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STATUS OF INSERTION DEVICE TUNING FOR THE APS UPGRADE*

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Abstract

The Advanced Photon Source Upgrade (APS-U) project is developing a multi-bend achromat (MBA) lattice at 6.0-GeV beam energy to replace the existing APS storage ring lattice operating at 7.0 GeV. One of the key components of the project is to design, fabricate, and install optimized insertion devices (IDs) for 35 beamlines. A plan was developed to standardize on four new undulator period lengths for 44 new undulators and to reuse 23 existing undulators with four more different period lengths.

Early in the Upgrade project we anticipated there would be large challenges in meeting the tight fabrication and tuning schedules so that all undulators would be ready for installation in the upgraded storage ring prior to beam commissioning. With recent developments and techniques used in the magnetic measurement laboratory, we have successfully tuned many of the new and reused undulators to demanding magnetic field requirements. We will report on the tools and techniques used and on results to date.

INTRODUCTION

Since the first stored beam in 1995, the APS has enabled breakthrough science in most scientific disciplines. The ongoing work to upgrade the storage ring to a 4th-generation low-emittance lattice will further advance the scientific endeavors using increased x-ray brightness and coherent flux by several orders of magnitude [1-3]. New hybrid permanent magnet undulators (HPMUs) were designed and fabricated for about two thirds of the beamlines, so a combination of legacy (old) undulators and new undulators are planned, as shown in Fig. 1. The planned superconducting undulators for the APS-U are presented elsewhere at this conference [4].

Magnetic Per. (cm)/Min Gap (mm)	Total	Comments
3.3 / 10.0	3	Existing IDs
3.3* / 10.0	6	Existing canted IDs
3.0 / 9.0	3	Existing IDs
3.0* / 9.0	3	Existing canted IDs
2.7 / 8.5	2	Existing IDs
2.7* / 8.5	3	Existing canted IDs
2.3 / 8.5	2	Existing IDs for 2 revolvers
2.3* / 8.5	1	Existing canted IDs
Existing	23	
2.8 / 8.5	3	New IDs
2.8* / 8.5	9	New canted IDs
2.5 / 8.5	9	New for 2 IDs & 7 revolvers
2.5* / 8.5	3	New for 3 canted revolvers
2.1 / 8.5	10	New for 3 IDs & 7 revolvers
2.1* / 8.5	5	New for 2 canted IDs & 3 revolvers
1.4 / 8.5	2	New IDs for 2 revolvers
1.35 / 8.5	2	New IDs
1.35*/ 8.5	1	New canted ID
New	44	
Total	67	

Figure 1: Planned HPMUs for the APS Upgrade. The ID operational minimum gap is also shown. The nominal length is 2.4 m. The star (*) indicates a length of 2.1 m.

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HYBRID PERMANENT MAGNET UNDULATORS

The tuning of the undulators can be divided into two phases:

- Phase 1 – Prior to the storage ring shutdown (shutdown planned for April 2023).
- Phase 2 – During the 12-month shutdown (for removal and installation of components and commissioning of the new storage ring).

It is desirable to complete final tuning of as many IDs as possible during phase 1 prior to the shutdown. However, many of the gap separation mechanisms (GSMs) will be reused due to substantial cost savings and will be harvested at the beginning of phase 2, causing many of the IDs to undergo their final tuning during phase 2. Therefore, efficient tuning procedures and techniques were developed in the Magnetic Measurement Laboratory that will make it feasible to complete all tuning on schedule.

Undulator Types

All undulators at the APS are out-of-vacuum undulators and stem back to the designs made in the early 1990s of the ubiquitous 3.3-cm-period undulator. Later, in-house designs were developed, and several (shorter) period lengths were fabricated; many of these will be reused for the APS-U (see Fig. 1) but tuned to tighter requirements at smaller gaps. New designs for the APS-U were further developed, and those are exemplified in Figs. 2 and 3. Figure 2 shows a model of a new ID with redesigned magnetic structures mounted on a legacy 4-motor GSM, and Fig. 3 shows a model of two revolver undulators with a phase shifter in the middle.

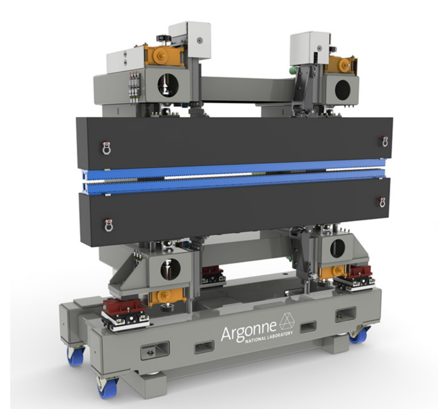

Figure 2: Model of a standalone new ID. The magnets and poles are retained in the top and bottom jaw mono-keepers (blue), which are mounted on super-strongbacks (black). The legacy 4-motor GSM is shown in gray.

