Analysis of the beam orbit motion in the HEPS storage ring

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Abstract

The High Energy Photon Source (HEPS) is a high-performance and high-energy synchrotron radiation light source with a beam energy of 6 GeV and an ultra-low emittance of 34 pm · rad. In order to enable users to fully harness the potential of this high-brightness beam, it is essential to maintain the stability of the beam orbit with precision to a fraction of the beam size, which corresponds to a sub-micron level of orbit stability. The primary sources of orbit motion in accelerators are ambient ground vibrations and electrical noise from the power supply of the magnets. The extremely strong focusing required to achieve low beam emittance will amplify the impact of such noise sources on the beam orbit compared to existing accelerators. Hence, predicting the expected beam orbit motion becomes crucial for validating the design approaches of the components. In this paper, we will describe the calculation of the anticipated beam orbit motion in HEPS, taking into account the effects of the measured frequency-dependent ground motion coherence, structural resonances of magnet supports and power supply noise. By comparing with the actual beam motion PSD, we verify the model and calculation accuracy and check for extra noise sources affecting the light source. Finally, by predicting the beam orbit with fast orbit feedback (FOFB) using the measured hardware response, we confirm it meets the orbit stability requirements.

Full Text

Preamble

Analysis of the beam orbit motion in the HEPS storage ring∗ Xiyang Huang,1, 2 Haisheng Xu,1, 2 Fang Yan,1 Zhe Duan,1, 2 Zihao Wang,1 Gang Xu,1, 2 Na

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The High Energy Photon Source (HEPS) is a high-performance, high-energy synchrotron radiation light source featuring a beam energy of 6 GeV and an ultra-low emittance of 34 pm • rad. To enable users to fully harness the potential of this high-brightness beam, it is essential to maintain beam orbit stability to a fraction of the beam size, corresponding to sub-micron level stability. The primary sources of orbit motion in accelerators are ambient ground vibrations and electrical noise from magnet power supplies. The extremely strong focusing required to achieve low beam emittance will amplify the impact of such noise sources on the beam orbit compared to existing accelerators. Hence, predicting the expected beam orbit motion becomes crucial for validating component design approaches. In this paper, we describe the calculation of anticipated beam orbit motion in HEPS, taking into account measured frequency-dependent ground motion coherence, structural resonances of magnet supports, and power supply noise. By comparing with the actual beam motion PSD, we verify the model and calculation accuracy and identify additional noise sources affecting the light source. Finally, by predicting the beam orbit with fast orbit feedback (FOFB) using measured hardware response, we confirm that it meets the orbit stability requirements.

Keywords: light source, orbit motion, ground vibration, electrical noise

Introduction

The High Energy Photon Source (HEPS) is a fourth-generation synchrotron facility located in Beijing, China [?, ?, ?]. Operating at 6 GeV, HEPS features an ultralow-emittance storage ring designed with 48 modified hybrid 7-bending achromats (7BA), achieving a natural emittance of 34.8 pm • rad. This configuration enables HEPS to produce remarkably high synchrotron radiation brightness, peaking at 1 × 10^{22} phs/s/mm$^{2/\mathrm{mrad}}$2/0.1%BW in the hard X-ray regime. The stability of the electron beam orbit is one of the most important performance criteria at synchrotron light sources, as they support ultrafast and time-resolved experiments across diverse beamlines. For example, the hard X-ray nanoprobe (HXN) is a high-resolution imaging tool designed for nanoscale material characterization, offering 10 nm spatial resolution and 1 nm motion precision at the sample, which corresponds to tens of nrad angular stability [?]. The soft inelastic X-ray scattering (SIX) studies electronic excitation with ultra-high energy resolution, which is determined by the gratings and exit slit with a critical vertical aperture. During measurement, efforts focus on improving noise sources to minimize disturbances and maintain sub-µm stability at the exit slit [?].

Variations in beam position can lead to synchronization issues, compromising experimental accuracy. To maintain orbit stability, the root mean square (rms) position and angular motion of the electron beam must be minimized to less than 10% of the beam size and its divergence in both transverse planes. Specifically, for HEPS, in the frequency range of 0.1 Hz to 1 kHz, the allowed orbit fluctuation tolerances are set at 0.9 μm for the horizontal plane and 0.3 μm for the vertical plane at the light source point in low-beta straight sections [?, ?]. In this context, developing predictive models for orbit motion is essential. Such models will ensure that the design and operational protocols of the storage ring are adequately aligned with user needs, thereby facilitating the high-quality experimental outcomes that HEPS aims to deliver. As research and methodologies evolve, the capabilities of HEPS are poised to significantly enhance scientific exploration across a range of fields.

Within the frequency range of our concern, electron beam motion is primarily influenced by two significant factors: the movement of focusing elements due to ground vibrations, and fluctuations in the guiding field of magnets due to electrical noise from power supplies [?]. To minimize relative motion among individual magnets, they are typically mounted on rigid girders. This strategy effectively reduces random relative motion between nearby magnets. However, it is essential to acknowledge that girders are not entirely rigid structures; they have resonant modes due to deformation [?, ?]. This means that beam motion analysis must incorporate these resonant modes. Consequently, the motion of magnets driven by ground vibrations can be decomposed into two distinct components: the motion of the girders driven by ground vibration, and the motion of the magnets on the girders corresponding to the resonant modes of the girders.

In the HEPS storage ring, the beam orbit will be affected by noise from quadrupoles and correctors, which are all equipped with individual power supplies. Since the magnetic field is directly proportional to the current, any fluctuations in current can lead to magnetic field variations. Such instabilities can cause beam particles to deviate from their designated paths, resulting in unwanted orbit distortions. This issue is particularly critical in regions of strong focusing, where even minor changes in magnetic field can produce magnified effects on beam trajectory. In the case of HEPS, quadrupole gradients can reach up to 80 T/m, indicating that contributions from power supply noise to orbit perturbations are substantial and cannot be ignored.

The transmission pathways through which these two noise sources affect the beam orbit are clearly illustrated in Fig. 1 [Figure 1: see original paper], highlighting the interplay between ground vibrations and power supply fluctuations on beam stability. Understanding these pathways is essential for developing effective strategies to mitigate their impact and enhance orbit stability at HEPS.

Furthermore, it is essential to consider several other potential sources that may affect beam stability [?, ?]. Beyond the previously mentioned influences, additional sources can impact beam orbit stability. One significant source arises from vibrations of the conductive vacuum chamber within the quadrupoles [?]. The vibrations of this chamber can effectively mirror the motion of the quadrupole itself due to eddy currents induced within the vacuum chamber. These eddy currents seek to stabilize the magnetic field in the moving frame of the chamber, which can result in additional complexities for orbit stability. Such vibrations can originate from several factors, including cooling water flow around the vacuum chamber. Although this type of vibration has not yet been quantified, it is anticipated that any potential issues can be readily mitigated and effectively damped by inserting shims between magnet poles and vacuum chambers.

