

Impedance characterization and optimization of the High Energy Photon Source in-vacuum undulator

Na Wang^{✉,*}, Sen Yue, Jintao Li, Saiké Tian,[†] Lei Zhang, Shuchen Sun,
Yi Jiao[✉], Huihua Lu, and Yuhui Li

*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
and University of Chinese Academy of Sciences, Beijing 100049, China*



(Received 1 February 2025; accepted 6 August 2025; published 11 September 2025)

In storage ring-based synchrotron radiation light sources, in-vacuum undulators (IVUs) are widely used considering their advantages of short period length and high field quality. The impedance of the IVU and heat load deposition due to the beam passage are among the main concerns during the design and operation of the IVU. In this work, both transverse and longitudinal trapped modes are investigated, and novel mitigation strategies to reduce the impedance are proposed. Additionally, the longitudinal broadband impedance increase introduced by the bulge flexible taper transitions is presented. To obtain comprehensive and reliable information on the impedance, laboratory bench measurements are performed to identify the longitudinal and transverse impedance of the IVU experimentally. A reasonably good agreement was reached between the numerical predictions and the measurements.

DOI: [10.1103/zt5-848v](https://doi.org/10.1103/zt5-848v)

I. INTRODUCTION

Insertion devices show important contribution to the beam coupling impedance of synchrotron radiation light sources due to their small gap, especially for in-vacuum undulators (IVUs), which interact directly with the electromagnetic field generated by the beam during its passage [1,2]. The electromagnetic interaction can induce heat load dissipation in the IVUs and perturb the beam dynamics.

Measures to reduce the beam coupling impedance are commonly adopted in the design of IVUs. For instance, magnet covers are attached on top of the magnet arrays to serve as a smooth surface to the beam, while flexible tapers are attached at both ends of the magnet blocks to ensure smooth transitions to the nominal beam pipe [3–5]. In addition, several instability issues and mitigation strategies related to the impedance of IVUs have been reported. The vertical trapped modes formed between the magnet blocks and the vacuum tank constitute a major concern of IVUs, and related coupled bunch instabilities have been observed in several machines [6–8]. To damp these modes, adding lossy absorbers at appropriate locations [6] or shielding curtains [6,7] to connect the magnet blocks has been proposed. In addition, the extra heat load due to the

cavitylike structure formed by the bulge transition tapers has been reported at the TPS storage ring [9]. Therefore, the impedance of the IVU needs to be well understood and investigated during the design stage.

The impedance effects are of greater concern in the frontier fourth-generation synchrotron light sources, as the beam is more sensitive to beam stability. The impedance of IVUs introduces new challenges to stable beam operation. In this paper, we discuss impedance characterization and mitigation for the IVU design in the High Energy Photon Source (HEPS) [10]. Numerical simulations and bench measurements to characterize the vertical trapped modes in the IVU are performed, and mitigation strategies with absorbing materials are verified. In addition, as discussed in Ref. [6], incorporating ferrite damper in the IVU introduces several potential challenges, which include HOM-induced heating of the dampers, vacuum degradation due to outgassing, and perturbation of the magnetic field. To address these concerns, several measures have been adopted at SPEAR3. The ferrite blocks are coated with copper and positioned far away from the magnetic poles, and an additional vacuum pump has been installed. The operational studies on ferrite dampers installed in the IVU at SPEAR3 have demonstrated both the effectiveness in damping the modes and the robustness of the damper design [11]. Considering the potential risks of adding ferrite in the IVU, new damping strategies for the vertical trapped modes by optimization of the IVU geometry are proposed. For the longitudinal plane, we observe an increase of the longitudinal impedance when bulge taper transitions were used rather than flat tapers. We also

*Contact author: wangn@ihep.ac.cn

[†]Contact author: tiansk@ihep.ac.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

observe the longitudinal higher-order modes (HOMs) caused by the gap between the copper foil fasten structure and the magnet block, and proposed a method to reduce the effect of the longitudinal modes. To characterize the impedance experimentally, and to identify the effectiveness of the mitigation strategies, coaxial wire measurements are carried out. To our knowledge, this is the first case of longitudinal impedance bench measurement of an in-vacuum undulator. The measurements provide important supplement and benchmark to the theoretical evaluations.

The rest of this paper is structured as follows: In Sec. II, the design features and impedance characteristics of the in-vacuum undulators are introduced. Section III presents the longitudinal impedance and relevant optimization studies. In Sec. IV, the properties of the transverse trapped modes and their mitigation strategies are investigated. Section V describes the impedance bench measurements launched to identify longitudinal impedance and transverse impedance experimentally. Conclusions are given in Sec. VI.

II. DESIGN FEATURES AND IMPEDANCE CHARACTERISTICS

In-vacuum undulators commonly have complex mechanical designs, including adjustable magnet blocks with supporting rods, conductive metal covers on the magnet surface, taper transitions with adjustable angles, photon absorbers for protection of the downstream components, and cooling channels for heat load management. As a demonstration, the in-vacuum undulator of the HEPS is shown in Fig. 1. The HEPS IVUs are identical in terms of structural design. The magnet blocks are approximately 4 m long, and 26 pairs of rods are attached to hold the magnet blocks and adjust the gap between them. The minimum operating gap between the magnet blocks is 5 mm. A pair of flexible rf fingers made of BeCu is attached at both ends of the magnet blocks for a smooth transition to a nominal cylindrical beam pipe with a radius of 11 mm.

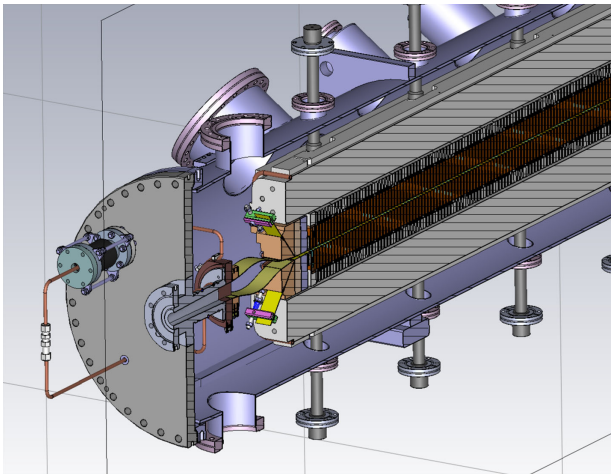


FIG. 1. CAD view of an in-vacuum undulator.

A nickel-plated copper foil of 85 μm in thickness serves as a magnet cover to provide a smooth and low resistance surface on top of the magnet blocks. A photon absorber, which is located in the horizontal plane at a distance of 9.5 mm away from the beam, is inserted between the downstream flexible tapers. The whole structure is hosted inside a vacuum tank with a diameter of 400 mm.

The impedance contributions from the in-vacuum undulator include the resistive wall impedance and the geometrical impedance. The resistive wall impedance is directly related to the aperture and material of the beam pipe. With a layer of copper foil attached to the surface of the magnet arrays, the resistive wall impedance and the beam-induced heat load on the surface of the magnet block can be significantly reduced. However, they still make a large contribution to the vertical resistive wall impedance due to the small gap of the insertion devices in the vertical direction. In HEPS, the insertion devices contribute to approximately half of the growth rate of the transverse resistive wall instability [12].

Concerning the geometrical impedance of the IVU, as the transverse impedance is roughly inversely proportional to the cube of the aperture size [13], the vertical impedance is one of the main concerns during the impedance evaluation. There are vertical trapped modes due to electromagnetic fields trapped between the magnet blocks and the vacuum tank, which result in high shunt impedance and need to be further mitigated by optimization of the structure or positive feedback damping [6–8,12]. Owing to the small gap, the IVUs are also important origins of the transverse broadband impedance, which contributes to the transverse mode coupling instabilities and betatron tune shifts.

