# NUMERICAL STUDIES OF GEOMETRIC IMPEDANCE AT NSLS-II WITH GdfidL AND ECHO3D

A. Khan*, V. Smaluk, M. Seegitz, R. Todd, A. Blednykh, BNL, NSLS-II, Upton, NY 11973, USA

### *Abstract*

The beam intensity in low-emittance light sources with small gap wigglers and undulators is limited by the effects of short-range wakefields or impedance, especially by the beam-induced heating of the vacuum chamber components. We have cross-checked two electromagnetic solvers, GdfidL and ECHO3D, by simulation of the geometric impedance in the NSLS-II flange absorber and in the bellows to test the consistency and precision of the models.

## INTRODUCTION

In modern and future low-emittance light sources, cross-sections of the vacuum chambers of strong focusing magnets and light-generating wigglers and undulators are quite small. Interaction of the electron beam with self-induced electromagnetic fields excited in the vacuum chamber components can have a significant impact on beam quality. The beam coupling impedance quantifies this interaction and allows for the prediction of the dynamics of high-intensity beams. Computation of wake functions and impedances for a given accelerator component is typically a complex task that requires the numerical solution of Maxwell's equations for certain particle distribution.

Even with the most powerful computers, the computation of wake fields of very short bunches in long structures is quite challenging. The choice of simulation code is determined by a variety of factors such as geometry, application, problem type, and computational effort, specifically computational time and memory size. Another key factor is the mesh size of the finite-difference equation solver. Furthermore, the length of wake fields required is an important factor in determining the code and algorithm.

The computed wakefield and its Fourier Transform, the impedance, are used to simulate the collective effects of beam dynamics. To estimate the beam-induced heating, the longitudinal loss factor is used [1]:

$$k_{\mathrm{loss}} = \frac{1}{\pi} \int_0^\infty d\omega \, \mathrm{Re} Z_{\parallel}\,(\omega)\; e^{-\omega^2 {\sigma_s}^2 / c^2} \qquad (1)$$

where $Z_{\parallel}$ is the longitudinal impedance and $\sigma_s$ is the bunch length.

## SIMULATION TOOLS

At NSLS-II, we use GdfidL [2] to compute the impedance budget and started to use relatively new fast code ECHO3D [3]. Both codes use an STL input file created by external software as input to describe the geometry of the structure. Then the code creates the mesh, solves the 3D electromagnetic field, and calculates the wake potential using different numerical techniques. Here is a brief summary of both codes.

### *GdfidL*

GdfidL computes the electromagnetic fields using Yee's finite-difference time-domain method (FDTD). As any numerical mesh approach, this method is affected by an anisotropic numerical dispersion. This means the numerical wave phase speed is slower than the physical one. Hence, the high-energy particles can travel in vacuum faster than their own radiation. The resulting numerical error is comparatively large, especially, in calculations involving short bunches. As it is well known, the FDTD method at the Courant limit is dispersion-free along the grid diagonals and this property can be used effectively in numerical simulations [4]. However, the only reasonable choice, in this case, is to take equal mesh steps in all three directions. This is doable as GdfidL code has the ability to perform parallel computing.

### *ECHO3D*

ECHO3D is based on a low-dispersive numerical technique for calculations of electromagnetic fields in accelerators. This technique allows for the calculation of wakefields of ultra-short bunches in very long structures by eliminating the numerical dispersion in the beam direction [5]. In accelerator applications, the domain of interest is very long in the longitudinal direction and relatively narrow in the transverse plane. The ECHO3D technique allows for giving high-quality results even on a coarse mesh in transverse directions with a large time step. The only limitation of ECHO3D is that it is only thread-parallelized.

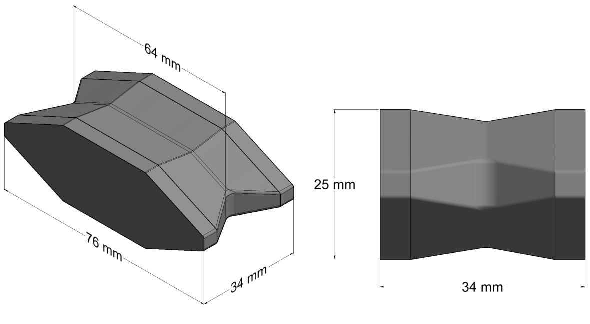

Figure 1: Schematics of the NSLS-II flange absorber.

## CONVERGENCE STUDIES

We performed the convergence studies for the NSLS-II flange absorber and bellows using GdfidL and ECHO3D for various bunch distributions. Such cross-checking helps us

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* akhan1@bnl.gov

to set up the simulation model properly and to identify some bugs in the simulation codes, as well as to check consistency in the 3D geometry models.

