FIELD CHARACTERIZATION OF XFEL QUADRUPOLE MAGNETS

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Abstract

A rotating coil setup for magnetic field characterization and fiducialization of XFEL quadrupole magnets is presented. The instrument allows measurement of the relative position of the magnetic axis with accuracy better than 1 μm and measurement of weak magnetic error field components. Tests and evaluation based on a FLASH quadrupole magnet are presented together with a discussion for fiducialization of XFEL quadrupole magnets with accuracy better than 50 μm.

INTRODUCTION

The European X-ray free electron laser (XFEL) will be one of the most advanced light source facilities and produce high intensity laser light of wavelengths down to 0.1 nm [1]. The laser light is produced and amplified by electrons moving through long undulator systems, each consisting of many 5 m long segments. Between the segments adjustable quadrupole magnets focus the electron beam. For optimum control of the laser light, the center of the quadrupoles need to be positioned along a straight line with an accuracy of 2 μm, which only can be reached by beam based alignment (BBA). Prior to the BBA procedure the magnets need to be optically aligned along the beam path, therefore the center position of the magnet has to be determined relative to alignment markers, or fiducials, on the magnet with an accuracy of approximately 50 μm.

A rotating coil system has been set up at the Manne Siegbahn Laboratory to characterize and fiducialize the XFEL quadrupole magnets. Fourier analysis of the induced voltage from the coils rotating in the quadrupole magnetic field gives the position of the magnetic axis relative to the axis of rotation. It also gives information of higher order error field components, i.e. the quality of the magnetic field topology [2, 3]. Initially the intrument will be used to investigate suitable materials for the XFEL quadrupole magnets and in a later stage characterize and fiducialize these magnets. The instrument has been tested on a FLASH quadrupole magnet and include measurements of magnet exitation dependence and long term stability of the magnetic axis position.

MAGNET CHARACTERIZATION

The rotating coil setup consists of a hollow steel shaft supported by ball-bearings. A 12 mm diameter epoxy G-10 rod extends 25 cm from the shaft. The rod has a long slit through it that holds two coils sitting side by side. The coils are 17 cm long, 6 mm wide and wound with 60 turns of 100 μm diameter copper wire. During measurement the coils are positioned symmetrically in the 12 cm long quadrupole magnet leaving 2.5 cm of coil on either side to accurately measure the magnetic field. A computer controlled stepper motor rotates the coils with a frequency of approximately 1 Hz and an incremental encoder measures the angular position of the coils. The electrical signal from the coils passes through the shaft via a mercury slip ring to a preamplifier before connection to a data acquisition card in a computer. Figure 1 shows the experimental setup ready for measurement with the coils inserted into the magnet. The position of the coils in the epoxy rod is shown in figure 2.

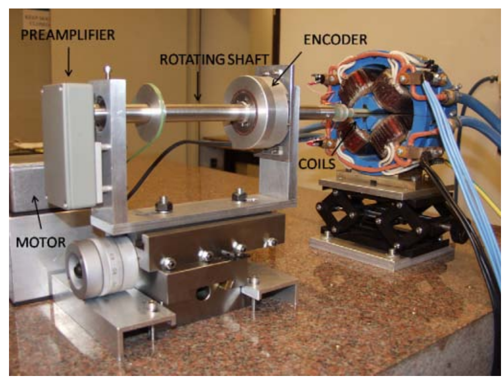

Figure 1: Rotating coil setup

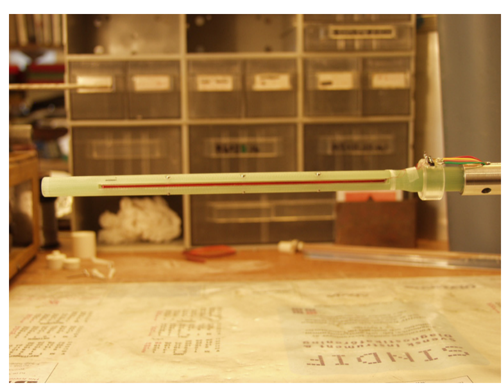

Figure 2: Coil in the G-10 rod

The induced voltage from the coils rotating in the quadrupole magnetic field can be represented by a Fourier series. The distance r from the axis of rotation to the magnetic axis is directly proportional to the ratio of the dipole and quadrupole components,

$$r = R\frac{V_{dipole}}{V_{quadrupole}} \quad (1)$$

where R is the width of the coils. Beside the dipole and quadrupole terms are higher order field error components with mode numbers $6, 10$ and $14\ldots$ possible in a four-fold symmetry. Figure 3 shows the amplitude of all mode numbers from 1 to 40 with the allowed error field components clearly visible above the background level. At this particular position of the coils in the magnet the ratio of mode numbers $n = 1$ and $n = 2$ is 0.0319 and consequently the distance between the axis of rotation and the magnetic axis is 191.4 μm.

