ALIGNMENT STRATEGY FOR APS UPGRADE*

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Abstract

The Advanced Photon Source (APS) at Argonne National Laboratory is a 7 GeV third generation light source providing X-ray beams for research to the scientific community since 1995. In order to remain the leading hard X-ray synchrotron radiation facility in the western hemisphere, delivering X-ray beams of high-brightness and high-energy is critical. In 2013, the U.S. Department of Energy (DOE) identified the national need for the APS Upgrade (APS-U) project. Currently, the detailed preliminary design is under development to replace the existing APS storage ring (SR) with a lattice incorporating multi-bend achromat (MBA) technology. Extremely strict alignment tolerances in combination with a very aggressive installation schedule pose unique alignment challenges. The geodetic control network configuration, design of magnet support and alignment systems, magnet mapping and fiducialization, as well as alignment strategy for assembly, testing, and installation in the APS storage ring are discussed.

INTRODUCTION

The APS-U project will upgrade APS to a fourth-generation facility optimized for hard X-rays, ultra-low emittance, and a round source highly preferred by users for imaging. The APS-U will exceed the capabilities of today's storage rings in brightness, coherent flux, and nano-focused flux by two to three orders of magnitude. As part of the APS-U project the APS storage ring will be completely removed and replaced with an MBA lattice [1]. Like today's APS, the proposed APS-U consists of forty repeating sectors. Each APS-U nine-degree-arc sector contains nine magnet modules supported by five concrete plinths (Figure 1). One of the key APS-U deliverables is a one-year dark period, allowing only six months for installation with the rest divided between removal of the old APS hardware and commissioning of APS-U. As a result, the current plan is to install pre-assembled, pre-aligned magnet modules as units. The challenge of a short installation period is matched by equally stringent alignment tolerances. Table 1 lists tolerances relevant to alignment that were derived from the APS-U accelerator physics requirements. The tolerances can be divided into three groups, each requiring a different approach and methodology to meet the requirements. The global tolerances (1 mm level) will be met by survey techniques and APS geodetic control network. The 100 μm tolerances of girder to girder alignment will be achieved by survey measurements, free network bundle adjustment, and relative girder to girder smoothing without engaging the APS reference control. The within girder tolerance of 30 μm component-to-component alignment will be accomplished by a combination of mechanical design, machining tolerances, and magnetic measurements.

Table 1: Survey and Alignment assembly and installation tolerances at start of commissioning.

Parameter	value	units
Storage ring		
Circumference	30	mm
Girders		
Girder to girder alignment	100	μm rms
Elements within a girder		
Magnet to magnet	30	μm rms
Dipole tilt	0.4	mrad
Quadrupole tilt	0.4	mrad
Sextupole tilt	0.4	mrad

Retrofitting an existing facility with a new machine has many advantages but also some downsides, such as physical constraints of the storage ring tunnel walls. On the other hand, the advantages are very significant. Some of the positives are the reuse of existing infrastructure valued at over $1B and intimate knowledge of building behaviour, and existing survey networks. The current plan is to verify and densify the APS survey control network and use it for initial global positioning of accelerator components within the storage ring tunnel. The opinion that global 30 mm circumference tolerance is achievable using the existing reference framework is based on past experience with the network.

SUPPORT AND ALIGNMENT SYSTEMS

The very strict alignment and vibrational tolerances as well as a short installation period are the main driving forces behind the design of the support structures and alignment system. The early involvement of survey and alignment personnel is important for a successful design of a system that will be functional, easy to use, and satisfies physics requirements. The S&A group is involved in providing QA measurements, prototype testing, and validating design performance. Survey data is also important for establishing several key design parameters, like range of the adjustment system and overall height of the support structure.

Having over twenty years of floor settlement data is one of the benefits of upgrading the existing APS storage ring tunnel. The charts of storage ring settlement between 1993 and 2015 (Figure 2.) indicates a few standout areas (around sectors 6, 16, and 33) with noticeably larger settlement. These areas correlate with location of wetlands, that were

