MAGNETIC CENTER MEASUREMENTS OF THE XFEL UNDULATOR QUADRUPOLES

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Abstract

A measurement system has been set up at the Manne Siegbahn Laboratory to measure the magnetic center of the European XFEL undulator quadrupoles. A rotating coil setup measures the center of the quadrupole magnetic field with respect to the rotational axis. The distance from the rotational axis to fiducials on the magnet is then measured with a coordinate measuring machine. The experimental setup and results from measurements on a test magnet are presented. The results show that the goal of measuring the quadrupole magnetic center better than 50 μm is feasible with this setup.

INTRODUCTION

The undulators of the European free-electron laser (XFEL) are 128 to 226 meters in length and divided into five meter long segments. Each segment ends with a quadrupole magnet to focus the electron beam and to maintain optimum spatial overlap between the electron and photon beams. The Manne Siegbahn Laboratory in Stockholm has an ongoing collaboration with DESY in Hamburg to characterize and fiducialize the undulator quadrupoles for the XFEL.

The magnetic center of all quadrupole magnets in an undulator must be aligned along a straight line with an accuracy better than 2μm. This can only be achieved with beam based alignment (BBA). Before BBA the magnets are optically aligned using fiducials on the magnets and therefore the distance from the magnetic center to these fiducials needs to be measured. The aim is to measure the position of the magnetic center within 50 μm with respect to the fiducials.

At the Manne Siegbahn Laboratory a rotating coil instrument has been built to measure the position of the quadrupole magnetic center [1, 2, 3]. In combination with a coordinate measurement machine the distance from the magnetic center to the fiducials can be determined. A similar technique was used to fiducialize the LCLS undulator quadrupoles [4]. In this work the rotating coil system and the coordinate measuring machine are presented together with results from measurements on a prototype magnet.

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EXPERIMENTAL SETUP

The measurement system consists of two separate parts, a rotating coil system and a commercial coordinate measuring machine (FaroArm). The rotating coil measures the distance from the rotational axis to the center of the quadrupole magnetic field. The distance from the rotational axis is then measured with a portable FaroArm.

Rotating Coil

Figure 1 is a photograph of the rotating coil setup. Two coils are placed side by side in an epoxy G-10 rod inserted in a 2 cm diameter metal shaft supported by ball bearings. The metal shaft is rotated with a frequency of about 1 Hz by a stepper motor situated next to the rotating shaft and an incremental encoder monitors the position of the shaft. The signals from the two coils go through a mercury wetted slip ring and are amplified before registered by a DAQ card in a PC. Each coil is made from 100 μm copper wire wound 60 turns on a 17 cm long and 6 mm wide piece of epoxy.

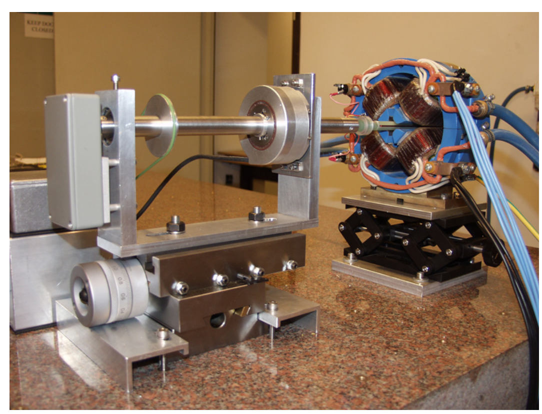

Figure 1: Rotating coil setup.

