

# IMPEDANCE DATABASE II FOR THE ADVANCED PHOTON SOURCE STORAGE RING\*

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## Abstract

The first Impedance Database [1] constructed at the Advanced Photon Source was successfully used in reproducing the main characteristics of single-bunch instabilities observed in the storage ring. However, the finite bandwidth of the corresponding impedance model was limited to 40 GHz, which happens to be the resolution limit of the density modulation observed in the microwave instability simulation. In order to resolve simulation results never verified in the experiments, we decided to extend the calculated bandwidth of impedance to 100-200 GHz by recalculating the wake potentials excited by a shorter bunch. Since low-order electromagnetic code requires 20-40 grid points per wavelength, reducing the bunch length required a large number of grids for the 3D structure. We used bunch lengths of 1- and 2-mm in the Gaussian distribution in the Impedance Database II project. For the large-scale computation we used the 3D electromagnetic code GdfidL [2] for wake potential calculation at the cluster equipped with 240 GB of memory. The resultant wake potential excited by the short bunch together with application to the storage ring for collective effects is presented in this paper.

## INTRODUCTION

The first Impedance Database (IDB-1) for the APS storage ring consists of a collection of wake potentials excited by a 5-mm-long bunched beam. The computation was accomplished by using the program MAFIA. Since then, the three-dimensional wake potentials have been used in order to characterize the single-bunch instabilities observed in the ring. The most important of them was to predict the single-bunch current limit.

The past experience showed that the current was limited by transverse mode coupling instability (TMCI) in the vertical plane [1,3]. Above the threshold current there was beam size blow-up followed by beam loss. The accurate prediction of the threshold current by TMCI required the correct information on the bunch length consistent with the measurement in the ring. Thus, the numerical simulation should reproduce the experimental data in the longitudinal and transverse planes self consistently.

We found that it was necessary to modify the computed impedance of IDB-1, initially reported in Ref. [1], in order to achieve a good agreement with the measured bunch lengths. We used this modified impedance as a working impedance derived from the 5-mm wake potential. However, we want to remove the ad-hoc nature

of the working impedance in the Impedance Database II (IDB-2) by using a 1-mm-long bunched beam in the calculation of wake potentials.

In this paper, we describe the working impedance model of IDB-1, which has been used to predict the single-bunch current limit in the current APS storage ring; the proposed 1-nm ring [3]; and the ring with pulsed crab cavities [4]. This will be followed by the new results of IDB-2, from which we show that the superior result removes the many deficiencies of IDB-1.

## WORKING IMPEDANCE MODEL

The total longitudinal wake potential of the APS storage ring, which was computed by the program MAFIA with a 5-mm-long bunched beam, is shown in Fig. 1. From this we can obtain the longitudinal impedance defined as  $Z_z(\omega) = W_z(\omega)/\lambda(\omega)$ , where  $W_z(\omega)$  and  $\lambda(\omega)$  are the Fourier transform of wake potential  $W_z(t)$  and the charge density  $\lambda(t)$ , respectively; this is shown in Fig. 2.

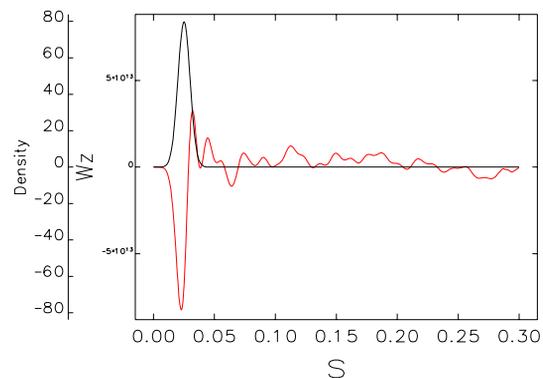


Figure 1: The total wake of bunched beam in the APS storage ring.

We define two frequencies in Fig. 2: One is the maximum or Nyquist frequency,  $f_{\max}$ , at 300 GHz, and the other is the upper limit of valid range,  $f_{\text{up}}$ , at 40 GHz. Since the bandwidth of a 5-mm-long Gaussian beam is  $\sigma_f = 9.5$  GHz, the frequency  $f_{\text{up}}$  roughly corresponds to  $4 \times \sigma_f$ . We used this impedance in the numerical simulation to characterize the microwave instability observed in the ring.

We used the program *elegant* [5] to track multiparticles with the impedance included. The typical number of macroparticles used in the simulation was 200k while tracking 15,000 turns. The simulated bunch lengths and energy spread as a function of current is shown in Fig. 3 together with measured data for comparison. There is a good agreement between the simulation result and the experimental data; however, this was achieved by adding imaginary  $Z/n$  to the computed  $Z/n$  by an amount of 0.1

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$\Omega$ . The added impedance was necessary in order to compensate the missing impedance above the frequency  $f_{up}$ . The impedance obtained this way is a working impedance used in the APS.