The structure of this paper is as follows: The forthcoming section introduces the general methodology employed in analyzing orbit motion. Section III initiates the examination of vibration-induced orbit motion by investigating the coherence measurement of floor motion. This parameter is essential for understanding how the amplification factor depends on the frequency of ground vibrations. Following the coherence analysis, the focus shifts to the characterization of beam orbit motion, particularly as it relates to resonances in girders. Shifting focus to electrical motion, the discussion begins with the presentation of findings from power supply noise measurements in Section IV. Utilizing these data, along with the associated amplification factors, we estimate the beam orbit motion induced by power supply noise from focusing magnets and correctors. With an assessment of beam motion originating from both vibration and electrical sources in hand, we synthesize these results to formulate a predictive spectrum of beam motion. Through previous calculations, the total orbit motion can be obtained in Section V. In Section VI, we present the initial beam commissioning results of the HEPS storage ring and the actual power spectral density (PSD) spectrum of beam orbit fluctuations. By comparing these with computational results, we aim to identify external noise sources not previously considered in the model. The final section provides a summary and includes discussion of the results. This structured approach guarantees a comprehensive and systematic evaluation of factors influencing beam motion. The insights derived from this study lay a robust foundation for future design improvements and experimental strategies aimed at reducing the adverse effects of these disturbances.

Methodology in the Orbit Motion Analysis

The PSD of a stationary random signal x(t) is defined as [?, ?]:

$$S_x(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} dt \right|^2 = \int_{-\infty}^{\infty} e^{-i\omega\tau} R_x(\tau) d\tau,$$

where $\omega = 2\pi f$ is the angular frequency and $R_x(\tau) = \langle x(t)x(t+\tau)\rangle$ is the autocorrelation function of x(t). With $S_x(f)$ known in frequency region $[f_1, f_2]$, measured or provided in the data sheet, x(t) can be generated by:

$$x(t) = \sum_{k=1}^{N} a_k \cos[2\pi(k\Delta f + f_1)t + \phi_k],$$

where $a_k = \sqrt{2S_x(k\Delta f + f_1)\Delta f}$, $\Delta f = (f_2 - f_1)/N$, and ϕ_k is a random phase angle distributed uniformly over the range $(0, 2\pi]$. As defined in Eq. (1), the PSD of a stochastic process is a statistical measure that characterizes its frequency content. Consequently, generating x(t) over a finite time interval from a given PSD is not unique due to the random nature of the process. Thus, the simulation should be repeated multiple times using different realizations to ensure reliable conclusions.

One of the main properties of the PSD is that its integral gives the motion variance:

$$\sigma_x^2 = \int_0^\infty S_x(f)df.$$

When integrating over a finite frequency range, the result represents the motion variance within that frequency band. If the motion arises from multiple independent factors, the PSD of the overall motion is the sum of the PSDs of each individual contribution, provided they are uncorrelated. This approach decomposes the complex motion into its constituent parts, enabling detailed analysis of the electron beam' s behavior and characteristics across the frequency range of interest.

The orbit motion due to a specific noise source can be analytically calculated using the PSD of the source and the amplification or attenuation factor along the propagation path, as illustrated in Fig. 1. Additionally, orbit feedback is implemented to correct fluctuations by adjusting the beam position based on real-time measurements. Finally, the total orbit motion resulting from various noise effects can be expressed in the form:

$$\sigma_{\text{tot}}^2 = \int_{f_1}^{f_2} \sum_i S_i(f)A_i(f)F(f)df,$$

where i denotes the ith noise source, A_i and F_i are the amplification factor and correction factor for each source. Additionally, based on the integration time and spatial resolution requirements of the beamline experiments, the frequency range we are concerned with is from 0.1 Hz to 1 kHz.

Orbit Motion Induced by Ground Vibration

Ground Vibration

Ground motion poses a significant challenge for particle accelerators, causing beam oscillations that degrade beam quality in synchrotron facilities and create beam-beam offsets in colliders [?]. At HEPS, ground vibrations have been measured for six years, beginning before construction. The measurements were conducted using CMG seismometers equipped with GPS, which recorded the wave velocity of ground vibration. The seismometers had a timing precision of 10^{-9} s and a sampling rate of 500 Hz. Fig. 2 [Figure 2: see original paper] displays the PSD of ground vibrations $S_g(f)$ measured in the storage ring tunnel in 2023.

At exceptionally low frequencies, specifically below 1 Hz, primary contributors include atmospheric phenomena, ocean tide movement, and temperature fluctuations, among others. Above 1 Hz, human activities such as machinery operation and vehicular traffic dominate. According to Eq. (3), the measurement in the storage tunnel gives approximately 23 nm rms ground vibration noise in the frequency range of 1-100 Hz, and the induced frequency-independent orbit motion is 1.4 µm in the horizontal plane and 0.8 µm in the vertical plane, which compares favorably with the orbit stability requirements. However, when the range is extended to 0.1-100 Hz, the induced orbit motion exceeds 6 µm in both planes. Even with perfect orbit feedback, the beam orbit cannot be controlled at a level of 0.3 µm in the vertical plane, let alone the fact that our BPMs are also vibrating with the floor at the same amplitude.

Fortunately, the long wavelengths of low-frequency ground vibrations cause nearby accelerator components, such as magnets and vacuum chambers, to move in phase, effectively reducing relative displacements. This synchronization mitigates the impact on orbit motion, as the wavelength at these frequencies may span the entire storage ring, resulting in negligible net motion. Understanding the coherence of ground motion is crucial for analyzing low-frequency beam orbit motion. Notably, diffusive ground movements lack spatial coherence, rendering the concept of coherence length irrelevant and having minimal impact on frequencies above 0.1 Hz.

Coherence of the Ground Vibration

The characterization of ground vibration coherence constitutes a fundamental procedure in site assessment for accelerator facilities [?, ?, ?]. The magnitude-squared coherence between two signals x(t) and y(t) is mathematically defined as:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)},$$

where P_{xx} and P_{yy} represent the PSD of individual signals and P_{xy} denotes their cross-spectral density [?]. Prior to conducting ground vibration coherence measurements within the tunnel, it was imperative to validate the consistency of data acquisition between two identical devices operating simultaneously at the same location, ensuring a high degree of coherence. Seismometric measurements were performed across three orthogonal directions, with each measurement comprising 900 seconds of data sampled at 1024 Hz. Fig. 3 [Figure 3: see original paper] illustrates the coherence spectrum of horizontal and vertical ground motion captured by two adjacent Guralp 6TD seismometers. The two sensors exhibit excellent coherence in the frequency range of 1.7-80 Hz. While theoretical predictions suggest sustained coherence at frequencies below 1.7 Hz, empirical observations reveal a notable decline in coherence within this regime. The observed incoherence at these lower frequencies cannot be readily attributed to any physical mechanism other than diffusion. However, the influence of diffusion is negligible in this context, as its effect diminishes with decreasing separation between measurement points. Consequently, this reduction in coherence is primarily ascribed to measurement noise.

