THE COLLECTIVE EFFECTS OF LONG STRAIGHT SECTIONS (LSSs) IN THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The Advanced Photon Source is a 7-GeV hard x-ray synchrotron light source. The APS Upgrade specifies additional beamlines delivering higher brightness and flux as well as for the short-pulse x-ray (SPX). In order to fulfill these demands we plan to provide long straight sections (LSSs), for which the total length of the insertion devices is increased to 7.7 m. The long straight section also helps in implementing the SPX scheme without removing insertion devices. However, the impedance of the LSS may reduce the single-bunch current of 16 mA per bunch delivered to the users during hybrid fill. We estimate the effect of LSS impedance on the bunched beam current and propose an impedance optimization of the undulator chamber with a small gap.

INTRODUCTION

In the storage ring the limit on the single-bunch current is determined during injection, and its efficiency can be improved by adjusting the lattice, sextupoles, kickers, closed orbit, and rf voltages for its optimal condition. The stored current reaches its limit during injection when the amount of charge lost by the stored beam equals the charge of the incoming beam that survives the process. The injection efficiency decreases with increasing stored bunch charge due to collective effects. Currently the APS delivers 16 mA in the single bunch during hybrid-fill for users. This amounts to 60 nC per bunch, which may be the largest charge producing x-rays per bunch delivered in light sources around the world. In the upgrade we plan to deliver the same charge per bunch to the users.

The sources of collective effects may include electron cloud, ions, and impedance elements in the ring. The phenomena caused by the first two were observed in the ring with specially arranged bunch patterns; however, the magnitude of these effects is very small and does not affect nominal operations. On the other hand, the impedance elements in the ring cause various instabilities, which often limit the high-current operation.

In the upgrade the same will be true, in that the impedance will dominate the collective effects on the stored beam. In order to predict the single-bunch limit, we will use the existing impedance model of the present ring [1-3] as a function of hypothetical impedance increase or decrease. Figure 1 shows the nonlinear change of single-bunch current limit as a function of ring vertical impedance (or wake potential) times a scaling factor *Zt*. The fit to the curve can be extrapolated to cover the upgrade once we identify and estimate the additional impedance sources.

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The upgrade will utilize all the present vacuum chambers except the ones for the long-straight sections (LSSs). In addition, there will be deflecting cavities used for generating the short x-ray. These are the main impedance sources we need to consider in the upgrade. In this paper we will discuss issues related to the impedance of undulator chambers at the LSSs. The deflecting cavity will be treated separately in [4].

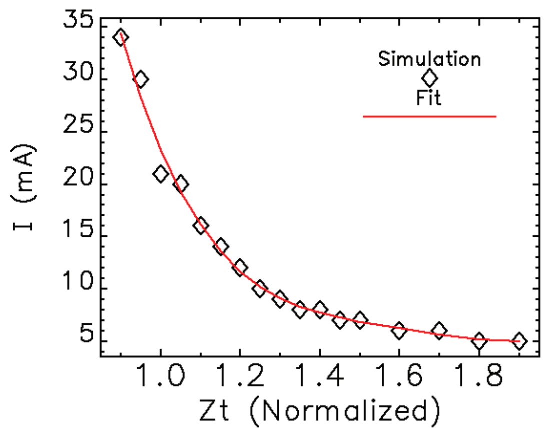

Figure 1: Single-bunch current limit as a function of vertical impedance. The symbols are simulation results. The line is a fit to guide the eye. The impedance axis is normalized to the current APS storage ring.

ISSUES FOR LSS

There will be four LSSs, each about 8 m long, that will replace the 5-m standard chamber; this effectively increases the impedance of transition by 8/5 due to the increase in β_y at the taper. In order to keep the same accumulation limit, we need to reduce the geometric impedance at the LSSs by 5/8.

Since the impedance of the taper is generated at the transition connecting the regular chamber to the undulator chamber, achieving smaller impedance will require designing a new transition. For this purpose we utilize the impedance formula of a rectangular chamber derived by Stupakov [5]:

$$Z_y^{rect} = j\frac{Z_0 w}{4}\int_{-\infty}^{\infty} dz\,\frac{h'(z)^2}{h(z)^3}, \tag{1}$$

where *w* is a (constant) half-width, and *h(z)* is the half-height defining the vertical profile. We note that only the tapered section with nonzero *h'(z)* contributes to the impedance. There are three parameters in the formula, namely, *h(z), w,* and *h'(z)*. We first consider optimizing *h(z)*. The optimal profile to minimize the functional Z_y/w was found in [6] and is

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$$h(z) = \frac{h_{\min}}{\left(1 + \left(\beta^{-1/2} - 1\right) z / L\right)^2}, \tag{2}$$

where $\beta \equiv \frac{h_{\max}}{h_{\min}}$. We note that the profile in Eq. (2) is nonlinear. The ratio of this impedance to that of the linear transition is [6]:

$$\frac{Z_y^{optimum}}{Z_y^{linear}} = \frac{8\beta}{(1+\beta)\left(1+\sqrt{\beta}\right)^2}. \tag{3}$$

Note that the above impedance expressions have no dependence on frequency, as the theory is developed in the limit of low frequencies. Thus we should stay aware of the applicability range. For example, we should not expect any bunch-length dependence using such impedances.

