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REFERENCE MEASUREMENT METHODS FOR PLANAR AND HELICAL UNDULATORS

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Abstract

The modern permanent magnet undulators are usually equipped with motors that have integrated feedback electronics. These are essentially rotary encoders that indicate the position of the motor axis. In addition, undulators are also equipped with linear encoders that provide the absolute value of the gap between the magnetic structures or the position of the magnetic girders relative to the undulator frame. The operating conditions of undulators should take into account the risks of failure of electronic equipment under the influence of radiation. In case of encoder failure, the motor or encoder must be replaced. To avoid the need to return the undulator to the magnetic measurement laboratory, reference measurements are required to restore the position of the magnetic structure after replacement. In this article, reference measurement procedures for planar and helical APPLE-X undulators used at the European XFEL are presented.

INTRODUCTION

Radiation damage is often a cause of failure of electronics installed in close proximity to a charged particle beam. This is the case for both synchrotron radiation sources and free-electron lasers. The causes of primary and secondary radiation can be errors in beam trajectory control as well as synchrotron radiation generated when the beam passes through deflecting magnets, undulators, wigglers, or other insertion devices (ID).

Such a situation occurred in particular with the helical undulators installed downstream of the SASE3 planar undulator system at the European XFEL [1]. A few months after the installation of these undulators in the tunnel, a considerable number of linear and rotary encoders were damaged by non-linear high-energy Compton scattering, as it turned out later. This radiation was apparently the result of scattering of spontaneous radiation from the planar undulators on the walls of the aluminum vacuum chamber of the helical APPLE-X undulator. As a result of this radiation damage to the feedback system, it was not possible to control the magnetic structures of the undulator [2].

To restore the functionality of the APPLE-X undulators, they had to be removed from the tunnel and the damaged encoders replaced. Since the position of the magnetic structures was lost after the encoders were replaced, new magnetic measurements had to be performed and the undulator had to be re-calibrated. Particularly, the magnetic measurements showed that the radiation that disabled the encoders did not affect the magnetic properties of the undulators. Thus, if reference measurements of the position of the magnetic structures had been made before the problems with the encoders occurred, it would not have been necessary to remove the undulators from the tunnel. Indeed, after replacing the encoder or the motor, the magnetic structure could be returned to the position determined by the reference measurements.

The methods proposed below can be used to perform reference measurements on planar insertion devices such as an undulator or phase shifter, as well as on helical undulators. In the case of the helical undulator, two methods are proposed for measuring the undulator gap and the longitudinal position of the magnetic structures.

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REQUIREMENTS FOR REFERENCE GAP MEASUREMENT FOR PLANAR INSERTION DEVICES

If the construction of the ID, i.e., undulator or phase shifter, is not done in vacuum, then the vacuum chamber of the electron beam is located between the magnetic structures. In this case, the direct gap measurement must consider this, since the goal is to determine the position of the magnetic structures without retrieving the ID from its position. The proposed setup consists of two flat gap measurement sensors. Each gap measurement sensor consists of two capacitive sensors located on opposite sides of a printed circuit board (PCB). One of the arguments in favor of the measurement principle is the fact that the undulator or phase shifter is located in a tunnel where the temperature changes over time do not exceed a few hundred millikelvin.

Under constant temperature conditions, changes in the thickness of the vacuum chamber are negligible. In the case of the European XFEL, the thickness of the vacuum chamber is 9.6 mm. This means that a 1 °C change in the temperature of the vacuum chamber from its nominal value of 21 °C results in a 0.22 µm change in its thickness. The same can be said about the change in the thickness of the sensors. The thickness of the printed circuit board on which the capacitive sensors are mounted is 0.8 mm. This means that the thickness of the sensors changes by 0.015 µm for a temperature change of 1 °C, i.e. 0.03 µm for two sensors. Therefore, if the temperature of both sensors and the vacuum chamber changes by 1 °C, the total thickness change corresponds to 0.25 µm.

For free-electron lasers, a necessary condition for achieving lasing is that the spread of the K parameter of the undulator does not exceed the Pierce or FEL parameter. Thus, for high-energy free-electron lasers, the $\Delta K/K$ must be less than 3x10e-4. The calculation of the boundary condition for the change of the gap is presented in chapter 2.3 of the article [3]. From this it can be seen that the change in the undulator gap should not exceed 3 µm. Therefore, the reproducibility of the relative reference measurements should not exceed this value.

