HIGHER-CURRENT OPERATION FOR THE APS UPGRADE*

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Abstract

The Advanced Photon Source is a 7-GeV hard x-ray synchrotron light source. Operation for users is delivered at a nominal current of 100 mA in one of three bunch patterns. The APS Upgrade calls for a minimum planned operating current of 150 mA, with an option to deliver beam up to 200 mA. The high-current threshold in the storage ring has been explored, and storage ring components have been identified that either drive collective instabilities or are subjected to excessive beam-driven wakefield heating. In this paper, we describe operations tests at 150 mA in a special lattice that simulates the upgraded APS. We also describe the accelerator upgrades that are required to accommodate 200-mA operation.

INTRODUCTION

The brightness and flux in a synchrotron light source are directly proportional to the beam current, which provides a clear path to delivering higher-brightness hard x-rays, an important component of the APS upgrade. The accelerator could operate today at 150 mA, the minimum planned current after the upgrade, but thermal limitations in the x-ray front ends (FEs) and beamlines prevent this. The plan is to upgrade the FEs and beamlines to handle the heat load for beam currents up to 200 mA [1], and keep an accelerator upgrade to 200 mA as an option.

The high-current threshold in the ring has been explored over the past several years, and the accelerator limitations were identified in an earlier paper [2]. Two components, the rf cavity higher-order mode (HOM) dampers and the vertical scraper chambers, presently limit 200-mA operation, especially in the 24-bunch operating mode [3], and would require upgrades.

In this paper, we review ongoing tests of operating the APS storage ring at 150 mA, then describe the upgrades required to accommodate 200-mA operation.

PRESENT CAPABILITIES

For nominal, 100-mA operation, we require two 1.1-MW 351.93-MHz klystrons to drive the 16 radio-frequency (rf) cavities, with each klystron delivering approximately 650-kW rf output power. Positive chromaticity is used to stabilize the beam against transverse multibunch instabilities [2]. A bunch-by-bunch transverse feedback system [4] is used in the 24-bunch mode to further stabilize the beam, allowing us to reduce the chromaticity by at least two units in each plane.

Operation at 150 mA can be achieved with two klystrons operating at nearly full rated power output, approximately 800 kW to 1 MW each depending on the total gap voltage required. To store 200 mA, four klystrons are required and they are operated in a parallel configuration [5]. The overall reliability of the rf systems will be reduced to some degree when operating at greater than 100-mA stored beam. Reasons for this reduced reliability include operation of the cavity input couplers closer to their design power rating, operation of the klystrons at or near their maximum rf power output, and the partial or total loss of rf system redundancy when two or more klystrons are operated in parallel configuration.

The maximum current and the reason for the limitation are summarized in Table 1. For these measurements, the insertion device (ID) gaps were open, the chromaticity was high (i.e., 10 units in each plane) and the bunch-by-bunch transverse feedback system was turned off.

Table 1: Maximum Stable Current for All Modes.

Operating mode (# bunches)	Current limit (mA)	Limitation at maximum current
24	164	Heating[a]
324	245	CBI (longitudinal)
Hybrid	170[b]	–[c]

[a] Vertical scraper, rf coupler, HOM dampers.
[b] Tested with two klystrons only.
[c] To be determined using all four klystrons.

The average individual klystron output power and average cavity input power were measured for higher current with ID gaps open; these data are shown in Fig. 1. In user operation, the klystron output power and cavity input power are both higher due to the additional ID radiation energy loss; the amount depends on the values of the ID gaps, each under individual beamline control. The average cavity power is less than 90 kW during 100-mA user operation. The highest beam current that the rf systems were operated for users with ID gaps closed was 130 mA with top-up injection for two 4-to-5-hour periods. These tests were limited to 130 mA because the FEs have not all been designed to handle higher heat loads [1].

The average cavity input power is fairly linear with beam current, as seen in Fig. 1, reaching a maximum value of 135 kW at 250 mA. The data overlap for 150 mA for all three user modes, with the rf voltage ranging from 8.8 to 9.0 MV. The figure also illustrates the limitation on the beam current with two klystrons (black “+”).

