Beam Dynamics of the SRRC 1.3 GeV Storage Ring

C.C. Kuo, C.S. Hsue*, J.C. Lee, M.H.Wang, and H.P. Chang
Synchrotron Radiation Research Center
No.1 R&D Rd. VI, Hsinchu Science-Based Industrial Park
Hsinchu, Taiwan, R.O.C.
*Department of Physics, National Tsing Hua University
Hsinchu, Taiwan, R.O.C.

Abstract

This paper presents the single particle dynamics of the 1.3 GeV storage ring in the presence of non-linear field errors, closed orbit errors and insertion devices and also gives the collective effects of the bunched beam. Using a proposed correction scheme the closed orbit distortion due to typical closed orbit errors can be corrected to 0.1 mm rms. With non-linear field errors, residual closed orbit distortions and insertion devices as well, the dynamic aperture is acceptable. The collective effects such as beam bunch lengthening, growth time of longitudinal and transverse instabilities, intra-beam scattering, and beam lifetime were calculated. The results show that good performance of the ring is achievable.

Introduction

A low emittance electron storage ring has been designed and is under construction at SRRC. This ring can produce light source of high brightness in the VUV and soft x-ray region. The magnet lattice of the ring is presented at this Conference.[1] In this paper, we investigated the beam behavior by introducing various magnet errors. The limitation of the error strength is used as a guide line of the design and construction tolerances. The requirements of the vacuum pressure, ring impedance were estimated to insure good performance in terms of beam instabilities and beam lifetime of the ring.

Magnetic Field Errors

Iron dominated magnets have limited pole face, thus there exist unwanted multipole fields, which are called systematic multipole errors. Due to the construction tolerance, there are also random multipole field components. In the simulations, we introduced a set of errors following LBL principle [2] and SRRC magnet design and measurement results as well. Magnetic field can be expressed as:

$$B_y(x)=B_0\rho\sum_{n=0}^{\infty}\frac{k_n x^n}{n!} \qquad (1)$$

Table 1 lists the integrated field errors of the bending, quadrupole and sextupole magnets. Notice that the decapole of the corrector in the sextupole magnet was taken into account in the simulations.

To observe the change of the dynamic aperture, we employed the code RACETRACK to simulate 1 particle in the phase space ellipse for 1000 turns in the presence of all multipole components.[3] The results for such errors are depicted in Fig. 1 and show that dynamic aperture are 22 mm and 15 mm in horizontal and vertical plane, respectively. The results are also confirmed by codes PATRICIA, MAD, etc.[4,5] For 100-particle tracking in a phase space ellipse, the dynamic aperture is a few mm smaller. In the worst case, the stable region is about 70 σ in both planes. Notice that the most harmful term is the random quadrupole component. The systematic sextupole field on both edges of the bending magnet is helpful in reducing the strength of the chromatic sextupole.

Table 1. Magnet Multipole Errors

systematic:	dipole	quadrupole	sextupole
$k_1\ell$	0.0	0.0	0.0
$k_2\ell$	0.5	0.0	0.0
$k_3\ell$	0.0	0.0	0.0
$k_4\ell$	-1740.0	0.0	0.0
$k_5\ell$	0.0	1.5×10^{5}	0.0
$k_8\ell$	0.0	0.0	-5.5×10^{11}
$k_9\ell$	0.0	-3.0×10^{14}	0.0
random:			
$k_1\ell$	1.22×10^{-3}	1.0×10^{-3}	0.0
$k_2\ell$	0.15	0.04	0.015
$k_3\ell$	25.0	2.0	1.6
$k_4\ell$	3200.0	425.0	7.0×10^{3}
$k_5\ell$	0.0	3.0×10^{4}	3.0×10^{4}
$k_8\ell$	0.0	0.0	2.0×10^{11}
$k_9\ell$	0.0	1.0×10^{14}	0.0

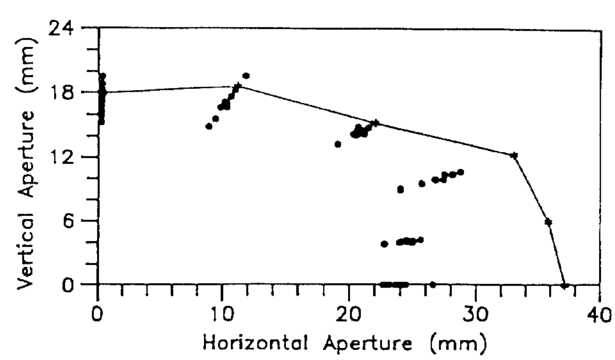

Fig.1: Dynamic aperture of the SRRC lattice. Solid line represents the dynamic aperture of the ideal lattice and dots represent the dynamic aperture for 10 random machines with systematic and random multipole errors listed in Table 1. The results are obtained using RACETRACK with 1 particle tracking for 1000 turns.