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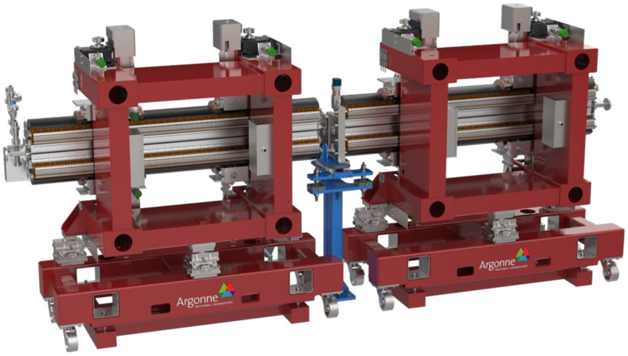

Figure 3: Model of two revolver undulators with a permanent magnet phase shifter in the middle.

MAGNETIC MEASUREMENT LABORATORY

All mechanical and magnetic tuning is performed at the APS. The laboratory has the following main equipment:

- Two granite benches (3 m and 6 m long).
- Capacitec probe systems for pole/magnet height and gap measurements.
- Fast scanning 2D Senis Hall probe systems for field measurements.
- Coil systems for integrated field measurements.

Figure 4 shows a photograph of the Hall probe and Capacitec probe mounted on the moving carriage.

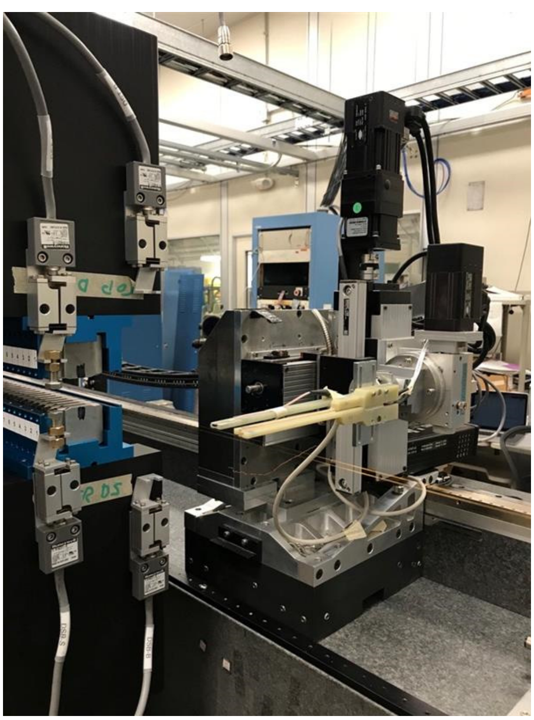
Figure 4: Hall probe and Capacitec probe mounted on the moving carriage on the 3-m-long bench.

TUNING REQUIREMENTS

With regard to the APS-U storage ring requirements, the commonly used first and second field integral requirements were replaced by electron beam entrance and exit angle requirements for the IDs. Additionally, there are integrated field multipole requirements. The normal and skew quadrupole requirements remain unchanged from the current storage ring, whereas the sextupole and octupole requirements were considerably relaxed for the APS-U [5]. Further, to maximize the photon brightness, the RMS phase errors need to be small if higher harmonics of the radiation is used. Therefore, a target value of 3º was set for all IDs with exceptions allowed depending on whether higher harmonics are used. Requirements shall be satisfied over the full undulator gap range (from smallest gap 8.5 mm to 30.0 mm).

TUNING TECHNIQUES

The following tuning techniques and procedures were developed and refined for fast and accurate tuning. The tuning steps are as follows [6, 7]:

- Optional gap tuning (from Capacitec scans):
  - Uses mechanical shims with placement from Capacitec measurements (if necessary).
- Trajectory tuning (from Hall probe scans vs. gap):
  - Uses primarily side shims supplemented with surface shims, if needed. Placement from optimization code.
- Phase tuning (from Hall probe scans vs. gap):
  - Uses wide surface shims or mechanical shims. Same code for trajectory tuning also works for phase tuning with surface shims. Phase-based optimization code is used for mechanical shimming.
- End angle tuning (from Hall probe scans vs. gap):
  - Uses side or surface shims. A search algorithm finds the best combination of shims to correct the end angles.
- Integrated field multipole tuning (from translating coil scans vs. gap):
  - Uses side or surface shims and the same search algorithm that is used for end angle tuning.

Magnetic side and surface shims are used for all tuning [8]. Figure 5 shows the typical signatures of such shims.

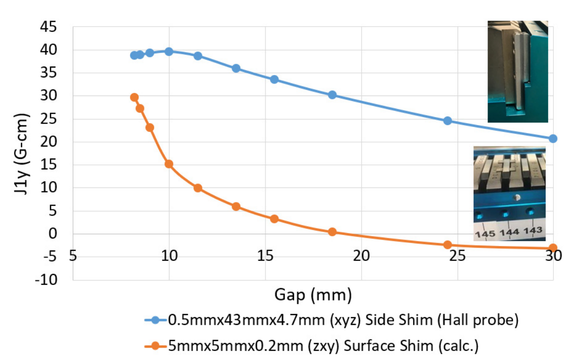

Figure 5: Integrated magnetic field signatures of side and surface shims vs. undulator gap.

