Analysis of the beam orbit motion in the HEPS storage ring

Authors: Huang, Dr. Xiyang, Xu, Dr. Haisheng, Yan, Dr. F, Duan, Dr. Zhe, Wang, Mr. Zihao, Xu, Prof. Gang 徐刚, Wang, Dr. Na, Peng, Yuemei, Ph.D., Dr. Xiaohao Cui, Li, Dr. Nan, Zhao, Dr. Yaliang, Lu, Dr. Xiao-Han, Tian, Dr. Saike, Dr. Hong-Fei Ji, Meng, Dr. Cai, Guo, Dr. Yuanyuan, Wang, Prof. Jiu Qing, Jiao, Dr. Yi (Accelerator), Wei, Yuanyuan, Ji, Dr. Da-Heng, Jiao, Dr. Yi (Accelerator)

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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 measured power spectral density (PSD) of actual beam motion, 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 Beam Orbit Motion in the HEPS Storage Ring

Xiyang Huang[12], Haisheng Xu[12], Fang Yan[1], Zhe Duan[12], Zihao Wang[1], Gang Xu[12], Na Wang[12], Yuemei Peng[12], Xiaohao Cui[1], Nan Li[1], Yaliang Zhao[1], Xiaohan Lu[1], Saike Tian[1], Hongfei Ji[1], Cai Meng[12], Yuanyuan Guo[1], Jiuqing Wang[12], Yi Jiao[12]†, Yuanyuan Wei[1]‡, and Daheng Ji[1]§

[1]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

[2]University of the Chinese Academy of Sciences, Beijing 100049, China

The High Energy Photon Source (HEPS) is a high-performance, high-energy synchrotron radiation facility featuring a 6 GeV beam energy and an ultra-low emittance of 34 pm · rad. To fully exploit the potential of this high-brightness beam, orbit stability must be maintained with precision better than 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 emittance amplifies the impact of these noise sources compared to existing accelerators. Therefore, predicting expected beam orbit motion becomes crucial for validating component design approaches. This paper describes the calculation of anticipated beam orbit motion in HEPS, accounting for measured frequency-dependent ground motion coherence, structural resonances of magnet supports, and power supply noise. By comparing with measured power spectral density (PSD) of actual beam motion, we verify the model and calculation accuracy and identify additional noise sources affecting the light source. Finally, by predicting beam orbit performance with fast orbit feedback (FOFB) using measured hardware response, we confirm that the system meets 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 ultra-low-emittance storage ring designed with 48 modified hybrid 7-bend 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/mrad^2/0.1%BW in the hard X-ray regime. Electron beam orbit stability represents one of the most critical performance criteria for 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 translates to tens of nrad angular stability [?]. The soft inelastic X-ray scattering (SIX) technique studies electronic excitations with ultrahigh energy resolution, determined by gratings and exit slits with critical vertical apertures. During measurement, efforts focus on minimizing noise sources to maintain sub-μm stability at the exit slit [?].

Variations in beam position can lead to synchronization issues that compromise 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 horizontal and vertical planes. Specifically, for HEPS, the allowed orbit fluctuation tolerances in the frequency range of 0.1 Hz to 1 kHz 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 to ensure that storage ring design and operational protocols adequately align with user needs, thereby facilitating the high-quality experimental outcomes HEPS aims to deliver.

Within the frequency range of interest, electron beam motion is primarily influenced by two significant factors: movement of focusing elements due to ground vibrations, and fluctuations in magnet guiding fields caused by power supply electrical noise [?]. 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, girders are not perfectly rigid structures and exhibit resonant modes due to deformation [?, ?]. Consequently, beam motion analysis must incorporate these resonant modes. The motion of magnets driven by ground vibrations can thus be decomposed into two distinct components: girder motion driven by ground vibration, and magnet motion on girders corresponding to girder resonant modes.

In the HEPS storage ring, the beam orbit is affected by noise from quadrupoles and correctors, each equipped with individual power supplies. Since magnetic field is directly proportional to current, any current fluctuations lead to magnetic field variations. Such instabilities 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 magnetic field changes produce magnified effects on beam trajectory. In HEPS, quadrupole gradients can reach up to 80 T/m, indicating that power supply noise contributions to orbit perturbations are substantial and cannot be ignored.

The transmission pathways through which these two noise sources affect 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 mitigation strategies and enhancing orbit stability at HEPS.

