BEAM LOADING MEASUREMENT AND ITS APPLICATION TO THE HARMONIC RF CONTROL OF THE APS PAR*

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Abstract

The Advanced Photon Source (APS) particle accumulator ring (PAR) has dual rf systems: a CW-mode fundamental rf system (RF1) operating at 9.77 MHz that accumulates multiple linac pulses into a 0.8-ns bunch, and a 12th harmonic rf (RF12) that compresses the bunch length further to 0.34 ns for injection into the booster. The RF12 capture process is critical for optimal performance of the PAR. We investigated the effects of beam loading during the RF12 capture and bunch length compression processes with both spectrum analysis and streak camera imaging. Based on these observations, a new timing scheme for the RF12 tuner and power control was implemented, which has substantially improved the performance of the PAR. We report our observation, the new timing scheme, and beam parameters after optimization.

INTRODUCTION

The Advanced Photon Source (APS) particle accumulator ring (PAR) has dual rf systems: a CW-mode fundamental rf system that accumulates multiple linac pulses into single bunches and a 12th harmonic rf system that compresses the bunch length further for injection into the booster. Ferrite-type electrical tuners are implemented on both rf systems. The fundamental cavity has a CW-mode tuner while the RF12 cavity has a pulsed tuner. The beam capture process by RF12 is critical for optimized bunch length and bunch purity. Beam centroid oscillations and satellite formation have been observed, which have impacted beam quality in the injector system. For this reason we investigated the effect of beam loading on the harmonic beam capture process.

Beam loading in rf cavities of accelerators has been investigated and reported by many authors [1, 2]. In the PAR the beam loading effect is relatively strong due to its low beam energy (currently at 325 MeV) and high single-bunch charge of up to 6 nC. We used both synchrotron spectrum analysis and streak camera imaging to observe beam parameter changes due to beam loading in the PAR. Based on these observations, a new timing scheme was implemented, which substantially improved PAR beam performance and consistency. This report describes the experimental observations, the new timing, and optimized beam parameters.

SYNCHROTRON TUNE OBSERVATIONS

In order to observe beam loading the PAR was in continuous injection/extraction mode with about 2.5 to 3.5 nC of beam charge. An HP vector spectrum analyzer (VSA) was connected to the field probe of the PAR RF12 cavity. The power of RF12 was turned off, but the tuner was on and varied so that RF12 cavity tuning changed from negative detuning to positive detuning. Figure 1 is a plot of the synchrotron spectra acquired 100 ms after the tuner pulse was turned on, for a series of values of the tuner currents. The stronger peaks in the plot are, in fact, the second sidebands of the synchrotron tune. It is obvious that the synchrotron tune shifted to higher values as the cavity was moved from the fully detuned state toward its resonance. The synchrotron frequency increased to a maximum of 29.5 kHz at a tuner current of about 17.6 A, and then moved downward before reaching a region where beam centroid oscillations became unstable, presumably due to Robinson instability.

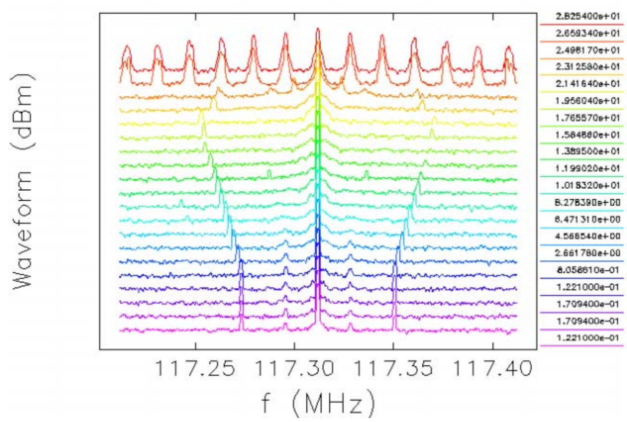

Figure 1: PAR synchrotron spectra vs. tuner current. Tuner currents are shown in the legend in units of Ampere. The cavity resonance frequency increases with tuner current. The spectrum waveforms are staggered vertically with 20-dBm spacing.

STREAK CAMERA IMAGING OF BUNCH PHASE AND BUNCH LENGTH

To further investigate the effect of beam loading, streak camera imaging was also employed to observe changes of the bunch centroid phase and bunch length during harmonic beam capture. Figure 2 shows the streak camera images of the beam centroid for different tuner currents with no harmonic rf drive.

