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PRESENT STATUS OF NAR

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Abstract

Transverse coupled bunch instability, ion trapping effect, and closed orbit distortion are shown to be fundamental problems of NTT normal-conducting accelerating ring (NAR), which adopted extremely low injection energy (15 MeV). Elucidation of these problems as well as present status of NAR are presented.

1. Introduction

NTT LSI Laboratories have constructed their own synchrotron radiation (SR) facility to develop X-ray lithography system. The facility consists of two storage rings, NAR [1)] and Super-ALIS [2)], and injector LINAC [3)]. NAR is a multi-purpose ring which functions as a booster synchrotron for Super-ALIS and as a storage ring for SR applications.

To minimize the size and cost of injector LINAC, low injection energy (15 MeV) is adopted. Therefore, beam dynamics in low energy region had to be clarified to attain enough beam current. Outline of NAR is shown in Fig. 1 and fundamental parameters are listed in table 1.

Operation of NAR started in November 1987. We succeeded in extracting SR in May 1988. A beam current was about 20 mA at the beginning and stayed the same level for a few years. At injection energy, because of the short life time and the lack of appropriate monitors, we had difficulties in analyzing the phenomena and improving the beam current. Closed orbit distortion due to small magnetic fields or magnet displacement also offered serious problems. With difficulty, transverse coupled bunch instability and ion trapping effect were shown to be current limiting factors. As a result of solving these problems, as much as 120 mA could be stored.

Table 1.
NAR parameters

	(designed)	(achieved)
Final energy	800 MeV	
Injection energy	15 MeV	
Circumference	52.8 m	
Radio frequency	125 MHz	124.985 MHz
Beam current	500 mA	120 mA
Betatron tunes		
ν_x	3.25	3.15
ν_y	1.25	1.46

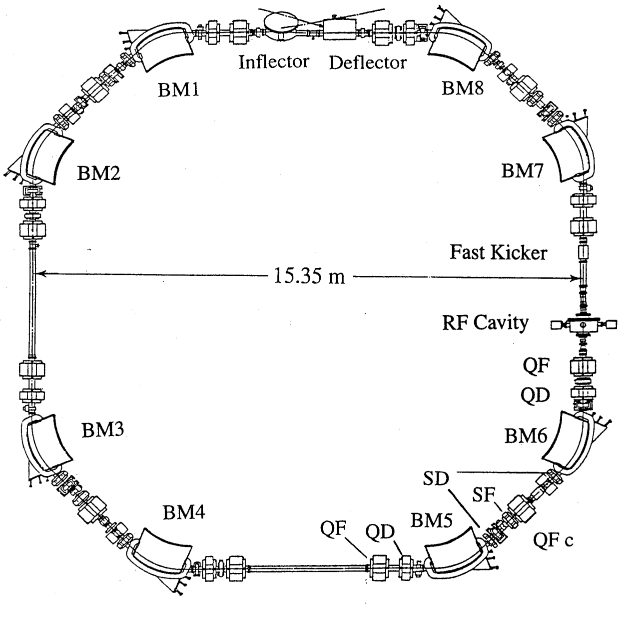

Fig. 1 Outline of NAR

On the other hand, we succeeded in extracting high energy electrons to inject Super-ALIS in 1992. Super-ALIS, which could have stored 200 mA with low energy injection scheme, attained more than 700 mA by injecting high energy electrons from NAR.

In this paper, improving process and present status of NAR are presented. Problems peculiar to low energy injection are also described.

2. Improvement Process and Present Status of NAR

Improvement process of NAR beam current is shown in Fig. 2. At the beginning of the operation, current limiting factors were not clear and suitable parameters were surveyed without any reference. In May 1991, the beam current increased by adjusting RF modulation pattern during acceleration but the reason why the modulation is effective was not clear. We can explain now that transverse coupled bunch instability was avoided by this modulation. The alignment of magnets suddenly displaced in October 1991 and then re-alignment were performed immediately. Closed orbit distortion was also corrected again both at injection and during storage. Octupole magnets were newly installed in April 1993 because transverse coupled bunch instability was shown to limit the beam current of NAR. After all, we can store maximum 120 mA. Although it is not shown explicitly in this improving process, the decrease of vacuum pressure also seems to contribute to the current increase because ion trapping effect became somewhat suppressed. These problems are described later.