For the APS 8-mm-gap chamber where h_{max} = 21 mm and h_{min} = 4 mm, the predicted reduction by using a nonlinear taper is, coincidentally, very close to 5/8, which happens to compensate the increased impedance effect caused by the LSS.

In order to verify Eq. (3) we numerically computed the wake potential of the nonlinear taper with *GdfidL* [7]. For a transition from 21 mm to 4 mm in the vertical plane and flat in the horizontal plane, the optimal profile predicted by Eq. 2, *h(z),* is shown in Figure 2.

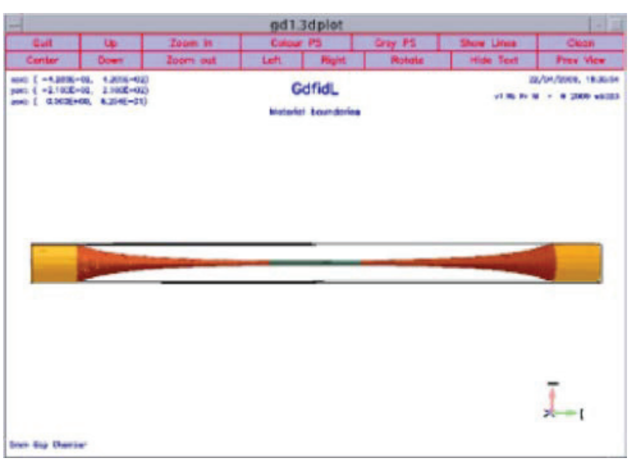

Figure 2: The vertical profile used in numerical simulation of an optimized nonlinear taper connecting regular APS chamber to an undulator chamber with an 8-mm vertical gap.

Kick factors were calculated for bunches of different lengths using the wake fields computed with *GdfidL* for the nonlinear and linear tapers. The ratio of kick factors is plotted in Figure 3. Recall that the goal is to have a small ratio, so that the APS can benefit from the nonlinear taper. However, there seems to be a reduction in benefit as the bunch becomes shorter. For reference, the expected improvement for the nonlinear taper from Eq. (3) is shown as a straight line. Thus, by using the nonlinear taper, we would fall short of our goal to reduce the impedance.

In addition we also found that the reduction could be much less if the horizontal profile was not flat. For the actual APS chamber, where the horizontal profile also varies, the optimization resulted in a reduction of less than 5% of the value for a linear taper, hardly justifying the modification. Hence, we decided not to adopt a nonlinear taper in the upgrade.

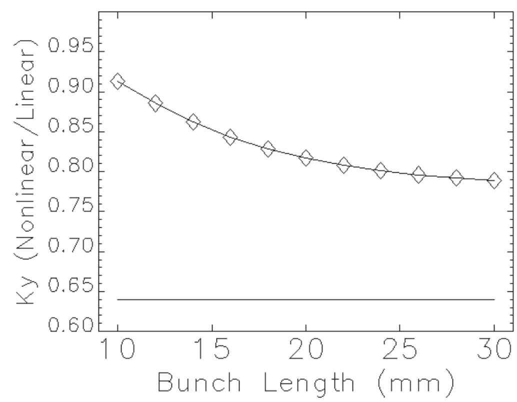

Figure 3: Ratio of vertical kick factors of nonlinear and linear tapers for different bunch lengths. The straight line is the prediction by Eq. (3), i.e., no frequency or bunch-length dependence.

Though an approximate expression, Eq. (1) suggests that the horizontal half-width *w* strongly controls the vertical impedance. In the long-wave approximation this linear dependence could be correct, but for high frequencies the behavior is unknown. So we investigated the quantitative effect of width for the 8-mm-gap chamber. Figure 4 shows that widening increases the impedance until it reaches some maximum. From this we can estimate the impedance increase of a hypothetical in-vacuum undulator (IVU) chamber if installed (IVUs are noted for wide chambers).

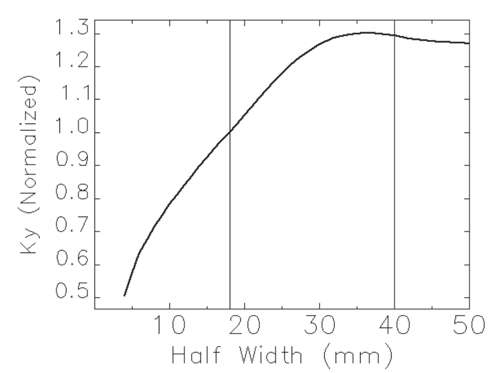

Figure 4: The vertical kick factor of bunched beam as a function of the half width of an 8-mm small-gap chamber connected to the regular chamber in the ellipse of (4.2 cm, 2.1 cm).

