STUDY ON BEAM ORBIT SHIFT DUE TO SYNCHROTRON RADIATION*

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Abstract

The beam orbit stability is the crucial indicator to evaluate the performance of the synchrotron radiation source. In order to obtain higher beam quality, higher stability requirements are placed on the beam orbit. The stability can be improved through accurate measurement of beam orbit by beam position monitors (BPMs) and appropriate feedback system. However, due to radiation of the synchrotron beams on the vacuum chamber, the thermal effect of synchrotron radiation causes the thermal deformation of the vacuum chamber. The thermal deformation drives the BPM fixed on the vacuum chamber to move, which will induce error to the beam orbit. We analyze the effect of beam current on the vacuum chamber movement and the effect of vacuum chamber movement on the beam orbit. We also built an online vacuum chamber displacement measurement system on Hefei Light Source II (HLS II), which is used to validate and correct our analysis. After analysis and verification, the vacuum chamber moves with the change of current. The larger the change of current, the larger the vacuum chamber displacement. The vacuum chamber displacement has a hysteresis compared to the current change.

INTRODUCTION

For the fourth-generation storage ring, a stable beam orbit is a basic requirement for achieving excellent beam quality. Generally, the beam orbit stability is required to be less than 10% of the beam size or 20% of the emittance growth [1]. The beam size of the fourth-generation storage ring is in the order of a few microns and the requirement of the beam stability is less than a few hundred nano-meter.

The measurement of BPM vacuum chamber movement was previously implemented on Hefei Light Source (HLS) [2], a second-generation storage ring with a circumference of 66 m. After measurement, BPM vacuum chamber moves 55-255 μm when HLS was in delay operation modes, which is far from meeting the requirements of beam orbit stability. Top-up operation has been performed to provide which is far from meeting the requirements of beam orbit. In order to obtain higher beam quality, higher stability requirements are placed on the beam orbit. The stability can be improved through accurate measurement of beam orbit by beam position monitors (BPMs) and appropriate feedback system. However, due to radiation of the synchrotron beams on the vacuum chamber, the thermal effect of synchrotron radiation causes the thermal deformation of the vacuum chamber. The thermal deformation drives the BPM fixed on the vacuum chamber to move, which will induce error to the beam orbit. We analyze the effect of beam current on the vacuum chamber movement and the effect of vacuum chamber movement on the beam orbit. We also built an online vacuum chamber displacement measurement system on Hefei Light Source II (HLS II), which is used to validate and correct our analysis. After analysis and verification, the vacuum chamber moves with the change of current. The larger the change of current, the larger the vacuum chamber displacement. The vacuum chamber displacement has a hysteresis compared to the current change.

ANALYSIS

 Requirement for Vacuum Chamber Displacement

According to Table 1, the minimum beam size of HLS II is 400 μm in horizontal, which means the stability of the beam orbit should be less than 40 μm in the horizontal direction. Here, we calculate the influence of vacuum chamber displacement on beam orbit and then derive the requirements of beam orbit stability on vacuum chamber displacement.

The movement of the vacuum chamber will drive the BPM fixed on it to move, as shown in Fig. 1. The dotted line represents the initial position of BPM, and the solid line represents the current position of BPM after moving. The BPM displacement \( x_d \) is equal to the difference between BPM actual reading \( x_{BPM} \) and real beam position \( x_{beam} \), as shown in Eq. (1):

\[
x_{beam} = x_{BPM} - x_d.
\]

(1)

The orbit feedback system will correct the beam to the reference orbit based on the BPM data. The error of \( x_d \) will be induced to the beam orbit. For the reason that the vacuum chamber displacement is a slow-motion, this error will only affect the beam orbit where the BPM position participating in the slow orbit feedback. Besides, for quadrupole magnets near these BPMs, quadrupole magnetic field will further affect the beam orbit. The local close orbit distortion \( \sigma_{co} \) caused by local vacuum chamber displacement can be calculated by Eq. (2) [4, 5]:

\[
\sigma_{co} = \frac{K l x_d \sqrt{[\beta_1 \beta_2]}}{2 \sin \pi Q} \cos (\varphi_2 - \varphi_1 - \pi Q) = \frac{K l \beta x_d}{2 \tan \pi Q},
\]