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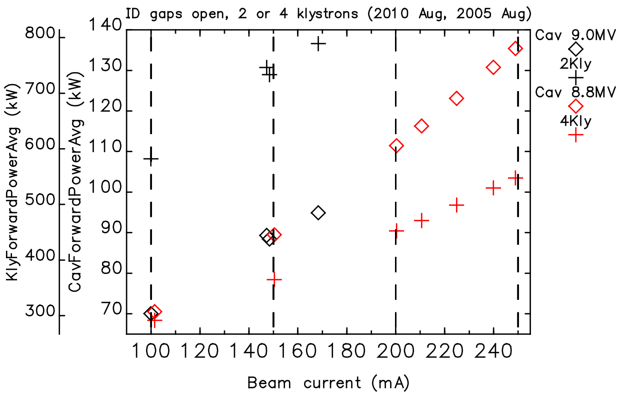

Fig. 1: Average klystron output power and cavity input power for high current (ID gaps open), for 24-bunch/hybrid modes (black) and 324-bunch mode (red).

TESTS WITH UPGRADE LATTICE

One of the goals of the APS Upgrade is to provide higher brightness x-ray beams and simultaneously increase beamline capacity. A provision is made to modify the lattice to accommodate several long straight sections (LSS), increasing the user ID length from 5 m to 7.7 m. The placement of these LSSs is expected to be non-symmetric based on the scientific needs of beamlines already fully built. To preserve the dynamic aperture and lifetime, a multi-objective direct optimization scheme was implemented to design the lattice [6].

Two lattices have been developed that incorporate eight LSSs, with sextupoles optimized for two different values of the chromaticity suitable for 100 mA and 150 mA, respectively. We have demonstrated stable 100-mA and 150-mA operation in 24-bunch mode in these LSS lattices, both with and without the transverse bunch-by-bunch feedback system. Without feedback, 9.5 units of chromaticity are required in each plane for 150 mA. Preliminary tests at 150 mA with the feedback system engaged demonstrate that the chromaticity could be reduced by more than 2 units while maintaining stable beam and good injection efficiency.

ONGOING IMPROVEMENTS

Rf Coupler

Past coupler failures caused by arcing, excessive ceramic heating, and the sudden appearance of pinhole vacuum leaks in ceramics have been analyzed in order to improve coupler performance. Improved fabrication methods, minor design changes, and an automated coupler conditioning process have been utilized to significantly reduce coupler failures for operation up to 100 mA. New couplers are routinely conditioned up to 100 kW input power in the Rf Test Stand [7].

In high-current studies with ID gaps open, the measured average cavity input power for 200 mA was about 110 kW (Fig. 1). This power level is still within the original design limit of 180 kW [8]. It is expected that operation at beam currents greater than 100 mA will place additional stress on the existing input couplers due to heating of the coupler ceramics by HOM power. Several design changes show promise in further improving the power handling capability and operational lifetime of the couplers. Improved titanium coating of the ceramic surface, and coating the conductor copper parts to suppress multipacting, gave favourable results in preliminary tests [7]. It is expected that reliable 200-mA operation can be achieved with these improvements.

Parallel-Klystron Operation

LLRF changes and software development are needed to improve this mode for use in routine operation. The present parallel-klystron scheme utilizes one existing phase control loop at two of the four rf stations for parallel-klystron phase control, which results in an increase in AC-power-line-related phase noise sideband levels of ~10 dB over the existing single-ended rf system performance. The existing low-level rf systems will require modification to reduce this noise. Also, due to the more complex operator involvement required for the parallel-klystron configuration, automation scripts will need to be developed to assist machine operators in consistent and rapid rf system start-up and reset.

UPGRADES

The high-current thresholds are dominated by longitudinal effects, either rf-cavity longitudinal HOM-driven coupled-bunch instabilities or heating by longitudinal wakefields in various accelerator components. With 24 bunches, several components are approaching temperature limits above 160 mA, including the HOM dampers and the vertical diagnostic scraper chamber. Below, we discuss the status and recent results relating to the HOM damper and scraper chamber upgrades.

HOM Dampers

Higher-order-mode dampers are presently installed on four of the sixteen storage ring rf cavities to mitigate longitudinal coupled-bunch instabilities (CBI) [9]. HOM damper performance has been adequate although their use as an rf diagnostic tool has been limited due to the nature of the ceramic load. The frequencies and amplitudes of the specific HOMs that couple into the dampers cannot be directly measured. An additional issue is excessive heating for certain machine conditions.

Figures 2 and 3 show the elevated power dissipated in the HOM damper ceramic body for two bunch patterns. For 24 bunches, the power rise is quadratic, showing a peak-current effect from the relatively high average bunch current. For the 324-bunch mode, the power appears to show a resonance effect, where the power peaks at a particular beam current. This effect can potentially be explained by noting that the HOM frequencies shift with input power and cavity temperature.