### *Flange Absorber*

This section presents our findings during convergence studies and cross-checking for the NSLS-II synchrotron radiation flange absorber as shown in Fig. 1. The flange absorber geometry transit from the regular octagonal chamber dimensions with a 76 mm full horizontal width and 25 mm full vertical height to one with 64 mm width.

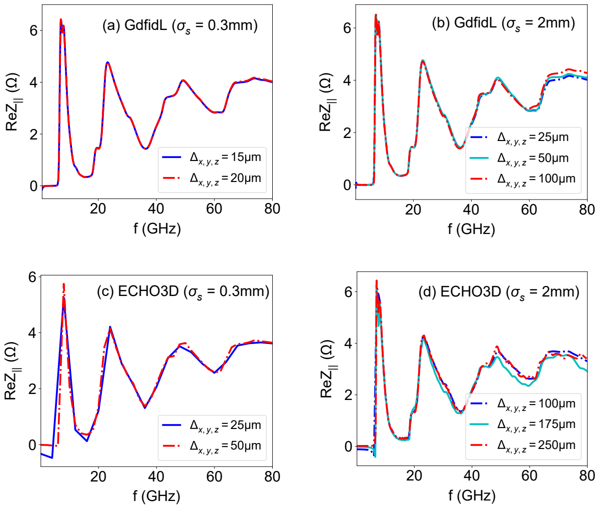

Figure 2: Convergence studies of real part of longitudinal impedance with (a) GdfidL for a point bunch 0.3 mm, (b) GdfidL for bunch 2 mm, (c) ECHO3D for bunch 0.3 mm, and (d) ECHO3D for bunch 2 mm of the flange absorber of NSLS-II.

Figure 2 shows the convergence studies of the numerically simulated real part of longitudinal impedance for different bunch lengths using GdfidL and ECHO3D. We can see that obtaining accurate results for a bunch length of 0.3 mm requires a GdfidL mesh spacing $\Delta \leq \sigma_s/15$, on the other hand, ECHO3D gives accurate results with coarse mesh $\Delta \leq \sigma_s/5$. In our experience, ECHO3D works well even if we use only 5 mesh steps on bunch sigma longitudinally and ten times more coarse mesh transversely.

The apparent discrepancy at the low frequency of ECHO3D for a short bunch is an artifact of the different wake potential lengths used for two different mesh sizes. The output file for such calculations is very memory consuming and sometimes it leads to the failure of post-processing of wake computation, which eventually impacts the frequency resolution of impedance calculations in ECHO3D.

Figure 3 shows the loss factor (Eq. (1)) as a function of bunch length for different bunch distributions used in GdfidL and ECHO3D simulations. It can be seen that there is a very good agreement of the loss factor with 0.3 mm and 2 mm bunch length in both codes. As the nominal bunch length for NSLS-II is approximately 3 mm, the heat load calculations can be performed with a long bunch rather than a point-like bunch of 0.3 mm length.

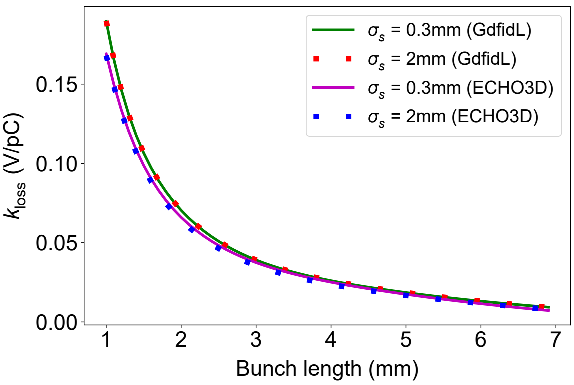

Figure 3: Comparison of loss factor as a function of bunch length for the NSLS-II flange absorber.

### *NSLS-II RF Bellows*

The schematic of the NSLS-II RF bellows geometry is shown in Fig. 4. The location of the RF contact fingers relative to the regular vacuum chamber (inside or outside) can play a significant role in producing the broad-band impedance and the heat load. Thus, it is important to consider the detailed 3D model of the bellows for the impedance analysis.

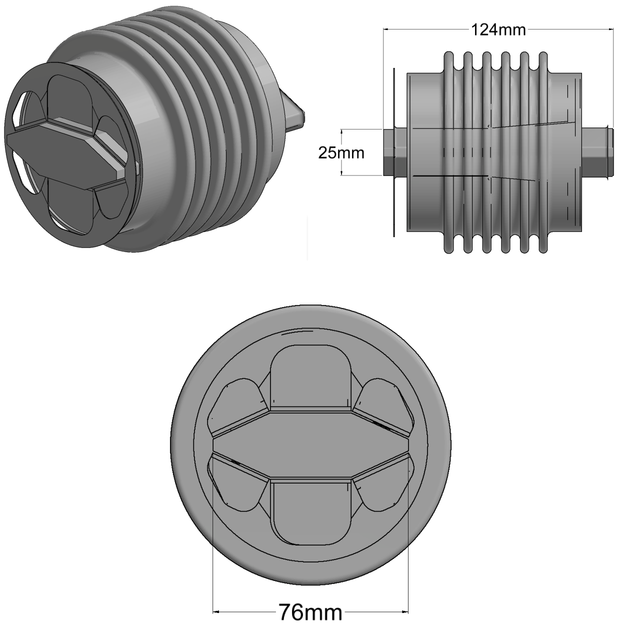

Figure 4: Schematic of the NSLS-II RF shielded bellows.