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As mentioned above, the thermal expansion/contraction of the components used for the measurement is much smaller than 1 µm under the conditions of time-dependent temperature stability in the tunnel <1°C.

The next requirement for the reproducibility of the measurements is the highly precise positioning of the measuring sensors in the longitudinal direction. This accuracy can be achieved by using a stop installed in one of the holes of the magnetic structure. In this case, the positioning of the sensor mounting block relative to the magnetic structure can be reproducible in the longitudinal direction to a maximum of 100 µm. This reproducibility of the installation in the longitudinal direction means that a maximum deviation from the nominal value of the gap of 0.1 µm is possible. This value is determined by the tolerances for the accuracy of the manufacture of the poles of the magnetic structures and the tolerances for the accuracy of the manufacture of the vacuum chamber.

High reproducibility of measurements depending on the vertical position of the sensors is ensured by the gap measurement method. This method is based on the measurement of the sum of four dimensions. The idea is that the total value of the measured gap does not change if the sensor installation deviates in the vertical direction by an amount that does not exceed the limit value for the working gap of the sensor. The limit value for the working gap in our case is 1 mm. Thus, it is necessary that the design of the measuring sensor block ensures such an installation that all sensors involved in the measuring process are within the working gap limit.

CONSTRUCTION OF THE PLANAR ID REFERENCE MEASURING UNIT

Considering the requirements outlined in the previous chapter, the proposed design of the measurement unit is shown in Fig. 1.

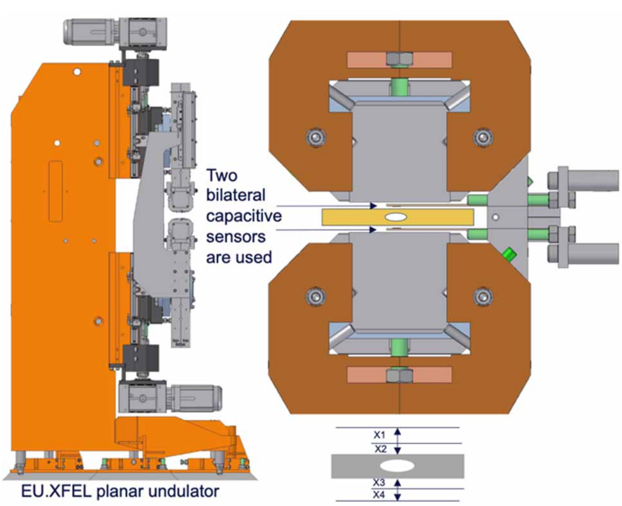

Figure 1: Layout the planar undulator (left) and the gap measurement unit (right).

The measurement unit consists of two double-sided capacitive sensors mounted in an aluminum frame. The distance between the sensors is determined by the thickness of the vacuum chamber and the sensitivity limit of the sensor. In our case, the thickness of the vacuum chamber is 9.6 mm and the sensitivity limit is 1 mm. Thus, the optimal distance between the sensor surfaces facing the vacuum chamber is 9.6 mm +2x0.5 mm = 10.6 mm. The design of the aluminum frame took into account the surfaces of the magnetic holders, which support the self-centering of the measuring unit with respect to the center of the gap between the magnetic structures. The undulator gap must be adjusted to ensure the distance between the two external capacitive sensors and the poles of the magnetic structures in the sensitivity range of the sensors. In our case, the thickness of the PCB board is 0.9 mm. If the surfaces of the external sensors have a distance of 10.6 mm + 2x0.9 mm = 12.4 mm, then the optimal distance between the poles of the magnetic structures should be 12.4 mm + 2x0.5 mm = 13.4 mm.

To fix the measuring block in the gap between the magnet structures, four steel screws are used, which are symmetrically placed in the upper and lower part of the measuring block. These screws are attracted by permanent magnets and press the measuring block against the surface of the magnet holders. The attraction force can be adjusted by adjusting the screws so that they are closer or farther away from the magnets. It should be noted that the screws must not touch the magnets by being turned too far in the direction of the magnets to avoid damaging them.

A stop is used for high-precision positioning of the measuring unit in the longitudinal direction. This stop is inserted into one of the holes in the housing of the magnet holder, which are used for the screws to fix the magnets.

