BEAM DYNAMICS IN THE SSRF STORAGE RING

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Abstract

The SSRF (Shanghai Synchrotron Radiation Facility) storage ring consisting of 20 Double Bend Achromatic cells with four super-periods is designed with a low emittance of 3.9nm.rad on 3.5GeV beam energy. Commissioning of the storage ring began on Dec. 21st 2007, and the beam was stored within sixty hours. After one and a half years commissioning, all specifications of the storage ring were reached in 2009. In this paper, study of beam dynamics in the SSRF storage ring is presented. Results of the measurement are given in detail, such as model calibration, orbit stability, etc.

INTRODUCTION

The Shanghai Synchrotron Radiation Facility (SSRF) is a third generation light source, which is designed to produce high brightness and high flux X-ray in the photon energy region of 0.1~40 keV. It consists of three major parts, a full energy injector, a storage ring, and synchrotron radiation experimental facilities. The SSRF storage ring is composed of 20 DBA cells, which are divided into 4 super-periods with 16 standard straight sections of length of 6.5m, and 4 long straight sections of 12.0m, and with distributed dispersion in the straight sections [1]. The main parameters of the storage ring are summarized in Table 1. The circumference and natural horizontal emittance are 432m and 3.9 nm·rad, respectively. The total length of straight sections is 35.18 percent of the ring's circumference. Two 12.0m long straight sections are used for the injection scheme and three super-conducting RF cavities, respectively. The remained two 12.0m and sixteen 6.5m short straight sections will be installed with the insertion devices of undulators/wigglers. Figure 1 is schematic for optical functions and magnet layout of one fold of the ring. The $\beta x/\beta y/\eta x$ is matched as 10/6/0.15m and 3.6/2.5/0.106m in the middle of the long and the short straight sections, respectively.

Table 1: SSRF Storage Ring Specifications

Energy	**3.5**	**GeV**
Circumference	**432**	**m**
Straight sections	**4×12 16×6.5**	**m**
RF frequency	**499.654**	**MHz**
Harmonic number	**720**	
Multi-bunch current	**300**	**mA**
Single bunch current	**5**	**mA**
Betatron tune	**22.22/11.29**	
Natural emittance	**3.9**	**nm.rad**
Natural chromaticities	**-55.7/-17.9**	
Momentum compaction	**4.27×10^{-4}**	
Radiation loss per turn	**1.44**	**MeV**
Damping times (H/V/L)	**7.0/7.0/3.5**	**ms**
Relative energy spread	**9.84×10^{-4}**	

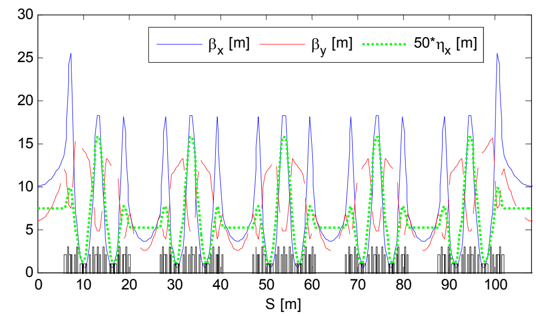

Figure 1: Optical functions and magnet layout of one fold of the storage ring.

Commissioning of the storage ring was started on Dec. 21st, 2007. Within about 60 hours, the first stored beam was successfully obtained on Dec. 24th, 2007. After one and a half years commissioning and a set of milestones, on July 18th, 2009, the final important design parameter 300mA was reached. Table 2 shows the important milestones during SSRF storage ring commissioning [2].

Table 2: Milestones during the SSRF Storage Ring Commissioning

Dec. 21st, 2007	Commissioning started
Dec. 21st, 2007	First turn and multi turns
Dec. 24th, 2007	Beam stored and accumulated
Mar. 16, 2008	RMS COD < 50μm
June, 2008	Few microns orbit stability reached
Sep. 30th, 2008	Stored 200mA @ 3.5GeV
Jul. 18th, 2009	Stored 300mA @ 3.5GeV

MACHINE CALIBRATION

LOCO (Linear Optics from Closed Orbit) [3] was used for machine calibration during the commissioning of the SSRF storage ring. By fitting the measured response matrix, which is a 160×280 matrix for SSRF storage ring, it is sufficiently to get most setting errors of the machine, such as quadrupole gradient, corrector and BPM gains and their coupling factors, and so on. To reducing the fitting error from LOCO, there are some works need to be done in prior, like beam based alignment and closed orbit correction.

