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Citation: Review of Scientific Instruments **63**, 753 (1992); doi: 10.1063/1.1142652
View online: http://dx.doi.org/10.1063/1.1142652
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# Superconducting storage ring NIJI-III

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(Presented on 16 July 1991)

NIJI-III is a compact, superconducting storage ring dedicated for use in several commercial applications, especially x-ray lithography. Assembly of the ring has been completed and NIJI-III has been operating since August 1990. A beam current of above 450 mA was attained at an injection energy of 280 MeV. Currents of more than 200 mA can be accumulated at the final energy of 600 MeV.

## I. INTRODUCTION

Recently, synchrotron radiation (SR) has been regarded as a practical light source for x-ray lithography. Sumitomo Electric Industries, Ltd. (SEI) has been developing a superconducting storage ring since 1986, called NIJI-III (NIJI means rainbow in Japanese). NIJI-III is dedicated for use in several commercial applications, especially x-ray lithography. A peak SR wavelength of ~5 Å can be achieved with a magnetic field strength of 4 T in each bending magnet. Two SR ports can be provided in each bending magnet. To expose a field of 50×50 mm, an electron-beam wobbling method is adopted in order to expand the exposure area in the vertical direction. The effect of the beam wobbling on a stored beam has been examined through research. This research confirmed, as will be discussed in Sec. IV, that there was no disturbance of the stable conditions of the stored beam by the beam wobbling.

## II. GENERAL DESCRIPTION OF NIJI-III

### A. Design (Refs. 1 and 2)

The main parameters and the schematic configuration of NIJI-III are shown in Table I and Fig. 1, respectively. NIJI-III is a rectangular-type ring with approximate dimensions of 3×5 m. The advantage of this design is its flexibility on lattice structure. A dispersion-free condition can be obtained in the long straight section. Also, an emittance of $2.67 \times 10^{-7}$ mrad can be obtained through small dispersion functions in the bending section. It is the key issue for realizing a small beam size at the light source point. Both horizontal and vertical beam sizes are smaller than 0.5 mm in the bending sections, which sufficiently satisfies the requirement for quarter-micron resolution needed for x-ray lithography.

The superconducting bending magnet consists of two coils: a main dipole coil to produce a dipole magnetic field, and a quadrupole coil to adjust a field. This index can be varied from 0 to 0.5 by adjusting the excitation current of the quadrupole coil. The superconducting bending magnet used in NIJI-III can produce a maximum magnetic field of 4 T. The problem of magnetic saturation is avoided by using an iron-free, curved magnet design. The superconducting coils, mounted directly on the beam chamber, are cooled down to liquid-helium temperature with the beam chamber. This combination acts as a cryosorption pump with a pumping speed of 5000 ℓ/s for nitrogen gas.[3]

### B. Injection performance

A maximum stored current of above 450 mA was obtained at the injection energy. Also, the maximum accumulation rate of 150 mA/min was obtained. The optimum horizontal and vertical betatron tunes of 2.22 and 1.20, respectively, agree with the designed values. Dispersion functions were estimated by measuring the change of closed orbit distortion associated with the rf frequency shift. Achromatic conditions are nearly realized in the long straight sections, as shown in Fig. 2.

### C. Acceleration performance

Accelerating the stored beam to the final energy of 600 MeV is accomplished by ramping all magnets simultaneously. Beam acceleration has been carried out in which currents of more than 200 mA could be accumulated at the final beam energy. The ramping performance at the usual operation is shown in Fig. 3. The beam lifetime was ~130 min for the stored current of 200 mA at 600 MeV. Since the lifetime is thought to be limited by the vacuum pressure of $1 \times 10^{-8}$ Torr, the lifetime will be lengthened by a decrease in pressure rise.

TABLE I. Main parameters of NIJI-III.

| | |
|---|---|
| Stored energy | 600 MeV |
| Bending magnetic field | 4 T |
| Bending radius | 0.5 m |
| Circumference | 15.5 m |
| Radiation loss | 23 keV/turn |
| Harmonic number | 8 |
| Critical wavelength | 13 Å |
| Betatron tune (horizontal) | 2.25 |
| (vertical) | 1.25 |
| Natural emittance | $2.67 \times 10^{-7}$ mrad |



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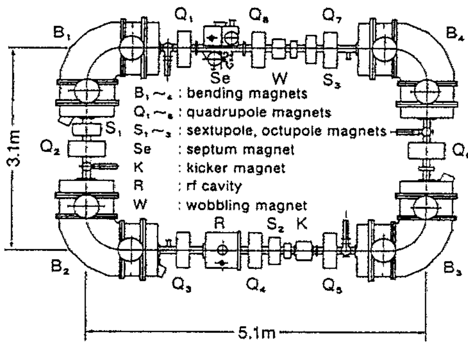


FIG. 1. Schematic configuration of NIJI-III.

