UPDATED ORBIT STABILITY EVALUATION FOR THE KOREA-4GSR INCOPORATING NEW MECHANICAL AND BEAM DISTURBANCE MEASUREMENTS

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Abstract

Beam orbit stability is a critical requirement for fourth-generation synchrotron radiation facilities. An initial evaluation for the Korea-4GSR quantified expected orbit disturbances from ground vibration, magnet current ripple, and energy oscillations. Since that baseline study, additional measurements and refined models have enabled a more accurate assessment. Newly acquired ground-motion data provide updated vibration spectra affecting magnet and girder motion. Orbit fluctuations induced by the EPU and the canted-ID configuration have been characterized and incorporated into the analysis. Vacuum-chamber vibration, previously unaccounted for, has also been measured to assess mechanical coupling to the beam. Using these updated disturbance sources, revised orbit-stability predictions have been obtained through beam-dynamics simulations. The study identifies the dominant contributors under current design conditions and discusses implications for orbit-feedback performance and mechanical design optimization.

INTRODUCTION

Beam orbit stability is a critical requirement for fourth-generation storage rings (4GSRs). The defining feature of these 4GSRs is a low emittance achieved through advanced multi-bend achromat (MBA) lattice designs. While this drastically increases photon brightness, it also makes the beam exceptionally sensitive to minuscule mechanical and electromagnetic perturbations. Even sub-micron displacements can degrade the effective emittance, causing beam spot movement and intensity fluctuations at user beamlines. Therefore, maintaining orbit stability for the requirement of the beamline user is imperative.

To address these stabilization challenges, global research regularly characterizes and mitigates dominant perturbation sources [1-5]. These typically include ground vibrations [1-3], power supply current ripples [2-3], and RF-driven longitudinal energy oscillations [2-5]. Standard mitigation strategies involve mechanical optimization of magnet girders, stable power supplies, and high-performance orbit feedback systems [6]. Furthermore, recent efforts emphasize feedforward compensation schemes to combat localized, deterministic orbit distortions induced by insertion devices (IDs), such as elliptically polarizing undulators (EPUs) [7].

In line with these stringent stability demands, the Korea-4GSR project [8] is currently under development utilizing a MBA concept lattice. A primary baseline evaluation was previously conducted to quantify expected orbit disturbances from initial ground motion, magnet current ripples, and energy oscillations [9]. However, that baseline study was influenced by nearby construction activities and omitted secondary mechanical effects. This paper presents a comprehensive update to the primary estimation, incorporating refined operational measurements and sophisticated modelling frameworks to establish a more rigorous orbit stability prediction.

This paper systematically outlines the updated disturbance inputs and their impacts on the Korea-4GSR orbit stability. First, the integration of newly acquired day-time and night-time ground-motion data alongside a modelled girder amplification factor is detailed. Next, the newly incorporated coupling of vacuum-chamber vibrations to the electron beam inside quadrupole magnets is evaluated. This is followed by a description of an EPU kick compensation scheme comparing advanced nonlinear kick maps with machine learning position-dependent models. Finally, combining all updated error source are presented and benchmarked against the facility's stability requirements.

GROUND VIBRATION AND GIRDER AMPLIFICATION

To achieve an updated, realistic assessment of mechanical disturbances for the Korea-4GSR, new ground vibration measurements were conducted. While the primary baseline study was severely impacted by transient ambient noise from nearby construction activity [9], this updated study evaluates ground motion under day-time and night-time conditions to isolate and characterize these noise level.

The raw ground motion power spectral densities (PSDs) were translated into electron beam orbit distortions at the ID source points by evaluating the mechanical response of the magnet support structures. The girder amplification factor across the frequency spectrum, illustrated in Fig. 3, was incorporated using a simplified approximation model [10]. By comparing the day-time and night-time spectra shown in Fig. 1 (horizontal) and Fig. 2 (vertical), a clear divergence in the integrated vibration amplitude is observed at lower frequencies, directly quantifying the impact of localized civil engineering works during operational hours.

The resulting integrated electron beam motion at the ID locations was evaluated over a frequency range of 1 Hz to 100 Hz. Incorporating the girder amplification factor, the horizontal root-mean-square (RMS) orbit distortion was determined to be 150.8 nm during the day and dropped 87.5 nm at night (Fig. 1). Vertically, the integrated orbit distortion reached 85.3 nm under day-time conditions and was reduced 58.7 nm during the night (Fig. 2). Because the baseline contribution of ground motion to the overall facility stability budget was already minor, the marginal variations introduced by this refined girder amplification model exert a negligible impact on the total expected orbit stability. Nonetheless, these updated profiles establish a highly reliable environmental noise baseline for the optimization of the global orbit feedback loop.