Beyond these primary influences, several other potential sources may affect beam stability [?, ?]. One significant source arises from vibrations of the conductive vacuum chamber within quadrupoles [?]. These vibrations can effectively mirror quadrupole motion due to eddy currents induced within the vacuum chamber, which seek to stabilize the magnetic field in the moving frame of the chamber. Such vibrations can originate from factors including cooling water flow around the vacuum chamber. Although this vibration type has not yet been quantified, potential issues can be readily mitigated by inserting shims between magnet poles and vacuum chambers.

This paper is structured as follows: Section II introduces the general methodology for orbit motion analysis. Section III examines vibration-induced orbit motion, beginning with coherence measurements of floor motion, which is essential for understanding how the amplification factor depends on ground vibration frequency. Following coherence analysis, the focus shifts to characterization of beam orbit motion related to girder resonances. Section IV addresses electrical noise, presenting power supply noise measurement findings and estimating beam orbit motion induced by power supply noise from focusing magnets and correctors. Section V synthesizes these results to formulate a predictive spectrum of beam motion. Section VI presents initial beam commissioning results from the HEPS storage ring and actual PSD spectra of beam orbit fluctuations, comparing them with computational results to identify external noise sources not previously considered in the model. The final section provides a summary and discussion of results.

II. Methodology in 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(τ) = x(t)x(t+τ) is the auto-correlation function of x(t). With S_x(f) known in frequency region [f_1, f_2], measured or provided in datasheets, 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 = √(2S_x(kΔf + f_1)Δf), Δf = (f_2 - f_1)/N, and ϕ_k is a random phase angle uniformly distributed over (0, 2π]. As defined in Eq. (1), the PSD of a stochastic process is a statistical measure characterizing 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, simulations should be repeated multiple times using different realizations to ensure reliable conclusions.

One main property of 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 motion variance within that frequency band. If motion arises from multiple independent factors, the PSD of overall motion equals the sum of PSDs from each individual contribution, provided they are uncorrelated. This approach decomposes complex motion into constituent parts, enabling detailed analysis of electron beam behavior across the frequency range of interest.

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 beam position based on real-time measurements. The total orbit motion resulting from various noise effects can be expressed as:

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

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

III. Orbit Motion Induced by Ground Vibration

A. 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. Measurements were conducted using CMG seismometers equipped with GPS, which recorded ground vibration wave velocity. The seismometers had 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 below 1 Hz, primary contributors include atmospheric phenomena, ocean tide movements, and temperature fluctuations. Above 1 Hz, human activities such as machinery operation and vehicular traffic dominate. According to Eq. (3), measurements in the storage tunnel yield approximately 23 nm rms ground vibration noise in the 1-100 Hz frequency range, with induced frequency-independent orbit motion of 1.4 µm in the horizontal plane and 0.8 µm in the vertical plane, which compares favorably with orbit stability requirements. However, when the range extends to 0.1-100 Hz, induced orbit motion exceeds 6 µm in both planes. Even with perfect orbit feedback, the beam orbit cannot be controlled at the 0.3 µm level in the vertical plane, particularly since BPMs also vibrate 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 impact on orbit motion, as wavelengths at these frequencies may span the entire storage ring, resulting in negligible net motion. Understanding ground motion coherence 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.

B. Girder Motion

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 PSDs 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 data acquisition consistency between two identical devices operating simultaneously at the same location, ensuring high 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 sensors exhibit excellent coherence in the 1.7-80 Hz frequency range. While theoretical predictions suggest sustained coherence below 1.7 Hz, empirical observations reveal notable decline in this regime. The observed incoherence in the DC-1.7 Hz range cannot be readily attributed to any physical mechanism other than diffusion. However, diffusion influence is negligible in this context, as its effect diminishes with decreasing separation between measurement points. Consequently, this coherence reduction is primarily ascribed to measurement noise.

Following device coherence validation, 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 maximum separation of 110 meters constrained by cable length. Results are demonstrated in Fig. 4 [Figure 4: see original paper], where horizontal and vertical axes represent frequency and distance between seismometers, respectively, and color indicates coherence level. Measurements reveal that vertical alignment shows high coherence below 1 Hz, even at distances up to 110 meters, with coherence levels above 0.9 (highlighted by yellow shading in the right figure). In contrast, horizontal plane measurements show diminishing coherence with increasing distance.