Closed Orbit Distortion and Correction

Closed orbit distortions of the circular beam are caused by dipole field errors, magnet misalignments, dipole tilt errors, etc. In the simulations, the following set of typical errors are given: (a) the integrated dipole field error $\Delta B\ell/B\ell = 1\times10^{-3}$ rms, (b) magnet misalignment 0.15 mm rms, and (c) dipole tilt 0.5 mrad rms. The average orbit distortions for 20 random machines are about 6 mm in both planes. A correction scheme consists of 24 horizontal and 30 vertical correctors, and 48 beam position monitors as well are shown in Fig. 2. Using beam bump and other minimization methods, the orbit can be reduced to 0.1 mm rms. Fig. 3 shows the distorted orbit before and after correction. Dynamic aperture in the presence of residual orbit distortions are almost the same as those without errors.

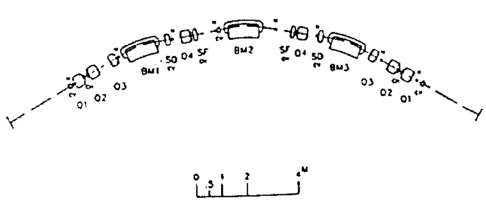

Fig.2: A schematic layout of the orbit distortion correction scheme of each cell. Some correctors are in the sextupole magnets.

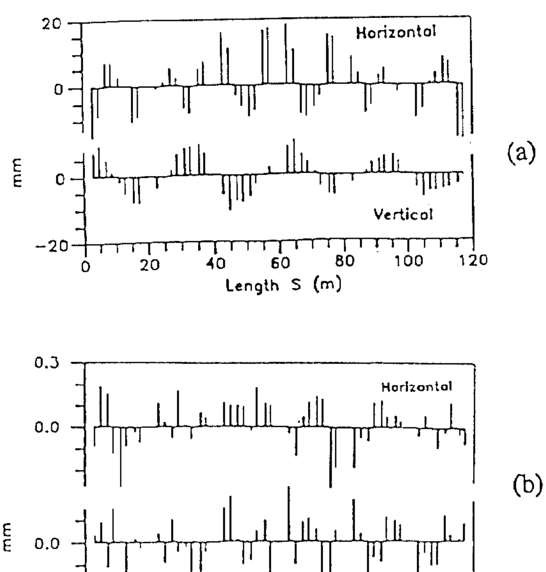

Fig.3: Orbit distortions of the ring of a random machine. (a) before correction (b) after correction.

Wiggler Effect

The effective vertical focusing component and the non-linear fields of the wiggler magnets cause the tune shift and the shrinkage of the dynamic aperture. Using the code RACETRACK the wiggler field can be introduced into the ring lattice. For a wiggler of 16 periods, 2.07 T peak field, and period length 13.6 cm, the tune shift is $\Delta\nu_y=0.05$. Tune can be restored by adjusting quadrupole triplets. Linear optics can also be matched by changing quadrupole triplets. The variation of quadrupole strength is less than 5%. Wiggler effect on the dynamic aperture is shown in Fig. 4. The vertical dynamic aperture is still larger than 80 beam sizes.

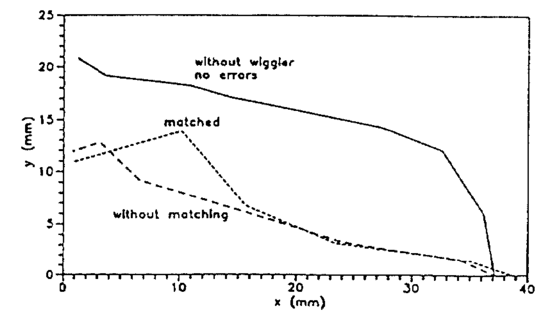

Fig.4: Dynamic aperture of the ring with a wiggler of 16 period, 2.07 T peak field, and 13.6 cm period length.. The results are obtained from RACETRACK code with 1 particle tracking for 200 turns. No magnet errors are included.