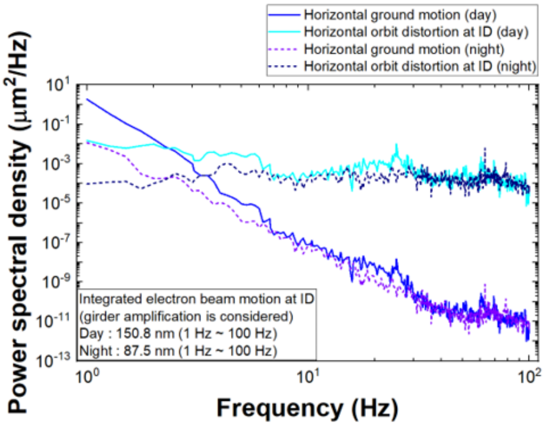

Figure 1: Horizontal ground motion PSD and the corresponding integrated electron beam orbit distortion at the ID source point, comparing day-time (solid lines) and night-time.

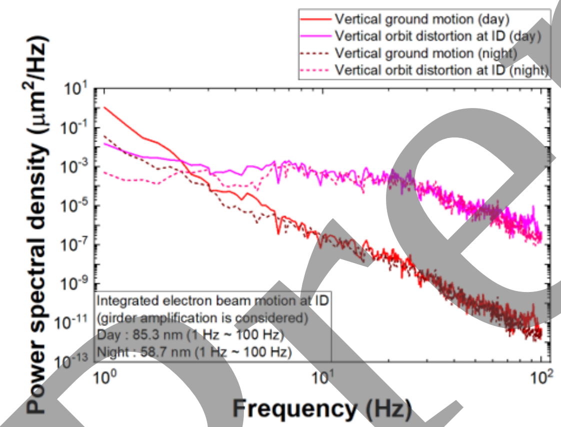

Figure 2: Vertical ground motion PSD and the corresponding integrated electron beam orbit distortion at the ID source point, comparing day-time (solid lines) and night-time.

VACUUM CHAMBER VIBRATION

Mechanical vibrations of the vacuum chamber inside quadrupole magnets can induce eddy currents, generating a magnetic field that perturbs the electron beam orbit [11]. Because the specific material inductance of the Korea-4GSR vacuum chamber has not yet been experimentally measured, a parametric scan analysis was performed over a range of chamber vibration frequencies and resistance-to-inductance ratios to quantify the beam disturbance shielding. The effective magnetic kick experienced by the beam can be expressed through a reduction factor, defined as

$$\xi = \frac{1}{\sqrt{1+\left(\frac{R}{wL}\right)^2}} \tag{1}$$

where the resulting chamber orbit distortion amplitude scales as $A_{chamber} = A_{kick} \times \xi$. To evaluate the shielding characteristics across parameter space, a reduction factor map was generated as a function of frequency and R/L, as shown in Fig. 4. For this baseline evaluation, a characteristic ratio of $R/L = 300\ s^{-1}$ was assumed alongside dominant vibration frequencies of 90 Hz in the horizontal plane and 40 Hz in the vertical plane. Under these operating conditions, the corresponding horizontal and vertical reduction factors were extracted from the map.

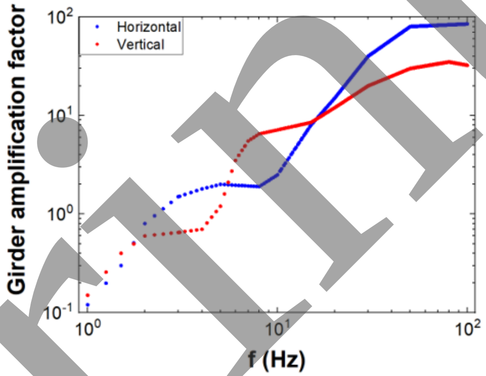

Figure 3: Modelled girder amplification factor as a function of frequency for the horizontal (blue) and vertical (red) planes.

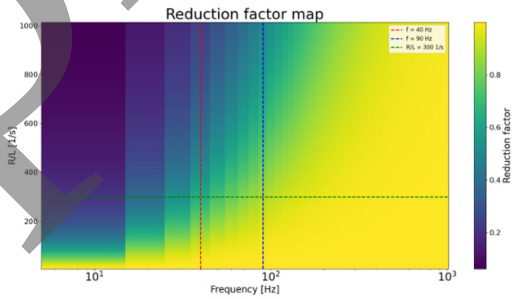

Figure 4: Modelled vacuum-chamber eddy-current reduction factor as a function of the vibration frequency and the chamber R/L ratio. Dashed lines highlight the evaluation baselines.

