Design and Beam Tracking of a Compact Storage Ring

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Abstract

An $800MeV$ compact storage ring is designed and under construction. The ring is a racetrack-type consisting of two bending mangets with a field index and the parameters are as follows: the critical wavelength is $0.65nm$, the circumference is $9.2m$, and the emittance is $1.2\pi mm \cdot mrad$. A straight section of the ring has only one quadrupole magnet. A beam tracking with a numerical integration method shows this ring has a sufficiently wide dynamic aperture of $|x| \simeq 30mm$ and $|y| \simeq 50mm$ at the center of the bending magnet, which has minimum β_x and maximum β_y.

Introduction

An 800MeV compact storage ring is under construction at the Mitsubishi Electric Corporation. The compact ring has around nine meters circumference where the betatron oscillation's amplitudes are not negligible compared with the bending radius. And 3-D magnetic fields of bending magnets are complicated. Therefore, calculations of lattice parameters, closed orbit errors and dynamic aperture should be done by different methods from conventional ones.

A tracking computer code PROVIDENCE[1] has been developed for designing the compact ring and for studying effects of nonlinear-terms of equations of motion. This code calculates a particle's orbit with a numerical integration of the exact equations of motion, which are transformed to a simple form so as to fit to the numerical calculation. The 3-D magnetic fields(B_s, B_x, B_y) of a bending magnet are accurately simulated. The design was carried out in comparing the calculated results with linear optics program with the results of the PROVIDENCE.

In this paper, the ring design, the calculated results of the dynamic aperture and closed orbit errors of the ring will be discussed. The difference between phase spaces calculated with the PROVIDENCE and with 'kick method'[2] will be also discussed.

Outline of the ring design

The energy of a compact storage ring for X-ray lithography is generally selected to be $500MeV \sim 700MeV$ for getting a critical wavelength of $1.0 \sim 1.5nm$.[3][4][5] However, the energy of this ring was determined to be $800MeV$, since this ring is used not only the lithography but also material analysis. The storage ring is operated with an injection energy of mainly $800MeV$ so as to make helium consumption in superconducting bending magnets small. A low energy injection can also be tested. Its injector is a $1GeV$ synchrotron.

A lifetime of a stored beam is designed to be longer than $4hr$, and a vacuum system was designed so that a vacuum pressure of $1.6 \times 10^{-9} Torr$ is attained at a stored beam of $220mA$. Synchrotron radiation is supplied from five ports per bending magnet chamber. In Fig.1 is shown a radiation spectrum obtained with the compact storage ring.

Lattice design

A racetrack configuration is selected because beam injection is easier than a circularly symmetric configuration. However, the racetrack type with a FODO lattice has a large emittance, which gives a large beam size and requires a large good field region of magnets. A solution of attaining a small emittance machine is to use bending magnets with a field index n and not to use QD-magnet in the straight sections. The solution makes the ring more compact by eliminating of one quadrupole magnet per straight section.

In Fig.2 is shown a schematic drawing of a compact storage ring designed on the basis of the above discussion. The circumference is $9.2m$. The ring parameters are listed in Table 1, and the twiss parameters along the beam axis are shown in Fig.3. These parameters were calculated using a linear optics program and a magnetic field calculated with a superconducting bending magnet (SCM) described in the next section. The SCM with the non-isomagnetic field was treated as 40 sector magnets with various ρ and n which were calculated along the beam axis. The twiss parameters are different from values obtained with the PROVIDENCE, but the difference is less than 10%.[6]

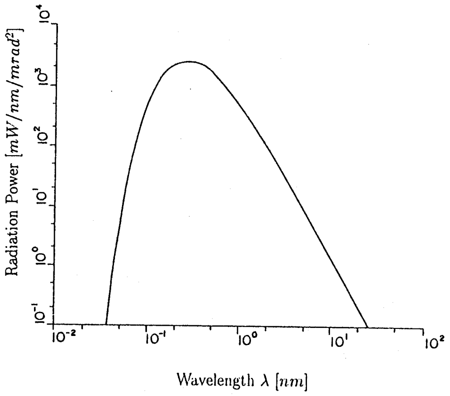

Fig.1 Spectrum of synchrotron radiation from the compact storage ring.