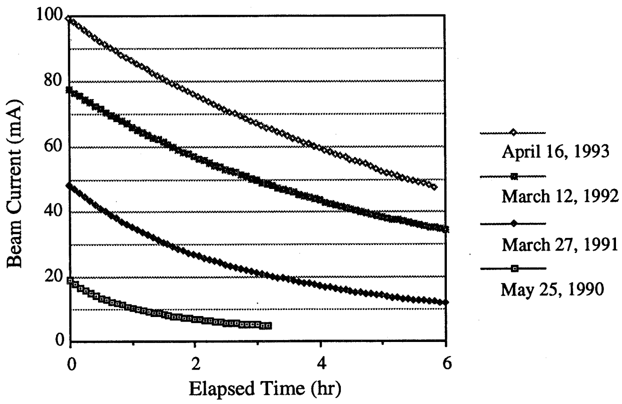

Fig. 2 Improvement process of NAR

In NAR, six beamlines have been constructed and are used. Normally, three days a week (Wednesdays, Thursdays, and Fridays) are used for SR applications. The other two weekdays (Mondays and Tuesdays) are used for machine study or system maintenance of NAR and/or Super-ALIS.

3. Problems of Low Energy Injection Scheme

Through the machine study of NAR, several problems of low energy injection scheme were shown. These problems are summarized here.

As lower energy electrons are more liable to be affected by electromagnetic fields, collective phenomena such as beam instabilities are apt to be induced. However, in such low energy as adopted in NAR, radiation damping time is so long that large beam size at injection preserves over a long period. Large beam size may weaken the collective phenomena. Therefore, the effect cannot be estimated simply from electron energy. For example, average beam size of NAR at injection is estimated as large as $(\sigma_x, \sigma_y) = (5\ \mathrm{mm}, 2\ \mathrm{mm})$ by simulation while the size in final energy is calculated as $(\sigma_x, \sigma_y) = (1.2\ \mathrm{mm}, 0.35\ \mathrm{mm})$ from theory. Longitudinal beam size (bunch length) at injection is also much larger than that in storage. This beam size difference affects drastically in case of transverse coupled bunch instability or ion trapping effect. The analyses are described later.

Concerning single particle behavior, closed orbit distortion due to small magnetic fields such as geomagnetism or residual fields is fatal. More than a few tens milli-meters closed orbit distortion is roughly estimated. Meanwhile, the velocity of low energy (15 MeV) electrons is not so close to the light velocity that the electrons in NAR can be accelerated without radio frequency modulation $^{4)}$.

The reproducibility worsens at injection in case of NAR because the stability limit required to magnet sources is determined supposing the stability in final energy.

4. Transverse coupled bunch instability

Abrupt loss of electrons is often observed just after injection or in the middle of acceleration. Whether the electron loss occurs or not or when the loss occurs depends on various injection conditions. Furthermore, once the loss occurs, electrons are lost immediately. These factors made it difficult to examine the case.

Judging from the symptom, the phenomena were supposed to be due to transverse coupled bunch instability. To ascertain this assumption, it is difficult to use conventional method, that is, observing the corresponding peak in RF pick up signal with spectrum analyzer because the loss occurs faster than the scanning speed of spectrum analyzer. Fortunately, the higher order mode of RF cavity was measured before the installation and TM110-like mode was supposed to cause the instability. RF pick up signal was observed with a spectrum analyzer triggered by injection pulse. The center frequency was set nearby 493.5 MHz (the corresponding frequency of TM110-like mode) and the frequency span was set to 0 MHz. The timing of beam loss was monitored by fundamental mode frequency component of RF pick up signal. As shown in Fig. 3, the frequency component near by TM110-like mode appears in the beam signal in coincidence with beam loss. This is a distinct proof that the beam loss is due to transverse coupled bunch instability induced by TM110-like mode RF cavity.

As a result of above experiment, we decided to introduce four octupole magnets. Then we could store more than 100 mA.

Meanwhile, transverse coupled bunch instability shows an interesting aspect in low energy region $^{5)}$. The strength (growth rate) of the instability is expressed by the following formula $^{6)}$,

$$\frac{1}{\tau_{\mathrm{inst}}} = \frac{eIf_0\beta_{\mathrm{cav}}}{2E}\,\mathrm{Re}\,Z(|f_{m,n}|)\,F(f_{m,n})$$

where e is the electron charge, I is the beam current, f_0 is the revolution frequency, β_{cav} is the betatron function at the RF cavity, E is the electron energy, Re Z is the real part of transverse coupling impedance and F' is the form factor. F' represents the frequency components of an electron bunch. The center of F' is determined by chromaticity of the ring while the width of F' is inversely proportional to the bunch length. The value of F' at higher order mode frequency determines the strength of transverse coupled bunch instability. From the shape of F' distribution, it is clear that the instability is slightly dependent on chromaticity in final energy whereas it has strong dependence at injection energy. Fig 4 is the chromaticity dependence of the transverse couple bunch instability observed in NAR at injection energy. The strength of the instability is measured by the octupole current required to suppress the instability. That is, direct observation of the form factor distribution became possible in low energy injection storage ring.