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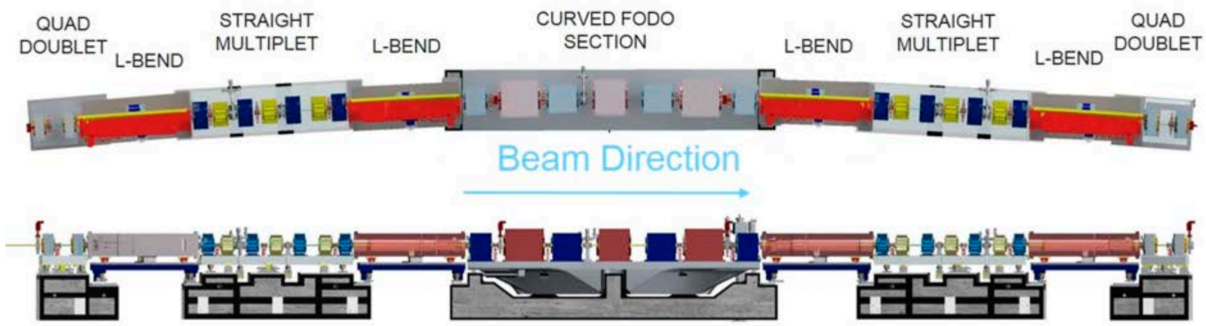


Figure 1: APS-U storage ring sector layout.

relocated and backfilled prior to building construction. Closer analysis of the data reveals that the settlement in these areas has decreased over time. The settlement rate was about 0.45 mm/year over the first ten years but slowed down about fivefold during the second decade to approximately 0.09 mm/year. The worst monitored location settled 6.51mm in total over 22 years, while uplift of the worst point was only 0.86 mm total. Based on this historical data, the range of the girder adjustment system was set at ±13 mm (X,Y,Z) for all APS-U support structures.

The magnet support and alignment system is designed in a modular fashion for a fast installation of pre-assembled units in the storage ring [2]. To speed up the alignment process of magnet modules in the storage ring, a three-point, semi-kinematic, six degree of freedom (DOF) support and alignment system is adopted throughout the design of all module supports. Typically, top to bottom, magnet groups are mounted on a girder (magnet support structure) supported by a concrete plinth via a three-point, semi-kinematic alignment system (Figure 3.). Each concrete plinth is equipped with three temporary outriggers that provide a six DOF alignment system for the whole assembly prior to grouting the plinth to the storage ring floor. During the installation the assembled module consisting of plinth, girder, magnets, and vacuum chamber

