CHARACTERIZATION AND FIDUCIALIZATION OF THE XFEL UNDULATOR QUADRUPOLES

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Abstract

A rotating coil system together with a coordinate measuring machine have been set up at the Manne Siegbahn Laboratory in order to fiducialize the European XFEL undulator quadrupoles. The experimental setup is presented together with results from measurements on a test magnet which show that the goal to measure the quadrupole magnetic center better than 50 µm is achievable with this setup. The rotating coil was also used to measure the magnetic center stability of a prototype magnet made of Russian relay iron. The magnetic center stability is similar to previous results on prototype magnets made from different soft magnetic materials. The Russian relay iron is less expensive than the other materials and therefore preferred.

INTRODUCTION

In the longest of the three XFEL undulators there are 37 quadrupole magnets which all have to be aligned along a straight line with an accuracy better than 2 µm for the free electron laser to perform according to specifications. Optical alignment is not sufficient to meet this requirement and in addition beam based alignment (BBA) techniques will be used. One way of performing BBA is to monitor how the electron beam is deflected when changing the excitation of the magnet. The X-Y position of the magnet is then adjusted with a quadrupole mover to align the magnetic center of the magnet to the electron beam. This procedure is then performed for all quadrupoles sequentially from the beginning to the end of the undulator. When performing BBA it is important that the position of the magnetic center does not change after magnet excitation. DESY has made several prototype magnets from a specific lamination design, each one made of a different soft magnetic material, to investigate the influence of the magnetic material on magnetic field properties such as the magnetic center stability. Soft magnetic materials have properties such as low remanence and hysteresis and symmetric fields which should influence the magnetic center stability. Results have previously been presented for magnets made of two commercially available types of steel named Vacofer and Permenorm [1]. That work was here extended to measurements on a magnet made of Russian relay iron [2]. The Russian relay iron is a more cost efficient alternative than Vacofer and Permenorm.

The XFEL undulator is divided into 5 m long segments and after each segment a quadrupole magnet is positioned together with a phase shifter and a beam position monitor. Each quadrupole magnet is positioned on a quadrupole mover and they are all optically aligned using fiducials on the magnets. The goal is to determine the quadrupole magnetic center with an accuracy of 50 µm with respect to the fiducials. There are several methods of doing this. The LCLS undulator quadrupoles were fiducialized with an accuracy of 13 µm using a vibrating wire technique in combination with a coordinate measuring machine [3]. Here another method using a rotating coil and a coordinate measuring machine is presented together with results on a test magnet.

EXPERIMENTAL SETUP

The experimental setup consists of a rotating coil system and a coordinate measuring machine. Rotating coils are widely used to characterize the magnetic field in accelerator magnets [4]. Here it is used to measure the distance from the rotational axis to the symmetry axis of the quadrupole magnet. The coordinate measuring machine is then used to measure the distance from the rotational axis to tooling balls on the magnet.

Rotating Coil

A schematic picture of the rotating col setup if shown in Figure 1 and it has been described elsewhere [1, 5, 6]. The measuring probe consists of two coils placed side by side in an epoxy G-10 rod. Each coil is made from 100 µm copper wire wound 60 turns on a 17 cm long and 6 mm wide piece of epoxy. The epoxy rod is inserted in a 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. The metal shaft is connected to the motor axis using a rubber band. The position of the shaft is monitored by an incremental encoder. The encoder signal and the signals from the two coils are registered by a DAQ card in a PC.

The induced voltage from the coils rotating in the magnetic field 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.

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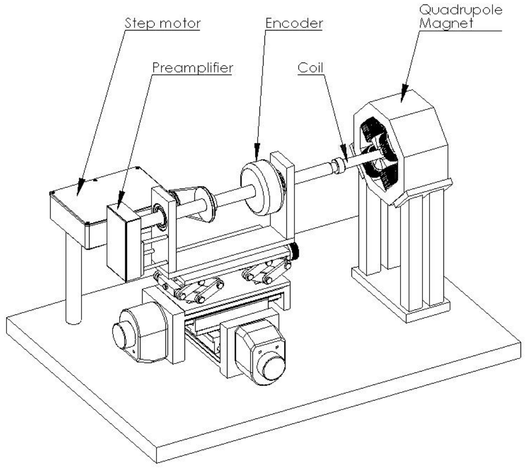

Figure 1: Rotating coil setup.

