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MAGNET MEASUREMENT SYSTEMS FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The present storage ring at the Advanced Photon Source will be replaced with a new ring based on a Multi-Bend Achromat (MBA) design as part of an upgrade currently in construction. The new ring will require about 1320 new magnets which need to be measured and fiducialized to ensure field quality and alignment requirements are met. Seven test benches were designed and built to meet these measurement requirements. Field quality in the multipole magnets is measured using four rotating coil benches, whereas the longitudinal gradient dipoles are mapped using a Hall probe system. Two rotating wire benches are used to find the magnetic centers of multipoles and relate them to magnet fiducials using laser trackers. Mechanical designs of the measurement benches are presented.

INTRODUCTION

The Advanced Photon Source-Upgrade (APS-U) project [1] is under construction at Argonne National Laboratory. As part of this upgrade the present storage ring will be replaced with a new ring based on a Multi-Bend Achromat design. The new storage ring will require about 1320 new magnets and magnetic measurements are needed to characterize and fiducialize all these magnets to ensure field quality and alignment requirements are met.

Seven specialized test benches, as listed in Table 1, were designed and built to meet the measurement requirements for the APS-U project. Four of these benches are rotating coil benches for measuring field harmonics in multipole magnets (quadrupoles Q1-Q3, Q6 and Q7, sextupoles S1-S3, fast correctors FC, and combined dipole-quadrupole magnets Q4, Q5, Q8, M3 and M4). Two rotating wire benches were setup to fiducialize all the multipole magnets. The longitudinal gradient dipoles (M1, M2) are mapped using a Hall probe system which is also designed and built in-house. The salient mechanical features of these benches are described in the following sections.

COMMON FEATURES

All the rotating coil and rotating wire benches employ similar design features and use standardized commercial hardware to the extent possible. All benches use a block of granite supported by a custom steel stand as the base on which the measurement equipment is mounted. The stand has six adjustable feet for levelling and to distribute the load. The magnet under test (MUT) is placed near the center of the granite on a 1.0-inch-thick ground steel plate. All APS-U magnets have built-in side and bottom reference surfaces and the benches make use of these same surfaces to quickly align the magnets to the rotating coil axis by banking against stop blocks fixed on the magnet support plate. Magnets of different sizes are accommodated on the same bench by changing aluminum shims between the stop blocks and the magnet reference surfaces.

Table 1: Magnetic Measurement Benches for APS-U

Bench	Magnet Types	Quantity
Rotating Coil (RC1)	Q1-Q6	492
Rotating Coil (RC2)	S1-S3, FC	411
Rotating Coil (RC3)	M3, M4	123
Rotating Coil (RC4)	Q7, Q8	164
Rotating Wire (RW1)	Q1-Q5, S1-S3	656
Rotating Wire (RW2)	Q6-Q8, M3, M4	369
Hall Probe (HP1)	M1, M2	164

The rotating coil and rotating wire systems have gravity sensors on the rotary encoders and magnet support plate to allow measurement of the magnetic roll angle in a frame where the bottom reference surface of the magnets is level. The measurement resolution is ~0.010 mrad and the absolute angle measurement is calibrated to better than 0.1 mrad.

ROTATING COIL SYSTEMS

A total of four rotating coil measurement benches (RC1-RC4) were designed and built to accommodate the large variety and quantity of magnets needed for the APS-U project (see Table 1). A typical rotating coil bench is shown in Fig. 1.

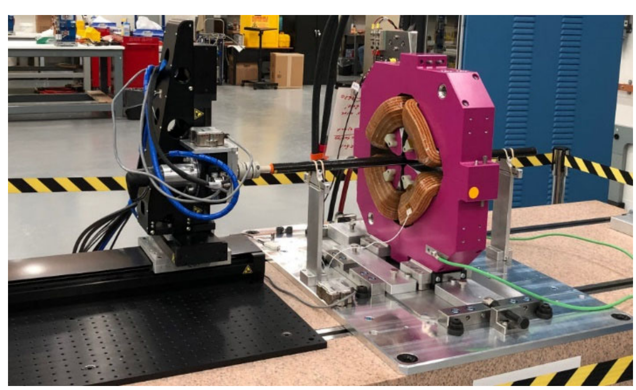

Figure 1: One of the rotating coil benches showing the granite block, XYZ-θ stages, magnet support plate, stop blocks and customized shim plates for alignment in X, Z.

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The RC1 and RC2 benches are functionally the same and were designed to measure the smaller quadrupole, sextupole and fast corrector magnets (Q1-Q6, S1-S3 and FC). Both RC1 and RC2 use the same 0.481 m long printed circuit (PCB) coil [2] built by Fermilab. The PCB coil design offers unbucked (UB) and suitably bucked signals for accurate measurement of field harmonics in dipoles, quadrupoles and sextupoles. The PCB coil is mounted on a 3-D printed coil support and rotates inside a carbon fiber cylindrical housing. The coil shaft is attached to a Newport rotary stage (θ-stage), which is mounted on Newport X-Y-Z linear translation stages. The transverse (X) and vertical (Y) stages have a travel of 100 mm in most benches. The Z-stages in these two benches have a travel of 0.6 m used to place the coil into and out of the magnet. Both benches have performed flawlessly over the course of more than 850 magnets measured so far.

