EXPERIMENTAL VERIFICATION OF SINGLE-BUNCH ACCUMULATION LIMIT DEPENDENCE ON IMPEDANCE AT THE APS *

V. Sajaev†, B. Borland, Y.-C. Chae, L. Emery, ANL, Argonne, IL 60439, USA

Abstract

One of the unique features of the Advanced Photon Source is operation with a small number of intense bunches — the standard operating mode has 24 16-nC bunches, while in a special operating mode one of the bunches has a charge of 60 nC. Such high single-bunch currents are achieved by a combination of high operational chromaticity and transverse bunch-by-bunch feedback. In the near future, more narrow-gap insertion device vacuum chambers will be installed, which will increase the impedance of the storage ring and make operation with high single-bunch current more problematic. Simulations exist that quantify the effects of increased impedance on the APS single-bunch accumulation limit; however, no direct experimental verification has yet been performed. In this paper, we will present a measurement of the single-bunch accumulation limit as a function of impedance. Different impedance values were achieved by changing the storage ring beta functions.

INTRODUCTION

The Advanced Photon Source (APS) is a 7-GeV third-generation synchrotron light source that has been in operation for almost 20 years. Presently, APS operates in three fill patterns: 24 equally spaced bunches — a pattern that is used for 60% of the time; 324 equally spaced bunches; and a special "hybrid" mode where one 60-nC bunch is separated from a train of weaker bunches by 1.5 μs. Total operating beam current is always 102 mA.

To achieve stable high-current single bunches, we operate at high chromaticities. Before introducing transverse bunch-by-bunch feedback, the operating chromaticity was +7 in both planes for the 24-bunch fill pattern and +11 for the "hybrid" pattern. The biggest downside of operating with high chromaticity is low lifetime. Even though APS operates in top-up mode, there is still a limit on how low the lifetime can be. The introduction of the feedback allowed us to lower chromaticity to +4 for the 24-bunches fill pattern and to +9 for the "hybrid" pattern.

The APS transverse impedance consists of three approximately equal parts [1]: the resistive-wall impedance of small-gap insertion device (ID) vacuum chambers, the geometrical impedance of the transitions from large- to small-gap chambers, and the geometrical impedance of the rest of the ring. Presently, there are 32 small-gap ID chambers installed. Of them, one has a 5-mm full gap, eight chambers have a 7.5-mm full gap, and the rest have an 8-mm gap. All ID chambers are 5 m long and are made of aluminum. At the time this work started, three ID locations were still unoccupied, meaning that three more small-gap vacuum chambers still needed to be installed. This would increase transverse impedance by about 6% and could affect our ability to provide users with 60 nC in a single bunch.

As we work on the APS Upgrade [2], a few things are clear: the lattice will be as strongly focusing as possible resulting in small dynamic aperture and short lifetime, the ID vacuum chambers will have as small gaps as possible resulting in higher impedance, and we still would need to provide high-charge bunches to the users performing timing experiments. In this situation, we need a good understanding of impedance effects in the APS and confidence in our simulation tools. We have developed an experimental program that would allow us to verify our simulation and predictive abilities.

SIMULATIONS

Simulation of the single-bunch accumulation limit is done by multi-particle tracking using `elegant` [3]. The impedance of the whole ring is represented as a single lumped element for each plane using the ZTRANSVERSE and ZLONGITUDINAL elements in `elegant`, which take calculated impedance as input. The ring itself is represented as a linear map of one sector (element ILMATRIX) with chromaticity. Special elements like cavities, radiation effects, etc. can be inserted between sectors. The simulated bunch consists of 200k particles, which is required for correct simulation of longitudinal effects. Wake potentials of all elements are computed using GdFidl [4] and a 1-mm-long bunch, in order to extend the resulting impedance bandwidth. Wake potentials are separated into dipole and quadrupolar components.

The simulated accumulation limit is strongly affected by the injection conditions, namely by the residual oscillations of the stored bunch. First, we used the most realistic approach and simulated both stored and injected bunches. But later we noticed that the losses that occur at the accumulation limit all come from the stored beam and are not affected by the injected bunch. After that, we simplified the simulation to a simple kick of the stored bunch. Ideally, there should be no vertical oscillations occurring after the injection, but due to small coupling inside the injection bump there is always some vertical motion of the

* Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

† sajaev@aps.anl.gov

stored beam. This vertical motion is what affects the accumulation limit the most. The amplitude of the vertical motion is a free parameter that we used to reach an agreement with measurement. It was achieved at the amplitude of 0.3 mm. This amplitude of the vertical kick was then used for simulations that were intended to predict changes in the accumulation limit due to impedance variations. Figure 1 shows the result of the accumulation limit simulation as a function of vertical impedance, where the impedance is normalized to the present value. We can see that the accumulation limit changes very quickly in the vicinity of the present impedance value. Therefore, it is important to verify these results before any design decisions are made based on this plot.

