

# SINGLE-BUNCH INSTABILITY ESTIMATES FOR THE 1-NM APS STORAGE RING UPGRADE WITH A SMALLER VACUUM CHAMBER\*

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## Abstract

We recently studied a lattice achieving 1-nm emittance at the APS storage ring [1]. The successful design required very strong sextupoles in order to tune the machine to the desired positive chromaticity. A preliminary design of such magnets indicated saturation in the poles unless the vacuum chamber gets smaller by a factor of two compared to the existing APS chamber. Since the resistive wall impedance scales as  $1/b^3$ , where  $b$  is the radius of the chamber, we questioned how much current we can store in a single bunch at the 1-nm storage ring. In order to answer this question quantitatively, we calculated all wake potentials of impedance elements of the existing APS storage ring with the transverse dimension properly scaled but with the longitudinal dimension kept unchanged. With the newly calculated impedance of a smaller chamber, we estimated the single-bunch current limit. It turned out that the ring with a smaller chamber would not diminish the single-bunch current limit substantially. We present both wake potentials of 1-nm and the existing rings followed by the simulation results carried out for determining the accumulation limit to the ring.

## INTRODUCTION

As an upgrade option for the APS storage ring we considered a new storage ring with lower emittance. A ring with 1-nm lattice was designed [1], satisfying the imposed boundary condition: The new ring should fit in the existing tunnel without moving the undulator source point and beyond, which are set for x-ray beamlines. Compared with the existing ring, the 1-nm lattice employed a triple-bend-achromatic (TBA) structure with stronger focusing, which in turn required very strong sextupoles to correct chromaticity. Yet a detailed study showed that the 1-nm lattice has ample dynamic aperture, guaranteeing efficient injection and long lifetime [1]. Thus, the single particle aspect of the ring has been established as feasible. As a next step we investigated multiparticle phenomena to see how much current we can store, which is often limited by the single-bunch instability caused by beam-impedance interaction.

One of the main parameters that is important in studying beam-impedance interaction is chamber dimension because, in general, the smaller the chamber, the stronger the impedance. Preliminary design of the quadrupole has bore radius of 2 cm, which should be compared to 4-5 cm of the current ring. Since transverse

dipole impedance satisfies the relation  $Z_{m=1}^{\perp} \sim 1/b^{\alpha}$ , where  $b$  is the chamber radius and  $1 \leq \alpha \leq 3$ ; the impedance in the 1-nm ring could be factor of 2-8 greater than the existing ring. As shown later in the paper, with this level of impedance increase in the current ring, we could store less than 5 mA in the single bunch. This is considerably less than the currently deliverable 16-20 mA.

One might argue that in the 1-nm lattice the strong focusing will reduce the average beta function so that the effective impedance effect, which is proportional to  $\beta_{x,y} Z_{x,y} \sim R Z_{x,y} / v_{x,y}$ , will be reduced. Since the horizontal tune is increased from 36.21 to 57.3, it will help compensating the increased horizontal impedance, but we can not expect much from the vertical tune increase raised from 19.28 to 21.4. However, it is in the vertical plane that we need compensation more, because we knew that the single-bunch current is limited by the vertical impedance effect in the current APS storage ring.

Since it is very difficult to predict the single-bunch current limit correctly by a simple scaling argument, we decided to calculate the whole impedance as accurately as possible so that we could use it to estimate single-bunch instability quantitatively including the single-bunch current limit. It turns out that the effort was worthwhile in saving the concept of the project, because we found that, as the radius of chamber was reduced (effectively increasing the impedance), the slope of transition was also reduced (effectively decreasing the impedance), resulting in the balancing act.

## IMPEDANCE DATABASE FOR THE 1-NM APS STORAGE RING

The Impedance Database for the current APS storage ring consists of a collection of wake potentials calculated for all impedance elements found in the ring [2], which includes small-gap undulator chambers, beam scrapers, radiation absorbers, beam position monitors of regular chambers and undulator chambers, bellows, rf cavities, rf transitions, strip-line monitors, flag chambers, and resistive walls. For the 1-nm lattice ring we assume that the same components will be installed in the ring. The difference would be mainly the cross section of the vacuum chamber. The current one is a 8-cm by 4-cm ellipse, and the new one is a 4-cm by 2-cm ellipse.

