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COMPARISON OF SIMULATION AND MEASUREMENT OF AN IN-VACUUM UNDULATOR COUPLING IMPEDANCE AT NSLS-II

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Abstract

The impedance of in-vacuum undulators (IVU) significantly influences the total broadband impedance and thus the beam dynamics in synchrotrons. Simulating the complete few-meter-long 3D structure of IVUs, which includes taper transitions with variable gaps and adjacent components like bellows and flanges, presents computational challenges. Typically, impedance is calculated for each component's simplified geometry, and resistive-wall impedance is determined using analytical formulas. This paper employs the ECHO3D code, which utilizes a low-dispersive numerical technique, to compute the wakefield induced by very short bunches within the full 3D model of the NSLS-II IVU. We compare these numerical simulations with beam-based measurements to validate our models and discuss the implications of our findings.

INTRODUCTION

In-vacuum undulators with small vertical gaps are integral part of modern synchrotron light sources, significantly impacting the total coupling impedance. One of the pivotal design challenges for these devices is impedance minimization. The vacuum chamber of such devices features complex geometries, including tapers, foils, and transitions between different cross-sections (see Fig. 1). This complexity makes it impossible to derive accurate analytical formulas for the impedance of the entire chamber. Moreover, full 3D computer simulations of such large and complex structures pose significant challenges, including number of nodes, extensive memory requirements and processor time, particularly when simulating the wakefields induced by short (a few millimeters) electron bunches.

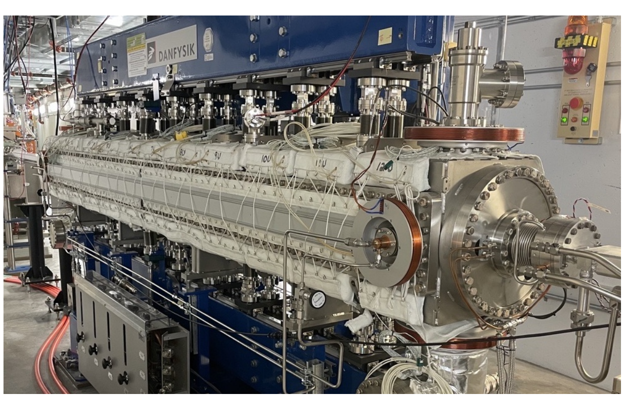

Figure 1: The in-vacuum undulator installed in Cell 10 at NSLS-II.

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For an operational accelerator like NSLS-II, impedance can be measured experimentally using beam-based techniques. However, these methods often fall short of capturing the detailed structure of the frequency-dependent total impedance due to its complexity. Typically, measurements yield integral parameters that combine the impedance with the bunch spectrum, such as the effective impedance, longitudinal loss factor, or transverse kick factor.

This paper presents a comparative analysis of the simulated and measured kick factors of an IVU with variable gaps at NSLS-II. The measurements were performed using the AC orbit bump method, as detailed in Ref. [1]. The kick factor, for a given transverse wake, is defined as:

$$k_{\mathrm{y}} = \frac{1}{\sqrt{2\pi}\sigma_s}\int_{-\infty}^{\infty} W_y(s)e^{-s^2/2\sigma_s^2}ds, \qquad (1)$$

where σ_s is the rms bunch length of a Gaussian electron bunch, and $W_y(s)$ is the vertical wake potential. The total kick factor comprises both geometric and resistive-wall components:

$$k_y = k_y^{\mathrm{geom}} + k_y^{\mathrm{rw}}.$$

In this study, we outline our simulation methodology, discuss the encountered challenges, and compare the results with measurements to assess the accuracy of impedance modeling in complex geometries.

SIMULATION OF KICK FACTOR

Typically, the geometric contribution to the kick factor is calculated using an electromagnetic field simulator, while the resistive-wall effect of the copper-coated liner is determined using the formula for parallel plates. The schematic representations of the IVU models used for simulations are shown in Fig. 2.

Model for Geometric Kick Factor

The geometric impedance is primarily determined by the chamber shape. The vacuum chamber of the IVU features flat tapered transitions with a variable vertical aperture ranging from a 6 mm gap (when the in-vacuum device is closed) to a 25 mm gap (when open). The transitions extend from the regular octagonal chamber dimensions, which are 76 mm in full horizontal width and taper to 25 mm over a length of 3.0 meters, as depicted in Fig. 2(a). Figure 2(b) provides a more detailed representation by enclosing the model in a vacuum chamber and adding adjacent bellows, thus more closely resembling the realistic setup for better comparison with measurement results.

