Measurements of the APS Storage Ring Beam Stability at 225 mA*

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Abstract. The Advanced Photon Source (APS) is a third-generation hard x-ray user facility that operates nominally at 100-mA stored beam current. As part of our probing of future operation regimes we have run at 130 mA for a user run, and we are on the path to test operations at up to 300 mA. Our most recent experiments have been at 225 mA in December 2003. One sector in the ring is dedicated to diagnosing the electron beam transverse and longitudinal parameters. We use a combination of imaging tools, including an x-ray pinhole camera and optical streak camera for the bending magnet source and x-ray monochromator measurements of divergence on the insertion device source. The onset of longitudinal instabilities due to rf cavity higher-order modes (HOMs) is one of the limitations in going to higher currents. These effects are seen in the horizontal plane of the pinhole camera images since the dipole source is at a dispersive point in the lattice. We observed about a factor of two increase in horizontal beam size and integrated bunch length in the unstable condition. By correlating the size changes with the temperature readouts of the 16 rf cavity cells, we identified the source of the instability. The cavity temperature set points were adjusted to avoid a HOM.

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INTRODUCTION

The Advanced Photon Source (APS) is a third-generation hard x-ray synchrotron radiation facility that was commissioned in 1996. The baseline design was to provide high-brightness x-rays from dipole sources and insertion device sources using a 7-GeV positron or electron beam with a stored beam current of 100 mA [1]. The installed rf power was designed to allow operations at up to 7.7 GeV or 300-mA current. In the last few years we have continued on the path to higher current, having operated in a User run at 130 mA and performed studies at 200 mA in September 2001. In our most recent study in December 2003, we operated at 225 mA and 7 GeV. During these studies our beam diagnostics sector instrumentation provided critical tuning information, and our insertion device beamline was the only one approved to run at this higher current.

The Sector 35 bending magnet pinhole camera views a dispersive point in the lattice so that the observed horizontal beam size provides information about changes in energy spread due to longitudinal instabilities. Optical synchrotron radiation (OSR) is also measured by a streak camera to correlate the bunch-length effects in the longitudinal dynamics. One of the main issues in these higher-current runs is control of the rf cavity higher-order modes (HOMs). As we raise the stored beam current and rf power, temperature variations in the rf cavities result in shifting resonance frequencies for HOMs in the 16 rf cells. If a HOM overlaps an upper synchrotron sideband of the beam longitudinal motion, the beam becomes unstable and may eventually be lost. By correlating the beam size changes with the rf cavity temperature, we identified which cavity temperature set-points should be adjusted to reduce the HOMs. We subsequently were able to store the 225 mA in a reasonably stable situation. Complementary information on the bunch length and the beam divergence were also obtained and will be discussed.

Experimental Background

The injector for the storage ring includes a thermionic rf gun, an S-band linear accelerator (linac), a particle accumulator ring (PAR) operating at 325 MeV, and a booster synchrotron that ramps the energy from 325 MeV to 7 GeV. Full energy injection is done at 2 Hz into the 1104-m-circumference storage ring. One of the standard fill patterns is for 24 singlets, each separated by 54 rf buckets of the 352-MHz rf frequency. However, for the high-current runs the single-bunch current is dramatically reduced by using 500 of the 1296 rf buckets available. Even at 225 mA, this results in only about 0.42 mA per bunch.

One sector of the storage ring is dedicated to state-of-the-art beam diagnostics [2,3]. These diagnostics include an x-ray pinhole camera viewing a dipole source; a dual-sweep synchroscan streak camera imaging the OSR from the same dipole source; a cryo-cooled monochromator on the 198-period diagnostic undulator source; and another x-ray pinhole camera viewing a dipole source at a low dispersion point in the lattice. The recently installed cryo-cooling feature for the crystal in the monochromator was involved in our heat load assessments so that this was the only sector permitted to open the x-ray shutter to allow x-rays into a beamline station.

