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Beam Loading Effects in the APS Booster*

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Abstract. Beam loading of the radio-frequency (rf) accelerating cavities is an important consideration in the design and operation of high-current circular particle accelerators and storage rings. The steady-state and transient perturbations of the rf cavity system by the circulating beam can be harmful to the beam and limit the accelerator performance. Transient beam loading effects have been observed soon after injection of the beam into the booster synchrotron of the Advanced Photon Source (APS). Data are presented quantifying the responses of both the beam and the rf cavities to beam loading under various conditions. A preliminary discussion addresses the compensation of these beam loading effects.

INTRODUCTION

The booster synchrotron is the final acceleration stage of the injector system for the storage ring of the Advanced Photon Source (APS). Positrons or electrons are first accelerated in the linac to a design energy of 450 MeV and then accumulated in the positron accumulator ring (PAR). The typical linac energy presently used is 400 MeV. The beam is transferred in a single shot from the PAR to the booster, where it is accelerated to 7 GeV in a single bunch and then transferred to the storage ring. The storage ring is filled to the desired current at the 2-Hz repetition rate of the booster ramp. The main parameters of the booster are listed in Table 1 [1,2].

The booster rf accelerating cavities provide the energy gain from 400 MeV to 7 GeV while also resupplying the energy lost to synchrotron radiation, which increases as the fourth power of the beam energy. There are two sets of two, five-cell 351.9-MHz rf cavities on opposite sides of the ring, one set near beam injection and one set near extraction. All four cavities are driven by a single 1-MW klystron rf source. The total rf gap voltage varies significantly over the acceleration ramp, from less than 1 MV at the beginning to about 10 MV at the end [2]. The rf voltage at the beginning of the ramp is adjusted to achieve high capture efficiency of the PAR bunch. The value of the rf voltage at the end of the ramp is determined primarily by compensation of the radiation losses. The values at 7 GeV are listed in Table 1. The time for the particles to travel once around the ring, or one turn, is

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1.2 μs. The rf cavities, beam transfer lines, and other elements are shown in a schematic of the booster ring in Figure 1.

TABLE 1. APS Booster Parameters

Circumference	368	m
Design Injection Energy	450	MeV
Extraction Energy	7.0	GeV
Ramp Repetition Rate	2	Hz
Acceleration Ramp Length	230	ms
Harmonic number	432	-
Rf Frequency	351.9	MHz
Energy Gain/turn	35	keV
Energy Loss/turn, at 7 GeV	6.4	MeV
Rf Gap Voltage, at 7 GeV	10.4	MV
Synchrotron Frequency, at 7 GeV	21	kHz
Nominal Charge per Ramp Cycle	5.8	nC
Maximum Achieved Charge per Cycle	3.5	nC

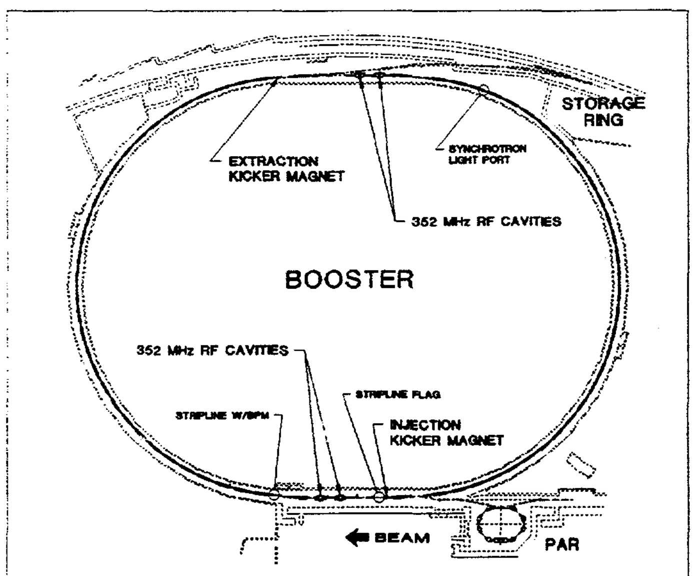

FIGURE 1. Schematic of Booster Ring.

BEAM LOADING

Beam loading is one of several current-dependent effects that arise as a result of the interactions between the electromagnetic fields generated by the beam and its surroundings. These interactions can potentially lead to unstable beam motion and/or beam loss. Beam loading involves beam-induced perturbations of the rf cavity system which in turn affect the beam. There is typically a threshold current above which these effects become important unless properly compensated. Beam loading effects in the booster can sometimes cause partial or total loss of the beam. Typically, the charge is limited to about 1 nC to simplify rf operation and maintain high capture efficiency. The extracted booster charge affects the filling time of the storage ring, while cycle-to-cycle fluctuations affect the uniformity of the fill. The focus of this work was to experimentally measure and characterize the beam loading effects in order to help design a beam loading compensation scheme, which is well understood in principle [3], and enable higher-charge operation in the future.

