200-mA STUDIES IN THE APS STORAGE RING*

K. Harkay#, Y.-C. Chae, L. Emery, L. Morrison, A. Nassiri, and G. Waldschmidt,
ANL, Argonne, IL 60439, U.S.A.

Abstract

The Advanced Photon Source (APS) storage ring is normally operated with 100 mA of beam current. A number of high-current studies were carried out to determine the multibunch instability limits. The longitudinal multibunch instability is dominated by the rf cavity higher-order modes (HOMs), and the coupled-bunch instability (CBI) threshold is bunch-pattern dependent. We can stably store 200 mA with 324 bunches, and the CBI threshold is 245 mA. With 24 bunches, several components are approaching temperature limits above 160 mA, including the HOM dampers. We do not see any CBI at this current. The transverse multibunch instabilities are most likely driven by the resistive wall impedance; there is little evidence that the dipole HOMs contribute. Presently, we rely on the chromaticity to stabilize the transverse multibunch instabilities. When we stored beam up to 245 mA, we used high chromaticity and the beam was transversely stable. The stabilizing chromaticity was studied as a function of current. We can use these experimental results to predict multibunch instability thresholds for various upgrade options, such as smaller-gap or longer ID chambers and the associated increased impedance.

INTRODUCTION

The normal APS operating current is 100 mA. Thermal limitations in the x-ray beamline optics, the monochromator in particular, introduce an important constraint on the maximum operating current. However, it is anticipated that some beamlines will be ready to use higher beam current in the future, possibly up to 200 mA (the APS design value is 300 mA). For this reason, the high-current threshold in the ring has been explored in machine studies. The goal of the studies is to identify storage ring components whose impedances drive collective instabilities, else are subjected to excessive beam-driven HOM heating. One can next identify cures to raise the threshold.

For normal, 100-mA operation, two 1.1-MW, 351.93-MHz klystrons drive the 16 rf cavities. To store more than 150 mA in the APS, up to four klystrons are required and are operated in a parallel configuration [1]. We studied high-current operation in the standard 24-bunch mode and in the special operation mode of 324 bunches, both of which have uniform bunch current and bunch spacing. The maximum stable total current for these modes is summarized in Table 1. We did not measure the thresholds for the hybrid mode and 1296-bunch patterns (for a complete description of the operating modes, see [2]).

For the high-current studies, we used the high chromaticity of the hybrid mode: ~10 units in each plane. At the current limit, the beam was transversely stable. The high-current thresholds are dominated by longitudinal effects, either rf-cavity longitudinal HOM-driven CBIs or heating by longitudinal wakefields in the case of the vertical scraper chamber.

Table 1: Maximum Stable Total Current for Two Operating Modes (HOM dampers installed, high chromaticity)

Operating mode (# bunches)	I limit (mA)	Limitation at max I	Date
24	164	Heating [1]	Apr. 2006
324	245	CBI (long.)	Aug. 2005

[1] Vertical scraper chamber, rf coupler, and sector 38 rf cavity HOM dampers

A number of improvements have already been implemented to address heating and/or impedance issues, namely, redesign of the ceramic injection kicker magnet chambers [3] and installation of HOM dampers in the rf cavities [4]. After a brief summary of these past improvements, we report on the present high-current limits with these improvements in place.

PAST IMPROVEMENTS

Ceramic Kicker Vacuum Chambers

The four pulsed injection kickers are mounted over ceramic vacuum chambers. With high-bunch currents like the 24-bunch mode, elevated temperatures were measured on the flanges, vacuum chambers, and attached bellows. The resistive coating was found to be inadequate or damaged, resulting in heating effects that are proportional to the square of the bunch current [5]. Improvements in the design included improving the rf finger contact and metalizing the inner surface with moly-manganese to a thickness of ~10 μm [3]. The improvement can be seen in Fig. 1, showing 324-bunch operation followed by 24-bunch operation before and after the redesign. The plot on the left includes blowers and water cooling of the flanges.

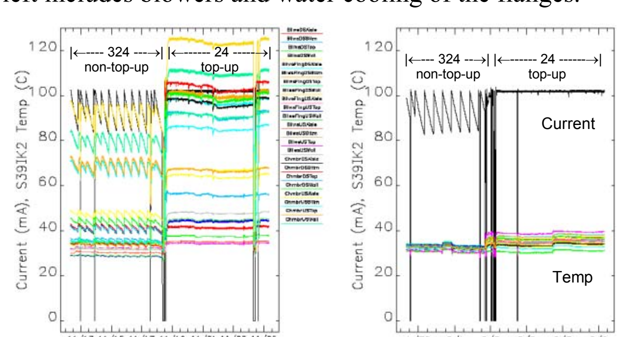

Figure 1: Kicker chamber temperatures before (left) and after (right) redesign (two-week period each, 100 mA).

