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INSTABILITY THRESHOLDS FOR THE ADVANCED PHOTON SOURCE MULTI-BEND ACHROMAT UPGRADE*

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Abstract

An important operating mode for the multi-bend achromat (MBA) upgrade at the Advanced Photon Source (APS) calls for 200 mA average current divided evenly over 48 bunches. Ensuring that the desired 4.2 mA single bunch current can be stably stored requires a detailed understanding of the impedance in the MBA ring. We briefly discuss modeling sources of impedance using the electromagnetic codes `GdfidL` and `ECHO`, and how we then include both geometric and resistive wall wakefields using the tracking code `elegant` to predict collective instabilities. We first validate our procedures by comparing APS experimental measurements to tracking predictions using the APS storage ring impedance model. We then discuss the MBA impedance model, for which we find that a chromaticity of 5 units is sufficient to obtain the required 4.2 mA single bunch current. Finally, we mention certain design changes that may reduce the impedance and allow for a reduction in chromaticity.

INTRODUCTION

There are many potential sources of instabilities, but observations at high-energy storage rings such as the APS have shown that the dominant collective effects are typically due to impedances/wakefields. To be more specific, transverse wakefields give rise to transverse beam instabilities that ultimately limit the single-bunch current at the APS, while longitudinal wakefields predominantly lead to bunch lengthening (which usually eases operational requirements), an increase in energy spread (which is typically not too detrimental), and rf-heating of vacuum components (which can be problematic). Transverse impedances will continue to be the dominant driver of collective effects for the MBA. Hence, understanding and calculating the impedance is critical for accurate predictions of the single-bunch current limit. Here we describe our efforts to model wakefields and predict collective effects for the APS MBA Upgrade including the bunch-lengthening higher harmonic cavity (HHC).

IMPEDANCE MODEL AND SIMULATION

We have adapted to the MBA lattice the impedance model and tracking simulation methods that Y.-C. Chae developed for the APS over the past decade. This model has successfully reproduced various impedance-driven collective effects observed in the APS ring [1, 2]; extending it to the MBA was straightforward once the primary impedance sources were identified and analyzed. In this model, the effects of impedances/wakefields are represented by a single "impedance element" in the code `elegant` [3]. To reduce the distributed impedance from the entire ring to a localized perturbation, we first divide the impedance into its resistive wall and geometric components. We compute the resistive wall contribution using analytic formulas, and calculate the geometric impedance with numerical simulation codes. We list the various resistive wall and geometric impedance sources identified for the MBA storage ring in Table 1.

We use two codes to compute the geometric impedance. We compute the wakefields for components possessing axial symmetry using the 2D `ECHO` code [4], while structures that vary in 3D are analyzed with the commercial code `GdfidL` [5]. To balance numerical efficiency and accuracy, within these codes we model the (point particle) wakefields by the wake potential generated by a 1-mm long bunch, as this approximation has had good success in predicting the onset of various instabilities in the present APS. In addition, we have performed several numerical tests that use wake potentials derived from shorter electron bunches, and these have proven to give the same results in terms of the single-bunch current limit for the APS-U lattice.

The total transverse wake potential of the ring is found by weighting each contribution by its local beta-function and summing. For example, if we label each element by j and the vertical geometric beta-function at that element by $\beta_{y,j}$, the weighted geometric wakefield along y is

$$\langle \beta_y W_y^{\text{geo}} \rangle = \sum_{\text{elements } j} \beta_{y,j} W_{y,j}^{\text{geo}}. \tag{1}$$

An analogous expression holds for W_x, while the total longitudinal wakefield is the simple sum $\langle W_z^{\text{geo}} \rangle = \sum_j W_{z,j}^{\text{geo}}$.

The corresponding impedances are then computed via the discrete Fourier transform, and the "total impedance" is obtained by adding the geometric and resistive wall contributions. Finally, we use these impedances with the particle tracking code `elegant` as a single element by dividing by the lattice function $\beta_{x,y}$ at its chosen location.

We show how well our impedance model and tracking simulations can perform by comparing the predictions of the present APS impedance model to recent experiments in Fig. 1. The first two plots show that the APS impedance model does a very good job predicting the longitudinal behavior; the first plot compares the current-dependent bunch lengthening predicted by simulation (blue points) with a fit to experimental data in red, while the second panel shows reasonably good agreement for both the microwave instability threshhold at approximately 6-7 mA and the subsequent growth in energy spread as I_{bunch} increases. Finally, the last panel compares the predicted single bunch current stability threshhold with I_{limit} measured at the APS storage ring for various levels of the chromaticity ξ defined by

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Table 1: Elements that contribute to the Resistive Wall and Geometric Impedances (BPM = Beam Position Monitor)