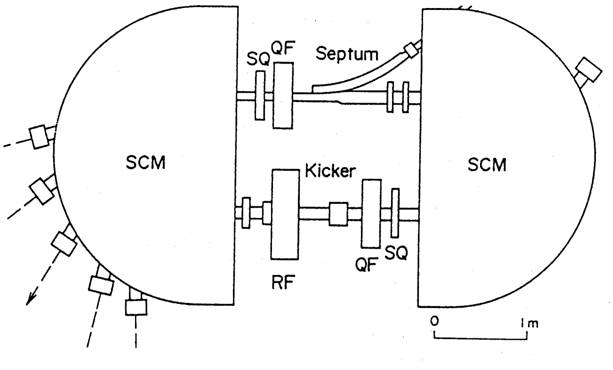

Fig.2 Schematic drawing of the compact storage ring.

The working point was determined to be (ν_x, ν_y)=(1.38, 0.43) because of a wider dynamic aperture. The emittance is 1.2 $\pi mm \cdot mrad$, and the beam sizes are σ_x=0.7mm and σ_y=0.9mm at the center of the SCM. The chromaticities were calculated with the PROVIDENCE, and were ξ_x = -0.92 and ξ_y = -0.69 in $\delta\nu/(\delta P/P)$.

The electron beam is injected through a horizontal septum magnet and kicked into a ring acceptance by a single fast kicker. The kicker excites a pulsed magnetic field with a pulse width of around 500 ns. The peak value of the kicker field is 9.0$mrad$ in a kick angle, and the injection angle is 12$mrad$. An efficiency of the injected beam from the synchrotron is 40% minimum.

Table 1. Parameters of the compact storage ring

Energy		800	MeV
Current		220	mA
Critical wavelength		0.65	nm
Radiation power at 1nm		500	$mW/mrad^2/nm$
Circumference		9.2	m
Bending field		4.5	T
Field index	n	0.16	
Radius of curvature		0.593	m
Strength of quadrupole	K_f	4.7	m^{-2}
Radiation loss		56	$keV/turn$
RF frequency		130	MHz
RF Voltage		120	kV
Harmonic number		4	
Coupling factor	κ	0.1	
Tune	ν_x	1.38	
	ν_y	0.43	
Natural emittance		1.2	$\pi mm \cdot mrad$
Energy dispersion		0.079	%
Momentum compaction		0.307	
Chromaticity	ξ_x	-0.92	
	ξ_y	-0.69	
Beam size	σ_x	0.7	mm
at center of SCM	σ_y	0.9	mm
Bunch length	σ_z	69.3	mm
Damping time	τ_x	1.7	$msec$
Life time		≥ 4	hr

Superconducting bending magnet

A dipole coil is a 'banana'-shaped coil which are turned up and away from the beam at each end, where the coils must cross over the electron beam path. The average field strength is 4.5T, and the radius of curvature is 0.593m. The coils are installed in a cryostat which is covered by a block of warm iron to shield the leakage field.

A field distribution along the beam axis is shown in Fig.4. The closed orbit obtained from the field distribution is shown in Fig.5 as displacement of the closed orbit from the reference orbit which is obtained with a hard edge field.

Closed orbit errors

Table 2 shows closed orbit errors at a center of bending magnet with alignment errors calculated with the betatron functions and point kicks. Because of 180 degrees bending angle and non-isomagnetic fields, it is necessary to divide the bending magnet into many segments, and to consider that each segment has its own misalignment. Each 180 degrees bending magnet was divided into 40 segments. The difference between the results calculated with this method and with using the PROVIDENCE was within 10%. The center of the bending magnet has nearly minimum β_x and maximum β_y. The bending magnet misalignments in the vertical axis are most serious for our ring.

The required good field region is defined as 10σ+(closed orbit errors). The 10σ is required for a sufficient quantum life time with 7.7mm in the x-coordinate and, 9.0mm in the y-coordinate, respectively, at the center of the bending magnet. The maximum magnetic misalignments are as follows: (1) 1.0 × 10^{-3} relative field strength error between two bending magnets, (2) 1.0mm misalignment and 1.0mrad roll of bending magnets, and (3) 0.5mm misalignment and 1.0mrad pitch of quadrupole magnets. The closed orbit errors are Δx = 2.3mm, Δy = 11mm, respectively, with these errors, and the required good field region(R.G.F.R) is $x = \pm 10mm, y = \pm 20mm$, respectively, at the center of the bending magnet.