Following validation of device coherence within the specified frequency band, systematic ground vibration coherence measurements were conducted. The experimental protocol involved maintaining one seismometer at a fixed position while progressively relocating the second device along the storage ring tunnel, with a maximum separation of 110 meters constrained by cable length. The results are demonstrated in Fig. 4 [Figure 4: see original paper], where the horizontal and vertical axes represent frequency and the distance between the two seismometers, respectively, and the color indicates the level of coherence. The measurement results reveal that vertical alignment shows high coherence at frequencies below 1 Hz, even at distances up to 110 meters, as indicated by a coherence level above 0.9, highlighted by the yellow shading in the left figure. In contrast, horizontal plane measurements reveal diminishing coherence with increasing distance. The relationship between coherence length and frequency was established through analysis of the dataset presented in Figure 4. By identifying the frequency threshold at which coherence exceeds 0.9 for each separation distance, we derived empirical models for both planes:

$$L_c(f) = \begin{cases} 11f^{-0.66}, & \text{for } f > 1 \text{ Hz} \\ 11f^{-2.1}, & \text{for } f \leq 1 \text{ Hz} \end{cases} \quad \text{(horizontal)}$$

$$L_c(f) = \begin{cases} 20f^{-0.73}, & \text{for } f > 1 \text{ Hz} \\ 20f^{-2.6}, & \text{for } f \leq 1 \text{ Hz} \end{cases} \quad \text{(vertical)}$$

The model parameters indicate coherence lengths of 11 meters and 20 meters at 1 Hz for the horizontal and vertical planes, respectively. Notably, the coherence length exhibits significant frequency dependence below 1 Hz, suggesting that low-frequency vibrations are unlikely to be amplified by the lattice structure.

The relationship between ground vibration coherence and the interplay of distance and frequency has been systematically established, providing a foundation for determining frequency-dependent orbit amplification factors. These factors quantitatively characterize the amplification of beam orbit motion in response to ground vibrations across varying frequencies. The orbit amplification factors are derived through static closed-orbit simulations utilizing the Accelerator Toolbox (AT) [?]. The comprehensive calculation process is outlined as follows:

1. A two-dimensional grid is constructed to encompass the entire storage ring. Each grid point is assigned random displacements that follow a Gaussian distribution with a predefined amplitude, ensuring a statistically representative model of ground vibrations.

2. A low-pass filter is implemented to smooth the random displacements in both transverse planes. The cutoff frequency of the filter is carefully selected to correspond to the coherence length being modeled, thereby maintaining the physical relevance of the displacement patterns.

3. The amplitude of filtered displacements is adjusted to match the initial predefined amplitude. Subsequently, the average displacement is subtracted to eliminate any potential bias, ensuring the displacement field remains zero-mean.

4. The resulting grid displacements are mapped onto the corresponding magnets. Linear regression is then applied to smooth the displacements of magnets sharing the same girder. While this smoothing process is not strictly necessary, its omission may lead to excessive deviations in certain results, potentially compromising the accuracy of the amplification factor calculation.

5. The closed-orbit distortion is calculated, and the orbit amplification factor is determined through systematic analysis of the resulting beam motion.

Next, we provide a detailed explanation of the numerical simulation. As indicated in step 1, the simulation process initiates with the generation of a two-dimensional grid, where points are uniformly spaced at intervals of 0.5 meters to encompass the entire ground area of the storage ring. Each grid point is assigned two random displacement values in horizontal and vertical planes, denoted as D_x and D_y. To reduce the inherent randomness of the displacements, a two-dimensional Gaussian smoothing technique is employed. This process is governed by a transfer function that maintains a constant value of 1 for frequencies below a lower threshold f_1, decreases linearly to 0 for frequencies above an upper threshold f_2, and exhibits a linear transition between these two cutoff frequencies. The application of this smoothing procedure yields ground displacements characterized by coherence lengths of 20 meters and 60 meters, as illustrated in Fig. 6 [Figure 6: see original paper]. From the figure, it is evident that the ground displacement profiles exhibit significant variations depending on the filter length applied. Specifically, a larger filter length results in a smoother distribution of ground displacements, highlighting the impact of the coherence length on the spatial characteristics of the displacement field.

The determination of magnet displacements is achieved through the extraction of ground displacement data at the entry and exit points of the magnetic components. This extraction employs bilinear interpolation, a computational technique that estimates values at target locations based on the four nearest points within the square grid. Subsequently, a linear regression analysis is performed across all elements of a single girder, aligning them to an optimal linear trajectory. The resulting displacements are then meticulously adjusted to ensure accuracy. Fig. 7 [Figure 7: see original paper] provides illustrative examples of the derived magnet displacements D_x and D_y for coherence lengths of 1 meter, 60 meters, and 600 meters. The results demonstrate a clear trend: as the coherence length increases, the variation in magnet displacements becomes progressively smoother. Notably, when the coherence length (or filter length) reaches a sufficiently large magnitude, the entire accelerator system behaves as a unified entity, effectively eliminating relative displacements between its constituent components.

The procedure outlined above was employed to generate 200 datasets of ground displacements, each associated with a distinct filter length. For every dataset, the closed orbit was computed, and the standard deviation σ_i of the orbit at the positions of insertion devices was evaluated relative to the ground position. These standard deviations were subsequently averaged across the 200 datasets to obtain the mean value, also denoted as $\langle\sigma_i\rangle$. The amplification factors were then calculated by normalizing $\langle\sigma_i\rangle$ with respect to the standard deviation of the ground motion:

$$A_c(L_i) = \frac{\langle\sigma_i\rangle}{\sigma_{\text{ground}}}.$$

The results of this analysis are presented in the left panel of Fig. 8 [Figure 8: see original paper]. For shorter coherence lengths, the simulated amplification factors exhibit excellent agreement with the analytically derived values, which are based on the assumption that all displacements are statistically independent. This alignment underscores the validity of the simulation approach and provides confidence in the robustness of the results for scenarios characterized by smaller coherence lengths. By utilizing the relationship between coherence length and frequency as described in Eqs. (6) and (7), we can derive the amplification factors at different frequencies $A_c(f_i)$. The results are plotted in the right panel of Fig. 8.

Subsequently, the PSD of the non-resonant orbit motion G_c at the source point, induced by ground vibrations, can be calculated using Eq. (9) and illustrated in Fig. 9 [Figure 9: see original paper]. The non-resonant orbit motion σ_c is obtained by integrating G_c over the frequency range from 0.1 Hz to 1000 Hz, as defined by Eq. (3), yielding values of 0.56 μm and 0.20 μm. It should also be noted that the ground vibration PSD in the 100–1000 Hz range depicted in the figure is extrapolated from the PSD below 100 Hz, with the amplification factor for this frequency range being identical to that at 100 Hz.

$$G_c(f) = \beta_0 A_c^2(f) S_g(f).$$

At the conclusion of this section, it is imperative to address the uncertainties associated with the measurement and calculation of coherence length. As previously discussed, a coherence threshold of 0.9 was selected, which yields a notably shorter calculated coherence length compared to scenarios where a lower threshold is applied (e.g., a threshold of 0.8 would result in exponential fits yielding coherence lengths of approximately 100 meters in both planes). In practical terms, adopting a lower coherence threshold would shift the curve in the right panel of Fig. 8 to the right, thereby reducing the amplification factor below 10 Hz and resulting in smaller calculated orbit motion. However, the influence of this coherence threshold-induced uncertainty on the calculations becomes negligible once orbit feedback is implemented, as the feedback system is particularly effective in mitigating low-frequency disturbances.