As the electron energy increases, the bunch length shortens and the width of the form factor becomes wide. Accordingly, even though the transverse coupled bunch instability can be avoided by controlling the chromaticity, it cannot help occurring in the middle of acceleration. This is one of the reasons why transverse coupled bunch instability occurs at rather high energy.

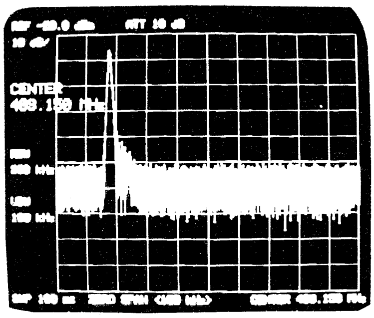

Fig 3. RF pick-up signal with the occurrence of transverse coupled bunch instability

5. Ion Trapping Effect

NAR has 12 button type electrodes to clear trapped ions. The high voltage of 200 V and 800 V is applied to the electrodes during injection and storage. They are effective but seem to be insufficient to clear ions completely.

At injection, the life time is much shorter than expected from vacuum pressure. This is supposed to be due to trapped ions which may be stored in neutralization pocket even if clearing electrodes are used $^{7)}$. This phenomenon seems to limit the beam current of NAR.

6. Closed Orbit Distortion

In NAR, which adopted 15 MeV injection energy, closed orbit distortion due to geomagnetism, residual fields from magnets, and leakage fields from Super-ALIS can be more than a few tens mm without correction.

As for geomagnetism, assuming the flat distribution of geomagnetism of 0.3 tesla in the straight section of 3.5 meters long, 15 MeV electrons are kicked about 2.1 mrad. Therefore, electrons cannot circulate the ring without correcting the effect of geomagnetism. To cancel the geomagnetism, solenoid coils are set at the two long straight section reserved for insertion devices. However, it is impossible to cancel the geomagnetism which exists narrow spaces between the magnets. Then, closed orbit distortion is corrected by the steering magnets together with the effects of residual fields or alignment errors of multi-pole magnets.

The effects of residual fields of magnets are also examined. NAR consists of several kinds of magnets which have iron poles. The injection energy of NAR is 1 / 50 times as small as the final energy. As a result, residual fields of the iron poles are not

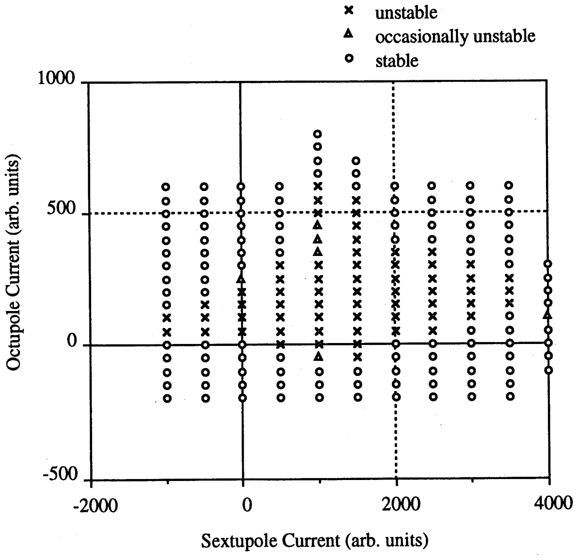

Fig. 4 Chromaticity dependence of transverse coupled bunch instability

negligible after magnetization. Even if the sextuple magnets or steering magnets are not magnetized, they get magnetized by the leakage field from the bending magnets which are fully magnetized. The residual field reaches a few gausses. Accordingly, magnets which are connected to bipolar power sources are demagnetized before routine operation. The other magnets with uni-polar power sources are used after the same magnetization pattern so that the reappearance of residual field is guaranteed. Then, closed orbit distortion can be corrected by steering magnets without adjusting in each operation.

Closed orbit distortion is also caused by leakage field from Super-ALIS though the situation is unique to our system. If the superconducting bending magnets in Super-ALIS are magnetized fully, the leakage fields attains as much as a few gausses on the NAR orbit. Luckily, if the current of the solenoid coil placed at the nearest long straight section from Super-ALIS is sent properly, the closed orbit distortion due to the leakage field can be roughly corrected.

