

# FIRST FIELD INTEGRAL MEASUREMENT CAMPAIGN FOR AIR COIL

Zhouyu Zhao<sup>1†</sup>, M. Yakopov<sup>2</sup>, J. Pflueger<sup>2</sup>, Baiting Du<sup>1</sup>, S. Karabekyan<sup>2</sup>, Qika Jia<sup>1</sup>

<sup>1</sup>National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, P.R. China

<sup>2</sup>European XFEL GmbH, Notkestrasse 85, Hamburg 22607, Germany

## Abstract

For the operation of the air coils, which are needed for the undulator segments of the European x-ray free-electron laser (E-XFEL), precise conversion constants are needed to properly convert excitation current to steering strength. This paper describes the measurement of all 200 air coils, needed for this purpose using the short moving wire (MW) system. A LabView program was developed to measure the distribution of first field integral of both vertical ( $B_y$ ) and horizontal ( $B_z$ ) magnetic field components in the median plane of an air coil automatically. The program is an adaptation of the existing program, which was used to characterize magnetic properties of the phase shifters (PS). Before doing the measurements the new program automatically finds the centers of  $B_y$  and  $B_z$  components, which are found to match with the geometrical centers with sufficient accuracy. After the measuring procedure is complete, the results are presented as graphics output and final tables. It shows that the measurement results can fully meet the design requirements of E-XFEL. For all measurements the excitation current of the coils was set to 1 Ampere.

## INTRODUCTION

Each undulator segment of the European XFEL facility is equipped with an upstream and a downstream horizontal/vertical air coil [1]. Their main task is to compensate gap dependent residual kicks. Their excitation is controlled by the undulator local control system. The air coils will be installed on both sides of each undulator. For proper control and compensation of residual kick errors precise conversion constants for each air coil are needed [2]. In order to collect this information the distribution of the first field integral across the air coil gap has been measured using the moving wire system. All measurements are done automatically using special created LabView software.

## STRETCHED WIRE THEORY

The stretched wire method could be used to measure the 1st field integrals of the air coil, which are used to compensate residual kicks [3]. The wire is insulated and attached to two holders. For measurements the wire can be moved in the horizontal and vertical direction. Both insulated ends of the wire are connected to an integrating

voltmeter. The stretched wire is placed inside the air coils gap [i.e. Fig. 1]. If the wire is moved in horizontal/vertical direction with applying current to the air coils, one can measure the horizontal/vertical magnetic 1st field integrals.

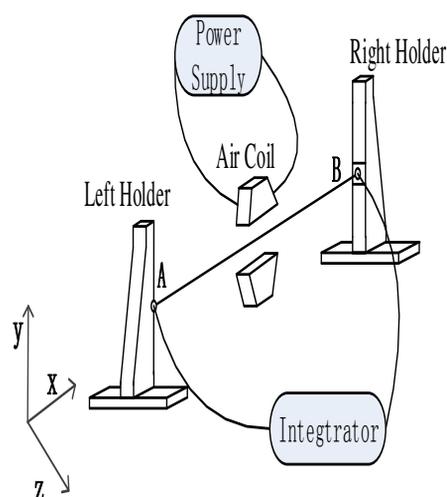


Figure 1: Schematic of the stretched wire system.

The first field integral is measured by moving the wire on both sides in one direction [4], see Figure. 2. According to Dino Zangrando' paper, for the field integral  $I_y$ , the first field integral in this case is determined by following equations:

$$\int V dt = N \Delta \Phi \tag{1}$$

$$\Delta \Phi = \iint B_y dx dz = \Delta z I_y \tag{2}$$

where  $V$  is the coil voltage,  $N$  is the coil turns and  $\Phi$  is the magnetic flux. It is assumed that  $\Delta z$  is small enough, and the magnetic field does not depend on  $z$ . The first field integral is thus determined as following equation:

$$I_y = \frac{\int V dt}{N \Delta z} \tag{3}$$

Therefore the horizontal field integral  $I_z$  is similar as the vertical field integral  $I_y$ .

<sup>†</sup>yuzz@mail.ustc.edu.cn

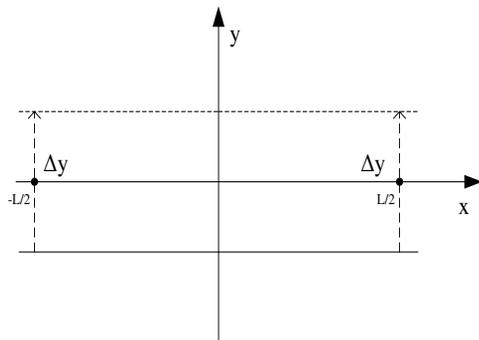


Figure 2: Parallel movement for the measurement of the first field integral.

