DEVELOPMENT OF A SUPERCONDUCTING COMPACT STORAGE RING "NIJI-Ⅲ" FOR INDUSTRIAL APPLICATION

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ABSTRACT

We have developed a superconducting compact storage ring "NIJI-Ⅲ" for industrial application. The configuration of NIJI-Ⅲ is a four-cornerd type whose size is typically 3m x 5m. Since this ring is designed for x-ray lithography, a peak wavelength of the synchrotron radiation spectrum is set about 5 Å and this ring is capable of wide exposure by the electron undulating method. We succeeded in the first beam storage with one superconducting bending magnet and three conventional magnets on September 27,1989 and a stored current is estimated at 20 mA at present. The general design and the present status of this ring will be reported in a later section of this paper.

INTRODUCTION

Recently synchrotron radiation(SR) has been regarded as a practical light source for x-ray lithography and photon-induced chemical vapor deposition. The compact rings, in order to apply an industrial use, have been developed around the world since the early 1980's. The key issues for realizing a compact ring system are a low-energy injection system and a superconducting bending magnet. The benefit of using a low-energy injection system is a lower cost system, but it has been pointed out that it is not easy to store a high beam current at this scheme. Electrotechnical Laboratory (ETL) and Sumitomo Electric Industries,Ltd. (SEI) developed a compact ring, NIJI-I , in order to examine a low-energy injection. In those experiments, it was demonstrated that the high beam current storage above a 500 mA was achieved at an injection energy of 100 MeV. On the other hand, a compact ring with superconducting bending magnets has been developed in recent years due to the advantage of being able to decrease a bending radius with its strong magnetic field. SEI has been developing a superconducting compact storage ring, NIJI-Ⅲ, since 1986 in the high energy experimental room of the ETL linac facilities. Since this ring is designed for x-ray lithography, a peak wavelength of the SR spectrum is set about 5 Å and this ring is capable of wide SR exposure by the electron undulating method[1]. Before the superconducting magnets are installed, NIJI-Ⅲ with conventional magnets has been already constructed in June 1989 in order to study a beam optics and the optimum injection parameters. The conventional magnets will be replaced with superconducting magnets one by one. One of four conventional magnets has been already replaced with a superconducting magnet, and we succeeded in the first beam storage on September 27,1989.

In this paper, the general design and the present status of this ring is reported.

GENERAL DESCRIPTION OF NIJI-Ⅲ

Since x-ray lithography needs a severe resolution of less than 0.25 μm, several specifications are needed as follows.

(1) A peak SR spectrum is set in the range of 5-10 Å, because of the resolution determined by Fresnel diffraction and the secondary electrons.

(2) A stored beam current of more than 200 mA is needed, because of the photon energy density on the surface of semiconductor wafers taking account of the sensitivity of resist material and the absorption property of Be window.

(3) A stored beam size of less than 1mm at the SR source points is needed in order to reduce a penumbra blurring.

The main parameters which satisfy those specifications are shown in Tab.1 and calculated SR spectrum is shown in Fig.1. The schematic configuration of NIJI-Ⅲ is shown in Fig.2. NIJI-Ⅲ is a four-cornered type whose size is typically 3m x 5m. This ring consists of four superconducting bending magnets, two vertical-focusing quadrupole magnets(Q2,6) and six horizontal-focusing type(Q1,3,4,5,7,8). The structure of lattice functions and a beam size at the conditions listed in Tab.1 are shown in Fig.3 and Fig.4 respectively. Achromatic conditions are realized in the long straight section (4.1m long). This brings a several advantages as follows.

(1) It is capable of avoiding a deterioration of injection efficiency due to an energy dispersion of injection beam.

(2) Suppressing syncro-betatron resonance because of keeping achromatic conditions in the rf cavity.

(3) By exciting a sextupole magnet at this section, it is capable of magnifying a dynamic aperture without a change in chromaticity.

The maximum beam size of both horizontal and vertical direction at the bending section are less than 0.5 mm, which satisfy the above specifications.