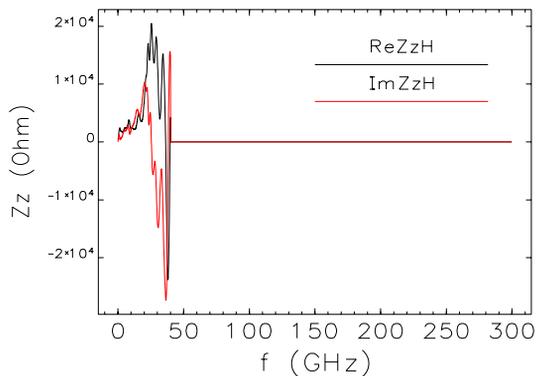


Figure 2: Longitudinal impedance obtained by Impedance Database I (IDB-I).

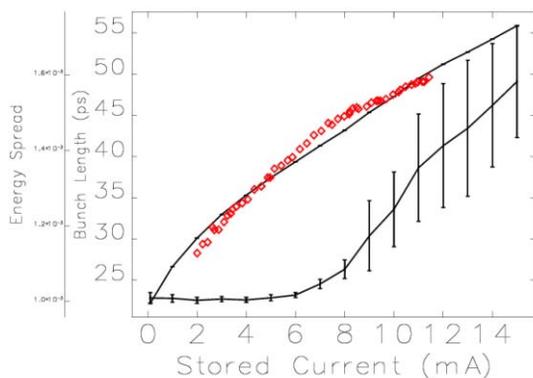


Figure 3: Bunch length measured (red symbols) and simulation results of bunch length and energy spread. The lattice was producing 8-nm emittance with momentum compaction factor  $2.284e-4$  operated with rf voltage of 8 MV inferred by synchrotron frequency.

Even if the working impedance was used successfully in characterizing the single-bunch instability in the ring, we decided to compute the impedance more accurately for better and reliable prediction without introducing an ad-hoc modification.

## IMPEDANCE DATABASE-II

### Choice of Bunch Length for IDB-2

In order to achieve the impedance of broad bandwidth we need to calculate wake potential with a shorter bunch. Since the computation of short-bunched wake takes a large amount of computer resources, we have to make a reasonable choice in the bunch length.

We set 1-mm as the bunch length. An argument is that we can construct an accurate quasi-Green function from the 1-mm wake. For example, if a broadband resonator has the resonant frequency  $\omega_r/2\pi=20$  GHz with  $Q=1$ , then the analytic Green function is very close to a quasi-Green function, which can be obtained via Bane's algorithm by

folding the wake in the head with respect to the center of the bunch to be added to the wake in the tail. The analytic and quasi-Green functions of an analytic broadband resonator are shown in Figure 4. Since the impedance of IDB-1 shows that the resonant frequency is about 25 GHz, the quasi-Green function obtained from the numerically computed 1-mm wake potential of IDB-2 could be accurate.

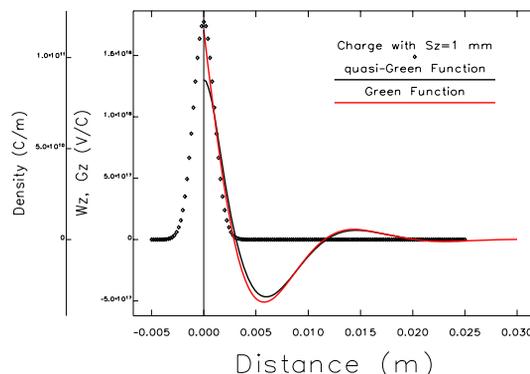


Figure 4: Comparison of quasi-Green function obtained from 1-mm bunched wake and analytic Green function of broadband resonator (we show negative wakes).

Certainly we would like to have an even shorter-bunched wake potential; however, we are limited by computer resources. As the bunch length gets shorter, the number of grid modeling 3D structures becomes very large. For instance, in order to resolve the structure size in  $10 \times 10 \times 100$  cm excited by a 1-mm long bunch, the program may use  $1000 \times 1000 \times 10000 = 10 \times 10^9$  grids. The memory requirement to hold the fields and currents will, then, be about 800 GB.

For the IDB-2 computation, we purchased the 60-node cluster equipped with 240 GB of memory as well as the commercial software GdfidL [2]. The program GdfidL has notable advantages over MAFIA, which we used for IDB-1: the program is parallelized and it has efficient memory management. As a result, we could calculate the 1-mm wake potential for almost all of the impedance elements found in the storage ring by using the 240-GB cluster.

### Wake Potential and Impedance

The impedance was obtained in the same way described in the previous section, and is shown in Fig. 5. Here we note that  $f_{max}=1.5$  THz and  $f_{up}=250$  GHz. The frequencies  $f_{max}$  and  $f_{up}$  can be varied when they are used in the tracking simulation, but the result reported here is obtained with the one in Fig. 5. A numerical quasi-Green function is shown in Fig. 6. This will serve as an official Green-function wake of the APS storage ring.