Vibration on Girder

As described in the preceding section, ground motion induces solid-body-like displacements of the girders. In addition to these rigid-body motions, such vibrations can also excite resonant deformation modes of the girders. In the case of uniform girder motion, the effects of focusing and defocusing quadrupoles tend to partially cancel each other out due to their opposing influences [**?**, **?**]. However, it is possible for a deformation mode to exist where the displacements of the focusing and defocusing quadrupoles on the girder act in a cumulative manner, thereby exerting a more significant impact on beam orbit motion. Therefore, it is crucial to consider the influence of these girder deformation modes in the analysis.

The High Energy Photon Source (HEPS) will incorporate focusing magnets mounted on six girders, in addition to longitudinal gradient dipoles spanning the plinths. All girders are supported by concrete plinths, and in our design, the vibration at the top of the plinths is assumed to be identical to that on the floor. Fig. 10 [Figure 10: see original paper] illustrates the panoramic layout of the magnet arrangement within one cell, which has a total length of approximately 22 meters. The beam direction runs from right to left, with the girders arranged as follows: DQ-I, MP-I, FODO-I, FODO-II, MP-II, and DQ-II. The girders at both ends of the cell are of the DQ type, each housing one focusing quadrupole (QF), one defocusing quadrupole (QD), and an independent fast corrector. The two central modules, which contain bending magnets with defocusing gradient (BD), are referred to as FODO. The remaining two modules, which include sextupoles, octupoles, and anti-bending magnets with focusing gradient (ABF), are designated as MP.

The vibration mode analysis was conducted utilizing ANSYS Mechanical software, specifically the Release 19.1 edition [?]. In order to accurately predict the modal response of the modules, dynamic stiffness testing was completed on the support components [?]. During accelerator operation, the primary cause of girder vibration is ground motion. For frequencies approaching resonance, the amplitude $z_g(f)$ can be characterized by the classical resonance curve:

$$z_g(f) = R(f) z_d,$$

where z_d is the drive amplitude, and:

$$R(f) = \frac{1}{\sqrt{(f^2 - f_0^2)^2 + (f f_0/Q)^2}},$$

where f_0 is the resonant frequency and Q is the quality factor of the girder, related to the damping ratio ζ by $Q = 1/2\zeta$. The damping ratio ζ is determined by striking the girder with a hammer and subsequently monitoring the resulting vibrations. Table 1 shows the first two deformation modes and the measured quality factors for three girder types.

To calculate orbit motion due to girder deformation, for quality factor Q, the full-width half-maximum of the resonance curve equals f_0/Q. A key feature, which will prove significant later, is that at low frequencies where f is far from f_0, Eq. (11) approaches 1. This indicates the absence of amplification, meaning the girder simply follows the ground motion. In our analysis, we consider the orbit motion due to one single mode in all girder assemblies. The orbit displacement at the source point (center of the straight section) due to a single girder assembly displacement in a resonant mode m is:

$$z_m = \kappa_{m,i} d \cos(\phi - \pi \nu_z),$$

where z denotes either x or y, $\kappa_{m,i}$ and d represent the normalized amplification factor and girder displacement for the mth mode, respectively; i distinguishes between the four girder types (type I/II of odd cells and type I/II of even cells), and ϕ is the phase advance between the girder and the source point. Since the girder motion induced by a resonant mode is oscillatory, one can also use rms values for z and d in Eq. (12). The motion of every girder assembly in the same mode is independent because the coherence length of ground motion at frequencies above 65 Hz is less than 0.69 m, which is smaller than the distance between two individual girders, as shown in Eq. (6). Consequently, the rms displacements generated by each girder can be combined in quadrature. Furthermore, because girder motion is driven by ground movement and the frequency spectrum of ground motion is largely consistent across all points around the ring, the amplitude of girder motion is approximately uniform for all girders at a given frequency. The total rms motion resulting from one mode of the same girder type around the whole ring can be calculated as:

$$\sigma_{z,m}^2 = \sum_{i=1}^{N} \beta_0 \kappa_{m,i}^2 d_{\mathrm{rms}}^2 \cos^2(\phi_i - \pi\nu_z) \approx N\beta_0\lambda_m^2 d_{\mathrm{rms}}^2/4,$$

where $N = 48$ is the number of periods, and λ_m^2 accounts for the contribution of m-type girder in both odd and even units. The normalized amplification factor Λ_m for the mth mode can be derived using Eq. (13):

$$\Lambda_m = \frac{\sigma_{z,m}}{\beta_0 d_{\mathrm{rms}}} \simeq \frac{\sqrt{N}\lambda_m}{2} \approx 3.46\lambda_m.$$

Fig. 12 [Figure 12: see original paper] presents the normalized amplification factors Λ_m for all resonant modes below 150 Hz.

To calculate the contribution of a single mode to orbit motion, we begin by multiplying the PSD of ground motion by the square of the resonance curve derived from Eq. (11). This resulting PSD is then further multiplied by the square of the mode' s amplification factor, yielding the PSD of the orbit motion attributed to this specific mode. The final step involves integrating this orbit motion PSD to obtain the rms orbit motion for the mode:

$$G_r(f) = \sum_m \Lambda_m^2(f) S_g(f),$$

$$\sigma_{z,r}^2 = \int_{f_1}^{f_2} G_r(f)df = \int_{f_1}^{f_2} \sum_m \Lambda_m^2(f) S_g(f) df.$$

Notably, the integration limits must be set close to the resonance frequency to avoid artificially inflating the PSD at lower frequencies. As previously noted, Eq. (11) approaches 1 when $f \ll f_0$. Thus, summing the effects of N resonant modes over a broad frequency range could erroneously amplify the low-frequency PSD to N times that of the ground motion PSD. To address this, the integration limits were carefully chosen as $0.9f_0$ to $1.1f_0$, which encompass approximately 97% of the total integral under the squared resonance curve for a given quality factor Q. The integrated rms orbit motion for each mode is plotted in Fig. 13 [Figure 13: see original paper].

Total Orbit Motion Induced by Ground Vibration

Based on the contents of Sections III.B and III.C, Fig. 14 [Figure 14: see original paper] presents the expected rms orbit motion induced by ground vibration, encompassing both non-resonant and resonant vibrations (as shown in the zoomed-in subplot). Using Eq. (3), the orbit motion σ_r induced by all resonant modes is 0.08 µm and 0.05 µm, while the total motion induced by ground vibration can be calculated as:

$$\sigma_{\text{vib}} = \sqrt{\sigma_c^2 + \sigma_r^2},$$

resulting in 0.57 µm and 0.21 µm in both planes, as shown in Fig. 15 [Figure 15: see original paper].

