THE WAKEFIELD EFFECTS OF PULSED CRAB CAVITIES AT THE ADVANCED PHOTON SOURCE FOR SHORT-X-RAY PULSE GENERATION*

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Abstract

In recent years we have explored the application to the Advanced Photon Source (APS) of Zholents' crab-cavity-based scheme for production of short x-ray pulses [1]. As a near-term project, the APS has elected to pursue a pulsed system using room-temperature cavities [2]. The cavity design has been optimized to heavily damp parasitic modes while maintaining large shunt impedance for the deflecting dipole mode [3]. We evaluated a system consisting of three crab cavities as an impedance source and determined their effect on the single- and multi-bunch instabilities. In the single-bunch instability we used the APS impedance model as the reference system in order to predict the overall performance of the ring when the crab cavities are installed in the future. For multi-bunch instabilities we used a realistic fill pattern, including hybrid-fill, and tracked multiple bunches where each bunch was treated as soft in distribution.

INTRODUCTION

A project to produce short x-ray pulses at the APS is underway, where a system of crab cavities is the central piece of the project. Progress made in the various aspects of the project are reported in these proceedings, which include the overall configuration of a pulsed crab-cavity system and its implementation in the APS storage ring [2], rf design of crab-cavity system [3], and multi-bunch instability analysis for the APS storage ring with crab-cavity installed [4]. Here we describe the single-bunch instability caused by a crab-cavity system. In order to be specific we choose a three 9-cell cavity system as a reference for detailed investigation of instability. This will give an insight toward final design; currently we adopt two pairs of two cavities, each with three cells, as a choice for the project [2].

Some aspect of multi-bunch instability is also included in the paper, which can be distinguished from the results described in Ref. [4], where the analysis is based on the analytic formula. Here we investigate the instability by tracking multiple bunches, each consisting of multiple macroparticles. Therefore, the single-bunch effect is also included in the context of multi-bunch instability. The scope of investigation is limited, for it required too many particles to track in the simulation; nevertheless we have a result interesting enough to report.

A goal of this study is to see if we can deliver the same fill pattern of the beam to the users even with the crab-cavity installed in the ring; currently the APS storage ring can deliver 20 mA in a single bunch totaling 100 mA in a hybrid fill-pattern.

WAKEFIELD CALCULATION

An initial design producing short x-ray pulses required one straight section equipped with three deflecting cavities (C1, C2, C3) and an undulator chamber (ID VC) connected by transitions (T1, T2) and bellows (B) as depicted in Figure 1. We initially considered installing three 9-cell cavities, one of which is shown in Figure 2. Even if the final configuration may differ, we calculated wake potential and impedance of the cavity and transition as shown in Figures 1 and 2, as a reference.

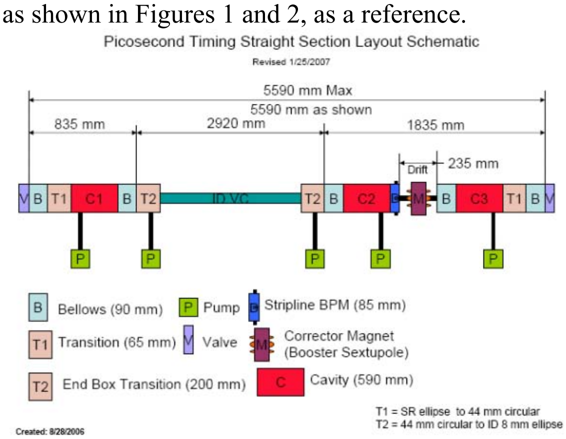

Figure 1: Short x-ray pulse straight section.