The bunch centroid shifted early in time after application of the tuner current. This was due to energy loss to the harmonic cavity. This energy loss was compensated for by the beam shifting its phase early so more energy was taken from the fundamental rf cavity. The amount of time or phase shift gives an estimate of the

* Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

amount of power the beam loses to the harmonic cavity. The measured gap voltage is around 4 to 6 kV.

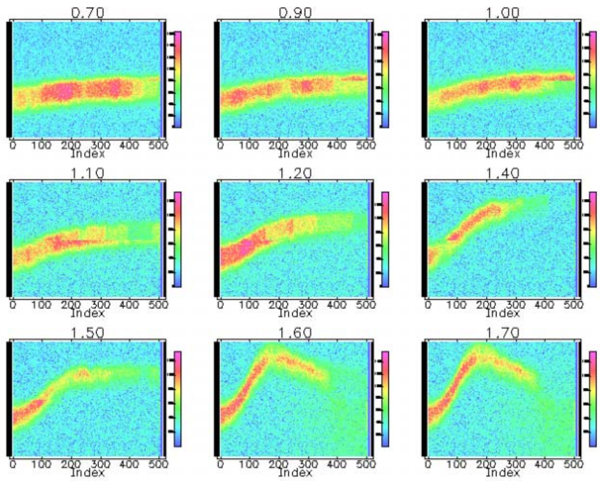

Figure 2: Streak camera images of bunch longitudinal position. The number on each plot is the tuner setpoint. The vertical range is 10 ns and horizontal is 50 ms for each subframe.

Figure 3 exhibits images showing beam phase change when RF12 is operated with both power and tuner on in the standard timing configuration. In this timing configuration, shown in Figure 4, the RF12 power is applied 15 ms ahead of the tuner current ramp. The beam centroid shifts earlier or later depending on whether a beam energy gain or loss to the harmonic cavity is produced during the process of the harmonic rf ramp. After the ramping, the beam centroid returns to its synchronous phase as defined by the settings of both the fundamental and harmonic rf systems.

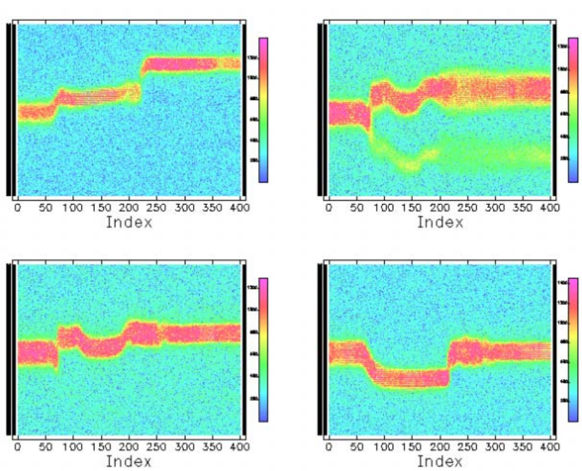

Figure 3: Streak camera images of beam longitudinal position. In one case there is a satellite formation. Top is later in time. Vertical range is 20 ns and horizontal is 25 ms for each subframe.

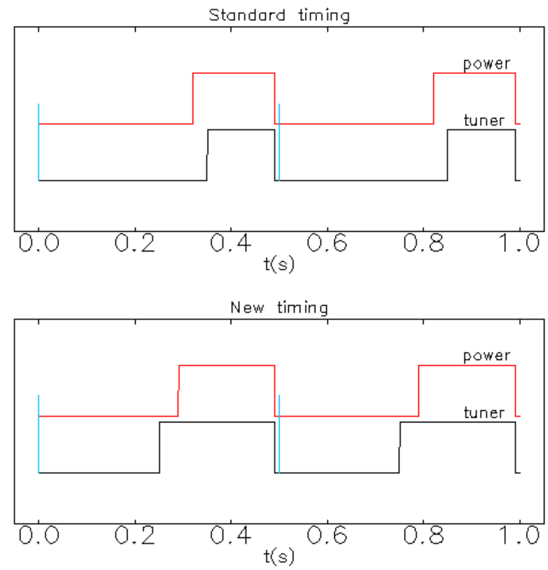

Figure 4: Ramping waveform of rf power and tuner current for standard timing and new timing with two PAR cycles. The vertical lines on the plot represent injection time.

NEW TIMING FOR HARMONIC RF CONTROL

With the standard timing, the harmonic rf power is applied first and the tuner current is applied later. Beam-induced gap voltage in the harmonic cavity grows together with the gap voltage driven by the amplifiers. The combined rf phase during the harmonic capture depends on beam-induced gap voltage, drive phase, drive power, and the character of rf control loops. Due to this complexity, the beam behaves differently from run to run. This also makes it difficult to maintain injector bunch purity.