The pinhole camera uses four tungsten blades with precision stepper motors to provide remote control of the aperture size and center. Generally, we run with a 15 µm ×15 µm aperture for the horizontal and vertical planes. The source-to-aperture distance is 9.0 m, and the aperture-to-crystal distance is 8.8 m, resulting in a magnification of about 1.0. The x-ray images are converted to visible light by a YAG:Ce single crystal and imaged by a pair of achromat lenses and a CCD camera. The total system resolution is 22 µm as determined by a scan of the skew quads at low vertical coupling [2]. Normal beam sizes at the source are 95 µm (H) by 30 µm (V) for the lower emittance of 2.5 nm rad. The observed horizontal beam size (σ_x) included the dispersion-energy spread product ($\eta_x\sigma_E$) in quadrature with the betatron size and system resolution (σ_{res}) as shown in Eq. (1), where β_x and ε_x are the beta function and emittance.

$$\sigma_{x=}\left(\beta_x\,\varepsilon_x + (\eta_x\sigma_E)^2 + \sigma^2_{res}\right)^{1/2} \quad (1)$$

The images are digitized by a dedicated Datacube MV200 video digitizer, and the beam parameters (size, emittance) are calculated and archived as process variables in the EPICS protocol.

The optical streak camera is a Hamamatsu C5680 with the vertical sweep unit being a synchroscan unit tuned to 117.3 MHz, the third subharmonic of the storage ring rf frequency. The dual-sweep plugin is installed to access the slower time scale of the ring period, 3.68 μs. Although the streak camera has ~ 0.6-ps (σ) resolution when operating on its fastest range, we use a slower sweep speed to provide the time span needed to cover bunch lengths of 20 to 80 ps. The effective resolution is then about 2 ps (σ), and this is a small effect when taken in quadrature with the bunch length. Generally, for single-bunch studies we can image 1 to 8 mA in a single bunch in a single turn. However, in these experiments the large number of bunches results in less than 0.5 mA per bunch. The synchroscan feature gives us the low jitter in the measurements so that we can synchronously sum the signal from many bunches in many turns. A newly-developed interface allowed EPICS control of the streak camera and hence, remote control. The readout camera video was sent to another MV200 video digitizer, and the images saved as needed. Online profile processing was also done.

The cryo-cooled monochromator was designed in-house, and commissioning was begun in the fall of 2003. A Si crystal used in the Laue Geometry for the [220] planes is used to monochromate the x-ray beam. The bandwidth is about 1.4×10^{-4}. The monochromatic x-rays at about 22 keV are transmitted out of the vacuum chamber through a Be window strip that covers angles from 10 to 90 degrees. The x-rays are converted to visible light by a 100-μm-thick YAG:Ce single crystal, and the beam spot is imaged onto a CCD camera. Since there are over 28 insertion device beamlines in the facility, our device was used as a surrogate for the high-current test. Scaling arguments were made that with cryo-cooling, our crystal would survive up to 300 mA, and the x-ray front end and beamline were safe if the ID gap was not reduced below 17 mm. The nominal minimum gap is 12 mm with 100-mA stored beam. We were interested in how the HOMs might affect the ID beam shape. The ID pinhole camera was not used for this run.

EXPERIMENTAL RESULTS

X-ray Pinhole Camera Results and Correlation to HOMs

As mentioned previously, the horizontal beam size at the bending magnet source point shows a clear signature of size increase when the HOMs are excited and the beam is still stored. Examples of the stable and unstable conditions are shown in Figs. 1(a) and (b), respectfully.