Beam Based Alignment

Beam based alignment [4, 5] is a well-known technique to find out the magnetic center of a quadrupole, and this is very important for the commissioning of a storage ring. After several rounds of BBA, the BPM offsets of the SSRF storage ring are precisely measured, as shown in Figure 2. The accuracy of the BBA results is better than 10μm in horizontal and 3μm in vertical, respectively. The RMS horizontal and vertical offsets of all BPM are 0.80mm and 0.59mm, respectively.

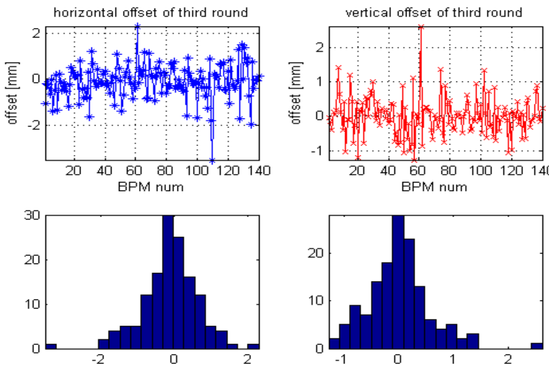

Figure 2: BPM offsets of SSRF storage ring.

Closed Orbit Correction

After setting all the offsets into the BPMs, the closed orbit was successfully corrected by using SVD method. On March 16 2008, the storage ring achieved RMS closed orbit deviations less than 50μm and the closed orbit deviations at all BPMs are within ±0.15 mm in both transverse planes [6].

LOCO

In fact, LOCO has been used each time when the beam based alignment measurement and closed orbit correction finished, in order to get more accurate results in next step. After two or three time's iteration of LOCO, the symmetry and periodicity of the SSRF storage ring lattice were successfully restored [7]. The maximum beta and dispersion beating between the fitting results and the ideal case is about ±15% in both plane before the machine calibration, and it is reduced to 2% after the machine calibration, expect the dispersion beating in some point, where the dispersion function is very small.

Orbit Stability

As a third generation light source, the demand of the stability is extremely high due to its small emittance. Normally, the requirement of the orbit stabilization should be less than 1/10 of the beam size. For SSRF storage ring, The smallest beam size is only 10μm, in the vertical plane at the center of the standard straight section, which means the orbit stability should be better than 1μm in vertical at this point [6]. As most light source, there are two orbit feedback system designed for different frequency range, the slow orbit feedback system will be used to correct the orbit drift under 0.1Hz, and the fast one will used for the correction up to 100Hz. Because of the hardware problems and the communication between these two feedback systems, only hardware test was done for the fast orbit feedback system.

From the experimental results, the current and bunch distribution dependence is very strong in most BPMs, much higher than 1μm. So it is very difficult to achieve the desired orbit stability in decay mode. Fortunately, SSRF is designed to be able to running with top-up mode. By carefully choosing the parameters of the slow orbit feedback system, such as BPM checking, eigenvalues used for SVD calculation, charge per injected bunch, and so on, the long term orbit stability is successfully controlled to the desired value with top-up injection. Figure 3 shows typical results of the vertical orbit drift in 18 hours with SOFB on, the small peak in the blue line is caused by the injection septum's leakage field during the injection.

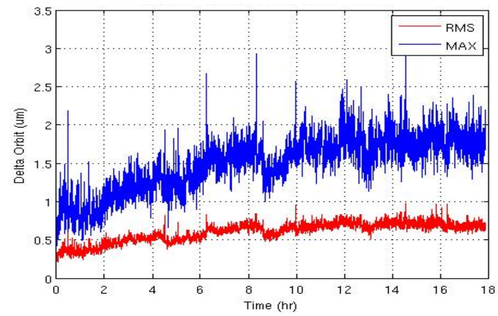

Figure 3: Vertical orbit drift in 18 hours with the slow orbit feedback on (Beam Current: 204-205mA, top-up mode; BPM: 40 BPMs at the end of straight sections; Blue line: Maximum orbit drift of these 40 BPMs; Red Line: RMS orbit drift of these 40 BPMs).

TOP-UP EXPERIMENT

As most third generation light source, top-up injection is considered as the regular operation mode from SSRF primary design, in order to provide more stable beam for users. Top-up injection was tested during SSRF machine study time. Because of the safety and interlock limitation, it is not allowed to running top-up mode with users now. Results from slow orbit feedback study shows that it is the most effective way to improve the orbit stability for SSRF storage ring. The effects on the stored beam were also studied carefully, a set of improvement projects were proposed and some of them will bring into effect during the summer shutdown of this year.

