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CONTROLLING TRANSIENT COLLECTIVE INSTABILITIES DURING SWAP-OUT INJECTION*

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Abstract

Previous work has shown that collective instabilities at injection may reduce injection efficiency even for on-axis injection as planned for the APS-Upgrade [1]. Stability at injection is governed by a number of factors, including phase-space mismatch between injected and stored bunch, strength of the impedance, degree of nonlinearities, and feedback. We find that the large tune-shift with amplitude of the most recent APS-U lattice largely tames the transient instability via Landau damping, and show that using octupoles to increase the nonlinear tune shift can stabilize the transient instability at injection that plagued a previously unstable lattice.

INTRODUCTION

Predicting and controlling collective instabilities is an important part of storage ring design. In addition to ensuring stability at equilibrium, it has also been found that non-equilibrium conditions during injection may lead to conditions that are uniquely susceptible to collective effects. Reference [2] showed several such effects, including one in which transient beam loading in passive rf cavities drove longitudinal instabilities while filling the ring from zero current, so that controlling such rf transients in a passive bunch-lengthening cavity such as is planned for the APS-U requires filling the ring in a balanced way and in multiple stages. Recently, we identified a transient transverse instability at injection that can lead to particle loss even for on-axis injection [1]; such phenomena must be considered when designing stabilizing feedback systems. In this paper we review this last transient transverse instability at the APS-U, and describe one way that it can be stabilized using the nonlinear betatron tune-shift provided by octupole magents.

THE TRANSIENT TRANSVERSE INSTABILITY

The APS-U storage ring is a seven-bend achromat based upon ESRF's hybrid design [3]. The APS-U lattice has been steadily improved over the last several years, including the addition of reverse bends to bring the equilibrium emittance down to 42 pm [4], and many iterations of MOGA optimization to improve lifetime and dynamic aperture. A few years ago we reported on a transient instability at injection that we observed in the lattice used for the preliminary design report (PDR). While the impedance model predicted that a bunch was stable to transverse instabilities up to a single-bunch current of 10 mA, simulations also showed a rather strong transverse instability during the injection of a 4.2 mA bunch. At that time we concluded that single-bunch, turn-by-turn feedback was necessary to avoid significant particle loss during injection into the planned 48-bunch mode.

Our studies of the transient instability at injection found that it depended upon several factors, including:

1. The strength of the transverse impedance.
2. The size of the initial transverse offset.
3. The longitudinal phase space mismatch between injected and stored beam.
4. Nonlinear resonances experienced by particles in the (relatively) large emittance injected beam.

The first two factors are relatively easy to understand, in that the collective transverse force is directly proportional to both the impedance and the transverse offset. The third point was further explained in Ref. [1] and can be summarized as follows: the longitudinal mismatch leads to "tumbling" in the rf bucket, which in turn gives rise to transient current spikes and anomalously high wakefields. In fact, we have found that the transverse feedback requirements can be relaxed somewhat by more closely matching the injected beam length and, importantly, energy spread, to that of the stored beam. Finally, simulations indicate that nonlinear resonances can exacerbate all these issues.

As progress on lattice modeling was refined and further optimization of the sextupole strengths continued, we discovered that not all variants of the 42-pm lattice were equally plagued by the transient instability at injection. In particular, we found that the lattice proposed in the final design report (FDR) eliminated the instability entirely. We discovered this using element-by-element tracking for a subset of 13 commissioned lattices, including the three errors sets with the worst dynamic aperture (DA), and one case randomly selected from each 10$^{\text{th}}$ percentile of DA. We found that the losses in every case was $< 0.1\%$ once the orbit was moved to within 200 microns of the injected beam (which simulates the expected transverse offset resulting from the accumulated injection system errors). Furthermore, we found that the instability was tamed and injection losses were low even if the assumed transverse impedance was doubled; the instability appeared when the impedance was increased by a factor of 2.25, while feedback improved this margin to about a factor of 3.

Because there appeared to be many contributing factors to the transient instability at injection, it was initially not clear why the final lattice was stable. After some work, we noticed that the stable, final lattice had a significantly larger tune-shift with amplitude, which we conjectured might

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Table 1: Injected and Equilibrium Beam Parameters Used in elegant Simulations

Name	Injected	Equilibrium
bunch length	100 ps	75 ps
energy spread	0.1%	0.135%
x-emittance	60 nm	32 pm
y-emittance	16 nm	32 pm
Charge	15.6 nC	15.6
Beta-functions	PDR: 4.9, 1.9 FDR: 5.2, 2.4	PDR: 4.9, 1.9 FDR: 5.2, 2.4

lead to larger Landau damping and increased stability. This hypothesis could also explain our rather surprising discovery that the instability in the PDR was actually made worse if we assumed a somewhat smaller emittance of the injected beam, since this case would also have a smaller tune shift over the bunch.