7. Reproducibility

One of the problems that makes machine study at early stage complicated is bad reproducibility of injection experiment.

One of the distinct reasons is the offset change of magnet power sources. Power sources of bending or quadrupole magnets are designed to achieve 10^{-4} stability against maximum output. However, this stability correspond to as much as 0.5 % against injection level. Moreover, the accuracy and stability of 10^{-4} are secured by the feedback system from the output current monitors (DCCT) to power sources but the offset value of this DCCT shows long term shift which results in the bad reproducibility of output current.

Another reason which affect the reproducibility is the characteristic change of LINAC. Energy, current, or position of electrons from LINAC changes slightly per pulse. After an interval, LINAC sometimes shows larger characteristic shift. In consequence, adjustment of microwave output is required in routine operation.

The reproducibility at injection is determined by various conditions but main factors are focused on the reasons described above.

8. Magnet Displacement

Another factor which made machine study more difficult is the displacement of the magnets. When we measured the vertical alignment of the magnets a few years after the installation, more than a few milli-meters alignment errors were found out (Fig. 5). These alignment errors are very large considering the error limit at initial installation is less than 0.1 milli-meters. When this displacement happened is not clear. As the operation condition was adjusted under these alignment errors, no correction was made even though these alignment errors were detected.

Moreover, the alignment suddenly changed in September 1991 (Fig. 5). The change must have happened in a week during which no-one used SR. An earthquake which happened in the middle of this interval might have caused this displacement. Fig. 5 shows the similarity between the original magnet displacement and the second alignment change. This similarity suggests that these displacements are caused by the same reason.

The second alignment change result in decrease of injection current and movement of SR position which could not be corrected satisfactorily with steering magnets. In consequence, the vertical re-alignment was performed and closed orbit distortion was re-corrected with steering magnets both at injection and during storage.

9. Shortening of Life

During the storage, sudden change of beam life is sometimes observed. Two kinds of life shortening seem to exist.

One of them is thought to be caused by dust particles trapped in electron beam. In this case, the life can be recovered by changing the electron orbit with steering magnets. The response time of steering magnets is so slow that lighter particles such as ions cannot escape. No distinct change in beam profile is observed before and after the shortening and the life changes sharply.

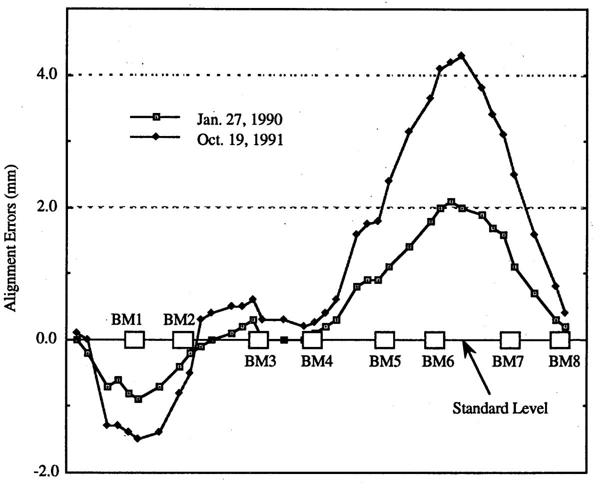

Fig. 5 Magnet displacement observed in NAR

The other seems to be related to ion trapping. According to the beam profile monitor, the vertical beam size changes before and after shortening of life. The life seems to be determined by touschek life from its dependence on RF voltage. This phenomenon is interpreted as follows. Trapped ions causes the coupling between horizontal and vertical oscillation. As a result, the enlargement of vertical beam size and the increase of bunch volume make touschek life longer. Trapped ions happen to escape and the decrease of vertical beam size and bunch volume shortens touschek life. In this case, the life cannot be cured by changing electron orbit with steering magnets and the life changes gradually.

10. Summary

After the first SR from NAR was extracted in 1988, it took about five years to improve the beam current and achieve more than 100 mA. The machine study at injection was complicated and difficult because a couple of factors limited the beam current and the reproducibility was not good. After all, the current limitation could be attributed to individual factors, i.e., transverse coupled bunch instability, ion trapping effect, and closed orbit distortion. At present, these phenomena can be examined independently.

While low injection method required several efforts, some interesting phenomena such as chromaticity dependence of transverse coupled bunch instability can be observed because the electron beam size is large in such low energy.

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