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Conversely, narrowing of the chamber decreases the impedance quite effectively. However, this decrease in aperture would require a smaller horizontal beta function to maintain injection, which would impose additional restrictions on the lattice design.

The last option is to simply make a longer linear transition. A detailed computation of vertical wakes showed that a transition length of over 50 cm is sufficient to achieve the target reduction of 5/8, as shown in Figure 5.

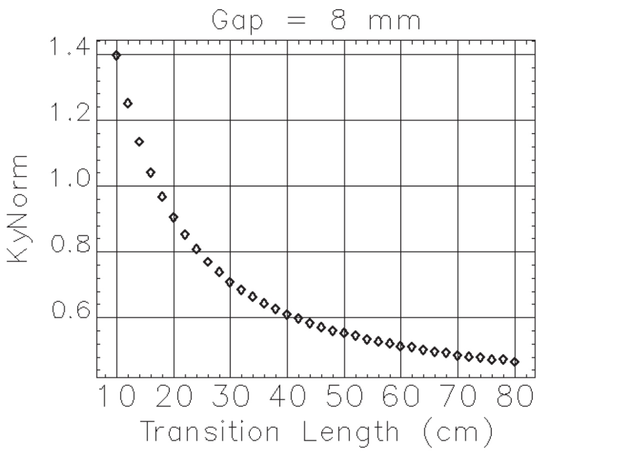

Figure 5: The vertical kick factor as a function of linear taper length. The values are normalized by the current APS 8-mm gap chamber.

In order to accommodate this long transition, the area needs to be redesigned as shown in Figure 6. The downstream will be mirrored with respect to the center of the straight section.

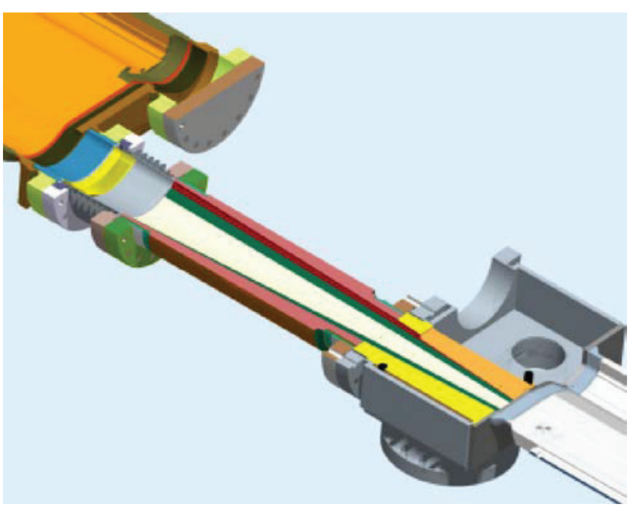

Figure 6: The new transition designed for LSS will have a 55-cm taper that is longer than the current taper with 18-cm effective length.

The new transition of the LSS chamber will reduce the effective transverse kick to a level equal to or less than the regular 5-m-long straight section. However, an 8-m LSS chamber will increase the resistive wall impedance by 8/5 per sector. If we had to build such a chamber, we could reduce the impact of the resistive wall effect by using a strip of copper on the top and bottom inside surfaces of the chamber. Fortunately in the LSS cases present in the upgrade, this will not be needed. In Sectors 1 and 11, a superconducting undulator with a cryogenically cooled chamber will occupy about 3 m of the LSS. In Sectors 5 and 7, a set of superconducting cavities will occupy about 2.8 m of the LSS. Due to the low temperature of the cryogenically cooled chamber as well as the large aperture of the SPX chamber, the resistive wall impedance should not increase.

After we mitigated the impedance issues, we completed the LSS design by removing a quadrupole and by repositioning beam position monitor and radiation absorber; the sector with magnets is shown in Figure 7.

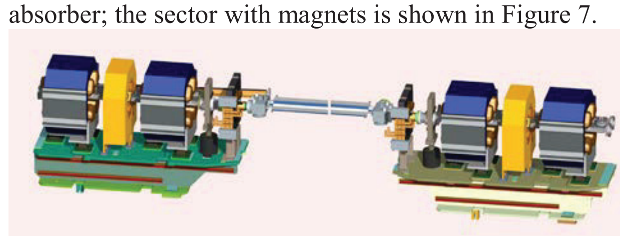

Figure 7: The LSS with quadrupoles on the girder.

SUMMARY

We determined that implementation of LSSs would significantly increase the effective impedance and reduce the single-bunch current, unless we devise a method of mitigating transverse instabilities. The method we chose for this mitigation was to control the impedance source by reducing the geometrical impedance of transition by making the taper longer at both ends, and reducing the resistive wall wake by providing a chamber with a copper-lined beam path or some other configuration that avoids a long, room-temperature chamber. This will leave the beam in the current storage ring unaffected impedance-wise by the LSS of the future upgrade.

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