COLLECTIVE EFFECTS AT INJECTION FOR THE APS-U MBA LATTICE *

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Abstract

The Advanced Photon Source has proposed an upgrade to a multi-bend achromat (MBA) with a proposed timing mode that calls for 48 bunches of 15 nC each. In this mode of operation, we find that phase-space mismatch from the booster can drive large wakefields that in turn may limit the current below that of the nominal collective instability threshold. We show that collective effects at injection lead to emittance growth that makes ordinary off-axis accumulation very challenging. On-axis injection ameliorates many of these issues, but we find that transverse feedback is still required. We explore the role of impedance, feedback, and phase-space mismatch on transverse instabilities at injection.

INTRODUCTION

The Advanced Photon Source (APS) Multi-Bend Achromat (MBA) upgrade [1] plans to replace the existing 3rd generation storage ring with a 7-bend achromat. The nominal APS-U lattice is based on the design from Ref. [2], and agressively pushes the emittance to 67 pm [3]. This results in strong nonlinearities and limited the dynamic aperture, such that on-axis swap-out injection [4, 5] is the only option. Recent work has investigated more forgiving alternate lattices that sacrifice the smallest emittance in exchange for a larger dynamic aperture and Touschek lifetime. The resulting 90 pm alternate lattice [6] has a dynamic aperture that appears to be suitable for accumulation. Since all conclusions regarding dynamic aperture are drawn from single particle tracking, here we discuss the extent to which collective effects may reduce injection efficiency and the charge-dependent (effective) dynamic aperture for the APS-U.

The APS-U plans to operate with an average current of 200 mA in one of two modes: the first is a "high brightness" mode that stores 324 bunches, while the second is a "timing mode" with 48 equally-spaced bunches. In the 324-bunch mode there is 2.4 nC/bunch, which is low enough that single-bunch collective effects typically do not play a major role. On the other hand, the timing mode has 15.3 nC/bunch, and collective effects can play a large role.

Our main focus will be how collective effects at injection reduce injection efficiency during accumulation in the 90-pm lattice. We will show that collective effects can result in significant emittance growth and particle loss within a few hundred turns of injection, so that the shared-oscillation method of top-up injection does not appear feasible at high charge with the assumed ±4-mm physical aperture. We then make a few comments for on-axis injection in the 67 pm lattice, showing that non-equilibrium effects can drive collective oscillations at injection that need to be controlled with appropriate feedback.

COLLECTIVE EFFECTS DURING ACCUMULATION

As mentioned previously, simulations indicate that the 90-pm lattice can be filled with traditional accumulation when operated in the 324 bunch mode, albeit only if residual oscillations are shared between the stored and injected beams. On the other hand, we find that collective effects can significantly reduce the injection efficiency in the timing mode that has ~15 nC/bunch. These simulations are based on element-by-element tracking with `Pelegant` [7, 8], and use the impedance model described in [9] divided into 16 local impedance elements per sector.

In the simplest case where we assume no transverse feedback, collective effects combined with nonlinearities result in phase space filamentation and emittance growth over the first hundred turns. This is turn leads to an effective spread in oscillation amplitudes to the point where a significant fraction of the beam is lost on the physical aperture. We show transverse phase space plots that illustrate the beam size growth and subsequent loss on the aperture at $x = -4$ mm in Fig. 1. The corresponding reduction in current as a function of pass number is included in the last panel.

Figure 1 shows that transverse wakefields substantially increase the spread in oscillation amplitudes during the first ~100 passes; the initially nearly point-like beam at pass 0 becomes a broad smear by pass 56. Subsequent evolution continues to spread the beam outwards, leading to significant particle loss between pass 63 and 84. After this point the beam is left with less than 75% of its initial charge, and it continues to lose particles for the next few hundred turns.

We have found that qualitatively similar dynamics also occurs at lower initial charge. For example, if the initial current is 3 mA the beam filaments in a similar manner but to a lesser degree, with losses greater than 10%. Only when the charge is reduced by one-half to an initial single bunch current of 2.1 mA do we find that the losses drop below the amount of injected charge.

Applying transverse feedback is one potential way to limit the stored beam oscillations and subsequent filamentation. To assess whether this possibility might work in practice, we implemented `elegant`'s transverse feedback element `TFBPICKUP` with a 6-turn FIR filter. In the first trial run we allowed the feedback system to have unlimited