Orbit Motion Induced by Electrical Noise

In addition to vibrations, another significant noise source contributing to orbit disturbances is noise from magnet power supplies. Given that there are over 2000 electromagnets in the HEPS storage ring, the impact of electrical noise could be more substantial than initially anticipated. All storage ring magnets, with the exception of sextupoles and octupoles, are equipped with independent power supplies, which fall into three categories: unipolar, slow bipolar, and fast bipolar power supplies [**?**, **?**]. Unipolar power supplies are used to power quadrupoles, BD, and ABF. Slow and fast bipolar power supplies are used to power slow correctors (SC) and fast correctors (FC), respectively.

The rms current ripple of a power supply, denoted as ΔI_{rms}, can be calculated by integrating the PSD of power supply noise, $S_n(f)$, over a specified frequency range:

$$\Delta I_{\text{rms}}^2 = \int_{f_1}^{f_2} S_n(f) df,$$

where n typically represents the maximum noise level in parts per million (ppm) relative to the maximum output current: $\Delta I_{\text{rms}}/I_{\text{max}}$.

Measurements of power supply current ripple were performed using a CoCo-80X oscilloscope operating in Dynamic Signal Analysis (DSA) mode. The schematic of the FC noise measurement setup is presented in Fig. 16 [Figure 16: see original paper], and the measured noise spectra of all types of power supplies are provided as illustrative examples in Fig. 17 [Figure 17: see original paper]. The measurement results revealed numerous additional spectral lines, predominantly identifiable as harmonics of 50 Hz. These lines are suspected to be artifacts originating from the measurement process itself, rather than genuine components of the power supply output.

Furthermore, the impact of electrical noise on the beam orbit is attenuated by the vacuum chamber. Based on the experimental results presented in Fig. 18 [Figure 18: see original paper], this attenuation effect for quadrupoles and slow correctors can be approximately characterized by the fitting curve given in Eq. (19):

$$H(f) = \begin{cases} e^{-0.0001\times f^{0.96}}, & \text{for FC} \\ e^{-0.031\times f^{0.52}}, & \text{for other magnets} \end{cases}.$$

As indicated by the measurement results in Fig. 18, negligible attenuation is observed for fast correctors at frequencies below 1 kHz. These correctors feature laminated cores and are positioned within Inconel vacuum chambers of 0.5 mm thickness. Therefore, when calculating orbit motion induced by power supply noise in fast correctors, the suppressive effect of the vacuum chamber will be neglected.

To account for the effect of different vacuum chambers, we define the reduced power supply noise $\tilde{n}$ as follows:

$$\Delta\tilde{I}_{\text{rms}} = \sqrt{\int_{f_1}^{f_2} H^2(f) S_n(f) df} / I_{\max}.$$

Next, we will directly use Eq. (20) to calculate the amplification factor.

Amplification Factors of Electrical Noise

Similar in form to ground vibration noise, the lattice-related normalized amplification factor for the reduced power supply noise $\tilde{n}$ can be expressed as:

$$A_{\text{ps}} = \beta_0 \frac{z_{\text{rms}}}{\tilde{n}},$$

where z representing either x or y denotes the orbit distortion at the source point generated by a kick angle θ:

$$z_{\text{rms}}^2 = \left(\frac{\sqrt{\beta_0}}{2\sin\pi\nu_z}\right)^2 \sum_{l=1}^{N_j} \beta_l \cos^2(\phi_l - \pi\nu_z)\theta_{\text{rms}}^2,$$

where $\Phi_j = \sum_{l=1}^{N_j} \beta_l \cos^2(\phi_l - \pi\nu_z)$ is computed across all N_j magnets in the jth family.

Combining Eqs. (21-25), the amplification factor of all quadrupoles and correctors on the orbit can be expressed as the sum over all quadrupole and corrector families:

$$A_{\text{ps},j} = \frac{\sqrt{\beta_0}}{2\sin\pi\nu_z} \times \begin{cases} \Phi_j (KL)_{\text{rms}}, & \text{for quadrupole} \\ \Phi_j \theta_{j,\max}, & \text{for corrector} \end{cases}.$$

In addition to regular quadrupoles, the BD and ABF magnets are designed as quadrupoles and installed with an offset. In the horizontal plane, the orbit displacement is dominated by a design offset of several millimeters—specifically, during operation, the offset for BD is set to 14 mm, while that for ABF is set to 2.5 mm. In the vertical plane, however, the orbit displacement remains characterized by the rms orbit error, similar to regular quadrupoles. Table 2 summarizes the normalized amplification factors for different magnet types.

Based on the definition of Eq. (18), for quadrupoles, $\theta_{\rm rms}$ can be written as:

$$\theta_{\rm rms} = \tilde{n} K L d_{\rm rms},$$

where K and I_K are the nominal strength and corresponding operational current of the quadrupole, L is the effective length, and $d_{\rm rms}$ is the rms displacement of the quadrupole. For correctors, however:

$$\theta_{\rm rms} = \tilde{n}\theta_{\rm max}.$$

As previously mentioned, quadrupoles and correctors in HEPS each have independent power supplies. For a given family j, $z_{j,\rm rms}$ represents the total effect of all magnets in that family, assuming each individual magnet generates an rms orbit kick of $\theta_{j,\rm rms}$. By categorizing the magnets into m distinct families, we can derive Eq. (25) as follows:

$$z_{j,\rm rms}^2 = \sum_{l=1}^{N_j} \left(\frac{\sqrt{\beta_0}}{2\sin\pi\nu_z}\right)^2 \beta_l \cos^2(\phi_l - \pi\nu_z)\theta_{j,\rm rms}^2 = \left(\frac{\sqrt{\beta_0}}{2\sin\pi\nu_z}\right)^2 \Phi_j \theta_{j,\rm rms}^2.$$

Orbit Motion Induced by Electrical Noise

As discussed earlier, the orbit motion $G_{\rm ps}$ induced by electrical noise for each magnet type can be calculated by multiplying the measured power supply noise PSD by the attenuation curve described in Eq. (19) and then by the corresponding amplification factors listed in Table 2, as shown in Eq. (27), where j represents different magnet families. One should note that fast correctors are subject to different attenuation effects. The PSD of total orbit motion induced by all power supply noise is shown in Fig. 19 [Figure 19: see original paper]:

$$G_{\rm ps}(f) = \sum_j H_j^2(f) S_{n,j}(f)/I_{\max,j}^2 \times A_{{\rm ps},j}^2.$$

The integrated orbit motion, calculated using Eq. (28), is summarized in Table 3 :

$$\sigma_{z,\rm ps} = \sqrt{\int_{f_1}^{f_2} G_{\rm ps}(f) df}.$$

It is evident that in the horizontal plane, the dominant contributions originate from the transverse gradient dipoles and SC, whereas in the vertical plane, SC and FC have relatively greater influence. All calculations based on electrical noise were performed using an idealized model of the storage ring lattice that incorporates the cross-talk effect [?]. However, in practical scenarios, coupling between horizontal and vertical orbital motions is unavoidable. In HEPS, the coupling is set to 10%, which leads to a 0.05 µm increase in the contribution of quadrupoles and horizontal gradient dipoles to vertical orbit motion. This increment is sufficiently small to be negligible. The total orbit motions induced by power supply noise are 0.75 µm and 0.24 µm, respectively, as illustrated in Fig. 20 [Figure 20: see original paper].