In the longitudinal plane, the beam power loss dissipation inside the IVU and longitudinal broadband impedance contributed from the flexible taper transitions between the magnet blocks and the vacuum tank are also important for promising operations. In addition, longitudinal narrowband impedance can be induced by improper rf contact of the fasten structure of the metal cover on top of the magnet arrays. The installation of the absorber in the IVU can also introduce trapped modes. Similar modes have been observed in the design of in-air undulators [14]. In both transverse and longitudinal planes, another important feature of the impedance of the IVU is the impedance variation while the gap between the magnet blocks is adjusted [2].

On the other hand, accurate impedance modeling of in-vacuum undulators is not easy, since the component is large and complicated. To address this, we used a simplified IVU model including only the main geometries to perform simulations with CST [15] to rapidly investigate the parametric dependencies of the impedance. In addition, the magnet blocks are shortened to a length of 1 m to ease the requirements on the computational memory and simulation time. The simplified model is shown in Fig. 2.

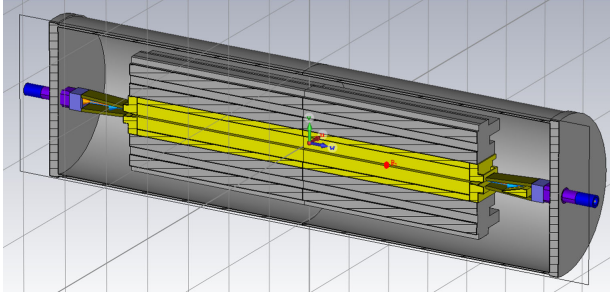


FIG. 2. Simplified model of the in-vacuum undulator used in the CST simulations. The magnet blocks are shortened to a length of 1 m.

The dependence of the results on the length of the magnet blocks was checked via numerical simulations. The longitudinal impedance showed little dependence on the length of the structure. On the other hand, the transverse mode characteristics were found to be sensitive to both the overall dimensions of the structure and the details of the model. Despite this, we believe that the impedance calculated with shortened magnet blocks is reasonable enough to represent the impedance characteristics of the real structure. A more detailed discussion of the influence of magnet length on impedances can be found in the Appendix.

III. LONGITUDINAL IMPEDANCE AND RELEVANT OPTIMIZATION STUDIES

A. Longitudinal HOMs due to the poor rf contact at the fasten structure of the copper foil

As discussed in the last section, nickel-plated copper foils are attached to serve as a smooth surface on top of the magnet arrays. To maintain the tension of the foil when the gap between the magnet blocks is adjusted or when their temperature varies under beam-induced heating, the copper foils are not fixed at either end of the magnet blocks but are held by flexible fasten structures with springs. Therefore, a gap between the fasten structure and copper foil was preserved to ensure that the foils were movable under the stretching by the springs. In this case, the passage of the image current of the beam, which is concentrated mainly at the center of the copper foil, is interrupted. A schematic view of the foil fasten scheme of the HEPS is shown in Fig. 3. The gap has a minimum value of 0.2 mm. In the original design, the electrical contact between the fasten structure and the magnet block only exists at the side parts of the fasten block, as shown by the red faces in the top right plot.

Owing to the interruption of the image current or poor rf contact between the fasten structures and the magnet blocks, longitudinal HOMs are generated. Based on the simplified model shown in Fig. 2, the longitudinal impedance was simulated with the CST wakefield solver. The wakefield simulations were performed with a 3 mm rms

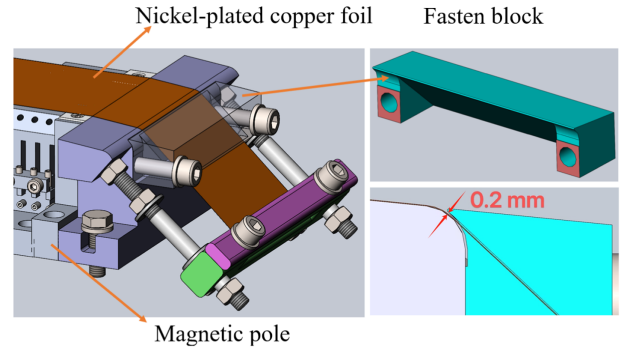


FIG. 3. Left plot shows the schematic view of the original design of the fasten scheme of the copper foil, and the fasten block is set to be transparent to demonstrate how the foil is fastened. The top right plot shows a close-up view of the fasten block, where the red faces show the contact faces to the magnet block. The bottom right plot shows the longitudinal cut view along the symmetrical plane of the foil, where the gap between the fasten block and the copper foil can be seen.

bunch length Gaussian beam. The selection of this bunch length is based on the nominal bunch length of 5 mm under the condition of zero bunch current and without harmonic cavities [16]. Additional margin was included to accommodate possible spectrum extension to higher frequencies arising from bunch distortion at higher beam current. The real part of the longitudinal impedance is shown by the red curve in Fig. 4. In the impedance spectrum, we clearly see two resonances at 2.1 and 6.1 GHz.

To confirm the origin of the resonances, eigenmode simulations are performed to obtain the detailed information on the modes. The electromagnetic fields are concentrated at the gap between the fasten structures and the magnet cover, as shown in Fig. 5. In addition, according to the wakefield simulations, this field

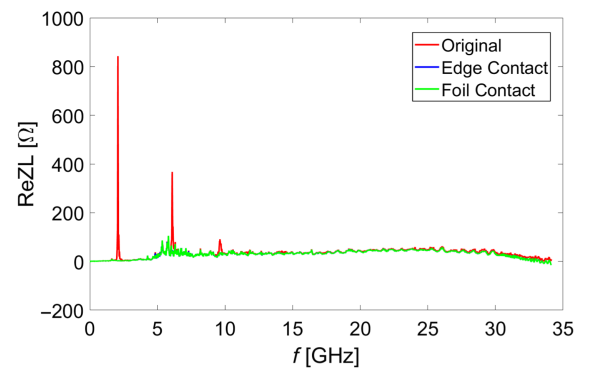


FIG. 4. Real part of the simulated longitudinal impedance under mitigation strategies and comparison with that of the original design. The red curve corresponds to the original design without mitigation. The blue and green curves represent the cases with mitigation through extending the contact face at the side parts of the fasten block to the edge facing the beam or adjusting the foil location to reduce the cavity seen by the beam.

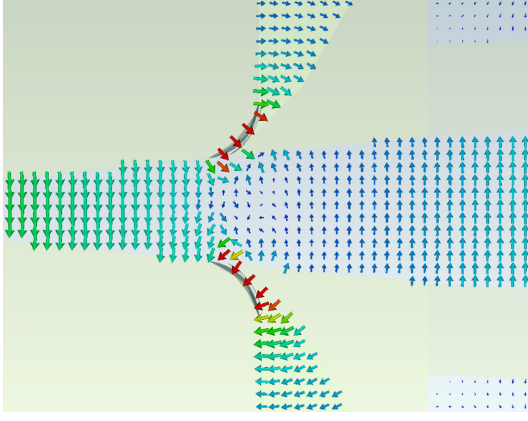


FIG. 5. Longitudinal cut view of the electric field distribution of the trapped mode at a frequency of 2.1 GHz observed at one end of the magnet blocks.

concentration also induces resonant behavior of the beam power deposition on the fasten structure during the beam passage. The strength of the resonances depends on the size of the gap between the fasten structure and the magnet cover. When the gap size is large enough such that strong resonances are excited by a relatively short bunch and the beam current is high, the modes will cause heating of the fasten structure and induce longitudinal coupled bunch instabilities.