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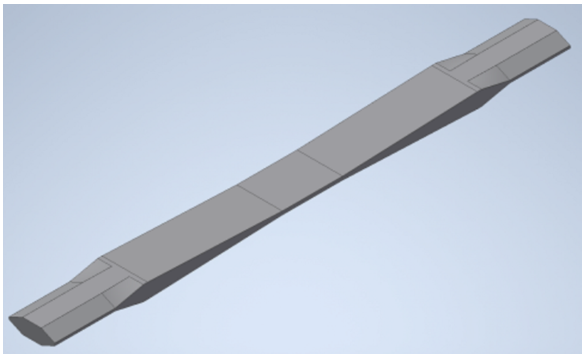
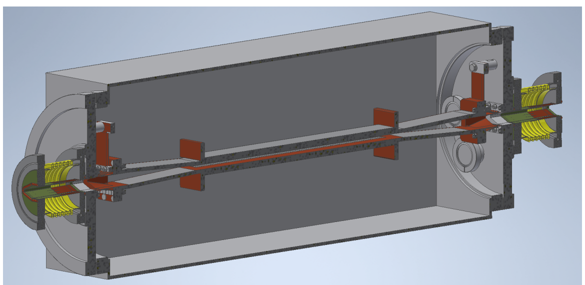


(a) Simplified model of closed gap IVU for wakefield simulation.



(b) Detailed model for wakefield simulation.

Figure 2: Schematics of the IVU model used for simulations.

Simulations are performed using ECHO3D, a tool based on a low-dispersive numerical technique for calculating electromagnetic fields in accelerators. This technique is beneficial for computing wakefields of ultra-short bunches in lengthy structures by reducing numerical dispersion along the beam direction [2]. Despite being thread-parallelized, ECHO3D efficiently handles long domains typical in accelerator applications, providing high-quality results even with a coarse mesh in transverse directions and a large time step, making it computationally advantageous over tools like GdfidL [3].

Resistive-wall Kick Factor

The analytical formula for a vertically displaced beam in a flat chamber formed by two infinitely wide plates, with a distance of $2b$ between them, is provided by Ref. [4]. The impedance per unit length is given by:

$$Z_y^{\text{flat}} = \pi \frac{\text{sgn}(\omega) + i}{8b^3} \sqrt{\frac{cZ_0\mu_r}{2\omega\sigma_c}} \left(\frac{1 + \frac{\pi y}{2b} \tan\left(\frac{\pi y}{2b}\right)}{\cos^2\left(\frac{\pi y}{2b}\right)} \right), \quad (2)$$

where y is the beam offset, b is the chamber inner radius, μ_r and σ_c are the relative permeability and conductivity of the chamber material, respectively, and Z_0 is the free space impedance.

Despite the presence of copper foil, the long (3 m) undulator with a narrow 6 mm gap when closed demonstrates that resistive-wall impedance significantly contributes to the kick factor, similarly to the geometric contribution. This effect is illustrated in Fig. 3:

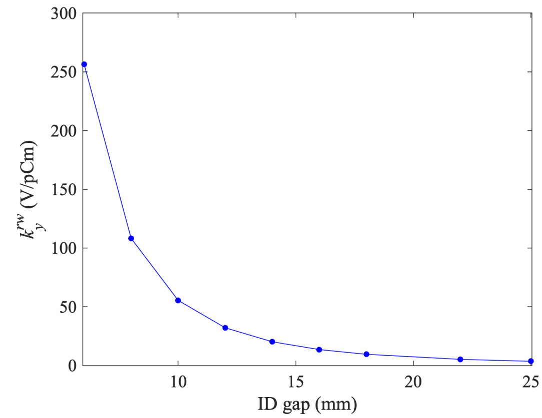


Figure 3: Resistive-wall kick factor as a function of IVU gap.