The RC3 and RC4 benches are functionally similar and were designed to measure the larger combined function transverse gradient dipoles (M3, M4 and Q8) and the larger quadrupoles (Q7). The two PCB coil-probe supports in these two benches are attached to two X-stages which allow programmable X-motion of the coil-probes. The three X-stages (two coil probe supports, and the coil drive system) move in unison to allow placing the coil-probe at a desired X-offset from the magnet's geometric center during measurements. The coil support assemblies have a custom designed set of concave rollers which constrain the coil probe in X and Y but allow the coil to move freely in the Z-direction. The Z-stages have a travel of 1.2 m. The coil-probe housings have a physical length of 2.5 m and are designed in two sections which can be easily separated using a custom screw joint. During magnet installation and removal, the section of the coil probe not connected to the rotary stage is removed and the remaining section is retracted from the magnet bore using the Z-stage. Without this removable section, one would need a much longer travel on the Z-stages, and nearly twice the space in the measurement laboratory.

The RC3 bench, designed for measurements of the M3 and M4 transverse gradient dipole magnets, utilizes a PCB which is 400 mm in length. These magnets are essentially offset quadrupoles, with curved poles to follow the curvature of the beam. In order to measure the field harmonics integrated along the curved beam path using straight rotating coils, a method was developed [3] where the field is measured in three axial segments with suitable X-offsets at each position to follow the beam path. The results of these three measurements are combined mathematically and post-processed to determine the field strength and harmonics integrated on the curved path.

The RC4 bench is designed for the Q7 and Q8 magnets and utilizes a 1-m long PCB coil for integral measurements. Although the Q8 magnet is also a combined function magnet with slightly curved poles, the sagitta is very small (0.433 mm). Analysis of field maps computed using Opera-3D simulations showed that it is sufficient to measure the integral field using a single long rotating coil. The supports for the coil-probe and the motion control configuration is identical to the RC3 system, so these two systems can serve as a backup for each other if such a need arises.

ROTATING WIRE SYSTEMS

The RW1 and RW2 rotating-wire systems were designed to locate the magnetic center of the multipole magnets and relate it to fiducials which are accessible on the magnet exterior. The uncertainty in determining the magnet center with this method has been shown to be better than 10 microns [4]. The main difference between the two benches is that the RW1 utilizes one granite base with 600-mm Z-stages and RW2 uses two granite bases with 1.2-m Z-stages to accommodate the large Q7, Q8, M3 and M4 magnets.

Each rotating-wire bench utilizes two XYZ-θ stage assemblies facing each other on each end of the MUT, as shown in Fig. 2. These stages allow programmable X and Y linear motion of a one-turn loop of 0.100 mm diameter Cu-Be wire which is stretched between the two sets of θ-stages. The width of the wire-loop, 8-mm for RW1 and 10 mm for RW2, is determined by precision-ground pulleys which are attached to the θ-stages. During magnetic measurements the wire-loop is rotated at 1 Hz via the two synchronized θ-stages. The offset from the wire-loop rotation center to the magnetic center is determined by analyzing the induced signal on the wire-loop.

The average wire sag over the magnet length is determined by measuring the resonant frequency and the wire length. The X-Y stages are placed such that the rotation axis of the wire-loop *at the magnet location* is at the magnetic center in X and is below the magnetic center in Y by the value of the wire-sag. The wire *ends* are thus aligned to the magnetic axis, compensating for wire sag.

The wire holders have a nest to affix a spherically mounted retroreflector (SMR) for laser tracker measurement of the wire rotation centers. The circular path of each wire-loop holder is measured, and the center of rotation is then fitted for each. A line constructed between the two end points defines the magnetic axis. Knowing the measured magnetic axis and surveying the magnet fiducials and other alignment features on the magnet, the magnetic center is related to externally accessible features. This relationship is used to align magnets to each other on module assemblies.

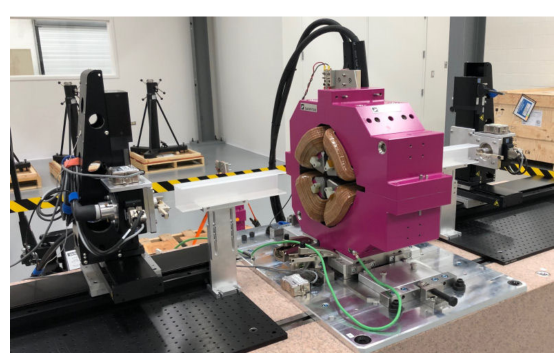

Figure 2: One of the two rotating wire benches showing motion stages and wire holders on both ends. Most of other mechanical features are similar to the rotating coil benches.