To reduce the resonances, two candidate solutions are proposed. One is to extend the contact faces between the fasten structures and the magnet blocks to the horizontal plane facing the beam, which means extending the red faces shown in the top right plot of Fig. 3 to the edge of the curved part. In this case, the image current sees smooth paths on both sides of the fasten block, while the gap between the fasten structure and the copper foil is preserved. Another solution is to adjust the location of the fixed ends of the foil to ensure that the cavity formed between the magnet cover and the fasten structure is small enough such that resonances are not excited by a relatively long bunch.

Both mitigation strategies are verified via numerical simulations. The longitudinal impedances are shown by the blue and green curves in Fig. 4 and are compared with the impedance of the original design, as given by the red curve. The results indicate that both methods can effectively damp the resonant modes, and the longitudinal impedance becomes mainly broadband. The mitigation strategy with further edge contact at the fasten blocks has been adopted in HEPS. The results also confirm that the origin of the resonances is the poor rf contact between the foil fasten structure and the magnet block. Therefore, during the design and mounting of an IVU that employs the similar type of foil fasten structure, the rf contact between the foil fasten structure and the magnet block should be carefully checked.

B. Longitudinal impedance contribution from the flexible taper transitions

To achieve smooth transition from the magnet blocks to the regular beam pipe, a pair of flexible rf fingers made of BeCu is adopted. In the initial simulations, straight taper transitions were used. However, during the coaxial wire measurement, we found that the measured broadband impedance is significantly higher than that in the original simulations, and the main cause of this increase is the improper modeling of the flexible tapers. In the actual model of the taper transition, the rf fingers bulge outward to ensure that the fingers do not bend in the opposite direction while adjusting the gap of the magnet blocks or under an extra heat load from the beam. These bulge tapers show a large contribution to the longitudinal effective impedance.

On the basis of the simplified model shown in Fig. 2, we replace the straight tapers with bulge tapers, which have a maximum separation of 45 mm, as measured in the real configuration. The comparison of the simulated longitudinal impedance for the model with different taper transitions is shown in Fig. 6. We have performed simulations tracing the wakefields over 15 m behind the bunch. Here, the resonant modes caused by the poor rf contact at the fasten structure were mitigated after optimization. The results indicate that the shape of the flexible rf finger significantly affects the longitudinal impedance. Both the

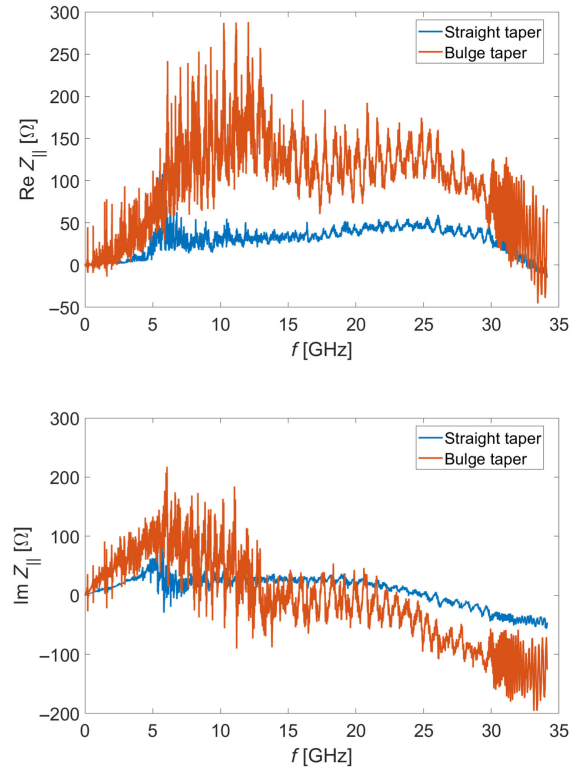


FIG. 6. Comparison of the real part (top) and imaginary part (bottom) of longitudinal impedance for IVU with straight and bulge taper transitions.

real and imaginary parts of the broadband longitudinal impedance increase remarkably with bulge tapers. Accordingly, the longitudinal effective impedance and loss factor also increase. For a Gaussian bunch with an rms bunch length of 5 mm, the longitudinal effective impedance is increased by a factor of 2, and the loss factor is increased by a factor of 4. However, the total longitudinal effective impedance of the machine increases by less than 5%, so we believe that it will not considerably influence the longitudinal beam dynamics. In contrast, an increase in the longitudinal loss factor means higher parasitic beam power loss, which is another important concern during beam operations, as the extra heat load can induce deformation of the flexible transition taper or affect the performance of the undulator.

The beam power dissipation in the IVU was simulated with the CST wakefield solver, by tracing the wakefields over 20 m behind the bunch. The power dissipation on different parts of the IVU during and after bunch passage with a bunch charge of 1 nC is shown in Fig. 7. The results show a high transient power density at the taper transitions, flexible rf fingers, and magnet blocks during beam passage. Compared with the results for the model with straight tapers, the transient power loss during bunch passage is considerably higher for the bulge taper. However, these beam powers vanish after the beam is transported out of the vacuum tank. In particular, the total power loss on the flexible rf fingers is less than 5 W at a nominal beam current of 200 mA and a bunch number of 680. This power loss is considerably low compared to the total beam power loss of 330 W calculated from the loss factor. Instead, the power density inside the vacuum tank remains at a medium power level for a long period of time, which means that the parasitic beam power loss is dissipated mainly in the vacuum tank. This can be explained that the field excited by the beam diffuses inside the tank and becomes trapped due to the large size of the tank, even though the beam field distribution is more concentrated on the components close to the beam during its passage.

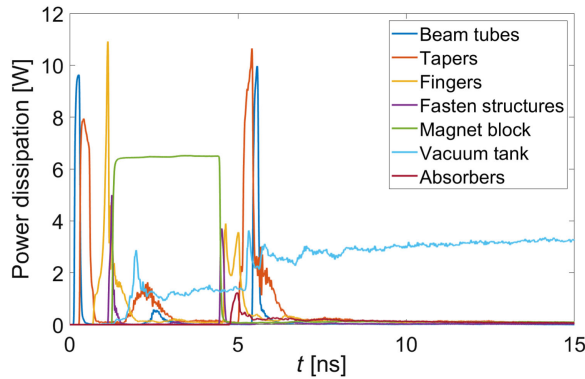


FIG. 7. Power loss dissipation on different parts of the IVU during and after the bunch passage with bunch charge of 1 nC and an rms bunch length of 5 mm.

The impedance contributions from the bulge flexible transition taper and the resonance from the poor rf contact at the fasten structure will be further checked via coaxial wire measurements, as discussed in Sec. V.

IV. TRANSVERSE TRAPPED MODES AND MITIGATION STRATEGIES

Based on the shortened simplified model shown in the last section, the transverse impedance of the in-vacuum undulator is investigated. According to the previous studies [6,7], the supporting rods have important contributions to the field distribution of the trapped modes; therefore, the rods have been added to the simplified model in transverse impedance simulations. We first demonstrated the mode characteristics and damping strategies via the shortened simplified model and then more detailed and time-consuming simulations were performed with the CAD model and the actual length of the undulator. The latter is used to benchmark with laboratory bench measurements and is discussed in Sec. V.