### Single-Bunch Instability

We used the impedance as in Fig. 5 in order to predict the bunch length and the energy spread in the ring. The measured bunch length together with simulation results are shown in Fig. 7. The symbols in blue and red

represent two sets of data measured on the 3<sup>rd</sup> and 10<sup>th</sup> of April, 2007, respectively. The value is the rms bunch length, which can be read off from a control screen available as an EPICS process variable (PV). The symbol in black is the same data set as the one in red; the difference is that the data are obtained by an offline processing of profile images to measure the rms bunch length [6]. It showed that an algorithm can measure the bunch length differently by 10%. The simulation results agree better with the one from an offline analysis. Also we have to mention that the reading of total rf-gap voltage from the control screen was 8.0 MV, but the measured synchrotron frequency, 1.8 kHz, actually corresponds to 7.5 MV. We used both 7.5 MV and 8.0 MV in simulations, but the result shown in Fig. 7 came from the 7.5-MV case. We note that the agreement was achieved without modifying the computed impedance.

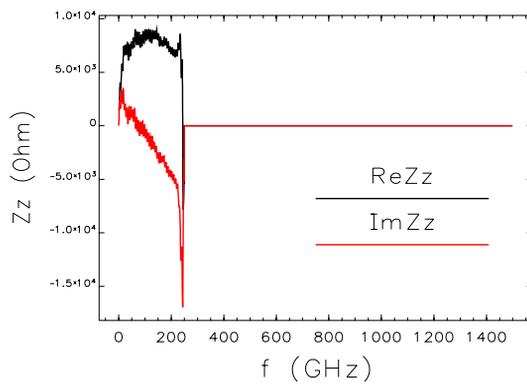


Figure 5: Longitudinal impedance of the APS storage ring.

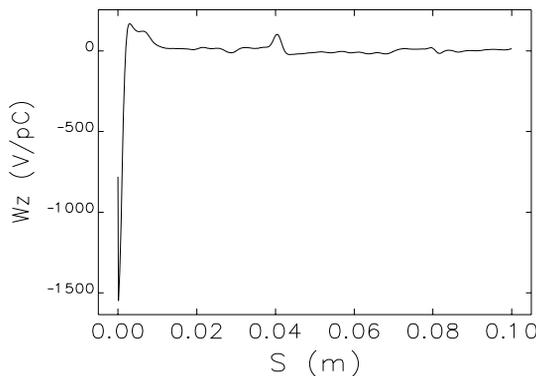


Figure 6: A quasi-Green function wake of the APS storage ring.

We also calculated energy spread, but the direct measurement of energy spread is difficult. Instead, we can only infer them from the horizontal beam size measured at non-zero dispersion. In the APS the dispersion of the undulator source is 17 cm on average, so we used the undulator radiation through a pinhole camera to measure the beam size. The measured and calculated horizontal beam sizes are shown in Fig. 8. Raw data from the simulation is the black curve. The red curve, offsetting the black curve by 10  $\mu\text{m}$ , shows better agreement. Since the camera has a 40- $\mu\text{m}$  resolution limit, this will have an

effective 4-5  $\mu\text{m}$  uncertainty in the measurement. Then, the difference is only 1-2% between the simulation and the experiment.

In transverse dynamics we were able to predict the single-bunch current to be 22 mA with chromaticity set at 10/10 in both planes and with the effective rf-gap voltage set at 8 MV. We have no space here to show the results, but we would like to mention that, unlike the transverse working impedance of IDB-1 [3], we have to include both horizontal and vertical resistive wall impedances in addition to the geometric impedance calculated through IDB-2.

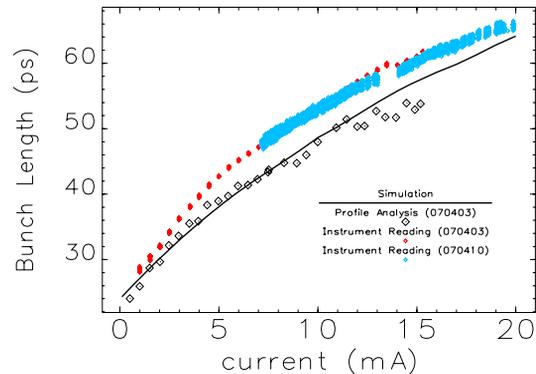


Figure 7: Bunch-length comparison.

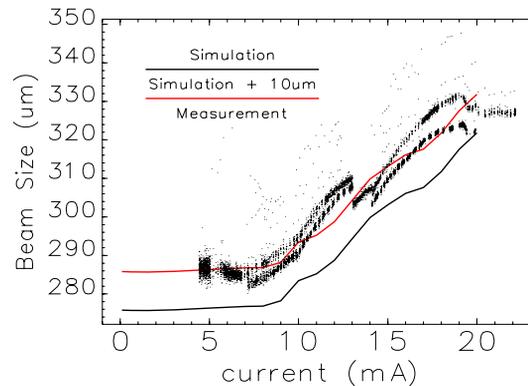


Figure 8: Horizontal beam size measured at undulator source with dispersion. The dots are measured data, and the lines represent simulation result.

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