HALL PROBE FIELD MAPPING BENCH

The M1 and M2 longitudinal gradient dipole magnets are magnetically measured with a Hall probe-based system (HP1). This system includes a Hall probe sensor translation bench (HP1-A), and a magnet support bench (HP1-B) as shown in Fig. 3.

The magnets are pre-surveyed on a separate bench (HP1-PS) with a laser-tracker by measuring the top and bottom pole profiles and magnet fiducials. This bench is a precision granite surface plate used to support one M1 or M2 dipole magnet at a time. The goal of the pre-survey is to define the local "Magnet Coordinate System" (MCS) based on the as-built geometry for each magnet and relate this to the magnet fiducials.

The HP1-A and HP1-B benches are located in a temperature-controlled room and are aligned laterally to one another, with approximately 100 mm gap between them. The HP1-B supports the MUT and is decoupled from the HP1-A bench which supports the motion control stages and the Hall probe assembly. The HP1-A bench is a unique profiled granite bench that supports the three independent linear motion stages used to position a 3-axis Hall probe. The profile is designed to facilitate mounting of the long Z-stage which needs to be bolted from below. Due to a very high aspect ratio of length-to-width of the granite, a unique support system for the granite was employed. Two independent leg support assemblies were designed to not only support the granite, but to allow for the granite to be levelled without imposing a longitudinal torsional moment load onto the granite.

The top surface of HP1-A supports a 3-m-long linear THK Z-stage. The carriage of the Z-stage supports an X-Y-θ stage assembly with Newport motion control stages. The θ-stage supports a cantilevered Hall probe holder assembly. The probe holder assembly contains a 3-axis F3 type Senis Hall probe and two Metrolab NMR probes used to calibrate the Hall probe in-situ in the MUT.

A "Stage Coordinate system" (SCS) was defined based on fiducials on the HP1-A granite bench. The motion of the XYZ stages was measured with a laser tracker over the range of the stages and "motion vectors" relative to the SCS were derived. It should be noted that while these motion vectors are nearly orthogonal, they do not constitute a true Cartesian coordinate system.

A permanent-magnet-based skew-quadrupole "Reference Magnet" (RM) is used to relate the sensitive area of the Hall probe elements in the SCS coordinates. A virtual magnetic center of the RM is determined and related to fiducials on its yoke.

Once a MUT is placed on the HP1-B bench, the MUT, HP1-A and RM fiducials are measured using a laser tracker. Using the pre-survey data, the MCS is related to the SCS. The required motion of the XYZ stages can then be computed such that the field map is measured on a rectangular grid aligned to the MCS. This procedure eliminates the need to precisely align the MUT to the SCS. Use of motion vectors also eases the requirement to precisely align the motion stages orthogonal to each other. Typically, field measurements are performed as a set of line scans along the magnet Z-axis at fixed X and Y positions. The Hall probe data are acquired on-the-fly at 1-mm increments in Z with a velocity of 27 mm/s. A zero-Gauss chamber is used to measure and record the Hall probe offset voltages which are later subtracted from the raw Hall voltages.

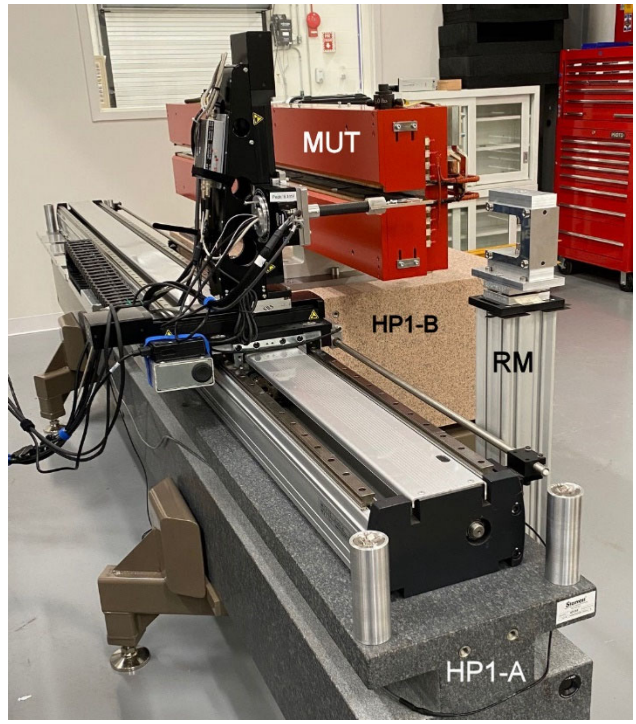

Figure 3: Hall probe field mapping system showing the HP1-A bench with a custom profiled granite block and support stand, the HP-1B bench used to support the magnet under test (MUT) and the reference magnet (RM).

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