ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P21

SOME BEAM DYNAMIC ISSUES IN THE HALF STORAGE RING

Jingyu Tang*, Penghui Yang, Gangwen Liu, Yihao Mo, Anxing Wang, Zhouyu Zhao, Tianlong He
Zhenghe BaiUniversity of Science and Technology of China, Hefei, China

Abstract

HALF (Hefei Advanced Light Facility) is a fourth-generation synchrotron light source that just started construction in 2023. With 2.2 GeV in energy, 350 mA in beam current and 86 pm.rad in emittance, the HALF storage ring faces several beam dynamics challenges. This presentation gives the recent study on some of these issues, in particular the beam collimation and the influence and compensation of the insertion devices. For beam collimation, different beam loss mechanisms have been studied, and the Touschek scattering and beam dumping are considered the two major effects in designing the collimation system. Then two collimators with movable horizontal blades and fixed passive vertical blades are being designed, with the main focus on the collimation efficiency and impedance. For the influence of the insertion devices, it is found that some of the long-period undulators have a high impact on the beam dynamic aperture due to low beam energy and originally small dynamic aperture. The local compensation methods for both linear and non-linear effects have been studied. Instead of the traditional compensation method by electrical wires, the method of using two combined magnets with quadrupole and octupole fields at the two ID ends in restoring the dynamic aperture is also studied and compared.

INTRODUCTION

HALF is a fourth-generation synchrotron light source. After many years of design study and R&D efforts, now it enters the construction phase of 2023-2028 [1-2]. The accelerator complex consists of a full-energy linac of 2.2 GeV and a storage ring of 20 periods with a circumference of 480 m. Figure 1 shows the lattice functions of one period. The main design parameters of the storage ring are listed in Table 1.

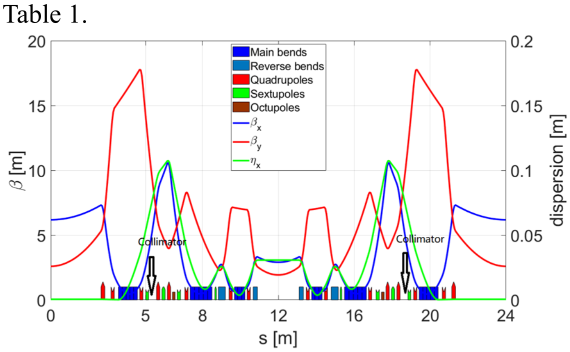

Figure 1: The lattice functions and magnet layout of the HALF storage ring (with collimator positions marked).

Table 1: Main Parameters of the HALF Storage Ring

Parameter	Value
Energy [GeV]	2.2
Current [mA]	350
Circumference [m]	479.86
Number of cells	20
Natural emittance [pm·rad]	85.8
Transverse tunes (H/V)	48.19/17.19
$\beta x/\beta y/\eta$ @ long straight [m]	6.78/2.55/0.00
$\beta x/\beta y/\eta$@ mid-straight [m]	2.51/1.95/0.03
Arc lattice	modified hybrid 6BA
Straight sections [m]	20*5.5, 20*2.2
RF frequency [MHz]	499.8

With a relatively low beam energy of 2.2 GeV, a modest beam current of 350 mA and a very small beam emittance of 86 pm.rad, the HALF storage ring faces several beam dynamics challenges. In this paper, we present the preliminary study results of some beam dynamics issues, including beam loss mechanisms, beam collimation, influences of the insertion devices (ID) on the beam dynamics and compensation methods.

BEAM LOSS MECHANISMS IN THE HALF STORAGE RING

Beam losses become much more important in fourth-generation synchrotron light sources, as compared to third-generation light sources, mainly due to the much higher loss rate and much smaller beam size. The beam loss knowledge is not only important for the design of the tunnel shielding but also for the safe operation of the machine, since a critical beam loss may damage the accelerator devices. A study on the loss mechanisms in the HALF storage ring was conducted. The following beam loss mechanisms are considered the most important: the Touschek scattering loss, beam loss during the injection, beam loss or dumping when the abnormal functions of the facility occur and intentional shutdown is launched, and beam losses in the non-standard operation modes.

The Touschek Scattering Loss

The Touschek scattering loss is the most important beam loss in the HALF storage ring. Due to that both the beam size and momentum aperture (MA) in fourth-generation light sources are significantly smaller than those in third-generation light sources, the Touschek scattering as the principal beam loss mechanism leads to a significant reduction in beam lifetime. In the normal operation mode

* jytang@ustc.edu.cn

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of the HALF storage ring, the Touschek lifetime is about two hours. The beam losses appear almost uniformly in twenty periods. Figure 2 shows the major locations in each period with superpositions from the whole ring).

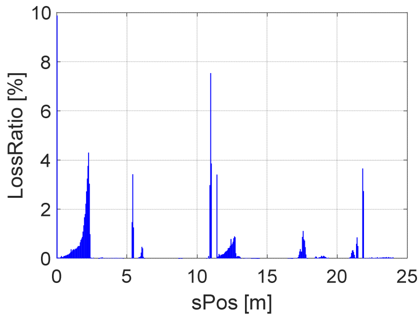

Figure 2: Distribution of the beam loss caused by the Touschek scattering effect (superpositioned into one period).