SUPERCONDUCTING MAGNET[2]

The most important issue for realizing a high current storage in the superconducting storage ring is that the superconducting bending magnet has precise magnetic field. Since the designs of the superconducting magnet for NIJI-Ⅲ was carried out at the above point of view, a cos θ winding type and an air-core type were introduced in it. A cos θ winding type, as well known, has an attractive property of having a good field region widely in comparison with the any other winding type. The magnetic field homogeneity of less than 5×10^{-4} was obtained within $\pm$ 30 mm in the radial direction ,which was in good agreement with the values calculated by 3-D magnetic field analysis. Also the compensation for the sextupole field at the magnet coil ends is easy by means of modifying a coil shape in order to produce the inverse field of the originally produced sextupole field. Although this type has a defect in difficulties of taking SR light out of inside the superconducting magnet, two SR ports can be installed in a superconducting magnet in practice. On the other hand, an air-core type has the advantage that a magnetic field distribution scarcely changes during an exciting phase because of no existence of magnetic material. This is a very important property in the compact storage ring with a low-energy injection scheme because of the enormous change in an exciting current. The superconducting magnet consists of two coils, a main coil to produce a dipole field and a quadrupole coil to adjust a magnetic field gradient called field index. This index can be varied from 0 to 0.5 by an independent operation of both coils. Since Nb-Ti material was used for superconducting wire, the coils must be cooled down by immersion into liquid helium. Its boil-off rate is about 10 l/h at the maximum exciting current of 1774 A. This rate is dominantly determined by the thermal penetration through a power lead. Therefore, if a high temperature superconducting wire is used as a power lead or a permanent current mode is used, this rate will be able to decrease.

Tab.1 Main parameters of NIJI-Ⅲ

Stored Energy [MeV]	615
Bending Magnetic Field [T]	4.10
Bending Radius [m]	0.5
Circumference [m]	15.54
Synchrotron Radiation Loss [keV/turn]	25.3
Periodicity	2
Harmonic Number	8
Radio Frequency [MHz]	154.317
rf Voltage [kV]	100
Stored Beam Current [mA]	200
Critical Wavelength [A]	12
Betatron Tune (vertical)	1.25
(horizontal)	2.25
Momentum Compaction Factor	0.077
Energy Spread	7.28×10^{-4}
Emittance (vertical) [mmmrad]	0.025
(horizontal) [mmmrad]	0.25
Injection Rate (maximum) [pps]	10

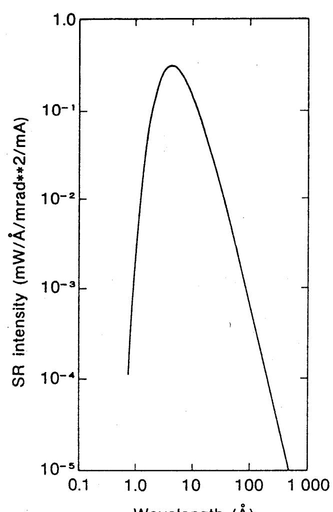

Fig.1 Calculated spectrum of SR from NIJI-Ⅲ

VACUUM SYSTEM[3)]

Since both Touschek and quantum lifetime at the beam energy of 615 MeV can be sufficiently lengthened due to high rf voltage, the lifetime of a stored beam is dominantly limited by the scattering effect caused by a residual gas at the early stage of beam experiments.

The vacuum system in NIJI-Ⅲ is designed to keep an ultra-high vacuum of less than 1×10^{-9} Torr in the beam duct even at the stored beam current of more than 200 mA. In order to realize the above condition, the total pumping speed of 9000 l/s is needed taking account of that the photon stimulated gas desorption coefficient is kept small owing to the sufficiently exhausted SR absorber. Eight sputter ion pumps and eight Ti getter pumps are installed in the four straight sections and the estimated total pumping speed reaches 8500 l/s. At the bending section, since the beam ducts which are cooled down at 4.2 K act as the cryogenic pump, the estimated total pumping speed will reach about 28000 l/s. This value is large enough in comparison with above specification because the photon stimulated gas desorption coefficient is expected too large at the early stage of beam storage experiments.

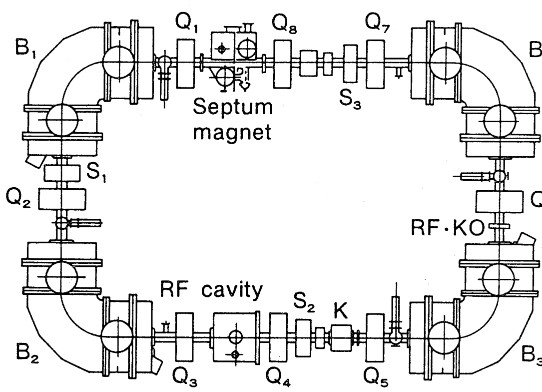

Fig.2 Schematic configuration of NIJI-Ⅲ

B_{1-4} : bending magnet
Q_{1-8} : quadrupole magnet
S_{1-3} : sextupole, octupole magnet
K : kicker magnet

