**A NEW HELMHOLTZ COIL PERMANENT MAGNET MEASUREMENT SYSTEM**

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**ABSTRACT**  
A Helmholtz coil magnet measurement system was upgraded at the Advanced Photon Source (APS) to characterize the insertion device permanent magnets [1]. The system uses the latest state-of-the-art field programmable gate array (FPGA) technology to communicate the speed variations of the magnet motion. Initial results demonstrate that the system achieves a measurement precision better than 2 \( \times 10^{-5} \) 

**INTRODUCTION**  
Most insertion devices (IDs) at the APS are permanent magnet based [2]. Before the magnets are installed onto the IDs, each of them has to be characterized and sorted to ensure that the magnets in a single ID are even and as identical as they can be to minimize the integral fields and the phase errors of the device. The APS Helmholtz coil system, designed to characterize magnets used in the APS permanent magnet IDs, has been recently upgraded. The system has improved the measurement precision by an order of magnitude. The system now consists of a pair of identical coils, a horizontal rotary table with two full ceramic spherical bearings, and a digital encoder on its main rotating shaft driven by a servo motor. The control and data acquisition system is a PXI-based computer system. With the latest state-of-the-art field programmable gate array (FPGA) technology, the system is capable of synchronous measurement precision of (0.05 degree in resolution), time (25 ns), and voltage (16 bit).

**THEORY OF OPERATION**  
A Helmholtz coil consists of two identical circular coils placed coaxially and separated by a distance equal to the radius of the coils. When the two coils carry the same current in the same direction, it creates a near uniform magnetic field within the center region between the two coils. Therefore, a magnet placed within the coils can be treated as a magnetic dipole by a Helmholtz coil system. Moving a magnet inside the Helmholtz coils causes the magnetic flux change, which in turn generates a voltage signal in the coil.

\[ V = \frac{d\Phi}{dt} \]  

(1)  

where \( V \) is the voltage, \( \Phi \) is the magnetic flux, and \( t \) is time. By rotating the magnet inside the Helmholtz coils, measuring the voltage signal in the coils, and integrating the signal over time, we have [1]

\[ \Phi = \int_{A} B \cdot dl \]  

(2)  

where \( B \) is the magnetic field, \( A \) is the coil area, and \( V \) is the time. The integral of \( B \) over the coil is the magnetic flux. The magnetic moment is the integral to the coil area.

\[ M = \int_{A} B \cdot dl = \int_{A} B \cdot 

(3)  

where \( M \) is the magnetic moment, \( B \) is the magnetic field, and \( A \) is the coil area. The magnetic field \( B \) is related to the magnetic moment \( M \) by the relationship:

\[ B = \frac{M}{2\pi \rho} \]  

(4)  

where \( \rho \) is the coil radius, \( \rho \) is the free space permeability constant, and \( N \) is the number of turns in each coil. Fitting the integral with a sinusoidal function of

\[ A = \sin(\theta + \theta) \quad \text{and} \quad \cos(\theta + \theta) \]  

(5)  

we have the vertical and horizontal components of the magnetic moment:

\[ M_{x} = k \cdot d \]  

(6)  

and the horizontal component of the magnetic moment:

\[ M_{y} = k \cdot b \]  

(7)  

Usually vendors provide the components of the induction information. The system measurement is the calibration of the Helmholtz coil constant \( k \) as defined in equation (3). Based on the design of \( R \) = 13 inches and \( N \) = 392, the value shall be 0.09362 Ampere per Gauss. However, the real system \( k \) value has to be calibrated.

**SYSTEM CALIBRATION**  
The calibration results are shown in table 1.

<table>
<thead>
<tr>
<th>Field (G)</th>
<th>+100 mA</th>
<th>-100 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>1.081190</td>
<td>-1.081188</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.000508</td>
<td>0.000412</td>
</tr>
</tbody>
</table>

Therefore, the \( k \) constant is 0.09362 Ampere per Gauss.

**MEASUREMENT RESULTS AND DISCUSSION**  
The file header field shows the basic parameters of the measurement. The rotary stage scanning speed was 2 revolutions per second. Each measurement consists of scans along the \( y \) axis (+My/+Mz), \( x \) axis (+Mx/+Mz), and \( -x \) axis (-My/-Mz). Averaging over the components cancels the mechanical asymmetries of the system. The integral plot field displays a specific integrated raw scan along with its sinuoidal fitting. Next to the integrals field are the fitting parameters to that specific measurement. According to equations (5) and (6), the sine component represents the vertical component of the field integral while the cosine component represents the horizontal component. Below the integral field plot display are the magnetic moment components \( M_{y}/M_{z} \), the measurement error \( \delta \), the moment density components \( p_{x} \), and the magnetic moment orientations \( \theta_{x} \) as well as the total moment \( M \), and its orientation to the \( x \) axis \( \theta_{x} \).

**CONCLUSION**  
A Helmholtz coil magnet measurement system has been constructed, tested, and commissioned at the Advanced Photon Source. With the latest state-of-the-art FPGA technology, the system achieves a measurement precision better than 2 \( \times 10^{-5} \).

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**REFERENCES**  