A. Characteristics of the trapped modes

The transverse wakefield simulations are first performed with an exciting Gaussian beam with an rms bunch length of 100 mm. This bunch length was chosen because the resonant frequencies of the dominant trapped modes are located in the range of hundreds of MHz. The transverse impedance is shown in Fig. 8. Two dominant resonances are observed at 96 and 189 MHz, along with two lower resonances at 316 and 379 MHz. Notably, the wake potential does not converge well even when the wakefield is tracked for 20 m. We did not pursue a longer wakefield since the simulation is quite time consuming, and the results already effectively show the key impedance characteristics.

To obtain detailed mode information, eigenmode simulations are performed. The results for the first five dominant modes are shown by the red asterisks in Figs. 9 and 10.

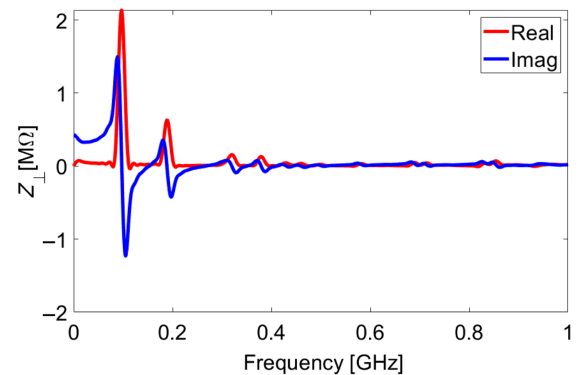


FIG. 8. Real and imaginary parts of the vertical impedance simulated with the shortened simplified model of IVU.

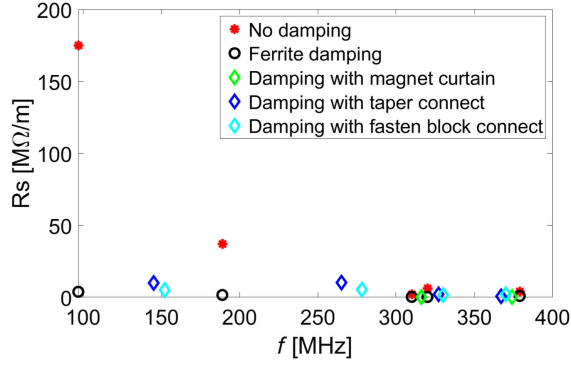


FIG. 9. Comparison of the shunt impedances of the vertical trapped modes for the cases of no damping, ferrite damping, or geometric damping.

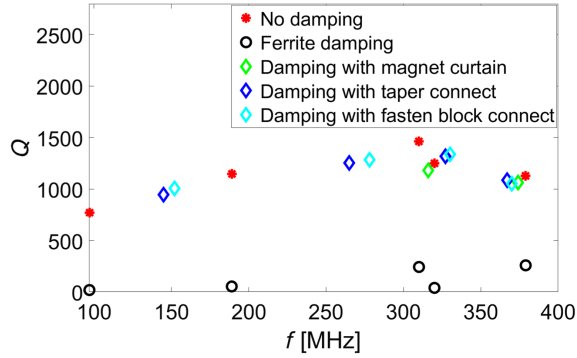


FIG. 10. Comparison of the quality factors of the vertical trapped modes for the cases of no damping, ferrite damping, or geometric damping.

The electromagnetic field distribution is concentrated mainly between the gap and the flexible taper transitions. There are also fields located around the rods and near the water cooling pipes. Owing to the small magnet gap, the electric fields of the HOMs, except HOM no. 4, are focused mainly inside the gap and show patterns with periods of one to four. As a demonstration, the field distribution of the HOM no. 2 is shown in Fig. 11. In contrast, the electric field of HOM no. 4 is concentrated around the rods. The mode frequencies are consistent with those of the wakefield simulations, except that there are two eigenmodes near the impedance peak at 316 MHz. From the field distribution, we suppose that HOM no. 4 is weakly coupled with the beam and is not strongly excited during the beam passage in the wakefield simulations. The Q values of the modes are approximately 1000. The shunt impedances of the modes are relatively high compared with the impedance thresholds of several $M\Omega$ determined by the synchrotron radiation damping. Therefore, these modes need to be further damped.

B. Mode damping

To damp the modes, the addition of absorbing materials, such as ferrite blocks around the supporting rods proposed

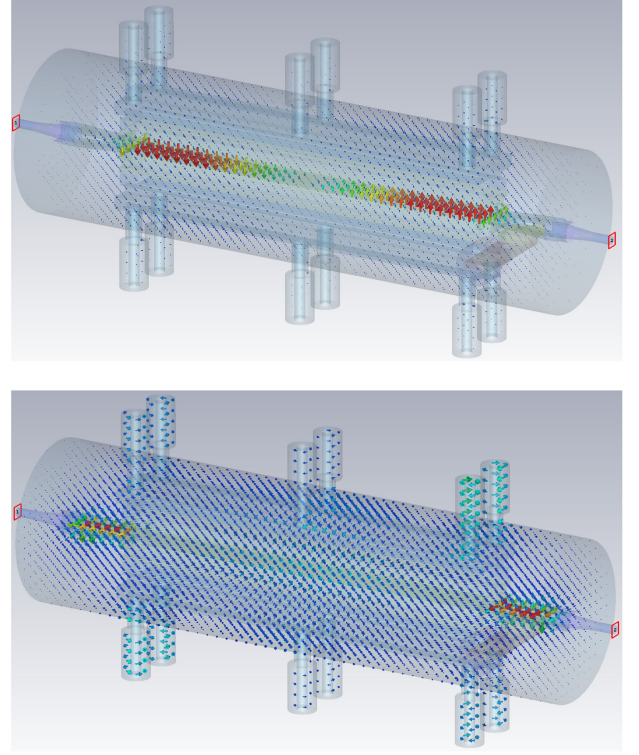


FIG. 11. Electric field (top) and magnetic field (bottom) distribution of HOM no. 2 at a frequency of 189 MHz.

in Ref. [6], is first tested via simulations. Here, we mainly focus on the impedance damping caused by the ferrite dampers. More discussions on the possible risks of introducing the ferrite dampers can be found in Ref. [6].

The eigenmode simulation results for the first five dominant modes provide information on the trapped modes with the ferrite damper, as shown by the black circles in Figs. 9 and 10. The permeability and permittivity of the ferrite measured in Ref. [17] are adopted. The damping effects depend on the field distribution of the modes. In addition, ferrite has little influence on the mode frequency and the R/Q factor. With the ferrite damper, the quality factors Q of the modes are reduced, and the shunt impedances of the dominant modes are decreased by approximately a factor of 10.

Another possible approach to damping the modes is optimizing the geometry of the structure. By further analyzing the field distribution of the modes, we see that the electric fields of the resonant modes are concentrated between the magnet gap, while the magnetic fields are mainly concentrated between the flexible tapers at both ends of the magnet blocks. So that the electromagnetic fields form a resonant structure between the magnet blocks and the flexible tapers. Therefore, to reduce the resonant field pattern, a possible mitigation scheme is shielding both sides of the opening gap between the magnet blocks with metal curtains or springs, as discussed in Ref. [7], another idea is adding connections to the top and bottom flexible

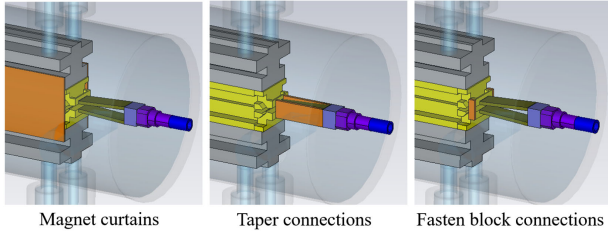


FIG. 12. Schematic view of the numerical models for the geometrical damping strategies, observed at one end of the IVU chamber, demonstrating the shielding solutions with magnet curtains, taper connections, and fasten block connections. The damping structures are represented by the orange blocks in the schematics.

tapers. We have also tried to directly connect the foil fasten blocks at both ends of the magnet blocks with metal plates. The schematic view of the numerical models for the geometrical damping strategies are shown in Fig. 12. It should be noted that the current work establishes only conceptual solutions, with detailed design optimization left for future implementation studies.

