ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB043

VALIDATION OF APS-U BEAM DYNAMICS USING 6-GeV APS BEAM*

L. Emery, R. Lindberg, A. Xiao, P. Kallakuri, ANL, Argonne, IL, USA

Abstract

Several beam measurements at the Advanced Photon Sources were done with a lowered-energy beam of 6 GeV in order to verify or validate calculation codes and some predictions for the APS-U. Though the APS lattice is obviously different from that of the APS-U some aspects of the beams at 6 GeV are similar, for example, the synchrotron radiation damping rate. At 6 GeV, one can also store more current and run with a higher rf bucket allowing the characterization of larger momentum aperture lattices. We report measurements (or plans of measurements) on general instabilities thresholds, lifetime, and other subtle effects. The important topic of ion instabilities at 6 GeV is covered in a separate paper by J. Calvey at this conference.

INTRODUCTION

The design of the 6-GeV Advanced Photon Source Upgrade (APS-U) hybrid multi-bend achromat lattice was checked with a large set of particle tracking simulations. Though we have high confidence in these codes to pursue a design and construction, it would be good to validate the results of these codes with existing accelerators whose beams approach aspects of APS-U's beam. Thus we use the available Advanced Photon Source (APS) storage ring in order to validate the predictions of APS ring running at the lower beam energy of 6 GeV.

Obviously the layout of the APS magnets limits the range of beam performance we can check, for example any effect related to the extremely-low-horizontal emittance we are seeking with APS-U. However at 6 GeV the synchrotron radiation damping rate is comparable to that of APS-U, and thus many collective effects would be similar, in particular in the vertical plane.

The longitudinal effects related to the small synchrotron frequency cannot be duplicated, however, because the dispersion and momentum compaction factor in the present APS is much greater than in APS-U. In addition, the APS-U will utilize a 4th-harmonic cavity to lengthen the bunch, which also further decreases the synchrotron frequency, and worsens collective effects, in particular coupled-bunch instabilities by a factor of 2-3.

A significant collective effect is the ion instability in bunch trains and the validation of its simulation is the subject of a stand-alone paper in these proceedings [1], and is not covered here.

In the following we list the various effects we would like to have measured and simulated, giving more details where a measurement was made. We note that most of the effects are dependent on impedances, for which we have a computed model from vacuum chamber geometry and resistive wall calculations. If we have a disagreement between measurement and simulation, then we must ponder whether the impedance model is incomplete, whether the simulation missed some physical effect, or whether they are close "enough."

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

MEASUREMENTS

The APS lattice quadrupole settings used at 6 GeV were simplified somewhat relative to the operational lattice at 7 GeV by removing one of the customized reduced-horizontal beamsize straight section optics.

Many performance parameters depend on the chromaticity and the distribution of sextupole gradients as well. For some measurements we use a reference chromaticity of about $(\xi_x, \xi_y) = (4,4)$ which is sufficient for storing a 324-bunch beam stably. Another variable is the sextupole family configuration, which can change the dynamic aperture or momentum aperture for a given chromaticity. For measurement requiring high charge per bunch, we use a high-chromaticity sextupole configuration, say with $(\xi_x, \xi_y) = (10,10)$, which happens to produce a large dynamic aperture at the same time. The normalized gradients of these sextupoles are taken from operational 7 GeV lattices.

High-current Limit

It is possible to store a larger current at 6 GeV than at 7 GeV because the energy loss per turn is much lower (2.94 MeV versus 5.45 MeV), and the rf gap voltage could be set lower. Unfortunately, in one attempt to achieve a target current of 300 mA, desirable for longitudinal coupled-bunch instability tests, the cavity-waveguide aperture coupling, being somewhat low (and not adjustable without breaking vacuum), caused a Robinson instability of the 2nd type, and limited the stored current to 250 mA. Thus very high-current runs with the target of 300 mA are not possible for now.