The induced voltage can be represented by a Fourier series,

$$V = \sum_{n=1}^{\infty} p_n \sin(n\theta) + q_n \cos(n\theta) \qquad (1)$$

where p_n and q_n are the Fourier coefficients. From the dipole and quadrupole coefficients the position of the magnetic center with respect to the rotational coordinate system is determined.

$$r = R\frac{\sqrt{p_1^2 + q_1^2}}{\sqrt{p_2^2 + q_2^2}}$$

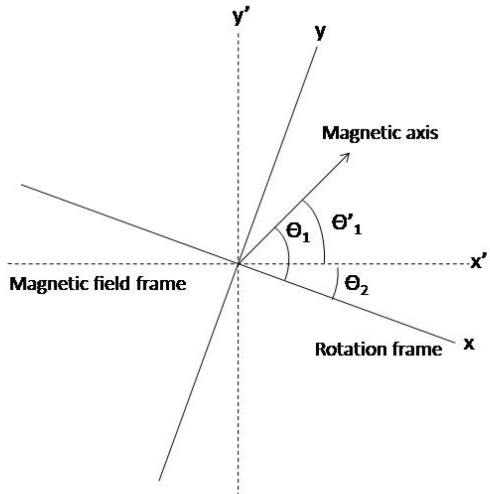

Figure 2: Rotation and magnetic field coordinate systems.

$$\theta_1 = \arctan(\frac{q_1}{p_1})$$
$$\theta_2 = \arctan(\frac{q_2}{p_2}) \quad (2)$$

The distance r from the axis of rotation to the magnetic axis is directly proportional to the ratio of the dipole and quadrupole components. R is a constant that depends on the geometry and position of the coil with respect to the rotational axis. The angles θ_1 and θ_2 are necessary for calculating the x and y positions and are illustrated in figure 2.

The magnetic center measurement is influenced by mechanical vibrations, electrical noise and temperature fluctuations. Both the temperature of the laboratory and the cooling water are controlled and kept within $\pm 0.2°\mathrm{C}$ and the main contributor to the error is probably due to movement of the rotational rod. The stability of the system under these temperature conditions has been measured to be approximately $\pm 1\ \mu\mathrm{m}$ [1].

Faro Arm

The Platinum FaroArm is a portable coordinate measuring machine and it is shown in figure 3. The arm is moved manually, has a spherical working volume and is very flexible due to its six joints. Each joint has a rotary encoder and the position data from these encoders are sent to a computer and analyzed by software to determine the position of the measuring probe. The probe here is a 6 mm diameter ceramic sphere. The inaccuracy of the Platinum FaroArm with 1.2 m working volume is maximum 13 μm, and better over shorter distances. In this work the FaroArm was used to measure the geometrical axis of the steel shaft of the rotating coil system and the geometrical center of the magnet with respect to the center of spherical tooling balls.

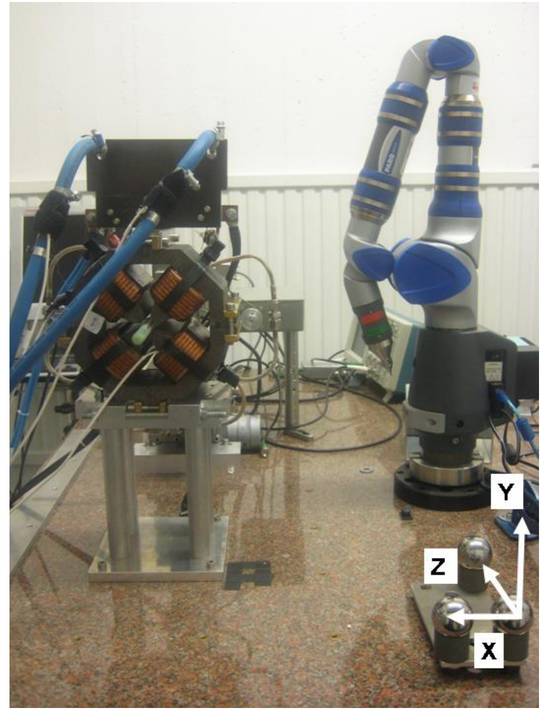

Figure 3: Platinum Faro arm and metal spheres defining the coordinate system.

RESULTS

In order to determine the accuracy of the present setup the rotating coil was positioned using two translation stages in the x and y direction while the quadrupole magnet was at a fixed position. The magnetic center was measured with the rotating coil placed at seven different positions, both to the left and to the right of the quadrupole magnetic center.