Total Orbit Motion Due to Vibration and Electrical Noise

The overall PSD of the orbit motion can be obtained by summing the individual PSD attributed to ground vibrations and power supply noise, based on Eqs. (9), (15) and (27):

$$G_{\text{tot}}(f) = G_c(f) + G_r(f) + G_{\text{ps}}(f).$$

The total integrated rms orbit motion σ_{tot} is calculated as:

$$\sigma_{\text{tot}} = \sqrt{\int_{f_1}^{f_2} G_{\text{tot}}(f)df} = \sqrt{\sigma_{\text{vib}}^2 + \sigma_{\text{ps}}^2}.$$

Fig. 21 [Figure 21: see original paper] presents the rms orbit motion derived by Eq. (30). It can be observed that power supply noise dominates across all frequency ranges in the horizontal plane. In the vertical plane, ground vibration is dominant below 100 Hz, while power supply noise prevails above 100 Hz. The total rms orbit motion within the frequency range from 0.1 Hz to 1 kHz is expected to be 0.94 µm in the horizontal plane and 0.32 µm in the vertical plane. Notably, the anticipated overall rms motion in the vertical plane exceeds the orbit stability criteria in the absence of a feedback system.

Validation and Discussion of Simulation Results and Actual Beam Motion

In this section, we verify the validity of our analytical approach by comparing the simulation results calculated above with actual beam motion in HEPS.

Commissioning of the HEPS Storage Ring and Optics Correction

Commissioning of the HEPS storage ring started on July 23, 2024, when first beam storage was achieved [?]. Initially, the electron beam was transmitted through the high-energy transfer line (BR) and injected into the storage ring using self-developed software, achieving single-turn transport. A semi-automatic correction program based on PYAPAS was employed to tune the beam, overcoming challenges like small apertures [?, ?]. During multi-turn commissioning, RF cavities and sextupole magnets were gradually activated, with parameters optimized to increase the number of revolutions. Despite issues including cumulative errors and strong nonlinearities, beam storage was accomplished on August 6, reaching a current of 60 mA. This milestone represented a crucial advancement in the HEPS project.

Following completion of beam accumulation, more detailed beam commissioning work was conducted, successively accomplishing closed-orbit correction, beam-based alignment (BBA), and optics correction, among other tasks. Detailed measurements of beam parameters were conducted, and local vacuum anomalies were repaired. The first synchrotron radiation light was obtained on September 23. By the end of December 2024, the beam intensity had reached 30 mA, the lifetime was 1000 s, the closed-orbit deviation was < 100 µm, beta-beating was $< 5\%$, chromatic dispersion deviation was < 5 mm, coupling was $< 10\%$, and emittance was < 100 pm.

Theoretical Calculation and Comparison with Actual Beam Oscillation

Since the hardware for our FOFB system has not yet been fully constructed, we can currently only analyze short-term beam orbit motion using turn-by-turn (TBT) data comprising 1 million turns. Fig. 22 [Figure 22: see original paper] presents a comparison between the PSD of the average orbit at the source points of all low-beta straight sections (recorded on January 7, 2025) and our simulation results. It can be observed that across most of the 0.1 Hz to 1 kHz frequency range, the calculated results are in good agreement with the actual beam orbit motion—particularly within the 70–86 Hz frequency band corresponding to support structure resonance. Below, we discuss three frequency bands where the agreement is less satisfactory.

First is the 50 Hz peak: in both horizontal and vertical planes, the measured peak amplitude exceeds the calculated result. By inverting the response matrix, we determined that the 50 Hz signal source is distributed across the entire ring, with a particularly strong contribution near the R42 cell—indicating an additional noise source in this region. Further precise measurements identified a water pump for the RF cavities near the R42 cell, which exhibits a vibration frequency of 49.6 Hz, as illustrated in Fig. 23 [Figure 23: see original paper]. Using a simplified vibration attenuation model, we evaluated its impact on the beam, finding it contributes an orbit fluctuation of approximately 0.2 µm rms around 50 Hz.

The second frequency band with notable discrepancy is around 300 Hz. This relatively broad peak arises from the synchrotron frequency, which couples longitudinal motion to transverse motion via residual dispersion [?]. To verify this hypothesis, we conducted a beam experiment: adjusting the total cavity voltage and monitoring the corresponding PSD peak. Results are shown in Fig. 24 [Figure 24: see original paper]. Currently, three RF cavities are in use in the storage ring. Initially, with a total cavity voltage of 3.84 MV, the peak appeared at 360 Hz (theoretical calculations predicted a longitudinal oscillation frequency of 380 Hz under this setting). Next, when we reduced the voltage of one cavity by 0.1 MV while keeping the other two constant, the peak split into two and shifted to lower frequencies. Conversely, reducing the voltage of all three cavities by 0.1 MV simultaneously caused the entire peak to shift to 320 Hz. These results confirm that the peak around 300 Hz is closely linked to longitudinal motion. Fortunately, it requires little attention at present, as its contribution to transverse motion is less than 1% in both planes.

Finally, discrepancies are observed in the low-frequency range: notable differences between calculated and actual beam motion appear in the 1–5 Hz band. Given that the floor vibration data used to calculate beam motion was measured earlier, we relocated some probes on the storage ring to monitor vibrations during light source operation, aiming to identify any significant low-frequency vibrations. As shown in Fig. 25 [Figure 25: see original paper], seismometers near the R42 cell exhibit significantly larger vibrations around 2.5 Hz compared to other locations. Based on the maximum ground vibration amplitude, the PSD of the beam at 2.5 Hz can be estimated as:

$$S_b \approx \beta_0 \times A(f)^2 \times S_g(f)|_{f=2.5} = 0.3\mu m^2/Hz,$$

which is consistent with the highest frequency observed in the beam PSD. However, since there is a large irrigation canal near the R42 cell in this direction, in addition to the pump room, we have not yet been able to identify the source of the 2.5 Hz peak. Although low-frequency noise currently has a significant impact on beam motion, it is anticipated that once our FOFB system is implemented [?], its impact will be less pronounced.