For the mitigation strategies with geometry optimization, the quality factors Q remained nearly unchanged, but the R/Q values of the modes decrease because of the interruption of the resonant structure of the field distribution. With the geometrical mitigation strategies, the simulated shunt impedance R_s of the vertical modes in the same frequency range as discussed above is shown in Fig. 9. A comparison with the results without mitigation reveals that with geometry optimizations, the strong modes can be well damped, and the shunt impedances of the modes in the simulation frequency range can be reduced to the $M\Omega/m$ level, which can be easily mitigated by Landau damping or weak feedback damping. The addition of connections at the magnet blocks is more efficient at damping the modes; however, adding connections at the flexible tapers or foil fasten blocks, as proposed in this work, is more convenient to implement with fewer modifications to the IVU configuration.

V. IMPEDANCE MEASUREMENTS

During the simulation studies, the model of the IVU was simplified to different extents. To characterize the impedance of in-vacuum undulator experimentally, as well as to identify the influence of the model simplification and the effectiveness of the mitigation strategies, bench measurements were performed on the B5 ID chamber of HEPS and compared with numerical simulations. The fasten blocks of the IVU used for the measurements have been extended to the magnet blocks, and bulge tapers have been adopted.

Although all IVUs in HEPS share identical structural designs, variations exist in both magnetic field strength and periodicity of magnet arrays among different IVUs. These differences are expected to have limited influence on the

broadband impedances, since the magnet arrays are shielded by conductive metal covers. However, they may contribute to the quality factors of the vertical HOMs, as the electromagnetic fields are extensively distributed within the tank. Additionally, the shape of the bulge taper, which depends on the specific installation of the rf finger, could also affect the impedances.

A. Longitudinal impedance measurement with coaxial wire method

To better understand the contribution of the foil fasten structure and rf tapers to the longitudinal impedance in the actual configuration, coaxial wire bench measurements were performed. In the measurement, a coaxial transmission line is formed by placing a thin conductive wire with diameter of 0.8 mm along the axis of the IVU chamber. The excited electromagnetic field in this configuration closely mimics the field pattern generated by a relativistic charged particle beam [18]. The transmission line is connected to a vector network analyzer (VNA) through fastening structures. The total length of the vacuum tank of the IVU is approximately 4.7 m, with the length of the magnet blocks being 4 m. During coaxial wire measurements, stretching the wire with reasonable deflection from gravity at such a long distance and a small gap of 5 mm is quite challenging. The wire fastening structure proposed in Ref. [19] was used for wire stretching. With a tension of approximately 150 N, the deflection of the wire under gravity is less than 0.9 mm, which is acceptable for the IVU measurement.

The scattering parameters are measured using the Keysight E5071C VNA, covering a frequency range from 300 kHz to 20 GHz. The impedance is calculated as the complex ratio between the scattering parameters measured for the IVU chamber and those of the reference tube. Comparison between the measured and simulated longitudinal impedance of the IVU with straight tapers indicated the simulation with a simplified IVU model underestimated the longitudinal impedance. After verifying that the magnet block lengths in the simplified model had negligible impact on the longitudinal impedance, subsequent simulations demonstrated that the bulge taper transition is primarily responsible for the observed impedance enhancement, as illustrated in Fig. 6. To include more geometric details in the simulation under available computing resources, we used GdfidL [20]. The numerical model of IVU in GdfidL simulations incorporates the actual dimensions of the CAD model, and preserves the mechanical details of the magnet blocks, vacuum tank and pumping ports, foil fasten structures, magnet supporting rods, photon absorber, and taper transitions to the regular beam pipe. Here, the bulge tapers with measured maximum separation have been implemented.

The measured longitudinal impedances are compared with those of the wakefield simulation results, as shown

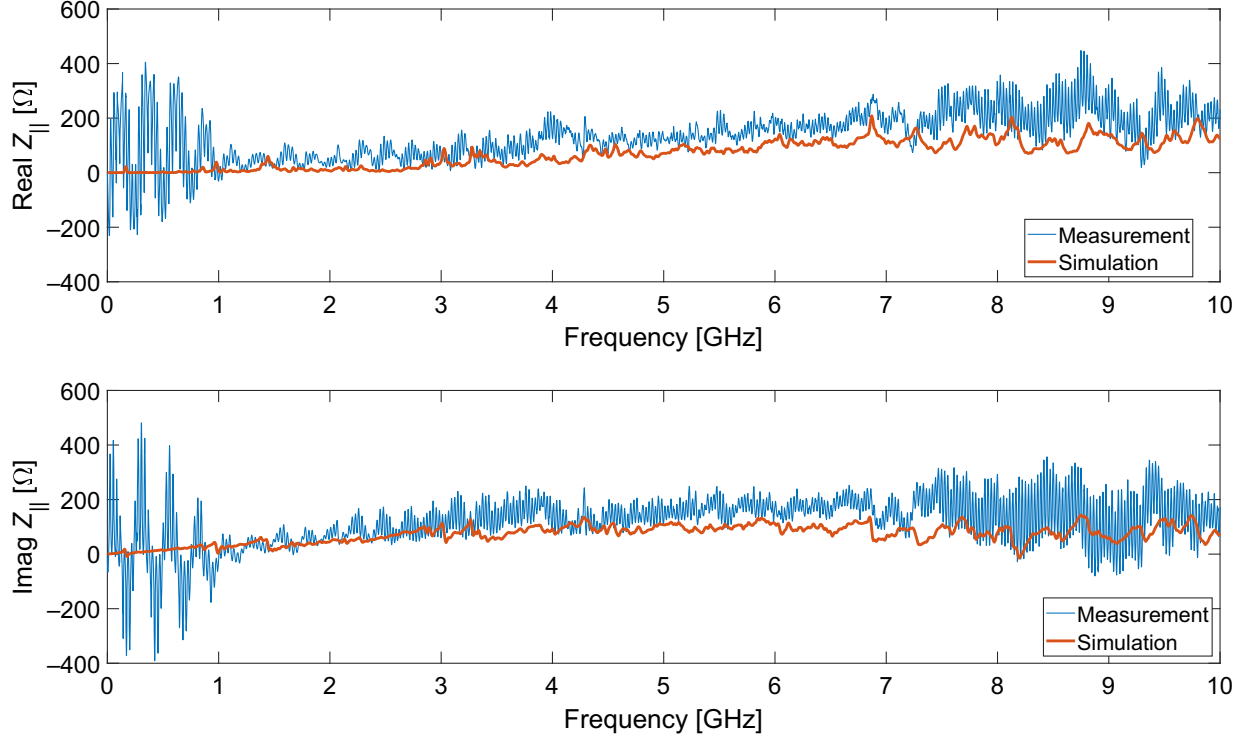


FIG. 13. Comparison of the real (top) and imaginary (bottom) parts of the longitudinal impedance of the IVU obtained by coaxial wire measurement and wakefield simulations.

in Fig. 13. The measured and simulated broadband impedance show similar frequency-dependent trends, with no prominent narrowband resonant peaks. In the measurement, there are periodic resonant structures below 1 GHz with an envelope of every 250 MHz. Transmission simulations performed to confirm the origin of these resonances show that they are contributed by impedance mismatches between the transition ends of the IVU and the connections to the coaxial cables. Therefore, these resonances can be treated as measurement uncertainties. A small divergence still exists between the simulation and measurement in a broadband way. We believe that this divergence is attributed to the difference between the model of the bulge flexible finger used in simulations and the real configuration. In the simulation, we only take the measured maximum separation between the flexible fingers and then use the loft function in the CST to form the bulge taper, which may not fully capture the actual complex geometry of the flexible rf fingers, as their final configuration is highly sensitive to the mounting conditions. In addition, the deflection of the wire under gravity also contributes to the increase in the measured impedance. The observed discrepancies at high frequencies can be primarily attributed to the cutoff frequency of the transverse electromagnetic mode in the coaxial transmission line, which is approximately 8 GHz for the given setup. Beyond this frequency, the excitation of higher-order modes may induce signal distortion and compromise measurement accuracy [18].