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#harkay@aps.anl.gov

HOM Dampers

Rf cavity HOMs have been long known to potentially drive longitudinal CBIs in the APS [6,7]. The instability threshold is strongly bunch-pattern dependent [8]. In 24-bunch operation, the lowest monopole 540-MHz HOM was found to drive a CBI at a threshold of about 85 mA. The peak HOM amplitude in the worst cavity was –40 dBm at a frequency of 536.76 MHz (Fig. 2). This frequency corresponds to a coupled-bunch mode (CBM) number of 16, consistent with the observed unstable beam spectrum. A second cavity in the same sector exhibits a spectral peak near the same mode. The beam was stabilized for 100-mA operation through a combination of detuning the offending cavities and adjusting the cooling water temperature, standard methods to shift the HOM frequency by changing the cavity volume. Over time, however, it became more and more difficult to find stable operating points for the cavities. HOM dampers were designed and installed on all four cavities in sector 38 to damp the 540-MHz mode [4]. In the final configuration, the deQing factor is about 8.

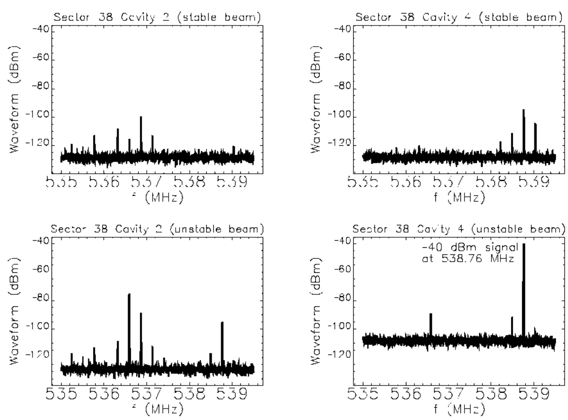

Figure 2: HOM spectra for cavities 2 and 4 in sector 38 for stable (top) and unstable (bottom) conditions (24 bunches, 100 mA) prior to installation of the dampers.

LONGITUDINAL LIMITS

We can stably store 164 mA in 24 bunches. No CBIs are observed up to this current, so we conclude that the HOM dampers have raised the threshold by at least 60%. However, several storage ring components are approaching temperature limits above ~160 mA (Table 1 and Fig. 3). The vertical scraper temperature is shown in red. The green and blue curves show the power absorbed by the sector 38 cavity 3 and cavity 4 dampers, respectively. The sector 37 cavity 4 coupler downstream/upstream temperatures (turquoise/magenta) show a large differential of almost 50°C in high-current operation. The heating issues need to be analyzed and mitigated before we can consider 200-mA operation in this bunch pattern.

With 324 bunches, the beam is stable up to a CBI threshold of ~245 mA. The longitudinal CBM spectra for unstable beam are shown in Fig. 4. The dominant mode numbers, in decreasing strength, are 36, 78, and 151. The computed CBM frequencies are nearest the measured monopole cavity modes near 538 MHz, 1211 MHz, and 915 MHz. When the beam is unstable, the cavities in sectors 38 and 36 show relatively strong HOM signals, and thus make good targets for future HOM dampers.

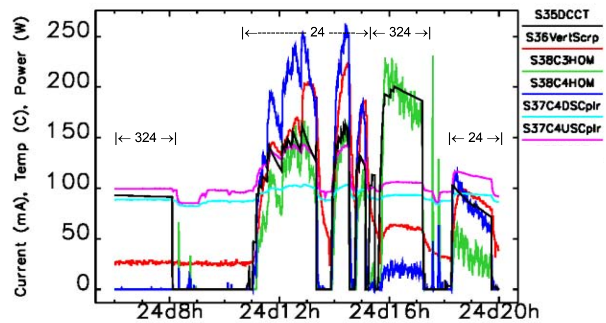

Figure 3: Temperature excursions for high-current studies.

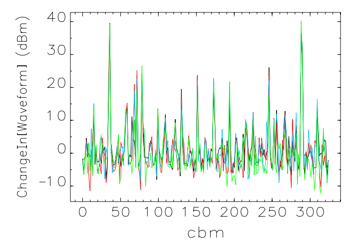

Figure 4: Dominant longitudinal CBMs for unstable beam, 324 bunches, 100 mA (8.5 MV rf voltage).

Scraper Chamber Heating

Two double-bladed vertical scrapers and three single-bladed horizontal scrapers are installed in the APS. One horizontal scraper is left inserted during operation to help localize beam losses [9]. The blades of all the other scrapers are retracted to the parked position. Simulations show that the transverse force exerted on the beam by wakefields induced by the vertical scraper is small compared to other components [10], but the energy lost by the beam due to the longitudinal wake could result in a serious heat-load problem. In high-current operation, a temperature rise of ~200°C is observed (red curve in Fig. 3) and is considered serious. Preliminary work has begun for a new mechanical design that mitigates the heating effects.