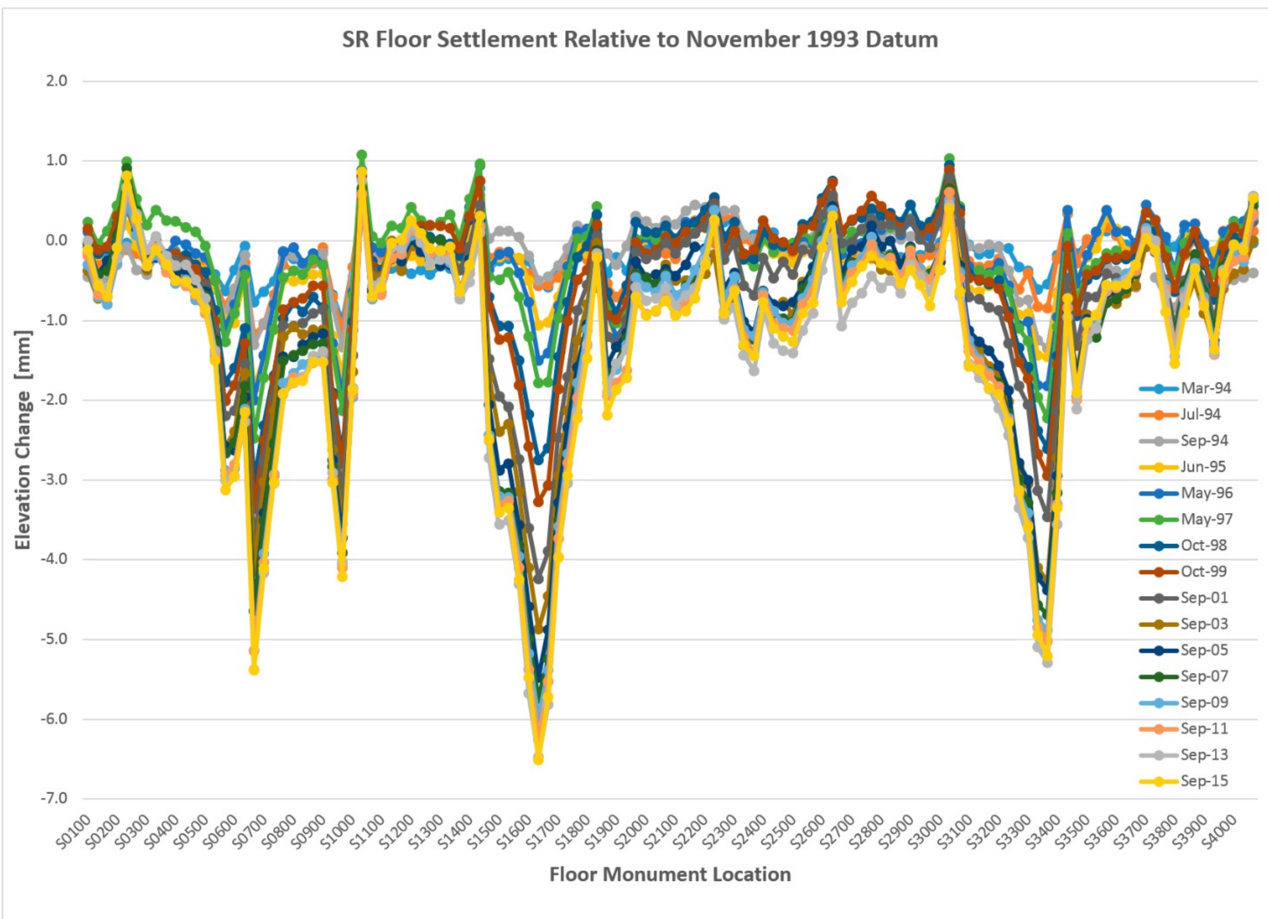


Figure 2: APS SR floor settlement 1993-2015.

is moved into location using an air caster system, rough aligned using the plinth outriggers and grouted to place. The temporary outriggers are removed and reused once the grout has cured.

Many key components of the preliminary design of the support system have already been prototyped and several procedures tested. Numerous prototypes of granite and concrete plinths were compared and analysed. The selected plinth is a hybrid steel and concrete structure developed through an R&D collaboration with a university, concrete fabricator, steel fabricator, and ANL. Through the use of a proprietary low-moisture, low-shrinkage concrete mixture, steel reinforcing bar, and a steel cage which surrounds the concrete, long term shrinkage rates were minimized. Several prototypes of concrete plinths were fabricated and dimensional stability measurements were made over time to monitor shrinkage and distortion (Figure 4.). Less than 20 μm of shrinkage was measured during the first two months when curing produces the greatest changes. During production the plinths will be allowed to cure for six months before sealing with paint.

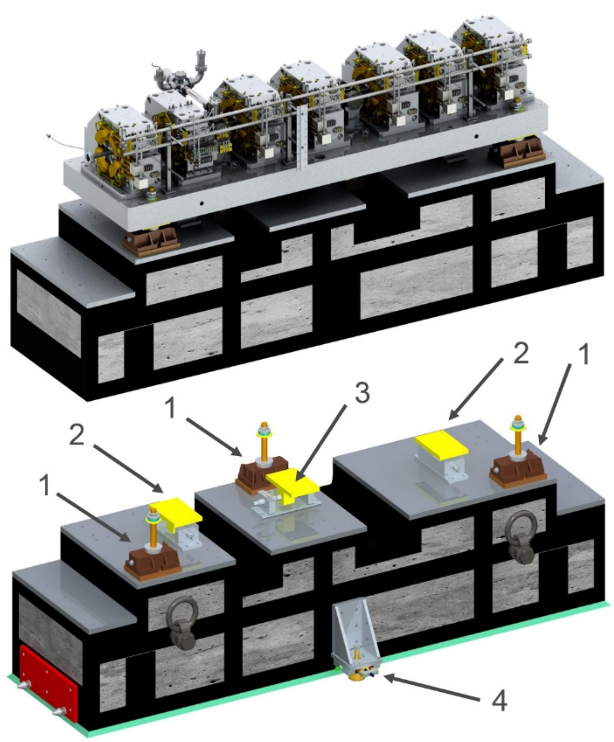


Figure 3: Typical magnet module assembly with concrete plinth support & alignment systems - (1) three-point vertical wedge jack supports, (2) lateral pushers, (3) longitudinal pusher, (4) support outriggers (3 total).