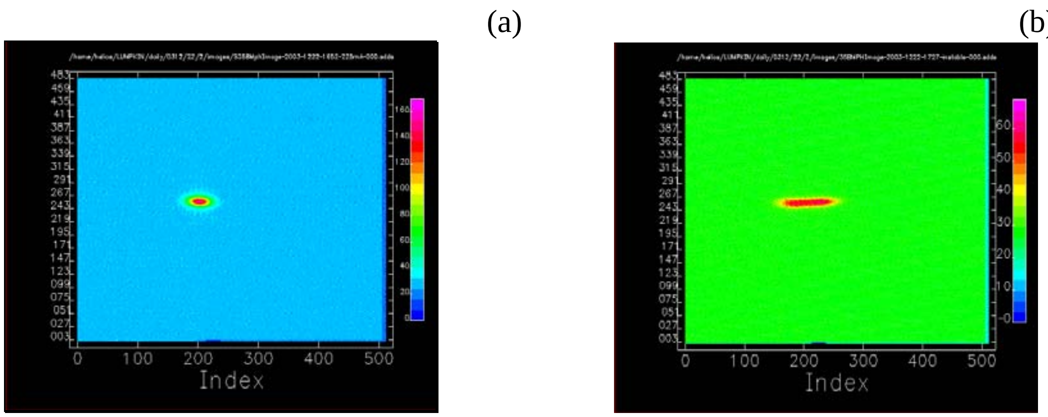

FIGURE 1. Examples of the x-ray pinhole camera image for stable (a) and unstable (b) conditions at 200 mA. The horizontal beam size is 90 μm and ~ 250 μm for (a) and (b), respectively.

The beam size, emittances, rf cavity temperatures, and rf reflected power are available as process variables (PVs) in EPICS. Using the SDDS toolkit [4], we were able to easily collect thousands of channels of data potentially related to the instability and to compute correlations with the horizontal emittance. Sorting on the magnitude of the correlations identified a particular cavity as having temperature readbacks highly correlated to emittance. The individual cavity temperature set point was adjusted to reduce/avoid the HOMs before more beam was stored. An example of the correlation of horizontal emittance with cavity cell temperature is shown in Fig. 2 for Sector 40 Cell 4. A strong correlation of 0.87 was calculated in this case.

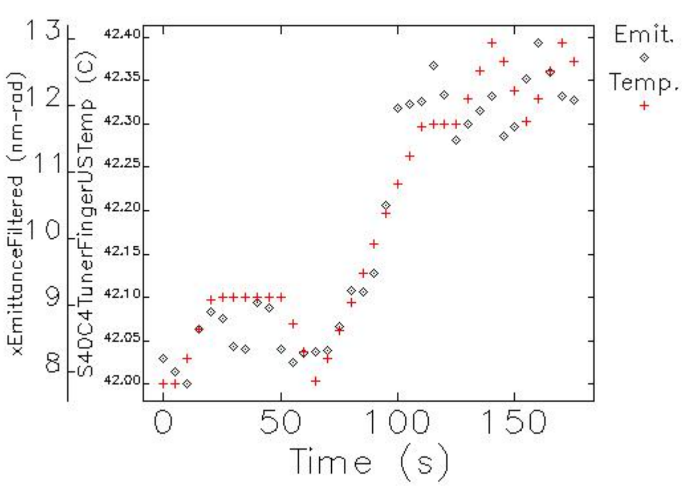

FIGURE 2. A plot showing the correlation of observed emittance and the cavity temperature. In this case, the temperature set point for Sector 40 Cell 4 was adjusted and subsequently, the emittance dropped to 2.5 nm-rad.

Optical Streak Camera Results

Complementary to the energy spread information is the actual effective bunch length. The streak camera is operated in the dual-sweep mode to provide access to the µs-scale information (one turn is 3.68 µs) and the ps-scale information for the bunch length (vertical axis). The observed bunch-length envelope in the region-of-interest (ROI) is about 46 ps as shown in Fig. 3(a). This is larger than expected for a 0.4-mA bunch and 9-MV gap voltage, but perhaps a phase oscillation is also involved, so the time averaged bunch is lengthened. Further studies are needed on this point.

(a) (b)

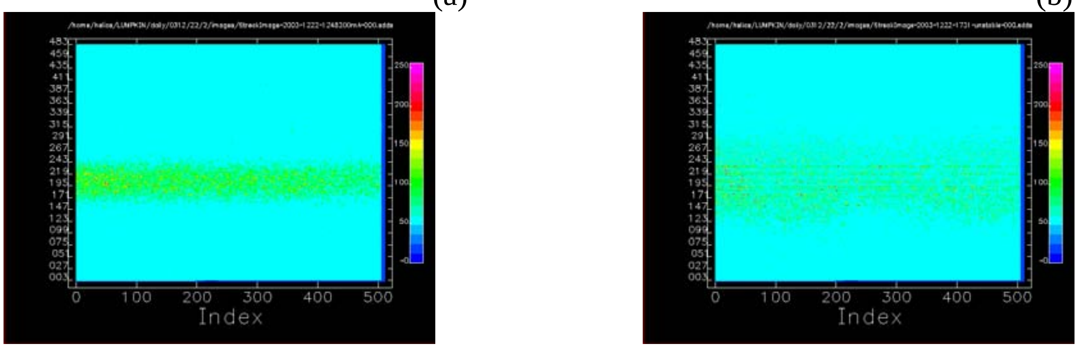

FIGURE 3. Examples of the dual-streak camera image for stable (a) and unstable (b) conditions near 200 mA. The horizontal axis covers 5µs and the vertical axis is 500 ps. The observed bunch lengths are about (a) 46 and (b) 90 ps.