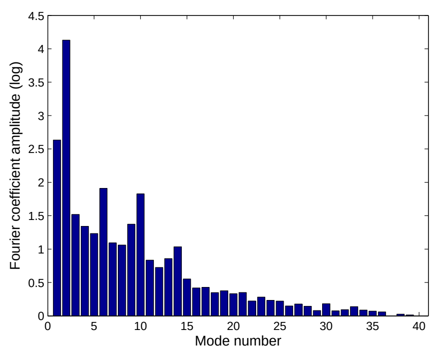

Figure 3: Fourier series components (normalized)

Figure 4 and 5 show the temporal evolution of the position of the magnetic axis during 12 hours. The x and y coordinates represent the position in the transformed magnetic field coordinate frame with the rotating coil at the origin. The average position of the magnetic axis $(x \pm 2\sigma_x, y \pm 2\sigma_y) = (111.7 \pm 0.8, 155.0 \pm 0.9)$ during the 12 hours. This is within the aim of the design of the rotating coil setup: to measure and monitor the stability of the position of the magnetic axis with accuracy better than 1 μm.

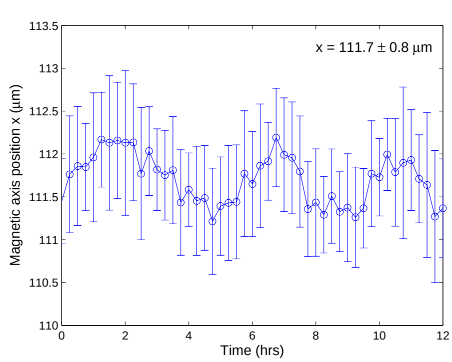

Figure 4: Magnetic axis position x during 12 hours

The variation in the relative position of the magnetic axis over time is not fully understood. The shaft (and thereby the coils) is supported by ball-bearings and there will be

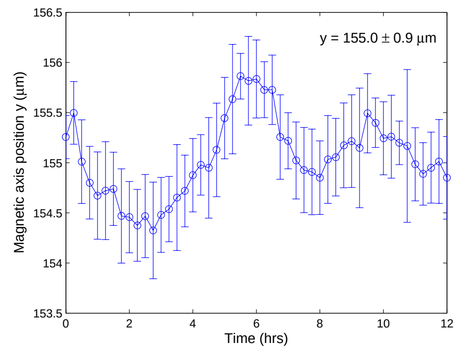

Figure 5: Magnetic axis position y during 12 hours

minor mechanical movement with respect to the magnet. Temperature fluctuations change the position of the magnetic axis and in particular the vertical position. The ambient temperature in the laboratory is controlled and kept within $\pm 0.1°$C during measurements. The temperature of the cooling water can change with as much as $\pm 0.5°$C and this affects the temperature of the magnet in much more direct way. A possible future improvement would be to control the water temperature better. However, the data from the 12 hour long measurement session selected here show no clear indication of any influence on the magnetic axis position from the cooling water.

The quadrupole magnets will operate at different currents depending on the electron beam energy. It is therefore essential that the position of the magnetic axis does not change too much with current, or at least moves in a predictable and reproducible fashion. Figure 6 and 7 show the result from a series of measurements where the current was increased from 0 to 45 A, then back to zero, and finally increased to 20 A. The position of the magnetic axis clearly depends on the excitation history.

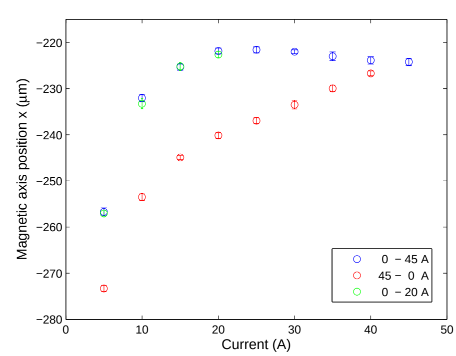

Figure 6: Magnetic axis position x vs current

Another very important aspect of the stability of the magnetic axis with respect to magnet excitation is the beam based alignment procedure. During BBA the magnets are aligned by changing the current and observing the change in position of the electron beam further downstream. When