## MODIFICATION AND FUNCTIONALITY OF THE SETUP

For the air coil measurements, the moving wire system, which was used for measurement of the PS needed to be modified. A number of software and hardware components, which were needed to control the PS were removed in order to run the setup in a more efficient and automatic way. Meanwhile, there is a LabView program which runs without these components. The functional diagram of the test setup is shown in Figure 3. In addition, a self-made interface has been created to control/switch ON/OFF the air coil power supplies by means of the XPS via the GPIO interface. The current settings of 1 Ampere on the two power supplies are adjusted manually.

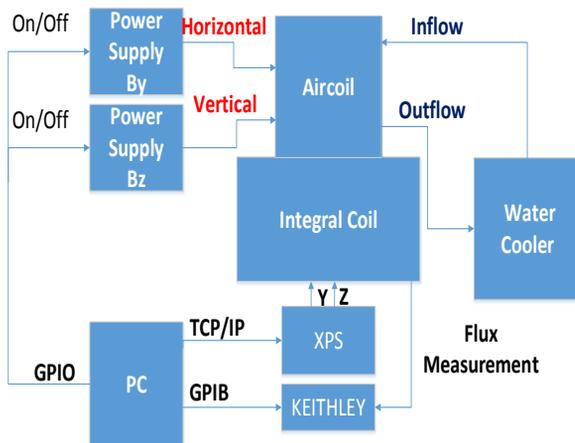


Figure 3: Functional diagram of air coil magnetic field measurement test setup.

The moving wire technique is described in [5]. Based on this technique, the distribution of the first field integral of  $B_y$  and  $B_z$  components across the air coils gap have been measured. Before starting the measurements, the air coils have been installed on the specially designed holder, and the front edge of the integral coil has been positioned at the approximate geometrical middle point of the air coil gap in X and Y directions. Figure 4 shows an air coil installed on the MW bench ready for measurements. After alignment

of the integral coil in the middle of the air coil gap, the automatic measurement software has been started.

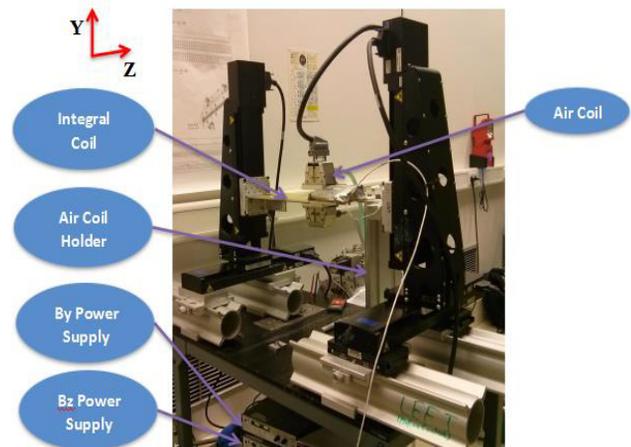


Figure 4: View of the moving wire setup designed for air coil measurements.

## MEASUREMENT PROCEDURES

The measurement process will run under different power supply condition automatically with the following steps:

The measurement procedure starts with the so called  $B_y$  scan. This step includes the powering of the  $B_y$  coil, then measuring the first field integral in 1 mm steps in the moving range -10 mm to 10 mm along Y from approximately middle point, then turning off the  $B_y$  power of the coil, and eventually moving the integral coil into the initial position. Once the measurements are done, the disagreement between the minimum value and the initial position of the integral coil is calculated. If it is needed, the integral coil is shifted to the minimum position and the measuring procedure is repeated until the start position of the integral coil fits with the minimum measured value, which corresponds to the geometrical middle of the air coil gap.

For the second step actually the same principle is implemented for the  $B_z$  component. In this step the only  $B_z$  coil is powered, the travel range is from -20 mm to 20 mm along Z coordinate, and the correspondence between the maximum measured value and the initial position of the integral coil needs to be found. Once it is done, the integral coil is aligned with respect to the Coil center in Y and Z direction.

The third step includes the measurement of the first field integral of  $B_y$  and  $B_z$  components in the median plane with both coils powered. Travel range is from  $Z = -20$  mm to 20 mm in 1 mm step.

The fourth step repeats the previous one just with powered only  $B_y$  coil, to measure the value of only  $B_y$  component without the contribution of  $B_z$  coil.

