

STATUS OF UNDULATORS FOR THE APS UPGRADE*

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Abstract

The Advanced Photon Source Upgrade (APS-U) project has developed and installed a multi-bend achromat (MBA) lattice operating at 6.0-GeV beam energy to replace the existing APS storage ring lattice that operated at 7.0 GeV. A major part of the project is to install 60 hybrid permanent magnet undulator (HPMU) insertion devices (IDs) that include 12 revolver undulators, each with two magnetic structures (for a total of 72 magnetic structures); and one electromagnetic undulator for intermediate energy x-rays (IEX). These IDs will outfit 35 sectors. We have developed new HPMU designs for five different period lengths used in 46 magnetic structures, and we will reuse 26 existing magnetic structures with four additional period lengths. Eight new superconducting undulators (SCUs) have been designed and built with two short period lengths and three different overall lengths [1-3]. The SCUs will be installed in both inline and canted configurations after beam commissioning is completed and the user runs start.

Demanding field requirements for the undulators were expected to be challenging for the undulator tuning, especially given the tight schedule. All undulators underwent rigorous tuning and control system tests before they were installed in the new storage ring. We will provide a status and schedule update including presenting measurement results of the IDs.

INTRODUCTION

The HPMUs for the APS are listed in Table 1 (each revolver contains two magnetic structures).

Table 1: Period lengths, minimum gaps, required K values and first harmonic energies of the APS undulators.

Period (cm)	Gap (mm)	Qty	K Value	E_1 (keV)	Comments
3.3	10.0	3	2.86	2.0	Existing IDs
3.3*	10.0	7	"	"	Existing canted IDs
3.0	9.0	3	2.63	2.6	Existing IDs
3.0*	9.0	5	"	"	Existing canted IDs
2.7	8.5	2	2.25	3.6	Existing IDs
2.7*	8.5	3	"	"	Existing canted IDs
2.3	8.5	2	1.62	6.5	Existing IDs for 2 revolvers
2.3*	8.5	1	"	"	Existing canted IDs
Existing		26			
2.8	8.5	3	2.48	3.0	New IDs
2.8*	8.5	10	"	"	New canted IDs
2.5	8.5	9	1.98	4.6	New for 2 IDs & 7 revolvers
2.5*	8.5	3	"	"	New for 3 canted revolvers
2.1	8.5	11	1.37	8.4	New for 4 IDs & 7 revolvers
2.1*	8.5	5	"	"	New for 2 canted IDs & 3 revolvers
1.4	8.5	2	0.46	22.1	New IDs for 2 revolvers
1.35	8.5	2	0.41	23.4	New IDs
1.35*	8.5	1	"	"	New canted ID
New		46			* Indicates shorter (canted) length ~2.1 m (full length ~2.4 m)
Total		72			

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Three years ago, at the IPAC'21 conference [4], we reported on tuning status, measurement techniques, and tuning schedule for permanent magnet IDs. In this paper we will present detailed tuning results of the IDs, discuss major associated components, and provide a timely status update. This is after less than one year of dark time (commissioning of the upgraded storage ring started in April of 2024).

HYBRID PERMANENT MAGNET UNDULATORS

Large efforts were devoted to prepare for the daunting task to design, build, refurbish, and tune both new and existing IDs in a short period of time. All IDs are the "stand-ard" out-of-vacuum undulator type, comprising a gap separation mechanism (GSM), strongbacks, and keepers holding the magnets and the poles. We pre-tuned many of the existing IDs during regular maintenance periods so that only final tuning (calibration) was required during the dark time. We also pre-tuned most of the new-period IDs on a set of existing GSMs. Their final GSMs would be harvested from the storage ring and reused, providing significant cost savings (except for the revolvers for which new GSMs were made). The IDs were also equipped with new controls and new motors and encoder components. All IDs will be allowed to reach a smaller minimum gap than previously, causing additional tuning challenges. To meet the schedule, period-specific magnetic shim signatures were predetermined to expedite the tuning. Additionally, we relied heavily on recent software developments for fast online magnetic measurements and postprocessing, and mechanical shimming to minimize the RMS phase errors [5]. A summary of the required and achieved tuning parameters is listed in Table 2.

Table 2: ID required and achieved tuning parameters.

Parameter	Requirement	Achieved ¹⁾
RMS phase error (degree) ²⁾	≤3	≤2.5
Horizontal Entrance/Exit angle (μrad) ³⁾	±3.9	±2
Vertical Entrance/Exit angle (μrad) ³⁾	±1.25	±1
Normal/Skew Quadrupole (G)	±50	±40
Normal Sextupole (G/cm) ⁴⁾	1100	150
Normal Octupole (G/cm ²) ⁴⁾	1700	150
Skew Sextupole (G/cm) ⁴⁾	560	150
Skew Octupole (G/cm ²) ⁴⁾	280	150

¹⁾ Typical values.