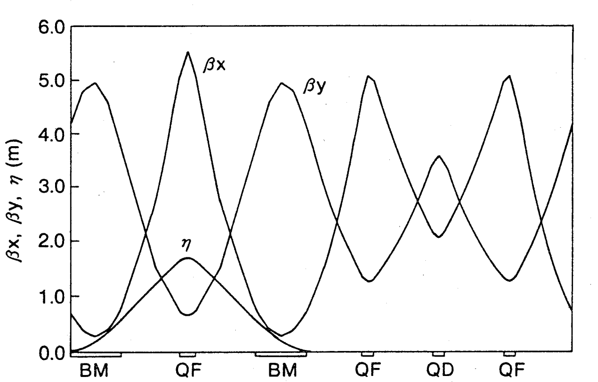

Fig.3 Structure of lattice functions

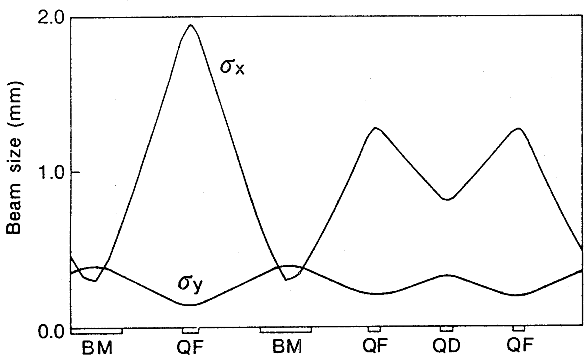

Fig.4 Calculated beam sizes

RF SYSTEM

The rf cavity is a re-entrant type and rf frequency is 154.3 MHz. Temperature of rf cavity is controlled within 40±1 degree in order to stabilize a resonant frequency . The rf power source with a tetrode is capable of 30 kW maximum. It is even enough to store high beam current 200 mA at 615 MeV. The measured values of shunt impedance and Q-value were 2.4 MΩ and 14000 respectively, those values are large enough to realize a compact rf system.

DIAGNOSTIC SYSTEM

Many diagnostics apparatus are installed in NIJI-Ⅲ in order to be easy in the replacement to superconducting magnets. Four destructive screen monitors to search for a suitable injection point are installed. Since the position of a screen monitor located near a septum magnet is externally controlled, it is very useful to certify a beam position of one-turned beam. The best suited beam positions of an injection beam were studied in detail in NIJI-Ⅲ with four conventional bending magnets. Therefore a suitable injection point is easily obtained by this data when the superconducting magnets are installed.

Also eight beam position monitors for closed orbit distortion (COD) correction are installed. It is a button shape and its output signal is detected by a superheterodyne system.

The stored current measurement was carried out using Silicon photo diode (SPD) which was irradiated by SR. The DC-CT which is often used in compact rings was not used due to a leakage magnetic field from the superconducting magnet.

INJECTION EXPERIMENTS OF NIJI-Ⅲ

At first, injection experiments were done with four conventional magnets in order to search for a suitable injection point, tune surveying, COD measurement and to adjust all components except for superconducting magnets. A stored current of 10 mA was achieved on July 1989 at injection beam energy of 185 MeV.

The replacement to superconducting magnets was started from early in September and we succeeded in the first beam storage on September 27 with one superconducting magnet and three conventional magnets. Fig.5 shows a SR light at a viewing port of superconducting bending magnet. A stored current is estimated at 20 mA at present. The measured horizontal and vertical betatron tune were 2.2 and 1.1 respectively, they were scarcely changed by that replacement. The horizontal and vertical beam size were 0.07 and 0.13 mm respectively, both values were a little large in comparison with the designed values. This phenomenon can be explained by the effect for the longitudinal coupled bunch instability, because the synchrotron side band is observed. It is suspected that such a beam size growth will be negligibly small at the conditions of 615 MeV and 200 mA according to a theoretical analysis.

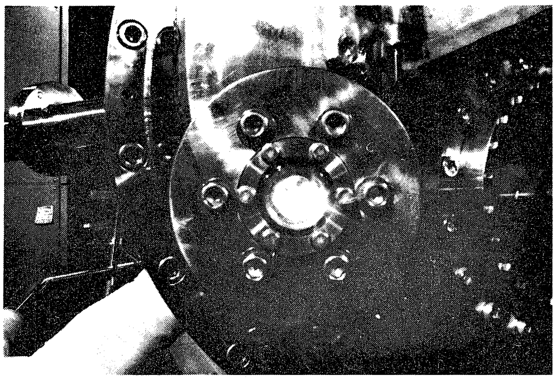

Fig.5 SR from a superconducting bending magnet

ACKNOWLEDGMENTS

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