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A NEW MAGNETIC MEASUREMENT SYSTEM FOR THE FUTURE LOW EMITTANCE NSLS-II STORAGE RING*

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Abstract

A new magnetic measurement system is under construction at BNL for accurate field harmonic measurements and fiducialization of magnets for a future upgrade of the NSLS- II storage ring. The entire storage ring is envisioned to be replaced with a new lattice concept, known as Complex Bend, which superimposes dipole and high-gradient quadrupole fields. The magnetic measurement system will use rotating wire and a PCB rotating coil specifically designed for small-aperture (< 15 mm) high gradient magnets. In this paper we describe in detail the mechanical design and the data acquisition hardware and software.

INTRODUCTION

Achieving a low-emittance ring design with high brightness is one of the most challenging aspects of advanced synchrotron light source projects. The major planned future improvement and upgrade of the National Synchrotron Light Source II (NSLS-IIU) at Brookhaven National Laboratory (BNL) is to replace the existing Double Bend Achromat lattice (DBA) with a new lattice element called "Complex Bend" [1-3], which consists of a combination of dipoles and high-gradient quadrupoles with superposing fields [4]. This approach provides reduction of the electron beam emittance to about 20 pm. Accurate and precise higher-order field harmonic measurements are essential to guarantee that the field performance of future magnets fulfils the demanding specifications.

MAGNETIC MEASUREMENT EQUIPMENT

The magnetic measurement system configured at NSLS-II is based on the measuring bench developed at Argonne National Lab (ANL) for the Advanced Photon Source (APS) upgrade project [5].

The new measuring bench consists of a Printed Circuit Board (PCB) rotating coil, designed for measuring field strength and field quality to a level of 0.1 units up to the 15^{th} harmonic and a rotating wire system for determining the magnetic center and for fiducializing multipole magnets with an accuracy better than 10 µm using a Laser Tracker.

Rotating Wire System

Field integral measurement with continuously rotating wire loop was first tried at SPring-8 for the magnetic measurement of an undulator with 3 mm gap [6]. Unlike a flip coil bench with finite rotation angle, continuously rotating system can use various techniques to improve a S/N ratio.

The measurement bench is assembled on a 2.75 m long granite block supported on 3 leveling jacks. The leveling jacks are JOYCE WJ123 with a 3 Ton capacity, 1 inch of screw travel and 12:1 ratio gearset. The granite block has machined T-slots and Survey & Alignment holes. Both the magnets and the stages are supported on three anodized aluminum plates affixed to the granite surface. Stop blocks on the center plate provide banking surfaces to align the magnet to the rotating wire. Other banking alignment features, such as magnet pushers and support assemblies, help to align the rotating wire and rotating coil to any type of magnet. Aluminum shims between the stop-blocks and the magnet reference surfaces are used depending on the geometry and dimensions of the magnet to be measured. The two outer aluminum plates are populated with Newport X,Y, Z and R stage assemblies as shown in Fig. 1. Thus there is independent X, Y, Z and R positioning at each end of the bench which can operate in tandem.

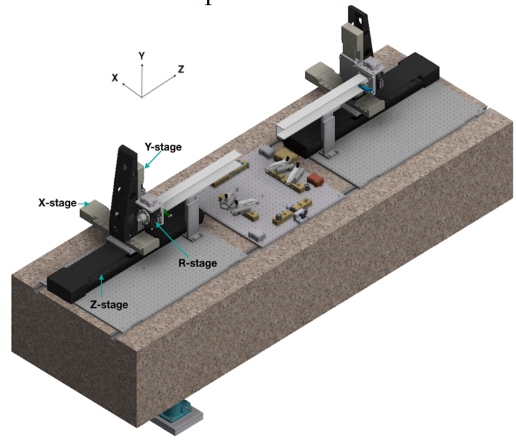

Figure 1: 3D rendering of the NSLS-II magnetic measurement system.

The longitudinal stages have a 600 mm travel range and a DC motor with a rotary encoder on the drive screw that provides 1.25 µm resolution and 2.5 µm bi-directional repeatability. The horizontal and vertical DC servo linear stages have a 200 mm and 100 mm travel range respectively. Both stages have a minimum incremental motion of 1 µm and a bi-directional repeatability of about ± 0.4 µm. A 4000 pts/rev. encoder is mounted directly on the screw in order to prevent screw/motor coupling errors consequently boosting stage motion accuracy. A compact rotation stage equipped with brushless direct drive technology

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provides fast rotation (maximum speed of 720°/s), with a resolution of 1.75 µrad and an accuracy of ± 2.6 µrad. The rotary encoder, with 15,000 line pairs per revolution, is precisely aligned with the stage's rotation axis to minimize position errors induced by eccentricity, wobble and axial runout. The displacement of the geometric center of the rotation stage from the rotation axis is about ± 1µm with a wobble error of ± 5 µrad. In order to reduce wire vibration induced by air flow in the Laboratory environment, two U-channel aluminum shields are used to cover the wire. An 8-axis Newport XPS-D integrated motion controller/driver provides coordinated motion of the upstream (US) and downstream (DS) stage assemblies. The motion controller is equipped with advanced compensation algorithms in the servo loop, for backlash and position error mapping. Four Digi-Pas inclinometers, with resolution less than 5µrad and accuracy of ±5 µrad, are used for monitoring bench and stage angles.