Injection Loss

Due to a small beam lifetime in the HALF storage ring, it requires frequent beam injection to maintain the quasi-constant beam current by the top-up injection mode. The beam dynamic aperture (DA) is very small here, about 6-7 mm after applying errors and corrections. The current injection scheme is the off-axis injection, with the injecting beam situated at the edge of the DA. For the two electron guns planned, the thermal-cathode gun that will be the baseline scheme delivers a much larger emittance than the photon-cathode gun, which leads significant reduction in the injection efficiency, e. g., 50-80%. The beam loss pattern is defined by the transverse acceptance around the ring, which is more uniform than that due to the Touschek loss. The fluctuation of the injecting beam due to the temporal errors in the linac and the transport beamline will have a similar effect to a larger beam emittance.

Another injection loss mechanism comes from the abnormal function of the injection devices (kickers or septa), which happens very rarely. In this case, both the stored beam and injecting beam are lost mainly in the downstream arc of the injection section.

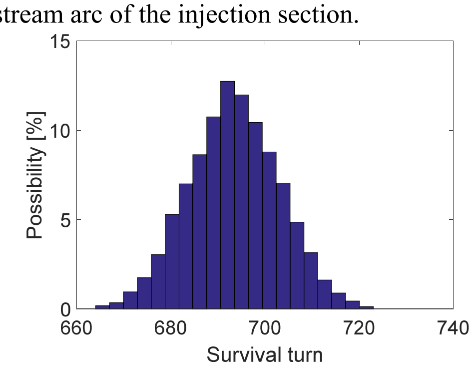

Figure 3: Beam loss pattern when the RF is turned off.

Beam Dumping

When one of the key devices in the storage ring or the beamline front-ends has a critical failure, the whole stored beam should be dumped to allow human intervention to fix the problem. Another scenario is the intentional shutdown of the machine, and there one also needs to dump the stored beam. In both cases, we will have time to trigger the beam dumping mode when both the RF system and the orbit correction system are turned off. The stored beam will be lost in less than 1000 turns, see Fig. 3.

Beam Loss in the Non-standard Operation Modes

The storage ring will work in different operation modes, such as the commissioning mode, high bunch charge mode and hybrid mode with one isolated bunch for high time resolution. In these modes, we will meet different beam loss patterns than in the normal mode. For the commissioning mode, the circulating beam current is increased step by step, thus a much larger beam loss rate can be tolerated according to the beam current. For the two other operation modes, the loss pattern is similar to the normal operation mode, but they have different beam lifetimes.

BEAM COLLIMATION

Collimation Scheme

To protect the IDs that are vulnerable to radiation damage, localize the beam losses for better shielding design, and alleviate critical heat deposition in the devices intercepting the dumping beam, a collimation system in the HALF storage ring has been designed. The current design scheme uses two collimators in two of the 20 periods. The first one will be placed in the upstream dispersion bump of the first period and the second one in the downstream dispersion bump of the 11th period, as shown in Fig. 2, where beta and dispersion functions are relatively large and there are enough spaces left for hosting the collimators. Both of them have movable horizontal blades and fixed passive vertical blades. The collimator with a small gap has a good collimation efficiency but may limit the DA and MA. Besides, it will lead to an increase in impedance such as resonance modes and resistive wall impedance, and may result in beam instability problems. Thus, the gaps of the two collimators have to be carefully considered.

Collimation Efficiency

As mentioned earlier, Touscheck scattering occurs continuously around the storage ring. The ELEGANT code based on the Monte Carlo method is applied to simulate the particle loss caused by the Touschek scattering effect [3]. The collimation efficiency and the effects on DA and MA with different values of horizontal gaps were studied. The simulation results show that a half gap of 6 mm is considered a compromised setting, which gives a collimation efficiency of larger than 70% and causes a reduction in the lifetime lower than 10%. Besides, the physical aperture from the collimator has almost no further limitation to the DA if the error effects and IDs are included. Figure 4 shows the distribution of beam loss with the horizontal collimators of ±6 mm in aperture, and it shows that the beam losses at the injection septum and all IDs are reduced to be lower than 5% and 15% of the total loss, respectively.

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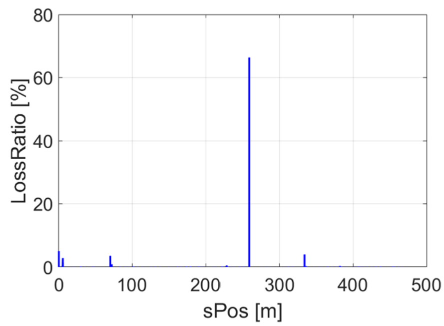

Figure 4: Distribution of beam losses caused by Touschek scattering with ±6 mm horizontal collimators in the normal operation mode.