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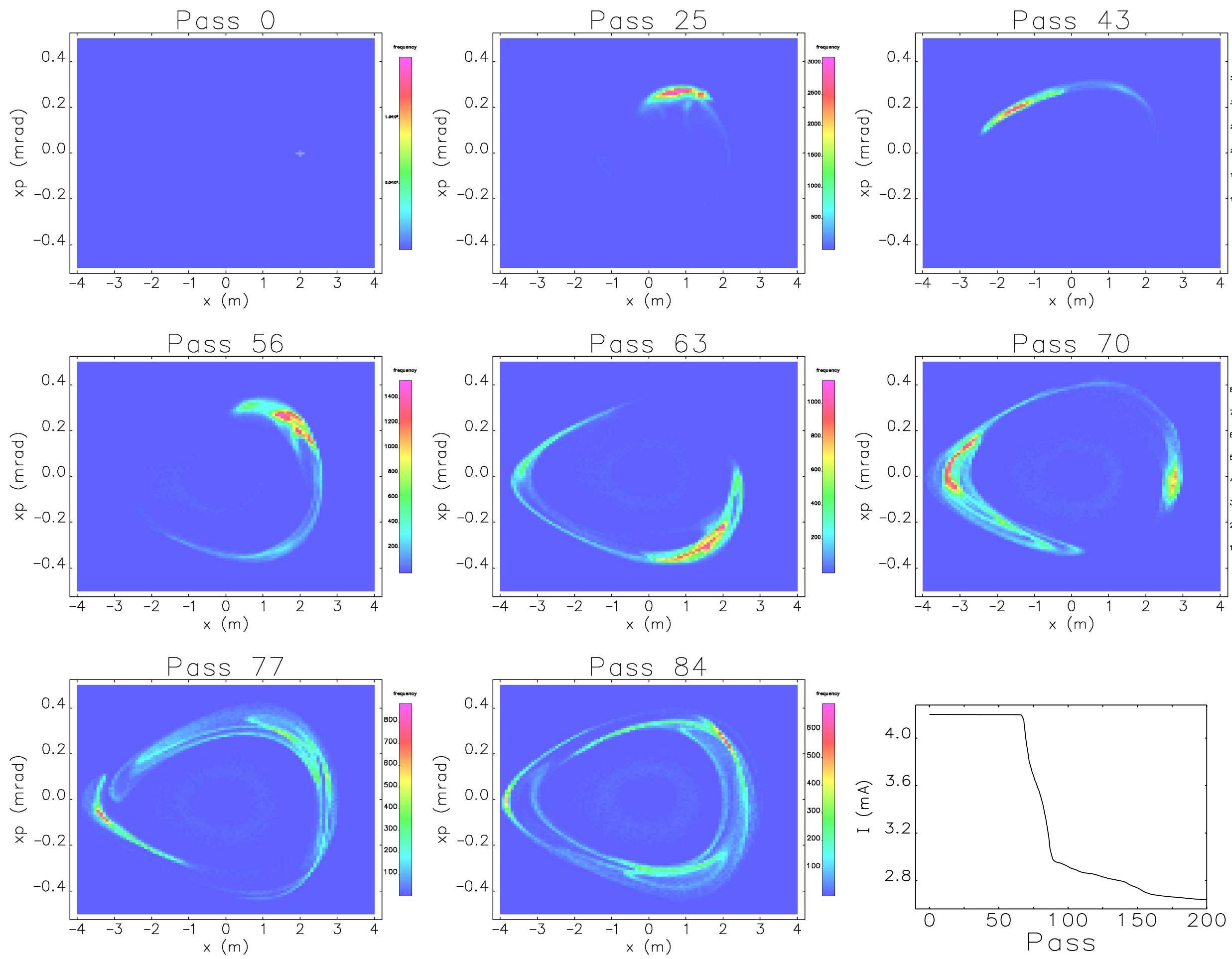

Figure 1: Horizontal phase space plots of the stored bunch after a top-up shot at Pass 0.

strength, and chose the gain to be approximately 0.3 of its ideal. Perhaps unsurprisingly, in this case the resulting feedback excites the injected bunch such that 30% to 40% of the injected charge is lost on the walls. Hence, not only is unlimited feedback unattainable, but it is also undesirable.

Next, we applied feedback of a more moderate (and perhaps realizable) strength. This amounted to setting a hard limit for the simulated feedback kick strength which, while somewhat idealized, should at least indicate whether any feedback level may eliminate losses during accumulation. We summarize the results of these simulations in Fig. 2, where we plot the difference between the injected and lost charge scaled by the injected charge as a function of the number of passes after top-up. Negative ratios, like those when the maximum feedback kick is less than 7 μrad, indicate that more charge is lost than was injected. In this case the feedback is too weak to damp the stored bunch oscillations before emittance growth and particle loss. On the other hand, when the feedback is too strong it kicks out a significant fraction of the injected charge. Interestingly, these simulations indicate that the feedback could have just the right strength to damp the stored oscillations while minimally disturbing the injected charge. Unfortunately, this

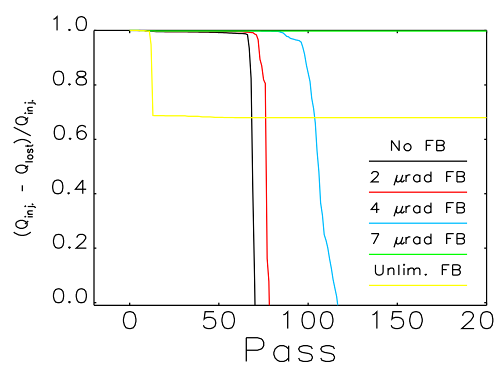

Figure 2: Injection losses as a function of pass for various maximum feedback strength limits during accumulation.