Resistive wall			**Geometric contributions**			
			Sector (×40)		**Ring**	
Metal	**Diameter**	**Length**	**Element**	**Number**	**Element**	**Number**
Cu	22 mm	224 m	Regular BPM	12	Injection kicker	4
Al	22 mm	605 m	ID BPM	2	Extraction kicker	4
SS	22 mm	80 m	ID transition	1	Feedback	2
Al	6 mm	50 m	Bellow	14	Stripline	1
Al	6 × 20 mm	125 m	Flange	52	Aperture	2
Al	140 mm	20 m	Crotch absorber	2	Fundamental cavity	12
			In-line absorber	12	Rf transition	4
			Gate valve	4	4^{th} harmonic cavity	1

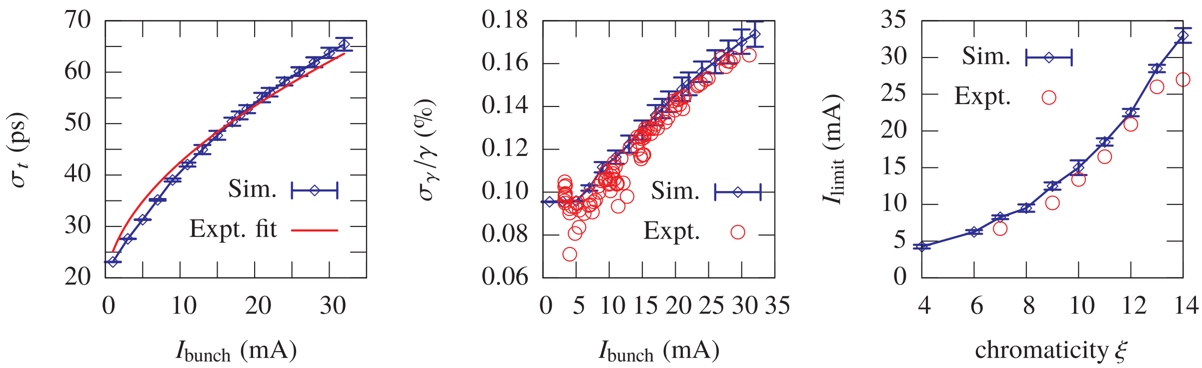

Figure 1: Comparison of APS impedance model predictions to experimental measurements made at the APS.

$\Delta\nu_\beta \equiv \xi\Delta\gamma/\gamma$, where $\Delta\nu_\beta$ is the change in betatron tune for a particle with normalized energy deviation $\Delta\gamma/\gamma$. We find that the model overestimates the maximum stable current by only 10% over the chromaticity range of 7-13 units.

Figure 1 indicates that our simulation methodology for predicting collective effects is sound, provided all the relevant impedance sources are identified. The remainder of this paper discusses our predictions when we apply these techniques to the MBA lattice using the impedance sources listed in Table 1 (more details are in [6]).

LONGITUDINAL COLLECTIVE EFFECTS

The longitudinal dynamics in the MBA are strongly influenced by the passive fourth harmonic bunch-lengthening cavity [7], which serves to lengthen the bunch and increase its lifetime. For simplicity we model the HHC as an active rf cavity whose voltage and phase is inferred from self-consistent simulations described in [8]. The top panel of Fig. 2 shows the bunch length as a function of I_{bunch} when the HHC is on (blue) and off (red). The HHC increases the zero-current bunch length from about 12 to 50 ps, while at the maximum planned operating current of 4.2 mA/bunch the longitudinal wakefields increase σ_t by $\sim$ 30 ps.

The bottom panel of Fig. 2 shows the energy spread as a function of the single bunch current. The energy spread increase characteristic of the microwave instability occurs when the single bunch current is approximately 0.8 mA if the HHC is off, and just over 1 mA with the HHC on. Note that in either case the microwave instability threshhold current is above the 0.62 mA single bunch current in 324 bunch mode. On the other hand, in 48-bunch mode with 4.2 mA/bunch the microwave instability markedly increases the energy spread to $\sim$ 0.22% without the HHC, and approximately 0.15% with the HHC. In addition, at 4.2 mA the longitudinal dynamics without any rf-induced bunch lengthening exibit rather large chaotic fluctuations typical of turbulent bunch lengthening. These large longitudinal fluctuations are reflected by the sizeable error bars, while turning on the HHC leads to much more stable operation.

SINGLE BUNCH CURRENT LIMIT

An important mode of Upgrade operation is a “timing mode” that has 200 mA average current divided into 48 equi-spaced bunches. Hence, it is crucial to understand the single-bunch current limit I_{limit}, and verify that the required 4.2 mA/bunch can be stably stored. We determine I_{limit} by tracking an injected bunch over thousands of turns, which corresponds to several damping times. In particular, at each chromaticity and ring condition we run several `elegant` simulations using a range of initial currents, and analyze the output for undamped transverse oscillations and/or particle loss. These simulations track 200,000 macroparticles over 20,000 passes, and initialize the bunch with a small initial offset of 200 μm in x and y.