Table 2. Closed orbit errors at the center of bending magnet with one magnet's misalignment.

element	error[$mm, mrad$]	X_{COD}[mm]	Y_{COD}[mm]
relative strength error of BM	0.10%	0.8	0.0
x displacement of BM	1.0	0.1	0.0
y displacement of BM	1.0	0.0	2.7
pitch of BM	1.0	0.0	2.7
roll of BM	1.0	0.0	1.6
x displacement of QF	1.0	0.23	0.0
y displacement of QF	1.0	0.0	1.2
pitch of QM	1.0	0.0	0.0

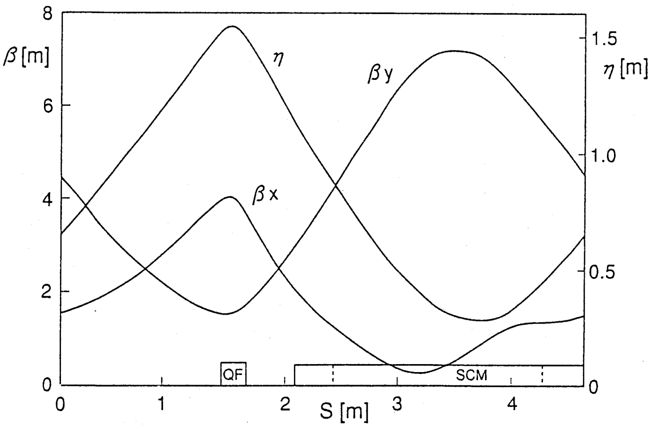

Fig.3 Twiss parameters along the beam axis.

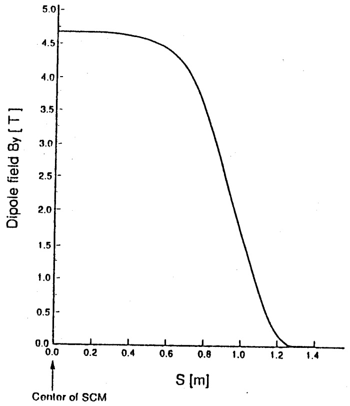

Fig.4 Field distribution of the SCM along the beam axis.

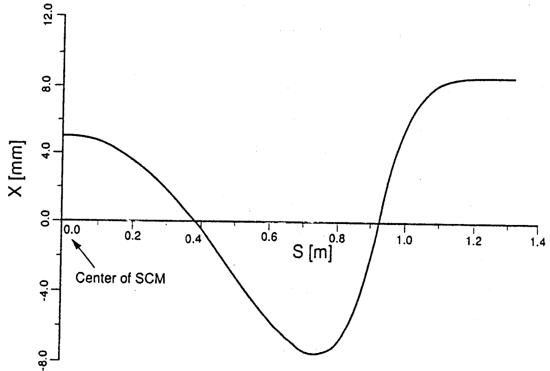

Fig.5 Displacement of the closed orbit from the reference orbit in the SCM.

Dynamic aperture

The differnece between the calculated results with the PROVIDENCE and those with 'kick method' are large at the following cases: (1)calculations of particles with large betatron oscillation's amplitudes, (2) 3-D magnetic fields(B_s, B_x, B_y) of a bending magnet are complicated. By way of example of (1), Figs.6 and 7 show phase spaces of 3000 turns in the y-coordinate at the center of the SCM. Magnetic fields were considerd to be isomagnetic, and the 4th order 3-D expansion coefficients were used. Figure 6(a) and (b) is the results calculated with the PROVIDENCE and Fig.7(a) and (b) is the results with the 'kick method'. Tunes are $\nu_x = 1.405, \nu_y = 0.391$ and initial conditions are as follows: Fig.6(a) and Fig.7(a) are $x_0 = 5mm$ and $y_0 = 15mm$,and Fig.6(b) and Fig.7(b) are $x_0 = 16mm$ and $y_0 = 15mm$,respectively. The figures show that the differences of phase spaces with two methods are large when particles have large amplitudes of horizontal betatron oscillation like Fig.6(b) and Fig.7(b). Only the particle of Fig.6(b) was unstable after tracking 10000 turns.