COMPARISON OF SIMULATIONS AND MEASUREMENTS

An important aspect of wakefield simulation is determining the accuracy and numerical resolution required for specific components. We performed convergence studies on the

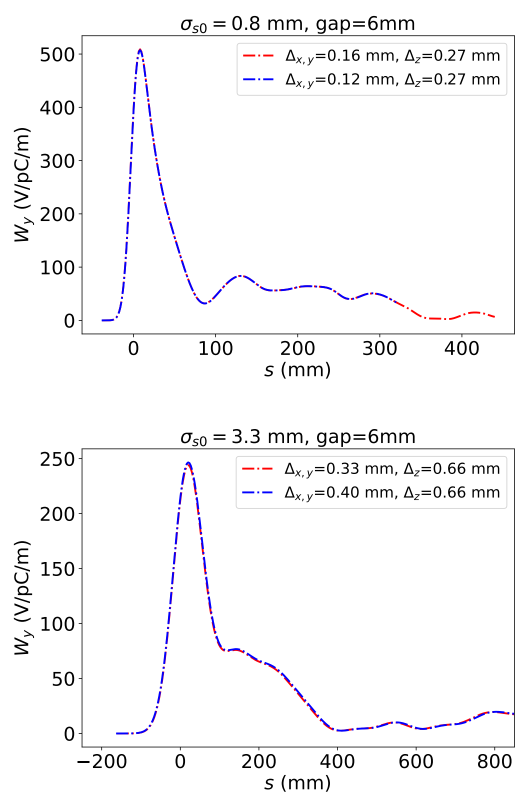


Figure 4: Convergence studies of dipole wake potential for source bunch lengths of 0.8 mm and 3.3 mm at a 6 mm gap in the IVU.

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IVU model using two source bunch lengths: 0.8 mm for the short bunch scenario (σ_{s0} = 0.8 mm), and 3.3 mm, which matches the standard bunch length used in the storage ring, implying $\sigma_{s0} = \sigma_s$ for this longer bunch case. These studies are essential for properly setting up the simulation model, identifying bugs in the simulation codes, and ensuring consistency in the 3D geometry models. We used these studies to simulate various IVU gap geometries ranging from 6 mm to 25 mm.

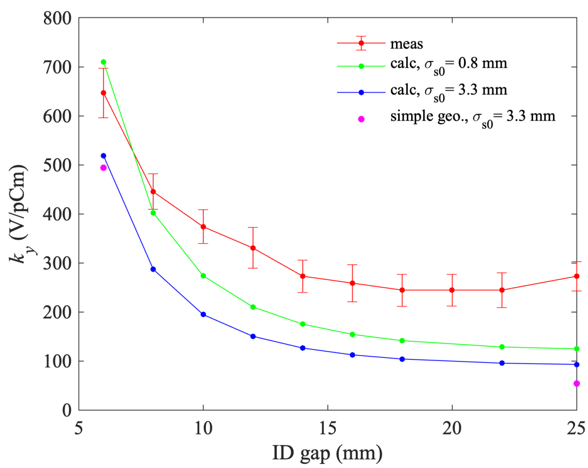

Figure 5: Comparison of measured and simulated kick factors as a function of undulator gap for different source bunch lengths. Here, the 'calculated' label refers to the detailed model, and 'simple geometry' corresponds to the simplified taper transition model of IVU.

Figure 5 shows the comparison of measured and simulated kick factors as a function of undulator gap for different source bunch lengths. The details of the measurement have been discussed in Ref. [1]. The error bars in the measured data include orbit measurement errors, beam current measurement errors, and orbit fitting errors.

The simulated geometric kick factor incorporates contributions from the IVU geometry, as well as 10 bellows and 4 flange absorbers, all located where the AC orbit bump measurements were conducted using four fast correctors in Cell 10. The simulation results suggest better agreement with measurements for the shorter bunch compared to the longer one. Both closed and open IVU cases were simulated using a simplified geometry. While the simplified geometry approximates well for the closed gap, adding more detail provides more realistic models, especially when computational resources allow. As the gap increases, the simulated kick factor shows that the wake's effect lessens. However, larger gaps also show more significant differences between the simulated and actual measurements. These differences might be due to errors in our measurements or limitations in our current simulation model. Improving the geometry detail might help us get a better match with our measurements. We would like to simulate even shorter bunch lengths, like 0.3 mm, but ECHO3D, has limitations due to thread parallelization and the large memory requirements for such detailed models.

CONCLUSION

In this paper, we have conducted a comprehensive comparison of simulated and measured kick factors for an in-vacuum undulator with varying gap widths, consisting of geometric and resistive wall contributions. Through simulations and studies with bunch lengths of 0.8 mm and 3.3 mm, we found that the simulated kick factor decreases as the undulator gap increases, as expected. The shorter bunch length of 0.8 mm showed better agreement with measurements. However, we noted discrepancies between simulations and actual measurements, especially at larger gaps. These discrepancies could be due to measurement errors and limitations of our simulation model, including ECHO3D's thread parallelization and the high memory needs for detailed modeling. This work highlights the need to keep improving our measurement and simulation methods to better model impedance effects in next generation light sources.

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