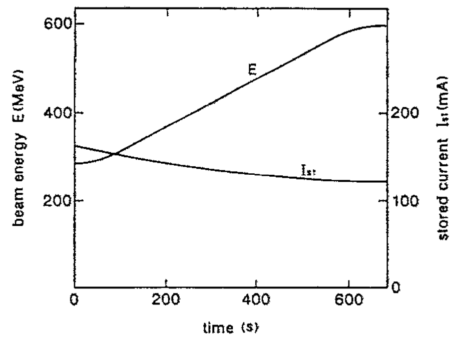


FIG. 3. Ramping performance at the usual operation.

## III. BEAM INSTABILITY

Longitudinal coupled bunch instability has been observed in NIJI-III at the injection energy. Synchrotron sidebands were clearly observed around the harmonics of the revolution frequency even with a stored current of $<5$ mA. The sidebands included not only a dipole-oscillation mode but also other multipole-oscillation modes. The spectral amplitude of these oscillations were slowly fluctuating. A frequency of the fluctuation was $\sim 75$ Hz. This is correlated to a coherent motion in longitudinal phase space.

Stored beam current was occasionally limited at 50 mA under the conditions with high overvoltage factor of $\sim 30$. Adjustment of the rf cavity conditions, in particular, overvoltage factor and plunger position, was very effective to avoid this limitation. Figure 4 shows an overvoltage factor dependence of the strength of dipole-mode sidebands which indicates the amplitude of its oscillation. It can be seen that the amplitude varies with the plunger position at the same overvoltage factor and the amplitude increases with the overvoltage factor. The former phenomena is due to the longitudinal coupling impedance of the higher order modes varying with the resonance frequency shift. This frequency shift is caused by a change in the plunger position. The latter is thought to be due to Landau damping. According to the stability criterion,[4,5] the Landau damping time increases with the overvoltage factor. This relation takes into account the measured bunch-lengthening dependence of the overvoltage factor. Landau damping time is dominant in suppressing the amplitude growth, because it is about 100 times faster than radiation-damping time at the injection energy. Therefore, the overvoltage factor should be sufficiently small to produce instability growth but should be large enough to provide a sufficiently large quantum lifetime.

Beam size growth due to a longitudinal coupled bunch instability was also examined. The horizontal and vertical beam sizes were measured using a CCD camera. The sizes, as a function of the beam energy, are shown in Fig. 5. The solid and dashed lines indicate the calculated beam sizes without the instability effect. It can be seen that the beam size growth is remarkable in the low-energy region and gradually decreases with an increase in beam energy. The beam sizes are smaller than 0.5 mm at the final energy of 600 MeV. Therefore, the beam size growth is not significant at the final energy.

## IV. ELECTRON-BEAM WOBBLING

It is well known that the vertical divergence of SR from the bending magnet is very small for application as a light source for x-ray lithography. Therefore, a method for solving this problem is required and several methods have already been proposed.[6] An electron-beam wobbling method, proposed by Tomimasu,[7] is adopted in an ac horizontal magnetic field used to produce a perturbation of the beam orbit. A conceptual outline of this method is shown

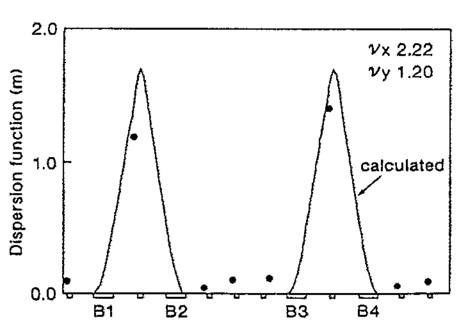


FIG. 2. Dispersion functions. The solid circles and solid lines represent the measured values and calculated values, respectively.

