A NEW MAGNETIC FIELD INTEGRAL MEASUREMENT SYSTEM*

Joseph Z. Xu and Isaac Vasserman
Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439 USA

Abstract

In order to characterize the insertion devices at the Advanced Photon Source (APS) more efficiently, a new stretched-coil magnetic field integral measurement system has been developed. The system uses the latest state-of-the-art field-programmable gate array (FPGA) technology to compensate the speed variations of the coil motions. Initial results demonstrated that the system achieves a system measurement reproducibility of 0.15 Gauss centimeter (G-cm) in a field integral measurement of 600 G-cm, probably the world's best of its kind.

INTRODUCTION

Insertion devices (IDs) at the Advanced Photon Source (APS) are characterized and fine tuned against their design specifications at the Magnetic Measurement Laboratory before installation into the storage ring [1]. A rotation-wire/stretched-coil system is used to measure the ID magnetic field integrals [2]. As a result of radiation damage, during each scheduled accelerator maintenance period specific IDs have to be pulled out and retuned back to their original design specifications. Due to the time constraints of the maintenance period, we wanted to design a system that achieves the highest accuracy possible to reduce the characterization time [3]. The new APS ID field integral measurement system consists of a set of a long coil supported by two automated 4-axis stages W, X, Y, and Z. The new system has the following operation modes:

1. Rotation Coil
   a. First field integral (horizontal and vertical) measurements.
   b. Second field integral (horizontal and vertical) measurements.
   c. Multipole components of first field integral measurements.
2. Translation Coil
   a. Multipole components of first field integral measurements.
3. Stretched Wire
   a. First field integral (horizontal and vertical) measurements.
   b. Second field integral (horizontal and vertical) measurements.

With the latest state-of-the-art field-programmable gate array (FPGA) technology, the system is capable of synchronized measurements of position (0.005 degree/0.5 micron in resolution), time (25 ns), and voltage (16 bit), which yield a system measurement reproducibility of 0.15 Gauss centimeter (G-cm) in a field integral measurement of 600 G-cm, which is 2.5×10^{-4}.

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SYSTEM DESCRIPTION

The field integral measurement system consists of the following subsystems:

1. A measurement coil made with 10-strand Litz wire. The coil is spring loaded onto a set of coil holders mounted on rotary tables. The spring constant is about 10 N/cm.
2. Two sets of precision rotary positioning stages, equipped with rotary encoders, each with a spring-loaded coil holder, remotely controlled by servomotors. The rotary encoder has a 20-mm hole on the shaft that allows the coil to go through. The encoder has 360 degrees of freedom with a 0.005-degree resolution. The rotary encoder is used to accurately define the angular position of the coil. The stages are mounted on precision linear positioning stages.
3. Two sets of 3-axis precision linear positioning stages, with linear encoders, remotely controlled by servomotors. The linear encoder has 0.5-micron resolution and is used to define the linear position of the coil.
4. A differential DC signal amplifier with low-pass signal filter and auto zero suppression. The signal conditioner pre-amplifies the coil signal ~3,000 times. The amplified signal is then fed to the 16-bit digitizer of an FPGA card.
5. The FPGA reconfigurable data acquisition card has eight 16-bit resolution analog inputs, 96 digital inputs/outputs, 25-ns time resolution, and 80-kB onboard memory. The digital I/Os are programmed to read the encoder positions. The analog inputs are configured to measure the coil signals synchronized with the position readouts and the time durations in real time.
6. A PXI shelf with a control card that hosts the FPGA card and the software program.

The proper choice of fitting function of rotation mode and a large number of data points allows us to eliminate distortions associated with stretched wire and rotation coil vibrations during measurements.

SYSTEM CONTROL, DATA ACQUISITION, AND ANALYSIS

LabVIEW-based system software has been developed to coordinate the stage control and data acquisition. Figure 1 shows the schematic layout of the system control and data acquisition architecture. The system can be accessed via the Internet from anywhere at any time, wired or wireless, through the embedded http interfaces inside LabVIEW.

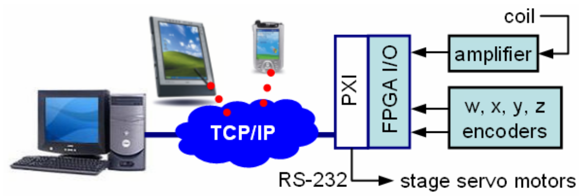

Figure 1: System control and data acquisition architecture schematic layout.

