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Transfer of the magnetic axis of an undulator to mechanical fiducial marks of a laser tracker system

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ABSTRACT

The exact geometric location of the magnetic centers of sensors or sensor systems using Hall probes or pick-up coils is usually not known with high precision. In order to transfer the high spatial accuracy of magnetic measurements to external mechanic fiducials a device called “Magnetic Landmark” was developed and is described in this report. Its purpose is to establish the exact relation between “magnetic” coordinates used on magnetic measurement systems and “mechanic” coordinates used for alignment.

The landmark consists of a permanent magnet configuration, which generates a field distribution with well-defined zero crossings in two orthogonal directions, which can be exactly localized with micrometer precision using magnetic measurement systems. For the “mechanic” measurements several redundant monuments for laser fiducials can be used.

Using flip tests for the magnetic as well as mechanic measurements the center positions are determined in magnetic and mechanic coordinates. Using them the relation between the magnetic and surveying coordinates can be established with high accuracy.

This report concentrates on the description of the landmark. A thorough analysis on achievable accuracy is presented. The method was developed for the alignment of the 91 undulator segments needed for the European XFEL but can be applied to other magnet systems as well.

1. Introduction

The magnetic axes of individual undulator segments in long X-ray FELs such as the European XFEL (EXFEL) or Linac Coherent Light Source (LCLS) need to be aligned with an accuracy of typically ± 50–$100\ \mu m$ or better [1,2]. This puts challenging requirements on magnetic measurements and geometric alignment.

State of the art magnetic measurements allow for high spatial resolution. As an example, the exact location of the magnetic center axis in an undulator can be measured with an accuracy of ± 5–$10\ \mu m$ in both transverse directions. It is, however, difficult to transfer this magnetic accuracy to geometric fiducials, which can be used for in situ alignment in the tunnels.

The basic problem is that the exact geometric location of the magnetic center of a sensor or a sensor system is only known to an estimated accuracy of ± 0.5–1 mm at best and moreover may slightly drift in time due to unwanted changes in the mechanical supports. In order to make full use of the spatial accuracy of the magnetic measurements a method is needed which transfers the magnetic coordinates to externally accessible fiducials for geometric alignment methods such as laser trackers. For LCLS a method was described [3,4] which makes use of two “Fiducialization Magnets”, which are temporarily attached to the ends of a 3.3 m long fixed gap undulator segment. A fiducialization magnet consists of two magnetic needles, which produce well-defined field distributions directly related to laser tracker monuments. For the transfer of the magnetic coordinates the undulator needs to be placed on a 3D coordinate measurement machine, which due to the compact size of the fixed gap LCLS undulator segments is straight forward to do.

For the EXFEL an alternative method is required since the undulator segments are gap adjustable and have a substantial size of 5 by 2.4 by 1.5 m^3. A device internally called “Magnetic Landmark” was developed, which allowed the transfer from magnetic to geometric coordinates using state of the art laser trackers. It is described in this paper.

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2. Detailed description

2.1. Basic principle

For the magnetic landmark described in this paper flip tests play a key role. The principle is shown in Fig. 1. The Y-center position of an object is determined by measuring the Y position of an object point, marked by the cross, in two orientations, one, Y_N, at 0° and the other, Y_F, at 180°. The center position, Y_C, of the object is determined by:

$$Y_C = (Y_N + Y_F)/2 \quad (1)$$

The Z-center positions are obtained accordingly. This principle can be applied to magnetic or mechanic objects and the results will be in mechanic or magnetic coordinates. For the flip test there must be provisions to place the object reproducibly in both orientations.

An excellent mechanical object point is the monument for a laser retro-reflector, which can be placed such that it can be measured in 0° and 180° positions.

2.2. Magnetic system

For the definition of a magnetic object point a suitable configuration of permanent magnets (PMs) is needed. Its field distribution should have zero crossings, which can be localized precisely. First ideas were presented in [5]. A configuration with this property for the Y component of the magnetic field, B_Y, is shown in Fig. 2(a) together with the definition of the coordinate system and its origin used in this paper. Low cost cubic shaped permanent magnets (PMs) made of NdFeB with a remanent field of 1.2 T and edge-length of 20 mm are used. Bottom and top magnets are separated by a gap of 12 mm. The left group is separated by the right pair by 10 mm. The exact dimensions are given here for information. In the median plane this magnet configuration has well defined zero crossings. Their Y and Z-coordinates can be localized precisely in normal and 180° flipped state as will be described in more detail below.