"Goldilocks zone" exists for feedback strengths that are several times higher than those planned for the APS-U. Furthermore, we expect that the details of this regime will depend on the way in which the feedback system "rails" to its maximum kick and on the noise characteristics of the system.

While stabilizing accumulation losses through feedback does not appear to be realistic for the APS-U when operated in its 48 bunch mode with narrow horizontal ID apertures, relaxing any of these constraints may enable accumulation. For example, we already mentioned that the 324 bunch mode does not appear to suffer any losses at all; including a modest feedback system should enable accumulation up to 2 mA. Alternatively, increasing the horizontal ID gap from ±4 mm may enable accumulation at full charge, but this would require assessing the role of errors in limiting the dynamic aperture.

COLLECTIVE EFFECTS FOR ON-AXIS INJECTION

We have shown that collective effects may play a large role for off-axis injection when the stored beam drives transverse wakefields that can lead to particle loss. While this is not surprising, we have also found that collective effects can be important during on-axis injection when the injected beam's longitudinal phase space is not matched to the lattice equilibrium [10]. In this case, oscillations in the peak current and bunch spectrum as the beam tumbles in the longitudinal potential can drive anomously large transverse wakefields. These transient wakefields can in turn drive transverse oscillations, emittance growth, and particle loss during the first few synchrotron periods after injection.

At the APS-U we expect the injected booster beam to have a Gaussian profile in both time and energy, with an rms duration of ~90 ps and rms normalized energy spread of 0.12%. On the other hand, at 4.2 mA the 67 pm lattice is predicted to have an rms duration and energy spread of 80 ps and 0.15 %, respectively. In addition, the MBA profiles are highly non-Gaussian due to both the 4$^{\text{th}}$ harmonic bunch lengthening rf system and longitudinal wakefields [11]. After injection, the longitudinally mismatched booster beam undergoes its most violent longitudinal oscillations within the first synchrotron oscillation (~ 420 turns). We show these temporal dynamics in Fig. 3(a). In particular, note how the current has a local peak after approximately one-half synchrotron period (turn 210).

The longitudinal oscillations lead to higher-harmonic content in the bunch spectrum and peaks in the local current which lead to large transverse wakefields. The wakefields drive bunch oscillations which in turn lead to emittance growth and beam size blow-up that we show in Fig. 3(b). For the red line with no feedback, the beam size increases sharply after one synchrotron oscillation, and charge is lost on the ID aperture. Fortunately, a modest feedback system can cure the instability. We show that adding a 6-turn FIR feedback system with a maximum amplitude of 1 μrad completely eliminates loss for lattices both with and without errors as the blue and black lines, respectively.

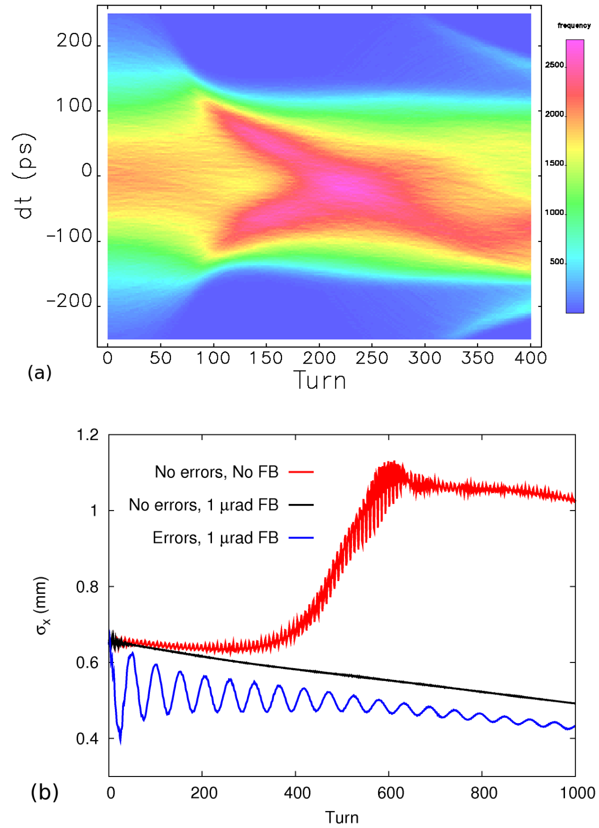

Figure 3: Injection losses due to transient wakefields during on-axis injection in the 67 pm lattice.

CONCLUSIONS

Collective effects can negatively impact the (effective) dynamic aperture at injection by blowing up the beam to amplitudes beyond those predicted with single particle tracking. The effects from wakefields can be particularly pronounced in MBA lattices due to their strong nonlinearities and small dynamic aperture. We have found that collective effects make accumulation at high charge very difficult for the 90 pm lattice, even though this lattice was designed to accomodate accumulation. While feedback may mitigate these injection losses, it requires a high gain with little noise, and does not appear feasible with the present design constraints.

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