A National Instrument (NI) PXI system is employed for trigger generation and data acquisition (DAQ). The NI-PXI (PCI eXtensions for Instrumentation) is composed of three main hardware subsystems: a PXIe-1078 9-slot chassis, a PXIe-8840 embedded controller and seven plug-in modules. The PXI modules and the DAQ system diagram is illustrated in Fig. 2.

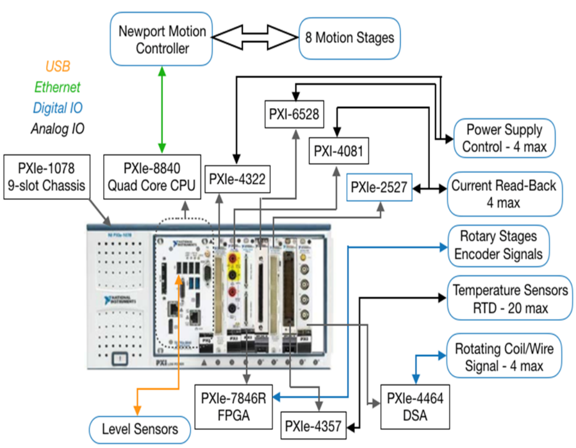

Figure 2: NI DAQ block diagram.

The PXI chassis provides power, cooling, and a 32-bit, 33 MHz communication bus to each hybrid slot, as well as timing and synchronization of the various hardware components with a mix of analog and digital I/O data transfer. The PXIe-8840 embedded controller, configured with LabView Real-Time software and NI drivers, eliminates the need for an external PC. The full control of the measuring bench, such as homing, multi-axis positioning and movement, as well as data acquisition and signal processing are driven by an APS custom-made LabView Virtual Instrument. The instrumentation modules that populate the PXI chassis are: a 24-bit Dynamic Signal Analyzer (DSA) for wire signal acquisition, a 7½-digit Digital Multi-meter for power supply (PS) current readback, a PXI 48-channel parallel digital I/O interface, a 16-Bit, 8-channel, 250 kS/s Ch-Ch isolated PXI Analog Output module for PS control, and a user-programmable FPGA I/O module for the rotary trigger generation. The PXIe-1078 chassis is also equipped with a 20-Channel, 24-Bit wire resistance temperature detector (RTD) and a 32-Channel, 300 V, 2-wire PXI Multiplexer switch module for PS DCCT current readback. Both the NI and the Newport equipment are housed in a UL listed NI equipment rack.

Rotating Wire Signal Acquisition

The voltage induced, as the wire rotates about the longitudinal magnet axis, is picked up by a Mercotac two conductor slip-ring and sent to the PXIe-4464 Dynamic Signal Analyzer module. The DSA module is set to 200 kS/s and acquires 10 revolutions of rotating wire signal. The acquired signal is 10 seconds long and contains 2 Msamples, as the rotary stages are set to spin at 1 rev/s. The 2 Msamples of data are integrated and interpolated at 1000 rotary positions per revolution and then averaged to obtain a flux vs rotary position signal.

The rotary data acquisition is trigged by a signal from the FPGA module after an index pulse from the downstream rotary stage is detected. The FPGA code counts the level-shifted and squared sin/cos rotary encoder signals generated by a comparator circuit and fed into the NI SCB-68A terminal box. Upon detection of the index pulse the DSA module promptly begins acquiring the rotating-wire signal. After acquisition, the voltage waveform is numerically integrated to obtain flux as a function of time. The rotary stage has 60k encoder counts per revolution and the time is captured for each 1/1000th of a revolution, therefore, 60 encoder counts is equivalent to 0.36 degrees. The FPGA code runs in a timed loop at 40 MHz, thus the time resolution is 25 ns. The loop index value is saved to memory every 60 encoder counts and the time for each position is equal to the loop index times 25 ns. The time values are used to interpolate the flux values at each 0.36 degree increment yielding a flux signal as a function of angular position.