As part of the extensive R&D program, the Demonstration Multiplet Module (DMM) was built as well as prototypes of plinth outriggers. From an alignment point of view, both systems performed well in terms of sensitivity, repeatability, and ease of use, with only a few minor design changes suggested. Parallel to DMM testing, some installation procedures were also tested, for example transportation of the plinth with an air caster system and plinth grouting.

While the DMM uses thick steel plate as the magnet support structure (girder), for the future preliminary design R&D is investigating using engineered cast ductile iron structures as girders for a majority of magnet modules. Taking advantage of topology optimization software (GTAM), cast iron girders can be designed to minimize the static deflection along the beam path and maximize the fundamental frequency [3]. The first prototype of the cast iron girder is expected to arrive at APS in December 2016 as part of the FODO module support system. The FODO module is the largest of all the APS-U modules and is a core of many R&D activities [4].

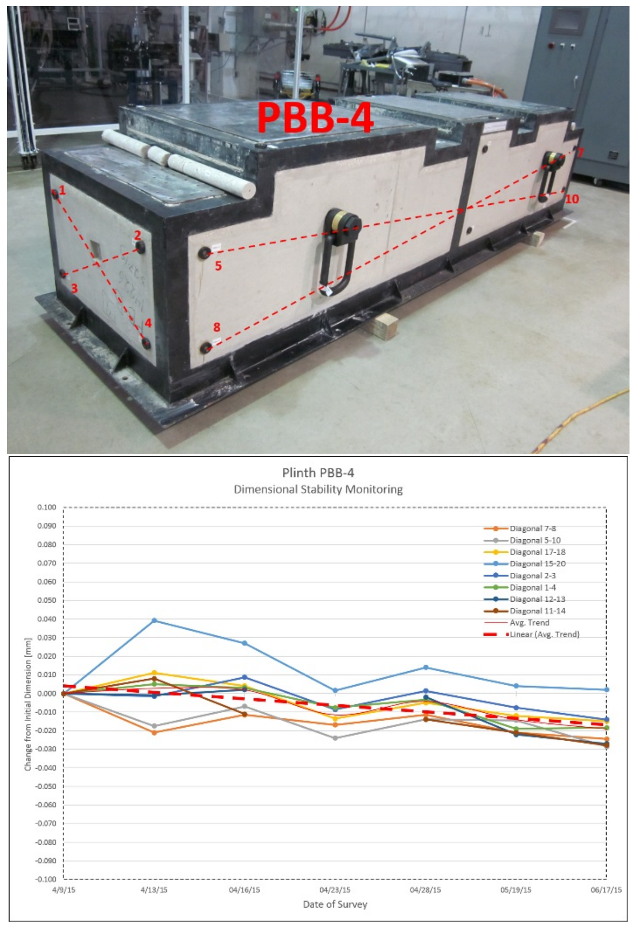


Figure 4: Concrete plinth shrinkage monitoring.

MAGNET MAPPING AND FIDUCIALIZATION

Early in the project it was recognized that meeting 30 μm magnet-to-magnet tolerance will be very challenging. The decision was made to pursue a solution of combining mechanical design with machining tolerances and magnetic mapping to achieve this tolerance. A major part of the R&D program for preliminary design was building a Demonstration Multiplet Module to investigate feasibility of this approach.

The DMM module consists of a string of four quadrupoles and one sextupole resting on a thick steel plate representing a girder. The plate is supported by a prototype alignment system and a concrete plinth (figure 5). Magnet

Figure 5: The DMM module measurements.

poles are precisely machined relative to the fiducial surfaces on the outside of the magnet that match the corresponding precisely machined surfaces of the girder. The initial alignment of the magnets on the girder relies strictly on the machining tolerances of the mating parts. After assembly, the magnetic fields of the magnets are measured with a rotating wire. Based on the magnet mapping data, magnets are then shimmed and the process is repeated if necessary. The DMM magnets were aligned within 10 microns after two iterations as indicated in figure 6. It is worth noting that the initial position of quadrupole Q-A002 was not quite as good as the other magnets. The Q-A002 was the first magnet built without the post-assembly machining step incorporated into the assembly procedure for the other magnets. One iteration took about 45 minutes to accomplish and it is expected that only one iteration will be needed when using the improved assembly procedure. The magnet and girder fiducials are then measured with respect to the axis of rotation of the wire with a laser tracker. The axis of wire rotation is defined by connecting

