VALIDATION OF APS-U MAGNET SUPPORT DESIGN ANALYSIS AND PREDICTION*

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ABSTRACT

The Advanced Photon Source Upgrade (APS-U) accelerator magnets have stringent stability requirements [1]. The project schedule and budget did not allow for full prototyping of the final design. Therefore, the engineers relied on accurate simulation to ensure that the design would meet the specifications. Recently, assembly and free-boundary vibration tests have been done on the first article of the upstream quadrupole Doublet, Longitudinal gradient dipole and Multipole module (DLM-A). The top surface flatness of the girder and the magnet alignment measurement results demonstrate the static positioning requirement of magnet-to-magnet is met. The free-boundary condition modal test results were used to validate dynamic performance of the FEA analysis used in the DLM-A design. These validations then confirm the predicted performance of the magnet support system design. Mode shapes and corresponding frequencies from the FEA modal analysis agree with the experimental modal analysis within an acceptable tolerance. The validation approves not only the procedure for accurate modelling of magnet support system that APS-U has developed, but also provides confidence in predicting the accelerator performance.

INTRODUCTION

The Advanced Photon Source Upgrade (APS-U) accelerator magnets have stringent stability requirement [1]. Some of the requirement are listed in Tables 1 and 2, which service as a guideline through all design phases.

The APS-U magnet support design has gone through phases of conceptual, preliminary, and final design. In preliminary design a prototype of FODO module assembly was reported [2-5]. The magnet grouping has been changed through the design phases [6]. Figure 1 shows APS-U magnet grouping of final design. The "QMQ" places a dipole magnet with its adjacent two quadrupoles on a common support (girder), while "A" and "B" imply upstream and downstream positions. Three plinths provide support to corresponding girders above each, while a QMQ girder is supported on adjacent plinths at each end.

A testing and modelling process has been developed and established to close the loop on the design-analysis-testing workflow [4, 7]. This process provides confidence in simulation results and enables the exploration of many different design iterations using the same components.

These design iterations reflect updates of constraints, such as more stringent space limitations from interfacing systems. The support components between girder and plinth are also updated. Some constraints remained the same throughout the process, such as maximizing eigenvalues of low vibration modes of the system, whose mode shapes would cause dynamic deformation in a direction transverse to the beam path. For static deformation, minimizing the girder deformation improves alignment between magnets within a girder. One must also ensure that thermal fluctuations within the storage ring tunnel will not cause unacceptable changes in magnet alignment. Fabrication and material selection also constraint the design. All these constraints play roles in optimizing the design at each iteration.

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Table 1: Positioning Tolerances

Elements within a girder		
Magnet to magnet (2 sigma cutoff)	30	µm rms
Dipole roll	0.4	mrad
Quadrupole roll	0.4	mrad
Sextupole roll	0.4	mrad

Table 2: Vibrational Tolerances

(1-100 Hz)	X (rms)	Y (rms)
Girder vibration	20 nm	20 nm
Quadrupole vibration	10 nm	10 nm
Dipole roll vibration	--	0.2 µrad

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Recently, the first article of the DLM-A module magnet support system arrived. Girder flatness was measured, both with and without magnets installed. Then, assembly of the DLM-A module without the APS-U vacuum system was completed. A free-boundary condition experimental modal analysis (EMA) was conducted using a Data Physics Abacus DAQ system [8] and Vibrant Technology MEScope [9] for modal property estimation. These results were used to validate the finite element (FE) analysis used in the DLM-A design.

This design-analysis-measurement chain for the DLM-A module validates the FEA prediction and modelling process. This validation provides confidence in predicting the accelerator performance.