Figure 8 shows the dynamic aperture with 5000 turns tracking at the center of the bending magnet where β_y is almost maximum. In general a dynamic aperture is defined as a region where particles can be stable in the absence of any physical aperture limitation. But in this paper a stable amplitude area **with actual aperture** is called a dynamic aperture. The chamber sizes are actual size. The 3-D magnetic fields B_s, B_y, B_z are calculated with TOSCA. The dynamic aperture for the x is small comparing with the chamber size (x=50mm), because β_x at this point is almost minimum, and therefore the dynamic aperture is limited at other point. The dynamic aperture and required good field region in the x-coordinate are not symmetric due to the displacement of the closed orbit from the reference orbit because of non-isomagnetic fields. The dynamic aperture is $|x| \simeq 30mm$ and $|y| \simeq 50mm$. The dynamic aperture is wider than the required good field region.

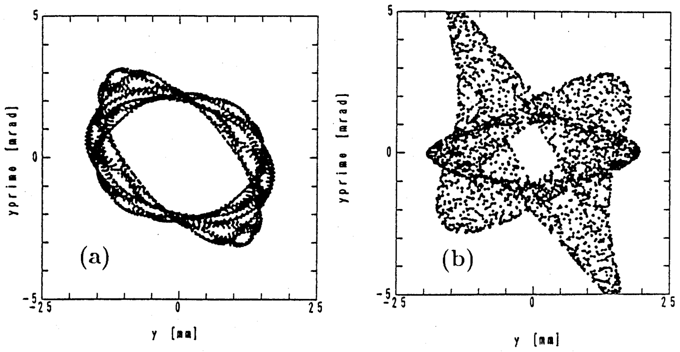

Fig.6 Phase spaces in the y-coordinate calculated with the PROVIDENCE: initial conditions are $x_0 = 5mm, y_0 = 15mm$ in (a) and $x_0 = 16mm, y_0 = 15mm$ in (b) respectively.

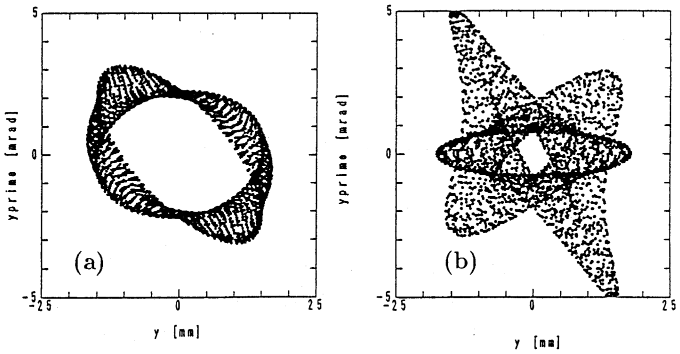

Fig.7 Phase spaces in the y-coordinate calculated with the 'kick method': initial conditions are $x_0 = 5mm, y_0 = 15mm$ in (a) and $x_0 = 16mm, y_0 = 15mm$ in (b) respectively.

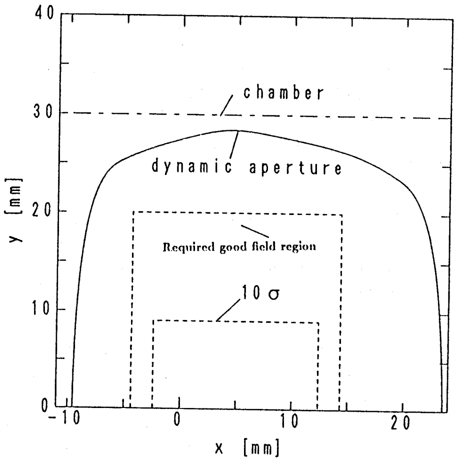

Fig.8 Dynamic aperture at the center of the SCM.

Conclusions

Design of the $800MeV$ compact storage ring was described on mainly beam dynamics. The ring is a racetrack type consisting of two superconducting bending magnets and two quadrupole magnets. The circumference is $9.2m$. The emittance is $1.2\pi mm \cdot mrad$. It was found that the bending magnet misalignments in the vertical axis are most serious for our ring. It was also found that the dynamic aperture is sufficiently wide, even if fairly large closed orbit errors existed.

References

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