The fifth step repeats the previous one with the measuring the  $B_z$  component of the  $B_z$  coil without the  $B_y$  coil contribution.

The sixth step repeats the same measurements just with unpowered coils. Actually, it gives the ambient magnetic field values which have to be subtracted before creation of the final table. As it was already mentioned, all measurements have been done with the powering of the air coils with 1 A current. The current is set manually.

Once the measurements are done, the final table and plot will be generated automatically. The final plot is given in Figure 5.

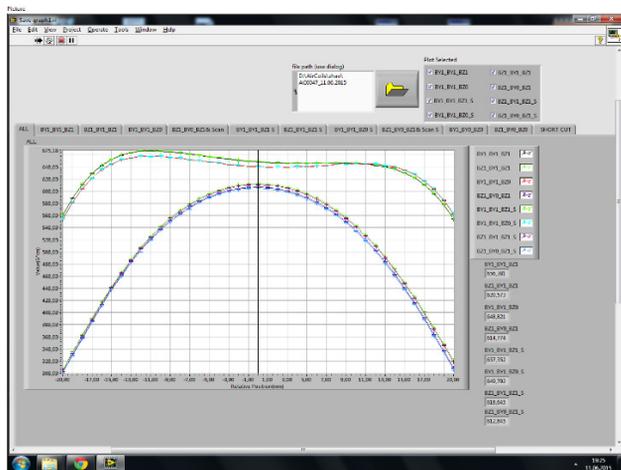


Figure 5: Screenshot shows how all possible plots based on obtained data are created.

### ANALYSIS OF OBTAINED DATA

For each air coil the main result is the first field integral value of both components with the ambient magnetic field subtracted, measured in the center of the air coil. An example of the results is shown in Figure 6, in which the BZ1\_BY0\_BZ1\_S\_Value means measured  $B_y$  component in (Gs\*cm) with powered only horizontal  $B_z$  coil with 1 A current and subtracted ambient magnetic field. Any other results are similar with the figure 6.

Based on all the results, it is found that the total error of  $C_{Ave}$  (transfer coefficients) is 0.9%. It is seen that for all coils the total error of  $C_{Ave}$  is 1.1% in the worst case. Therefore, for air coils fully excited with 1 A errors of 4-6 Gs\*cm are expected [6]. The specs on the undulator end kicks is only  $\pm 150$  Gs\*cm or less. In regular FEL operation the maximum excitation is therefore limited to  $\pm 150$  Gs\*cm as well.

The larger steering power is foreseen for special operational modes for commissioning such as ballistic steering. They require larger steering power of the air coils but allow larger errors. With a maximum excitation of  $\pm 150$  Gs\*cm the error is limited to about  $\pm 1.5$  Gs\*cm. This is acceptable since it is well below the E-XFEL 1st field integral specs ( $\pm 4$  Gs\*cm) and the measurement accuracy of the long moving wire stand ( $\pm 5$  Gs\*cm), which is used to measure and determine the required air coil excitation for a specific undulator segment. Therefore, it is concluded that it is sufficient to use the average coefficients  $C_{Ave}$  for the commissioning phase. This is a great simplification for the implementation into the undulator control systems.

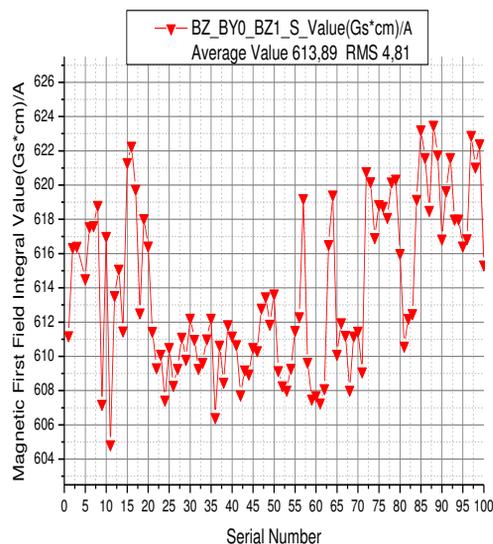


Figure 6: 12 mm Air Coil measurements. Results of the first Bz field integral of all 100 air coils (serial numbers from 1 to 100). The ambient magnetic field is subtracted.

### CONCLUSIONS

At first, we discussed the theory of the moving wire system, then we modified a program based on phase shift measurements. And it is obvious that the automatic program greatly enhanced the measuring efficiency. After the whole measurements were done, we got final results of about 200 air coils. The data analysis showed the air coil can completely meet the design requirements of E-XFEL. Nevertheless, the implementation into the control system is straight forward, but requires a significant effort.

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