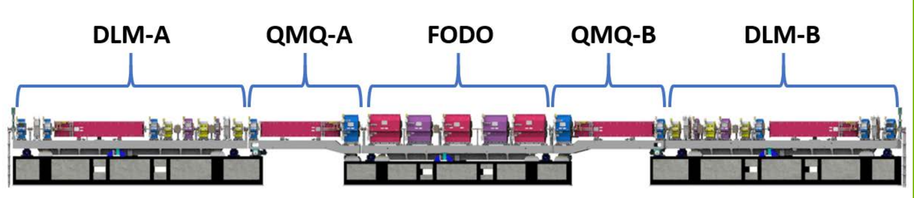

Figure 1: APS-U magnet grouping of final design

VALIDATION: STATIC RESULTS

The girder was machined and measured with a Leica AT930 laser tracker while constrained by three vertical supports at the same locations used to support the girder in operation. The location of those three supports was chosen to minimize the girder static deflection.

In addition, mounting surface of magnets and stop blocks are precisely machined. Magnet alignment is achieved by precisely machining the girder reference surfaces, combined with shimming in the cases where it is necessary.

The flatness of the girder prior to mounting magnets reflects machining accuracy. It's checked using the Leica AT930 laser tracker. The DLM-A girder is coated in a thin layer of Molykote Tecnite 3402 for rust prevention. The thickness of the coating varies from ~10 to 30 microns over the girder surface. The measurements include the effect of the coating. Many points on the top magnet-mounting surface of the 5.6m long girder were measured (Fig. 2). Flatness of the girder is ±18 microns peak-peak [10]. After the magnets are positioned, the measured surface flatness of DLM-A girder is ±23 microns (Fig. 3), while FEA predicted flatness is ±29 microns in Fig. 4. Part of the magnet alignment survey data [10] are listed in Table 3, approving the magnet alignment in the critical X and Y directions meet the 30 microns RMS tolerance in Table 1.

Table 3: Magnet Alignment Survey Results

	X offsets (µm)	Y offsets (µm)
Measurement	9, rms	13, rms
Uncertainty	7, rms (magnitude)	

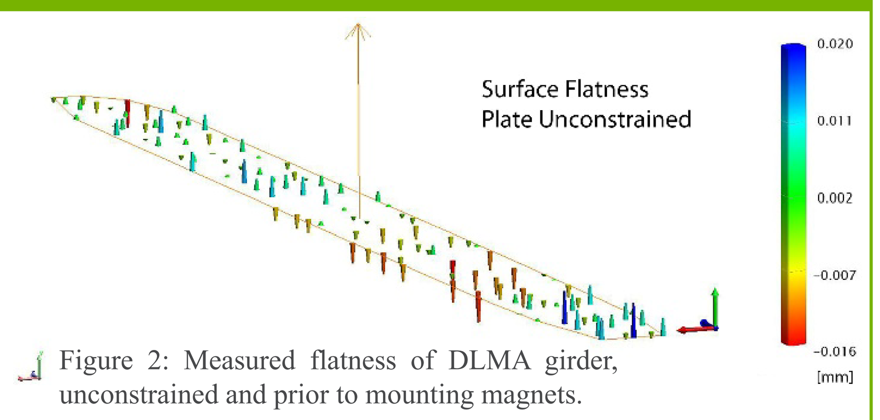

Figure 2: Measured flatness of DLMA girder, unconstrained and prior to mounting magnets.

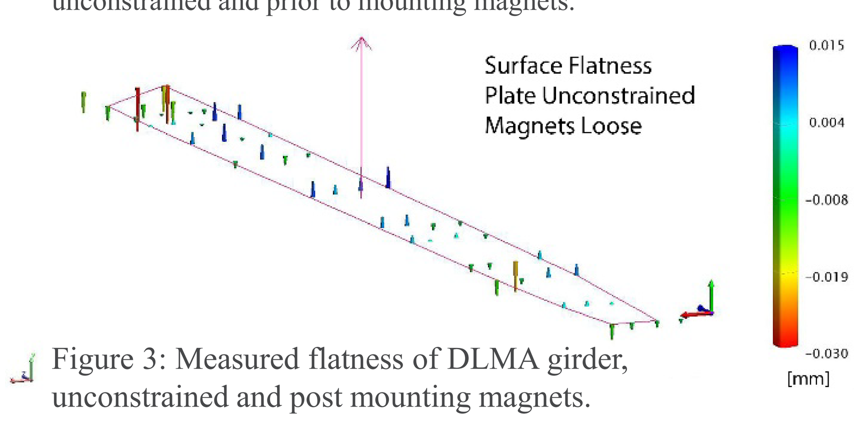

Figure 3: Measured flatness of DLMA girder, unconstrained and post mounting magnets.