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TUNING SCHEDULE

Although challenges were anticipated early on, the tuning schedule now appears realistic due to recent tuning technique developments and the following design features and efforts for new IDs:

- 12 new revolver GSMs fabricated:
  - The revolver IDs undergo final tuning prior to the APS shutdown.
- 10 regular GSMs available for swapping magnet structures:
  - 6 new and 4 spare GSMs used for pre-tuning prior to the APS shutdown.
- New mechanical design:
  - Single magnet keepers (mono-keepers) machined with extreme accuracy.
  - Mono-keepers mounted on either new super-strongbacks or new baseplates (using old strongbacks).
  - Magnets and poles fabricated with high accuracy
  - Magnetic properties tightly controlled (moments, north/side field difference).
  - Narrower magnets and poles → lower forces and gap-dependent deflections.
  - Design proven because only limited phase error tuning was required for the IDs with super-strongbacks (2 of 12 needed minor phase tuning).
- Phase shifters [9]:
  - With magnetic shields to isolate them from IDs.

Due to the high quality of the magnets, it was found that it was not necessary to sort them although most of the 28-mm-period IDs were assembled with sorted magnets [10]. Going forward, this provides valuable time saved during assembly. Additionally, measurements scripts were developed, which are used for automatic gap scans for both magnetic measurement systems.

To date we have completed final tuning of 9 legacy IDs and have pre-tuned all 12 new 28-mm-period IDs (plus one extra), one 25-mm-period ID, and one 21-mm-period ID to the APS-U requirements.

With five remaining storage ring maintenance periods before the APS shutdown, we will continue to swap out IDs from the ring to complete final tuning of most of the 23 legacy IDs prior to shutdown. In parallel we will continue to pre-tune the new IDs and complete final tuning of all revolver IDs.

RESULTS

Although more tuning time is needed for the legacy IDs, with the implementation of the new phase-based mechanical shimming technique, we were able to achieve excellent results with reasonable efforts as can be seen in Fig. 6 (a trailing "S" in the names indicates a "Short" 2.1-m-long device). The RMS phase errors are well below 3° for all gaps. The RMS phase errors are typically even smaller for the new IDs, which are shown in Fig. 7 for three different period lengths.

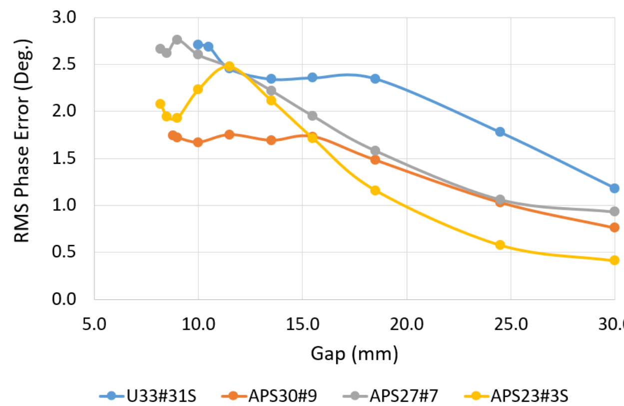

Figure 6: RMS phase error vs. gap of four tuned legacy IDs with 33 mm, 30 mm, 27 mm, and 23 mm period lengths.

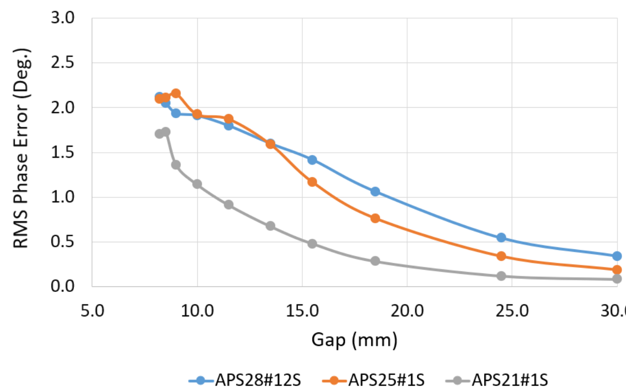

Figure 7: RMS phase error vs. gap of three tuned new IDs with 28 mm, 25 mm (non-revolver ID for testing purposes only), and 21 mm period lengths.

CONCLUSION

Efficient magnetic tuning procedures and techniques were developed and successfully deployed for both legacy IDs and new IDs. We estimate complete tuning takes about one week/device for new IDs and up to two weeks/device for legacy IDs. The final tuning of a pre-tuned device is expected to take less than one week for either type of device as it is a verification measurement to check that nothing changed during the installation of the magnet structures onto a different GSM.

The most time-critical period is during the APS shutdown, with about nine months available to harvest the GSMs from the storage ring, install pre-tuned magnet structures onto mated GSMs, and complete final tuning. However, with recent developments and experience we are optimistic that the tight tuning schedule can be met.

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