²⁾ Target value for all IDs.

³⁾ Most demanding case (applicable to all canted IDs).

⁴⁾ Normal/skew RMS values taken over all installed IDs.

Excellent RMS phase errors were achieved for both new and existing IDs. Figures 1 and 2 show examples of the gap dependence for typical legacy and new IDs, respectively.

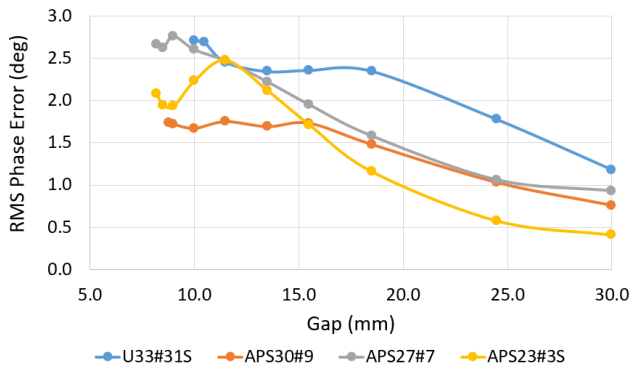


Figure 1: RMS phase error vs. gap for four legacy IDs.

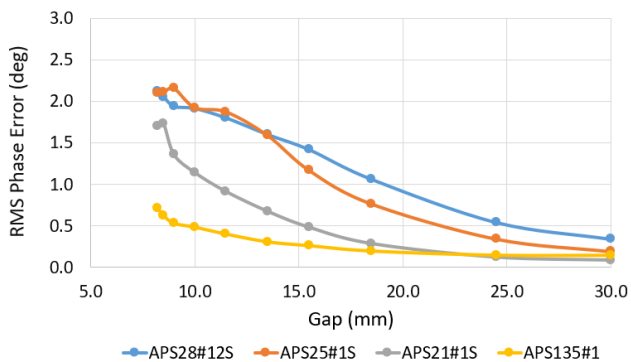


Figure 2: RMS phase error vs. gap for four new IDs.

Figure 3 shows the achieved performance for 69 of the 72 magnetic structures. For the new periods there is a clear trend of larger RMS phase error with increasing period length. For the old periods this is not the case because the mechanical tolerances of subcomponents are not as good and the K values are larger, hence it is more difficult to achieve small values. Lower values would have been feasible but due to the very tight schedule, they were not pursued since the IDs met the requirements.

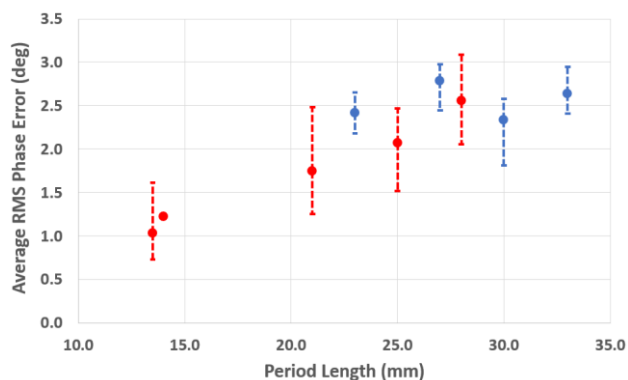


Figure 3: Average RMS phase errors of 69 measured magnetic structures out of 72 total. Red markers: new periods. Blue markers: Existing periods. Error bars show minimum and maximum values for each period over measured IDs.

Phase Shifters

There will be 11 phase shifters installed with correctors for inline devices. We have performed extensive measurements, both of individual components and of the full combination of components (see Fig. 4). Careful consideration was given in the design of shields and distances between components; as a result, data from individual measurements of the two undulators, the phase shifter, and the corrector can be concatenated into a dataset that agrees with full-sector measurements (see Fig. 5).



Figure 4: Photograph of two 2.5-cm-period HPMUs with phase shifter and corrector in the middle (insert) measured on the 6-m bench in the magnet measurement laboratory.