Before we detail the computation of wake potential in the new chamber, we illustrate the effect of chamber size on impedance by taking the undulator chamber as an example. In the current ring the undulator chamber has a dominant effect in vertical impedance because of its small gap. It has two components: one is geometric impedance due to tapered transition and the other is resistive wall

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impedance. The total resistive wall impedance of one 5-mm-gap and 29 8-mm-gap chambers installed in the ring is  $Z_{\perp} = 35 \text{ M}\Omega/\text{m}$  evaluated at 1 MHz. The regular chambers occupying 78% of the ring contribute only 1  $\text{M}\Omega/\text{m}$ . Then, in the 1-nm ring with modified regular chamber, the resistive wall impedance will become 43  $\text{M}\Omega/\text{m}$  (35  $\text{M}\Omega/\text{m} + 8 \text{ M}\Omega/\text{m}$ ); the increase is not significant. However, the geometric impedance of the undulator chambers will actually decrease, because the transition angle from regular to undulator chamber will be reduced by a factor of two. Thus, the impedance of the undulator, which is a combination of resistive wall and geometric impedances, remains roughly the same as in the current ring.

For the Impedance Database of the 1-nm lattice we used the program GdfidL [3] to calculate wake potentials. Every impedance element has been modeled as a 3-D structure, and the wake potential excited by a 5-mm long bunched beam is calculated in the simulations. Since the program is parallelized, we could utilize the 60-node cluster equipped with 240 GB of memory for fast completion of the project.

The total wake potentials of the 1-nm lattice are shown in Figure 1. We showed  $W_z$  and  $W_y$  in comparison with the current APS ring. For this comparison we assumed 30 8-mm-gap chambers installed in the ring. We notice that the wake potential of the small chamber is slightly less than that of the large chamber.

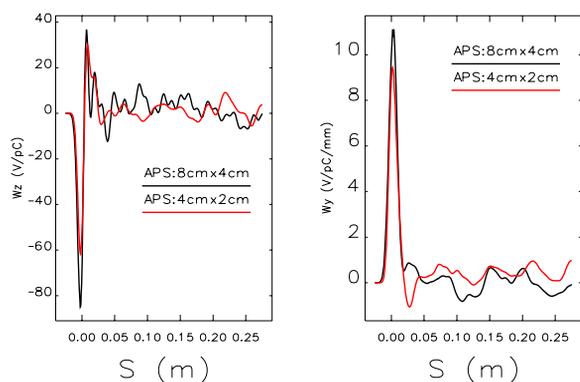


Figure 1: Total wake potentials of the APS storage ring excited by the 5-mm bunched beam. The one in the current vacuum chamber in black is compared to the one in the proposed small chamber in red curve:  $W_z$  (left) and  $W_y$  (right), respectively.

## WORKING IMPEDANCE MODEL FOR 1-NM LATTICE

The objective of the Impedance Database is to characterize the single-bunch instability in the ring. For the 1-nm storage ring the characterization includes predicting the single-bunch current limit before the ring is built. We accomplish this task by numerical simulation, which involves tracking multi-particles with impedance effects. However, the result obtained by simulation will

never be verified until the ring is actually built and operated. Thus, the validity of simulation based on the numerical model has been questioned. Fortunately, we have the computed impedance of the existing ring as shown in Figure 1, and the measured beam data are available for benchmarking the computed impedance. From this benchmark we learn how to use the 1-nm results of the Impedance Database effectively.

The longitudinal aspect of benchmarking for the current ring is described in a companion paper [4], where we found that we needed to add an imaginary part  $Z/n$  to the calculated  $Z/n$  by 0.1  $\Omega$  for a better agreement. This ad-hoc addition was necessary when the computed impedance is obtained via the 5-mm wake potential, but it was not necessary when the impedance is computed by the 1-mm bunch length. This implies that an additional 0.1  $\Omega$  compensates insufficient impedance bandwidth, which is limited by the bunch length used for computation of the wake potential. The impedance obtained this way is used as a working impedance model of the current ring [4].

Similar to the longitudinal working impedance, we also need to establish a transverse working impedance here. It was accomplished by simulating the injection process in order to determine the single-bunch current limit in the current ring. Since the APS adopted unmatched orbit bump during injection in order to reduce the injection amplitude of incoming beam from the booster, the injection process was modeled with an *elegant* [5] simulation by kicking the stored beam in the horizontal and vertical directions by 3 mm and 0.1 mm, respectively. Above a certain threshold current we observe the beam size blow up, especially in the vertical plane, leading to a significant amount of beam loss.

In the simulation we took the computed impedance as a reference impedance, and then varied the magnitude of impedance by multiplying by a factor,  $ztfactor$ . For each  $ztfactor$  we determine the accumulation limit. We did scan  $ztfactor$  twice: once with geometric impedance and once with geometric plus vertical resistive wall impedance. In the second scan we applied  $ztfactor$  to geometric impedance only. The results are shown in Figure 2. Comparison with actual delivered current in the current ring will determine a working impedance.

In the current APS storage ring we could store 16 mA to 24 mA in a single bunch depending on the lattice condition and rf gap voltage. During the preparation of a user run many parameters are adjusted until 20 mA can be stored in a hybrid fill. The adjustment is an optimization process to bring the condition of the storage ring close to the ideal lattice condition, which our modeling assumes in the simulation. Thus, the 22 mA predicted by simulation is in good agreement with the operational value, and we take this impedance, geometric plus vertical resistive wall impedance, as a transverse working impedance of the current ring.