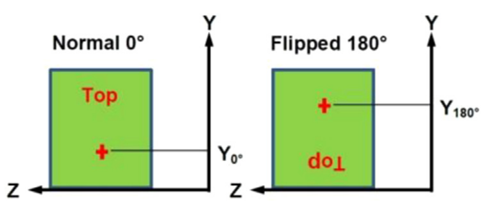

Fig. 1. Principle of a flip test.

This PM configuration is a combination of a normal and a skew planar PM quadrupole, which were first proposed by Tatchyn [6]. The leftmost four magnets in Fig. 2(a) form the normal PM Quadrupole. Near its center marked by the cross the B_y field component has a linear dependence in z.

$$B_y(z) = c_{Norm} \cdot (z - z_{Norm}) \quad (2)$$

Here c_{Norm} is the normal gradient. At the center position, z_{Norm}, the sign of the B_Y component changes. Near $x,y=0$ this point can be localized with high precision in magnetic measurements by scanning B_y vs. z.

The magnet pair on the right with anti-parallel magnetization is a planar PM skew quadrupole. The field near its center, which is the coordinate origin as well is described by:

$$B_y(y) = c_{Skew} \cdot (y - y_{Skew}) \quad (3)$$

Here c_{Skew} is the skew gradient and y_{Skew} the exact y-position, where the B_y component changes sign. In complete analogy to z_{Norm} y_{Skew} is localized by scanning B_y vs. y near $y,z=0$. The two zero crossings z_{Norm} and y_{Skew} define the magnetic object point in the Y–Z plane near $x=0$.

The magnetic Y and Z center positions are obtained by a flip test, i.e. by flipping the magnet array around the X-axis in the origin as sketched in Fig. 2(b). Now there are positions in normal and flipped state, which can be readily measured with the magnetic sensor sensitive to B_y: The magnetic centers are obtained using Eq. (1).

Fig. 3 shows the distribution of the B_y component in the Y–Z plane at $X=0$ for the magnet configuration shown in Fig. 2(a). Note, for better visibility the z-axis direction has been reversed from right to left. The skew quadrupole is seen on the left around $z=0$ mm by the linear increase along Y. Similarly the normal quadrupole is seen around $z=-40$ mm by the steep linear increase along z. Note the different scales of y and z.

Fig. 4 demonstrates the sensitivity to misalignment in the orthogonal directions. In Fig. 4(a) the exact value of the Y coordinate of the zero crossing under the skew quadrupole at $z=0$ mm is shown. It is seen that in the whole plotted area in the X–Z plane the Y zero crossing varies only by 80 μm in total and much less if the area is reduced. For ± 0.5 by ± 0.5 mm^2, which is a moderate alignment accuracy, the variation is estimated to < 10 μm in total. Similarly Fig. 4(b) shows the exact value of the Z-zero crossing in the plotted X–Y plane under the normal quadrupole located at $z=-40$ mm. It varies in total only by 36 μm. For $\pm .5$ by ± 0.5 mm^2 the total variation is 12 μm only. This demonstrates that there is only moderate dependence of the zero crossings to misalignment in the orthogonal directions.

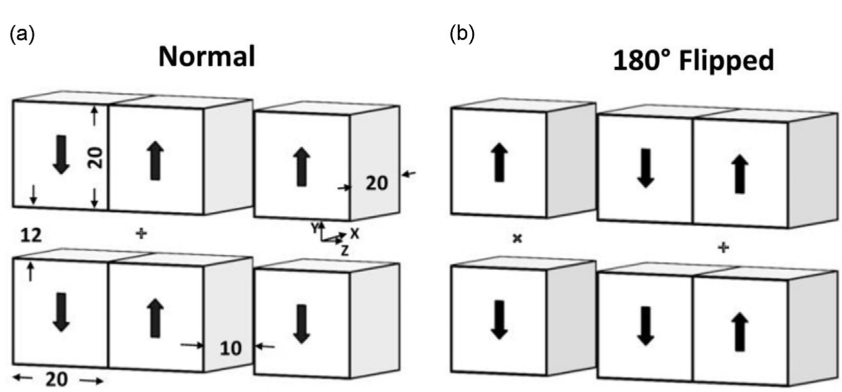

Fig. 2. Configuration of cubic PM blocks. (a) Normal position. In the median plane the left four blocks form a normal quadrupole with the Z center position at the position of the cross. The rightmost two blocks form a skew quadrupole. Its center defines the coordinate origin. (b) For the flip test the whole magnet configuration is rotated by 180° around the X-axis in the coordinate origin.