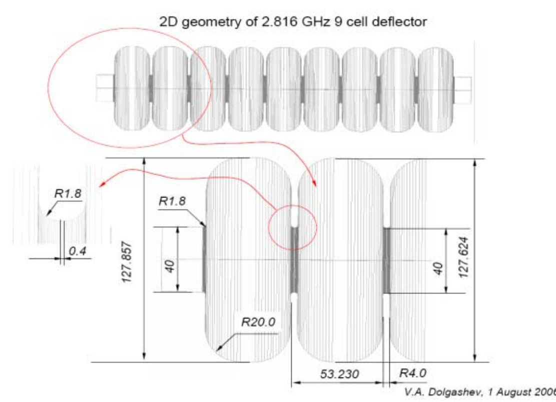

Figure 2: A 2.816-GHz 9-cell deflecting cavity.

The wake potential of a 9-cell deflecting cavity calculated by ABCI is shown in Figure 3 in comparison with total wake of the storage ring. The magnitude in the figure represents the summation of $\beta_{x,y}W_{x,y}$, and the average beta function of straight section is β_x/β_y=20/4 m.

Without the deflecting cavity the ring is dominated by the vertical wake, which is a factor of three greater than

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the horizontal. But, with three 9-cell cavities, the effective horizontal wake, $\beta_x W_x$, is doubled without increasing the vertical wake very much.

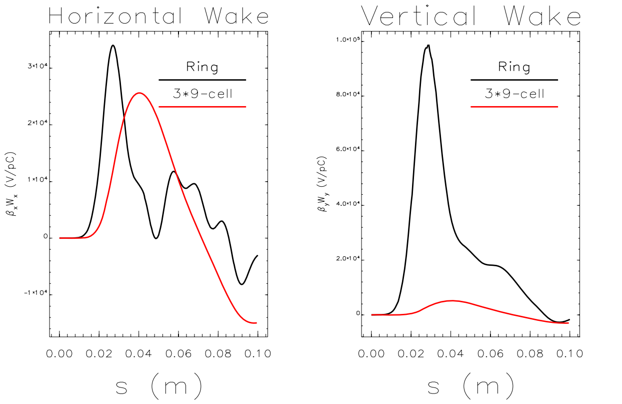

Figure 3: Comparison of a total wake potential of the ring and three 9-cell cavities: horizontal wake $\beta_x W_x$ (left) and $\beta_y W_y$ (right).

WAKEFIELD EFFECT

Single-Bunch Current Limit

We used the ring without deflecting cavities as a reference system. There the single-bunch current was determined by the vertical impedance; that is 20 mA when the chromaticity was set at 10. With three 9-cell cavities added, we performed an injection simulation similar to the one described in Ref. [5, 6]. In the simulation the stored beam is kicked by 3-4 mm in the horizontal plane. Depending on the current, the beam center and size evolve differently. Two traces of horizontal beam sizes of 14 and 15 mA are shown in Fig. 4. The dynamic aperture limits beam-size blow up at 15 mA followed by damped motion with reduced current in the bunch. From this we found that we can store the current in a bunch up to 14 mA without loss.

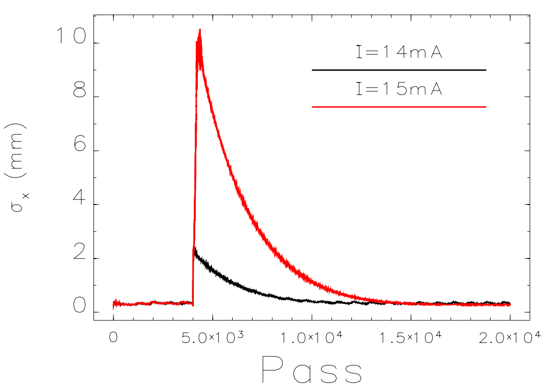

Figure 4: The evolution horizontal beam size after a 3-mm horizontal kick at pass 4000 shows the beam size blows up when the current is above 14 mA.

In order to find out the condition for 20 mA we varied the magnitude of impedance and calculated the single-bunch current limit. The result is shown in Figure 5, from which we found the condition $[\beta_x Z_x] < 0.6\times[\beta_x Z_x]_{ref}$ for 20 mA, where $[\beta_x Z_x]_{ref}$ corresponds to 14 mA. This can be achieved by either reducing the beta function β_x or the impedance Z_x.