The system software has a Main Interface and the following main modules and submodules:

1. The advanced motion control module fine-tunes the stage positions and encoder readouts. It has one submodule, the motor velocity and acceleration control and monitoring. The submodule sets and monitors the velocity and acceleration parameters of all eight servomotors.
2. The integral average measurement module automates coil rotation integral measurements averaged over ID half periods, i.e., Z=0 and Z=λ/2. It is necessary to average the measurements over the ID half period because of the unevenness of the coil width along the Z direction. The module rotates the stretched coil and sets the FPGA hardware to wait for the coil angular position to go to zero. When the angular position hits the zero mark, the hardware will simultaneously write the following data to its memory on the fly:
   a. The angular positions of the coil with a settable angular resolution (down to 0.1 degree per step),
   b. The integrated coil voltage signals across each angular step with a rate of 4.3 µs per sample at 16-bit resolution,
   c. The number of samples integrated within each angular step, and
   d. The time duration within each angular step.

   When the coil angular position reaches the 360-degree mark, the hardware sends an interrupt to the module. The module then reads the data and sets the hardware to start another scan. Meanwhile it integrates the signal, fits the integrated data with a sinusoidal function to extract the field integral components, and plots the raw data along with the fittings.

   After the measurements at Z=0 finishes, it sets the coil to the Z=λ/2 position, repeats the measurements, and averages the field integral measurement results at the two Z positions. The module records all the measured raw data, along with the real-time analysis results and other parameters into a file for later analysis and presentation.

   The module has one submodule, the Integral Average Measurement Analysis and Plot. The submodule reads the saved data file, analyzes the data, and plots the raw data along with the fittings and analysis results.
3. The integral multimeasurement module synchronizes multiple coil rotation integral measurements across the X axis. It carries out rotation integral measurements at certain X positions, extracts the field integral components, plots the components against the X axis, and then moves on to the next X position and repeats the rotation integral measurements. The module records all the measured raw data, along with the real-time analysis results and other parameters, into a file for later analysis and presentation.

   The module has one submodule, the Integral Average Measurement Analysis and Plot. The submodule reads the saved data file, analyzes the data, and plots the raw data along with the fitting and analysis results.
4. The integral translation measurement module orchestrates coil translation integral measurements along the X direction with a settable linear resolution (down to 0.5 µm per step.) When the translation position hits the start position on the X stage, the FPGA hardware will simultaneously write the position, voltage, number of samples integrated within each linear step, and the time duration within each step to its memory on the fly. When the coil angular position reaches the finish mark, the FPGA sends an interrupt to module. The module then reads the data and sets the hardware to start another scan. Meanwhile it integrates the signal, fits the integrated data with a polynomial function to extract the field integral components, and plots the raw data along with the fittings.

   The module has one submodule, the Integral Translation Measurement Analysis and Plot Submodule. The submodule reads the saved data file, analyzes the data, and plots the raw data along with the fitting and analysis results.
5. The system parameter database consists of three copies in a single file: Current, Backup, and Default. The Default copy is read only. Each copy contains the motor velocities, accelerations, voltage amplification and system normalization constants, coil parameters, encoder reference indexes, encoder resolutions, stage gear ratios, motor velocity ratios, motor acceleration ratios, and motor resolutions. The system parameter database control module and its advanced system parameter database control module manipulate and manage the system parameter database.
6. The integral measurement FPGA firmware module resides on the FPGA reconfigurable card. It monitors the positions of the encoders, samples the coil voltage, the number of samples, and the durations of time. It also interfaces with the measurement modules and submodules. The FPGA module executes all the tasks in parallel at the speed of 40 MHz.

Each module and submodule has its own GUI interface except the FPGA firmware module. The main interface provides an access interface to all the main modules and hence the submodules. It checks the status of the FPGA reconfiguration data acquisition. If the FPGA card is not initialized or is running on different firmware, the module

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will download and initialize the card with the appropriate firmware. It also checks the status of all eight servomotors. If the motors are not initialized, it will try to reinitialize the motors.