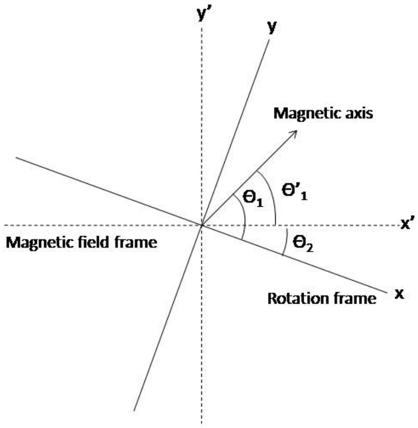

Figure 2: Rotation and magnetic field coordinate systems.

$$
\begin{aligned}
r &= R\frac{\sqrt{p_1^2 + q_1^2}}{\sqrt{p_2^2 + q_2^2}} \\
\theta_1 &= \arctan(\frac{q_1}{p_1}) \\
\theta_2 &= \arctan(\frac{q_2}{p_2})
\end{aligned}
\tag{2}
$$

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.

To minimize the influence of temperature fluctuations on the magnetic center an effort was made to stabilize the temperature of the cooling water and the ambient temperature. Approximately 10°C water from an in house cooling water system passed through a 10 liter metal vessel with approximately 0.2 l/minute. The vessel is placed on a hotplate magnetic stirrer device with a thermostat to increase the water temperature to the room temperature. The ambient temperature is stabilized with regular heaters with thermostats. Both the room temperture and the cooling water temperature are controlled and kept within ±0.2°C when no person is inside the room and the magnet current is kept constant.

The magnetic center measurements are not only influenced by temperature changes, but also by mechanical vibrations and electrical noise. Figure 3 shows results from 120 measurments during 2 hours at constant magnet current (20 A). The observed fluctuations are not dependent on the time between measurements, they are probably caused by displacements of the metal shaft due to imperfections of the ball bearings. The amplitude of the fluctuations seems to be dependent of the position of the step motor relative to the rotating shaft, i.e. the force on the metal shaft caused by the rubber band between the motor and the shaft. All results presented here are influenced by fluctuations similar in amplitude to the data in Figure 3.

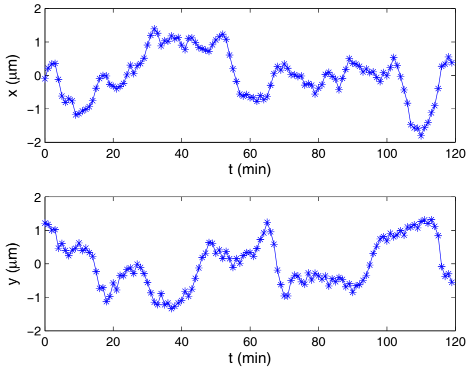

Figure 3: Magnetic center measurements at 20 A once a minute for two hours.

Platinum FaroArm

The Platinum FaroArm is a portable coordinate measuring machine and it is shown in Figure 4. 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 standard probe is a ceramic sphere with either 3 or 6 mm diameter and the points are taken manually by pressing a button. Here a Reinshaw T20 probe was used instead to minimize the force on the object to be measured, the data points are taken automatically when the probe touches the object. The inaccuracy of the Platinum FaroArm with 1.2 m working volume is maximum 18 µm, and better over shorter distances. The Polyworks software was used to determine the geometrical objects from the point clouds. 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.

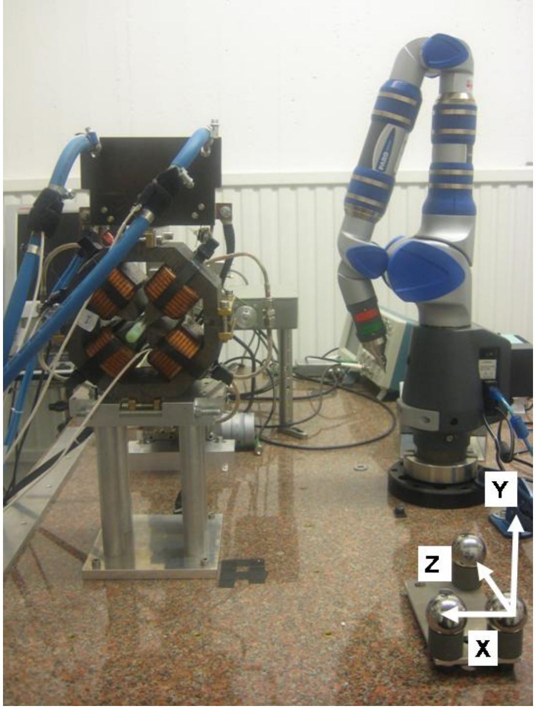

Figure 4: Platinum FaroArm and metal spheres defining the coordinate system.