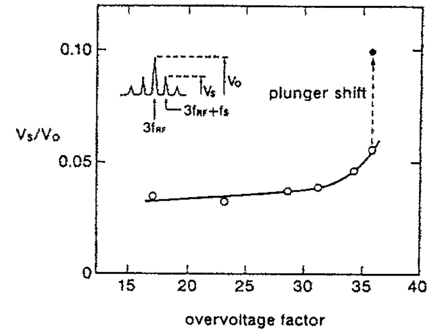


FIG. 4. Overvoltage factor dependence of the strength of dipole-mode sideband. (1) Plunger pulled down 41 mm from the inner surface of the rf cavity (open circles); (2) in case of 20 mm (solid circles).



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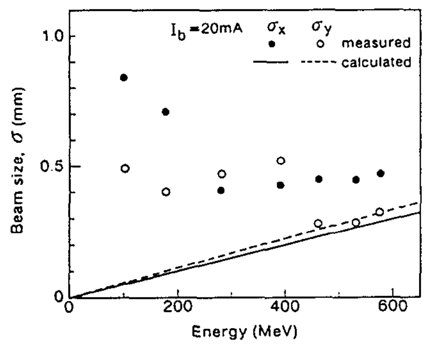


FIG. 5. Energy dependence of beam sizes.

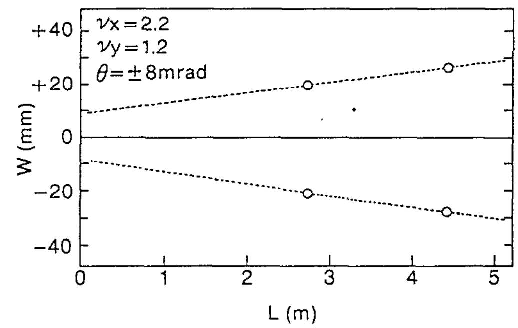


FIG. 7. Vertical displacement of the exposed-area center. The horizontal axis ($L$) means the distance from the SR light source point. The vertical axis ($W$) means the displacement of the exposed-area center.

in Fig. 6. This method is the most attractive because of the following properties:

(1) intensity of SR is not absorbed by the component in the beam line; (2) there are no moving parts in the beam line; (3) spectral distribution of SR is scarcely changed; and (4) provides easy control of the scan width and speed of SR exposure.

However, it is suspected that undesirable influences, such as tune shift, beam lifetime shortening, and growth of beam instability may occur with a large perturbation of the electron-beam orbit. Takada and Tomimasu[6] have already examined the tune shift using a dc steering magnet installed in NIJI-I (a normal conducting compact storage ring). They concluded that the tune shift was extremely small and that there was no disturbance of the stable conditions of the stored beam.

Electron-beam wobbling was carried out using an ac wobbling magnet installed in NIJI-III. The wobbling magnet consists of piled silicon steel sheets. The frequency of operation varies from 0 to 20 Hz. The power supply for the wobbling magnet generates a triangle-shaped current driven by a function generator.

### A. Exposed-area expansion

Figure 7 shows vertical displacement of the exposed-area center as a function of the distance from the SR light source point. The kick angle of the wobbling magnet is 8 mrad and the vertical tune is 1.2. The exposed area could be expanded to be wider than 50 mm at the distance of 4 m.

Beam positions at eight points along the ring were measured by the electrostatic monitor with a kick angle of 5.0 mrad. Figure 8 shows the results of the measured beam positions in comparison with the calculated beam orbit.

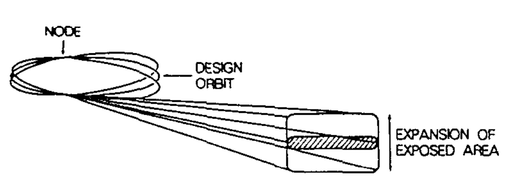


FIG. 6. Conceptual outline of the electron-beam wobbling method.

Both values agree quite well, although the calculation only considers a linear lattice perturbation.

### B. Beam lifetime

The effect of electron wobbling on the beam lifetime was also examined. It is suspected that the lifetime of an electron beam that experiences large orbit perturbations may be shortened by the following mechanisms: a decrease in the effective aperture of the beam chamber, and an increase in the gas desorption associated with SR irradiation of a wide area of the SR absorber which is installed inside the beam chamber. Figure 9 shows the lifetime and vacuum pressure as a function of the kick angle of the wobbling magnet. This relation indicates that the lifetime is virtually uneffected by a variation of the kick angle from 0 to 8.1 mrad. For an increasing kick angle of $>8.1$ mrad, the beam lifetime radically decreases. The vacuum pressure slightly increases with an increase in the kick angle but does not change enough to be the reason for the radical decrease in beam lifetime. Therefore, the beam lifetime is not restricted by the increase in gas desorption. However, at a kick angle of 8.1 mrad, the maximum orbit distortion is 25 mm which is close to the physical aperture of the beam chamber. It can be concluded that the decrease in the lifetime is correlated to the decrease in the effective aperture of the beam chamber in this present condition.