Prediction of Orbit Motion with FOFB

Since actual beam fluctuations exceed our calculations, we need to estimate the beam orbit after the FOFB system is implemented. The FOFB system of HEPS will include 192 FCs in each plane and is planned to operate at 22 kHz. The characteristic of the FOFB system can be investigated by the sensitivity equation [?]:

$$S(s) = \frac{1}{1 + G_{\mathrm{PI}}(s)G_{\mathrm{FC}}(s)e^{-\tau s}},$$

where $s = \Omega + j\omega$ is the complex frequency, $G_{\mathrm{PI}}(s)$ and $G_{\mathrm{FC}}(s)$ are the transfer functions of PID compensation and correction system in the s-domain, and τ is the total delay of the FOFB system. $G_{\mathrm{FC}}(s)$ can be obtained by measuring the amplitude-frequency response of the correction system, and is simply expressed as a first-order plus time-delay transfer function [**?**]:

$$G_{\mathrm{FC}}(s) = \frac{33770}{s + 33770} e^{-0.00002s}.$$

When we select a simple integral controller, $G_{\mathrm{PI}}(s) = 7000/s$, with Eqs. (33) and (34), the disturbance rejection gain $G_0(f)$ at each frequency point can be calculated from Eq. (32). Note that $G_0(f)$ is in units of dB, then the attenuation ratio is derived as:

$$F(f) = 10^{G_0(f)/20}.$$

The orbit motion with FOFB control can be expressed as:

$$G_f(f) = G_{\mathrm{tot}}(f) F(f),$$

$$\sigma_f^2 = \int_{f_1}^{f_2} G_f(f) df,$$

which is reduced to 0.36 µm and 0.26 µm in both planes, respectively, as shown in Fig. 26 [Figure 26: see original paper] and Fig. 27 [Figure 27: see original paper].

Summary and Discussion

This study provides a comprehensive analysis of electron beam orbit motion in the HEPS storage ring, focusing on the two primary sources of noise: ground vibrations and power supply noise. Through a combination of advanced computational modeling, experimental measurements, and theoretical analysis, we have quantified the contributions of these factors to beam motion and validated the predictive model against experimental data.

Ground vibrations have been identified as a critical contributor to beam orbit motion, affecting the beam through both non-resonant and resonant mechanisms. Non-resonant motion, derived from frequency-dependent coherence measurements, results in rms displacements of 0.56 µm in the horizontal plane and 0.20 µm in the vertical plane within the 0.1 Hz–1 kHz range. Resonant deformations of magnet support girders, characterized using ANSYS simulations and dynamic testing, further contribute 0.08 µm and 0.05 µm to the horizontal and vertical motions, respectively. This leads to total vibration-induced rms values of 0.57 µm and 0.21 µm.

Electrical noise from magnet power supplies also significantly impacts orbit stability, with contributions varying by magnet type. Transverse gradient dipoles and SC dominate horizontal orbit motion, while SC and FC dominate the vertical orbit, resulting in total electrical noise-induced rms displacements of 0.75 µm and 0.24 µm in both planes. When combining both vibration and electrical noise sources, the total anticipated orbit motion without feedback reaches 0.94 µm and 0.32 µm.

The accuracy of the predictive model has been confirmed through comparisons between simulated and measured beam motion PSD spectra, particularly in the 70–86 Hz band corresponding to girder resonances. However, residual discrepancies were observed at specific frequencies: the 50 Hz line exceeds the power supply noise contribution by a small margin, a feature near 360 Hz arises from longitudinal–transverse coupling driven by synchrotron oscillations, and the pronounced low-frequency beam motion observed throughout the ring, especially around 2.5 Hz, is likely excited by vibrations near the R42 cell. These observations underscore the need for targeted suppression of these additional noise sources. Finally, after inclusion of FOFB, the predicted beam motion is 0.36 µm and 0.26 µm in both planes, well within the orbit stability specification for the HEPS storage ring.

This study demonstrates the feasibility of achieving the stringent orbit stability requirements for the HEPS storage ring and highlights the importance of integrating precise measurement techniques with sophisticated simulation methodologies. The findings provide a robust framework for understanding and mitigating beam motion in high-performance electron beam systems. Furthermore, the methodology developed in this work can be extended to model and calculate orbit motion in future large-scale circular accelerators, such as the 100 kilometer-long Circular Electron-Positron Collider (CEPC) [**?**]. This approach will enable the clear definition of required parameter thresholds and their impacts on beam motion, advancing the field of accelerator physics and supporting the development of next-generation light sources and particle colliders.

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References

[1] Y. Jiao, G. Xu, et al., The HEPS project. J. Synchrotron Radiat. 25(6), 1611–1618 (2018). https://doi.org/10.1107/S1600577518012110
[2] Y. Jiao, W. Pan, High energy photon source. High Power Laser Part. Beams

34, 104002 (2022).(in Chinese) https://doi.org/10.11884/HPLPB202234.220080
[3] Jiao, Y., Chen, F., He, P. et al., Modification and optimization of the storage ring lattice of the High Energy Photon Source. Radiat. Detect. Technol. Methods 4, 415–424 (2020). https://doi.org/10.1007/s41605-020-00189-7
[4] He, Y., Jiang, H., Liang, DX. et al., The hard X-ray nanoprobe beamline at the SSRF. Nucl. Sci. Tech. (2024). https://doi.org/10.1007/s41365-024-01485-3
[5] Pelliciari, J., Lee, S., Gilmore, K. et al., Tuning spin excitations in magnetic films by confinement. Nat. Mater. 20, 188–193 (2021). https://doi.org/10.1038/s41563-020-00878-0
[6] Xu, H., Meng, C., Peng, Y. et al., Equilibrium electron beam parameters of the High Energy Photon Source, Radiat. Detect. Technol. Methods 7, 279–287 (2020). https://doi.org/10.1007/s41605-022-00374-w
[7] G. Decker, Beam stability in synchrotron light sources. In Proc. DIPAC2005, Lyon, France (2005), pp. 233-237.
[8] R.O. Hettel, Beam Stability at Light Sources, Rev. Sci. Instrum. 73, 1396 (2002). https://doi.org/10.1063/1.1445484
[9] Shin, S. New era of synchrotron radiation: fourth-generation storage ring. AAPPS Bull. 31, 21 (2021). https://doi.org/10.1007/s43673-021-00021-4
[10] Z. Dai, et al., Study of orbit stability in the SSRF storage ring. Nucl. Sci. Tech. 3, 157-160 (2003).
[11] S. Tang, et al., Synchrotrons radiation stability measurement and improvement. Nucl. Sci. Tech. 23, 7-9 (2012).
[12] I. Martin, et al., Orbit stability studies for the DIAMOND-II storage ring. In Proc. IPAC2022, Bangkok, Thailand (2022), pp. 2602-2605. https://doi.org/10.18429/JACoW-IPAC2022-THPOPT017
[13] M. Boge, Achieving sub-micro stability in light sources. In Proc. EPAC' 04, Lucerne, Switzerland (2004).
[14] S. Marques, et al., Improvement on SIRIUS beam stability. In Proc. IPAC2022, Bangkok, Thailand (2022), https://doi.org/10.18429/JACoW-IPAC2022-MOPOPT002
[15] F. de. Sa, Perturbation sources and improvements of SIRIUS beam stability. 9th Low Emittance Rings Workshop, Geneva, Switzerland (2024).
[16] R. Bartolini, Performance and trends of storage ring light sources. In Proc. EPAC' 08, Genoa, Italy (2008) pp. 993-997.
[17] V. Sajaev, et al., Calculation of expected orbit motion due to girder resonant vibration at the APS upgrade. In Proc. IPAC2018, Vancouver, Canada (2018), https://doi.org/10.18429/JACoW-IPAC2018-TUPMF011
[18] S. Matsui, et al., Orbit fluctuation of electron beam due to vibration of vacuum chamber in quadrupole magnets, Jpn. J. Appl. Phys. 42, 338–341 (2003). https://doi.org/10.1143/JJAP.42.L338
[19] N. Hubert, et al., SOLEIL beam orbit stability improvements. In Proc. DIPAC2011, Hamburg, Germany (2011), pp. 488-490.
[20] C. H. Huang, et al., Study of 60 Hz beam orbit fluctuation in the Taiwan Photon Source. In Proc. IPAC2017, Copenhagen, Denmark (2017), pp. 1566-1569. https://doi.org/10.18429/JACoW-IPAC2017-TUPAB107