Bunch length and Beam Instabilities

To study the impedance effects on the beam behavior, we used code ZAP to calculate the bunch length, coupled bunch instabilities, and emittance growth due to intra-beam scattering.[6]

We have estimated the parasitic modes of the cavity using MAFIA code.[7] These higher order modes are high Q, narrow-band impedance. Low Q impedance arises from vacuum chamber and diagnostic elements, etc. With careful design of the vacuum chamber environment, this low Q, broad-band impedance of the ring is estimated to be $|Z_{||}/n| \leq 2\Omega$.

RF bucket of the ring determines the bunch length. However, bunch can be lengthened if the bunch current is higher than the threshold current when microwave instability occurs. Threshold current is sensitive to the effective broad-band impedance, which exhibits the so called SPEAR scaling law. Fig. 5 shows the bunch length as a function of the bunch current for the cases with and without SPEAR scaling for the rf system of 500 Mhz and 0.8 MV.

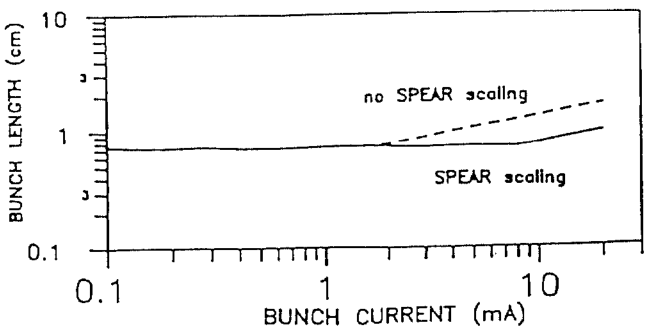

Fig. 5: Bunch length as a function of bunch current for the cases with and without SPEAR scaling for the RF system of 500 MHz and 0.8 MV.

Longitudinal and transverse coupled bunch instabilities for the ring were calculated. In the calculations, the broad-band impedance was taken as $|Z_{||}/n| = 2\Omega$ and the Al pipe of 3 cm in radius was assumed. We assumed gaussian bunch shape with emittance ratio 10:1. Bunch length and energy spread were taken to be 0.74 cm and 6.6×10^{-4}, respectively. All 200 buckets were assumed to be filled with 1 mA bunch current. Hence results are conservative. The calculations indicate that synchrotron dipole mode and synchrotron quadrupole mode for the longitudinal instability are unstable. The other higher longitudinal modes are stable. For transverse coupled bunch instabilities, the only unstable mode is non-rigid synchrotron dipole mode. Some of the unstable modes grow faster than synchrotron damping rate. Similar results were obtained with no SPEAR scaling. The results show that the higher order mode-suppression of the rf cavity and feedback system will be needed.

Emittance growth due to intra-beam scattering at 1.3 GeV was estimated. The results show only 3.2% increase at 5 mA bunch current.

Beam Lifetime

Beam lifetime is limited mainly by Touschek scattering and gas scattering. Long beam lifetime is an essential experimental condition in a synchrotron radiation facility. Normally, one requires at least several hours of beam lifetime.

Touschek lifetime is determined by the density of the bunch beam and by the momentum acceptance. In the calculations, we assumed that emittance ratio was 10:1 and bunch current were 5 mA for the few bunch mode and 1.43 mA for the multi-bunch mode, respectively. At 5 mA bunch current the bunch lengthening is significant with no SPEAR scaling, hence the Touschek lifetime is about twice longer for the case with no SPEAR scaling. The momentum acceptance is limited by the longitudinal rf bucket.

Touschek half-life time are 19 hours and 5.5 hours for multi-bunch and the few bunch modes, respectively, if SPEAR scaling law is applied. With no SPEAR scaling, the Touschek half-life time is 8 hours for 5 mA bunch current operation.

Gas scattering is determined by the combination of the Coulomb scattering and Bremsstrahlung scattering. We estimated gas lifetime for two cases: (a) without undulator gap, and (b) with 1 cm gap. Gas half-life time are 31 and 15 hours, respectively, for a pressure of 1 nTorr of nitrogen gas equivalent.

Total lifetime is $\tau_{tot}^{-1}=\tau_{Touschek}^{-1}+\tau_{gas}^{-1}$. In summary, one can expect that beam lifetime is about 8 hours for the multi-bunch mode operation with bunch current of 1.43 mA , a ring pressure of 1 nTorr, and undulator gap open. For the few bunch operation mode with bunch current 5 mA and 1 cm undulator gap, beam lifetime is about 3 hours.

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