The relationship between coherence length and frequency was established through analysis of the dataset presented in Fig. 5 [Figure 5: see original paper]. By identifying the frequency threshold at which coherence exceeds 0.9 for each separation distance, we derived empirical models for both planes:

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

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

Model parameters indicate coherence lengths of 11 meters and 20 meters at 1 Hz for horizontal and vertical planes, respectively. Notably, 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 beam orbit motion amplification in response to ground vibrations across varying frequencies. 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 following a Gaussian distribution with predefined amplitude, ensuring a statistically representative model of ground vibrations.

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

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

4. Resulting grid displacements are mapped onto corresponding magnets. Linear regression then smooths 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 amplification factor calculation accuracy.

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

Next, we provide detailed explanation of the numerical simulation. As indicated in step 1, the simulation initiates with generation of a two-dimensional grid, with points uniformly spaced at 0.5 meter intervals 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 inherent randomness, a two-dimensional Gaussian smoothing technique is employed. This process is governed by a transfer function that maintains constant value 1 for frequencies below lower threshold f_1, decreases linearly to 0 for frequencies above upper threshold f_2, and exhibits linear transition between these cutoff frequencies. 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]. The figure shows that ground displacement profiles exhibit significant variations depending on filter length. Specifically, larger filter length results in smoother ground displacement distribution, highlighting coherence length impact on spatial characteristics of the displacement field.

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

The outlined procedure generated 200 datasets of ground displacements, each associated with distinct filter length. For every dataset, the closed orbit was computed and standard deviation σ__i of the orbit at insertion device positions was evaluated relative to ground position. These standard deviations were subsequently averaged across 200 datasets to obtain mean value σ__i . Amplification factors were then calculated by normalizing σ__i with respect to standard deviation of ground motion:

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

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

Subsequently, PSD of non-resonant orbit motion G_c at the source point, induced by ground vibrations, can be calculated using Eq. (9):

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

and illustrated in Fig. 9 [Figure 9: see original paper]. Non-resonant orbit motion σ_c is obtained by integrating G_c over 0.1 Hz to 1000 Hz frequency range, as defined by Eq. (3), yielding values of 0.56 µm and 0.20 µm. Note that ground vibration PSD in the 100-1000 Hz range depicted in the figure is extrapolated from PSD below 100 Hz, with amplification factor for this frequency range identical to that at 100 Hz.

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

C. Vibration on Girder

As described previously, ground motion induces solid-body-like girder displacements. In addition to these rigid-body motions, vibrations can excite resonant deformation modes of girders. For uniform girder motion, effects of focusing and defocusing quadrupoles tend to partially cancel due to their opposing influences [**?**, **?**]. However, deformation modes may exist where focusing and defocusing quadrupole displacements on the girder act cumulatively, exerting more significant impact on beam orbit motion. Therefore, considering girder deformation mode influence is crucial.

HEPS incorporates focusing magnets mounted on six girders, plus longitudinal gradient dipoles spanning plinths. All girders are supported by concrete plinths, and in our design, vibration at plinth tops is assumed identical to floor vibration.

Fig. 10 [Figure 10: see original paper] illustrates the panoramic layout of magnet arrangement within one cell, with total length approximately 22 meters. Beam direction runs from right to left, with girders arranged as: DQ-I, MP-I, FODO-I, FODO-II, MP-II, and DQ-II. End cell girders are DQ type, each housing one focusing quadrupole (QF), one defocusing quadrupole (QD), and an independent fast corrector. Two central modules containing bending magnets with defocusing gradient (BD) are designated FODO. Remaining two modules including sextupoles, octupoles, and anti-bending magnets with focusing gradient (ABF) are designated MP. Vibration mode analysis was conducted using ANSYS Mechanical software, Release 19.1 edition [**?**]. To accurately predict modal response, dynamic stiffness testing was completed on support components [**?**]. Fig. 11 [Figure 11: see original paper] shows the first-order deformation mode of the FD-type girder in the horizontal plane.