SYNCHROTRON TUNE MEASUREMENTS

The rf system must provide phase stability of the motion so that the particles, which have a spread in energies, remain bunched. The frequency of the motion of off-energy particles around the stable rf phase is known as the synchrotron frequency, f_s. Measuring f_s as a function of the beam energy gives a measure of the total gap voltage during the course of the ramp cycle. The synchrotron frequency can be measured by deliberately kicking the beam, if necessary, and measuring the resulting longitudinal oscillations using a stripline beam pickup. The location of the striplines are shown in Figure 1.

A spontaneous (unkicked) f_s signal can be seen over almost the entire ramp in the booster in a spectrograph display using the HP 89440A Vector Signal Analyzer, shown in Figure 2a. Higher intensity is at the left in the scale under the display. The strong signal is evidence of longitudinal oscillations of the bunch as a whole. Higher harmonics of the synchrotron frequency are also evident. Although these could be indicative of bunch shape fluctuations, they are possibly due to saturation of the detector electronics. A most unusual feature is the split in the synchrotron frequency. The explanation for this is more clear in the streak camera measurements described next. The total gap voltage calculated from the measured f_s is plotted in Figure 2b and the solid line is in good agreement with the expected values. The dotted line in the figure corresponds to the lower measured value of f_s.

STREAK CAMERA MEASUREMENTS

The streak camera records the synchrotron light emitted by the particles in the bunch, the intensity of which is proportional to the particle density. The location of the light port is shown in Figure 1. A striking streak camera image of the bunch length distribution as a function of time during periods of significant beam loading is shown in Figure 3a. The horizontal time scale is 100 ms during the ramp and the vertical scale is 1.5 ns along the length of the bunch. A bunch length "blowup" occurs at roughly the same time in the ramp as the split in the synchrotron frequency. The highest charge density is near the center of the bunch (lighter grey),