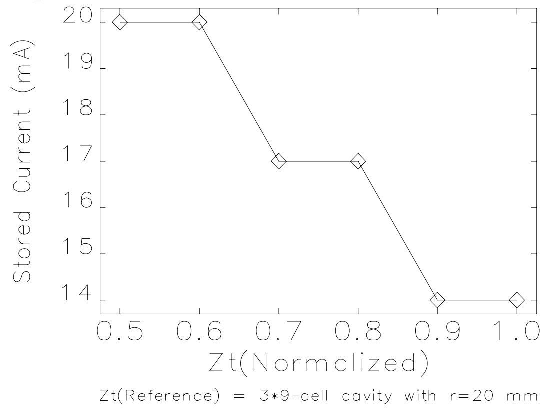

Figure 5: Single-bunch current in the storage ring as a function of deflecting cavity impedance

We considered impedance reduction by increasing the cavity aperture. In the simulation we kept the tube radius intact at 20 mm while varying the cavity iris aperture. For each aperture we computed the transverse kick factors; the result is shown in Figure 6 as a function of aperture radius. The two graphs represent 2-cell and 9-cell cavities, respectively. In a 2-cell cavity we found the Z_t varies as 1/a, while in a 9-cell cavity Z_t~$1/a^2$. Using this finding, we concluded that a proposed system consisting of a 3-9-9-cell cavity with 23.5-mm aperture radius can satisfy the requirement for 20 mA. Four 3-cell cavities described in Ref. [2] also satisfy the requirement without lowering β_x.

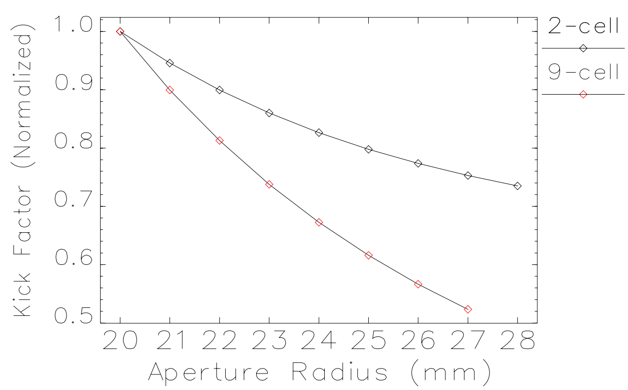

Figure 6: Transverse kick factor variation as function of aperture radius.

Hybrid-Fill Pattern

The single-bunch current of 20 mA is delivered at the APS in a hybrid-fill pattern, which consists of one bunch followed by eight groups of seven bunches. The current distribution with bucket index is shown in Figure 7. In this inhomogeneous distribution it is difficult to distinguish single-bunch from multi-bunch effects, because it has a mixture of both effects. In the previous section we showed that we could store 20 mA if we have only one bunch in the ring. However, the question arises: Can we still store 20 mA in the realistic hybrid-fill? It is in this context that we simulate multiple-bunched beam with high-order modes (HOM) of the 9-cell deflecting cavity.

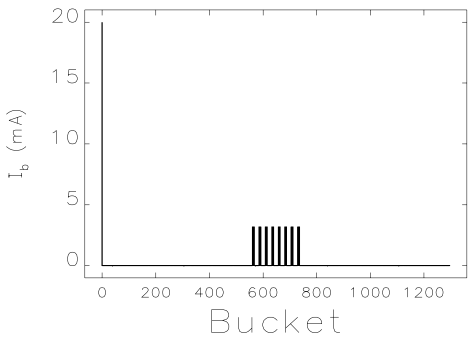

Figure 7: Hybrid-fill pattern 1+7*8 used in the APS storage ring.