In summary, a recipe for a working impedance model based on benchmarking the current storage ring is to add 0.1  $\Omega$  to an imaginary part of  $Z/n$  and to use geometric

and vertical resistive wall impedances in the transverse impedance. This is valid for the impedance obtained via the wake potential of a 5-mm bunched beam.

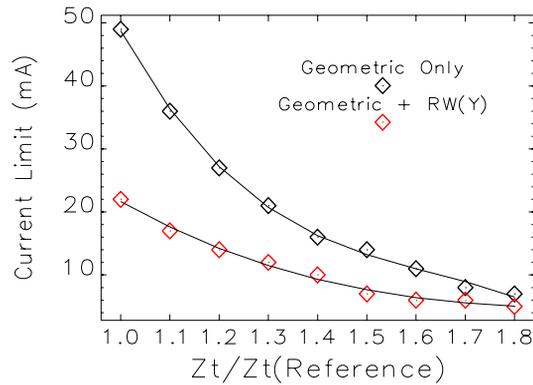


Figure 2: Single-bunch current as a function of ztfactor.

### SINGLE-BUNCH INSTABILITY IN THE 1-NM STORAGE RING

We applied the recipe of working impedance to the 1-nm storage ring with a small vacuum chamber. A lattice file was prepared for 1-nm lattice tracking, where nonlinear beam dynamics by sextupoles is approximated as chromatic and amplitude-dependent tune shift in phase space. Previous experience showed that the amplitude-dependent tune shift stabilizes unstable beam motion via Landau damping in the current ring.

With the working impedance and lattice files for the 1-nm lattice, an injection process is simulated with a bunched beam of various current. As we increase the current, we observe the beam size blow-up in the vertical plane. This was very similar to the one observed in the current ring. We believe that blow-up is due to transverse mode coupling instability (TMCI). Typical traces of vertical beam size are shown in Figure 3. The particles in the bunch with current above 19 mA were lost due to the aperture set by the 5-mm-gap chamber.

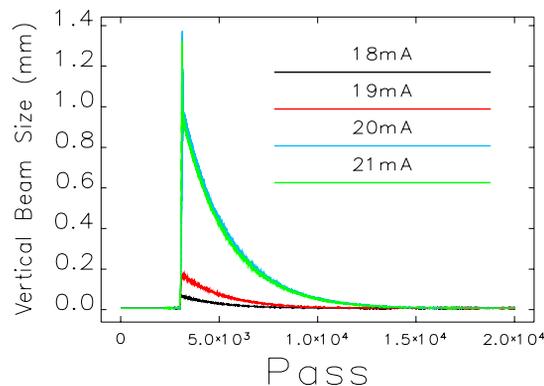


Figure 3: The vertical beam size variation of the bunched beam kicked in the vertical plane by 0.1 mm at turn 3000.

The effect of chromaticity is also investigated. We considered the ring operating at two chromaticities at 2

and 10. Transmission of particles at 12000 turns after the kick is shown in Figure 4, from which we determine the accumulation limit as 19 mA and 3 mA with chromaticities of 10 and 2, respectively.

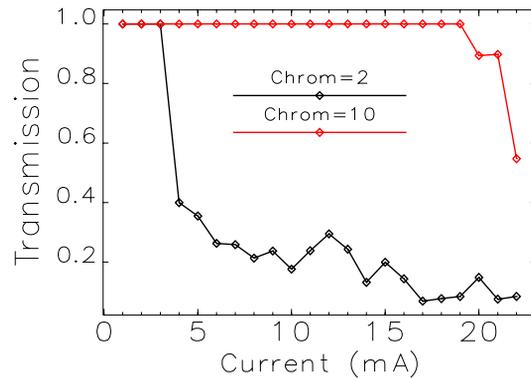


Figure 4: Transmission as a function of current.

As we understand it, raising chromaticity plays two roles: one is to reduce the effective impedance by shifting the beam spectrum by an amount of chromatic frequency, and the other is to increase the Landau damping rate via increased amplitude-dependent tune shift. Since the growth rate of TMCI is not sensitive to chromaticity, as the theory of strong head-tail instability predicts, the latter effect could be dominant in raising the accumulation limit.

### SUMMARY

The proposed 1-nm storage ring requires a smaller vacuum chamber in order to accommodate very strong quadrupoles and sextupoles. With the new chamber we recomputed wake potentials of all impedance elements found in the current APS storage ring. To our surprise the total wake potential of a small-chambered ring is slightly smaller than the existing ring. But, with lattice function weight, the total vertical wake is slightly bigger than the current ring, which results in slightly smaller stored current in a single bunch. But the amount of reduction is only 1 mA, so we conclude that both rings will be comparable in current-dependent phenomena.

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