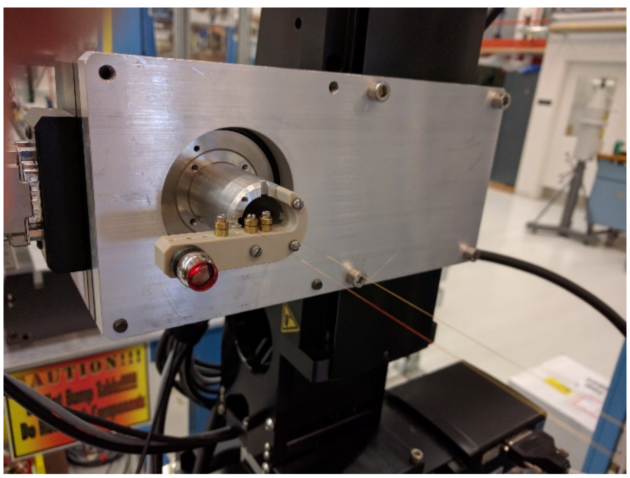


Figure 7: Rotating wire measurements and alignment.

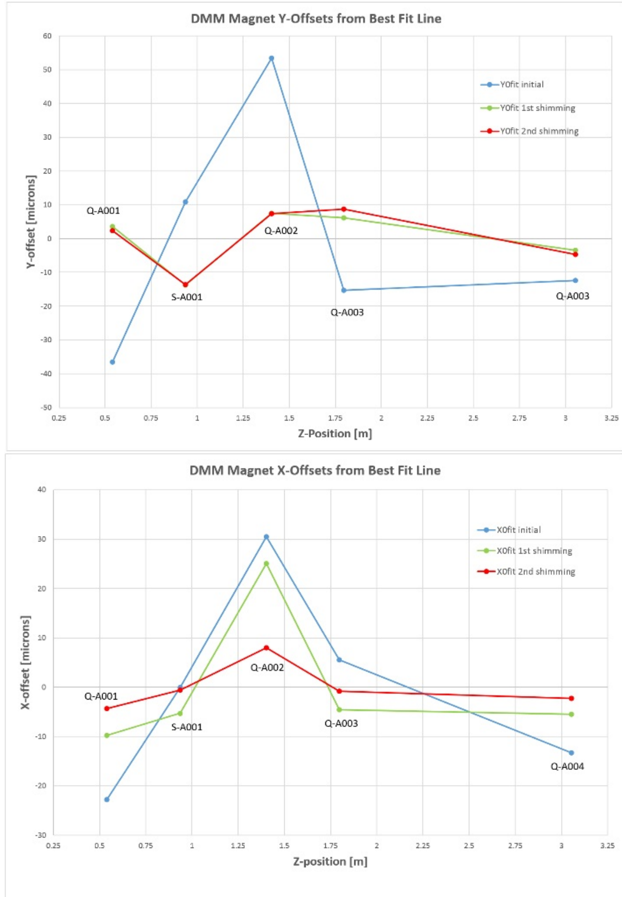
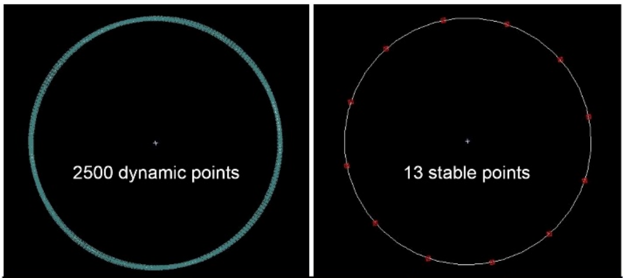


Figure 6: DMM magnet alignment.

centers of circles traced by a small 0.5” laser tracker retroreflector that is attached to the same fixture that rotates the wires (figure 7). Two methods of measuring the circles were compared. In the first one, 2500 dynamic measurements were taken 1 mm apart while the fixture was spinning. In the second method 13 stable points were measured after rotating and stopping the fixture in 30 degree intervals. Viability of both methods is imperative since spacing of magnets in some cases forces the tracker to measure a circle from a side in a static mode and the operator has to point the retroreflector manually to the tracker. The results of both methods are encouraging and shown in figure 8. The center of the rotation is determine with an accuracy of a few microns by both methods. This is on par with uncertainty of fiducial points, that is in the range of 10-15 microns determined from bundle adjustment of several stations measured with a Leica AT930 laser tracker.