Effects of Injection Elements

Because of the frequently injection process, the orbit disturbance caused by injection elements should be controlled to an acceptable level, such as a half of the beam size. By setting the strengths and the timing of the injection kickers carefully, the disturbance from injection kickers was successfully reduced to less than 100μm and 30μm in horizontal and vertical plane, respectively, which is corresponding to $\sigma_x/3$ in horizontal and σ_y in vertical. As shown in figure 3 above, there is some extra 1~10Hz interference source during the electron refilling. By analyzing the turn-by-turn data from all BPMs, the source is finally pointed to the leakage field of the two septa. The maximum closed orbit difference between septa on and off is about 10 microns, and the field strength can be easily calculated from the model, which is about 1μrad, only 0.002% of the septum setting value [9].

Injection Efficiency

The injected beam stabilization and the injection efficiency are very important for top-up operation. For

SSRF storage ring, the injection efficiency is higher than 95% and the injected beam current stabilize is also better than 5%, as shown in figure 4. The left figure is the booster DCCT current at 20ms after the booster injection, and the right one is the storage ring DCCT current for a 500 buckets filling process.

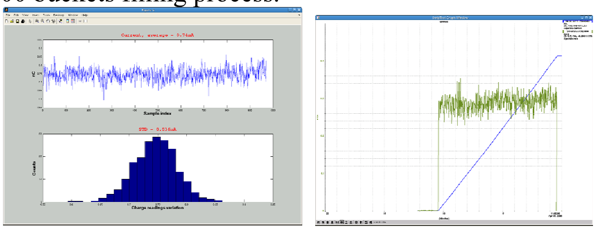

Figure 4: Injection efficiency measurement. Left: Booster DCCT 0.74mA ~ 0.444nC. Right: SR DCCT 0.3mA ~ 0.43nC per shot.

Collimators

To protect the two installed 7mm small gap in-vacuum undulators (IVU), two collimators are installed in the injection straight section, one horizontal and one vertical. The vertical one is now set to ±2.3mm, which is small enough to protect the IVUs from both the simulation and the experimental results. The horizontal one will be used for top-up injection, in order to limit the injection beam.

OTHER MACHINE STUDY

Coupling

The natural global coupling of the SSRF storage ring is about 0.26%. The skew quadrupoles are designed in all 140 sextupoles, but only 20 of them are powered for the coupling correction. After the correction, the minimum global coupling can be reduced to less than 0.02% by measurement it from mode frequencies. When the coupling is lower than about 0.5%, the vertical beam size will be mainly determined by the vertical dispersion distribution along the ring, this could be corrected by using LOCO.

Insertion Device

There are five insertion devices installed in the SSRF Project Phase I, which includes two wigglers, two in-vacuum undulators (IVU) and one EPU, the minimum gap of the IVU is 7mm. From the commissioning results, when the gaps change, there is no obvious effect on the electron beam for all these insertion devices, except the closed orbit. The maximum closed orbit change is from tens to about one hundred microns, all the orbit change can be corrected to less than 5μm in horizontal and 2μm in vertical along the whole ring. For the working point and the lifetime, the effects can be negligible.

Flexibility

By using the powerful tools LOCO, it is much easier to do the machine calibration of a new lattice than before. During the past two and a half years, almost ten modes were successfully commissioned on SSRF storage ring, with different energy and different optics. Table 3 shows an example which includes four different modes with well-calibrated at the energy 3GeV [8].

Table 3: The Main Parameters of the Different Modes @ 3GeV in the SSRF Storage Ring

Modes	Dispersion Mode	Dispersion-free Mode	Low-tune Mode	High-tune Mode
Tune Qx/Qy	22.22/11.29		19.22/7.32	23.32/11.23
$\beta x/\beta y/\eta x$(m) in the centres of straights	10/6.0/0.15 3.6/2.5/0.10	10/6.0/0 3.6/2.5/0.006	15/8.0/0.15 13.5/4.6/0.14	12/6.0/0.17 2.5/2.0/0.102
Natural emittance (nm.rad)	2.86	8.4	3.98	2.47
Natural chromaticity $\xi x/\xi y$	-55.64/-17.94	-55.56/-18.09	-45.77/-21.81	-64.39/-19.93
Momentum compactor	4.2118×10-4	5.4249×10-4	5.89×10-4	3.61×10-4
Natural energy spread (rms)	8.44×10-4	8.44×10-4	8.44×10-4	8.44×10-4

CONCLUSIONS

SSRF reached its all specifications in the past two years, such as energy, current, orbit stability, emittance, etc. and it has already opened to users on May, 2009. In the next five years, more than 20 new beamlines will be installed around the storage ring, the top-up injection is also considered to be set as a routine operation mode in this year, optimization of the low-alpha lattice has already been finished and it is waiting for the machine time. Finally, the most important thing for SSRF storage ring is to provide more and more stable synchrotron radiation source to the users.

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