PCB Rotating Coil

A 12 mm diameter PCB-based rotating coil is being developed under a BNL contract in which Fermilab will provide the conceptual design, prepare the engineering drawings, procure components, fabricate, and perform testing, assembly and commissioning.

The PCB coil design calls for a cylindrical sapphire support to ensure sufficient stiffness, thereby minimizing unwanted vibration and sag. The sapphire also curtails thermal expansion, with a coefficient of 4.3×10^{-6} units/°C. The sapphire support assembly design is similar to that of a small diameter probe built by CERN [7], which had a surface roughness on the bearing surfaces after polishing of 100 nm, and ends which were concentric with a straightness error between 1-3 µm. The PCB structure outer diameter will be 12 mm and the ends will have 6 mm outer/ 3 mm inner diameter in order to accommodate the 1.8 mm thick printed circuit board, wiring, and ABEC 5 all-ceramic bearings. The active coil length is 270 mm, and the overall probe length is 390 mm. The main parameters of the PCB coil are shown in Table 1. In order to boost the signal amplitude, the probe is designed with a high density of turns

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and multiple layers (75 µm wide traces with 75 µm space between them). The layers are very thin -- about 100 µm -- and the connection 'vias' between the layers is small - 350 µm diameter. The PCB coil has the capability of providing un-bucked (UB), dipole bucked (DB), dipole-quad bucked (DQB) and dipole-quad-sextupole bucked (DQSB) signals, in order to ensure minimal spurious harmonics in measurements of both quadrupole and sextupole magnets. The coil will be suitable for measuring field quality to a level of 10 ppm of the main field (0.1 "units") up to the 15^{th} harmonic with a sensitivity between 0.01 m^2 and 0.02 m^2 at the reference radius of 5 mm. The bucking factors are expected to be about 1000, therefore the DBuck signal should have a typical absolute measurement of the quadrupole field with an accuracy of about 0.15% (with no calibration).

Table 1: PCB Coil Parameters

Total PCB thickness	< 2 mm
Active coil length	270 mm
Length of each end stem	25 mm
Total probe length	390 mm
Reference radius	5 mm
Diameter	12 mm

For location and dimension control of the traces, a Laser Direct Imaging (LDI) process will be used, which is a precise means of fabrication that avoids physical contact effects, diffraction, temperature and humidity distortions, dimensional changes, etc. Therefore, the PCB coil should have traces with micron level control of both size and position. The PCB design cross-section is shown in Fig. 3. It will have a total of six windings, 16 layers and will be 1.8 mm thick.

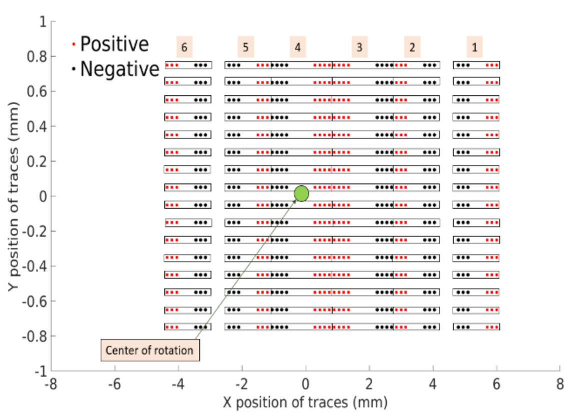

Figure 3: PCB design cross-section showing positive and negative wires of the 6 windings and the rotation center.

A high-accuracy calibration technique will be used to determine at the level of microns the radial and vertical offset of the PCB coil placement into the sapphire support structure, by using the bucked and un-bucked signals [8].

Measurement Plan

The rotating wire bench is currently under survey and alignment. The granite block, surface plates, stages, magnet mounting plate and the rotating wire holders will be aligned using a Laser Tracker. The alignment process will ensure that the linear stages in each assembly are orthogonal to each other and that the upstream and downstream stage assemblies are parallel. Several small fiducial nests will provide the reference datum for the dimensional control and alignment of the stage assemblies, wire holder runout and for magnet fiducialization.

A 40 mm aperture quadrupole, previously measured at APS, will be used as a test magnet for calibration and comparative measurement of the harmonics in absolute strengths. Also, a set of nine Halbach-style permanent magnet quadrupoles (PMQ) with a bore diameter of 12.7 mm built by RadiaBeam, are planned to be measured using the new PCB coil. These PMQs are designed to produce the desired quadrupole strengths for a prototype Complex Bend application [9].

CONCLUSION

The rotating wire magnetic measurement bench is now fully assembled and nearly operational. The bench can also be used with a PCB coil for high precision harmonic field measurements. The NI hardware, the Newport stages and controller have been successfully tested and commissioned.

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