During accelerator operation, girder vibration' s primary cause is ground motion. For frequencies approaching resonance, amplitude z_g(f) can be characterized by the classical resonance curve:

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

where z_d is drive amplitude and:

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

where f_0 is resonant frequency and Q is girder quality factor related to damping ratio by Q = 1/(2). Damping ratio is determined by striking the girder with a hammer and monitoring resulting vibrations. Table 1 shows first two deformation modes and 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 resonance curve equals f_0/Q. A key feature, significant for later analysis, is that at low frequencies where f f_0, Eq. (11) approaches 1, indicating absence of amplification—meaning the girder simply follows ground motion. Our analysis considers orbit motion due to a single mode in all girder assemblies. Orbit displacement at the source point (center of straight section) due to single girder assembly displacement in resonant mode m is:

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

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

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

where N = 48 is number of periods and λ_m^2 accounts for contribution of m-type girder in both odd and even units.

Normalized amplification factor Λ_m for mth mode can be derived using Eq. (13):

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

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

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

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

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

D. Total Orbit Motion Induced by Ground Vibration

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

$$\sigma_{\mathrm{vib}} = \sqrt{\sigma_c^2 + \sigma_r^2}.$$

Total motion is 0.57 µm and 0.21 µm in the two planes respectively, as shown in Fig. 15 [Figure 15: see original paper].

IV. Orbit Motion Induced by Electrical Noise

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

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

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

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

Power supply current ripple measurements were performed using a CoCo-80X oscilloscope operating in Dynamic Signal Analysis (DSA) mode. FC noise measurement setup schematic is presented in Fig. 16 [Figure 16: see original paper], and measured noise spectra of all supply types are provided as illustrative examples in Fig. 17 [Figure 17: see original paper].

Measurement results revealed numerous additional spectral lines, predominantly identifiable as 50 Hz harmonics. These lines are suspected to be measurement artifacts rather than genuine power supply output components. Furthermore, electrical noise impact on beam orbit is attenuated by the vacuum chamber. Based on experimental results in Fig. 18 [Figure 18: see original paper], this attenuation effect for quadrupoles and slow correctors can be approximately characterized by 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 measurement results in Fig. 18, negligible attenuation is observed for fast correctors below 1 kHz. These correctors feature laminated cores and are positioned within 0.5 mm thick Inconel vacuum chambers. Therefore, when calculating orbit motion induced by power supply noise in fast correctors, vacuum chamber suppressive effect will be neglected.

To account for different vacuum chambers, we define reduced power supply noise ñ as:

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

We will directly use Eq. (20) to calculate amplification factor.

A. Amplification Factors of Electrical Noise

Similar to ground vibration noise, the lattice-related normalized amplification factor for reduced power supply noise ñ can be expressed as:

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

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

$$z = \frac{\sqrt{\beta\beta_0}}{2\sin\pi\nu_z}\cos(\phi - \pi\nu_z)\theta.$$

Based on Eq. (18) definition, for quadrupoles, _{rms} can be written as:

$$\theta_{\text{rms}} = \tilde{n}KLd_{\text{rms}},$$

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

$$\theta_{\text{rms}} = \tilde{n}\theta_{\max},$$

remains valid when power supply noise is expressed as rms value. As mentioned, quadrupoles and correctors in HEPS each have independent power supplies. For given family j, z_j,rms represents total effect of all magnets in that family, assuming each individual magnet generates rms orbit kick _j,rms. By categorizing magnets into m distinct families, we derive:

$$z_{j,\mathrm{rms}}^2 = \sum_{l=1}^{N_j} \frac{\beta_0\beta_l}{4\sin^2\pi\nu_z}\cos^2(\phi_l - \pi\nu_z)\theta_{j,\mathrm{rms}}^2 = \frac{\beta_0\Phi_j}{4\sin^2\pi\nu_z}\theta_{j,\mathrm{rms}}^2,$$

where Φ_j = Σ β_l cos²(_l - π _z) is computed across all N_j magnets in jth family.

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

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

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

B. Orbit Motion Induced by Electrical Noise

As discussed earlier, orbit motion G_{ps} induced by electrical noise for each magnet type can be calculated by multiplying measured power supply noise PSD by attenuation curve from Eq. (19) and corresponding amplification factors from Table 2, as shown in Eq. (27):

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

where j represents different magnet families. Note that fast correctors are subject to different attenuation effects. PSD of total orbit motion induced by all power supply noise is shown in Fig. 19 [Figure 19: see original paper].

Integrated orbit motion, calculated using Eq. (28):

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

and results are summarized in Table 3 . Evidently, in horizontal plane, dominant contributions originate from transverse gradient dipoles and SC, whereas in vertical plane, SC and FC have relatively greater influence. Fig. 20 [Figure 20:

see original paper] shows total orbit motion induced by power supply noise in horizontal and vertical planes.