In the unstable mode (also correlated with the larger horizontal beam size), the bunch-length envelope is about 90 ps (σ). We should note that for a single bunch at such low current at 9.0 MV rf gap voltage, we would expect a bunch length of 20-25 ps. The image profile from the MV 200 for stable conditions is shown in Fig 4.

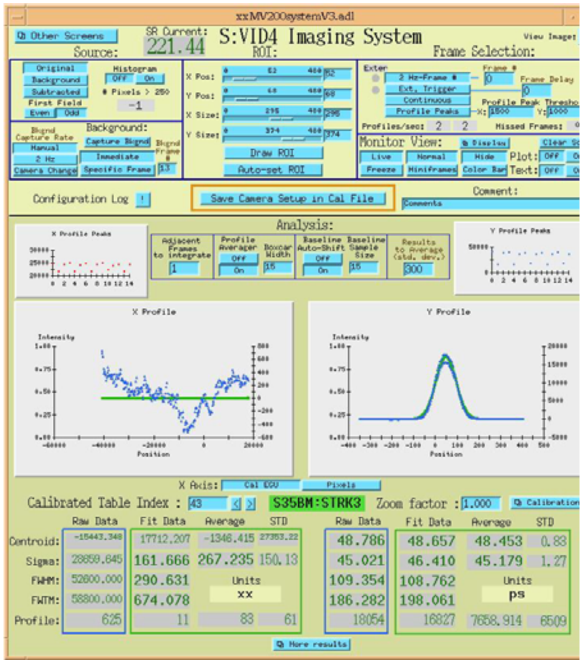

FIGURE 4 A longitudinal profile for the streak camera image of Fig. 3(a). The bunch-length profile is the y profile on the right, in this case.

ID Divergence Results

The cryo-cooled monochromator data are used to provide information about the e-beam's horizontal and vertical divergence. By using the known source distance to the monochromator and converter crystal, the projected beam image spot size at the crystal can be used to determine the beam divergence. The nominal values at 100 mA are $\sigma_{x'}$ = 13 μrad and $\sigma_{y'}$ = 6.4 μrad. For the 200-mA regime data we see slight effects, including when the HOM instability was purposely stimulated by changing the cavity temperature set points at the end of the run. The unstable condition image is shown in Fig. 5.

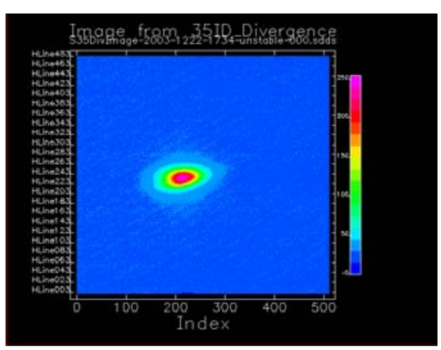

FIGURE 5. Beam divergence image from the ID source in the HOM unstable condition.

There is dispersion in the ID straight for this lattice; however, the effects of energy spread in the projected divergence images are masked compared to the x-ray pinhole image. There is detectable tailing in the $\sigma_{x'}$ profile. Further studies are warranted since beam trajectory was not as well controlled for the high current run. A subset of the beam missteering interlocks was applied, and orbit feedback was off.

SUMMARY

In summary, the APS team successfully stored 225 mA in the ring for the first time. One of the critical aspects was the control of the HOMs. The correlation of observed horizontal beam size and cavity cell temperatures was effective. For both stable and unstable conditions the beam quality was assessed using the x-ray pinhole camera, the streak camera, and the cryo-cooled monochromator. We are developing the techniques needed to support operations at 250 to 300 mA. If the machine does operate at these elevated currents, the x-ray front ends would need upgrades for the higher heat loads.

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