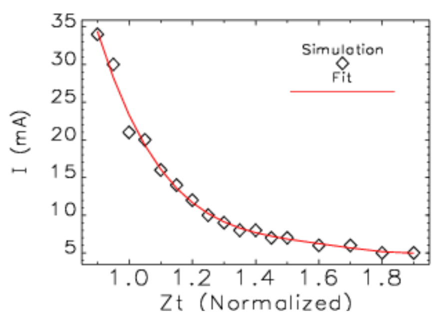

Figure 1: Single-bunch current limit as a function of vertical impedance. The impedance axis is normalized to the value for the current APS storage ring impedance.

To estimate the effect of different small-gap vacuum chambers on the accumulation limit, we have developed a simple spreadsheet that uses scaling laws taken from theory and simulations [5]: the effect of transitions is scaled as gap in the power of 2.4, and the resistive wall effect is scaled as gap in the third power, while the impedance effect is taken from a fit to the data in Figure 1. The spreadsheet was also used to calculate the expected results for the experiments described below.

EXPERIMENTAL RESULTS

The simplest way to vary the effective impedance in the storage ring is to change beta functions at impedance locations. Since about two-thirds of the vertical wake comes from the small-gap ID vacuum chambers, we need to change beta functions at ID locations. For operational convenience, we need to maintain the betatron tune close to its original value of 19.24; therefore, if beta function is increased at an ID location, it has to be decreased inside the sector. About one-third of the vertical wake is generated outside of the ID chambers; therefore, the reduction of vertical beta function outside of the ID chambers decreases the overall effect of beta function change on the effective impedance. Luckily, the simulations showed that the effect on the accumulation limit is still sufficiently large and should be visible in the experiment [6].

Lattice Development

We developed five lattices with vertical beta function in the ID ranging from 3.0 m to 5.0 m with 0.5-m steps. Figure 2 shows a set of five vertical beta functions for one sector (APS consists of 40 nearly identical sectors). The changes to the horizontal beta function were kept to a minimum. Also, when adjusting chromaticity, we excluded the sextupoles located inside the injection bump to keep injection conditions as close to the original as possible. All five lattices were implemented during machine studies. As always, the beta functions were measured and corrected to a high accuracy using the response matrix fit [7].

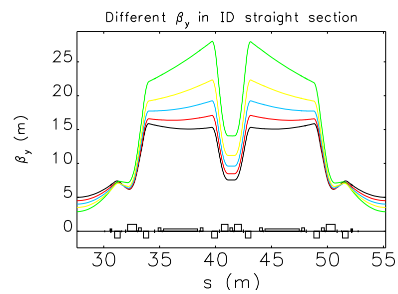

Figure 2: Vertical beta functions of one sector with ID value changing from 3 m to 5 m.

Accumulation Limit Measurement

The measurement of the accumulation limit is simple in essence: the injection is performed into a single bunch until no more charge can be injected or there is a drop-out of the stored bunch. In reality, however, it is hard to achieve a good reproducibility of this measurement because the accumulation limit is a complicated parameter depending on many variables. To ensure that all possible conditions are reproduced as closely as possible, for every lattice we followed the identical procedure:

- the lattice is corrected and coupling is minimized using the response matrix fit;
- the chromaticity is set to +11 in both planes, bunch-by-bunch feedback is tuned off;
- the orbit is well corrected;
- the injection conditions are reproduced — the injected beam trajectory is recovered, the stored beam closed bump in the horizontal plane is matched and spurious vertical oscillations of the stored beam after the kick are minimized;
- rf voltage is always maintained at 9 MV.

Figure 3 shows the results of the accumulation limit measurement for all five lattices as a function of the normalized effective vertical impedance. The accumulation limit is also normalized to the limit of the initial lattice. The vertical error bars show the accuracy of the accumulation limit measurement. The impedance error bars are calculated assuming 3% errors in the lattice beta functions. We can see a reasonable agreement between measurements and simulations.