(2)

where \( \beta \) is the beta function, \( Q \) is the betatron tune, \( K \) is focusing constant of quadrupoles and \( l \) is the quadrupoles length. The beam size and betatron tune \( Q \) of HLS II, as well as \( \beta \), \( K \) and \( l \) of a certain quadrupole magnet, are shown in Table 1. The \( \sigma_{co} \) in horizontal should be less than 40 μm for HLS II. Substitute \( \sigma_{co} \leq 40 \) μm into Eq. (2), \( x_d \) for HLS II should be no more than 36.41 μm.

Figure 1: The movement of vacuum chamber.
Analysis for Radiation from the Bending Section

In the storage ring, the radiation power of the bending magnets is given by Eq. (3) [6],

\[
\frac{dP}{d\theta_x} \left[ \text{W/mrad} \right] = \frac{10^{-12} q c E^4}{6\pi \epsilon_0 E_0^4} \left[ \text{GeV} \right]^3 \left| A \right| B_0 \left[ \text{T} \right],
\]

where for electrons \( q = 1.6 \times 10^{-19} \, \text{C} \), \( c = 3 \times 10^8 \, \text{m/s} \), \( \epsilon_0 = 8.85 \times 10^{-12} \, \text{F/m} \) and \( E_0 = m_0 c^2 = 511 \times 10^6 \, \text{eV} \).

Substitute the parameters into Eq. (3), we get:

\[
\frac{dP}{d\theta} \left[ \text{W/rad} \right] = \frac{8.85 \times 10^4 E^4 \left[ \text{GeV} \right] \cdot \left| A \right|}{2 \pi \rho \left[ \text{m} \right]}.
\]

According to Eq. (4), when the energy, current and bending radius of the electron storage ring are determined, the energy radiated per unit angle is constant. Thus, the radiation angle corresponding to the unit length of the straight section is proportional to the synchrotron radiation power. Most of the radiation on the vacuum chamber is emitted by electrons at the bending magnets. Assuming that the electrons are running in the reference orbit, the radiation on the vacuum chamber is shown in Fig. 2. The solid black lines indicate vacuum chamber viewed above the storage ring.

![Figure 2: Diagram of bending magnet radiation on vacuum chamber.](image)

In Fig. 2, the blue area represents for the ideal dipolar magnetic field. The electrons move along the track of \( O_0A_1A_2O_1O_2 \). \( \theta_0 \theta_1 \) is the bending section and \( O_1O_2 \) is the straight section. \( O_1 \) and \( B_1 \) are located at the connection point of the straight section and bending section. The synchrotron radiation from \( A_1 \) irradiated at \( B_1 \), so as to \( A_2 \) and \( B_2 \). We define \( B_1B_2 = L \), \( \angle A_2O_0A_1 = \theta_1 \), \( O_0O_1 = \rho \) and the radius of vacuum chamber as \( r \). According to geometric relationship,

\[
\theta_1 = \arccos \left( \frac{\rho}{\sqrt{(\rho + r)^2 + L^2}} \right) - \arccos \left( \frac{\rho + r}{\sqrt{(\rho + r)^2 + L^2}} \right).
\]

Take the partial derivative of \( L \) in Eq. (5):

\[
\frac{d\theta_1}{dL} = \frac{1}{(\rho + r)^2 + L^2}.
\]

According to Eq. (6), the radiation power per unit length on the outside of the vacuum chamber is shown as the green line in Fig. 4. On the outside of the vacuum chamber in the straight section, the upstream section will receive more synchrotron radiation than the downstream section.