MAGNETIC CENTER STABILITY

Prototype quadrupole magnets made of different soft magnetic materials have been made by DESY in order to find a material good enough to be used for the XFEL undulator quadrupoles. For the BBA to work the magnetic axis must not change more than ±5µm when the magnet current is changed by 10 % [7]. Previous measurements have shown that the prototype magnets made of Vacofer (pure Fe) and Permenorm (Ni-Fe alloy) have good magnetic center stability between 15 and 75 A [1]. That work has now been extended with one more magnet made of Russian relay iron [2] which is less expensive than both Permenorm and Vacofer. This magnet was made from 3 mm sheets, the laminations were welded and annealed. Figure 5 and 6 show the results from eight scans between 1 and 75 A. The scans were performed over 24 hours. The measurements are influenced by the fluctuations shown in Figure 3, therefore the average of the eight scans was also calculated and it is shown in Figure 5 and 6 (black curves). The position of the magnetic center seems to be more stable along the y-axis between 10 and 75 A, but over all the results are similar to the results from the measurements on magnets made of Permenorm and Vacofer [1].

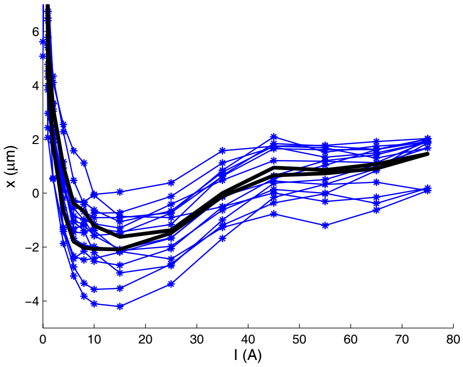

Figure 5: X-position of magnetic axis as function of coil current.

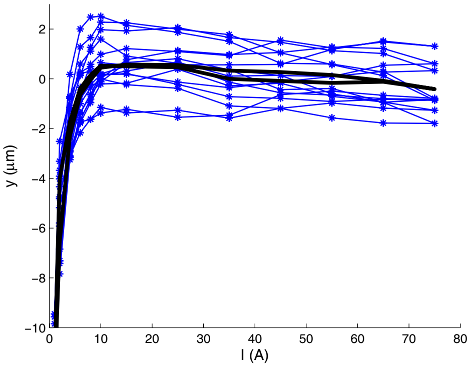

Figure 6: Y-position of magnetic axis as function of coil current.

FIDUCIALIZATION

To evaluate how well the rotating coil and the Faro arm can be used to determine the magnetic center with respect to fiducials, the rotating coil was positioned both to the left and to the right and above and below the magnetic center. Results from four measurements are shown in Figure 7. For each measurement a coordinate system was determined using three metal spheres that were used in the absence of fiducials on the magnet (see Fig. 4). The geometrical center of the steel shaft was then measured four times. After each measurement the shaft was rotated a quarter of a turn. The x and y positions (o in Figure 4) are the positions where the geometrical axis of the steel shaft crosses the xy-plane at the center of the magnet (in the direction of the z-axis). The rotational center was then estimated to be the mean value of the four measurements (+). Before and after the rotational center was determined the coil was rotated and the induced signal was registered over 20 turns to measure the magnetic center. The mean value of those two measurements was added to the position of the rotational axis measured by the FaroArm (* in Fig. 4). The mean value of the four measurements was determined to be x = 216.592 ± 0.010 mm and y = 236.289 ± 0.010 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=216.566 mm and y=236.275 mm (o in Fig. 7), 30µm from the magnetic center. A similar set of data has been presented before [5], the only difference here is that a new coordinate system was determined before each measurement not to exclude the error coming from measuring the position of the tooling balls. These tests have shown that the rotating coil setup together with a FaroArm can be used to determined the magnetic center within 50µm.

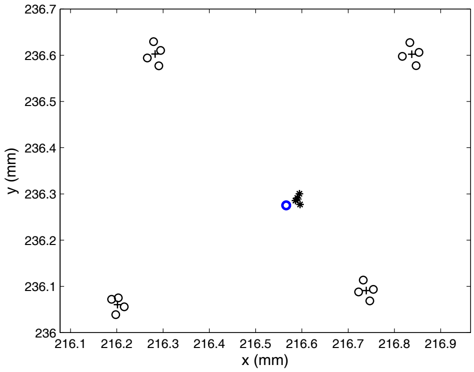

Figure 7: Magnetic center with respect to fiducials for 4 positions of the rotating coil. Black circles are the geometrical axis of the steel shaft, + is the axis of rotation and * is the magnetic center. Blue circle is the geometrical center of the magnet.

SUMMARY

A rotating coil setup together with a FaroArm have been set up at the Manne Siegbahn Laboratory to characterize and fiducialize the XFEL quadrupoles. Test measurements have shown that this setup can be used to determine the magnetic center better than 50µm. The rotating coil has also been used to study the magnetic center stability for prototype quadrupole magnets made from different soft magnetic materials. Here measurements on a quadrupole magnet made of Russian relay iron show good enough magnetic center stability for this material to be used for the XFEL.

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