Single Bunch Thresholds

The single-bunch instability due to the ring's broad-band impedance can be benchmarked at 6 GeV, as was done for 7 GeV earlier [2]. We focused on the vertical plane and varied the vertical chromaticity ξ_y and leaving horizontal chromaticity ξ_x high at 5 units. There was no feedback considered. The result is shown in Fig. 1. The measurement threshold is determined by the presence of betatron sidebands of the beam spectrum. The current is increased in steps of 0.1 mA. A partial beam loss usually occurs a few tenths of mA above the threshold. A curious second boundary of instability had been noticed in tracking. That is, there is a small peninsula of stability for a range of $4 < \xi_y < 6$, for which a bunch injected in the space between the two curves at, say, 3 mA, the bunch would be stable. As the current is increased past the second threshold, the beam becomes

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB043

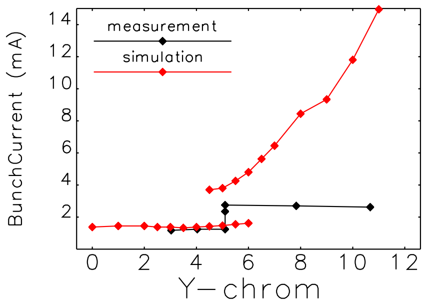

Figure 1: Single bunch threshold versus ξ_y from simulation and measurement. The simulation shows two lines of accumulation limit explained in the text. The measurement shows two lines also but much smaller overlap in ξ_y. $V_{\mathrm{rf}} = 9.5$ MV.

unstable. This was reproduced in actual measurement, but for a much smaller range of ξ_y, too small to represent in Fig. 1, but is located between the two top points at $\xi_y = 5$. The difference between simulations and measurements in the second instability threshold line may be because of the horizontal plane instability. The simulation used $\xi_x = 12$, while the measurement used $\xi_x = 5$. Measurements should be repeated at $\xi_x = 12$ if possible. For a gap voltage of 7.5 MV in Fig. 2 the peninsula of stability is larger and easier to depict. The same peninsular feature was observed

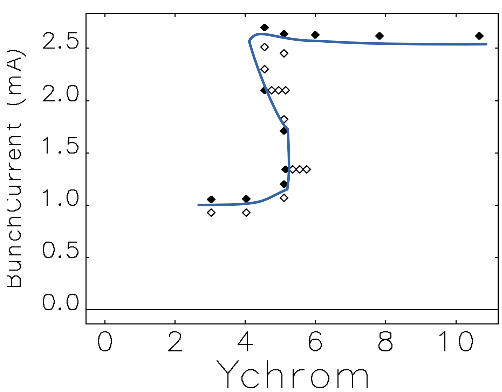

Figure 2: Higher-resolution determination of demarcation line of stability with $V_{\mathrm{rf}} = 7.5$ MV. Filled diamonds unstable, open diamonds stable.

in measurements at NSLS-II [3].

Adding feedback would add an extra complexity in the comparison. The closed loop comparison would not tell us much more the correctness of modeling single-bunch feedback since the open loop behavior already shows a noted difference.

Bunch by Bunch Feedback Testing

As of Jan 2021 APS-U owns two iGp-1296F Dimtel signal processor boxes (along with bpm front-ends provided by Dimtel) for running bunch-by-bunch feedback in the two transverse planes. They have been incorporated in APS operations at 7 GeV as an acceptance test. The benefits of the Dimtel processing boxes over our in-house system are that they can samples all rf buckets at 352 MHz and have more internal diagnostics. We are presently characterizing the feedback operation at 6 GeV to learn more about the chromaticity requirement for running 48 bunch uniform pattern at the target total current of 200 mA. Drive-damp measurements would a good opportunity to check our model of feedback in particle tracking.

Resistive Wall Impedance

Theory and simulation tell us that chromatic damping will stabilize APS-U against resistive wall instability. However, for 6 GeV APS, the threshold was found to be lower (in measurement as well), particularly in the horizontal plane where $\beta_x >> \beta_y$.

The 7 GeV APS beam at a reasonable chromaticity ($\xi_x = 4$) is known to be stable against resistive wall instability. At 6 GeV, the transverse damping is lessened, effect of impedances is increased and Landau damping effect from tune spread is reduced. One must also consider bunch lengthening from longitudinal impedance which, in combination with chromaticity ξ_x, is a stabilizing for high charge bunches, but overall lessened for 6 GeV.