Analysis for Radiation from the Straight Section

Ideally, all synchrotron radiation is irradiated on the outside of the vacuum chamber. The vacuum chamber will move outward as the beam current increases. However, the bending magnets are not always the fan bending magnets, and the rectangular bending magnets are more commonly used. The dipolar magnetic field is not only limited in the bending section of \( O_0A_1 \), but also exists in the initial segment of the straight section. The synchrotron radiation from \( O_1A_3 \) will be irradiated on the outside of the vacuum chamber, as shown in Fig. 3.

![Figure 3: Diagram of dipolar magnetic field on straight section.](image)

In Fig. 3, the blue area represents for the rectangular bending magnets and the dipolar magnetic field. The electrons move along the track of \( O_1O_2A_3O_3 \). The synchrotron radiation from \( A_3 \) irradiated at \( C_2 \). We define \( C_1C_2 = L \), \( \angle A_3O_0O_2 = \theta_2 \). According to geometric relationship,

\[
\theta_2 = \arccos \left( \frac{\rho - r}{\sqrt{(\rho - r)^2 + L^2}} \right) - \arccos \left( \frac{\rho}{\sqrt{(\rho - r)^2 + L^2}} \right).
\]

Take the partial derivative of \( L \) in Eq. (7):

\[
\frac{d\theta_2}{dL} = \frac{1}{(\rho - r)^2 + L^2} \left( \frac{\rho L}{\sqrt{\rho^2 - 2\rho r + r^2}} \right).
\]

According to Eq. (8), the radiation power per unit length on the inside is shown as the yellow line in Fig. 4. Instead of using \( \frac{d\theta}{dL} \), we set \( \frac{dL}{d\theta} \) as the vertical axis to distinguish the amount of radiation obtained by the inside and outside of the vacuum chamber at the upstream of the straight section. In Fig. 4, \( \frac{dL}{d\theta} \) is uniformly used to replace \( \frac{dL}{d\theta} \).
The upstream of the straight section receives much more synchrotron than the downstream of the straight section. It is worth noting that on the straight section, unlike the outside vacuum chamber, the initial section of the inside of the vacuum chamber is not subject to synchronous radiation. At the upstream of the straight section, the yellow line is below the green line, which means the inside of the vacuum chamber receives more synchrotron radiation than outside.

Figure 4: The radiation power per unit length on the vacuum chamber.

MEASUREMENT RESULT

Two vacuum chamber displacement measurement systems were established on the upstream and the downstream of the same straight section at HLS II. Due to temporary equipment limitations, we only measured the temperature inside and outside the upstream vacuum chamber. The measurement time is from September 13 to September 16, 2022, including the shutdown, injection, decay and top-up operation modes of storage ring. The measurement results are shown in Fig. 5, Fig. 6 and Fig. 7. The increase of horizontal position indicates that the vacuum chamber moves outward.

According to Fig. 5 and Fig. 6, the vacuum chamber moves outward as the current increases at both upstream straight section and downstream straight section, which is due to the thermal expansion of the vacuum chamber caused by the thermal effect of synchrotron radiation. The displacement of vacuum chamber has hysteresis compared with the change of flow intensity. During the top-up mode, the upstream section moves farther than the downstream section.

Figure 5: Displacement at upstream straight section.

Figure 6: Displacement at downstream straight section.

Figure 7: Temperature inside and outside the upstream vacuum chamber on September 15th.

According to Fig. 7, the temperature inside upstream vacuum chamber is higher than the outside temperature. Fig. 7 validates the analysis that inside of the vacuum chamber receives more synchrotron radiation than outside.

CONCLUSION

In this article, we analyze the displacement of the vacuum chamber of the straight section from two aspects of requirements and causes. Through measurement, our analysis was validated. During the injection and decay mode, the vacuum chamber moves outward as the current increases. During top-up mode, the vacuum chamber at the downstream straight section is more stable.

For future work, we plan to analyze more relevant physical quantities to build a physical model of BPM displacement. We also plan to combine vacuum chamber displacement measurement and orbit feedback to improve beam orbit stability. In addition, we will also use machine learning to predict the displacement of vacuum chamber according to the existing analysis.

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REFERENCES