For the case of beam dumping, the RF cavities are switched off first, and the collimation efficiency is about 50%, and the other 50% of the particles will be lost at the twenty photon masks near the mid-straight sections due to the large local distortion of the beam distribution in the phase spaces with a large momentum deviation. The large beam losses at the masks are considered acceptable since it does not happen frequently. However, due to the very small beam size, there is a concern about the heat deposition density in the interception devices. One should include this effect in designing the interception surface and cooling system of the collimators and masks.

Monte Carlo Simulations of the Lost Particles in the Collimator

The impinging of electrons of 2.2 GeV in energy on the collimator blades will produce secondary particles, which lead to serious heat deposition and radiation effects. The Geant4 code is employed to simulate the interaction between the electrons and the collimator materials. The major secondary particles are the bremsstrahlung gamma rays, then secondary electrons, positrons and also some neutrons, which are strongly dependent on the blade material. At the moment, copper is found a good compromise for being good electrical and heat conductivity, modest stopping power, and production of secondary particles, especially neutrons. The design of the blade profile along the optics axis, the heat dissipation or cooling, and the local shielding will be based on the simulation results.

Collimator Structure and the Impedance Issue

From the study of beam loss mechanisms, the particle losses are almost in the horizontal blades of the collimators. To have good flexibility that allows the collimation in the different operation modes and acts as a measurement tool for the Touschek lifetime and DA, the gap between the blades is adjustable, with a nominal ±6 mm, thus a mechanical driving system is needed. There are water-cooling channels in the blades to bring out the heat load. The collimators are in-vacuum devices, thus it introduces a concern about the coupling impedance that is caused by the discontinuity of the vacuum duct and the cavity structure. The calculation of impedance shows that the impedance issue is very serious, concerning both the resonance modes and resistive wall impedance. The optimization of the structure is in the course, which focuses on the tapering of the two longitudinal ends and applying the upper and lower plates with a fixed aperture.

INFLUENCE OF THE INSERTION DEVICES ON THE BEAM DYNAMICS AND COMPENSATION METHODS

The IDs in the HALF Phase-I include 6 elliptically polarized undulators (EPU), one helical undulator (HU), 4 linearly polarized undulators (LPU and IVU) and 2 damping wigglers [4], and most of them have a length of about 4 m. Among these IDs, the long–period undulators of EPU54, EPU102, and HU115 have relatively strong effects on the beam dynamics of the storage ring mainly due to a relatively low beam energy of 2.2 GeV. The two damping wigglers with high dipole fields have an obvious effect on linear optics but a weak impact on the DA. The EPU102 and HU115 result in both large beta-beatings and the deterioration of nonlinear dynamics.

Taking the vertical polarization mode (16 mm gap) of EPU102 as an example, based on the kickmap model, the beta-beating reaches several hundred percent and the horizontal DA reduces from about 9 mm to about 4 mm without considering the errors. The beta-beatings can be corrected to about 2% or less by using the neighboring quadrupoles, but the DA is restored only modestly. To compensate for the dynamic field integrals of the EPUs, the active shimming method with current strips has been used in several labs to minimize undesirable nonlinear beam dynamics effects [5]. At EPU102, the dynamic multipoles of the kick map can be suppressed with 28 current strips. The beta-beatings are reduced to about several percent and the DA is recovered to about 6 mm, as shown in Fig. 5. However, very small beam size and vacuum ducts in fourth-generation light sources have an important impact to apply this method due to the high strip currents, which is the case here.

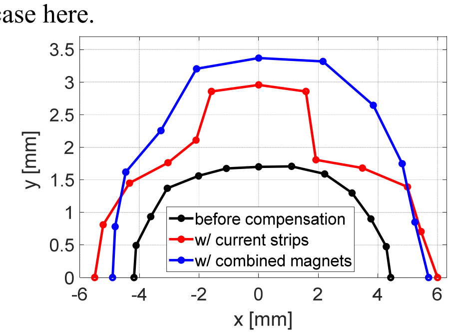

Figure 5: With the EPU102 vertical polarization mode, DAs before compensation and after compensation with current strips and combined magnets are compared.

The analysis of the kickmap shows that it contains linear and nonlinear (especially octupolar) components. Thus another kind of compensation method by using combined magnets with quadrupole and octupole fields was also studied. We place one combined field magnet on each side of the ID. The quadrupole field can effectively correct the beta-beatings and the octupole field helps to recover the

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nonlinear dynamics performance, as shown in Fig. 5. Further study is still ongoing to better recover the nonlinear dynamics performance.

SUMMARY

As a fourth-generation synchrotron light source, the design of the HALF storage ring meets beam dynamic challenges, and some of them are discussed in this paper. After the Touschek scattering and beam dumping are considered the key beam loss mechanisms, a collimation system that consists of two adjustable collimators are designed to protect the ID devices and localize the radiation sources. Some of the IDs with long periods especially those EPUs have an important impact on the beam optics and dynamic aperture. Both the compensation methods of using electrical wires and combined multipole magnets are used to restore the machine's performance. Although effective, more efforts are needed to obtain satisfying solutions for all the IDs in different working modes.

ACKNOWLEDGMENT

The authors thank the other colleagues of the HALF team and from other institutions who participated in the discussions. The work is jointly supported by the HALF Engineering Project and the National Natural Science Foundation of China (Project 12035017).

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