The measurements were performed on a FLASH prototype magnet. This magnet had no fiducials on it, instead three 38.1 mm diameter spherical metal balls were placed in holders next to the magnet (see figure 3). A coordinate system was determined from the geometrical centers of the metal balls measured by the FaroArm. Figure 4 shows the results from seven measurements of the quadrupole magnetic center, each one from a different position of the rotating coil. The x and y positions ((o) in figure 4) are the positions where the geometrical axis of the steel shaft cross the xy-plane at the center of the magnet (in the direction of the z-axis). The center position of the magnet along the z-axis was determined from measurements with the FaroArm of the pole ends of the magnet.

The rotational center does not coincide with the geometrical center of the rod. Because of the imperfections of the ball bearings, the rod follows a circular motion in the xy-plane. Therefore the geometrical axis of the rod was measured in four positions along one turn (o) and the rotational center was estimated to be the mean value of these four measurements (+). Before and after each set of four measurements, the distance from the rotational axis to the magnetic center was measured with the rotating coil. By adding the measured magnetic center position with respect to the rotational axis to the position of the steel rod (o) the magnetic center was determined (*). A better representation of the magnetic center positions are shown in figure 5. The mean value of the seven measurements was determined to be $x = 347.097 \pm 0.004$ mm and $y = 236.375 \pm 0.006$ mm (+). The geometrical center was determined by placing epoxy rods against the magnet poles and measuring the geometrical axis of these rods. With this method the geometrical center of the magnet was determined to be x=347.088 mm and y=236.371 mm (o in figure 5), in good agreement with the rotating coil measurements. There are other sources of errors such as systematic errors of the FaroArm, which is less than 13 μm according to specifications. The repeatability of defining the center points of the tooling balls defining the coordinate system also adds to the total error. Another source of error that has not been taken into account is the position of the rotating coil with respect to the magnetic axis. The angle between the normal vector of the pole ends and the direction of the rotational axis is $0.4°$ in the yz-plane and $0.1°$ in the xz-plane. This misalignment influences the position of the magnetic center by less than a micrometer.

Even though this method must be applied to the real XFEL quadrupole magnets assembled with fiducials, these results show that the magnetic center can be measured better than 50 μm with the present setup.

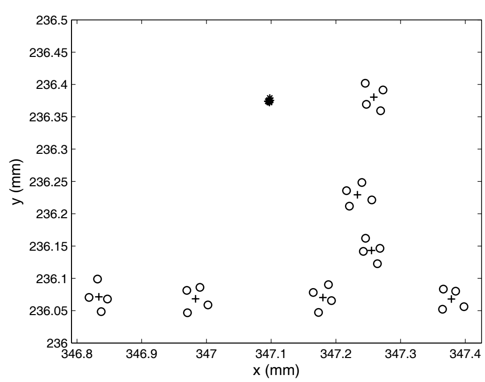

Figure 4: Magnetic center measurements. Circles are the geometrical axis of the steel shaft, + is the axis of rotation and * is the magnetic center. The area around the magnetic center is enlarged in figure 5.

SUMMARY

A measurement system consisting of a rotating coil and a coordinate measuring machine has been set-up at the Manne Siegbahn Laboratory to determine the magnetic center of the XFEL undulator quadrupole magnets. A series of measurements on a test magnet was performed to evaluate the accuracy of the method. Results show that the goal to measure the magnetic center position with respect to fiducials better than 50 μm is achievable with the present setup.

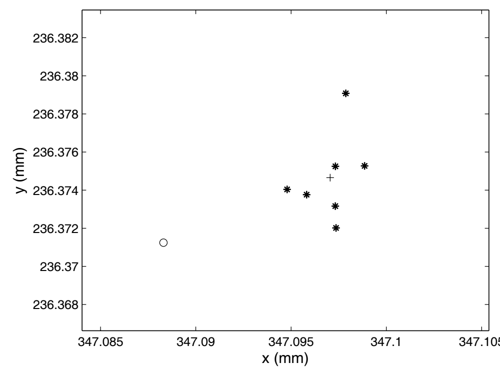

Figure 5: Magnetic center of the quadrupole magnet (*). The plus sign is the mean value of the seven measurements and the circle corresponds to the geometrical center.

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