In addition, according to the measurement, no apparent longitudinal HOMs are introduced by the foil fasten structure, which confirms that the mitigation strategy is effective in damping these modes. However, we do observe the resonance introduced by the photon absorber in the measurement. Figure 14 shows a comparison of the S21 transmission parameters from the two measurements with and without the photon absorber. With the photon absorber, one clear resonance is observed at approximately 198 MHz. Using the S-parameters measured without photon absorber as the reference, we applied the log formula [21] to determine the longitudinal impedance contributed from the photon absorber. The impedance amplitude at the resonance is approximately 100 Ω , which is acceptable from the beam; thus, no specific measures are taken to damp the resonance. This resonant mode induced by the photon absorber has also been proven via simulations. As a demonstration, the bottom plot in Fig. 14 shows the electric field distribution around the absorber monitored in the transmission simulations. In the wakefield simulation shown in Fig. 6, we also observe a small resonance at 198 MHz, as given by the first peak.

B. Transverse trapped modes measurement with probes

The coupling probe method is employed to characterize the transverse trapped modes. Two weakly coupled probes

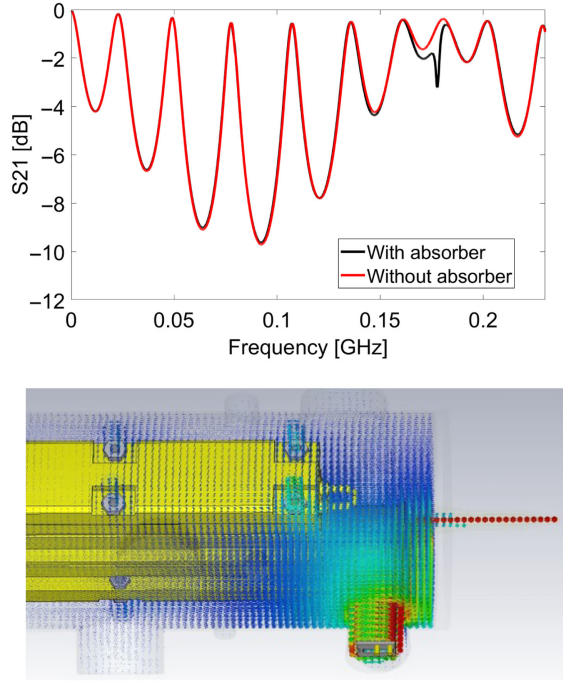


FIG. 14. Comparison of the two coaxial wire measurements for IVU with and without the photon absorber (top), and the simulated electric field distribution around the absorber at the resonant mode frequency of 198 MHz (bottom).

were inserted into the IVU through the side vacuum ports to excite and detect the trapped modes. Each round-shaped probe has a diameter of 100 mm and is connected to the VNA to measure the scattering parameters. The coupling between the probes and the trapped modes was kept weak by tuning the insertion depths and orientations of the probes, to minimize disturbance to the fields of the trapped modes.

At the nominal magnet gap of 5 mm, the resonant frequencies and Q values of the first four dominant modes are listed in Table I. Since the transverse modes are highly relevant to the dimensions, eigenmode simulations are also performed using the real dimension of the IVU. Compared with those of the simulations, the measured mode frequencies are highly consistent. However, the measured Q values are almost one order of magnitude lower than those of the simulations. Similar phenomena have also been observed in

TABLE I. Eigenmode simulation results for the first four dominant modes for the simplified IVU model with actual magnet length, compared with measurements.

HOM no.	f (MHz)	Q_{Sim}	f (MHz)	Q_{Meas}	R_s ($\text{M}\Omega/\text{m}$)
1	74.1	2483	75.9	153	0.2
2	87.8	1875	88.9	268	25.9
3	109.6	1531	110.0	241	34.8
4	136.7	1416	136.4	329	31.0

the studies at SPEAR3 [6]. The introduction of discrepancies is expected because some detailed structures have been omitted in the simulations, which increases the HOM power consumption. In addition, the convergence of the simulations and the magnetic permeability distribution along the magnet poles can also contribute to these discrepancies.

The shunt impedances of the modes are calculated by multiplying the measured Q values with the simulated R/Q values. The impedance amplitudes of the second, third, and fourth modes are still high compared with the impedance threshold determined by the synchrotron radiation damping, which is $4 \text{ M}\Omega/\text{m}$ for the HEPS case [12,22]. Therefore, further damping of the modes is still needed, either by active damping with absorbers and geometrical optimizations or by feedback systems.

The dependencies of the mode frequencies and Q factors for different magnet gaps were also measured and are shown in Fig. 15. The simulation results at the nominal gap of 5 mm are also shown in the plot with red stars. The mode frequencies increase almost linearly with increasing gap width. Conversely, the Q factors show no clear relationship with the variation of the gap, except that the Q values of HOM no. 3 decrease for larger gaps.

In addition, the damping of the vertical trapped modes with ferrite dampers was tested during measurements.

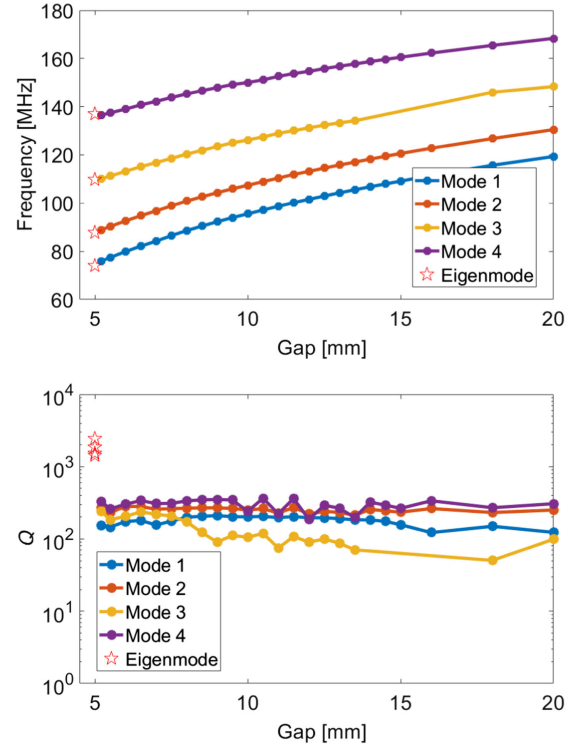


FIG. 15. Variation of the mode frequencies (top) and quality factors Q (bottom) with the magnet gap for the IVU obtained from the probe measurements. The curves labeled as modes 1 to 4 correspond to HOM no. 1 to 4 in Table I, and the stars show the results from the eigenmode simulations at nominal gap of 5 mm.