All calculations based on electrical noise were performed using idealized storage ring lattice model incorporating cross-talk effect [**?**]. However, in practical scenarios, coupling between horizontal and vertical orbital motions is unavoidable. In HEPS, coupling is set to 10%, leading to 0.05 µm increase in contribution of quadrupoles and horizontal gradient dipoles to vertical orbit motion. This increment is sufficiently small to be negligible. Total orbit motions induced by power supply noise are 0.75 µm and 0.24 µm, respectively, as illustrated in Fig. 20.

V. Total Orbit Motion Due to Vibration and Electrical Noise

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

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

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

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

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

VI. Validation and Discussion of Simulation Results and Actual Beam Motion

This section verifies analytical approach validity by comparing simulation results with actual beam motion in HEPS.

A. Commissioning of the HEPS Storage Ring and Optics Correction

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

Following beam accumulation completion, detailed commissioning work conducted successive closed-orbit correction, beam-based alignment (BBA), and optics correction. Detailed beam parameter measurements were performed, and local vacuum anomalies were repaired. First synchrotron radiation light was obtained on September 23. By December 2024 end, beam intensity reached 30 mA, lifetime was ~1000 s, closed-orbit deviation was <100 μm, beta-beating was <5%, chromatic dispersion deviation was <5 mm, coupling was <10%, and emittance was <100 pm.

B. Theoretical Calculation and Comparison with Actual Beam Oscillation

Since FOFB system hardware is not yet fully constructed, we currently analyze short-term beam orbit motion using turn-by-turn (TBT) data comprising 1 million turns.

Fig. 22 [Figure 22: see original paper] compares PSD of average orbit at source points of all low-beta straight sections (recorded January 7, 2025) with simulation results. Across most of 0.1 Hz to 1 kHz range, calculated results agree well with actual beam orbit motion—particularly within 70-86 Hz band corresponding to support structure resonance. Below we discuss three frequency bands where agreement is less satisfactory.

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

Second frequency band with notable discrepancy is around 300 Hz. This relatively broad peak arises from synchrotron frequency, which couples longitudinal motion to transverse motion via residual dispersion [?]. To verify this hypothesis, we conducted beam experiment: adjusting total cavity voltage and monitoring corresponding PSD peak, results shown in Fig. 24 [Figure 24: see original paper]. Currently, three RF cavities are in use. Initially, with total cavity voltage of 3.84 MV, peak appeared at 360 Hz (theoretical calculations predicted ~380 Hz longitudinal oscillation frequency). Next, reducing one cavity voltage by

0.1 MV while keeping others constant caused peak to split and shift to lower frequencies. Conversely, reducing all three cavities by 0.1 MV simultaneously shifted entire peak to 320 Hz. These results confirm peak around 300 Hz is closely linked to longitudinal motion. Fortunately, it requires little attention currently, as its contribution to transverse motion is <1% in both planes.

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

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

This is consistent with highest frequency observed in beam PSD. However, since large irrigation canal and pump room are near R42 cell in this direction, we have not yet identified 2.5 Hz peak source. Although low-frequency noise currently significantly impacts beam motion, its impact will be less pronounced once FOFB system is implemented [**?**].

C. Prediction of Orbit Motion with FOFB

Since actual beam fluctuations exceed calculations, we need to estimate beam orbit after FOFB system implementation. HEPS FOFB system will include 192 FCs per plane and is planned to operate at 22 kHz. FOFB system characteristics can be investigated using sensitivity equation [**?**]:

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

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

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

When selecting simple integral controller G_{PI}(s) = 7000/s, disturbance rejection gain G_0(f) at each frequency point can be calculated from Eq. (32). Noting G_0(f) is in dB units, attenuation ratio is derived as:

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

Orbit motion with FOFB control can be expressed as:

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

reducing motion 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].

VII. Summary and Discussion

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

Ground vibrations have been identified as critical contributor to beam orbit motion, affecting 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 horizontally and 0.20 µm vertically within 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 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 vertical orbit, resulting in total electrical noise-induced rms displacements of 0.75 µm and 0.24 µm. Combining both sources, total anticipated orbit motion without feedback reaches 0.94 µm and 0.32 µm.

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

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

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