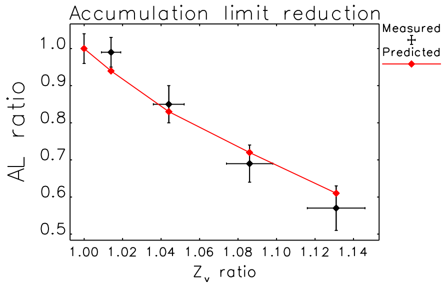

Figure 3: Comparison of measured and simulated accumulation limits as a function of vertical effective impedance.

To further validate our impedance model, two spare small-gap vacuum chambers were installed in two free sectors in May 2013. The expected increase of the vertical impedance due to this installation was 4% and the expected reduction of the accumulation limit was about 3 mA. The accumulation limit measurement procedure as described above was followed to measure the limit before and after the installation. A reduction by 2 mA was measured as shown in Figure 4, where the dependence of the accumulation limit on chromaticity is presented before and after the installation.

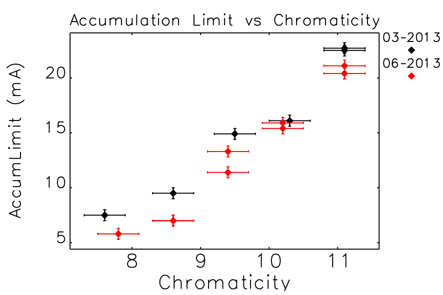

Figure 4: Accumulation limit as a function of chromaticity before and after the installation of two small-gap vacuum chambers.

Local Impedance Measurement

We also have measured the local impedance before and after installation of the two new chambers. The local impedance is obtained by analyzing response matrices measured at different values of the single-bunch current [8]. It is known that impedance acts on the beam as a defocusing element, so a response matrix fit can be used to measure this defocusing effect locally. In detail, the measurement and impedance determination is as follows: With a single bunch in the storage ring, the response matrix measurement is done for several beam currents. Then, the response matrix fit is performed for every measurement. The results of these fits is the set of beta function files — one for each beam current. The beta functions vary slightly from one file to another due to the defocusing effect of the impedance. The betatron phases from these files are combined for every location in the storage ring (for example, for all BPMs) to calculate the local betatron phase slope with current. The result of this processing is the betatron phase slope with current as a function of s along the storage ring. Then, a small number of artificial quadrupoles are used to reproduce the betatron phase slope dependence on s. The strengths of these quadrupoles will be proportional to the local impedance values. Here we need to emphasize that this approach works only for the vertical plane. In the horizontal plane at the APS the tune shift with current is very small due to smaller impedance and due to contributions from quadrupolar wakes that counteract the dipole wakes and make tune shift with current very small. Figure 5 shows the results of local impedance measurements before and after installation of new ID chambers. We can see a clear difference at the locations of the new chambers.

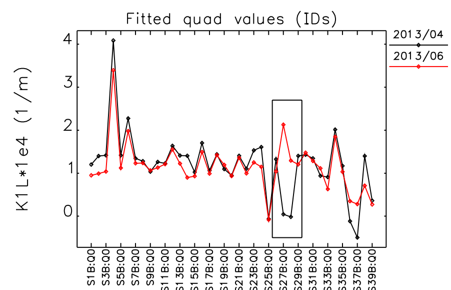

Figure 5: Local impedance distribution before and after installation of new vacuum chambers. A rectange shows where the chambers were installed.

CONCLUSIONS

We have developed a model that predicts how the single-bunch accumulation limit changes with storage ring impedance. We have varied the effective vertical impedance of the storage ring by changing beta functions at the small-gap vacuum chamber locations and measured the accumulation limit as a function of effective impedance. The measurements agreed reasonably well with the predictions. We have also verified the model by installing two new small-gap vacuum chambers and comparing the resulting accumulation limit reduction with predictions.

REFERENCES

[1] Y. Chae and Y. Wang, PAC 2007, FRPMN104, 4336 (2007).

[2] APS Upgrade Preliminary Design Report (2012).

[3] M. Borland, ANL/APS/LS-287 (2000).

[4] W. Bruns, LINAC 2002, TU444, 416 (2002).

[5] M. Borland, Private Communication (2012).

[6] M. Borland, Private Communication (2012).

[7] J. Safranek, NIM A 388 (1997).

[8] V. Sajaev, ICFA Beam Dynamics Newsletter 44 (2007).

ISBN 978-3-95450-138-0