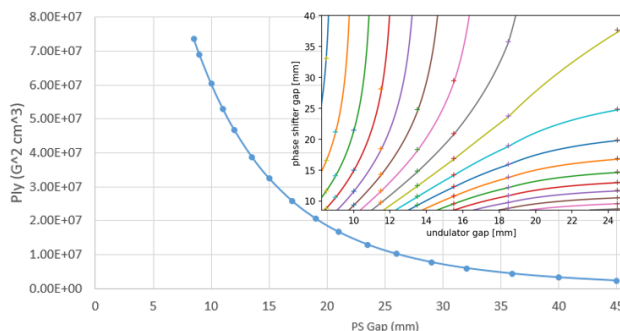


Figure 5: Measured phase integral vs. phase shifter gap settings and required phase shifter gap vs. undulator gap for in-phase radiation (insert). Curves: Predictions from concatenated data. Markers: Measured optimized settings from full-sector configuration.

The computed in-phase angular flux density for one case is shown in Fig. 6.

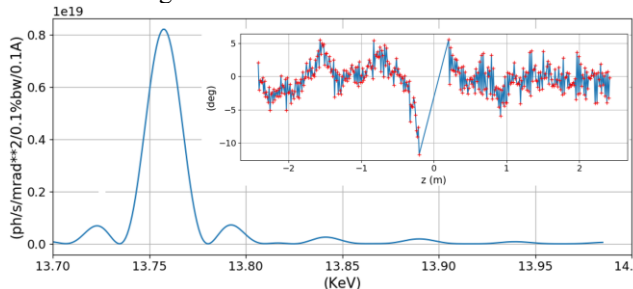


Figure 6: Computed zero-emittance 3rd harmonic angular flux density at 6.0 GeV for two in-phase 2.5-cm-period IDs at 8.5-mm gap. The total RMS phase error for the sector is 2.37 degrees.

New Insertion Device Control System

A new modular ID control system has been designed and built to handle four distinct mechanical support designs in six different combinations with up to 13 axes each (see Fig. 7) [6]. This system provides reliable and precise synchronized motion to control the photon energy to within ~ 1 eV while scanning at speeds of 1 keV/s. Modules are installed and are currently undergoing final tests and checkouts prior to ID operations in the storage ring. Delays from supply chain issues were minimal due to the great support from vendors. Development efforts are currently focused on software and automated deployment.

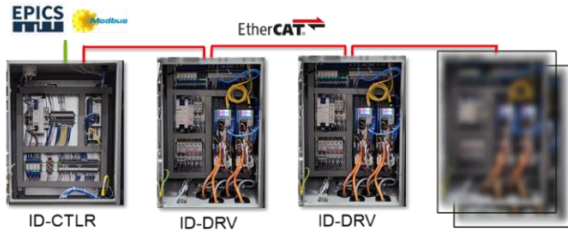


Figure 7: Diagram of the modular hardware components of the new ID control system.

New Insertion Device Vacuum Chamber

New ID vacuum chambers (IDVCs) were designed and fabricated for the APS-U [7]. The new 5-m-long IDVCs are produced from aluminum alloy extrusions. The interior beam aperture has an elliptical profile of 6.3 mm (h) \times 16.0 mm (w). The vacuum chamber height, straightness, and wall thickness are some of the important parameters that are machined with tight tolerances. The nominal wall thickness is 0.6 mm. The IDVCs, shown in Fig. 8, are equipped with a photon absorber, ion pump, and non-evaporable getter (NEG) cartridges and are leak checked prior to pre-alignment. The thin-nose surface profile is adjusted to a height within a ± 75 -micron tolerance band, and the entire vacuum chamber assembly was adjusted during installation to match the electron-beam axis.



Figure 8: The new ID vacuum chamber undergoing pre-alignment in preparation for storage ring installation. Left: Thin-nose view. Right: Rear-side (outboard) view. The downstream photon absorber is seen at the near end in both views.

CONCLUSION

We have completed final calibration of nearly all the planned magnetic structures for the APS upgrade with excellent performances achieved. Typical tuning time from start to finish for a single-period undulator is less than 2 weeks (and less than one week if pre-tuned); for a revolver undulator with two magnetic structures tuning time is less than 3 weeks (not pre-tuned). The successful tuning schedule was made possible due to careful planning with sets of well characterized magnetic shims readily available, and due to pre-tuning of many magnetic structures prior to the dark time. The new ID vacuum chambers were installed and aligned according to plan during the shutdown phase of the APS. The new ID control system is functioning well. Most devices are already installed in the upgraded storage ring using the new control system. The electromagnetic IEX undulator was also installed, unchanged but with a new vacuum chamber. The SCUs are planned to be installed later. The new storage ring is currently undergoing beam commissioning after less than one year of dark time.

ACKNOWLEDGEMENTS

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