MEASUREMENT RESULTS AND DISCUSSION

A typical earth magnetic field integral measurement taken with the Integral Average Measurement Module is shown in Figure 2. It is displayed in the Integral Average Measurement Analysis and Plot submodule. The File Header field shows the basic parameters of the measurement. The coil was 4.1 meters long and 5 mm wide with 10 loops. The W rotation speed was 0.3 revolutions per second. The Integrals plot field shows a specific integrated raw scan along with its sinusoidal fitting. Next to the Integrals field are the fitting parameters to that specific measurement. According to equation (1) in the theory of operation section of reference [3], the sine component represents the X component of the field integral while the cosine component represents the Y component. The X and Y Components field displays the X and Y components of all five scans. To the right are the mean component values and the standard deviations over the five scans. The two fields at the bottom show the component averages over Z=0 and Z=1/2 λ. The standard deviation of the Y component over the five scans represents the system measurement reproducibility of 0.08 G-cm over the mean value of the component of 189 G-cm.

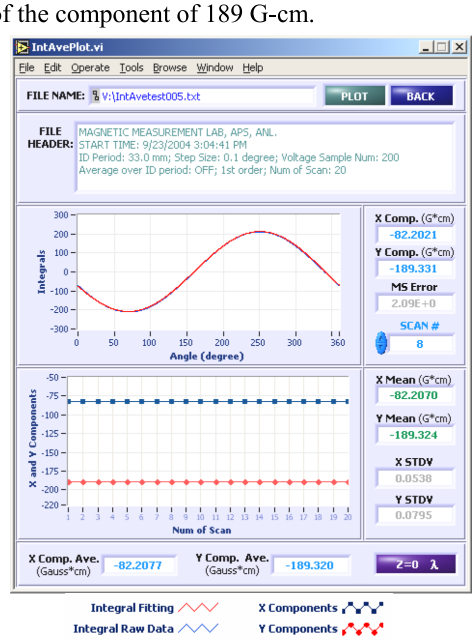

Figure 2: Earth magnetic field integral measurements.

Figure 3 presents a permanent magnet field integral translation measurement across the X direction. The results are displayed in the Integral Translation Measurement Analysis and Plot submodule. Again, the File Header field shows the basic parameters of the measurement. The Integrals plot field shows a specific integrated raw scan along with its polynomial fitting across the X position. To the right and the bottom of the Integrals field are the fitting parameters to that specific measurement. The integral signals vs. the X positions are ruled by equation (3) in the theory of operation section of reference [3]. The Flux Average field shows the average of the multiple raw scans along with its polynomial fitting across the X position vs. the X positions. To the right and the bottom of the Flux Average field are the fitting parameters at the specific X position. The wiggled tail was caused by the coil vibration.

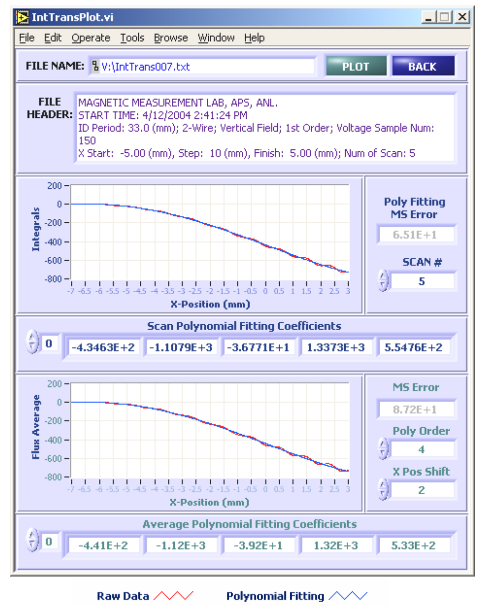

Figure 3: Field integral translation measurements.

CONCLUSION

A new stretched coil magnetic field integral measurement system has been constructed, tested, and commissioned at the Advanced Photon Source. With the latest state-of-the-art FPGA technology, the system is tailored at the hardware level to be a true real-time system, to achieve the world's highest system measurement reproducibility of 0.15 G-cm in an integral measurement of 600 G-cm.

REFERENCES

[1] L. Burkel, R. Dejus, J. Maines, J. O'Brien, J. Pflueger, I. Vasserman, "The Insertion Device Magnetic Measurement Facility: Prototype and Operational Procedures," ANL/APS/TB-12, March 1993.

[2] Yu. Eidelman, B. Deriy, O. Makarov, I. Vasserman, "The New Magnetic Measurement System at the Advanced Photon Source," Proc. of ICALEPCS 2001, San Jose, p. 160, November 2001.

[3] Joseph Z. Xu and Isaac Vasserman "A New Magnetic Field Integral Measurement System," ANL/APS/TB-49, March 2005.