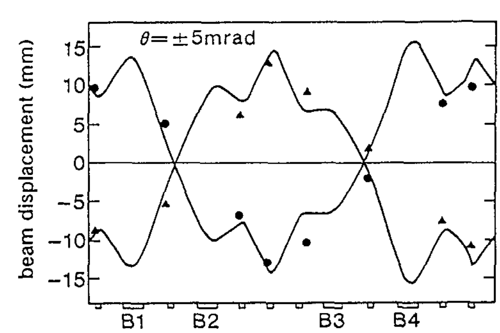


FIG. 8. Displacement of the beam orbit in the vertical direction. Solid circles and triangles indicate the measured beam positions with a kick angle of 5.0 mrad. Solid lines indicate the calculated orbit with a linear lattice perturbation.

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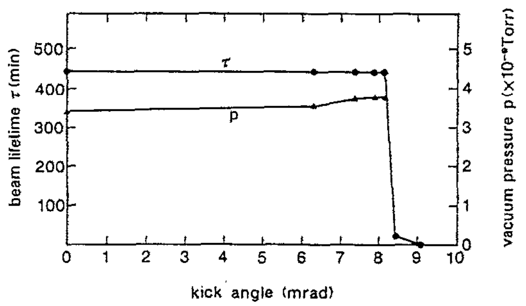


FIG. 9. Beam lifetime and vacuum pressure as a function of the kick angle of the wobbling magnet.

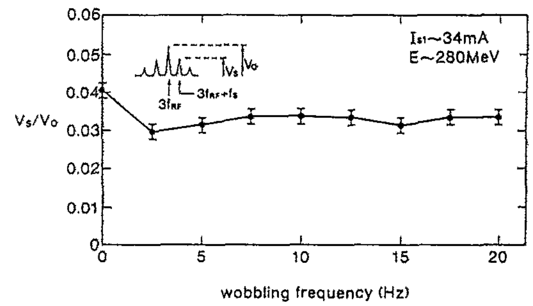


FIG. 10. Strength of dipole-mode sideband dependence of a wobbling frequency.

### C. Beam instability growth

An electromagnetic wave is generated in the surrounding environment of the beam by the coherent oscillation associated with the beam wobbling. However, this wave does not lead to a beam instability such as the coupled bunch instability. This is because the frequency of the coherent oscillation generated by a coupled bunch instability is quite different from the wobbling frequency. Low-frequency fluctuation of the phase oscillation, typically 75 Hz in NIJI-III, occurs due to a longitudinal coupled bunch instability as mentioned in Sec. III. This frequency is close to the wobbling frequency. Therefore, it is very important to examine the dependence of the growth rate of the longitudinal coupled bunch instability on the wobbling frequency. Figure 10 shows the strength of the dipole-mode sideband as a function of the wobbling frequency. Remarkably, no changes were observed. It can be concluded that the additional beam instability growth does not occur due to the beam wobbling.

## V. CONCLUSIONS

The superconducting storage ring NIJI-III has been operated. A beam current of above 450 mA was attained at the injection energy. The maximum accumulation rate is $\sim 150$ mA/min. Currents of more than 200 mA could be accumulated at the final energy. Under these conditions, the beam lifetime, $\sim 130$ min, was thought to be limited by the vacuum pressure.

Longitudinal coupled bunch instability has been observed in NIJI-III. The overvoltage factor should be small so as to suppress this instability. This mechanism is explained by the Landau damping effect.

Electron-beam wobbling was carried out using an ac wobbling magnet. The following influences of beam wobbling on the stored beam were examined: exposed-area expansion, beam lifetime shortening, and beam instability growth. It was confirmed that there was no disturbance of the stable conditions of the stored beam by the beam wobbling.


## ACKNOWLEDGMENTS

The authors would like to thank the staff of the High Energy Radiation Section in Electrotechnical Laboratory and the engineers of SEI for their support. Also, the authors wish to thank J. Fitzsimmons for his critical reading of this manuscript. This project was entrusted by the Research Development Corporation of Japan.



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