Figure 5 is a plot of simulated gap voltage produced by beam loading in a passive harmonic rf cavity, simulated with the program elegant [3]. It shows that beam-induced rf voltage can be as high as 7 kV, which is sufficient to achieve self-bunching and harmonic capture. The simulation also shows that after being compressed and captured into harmonic buckets, the beam is very stable and does not jump buckets due to phase glitches during harmonic power ramp.

Based on these observations, we implemented a new timing configuration in which the application of rf power is delayed until 40 ms after the ramping of the tuner current, as shown in Figure 4. Under the new timing, the beam goes through a self-bunching process and settles into an RF12 bucket with a fixed phase relative to the fundamental rf. The bunch length decreases due to the self-bunching process. The rf power is then applied. Optimization is realized by adjusting the cavity tuning current, ramping rate, and phase of the harmonic rf system. The new timing scheme was implemented in March of 2005. PAR efficiency and beam stability showed obvious improvement after the change. With the new timing the PAR injection efficiency increased from 80% to about 100% with up to 4.5 nC of charge.

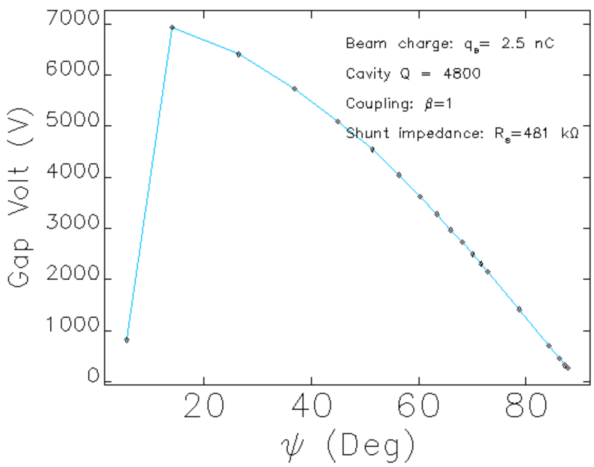

Figure 5: Simulated harmonic rf gap voltage due to beam loading.

BUNCH LENGTH AND BUNCH PURITY OPTIMIZATION

Beam optimization was performed as part of the effort to improve the bunch compression and injector bunch purity. Figure 6 shows streak camera bunch length measurement results. We found three different rf phase settings for which beam was well compressed and stable, but each had different characters. We selected the setting with a relatively longer bunch that did not produce later-side satellites, which is beneficial for user experiments. We are working to improve the harmonic phase control loop so that shorter bunch lengths can be achieved without sacrificing injector bunch purity.

During normal operation, a workstation-based tuner feedforward program runs continuously, which adjusts the harmonic rf tuner setpoint and fundamental rf phase based on the current reading of the incoming injection beam. We plan to implement this program in the new tuner and phase-control loops.

CONCLUSION

The effects of beam loading of the harmonic rf cavity were investigated both by tune spectra and streak camera imaging techniques. The results led to the implementation of a new timing scheme for the harmonic rf system, which utilizes beam self-bunching and has improved the injection efficiency. Further optimization of rf phases was performed, which produced a configuration with better beam stability and bunch purity.

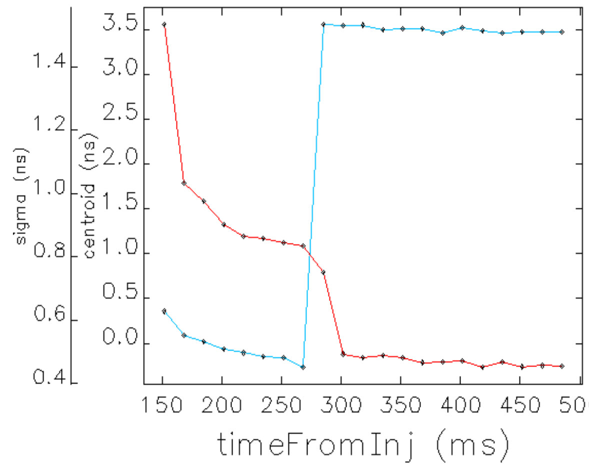

Figure 6: Bunch length measurement results. The red trace is bunch length, while the blue trace is the beam centroid.

ACKNOWLEDGEMENTS

The authors would like to thank Y. Chae, M. Borland, N. Sereno, F. Lenkszus, and A. Nassiri for many discussions and consultations.

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