New HOM dampers are currently being designed to address the limitations of the present design. Magnetic-field coupling is employed to achieve strong coupling to the HOMs, and two sets of dampers will be used, one optimized for lower frequency (535 MHz and 1.2 GHz) and the other for higher frequency (> 850 MHz). The new design includes a detachable rf load that enables mode spectra to be extracted to allow rf diagnostics.

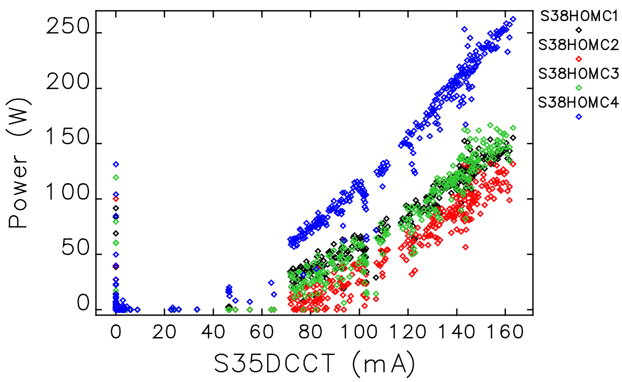

Fig. 2: Power dissipated in HOM damper ceramic body with beam currents above 100 mA, 24 bunches.

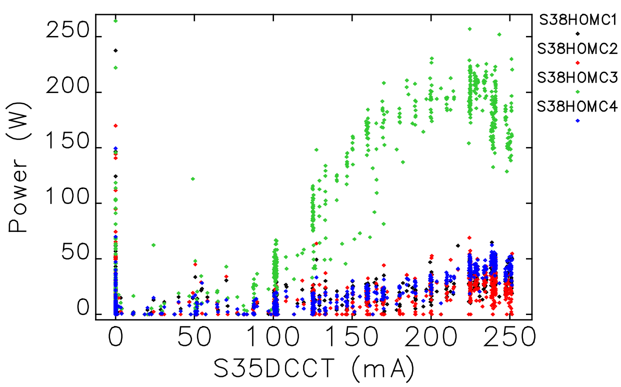

Fig. 3: Power dissipated in HOM damper ceramic body with beam currents above 100 mA, 324 bunches.

Vertical Scrapers

Simulations show that the transverse force exerted on the beam by wakefields induced by the vertical scraper is small compared to other components, but the energy lost by the beam due to the longitudinal wake could result in a serious heat-load problem [10]. The longitudinal loss factor k_{z0} is computed to be 1.2 V/pC, assuming a zero-current rms bunch length σ_{z0} of 5 mm, and the loss factor scales approximately with bunch length as $(\sigma_z/\sigma_{z0})^{-1.5}$. The power dissipated by the beam can be estimated using $I^2 k_z/(N_b f_{rev})$[11], where I is the total beam current, N_b is the number of bunches, k_z is scaled to the bunch length, and f_{rev} is the revolution frequency. The rms bunch length σ_z is about 37 ps (11 mm) for 100 mA and 45 ps (14 mm) for 200 mA (24 bunches), which give k_z scaling factors of 0.31 and 0.21, respectively. The dissipated power is about 570 W for 100 mA and would be expected to be about 1.5 kW for 200 mA. If this power is dissipated in the small volume between the scraper and the housing, undesired heating could result.

For the high-current test with 24 bunches, the beam current was 160 mA and σ_z was 42 ps (13 mm), giving a scaling factor of 0.24 and a dissipated power of about 1.1 kW. The measured scraper tube temperature rise is about a factor of two from 100 mA to 160 mA [2]. This temperature rise appears to be consistent with the rough estimate of the beam-induced power.

Preliminary machine studies suggest that the scraper chamber heating is sensitive to beam steering. Additional thermocouples are being installed in the near future to enable the temperature to be mapped more completely. The sensitivity of the chamber heating to beam steering at higher current will then be characterized in more detail.

Preliminary work has been carried out on a new conceptual design that mitigates the heating effects. Simulations show that a reduction of k_z by a factor of six can be achieved [11]. Further work is needed to develop a mechanical design [12].

SUMMARY

We have high confidence in achieving reliable performance of the APS storage ring at 150 mA, the minimum planned current after the upgrade. Stable 150-mA beam has been demonstrated in all three user modes, 24 bunches, 324 bunches, hybrid (16 mA main bunch). The 8-LSS upgrade lattice has been tested with 24 bunches up to 150 mA with bunch-by-bunch feedback. For operation at the 200-mA upgrade option, the physics issues are understood and preliminary designs have been investigated for all sensitive components.

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