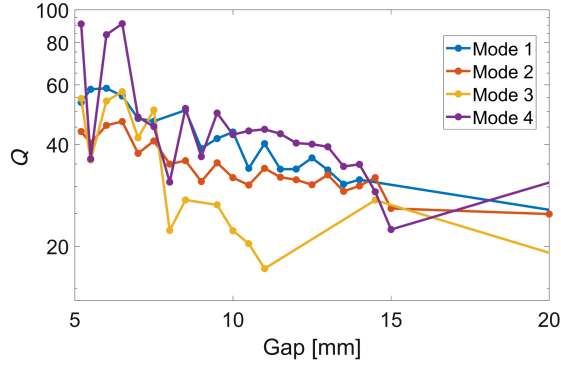


FIG. 16. Variation of the mode quality factor Q with the magnet gap measured for the IVU with ferrite dampers.

Rectangular ferrite blocks are designed with dimensions of $70 \times 50 \times 3$ mm and a center hole of 13 mm radius, which are located around the supporting rods of the magnet blocks. Owing to technical constraints, only half of the rods on the top magnet block have been installed with ferrite blocks. The measured Q values with ferrite dampers are shown in Fig. 16. The Q values are reduced to below 100, and deeper damping of the modes is achieved for larger magnet gaps. The measurement confirms that the ferrite dampers are effective to damp the trapped mode. By adding different number of ferrite blocks, we observe that the ferrite absorbers at the rods close to either ends of the magnet blocks are more efficient to reduce the Q values. It is expected that further Q factor reduction could be achieved with more supporting rods being installed with ferrite dampers.

VI. CONCLUSIONS

In this work, numerical simulations and bench measurements to characterize the impedance of in-vacuum undulators are reported. The impedance comparisons between simulations and measurements identified the influence of the model simplification and demonstrated the effectiveness of the mitigation strategies. The corresponding findings can also apply to the cryogenic permanent magnet undulators, whose magnet arrays are also located inside the vacuum tank but under cryogenic state.

In the longitudinal plane, the bulge flexible taper transitions between the magnet blocks and the nominal beam pipe induce a remarkable longitudinal broadband impedance increase, as well as a higher total beam power loss. Fortunately, the power loss from the beam is mainly dissipated inside the vacuum tank, and the power dissipation on the flexible rf fingers is considerably low. Even so, the bulge height of the flexible taper transition should still be controlled to a considerably low level to avoid extreme impedance increases in the longitudinal broadband impedance or unfavorable resonances. In addition, the poor rf contact due to the gap at the fasten structure of the magnet

cover results in longitudinal HOMs. Mitigation strategies to damp the modes are proposed and adopted in the HEPS IVU. The longitudinal impedance and mitigation strategies are verified through coaxial wire measurements.

In the transverse plane, the vertical trapped modes inside the IVU and the corresponding mitigation strategies are investigated numerically and with probe measurements. The simulations overestimate the quality factor of the modes because some detailed structures that can increase HOM power consumption have been omitted in the simulations. The damping of the modes with ferrite dampers was also tested during measurements and proved to be effective in damping the modes. In addition, new damping strategies for the vertical trapped modes through geometrical optimization are proposed. The conceptual design of damping methods has been proven to be effective through numerical simulations. However, there are several concerns regarding practical implementation of the geometrical damping methods, including feasibility of implementing these shielding structures and synchrotron radiation heating, which necessitate further design refinements for future implementation studies. Since the probe measurements have been done before proposing the new transverse damping strategies, we did not have the chance to test the geometrical mitigation strategies experimentally.

ACKNOWLEDGMENTS

The work was supported by the National Natural Science Foundation of China (Grant No. 11775239), the Youth Innovation Promotion Association CAS, and the project of High Energy Photon Source. The authors would like to thank the colleagues of HEPS team for the fruitful discussions and their support during the bench measurements. Specially thank Kai Tian and Fritz Caspers for the fruitful discussions on the transverse mode evaluation and damping.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX

The dependence of the longitudinal impedance and transverse HOMs on the length of the magnet blocks was checked via numerical simulations.

In the wakefield simulations, we only consider the geometrical impedance by setting the material of the IVU as perfect conductor. The simplified model as shown in Fig. 2 has been used in the simulations. The length of the magnet blocks has been set as 0.5, 0.75, and 1 m. We did not pursue for longer magnet blocks because the simulation becomes too heavy to get reasonable results. The simulation results of the real and imaginary part of the longitudinal impedance for different cases are shown in Fig. 17.

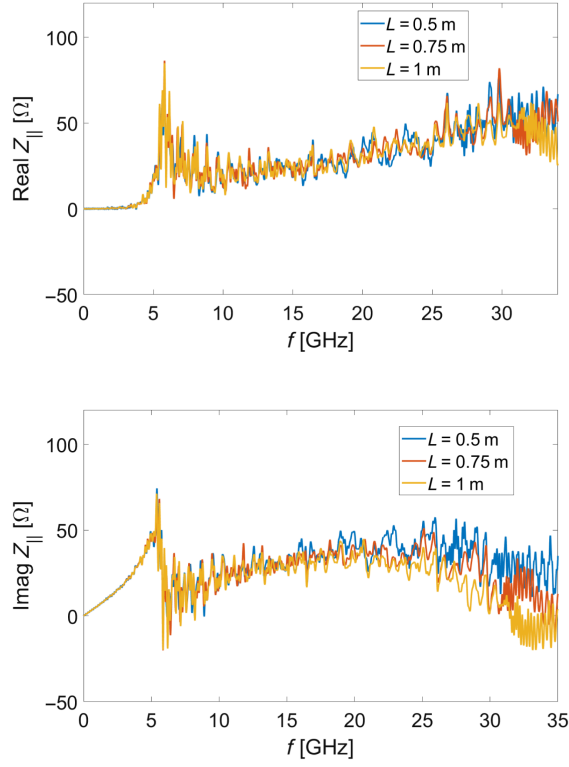


FIG. 17. Dependence of the real (top) and imaginary (bottom) parts of the longitudinal impedance on the length of the IVU model in simulations. The magnet block lengths were set to 0.5, 0.75, and 1 m, with the wakefield tracked over a 2 m distance in all three cases.

The simulation results demonstrate that the length of the IVU model has a negligible impact on the longitudinal impedance. While keeping the number of cells per wavelength constant in the simulations, the analysis reveals a more pronounced dependence on the model length at higher frequencies, particularly for the imaginary part of the longitudinal impedance. The agreement of the high frequency impedance of the IVU models with different simulated lengths improved as a finer mesh was used, suggesting that numerical errors also contribute significantly to the observed high-frequency discrepancies. Consequently, the shortened model remains an effective representation of the IVU's longitudinal impedance generally.