For this 124mm-long rf shielded bellows, GdfidL takes about 42 hours to simulate for the bunch length of 0.3 mm with a $\Delta = 20\,\mu$m and over a wakefield length of s = 1 m on the NSLS-II cluster using 8 nodes. Contrary, ECHO3D takes about 8 hours for $\Delta = 25\,\mu$m with 96 threads on a single node.

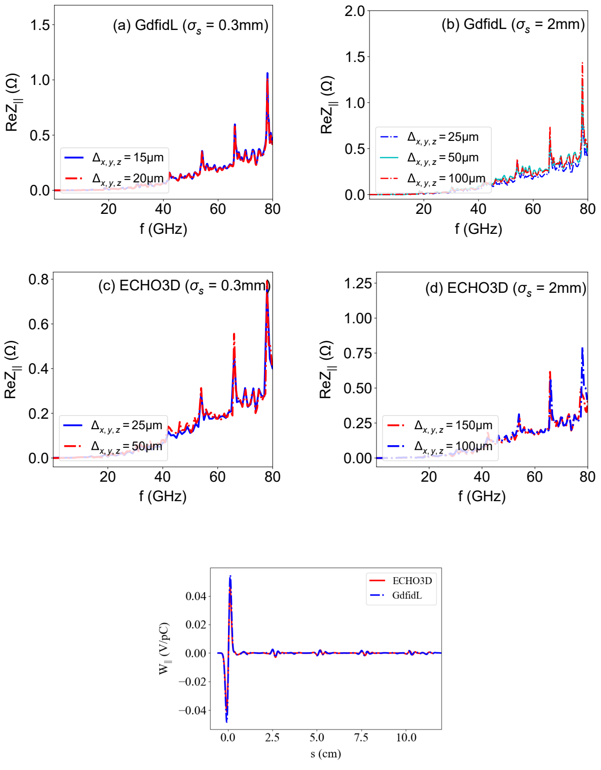

Figure 5: Convergence studies of real part of longitudinal impedance with (a) GdfidL for bunch 0.3 mm, (b) GdfidL for bunch 2 mm, (c) ECHO3D for bunch 0.3 mm, (d) ECHO3D for bunch 2 mm, and (e) comparison of wake potential in ECHO3D and GdfidL of the RF bellows of NSLS-II.

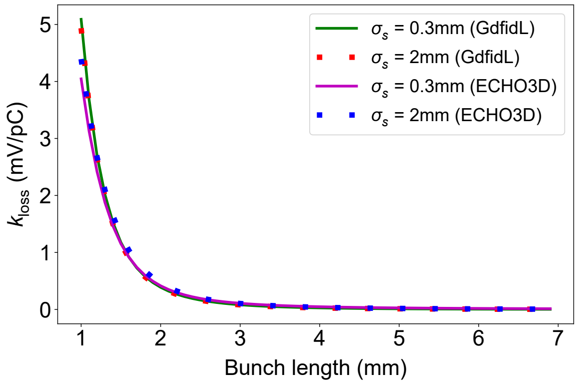

Figure 6: Comparison of loss factor as a function of bunch length for the NSLS-II RF bellows.

Figure 5 shows the convergence studies of the longitudinal impedance of bellows computed by GdfidL and ECHO3D. It can be seen that results are converging well with both codes. There is also a good agreement between the wake potentials. The loss factor as a function of bunch length also shows good agreement, see Fig. 6.

## CONCLUSION

A well-estimated impedance budget is a crucial part of estimating the performance of facilities with intense beams, and such estimates should be based on vacuum component designs as installed in the ring. This is crucial throughout the final stages of component design, production, and installation since even apparently minor changes might result in changes to the associated impedance. In this work, we present impedance convergence studies for several components of the NSLS-II vacuum chamber using GdfidL and ECHO3D. The longitudinal impedance and loss factor calculated by both codes show very good agreement. For high-resolution wakefields in complex 3D geometries, we observed that GdfidL is computationally heavy and RAM consuming, contrary it is doable in ECHO3D with a coarse mesh. The only limitation of ECHO3D is in the limit of wake length due to the huge size of output files, which is troublesome for post-processing.

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