A HOM pickup is installed on one of the horizontal scrapers. The HOM spectrum is plotted in Fig. 5, showing about five relatively high-Q peaks. A comparison of these HOMs with the modeled impedance is planned.

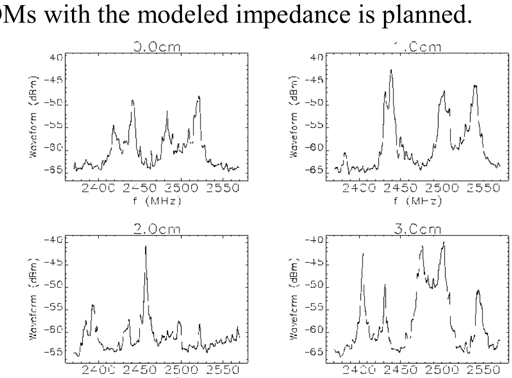

Figure 5: Horizontal scraper HOMs vs. inserted position.

TRANSVERSE LIMITS

The transverse multibunch instabilities are driven by long-range wakefields such as the resistive-wall (RW) impedance. There is little evidence that the rf cavity dipole HOMs contribute to the instabilities observed in the APS [11], despite predictions of low transverse CBI thresholds [7] (i.e., no HOM signals are seen and cavity detuning does not consistently stabilize or destabilize the beam). Similar observations are reported at ESRF [12].

Presently, we rely on the chromaticity to stabilize the transverse multibunch instabilities at 100 mA [11]. When we stored beam up to 200 or 245 mA, we used high chromaticity, about 10 units in each plane. The beam remained transversely stable for 324 and 24 bunches up to the longitudinal current limits in Table 1. We performed a scan of current and chromaticity for 24 bunches, starting with 100 mA and chromaticities of (7,6) in the (x,y) planes. At 127 mA, a net increase of (1,1.5) was required for stability. At 140 mA, a net increase of (1.5,1.5) was required; i.e., a ~20% increase in the chromaticity for a 40% increase in the current. Using this rough scaling, increasing the total current by a factor of two (to 200 mA) should require a 50% increase in the chromaticities, giving (~10.5,~9). This estimate is rather consistent with the experiment. Continued studies are planned.

In the APS, the insertion device (ID) chambers dominate the RW impedance. The horizontal and vertical multibunch instability thresholds are comparable (horizontal is actually slightly higher), which implies that the impedance is also comparable. Intuitively, one might assume that the vertical RW impedance is orders of magnitude larger than the horizontal due to the 1:2 – 1:5 aspect ratio and inverse cubic dependence on the chamber radius. However, as shown in Fig. 6, the ID chamber is virtually open horizontally on one side. The result is a highly noncircular geometry with strong dipolar and quadrupolar wakes [13]. We plan to quantify and model this wakefield for instability analysis and comparison with the experimental results.

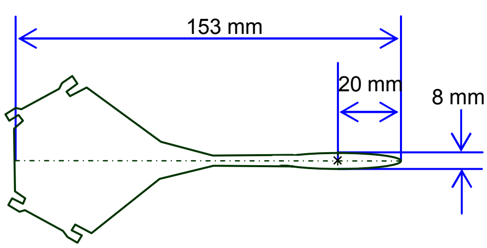

Figure 6: Cross-section schematic, 8-mm ID chamber.

SUMMARY

The high-current limits are being studied for standard operational bunch patterns in the APS storage ring. In the 324-bunch mode (every 4th rf bucket is filled), we can achieve ~245 mA. Above this limit, a longitudinal coupled-bunch instability is observed, driven by rf cavity HOMs. It may be possible to raise the threshold using the standard tactic of shifting the HOMs by detuning the cavity and/or changing the cavity temperature. In the 24-bunch mode (every 54th rf bucket is filled), we can achieve ~160 mA, which is 60% higher than without HOM dampers. This threshold is defined not by collective beam dynamics, but rather by ohmic heating of ring components, namely, the vertical scraper chamber, the rf coupler, and the HOM dampers. The redesigned ceramic kicker chamber temperatures stayed below their limits but continue to be monitored at high current.

The vertical scraper chamber needs to be redesigned to minimize the longitudinal impedance (more smooth transitions). It is likely that the coupler simply needs conditioning. The HOM damper also likely needs to be redesigned to overcome heating limitations. A preliminary design in which the lossy ceramic body is replaced by a water-cooled external load is being investigated.

We found that transverse instabilities do not limit the total current when high chromaticity is used. The threshold dependence on current and bunch pattern above 100 mA has not been fully characterized and is planned. High chromaticity will also impact beam lifetime; this also has not yet been characterized for high current. With these experimental results and further analysis of the impedances, we can estimate intensity limits for future ring upgrades.

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