CONTROLLING THE TUNE SHIFT WITH OCTUPOLES

To test our hypothesis more carefully, we decided to add octupoles to the unstable PDR lattice. While previous work showed that octupoles did little to benefit either the dynamic aperture or the lifetime, we thought that the additional tune shift with amplitude might help stabilize the transient instability at injection. Indeed, the Large Hadron Collider has what they refer to as “Landau octupoles” to improve equilibrium transverse stability via Landau damping in a similar manner (see, e.g., [5, 6]).

The simulations employ the code elegant [7] to track particles through the initial 4000 passes after injection. We use element-by-element tracking including synchrotron emission to account for all nonlinear resonances and radiation damping. The results presented here model the main and passive harmonic rf cavities as active systems with no beam loading, although other simulations have indicated that including self-consistent cavities in our case improves stability. Additionally, we apply the collective effects with a distributed set of impedance elements located at all 14 BPMs and at the center of the ID straight in each of the 40 sectors. Finally, we include the effects of errors in the injector chain as an initial 200 micron offset in both x and y. Other parameters of the injected and equilibrium beam are collected in Table 1.

We will present simulation results of the injection process for four separate cases: the first is the unstable PDR lattice, the next two are the PDR lattice including 4 thin-lens octupoles per sector, and the fourth is the stable FDR lattice. The octupoles strengths and placement were based on a previous lattice designed for accumulation [8]; here we denote the octupoles as “weak” when their integrated strength was 10% that of the previous lattice ($|K_3L| \leq 140$ m^{-3}), while for the other case $|K_3L| \leq 650$ m^{-3}.

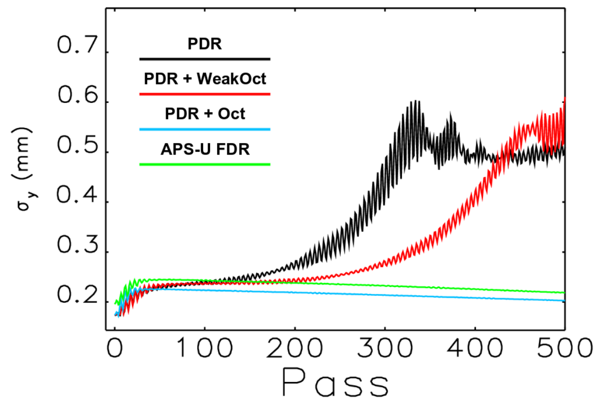

Figure 1: Vertical beam size after injection for the PDR lattice (black), the PDR lattice including weak octupoles (red), the PDR with stronger octupoles (blue), and the FDR lattice (green). The first two cases suffer signifcant particle loss, while the other two are stable.

We summarize the stability results by plotting the observed vertical beam size as a function of pass after injection in Fig. 1. We see that for the PDR lattice (black line), the beam size quickly grows to an rms value ~ 0.5 mm at pass 210, where particles are lost on the small ID chamber walls. The instability growth rate is reduced somewhat by adding weak sextupoles (red), such that particles are lost after about 450 passes. In both of these cases the beam size increase is due to coherent dipole oscillations in the vertical plane driven by collective effects. On the other hand, adding stronger octupoles effectively stabilizes the PDR lattice (blue), and the behavior is very similar to that of the FDR lattice in green.

We can understand the effect of the octupoles further by considering the associated tune-shift with amplitude of each case plotted in Fig. 1. We show this in Fig. 2, where we have chosen the range in x and y to be $2\sigma_x \times 2\sigma_y$, so that each panel contains 70% of the injected beam particles. Additionally, we have weighted the tune shift $\Delta\nu_y$ with the local particle density in 1/mm^2 to encapsulate both the magnitude and number of particles with a given $\Delta\nu_y$; the mean absolute deviation of the tune-shift over the bunch can be found by summing the absolute value of what is plotted.

Figure 2 shows that while adding weak octupoles in panel (b) does change the general behavior of the tune-shift with amplitude from (a), it does not result in a noticeable increase in the magnitude of the rms tune-shift over the bunch. Increasing the octupole strength as in (c) does have a significant effect, with the tune difference over the panel more than doubling. Finally, the stable FDR lattice in panel (d) has a significantly larger tune shift over the region shown, resulting in increased phase mixing and suppression of the coherent instability.