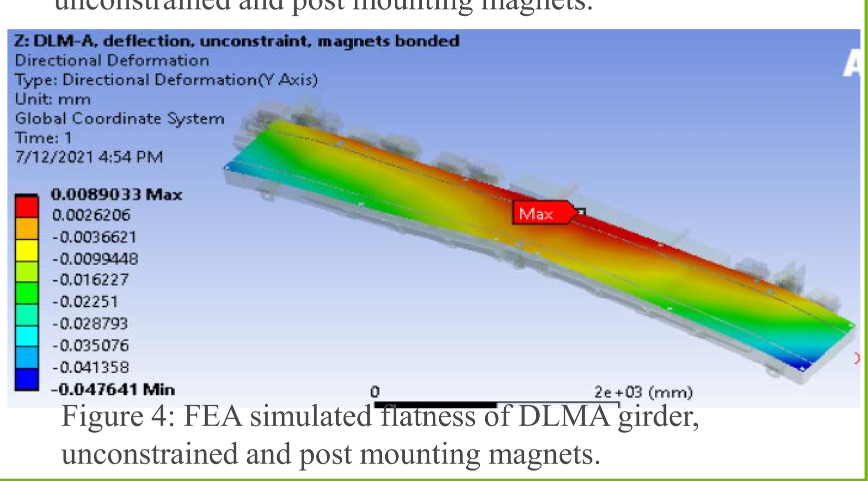

Figure 4: FEA simulated flatness of DLMA girder, unconstrained and post mounting magnets.

VALIDATION:FODO PROTOTYPE

Previously, the FODO prototype provided validation to the design and analysis process for the support systems [7]. A full prototype was constructed, consisting of the girder, the plinth, and a set of support and alignment mechanisms. Analyses were carried out, along with EMA of both the components and the whole prototype FODO module, including both free and grouted boundary conditions. The results of all tests were found to compare well with the results from the analyses.

Girder: Ductile cast iron, A536, GR-60/40/18 was chosen as the girder material because of its design flexibility, low cost, and favourable vibration damping properties [3, 5]. Figure 5 shows the FODO prototype girder casting at the manufacturer, rigging for a free BC EMA [7]. The EMA and FEA results are compared in Table 4. It confirms the assumption that material properties of the cast iron in FEA are sufficient to predict its behaviour.

Figure 5: FODO prototype undergoing free BC EMA.

Plinth: The prototype FODO plinth was a steel-reinforced concrete structure developed through a research and development collaboration with a university, concrete fabricator, steel fabricator, and ANL [5]. The steel-reinforced concrete structure was chosen for the favourable performance, cost, and convenience of local fabrication. As with the girder, a finite element modal analysis and EMA were performed. The results com-pared well and are shown in Table 5.

Table 4: Girder Modal Results (Avg. Difference 1.99%)

Mode	EMA (Hz)	FEA (Hz)	% Diff
1	106	104	1.89
2	157	154	1.91
3	232	227	2.16

Table 5: Plinth Modal Results (Avg. Difference 5.4%)

Mode	EMA (Hz)	FEA (Hz)	% Diff
1	38	41	7.9
2	83	84	1.2
3	97	104	7.2

Support Components:

Dynamic stiffness testing was conducted on the ver-tical and lateral support components. Linearized stiff-ness coefficients were determined for a variety of wedge jack adjusters, spherical bearings, metal-polymer bearings, and load conditions [7]. These com-ponents all have stiffnesses that are highly dependent on load. The experimentally measured values are the key information to be used with simplified geometry for accurate FEA.