The interaction between HOM of the cavity and multiple bunches in the ring can be illustrated in the frequency domain. The beam spectrum of the hybrid-fill and the transverse impedance of the cavity constructed by the computed HOM parameters of a 9-cell cavity are shown in Figure 8. The beam spectrum shows a pattern, superposition of a single bunch with 20 mA and a square pulse distribution, within a 352-MHz period; this pattern repeats at every rf-harmonic frequency. The resonant frequency of the deflecting cavity is chosen to satisfy the synchronous condition h=8, where h is the rf-harmonic number defined as f/f_{rf}. Another possibility could be h=8.5 where the beam spectrum is relatively weak.

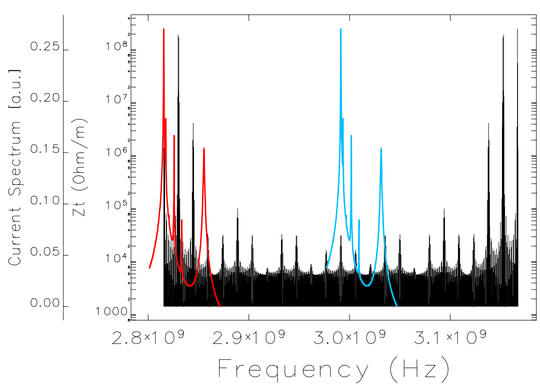

Figure 8: Beam spectrum and HOM impedance at h=8 and h=8.5.

In order to determine the total stored current in a hybrid-fill, we tracked multiple bunches by using the program *elegant* [7]. In addition to the broadband impedance of the ring and the deflecting cavity used for single-bunch instability simulation, we also included HOM impedances. The hybrid-fill pattern is prepared as a sequence of bunches in time with a number of macroparticles proportional to the bunch current. For this investigation we used 3000 particles per mA. With the resonant frequency of the deflecting cavity initially set to h=8, we found about 50% transmission after 10,000 turns. In order to find the optimum frequency, we detuned the deflecting cavity frequency to within 2 MHz bandwidth, and the transmission was recorded for each case. The results are shown in Figure 9; the red curve represents the de-tuning for h=8, and the blue curve for h=8.5. In general, the deflecting cavity tuned at a resonant frequency near h=8.5 will have fewer HOM effects, but other considerations prefer the frequency near h=8. With the h=8 as the chosen frequency, an in-depth study based on Monte-Carlo simulation has been performed, and the results are reported in Ref. [4].

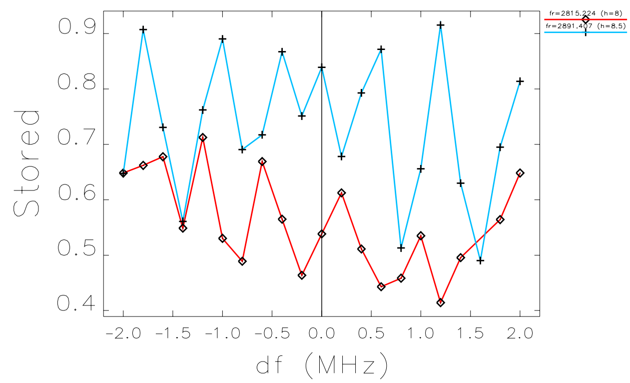

Figure 9: Fraction of current stored in the ring as a function of detuning of the deflecting cavity. The central frequency of the cavity considered is either h=8 (red curve) or h=8.5 (blue curve).

SUMMARY

We studied the deflecting cavity as a new impedance source in the existing APS storage ring. By using three 9-cell cavities tuned at the eighth multiple of the ring rf-frequency as the reference system, we found the condition for 20-mA single-bunch current. We also investigated single-bunch current in a hybrid-fill pattern that showed we may need to damp the HOMs by about a factor of two. The reduction can be realized in the new configuration, which only requires four 3-cell cavities instead of the three 9-cell cavities considered in this paper.

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