CONCLUSIONS

We found that stability at injection of multi-bend achromats depends in part upon the nonlinear tune-shift with amplitude over the (comparatively) large emittance injected

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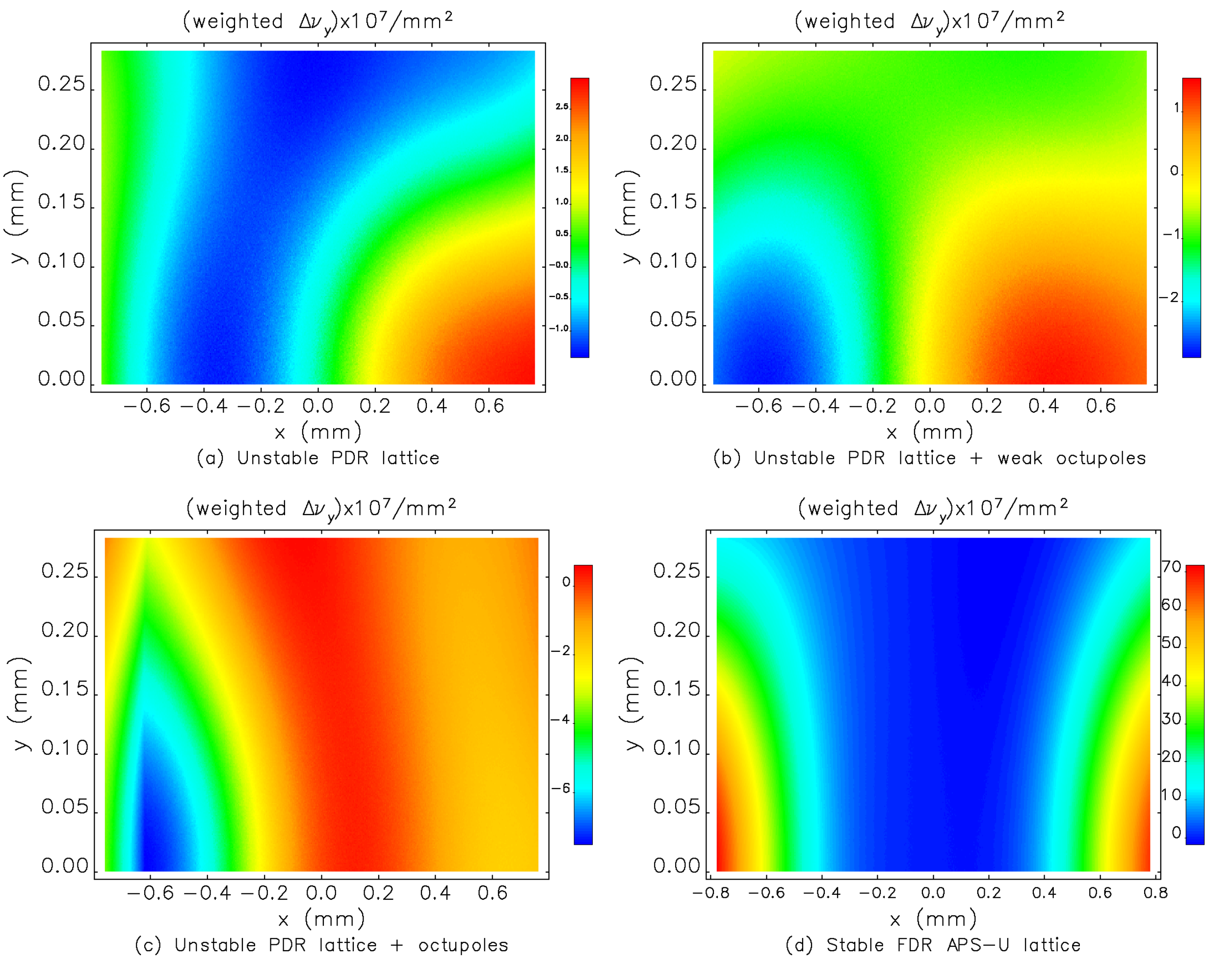

Figure 2: Vertical tune shift weighted by the local particle density in 1/mm^2. The spread in weighted $\Delta\nu_y$ for the two unstable cases in (a) and (b) are comparable, and noticeably smaller than that of the PDR lattice with stabilizing octupoles in panel (c). The stable FDR lattice has a significantly larger tune shift as shown in (d).

beam. While the present APS-U lattice has sufficient tune-shift with amplitude to be stable, we showed that stability can be improved in unstable systems by adding octupole magnets to increase the tune-shift with amplitude.

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