident like what happened in 2003 is eliminated.

3 is a measure for the accident occurred in 2003, and the temperature is always monitored during the operation. In addition, the temperature is included in the interlock system to eliminate the risk of the accident similar to the one happened in 2003.

On the other hand, in order to realize the low emittance optics, we have to pay attention to new factors:

1. the RF mask

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF041



Table 2: Comparison of Physical Aperture

| | $\varepsilon_x$ [nmrad] | $\Delta p/p$ | $\beta_x$ [m] | $\eta_x$ [m] | $\sigma_x$ [mm] | PA$_x$ [mm] | PA$_x$ [$\sigma_x$] |
|---|---|---|---|---|---|---|---|
| New Injection Point | 288 | $1.15 \times 10^{-3}$ | 18.5 | 1.34 | 2.78 | 28.0 | 10.1 |
| RF Mask | | | 11.7 | -0.05 | 1.84 | 19.0 | 10.3 |
| New Injection Point | 163 | $1.14 \times 10^{-3}$ | 13.6 | 1.42 | 2.20 | 28.0 | 12.7 |
| RF Mask | | | 27.8 | 0.00 | 2.13 | 19.0 | 8.93 |

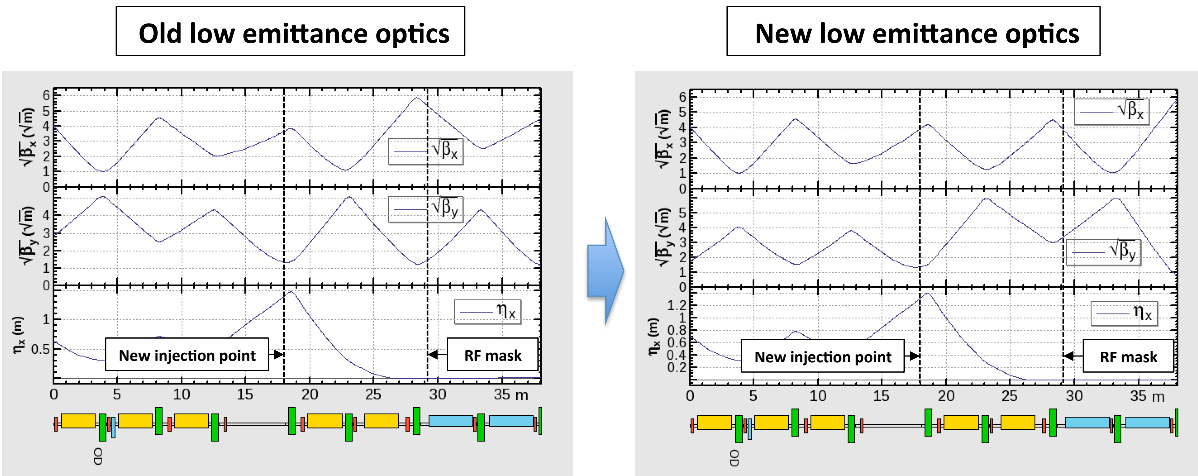


Figure 2: Optics of the low emittance ring. The left is the old optics designed for the study conducted in 2003 and 2004. The right is the design talking into account the existence of the RF mask with 19 mm-aperture.

2. the reduction of the number of the kicker magnet
3. the limitation of the optics due to the relocation of the injection point.

1 was installed in order to protect the accelerating cavity from the synchrotron radiation in 2007 [5]. This is a minimum physical aperture of 19 mm, and the mask will be radio-activated if the wider beam than the mask aperture passes through it. Table 2 summarizes the physical aperture in the case of the current optics with the emittance of 288 nmrad and in the case of the low emittance. Where $\sigma_x$ is the horizontal beam size and PA indicates the physical aperture. PA $_x$ [$\sigma_x$] is the value of the PA normalized by the beam size. In the current optics, the RF mask is wider than the new injection point, therefore the beam does not interfere with the RF mask. However, in the case of the low emittance optics with the new injection point, the RF mask becomes narrower.

2 reduces the degree of freedom for the injection. With the old injection point, there were four kicker magnets, and $x$ and $x'$ could be set independently. However with the new injection point, the number of the kicker magnets decreased to 3, then we cannot set $x$ and $x'$ individually.

3 means that with the old injection point it was possible to design the optics with some allowance because there is no restriction on the optics on the south section, however the optics design is restricted due to the relocation of the new injection point to the south-west section where the RF cavity is placed.

As explained above, there are some constraints that have not existed in the past, however we are currently designing a new low emittance optics that satisfies all these requirements. One example is shown in Fig. 2. In the past low emittance optics, the $\beta_x$ at the new injection point is smaller than the $\beta_x$ in the RF mask. A new optics need to reduce this difference or reverse the relationship of the magnitude.

## SUMMARY

PF-AR is a synchrotron radiation facility of 6.5 GeV, however its optics design has almost unchanged since the start of the user-run in 1987. We conducted the low emittance optics studies by changing the tune advance in 2003 and 2004, however these caused various equipment failures due to the repetition of the injection under the strong instability. In 2017, a new beam transport line dedicated for PF-AR was built. This enables the full-energy injection with 6.5 GeV same as the ring energy, and the beam instability is expected to be suppressed. To make use of this, we will carry out a study aiming at the low emittance optics again in this year.

## REFERENCES

[1] Nao Higashi, Seiji Asaoka, Kazuro Furukawa *et al.*, "Construction and commissioning of direct beam transport line for PF-AR", Journal of Physics: Conf. Series 874 (2017) 012024.

[2] Y. Kobayashi, "Low emittance operation of PF and PF-AR" in Japanese, The 22th PF Symposium, (2005).

[3] T. Kasuga, "Current status of PF and PF-AR" in Japanese, PF News, Vol.21, No.1, (2003).

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF041

[4] T. Kasuga, "Current status of PF and PF-AR" in Japanese, PF News, Vol.22, No.2, (2004).

[5] T. Takahashi *et al.*, "Installation and beam test of movable synchrotron mask for PF-AR accelerating cavity", PF-RING REPORT 905, (2007).