Table 6: Grouted FODO Prototype Modal Results (Avg. Difference 8.6%)

Mode	EMA (Hz)	FEA (Hz)	% Diff
1	41	42	2.4
2	54	62	12.9
3	69	77	10.4

Grouted FODO Prototype:

After the subcomponent test the full FODO assembly was grouted to the floor and underwent EMA. The first three EMA modes are shown in Table 6 to match well with the first three FE modes, with an average error of 8.6%. With the models of the girder, plinth, previously validated, the experimentally measured support stiff-nesses, and the assumed load on the supports, the close match confirms that the rigid ground assumption is valid. This also validated the whole design-modelling process, and this process was key for the final design.

VALIDATION: DLM-A FIRST ARTICLE

Evolving accelerator design constraints meant the magnet support final design was quite different from that in preliminary design. For example, the girder width is 750 mm rather than 1 m, the wedge jack of vertical supports is Nivell DK-2/10 rather than Airloc 2012-KSKCV, and the plinth geometry is simplified. The previous validation of the process with the FODO prototype and its components provides confidence in the approach to final design. The stiffnesses of the support components was obtained through the same dynamic testing process. The girder and plinth proper-ties did not change, only the geometry, so all previous assumptions are still valid. As discussed in ref [7], the confidence leads to production of the final design.

Without prototyping and further validating individual components in the final design phase, the first article of DLM-A support system arrived. Figure 6 shows the first article DLM-A being lifted for a free BC EMA. Table 7 shows the good comparison between the EMA and FEA for first five modes. Note the good match for even the higher modes. Figure 7 shows match of the first natural frequency and mode shape as example.

Figure 6: DLM-A first article undergoing free BC EMA.

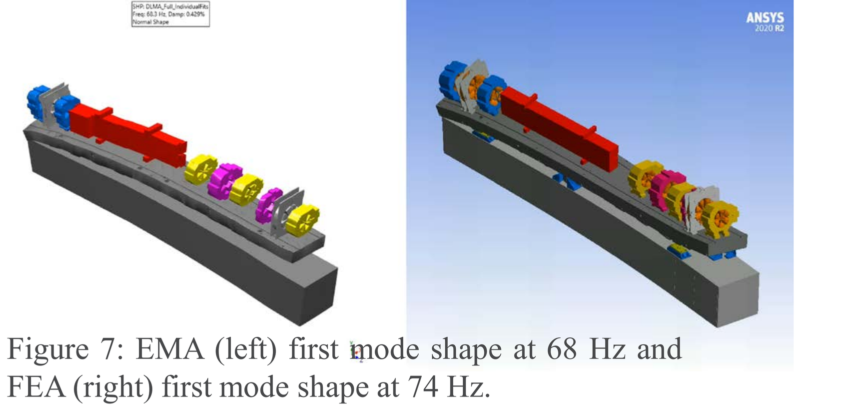

Figure 7: EMA (left) first mode shape at 68 Hz and FEA (right) first mode shape at 74 Hz.

Table 7: DLM-A First Article Free BC EMA Modal Results (Avg. Difference 6.0%)

Mode	EMA (Hz)	FEA (Hz)	% Diff
1	68	74	8.8
2	71	76	7.0
3	85	88	3.5
4	91	83	8.8
5	101	103	2.0

CONCLUSION

The FEA prediction of the FODO prototype in pre-liminary design is validated by the free BC EMA results, which provide confidence to start designing the final magnet modules without further prototyping and validation. The DLM-A design has been shown to exceed the 30 microns rms magnet-to-magnet positioning tolerance through measurements on the first article [10]. The free BC EMA data of the DLM-A first article also confirm the confidence in design iterations. The validation confirms not only the procedure for accurate modeling of the magnet support system that the APS-U has developed, but also provides confidence in predicting the accelerator performance. For example, a novel approach to estimating mechanical motion-related orbit distortions [6, 11] is based on FEA results of the modes of girders. The accuracy of FEA predictions is expected within 10 percent..

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