In production, the magnet modules will be assembled off-site and completely pre-aligned units will be transported into the storage ring. The magnetic mapping cannot be repeated in the storage ring and survey techniques are inferior to magnetic measurements in terms of accuracy. Additionally, there will be no time to re-align magnets on the girder in the SR tunnel, so importance of stability of alignment during transport is very significant. As part of the rigorous testing program, the DMM was



CIRCLE	CENTER X (mm)	CENTER Y (mm)	CENTER Z (mm)	RADIUS (mm)	NO. OF POINTS MEASURED
DS DYNAMIC 1	-0.003	0.002	3482.250	36.594	2500
DS DYNAMIC 2	0.001	0.002	3482.251	36.591	2500
DS DYNAMIC 3	-0.002	0.002	3482.251	36.595	2500
DS STABLE MODE (REF)	0.000	0.000	3482.251	36.597	13

Figure 8: Determining point on axis of the rotating wire.

subjected to a transportation test. After the baseline magnet mapping, the DMM plate with magnets was loaded on a truck and went for a test ride. Then the second set of magnetic measurements were taken and later the whole assembly, including plinth, was driven around the site and then re-measured. The positioning of magnets repeated within 5 μm, the three sets of data are plotted in Figure 9.

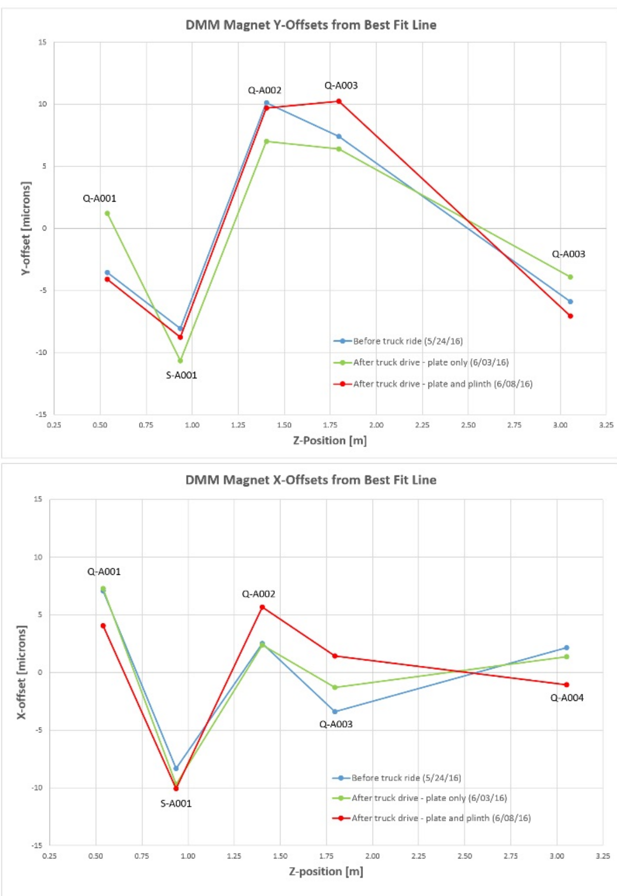


Figure 9: DMM transportation test results.

CONCLUSION

The importance of the Survey and Alignment Section during the assembly and installation phase of the APS-U is clear but the role of S&A during the preliminary design is equally significant. Quality control of component hardware, testing of prototype support and adjustment systems, and assistance during fiducialization and magnet mapping - these all contribute to the development of a successful design that will be easier to implement. Besides, there are many R&D activities related directly to survey and alignment. Although we are only in the preliminary design stage we are becoming more comfortable with the alignment tolerances that need to be achieved. We have reached initial agreement on several ideas of how to approach each group of tolerances and what directions R&D for survey and alignment needs to pursue to validate them. The global tolerances can be met with the existing APS control survey network. The network will need to be verified and optimized, and an observation plan developed. The solution for the most challenging tolerance of 30 μm alignment of component-to-component within girder looks very promising. The DMM tests validated the approach of a combination of mechanical design with machining tolerances, and magnetic measurements. Again, more work has to be done on optimization of this process and testing the effects of thermal changes, transportation, and long term storage on the stability of alignment within a magnet module. Also significant R&D effort will be needed for areas so far neglected – development of a database for S&A data and survey data flow for APS-U

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