Thus we have stability predictions for 6 GeV (and 7 GeV, for that matter) as a function of ξ_x for 324 bunches shown in Fig. 3, with which we can compare with a measurement. For 24 bunches the thresholds would be higher because of bunch lengthening and microwave instability. Bunch by bunch feedback is not simulated yet.

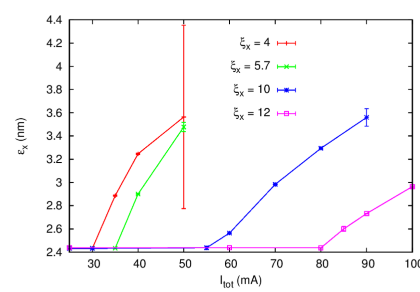

Figure 3: Emittance as a function of total current for APS 6 GeV, 324 bunches, and various ξ_x. $V_{\mathrm{rf}} = 9.5$ MV.

The threshold measurements at 6 GeV had been complicated by the fact that ions may contribute to the instability. We should make bunch trains with small gaps in order to eliminate any contributions from ions. The simulated growth rates for resistive wall should be unchanged.

Monopole HOM Search

Over the last two years, we have demonstrated a reproducible temperature model of the APS rf cavity high-order mode (HOM) resonator frequencies, which in turn control the coupled-bunch mode frequency shift and growth rates [4, 5]. APS-U, having a slightly large circumference than APS, will operate at a 110-kHz lower rf frequency. Thus monopole HOMs resonator frequencies located with APS beam will not be the same ones as those that would impact

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB043

APS-U. One can nevertheless determine the frequencies of a majority of HOMs by scanning the water temperature of the rf cavities, and also determine the shunt impedances (and Q) of the individual HOM of each family. We found and reported [4] that only a few HOM families are expected to be significant compared to predictions of cavity codes.

We have made most of the monopole HOM search at 7 GeV rather than 6 GeV, since the lowered damping at 6 GeV makes the beam very unstable when a beam resonance is encountered and cause beam loss. As explained in [4] we intend to create a procedure to circumvent the HOM resonances by adjusting individual cavity temperatures during general high-current machine studies at 6 GeV in which the total rf gap voltage requires changing, e.g. an rf gap voltage scan for determining momentum aperture.

Dipole HOM Search

We don't expect a strong instability from dipole HOMs in APS (or APS-U) since we operate with high chromaticity and expect decoherence to damp the modes. However during the very-high-current run at 6 GeV, we momentarily noticed a dipole coupled-bunch mode with 48 bunch pattern at 150 mA. At lower currents (<100 mA) the search continued with rf cavity temperature scans at 7 GeV since, again, at 6 GeV, the monopole HOMs occasionally cause beam loss. We found only one mode from only one of the 16 cavities, which is curious, as we would expect several cavities to present themselves with the same HOM type.

Touschek Lifetime

It would be good to compare measurements and predictions of Touschek lifetime for various MOGA-optimized lattices as the β-function correction is improved or worsened. Touschek calculation had already been benchmarked at APS with a 7 GeV beam in [6]. Measurement at 6 GeV is particularly useful because of higher available rf bucket of 4.0% compared to 2.5% for 7 GeV. We had implemented some high momentum aperture lattices at 7 GeV, but will still need to apply them to 6 GeV for measurement. After correcting the linear model of the lattice in the ring, we use the model to determine the local momentum aperture over the ring, and the lifetime.

As the measurement of accurate small vertical beam size is critical for lifetime comparison, we recently found the need to measure the x-ray pinhole imaging system more accurately (at least with a 6 GeV beam, though we think the resolution should not depend on beam energy). The measurement consists of first minimizing the measured vertical beamsize $\sigma_{y,\mathrm{m}}$, then scanning a skew-quadrupole knob for vertical dispersion while measuring the lifetime τ. The dependence of τ versus $\sigma_{y,\mathrm{m}}$ can be modeled with a fixed gas scattering lifetime τ_g and the pinhole resolution σ_r. The quantity τ_g can be fitted at the same time, which is not usually considered. One has to plot an adjusted lifetime squared $[1/\tau - 1/\tau_\mathrm{g}]^{-2}$ (i.e., the Touschek lifetime) versus $\sigma^2_{y,\mathrm{m}}$ and fit a straight line. The intercept gives $\sigma_{y,\mathrm{m}}$, and the value of τ_g that minimized the residual rms gives the fitted τ_g. Figure 4 shows how the resolution and gas scattering lifetime is fit.