[21] C. Spataro, et al., Investigation on mysterious long-term orbit drift at NSLS-II. In Proc. IPAC2019, Melbourne, Australia (2019), pp. 2728-2730. https://doi.org/10.18429/JACoW-IPAC2019-WEPGW102
[22] J. Bendat, A.Piersol, Random Data: Analysis and Measurement Procedures, 4th Edition, John Wiley & Sons, Inc. 2010.
[23] R. Edwards, Processing Random Data: Statistics for Engineers and Scientists, World Scientific Publishing Co. Pte. Ltd. Singapore, 596224, 2006.
[24] Baklakov, B., Bolshakov, T., Chupyra, A. et al., Ground vibration measurements for Fermilab future collider projects. Phys. Rev. ST-AB, 1, 031001 (1998). https://doi.org/10.1103/PhysRevSTAB.1.031001
[25] S. Redaelli, et al., Vibration measurements at the Swiss Light Source (SLS). In Proc. EPAC' 04, Lucerne, Switzerland (2004), pp. 2278-2280.
[26] V. Juravlev, et al., Investigations of power and spatial correlation characteristics of seismic vibrations in the CERN LEP tunnel for Linear collider studies, CERN Report SL/93-53 (1993).
[27] V. Shiltsev, Review of observations of ground diffusion in space and time and fractal model of ground motion. Phys. Rev. ST Accel. Beams, 13, 094801 (2010). https://doi.org/10.1103/PhysRevSTAB.13.094801
[28] M. Schaumann, D. Gamba, H. Garcia Morales et al., The effect of ground motion on the LHC and HL-LHC beam orbit. Nucl. Instrum. Methods Phys. Res. Sect. A 1055, 168495 (2023). https://doi.org/10.1016/j.nima.2023.168495
[29] Chen, J., Dai, Z., Deng, R. et al., Ground motion effects on the beam orbit stability at Shanghai Synchrotron Radiation Facility. Synchrotron Radiat. News, 32, 27–31 (2019). https://doi.org/10.1080/08940886.2019.1654829
[30] V. Sajaev, C. Preissner, Determination of the ground motion orbit amplification factors dependence on the frequency for the APS upgrade storage ring. In Proc. IPAC2018, Vancouver, Canada (2018), pp. 1272-1275. https://doi.org/10.18429/JACoW-IPAC2018-TUPMF012
[31] A.Terebilo, Accelerator Toolbox for MATLAB, SLAC-PUB-8732, 2001.
[32] J. Nudell, et al., Calculation of orbit distortions for the APS upgrade due to girder resonances. In Proc. MEDSI2018, Paris, France (2018), pp. 95-98. https://doi.org/10.18429/JACoW-MEDSI2018-TUPH28
[33] https://www.ansys.com/zh-cn.
[34] Li, C., Wang, Z., Li, M. et al., Design and test of support for HEPS magnets. Radiat. Detect. Technol. Methods 5, 95–101 (2021). https://doi.org/10.1007/s41605-020-00223-8
[35] Guo, X.L., Long, F.L., Chen, B. et al., Development of high precision and stability DC power supply prototype for High Energy Photon Source. Atomic Energy Sci. Technol. 53, 1523-1529 (2019).(in Chinese) https://doi.org/10.1007/s41605-018-0087-6
[36] Liu, P., Wang, X., Long, F., Fast corrector power supply design for HEPS. Radiat. Detect. Technol. Methods 4, 56-62 (2020). https://doi.org/10.1007/s41605-019-0149-4
[37] N. Li, et al., The fringe field and cross-talk effects of magnets in the HEPS storage ring, to be submitted to Nucl. Instrum. Methods Phys. Res. Sect. A, 2025.

[38] Xu, H., Cui, X., Duan, Z., et al, First beam storage in the High Energy Photon Source storage ring. Radiat. Detect. Technol. Methods 9, 70–81 (2025). https://doi.org/10.1007/s41605-024-00518-0
[39] X. Lu, et al., A new modular framework for high-level application development at HEPS. J. Synchrotron Radiat. 31, 385 (2024). https://doi.org/10.1107/S160057752301086X
[40] W. Bao, et al., A novel machine Model Manager for the fourth-generation light source. J. Inst. 20, P06059 (2025). https://doi.org/10.1088/1748-0221/20/06/P06059
[41] K.Ormond, J. Rogers, Synchrotron oscillation driven by rf phase noise. In Proc. PAC' 97, USA (1997), pp. 1822-1824.
[42] G. Gao, P. Liu, F. Long et al., Design and implementation of network topology for HEPS fast orbit feedback system. Nucl. Tech. 46, 050102 (2023).(in Chinese) https://doi.org/10.11889/j.0253-3219.2023.hjs.46.050102
[43] O. Singh, Y. Tang, S. Krinsky, Orbit feedback at the NSLS. Nucl. Instrum. Methods Phys. Res. Sect. A 418, 267 (1998). https://doi.org/10.1016/S0168-9002(98)00870-1
[44] D. Tavares, et al., Commissioning and optimization of the SIRIUS fast orbit feedback. In Proc. ICALEPCS2023, Cape Town, South Africa (2023), pp. 123-130. https://doi.org/10.18429/JACoW-ICALEPCS2023-MO3AO03
[45] P. Kallakuri, et al., Modeling the fast orbit feedback control system for APS upgrade. In Proc. IBIC2017, Grand Rapids, MI, USA (2017), pp. 196-198. https://doi.org/10.18429/JACoW-IBIC2017-TUPCF02
[46] S. Kongtawong, Y. Tian, L. Yu et al., Numerical simulation of NSLS-II fast orbit feedback system. Nucl. Instrum. Methods Phys. Res. Sect. A 997, 165175 (2021). https://doi.org/10.1016/j.nima.2021.165175
[47] X. Huang, et al., Characterization of fast corrector dynamic response at HEPS. In Proc. IPAC2023, Venice, Italy (2023), pp. 3619-3620. https://doi.org/10.18429/JACoW-IPAC2023-WEPM030
[48] CEPC Accelerator Study Group, CEPC Conceptual Design Report Volume I (Accelerator), August 2018, IHEP-CEPC-DR-2018-01.

Note: Figure translations are in progress. See original paper for figures.