To prevent severe emittance degradation, the allowable orbit distortion from vacuum-chamber vibrations is budgeted at a maximum threshold of 500 nm horizontally and 100 nm vertically. Utilizing these strict beam-spot criteria, the maximum permissible mechanical vibration tolerance for individual magnet families was inversely calculated and is summarized in Table1.

The results indicated that the tightest vibration limits occur in the inner triplet quadrupole families, with the horizontal tolerance dropping to 21 nm for the Q11 family and the vertical tolerance reaching a minimum of 8 nm for the Q31 family. These strict thresholds suggest that relaxing the mechanical tolerances will require either lowering the vacuum-chamber resonant vibration frequency or optimizing the chamber cross-section to decrease its effective inductance.

Table 1: Individual quadrupole chamber mechanical vibration tolerances

	Horizontal	Vertical
QH1	183 nm	166 nm
QH2	147 nm	68 nm
QH3	83 nm	51 nm
QH4	373 nm	89 nm
Q11	21 nm	11 nm
Q12	53 nm	10 nm
Q31	40 nm	8 nm
Q32	46 nm	10 nm
Q51	24 nm	11 nm
Q52	66 nm	16 nm

ID KICK COMPENSATION SCHEME

ID gap and phase adjustments of elliptically polarizing undulators (EPUs) introduce highly nonlinear magnetic fields that cause localized electron beam orbit distortion. The conventional method for mitigating these perturbations relies on feedforward compensation using look-up tables evaluated at a fixed orbit. However, this traditional lookup has the limit because the precise magnitude of the nonlinear kick maps exhibits a non-negligible dependence on subtle shifts in the incoming orbit conditions, the lookup table performance is inherently degraded when the baseline orbit shifts.

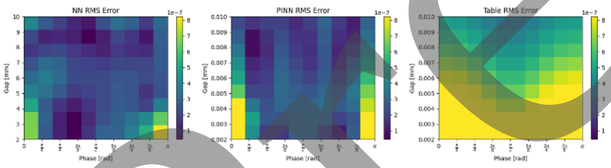

Figure 5: Residual RMS error maps across the EPU operational gap and phase space, comparing the performance of the standard NN (left), PINN (centre), and the conventional lookup table method (right).

To overcome these structural limitations and achieve position-dependent robustness, advanced machine learning compensation frameworks were implemented [7]. Artificial Neural Network (NN) and Physics-Informed Neural Network (PINN) architectures were trained to incorporate both EPU geometric settings and variable initial electron position conditions. The residual RMS tracking errors for the NN, PINN and the classical lookup table approach were systematically benchmarked across parameter space, as shown in Fig. 5. The comparative performance metrics demonstrate that the both neural network configurations dramatically suppress the residual RMS kick errors across a broad spectrum of gaps and phases compared to the conventional table approach. By explicitly mapping the entrance coordinate dependencies, these machine learning models ensure a significantly more stable feedforward compensation performance during dynamic ID operations.

UPDATED TOTAL ORBIT STABILITY

While a comprehensive baseline estimation of the beam orbit stability was previously calculated [9], this paper updates the total expected stability values by incorporating the newly refined mechanical measurements. The consolidated estimation results are summarized in Table2. Because the baseline orbit distortion contribution originating from environmental vibrations was already a minor component of the overall stability budget, the minor variations introduced by the updated girder amplification factor exert a negligible impact, leaving the final total stability metrics practically unchanged.

Table 2: Summary of updated RMS orbit distortion contributions at the ID source points from individual error sources compared with the Korea-4GSR design requirements.

Error source	Horizontal [nm]	Vertical [nm]
Vibration	52.7 → 87.5	81.6 → 58.7
Current ripple	1227	240
Energy oscillation without HC	19	9
Energy oscillation with HC	1046	523
Total without HC	1231	274
Total with HC	1615	590
Stability requirement	1923	408

CONCLUSION

This paper presents an updated beam orbit stability evaluation for the Korea-4GSR by integrating newly refined mechanical and beam disturbance assessments. Refined day-time and night-time ground-motion profiles alongside an institutional girder amplification model were successfully incorporated into tracking simulations. Additionally, the vacuum-chamber vibration tolerance was evaluated to establish individual magnet mechanical thresholds, and a position-dependent neural network-based insertion device compensation scheme was explored for the orbit stability. Because vibration contributions constitute a minor fraction of the global stability budget, the modifications introduced by the updated girder response exert a negligible impact on the overall facility performance, leaving the total stability practically unchanged.

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