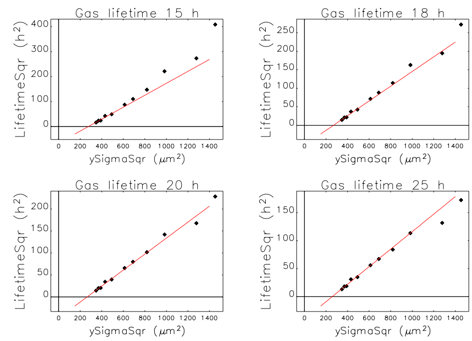

Figure 4: Fit of "adjusted" lifetime $[1/\tau - 1/\tau_\mathrm{g}]^{-2}$ versus $\sigma^2_{y,\mathrm{m}}$ producing a value for σ^2_r at the x-intercept. The best fit for τ_g is 20 h, and the resolution is 16.3 µm.

We have noted that gas scattering lifetime varies with various sextupole configurations, either due to the bremsstrahlung logarithmic dependence or the vertical dynamic aperture.

Other Measurement

We have made measurements of the entrance and exit angle perturbation of the hybrid permanent magnet (HPM) undulators at 7 GeV. The perturbation is small and the measurements are done on many HPM simultaneously, thus the measurement must takes into account the dispersion closed orbit due to the energy loss. The effect is somewhat lessened for 6 GeV beam, thus we make the measurements at 6 GeV. The data will be used to produce specifications of accuracy and long-term changes in steering feedforward, in particular for the straight sections that share independently-running HPMs.

Other measurements for 6 GeV to be compared with simulation are charge-dependence of energy spread, bunch lengthening, centroid stability, accumulation limits, charge dependence of dynamic aperture, effect of optics changes. They will be done it time permits.

CONCLUSIONS

Some measurement and simulations at 6 GeV have begun. Obviously the completion of some measurements and procedures is holding up the start of others. Some interesting behavior have been seen in the instability threshold as a function of chromaticity.

REFERENCES

[1] J. R. Calvey *et al.*, "Advances in Understanding of Ion Effects in Electron Storage Rings", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUXA01, this conference.

[2] Y.-C. Chae and Y. Wang, "Impedance Database II for the Advanced Photon Source Storage Ring", in *Proc. 22nd Particle*

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB043

Accelerator Conf. (PAC'07), Albuquerque, NM, USA, Jun. 2007, paper FRPMN104, pp. 4336–4338.

[3] A . Blednykh, private communication, 2020.

[4] L. Emery, P. S. Kallakuri, U. Wienands, and D. Teytelman, "Precision Cavity Higher-Order Mode Tuning Scheme for Stabilizing the Stored Beam in the Advanced Photon Source Upgrade", in *Proc. North American Particle Accelerator Conf. (NAPAC'19)*, Lansing, MI, USA, Sep. 2019, paper WEPLM04, pp. 670–672.

[5] K. C. Harkay *et al.*, "Characterizing the Coupled Bunch Driving Terms in a Storage Ring", in *Proc. 6th Int. Beam Instrumentation Conf. (IBIC'17)*, Grand Rapids, MI, USA, Aug. 2017, pp. 21–27. doi:10.18429/JACoW-IBIC2017-MO3AB1

[6] A. Xiao and B. X. Yang, "Benchmarking of Touschek Beam Lifetime Calculations for the Advanced Photon Source", in *Proc. North American Particle Accelerator Conf. (NAPAC'16)*, Chicago, IL, USA, Oct. 2016, pp. 940–942. doi:10.18429/JACoW-NAPAC2016-WEPOB21