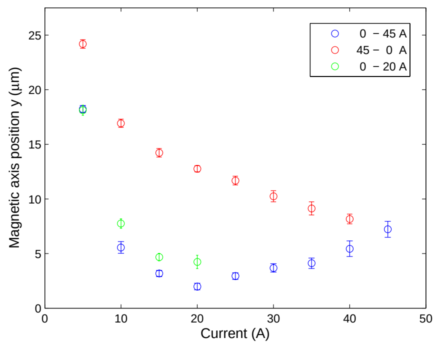

Figure 7: Magnetic axis position y vs current

the magnets are properly aligned there is a minimum movement of the electron beam when changing the current. At XFEL, for the BBA procedure to work, the position of the magnetic axis must not move by more than 5 μm when the current changes by 10 $\%$ [4]. The FLASH quadrupole magnet was tested by changing the current by $\pm 10\%$ at $20, 30, 40$ and 50 A. The result is shown in figure 8 and 9 (the pattern looks very similar for 20 to 40 A). At lower currents, the magnetic axis moves by less than 4 μm. When the current increases from 45 to 50 A, the magnetic axis moves by more than 30 μm. Although the magnet can operate up to 75 A, magnet gradient data shows that saturation occurs already at 50 A and this may cause effects that explains the sudden change in behaviour [4].

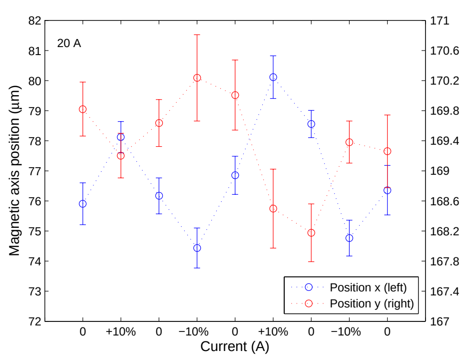

Figure 8: Magnet excitation for BBA at 20 A

FIDUCIALIZATION PLAN

The rotating coil setup measures the relative position of the magnetic axis with respect to the axis of rotation. To fiducialize the magnet, the position of the axis of rotation must be determined with respect to alignment markers, or fiducials, on the magnet. These fiducials will be high precision spheres on a plate positioned on top of the magnet. The measurement of the position of the axis of rotation with respect to the fiducials on the magnet will be done with a coordinate measuring machine (CMM). Initially, the measurement will be done directly on the rotating shaft and the

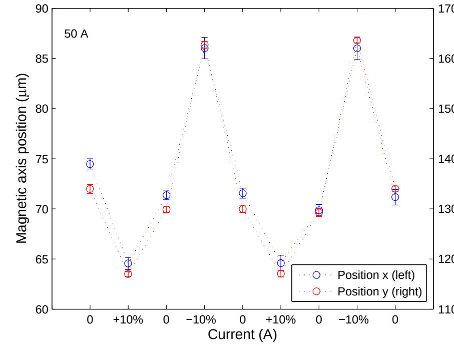

Figure 9: Magnet excitation for BBA at 50 A

fiducials with the CMM. This assumes that the geometrical centre of the rotating shaft coincides with the axis of rotation. Measurements with a dial indicator show a 10 to 15 μm discrepancy, which will add to the measurement uncertainty. The CMM will measure the distance from the shaft to the fiducials with accuracy better than 10 μm, leaving in total an error of less than 30 μm. Additionally, the CMM will be used to measure the position of the geometrical centre of the magnet (from the poles) relative to the fiducials as a check of the magnetic measurement.

A possible future development is to use a laser scanning micrometer to measure the position of the shaft (and thereby the axis of rotation) with respect to a fixed point, e.g. a sphere located near the shaft, and then measure this position with respect to the fiducials on the magnet. This allows non-contact measurement of the shaft. It will also be possible to measure the position of the axis of rotation continuously and simultaneously with the rotating coil measurement resulting in a time-resolved measurement of the stability of the magnetic axis, with respect to the fiducials.

CONCLUSIONS

A new rotating coil setup at the Manne Siegbahn Laboratory designed for magnetic field measurements of XFEL quadrupole magnets allows measurement of the relative position of the magnetic axis with accuracy better than 1 μm. Initially the intrument will be used to investigate suitable materials for the XFEL quadrupole magnets and in a later stage characterize and fiducialize these magnets with an accuracy better than 50 μm.

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