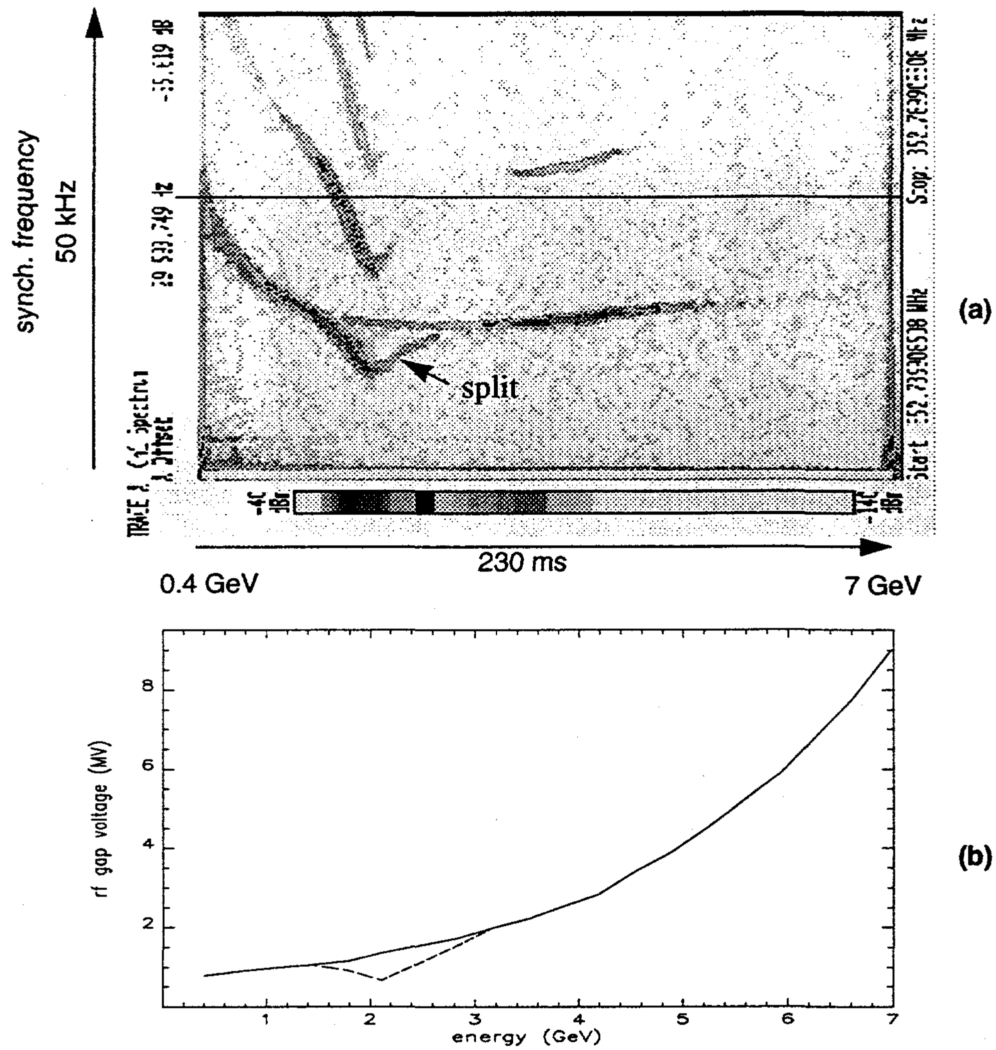

FIGURE 2. Measured synchrotron frequency (a) and calculated rf gap voltage (b) vs. energy in the booster. The bunch charge is 1.3 nC.

while the blowup involves less charge (darker grey.) The image suggests a main bunch with a satellite bunch that is oscillating with growing amplitude. The fluctuations are later damped naturally by the synchrotron radiation loss. Beam is lost, however, when the amplitude becomes very large.

Severely detuning the rf cavities had the desired result of eliminating the blowup. The streak image for this severely detuned condition is shown in Figure 3b. The split in f_s also disappeared (not shown). We could achieve this by detuning either the injection side rf cavities to nearly 50% reflected power or all cavities to about 25% reflected power. Unfortunately, this is not a permanent solution because at present, the rf cavities cannot be retuned automatically after the beam loading effects become negligible at high energies. Increasing the rf gap voltage at injection also reduced the splitting in f_s, but this decreases the injection efficiency.

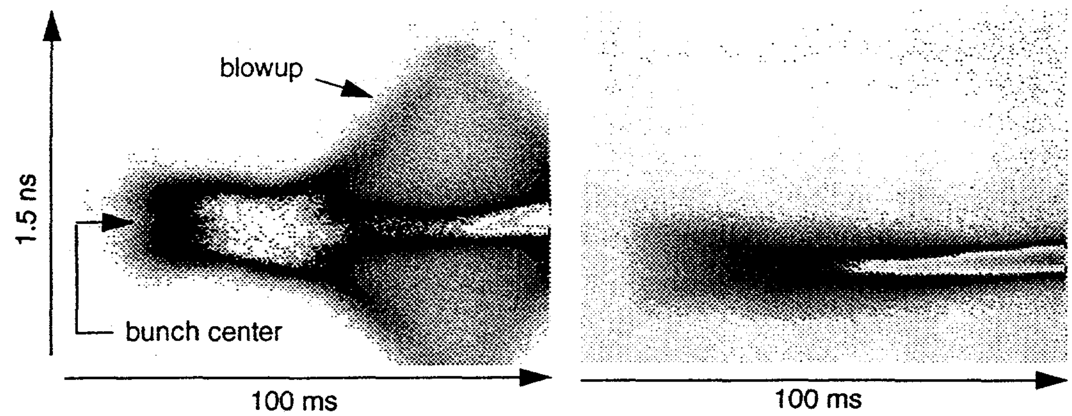

FIGURE 3. Streak camera image of the longitudinal bunch distribution (vertical) vs. time during a beam loading episode (a) and after the initial beam loading is compensated (b). Beam is injected at left. The bunch charge is about 1.5 nC.

DISCUSSION

The maximum charge in the booster appears to be presently limited by rf beam loading effects. Above about 1 nC, the bunch has been seen to blow up longitudinally about 30 ms into the acceleration ramp (about 1.5 GeV energy.) This is accompanied by a split in the measured synchrotron frequency. Preliminary studies show that compensation of beam loading by detuning the rf cavities largely eliminates the beam blowup. Increasing the rf voltage at injection also reduces the blowup. The splitting of the bunch appears to be more complex than that simply due to transient beam loading on injection. The character of the blowup has been seen to vary. However, the blowup may be affected by initial beam loading effects.

At this time there is only speculation as to why the beam splits into two stable bunches. One explanation is that the splitting is due to a higher-order mode (HOM) being driven by the beam. Detuning the cavities may simply push the mode out of resonance with a revolution harmonic of the beam. This can be tested by observing the bunch after varying the cavity temperatures to shift the HOMs and tuning the rf cavities onto resonance. The dependence of the beam blowup on the initial conditions, such as the bunch length, rf voltage, and rf feedback parameters is to be studied further. These data will be used to design a dedicated compensation scheme.

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