For the transverse HOMs, the mode frequency and mode distribution vary with the length of the model. In Fig. 18, we compared the frequency of the first dominant mode and the shunt impedances versus frequencies for different cases. The resonant frequency of the first mode decreases with the length of the IVU and increases with the introduction of the supporting rods. In the bottom plot of Fig. 18, the shunt impedances of the modes with amplitude higher than 1 MΩ/m below a frequency of 400 MHz are listed. We can see that the shunt impedances and frequency of the modes vary with the length of the IVU and introduction of the supporting rods. The number of modes above 1 MΩ/m

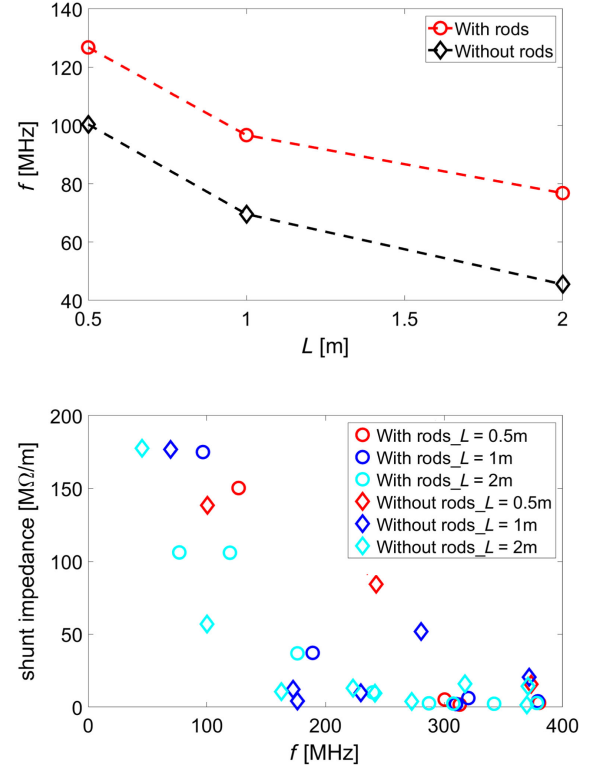


FIG. 18. Variation in the frequency of the first dominant mode with respect to the length of the magnet blocks (top), and the shunt impedances of the dominant modes below 400 MHz for different lengths of the magnet blocks (bottom). The magnet block lengths were set to 0.5, 1, and 2 m.

increases with the length of the magnet blocks; however, the amplitude of the shunt impedances is comparable among different cases. So we believe that the simulation with shortened magnet blocks is still reasonable enough to represent the transverse impedance characteristics of the real structure.

-
- [1] J.-C. Huang, H. Kitamura, C.-K. Yang, C.-H. Chang, C.-H. Chang, and C.-S. Hwang, Challenges of in-vacuum and cryogenic permanent magnet undulator technologies, *Phys. Rev. Accel. Beams* **20**, 064801 (2017).
 - [2] V. Smaluk, R. Fielder, A. Blednykh, G. Rehm, and R. Bartolini, Coupling impedance of an in-vacuum undulator: Measurement, simulation, and analytical estimation, *Phys. Rev. ST Accel. Beams* **17**, 074402 (2014).
 - [3] A. Q. R. Baron, T. Tanaka, K. Soutome, M. Takao, T. Nakamura, K. Kobayashi, T. Fujita, S. Takahashi, H. Aoyagi, Y. Shimosaki, T. Seike, H. Uchiyama, D. Ishikawa, T.-H. Chuang, H. Kimura, H. Tanaka, H. Kitamura, and T. Ishikawa, Toward operation of series IDs at BL43LXU of SPring-8, *AIP Conf. Proc.* **1741**, 020033 (2016).
 - [4] T. Bizen, T. Seike, T. Hara, H. Kitamura, X. Marechal, and T. Tanaka, Design criteria and technology challenges for

- the undulators of the future, in *Proceedings of the EPAC'04, Lucerne, Switzerland* (EPS-AG, Lucerne, 2004).
- [5] R. Reiser, S. Zelenika, G. Ingold, A. Keller, L. Schulz, T. Hara, and H. Kitamura, The flexible taper transitions for an in-vacuum undulator, in *Proceedings of the MEDSI'02, Chicago, USA* (Argonne National Laboratory, Argonne, IL, 2002).
- [6] K. Tian, J. J. Sebek, A. D. Ringwall, and Z. Li, Damping trapped modes in an in-vacuum undulator at a synchrotron radiation light source, *Phys. Rev. Accel. Beams* **22**, 050702 (2019).
- [7] E. Ericson, D. Bertwistle, M. J. Boland, and D. Pelz, Analysis of rf modes in an in-vacuum undulator, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1070**, 170027 (2025).
- [8] R. Dowd, M. Atkinson, M. Boland, G. Leblanc, Y.-R. E. Tan, and D. Teytelman, Investigation of trapped resonant modes in insertion devices at the Australian synchrotron, in *Proceedings of the IPAC-2016, Busan, Korea* (JACoW, Geneva, Switzerland, 2016), <https://api.semanticscholar.org/CorpusID:125387522>.
- [9] J. Chen, P. Chou, J. Huang, and D. Huang, An issue of the cavity-like structure inside the insertion device at the TPS storage ring, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1015**, 165772 (2021).
- [10] Y. Jiao, G. Xu, X.-H. Cui, Z. Duan, Y.-Y. Guo, P. He, D.-H. Ji, J.-Y. Li, X.-Y. Li, C. Meng, Y.-M. Peng, S.-K. Tian, J.-Q. Wang, N. Wang, Y.-Y. Wei, H.-S. Xu, F. Yan, C.-H. Yu, Y.-L. Zhao, and Q. Qin, The HEPS project, *J. Synchrotron. Radiat.* **25**, 1611 (2018).
- [11] K. Tian, A. Ringwall, J. Sebek *et al.*, Beam-based measurement on the performance of ferrite dampers in an in-vacuum undulator, in *Proceedings of the IPAC-2021, Campinas, SP, Brazil* (JACoW, Geneva, Switzerland, 2021), [10.18429/JACoW-IPAC2021-MOPAB088](https://doi.org/10.18429/JACoW-IPAC2021-MOPAB088).
- [12] N. Wang, J. Li, S. Tian, S. Yue, and X. Liu, Narrowband impedance studies in the HEPS storage ring, in *Proceedings of the IPAC-2024, Nashville, TN* (JACoW, Geneva, Switzerland, 2024), [10.18429/JACoW-IPAC2024-THPC58](https://doi.org/10.18429/JACoW-IPAC2024-THPC58).
- [13] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators* (John Wiley & Sons, Inc., New York, 1993).
- [14] J. Li, N. Wang, S. Yue, and S. Tian, Impedance of in-air undulator vacuum chamber in HEPS, *J. Instrum.* **18**, P12003 (2023).
- [15] CST Studio Suite, <https://www.3ds.com/products/simulia/cst-studio-suite>.
- [16] H. Xu *et al.*, Equilibrium electron beam parameters of the High Energy Photon Source, *Radiat. Detect. Technol. Methods* **7**, 279 (2023).
- [17] F. Meng *et al.*, The recent research of HOM damper for superconducting cavity in IHEP, in *Proceedings of the SRF2017, Lanzhou, China* (JACoW, Geneva, Switzerland, 2017), <http://jacow.org/srf2017/papers/mopb071.pdf>.
- [18] F. Caspers, Beam impedance measurement by the wire method using a synthetic pulse technique, *IEEE Trans. Nucl. Sci.* **32**, 1914 (1985).
- [19] N. Wang, S. K. Tian, L. Wang, H. Shi, S. Yue, G. W. Wang, and J. H. Chen, Impedance optimization and measurements of the injection stripline kicker, *Phys. Rev. Accel. Beams* **24**, 034401 (2021).
- [20] W. Bruns, Electromagnetic field solver Gdfidl, <http://www.gdfidl.de>.
- [21] L. Walling, D. McMurry, D. Neuffer, and H. A. Thiessen, Transmission-line impedance measurements for an advanced hadron facility, *Nucl. Instrum. Methods Phys. Res., Sect. A* **281**, 433 (1989).
- [22] N. Wang, H. Xu, S. Tian, Z. Duan, and X. Li, Study of beam coupling impedance and beam collective effect in high energy photon source, *At. Energy Sci. Technol.* **53**, 1601 (2019).