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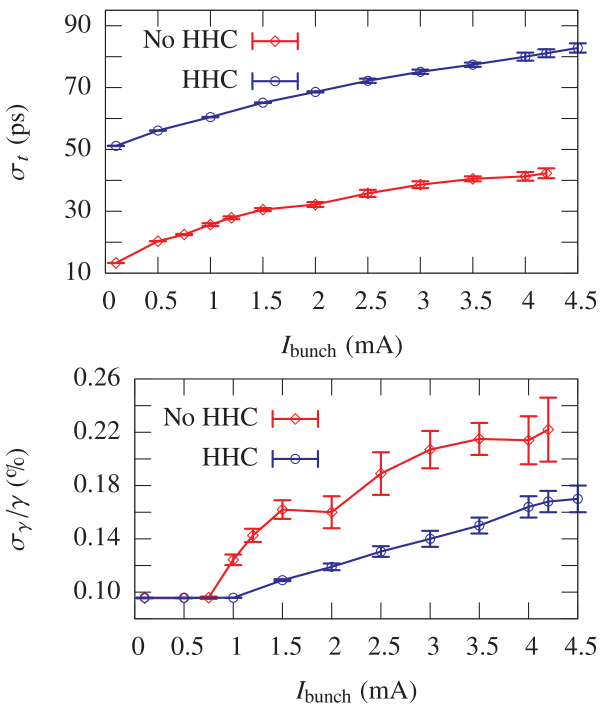

Figure 2: Longitudinal bunch length and energy spread both with (blue) and without (red) the bunch lengthening HHC.

The results do not significantly change if the number of macroparticles is varied by a factor between 0.25 and 4, with numerical uncertainties typically playing a role at the level of about ±0.1 mA. Since most choices of chromaticity and impedance exhibit a clear threshhold current below which the beam is stable, the simulation error bars are typically dominated by the discrete steps of current at which the simulations are run. On the other hand, loss threshholds for $\xi \geq 4.5$ appeared to be dominated by physics at or near injection, and additionally showed some dependence on the initial offset. Hence, for these cases our simulation results represent limits to injection efficiency due to the impedance and assumed injection system tolerances, rather than intrinsic stability constraints from collective effects alone. These injection-related issues demand further investigation.

We summarize our single-bunch stability results in Fig. 3, in which the magenta line indicates the 4.2 mA requirement. The red and blue points plot I_{limit} for the full impedance model of Table 1 assuming that the HHC is on or off, respectively. The HHC increases the single bunch current by about 0.5 mA if $\xi < 4$. For $\xi = 5$, the single-bunch current with the HHC is limited by loss at injection; decreasing the initial displacement from 200 to 100 microns increases the maximum stable current by about 1 mA, suggesting an advantage for on-axis swap-out injection. Future study of injection kicker tolerances and e-beam parameters is planned.

The cyan points in Fig. 3 show that I_{limit} can be increased by at least 1 mA if the small-gap ID BPMs were moved to the bellows assembly just before the ID transition. Not only does moving the small-gap BPMs increase the current limit by reducing the BPM-associated impedance by a factor ~2, but it will also significantly reduce the rf heating of the ID BPM buttons. The APS Diagnostic Group has proposed this design change as a way to potentially increase the mechanical stability of the BPMs while reducing their sensitivity by a tolerable amount.

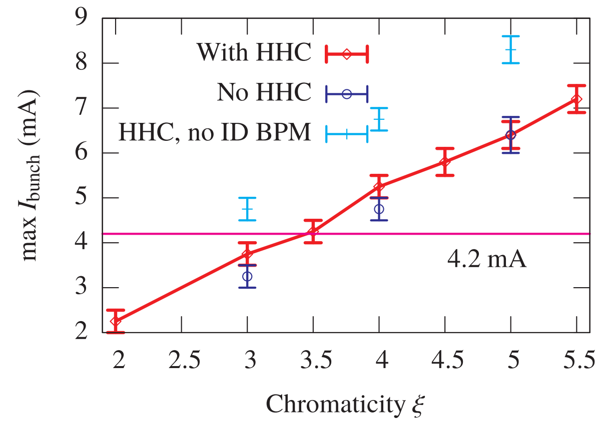

Figure 3: Transverse stability predictions.

Moving the ID BPMs from the small-gap ID chamber is only one of the possible ways by which collective effects might be reduced in the ring. In fact, some reduction in impedance associated with the ID BPMs may be found by optimizing their design. Alternatively, the vacuum group has considered alternate designs for the in-line photon absorbers that will increase their distance from the beam. Such a design change may reduce synchrotron radiation loads while also reducing the impedance.

CONCLUSIONS

As presently envisioned, we predict that the APS MBA Upgrade can stably store 4.8 mA/bunch if $\xi = 5$ units. Future work will continue to identify and optimize large sources of impedance, and study how collective effects may result in the observed limits to injection at high charge.

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