To perform reference measurements, the measuring block is inserted into a predetermined area of the undulator gap. The selected position resp. the poles of the magnet structures then are used as reference point for the measurement. The longitudinal direction stopper is inserted in advance into the intended hole to align the centers of the capacitive sensors with the center of the selected reference poles. After inserting the measuring block into the gap of the undulator, it must also be pressed in all the way to the stop in order to achieve reproducible measuring conditions.

The design of the European XFEL planar undulators also allows a gap taper. This means that in case of damage to the two linear encoders located on either side of the magnetic girders, at least two reference measurement points are required, each closer to the position of the linear encoders, i.e., closer to the edges of the girders. We selected three reference points, one in the center and two points equidistant from the center.

The values of the sum of the measurements from all four sensors were entered into the database. The measurement statistics show that the reproducibility of the relative reference measurements of the undulator gap is within 1 µm.

The same method has been used to make the reference measurements for the phase shifters. The design of the measurement block is similar to that of the undulator, taking into account the geometry of the magnetic holders of the phase shifter.

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REFERENCE MEASUREMENTS OF HELICAL APPLE-X UNDULATOR.

A specific design feature of the APPLE-X Helical Undulators is that the magnetic structures mounted on the girders can be moved in two directions. One direction is perpendicular to the magnetic axis of the undulator. Moving the magnetic structures in this direction changes the distance between the magnetic structures and thus the strength of the magnetic field, similar to planar undulators. Another direction is the longitudinal movement of the magnetic structures. This movement can be used to adjust the polarization of the radiation.

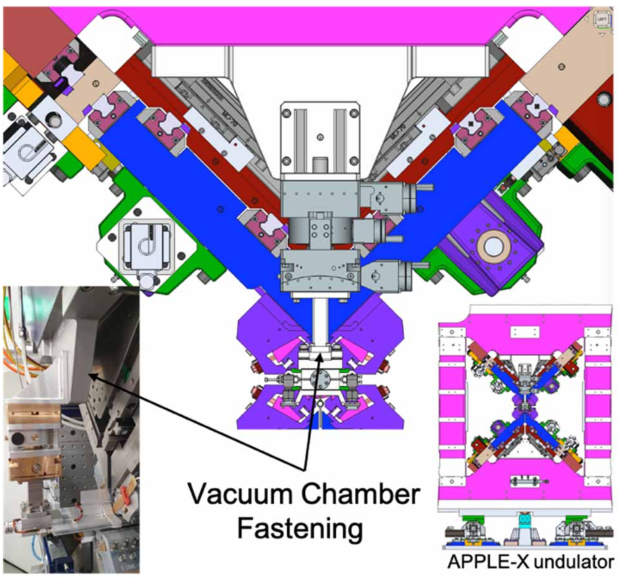

Figure 2: Layout of the vacuum chamber fixation for the APPLE-X undulator.

This means the helical undulator has four magnetic structures, which means eight motors with encoders are used to position the four magnetic structures in both directions. Eight linear encoders are used as precision feedback devices. Therefore, for reference measurements, it is necessary to perform them in both the transverse and longitudinal directions.

The construction of the vacuum chamber fixture for the EU.XFEL APPLE-X undulator allows horizontal and vertical translations as well as rotation around the longitudinal axis, but no longitudinal movements. (see Fig. 2).

Radial Measurements

To measure the gap, i.e., the position of the magnetic structures in the perpendicular direction, a method similar to the measurement of the gap in planar undulators is proposed. For this purpose, two bilateral capacitive sensors are used. They are inserted into the gap between opposing magnetic structures and the vacuum chamber. The sensors are equipped with 0.5 mm thick steel tapes. These tapes are used for two purposes. First, the attractive force of magnets is to be used to position the sensor in the gap. The second is to create a gap of about 0.5 mm between the surface to be measured and the sensor (see Fig. 3). After the installation of both sensors, the gap between the magnetic structures of the undulator is reduced until the center of the sensitive zone of the sensors directed to the vacuum chamber is reached. The sum of the four measurements gives the measurement of the reference gap. This value can later be used to position the magnetic structures on which the measurements were made. Since the design of the APPLE-X undulator does not provide tapping capabilities, measuring at one reference point is sufficient for a perpendicular direction. These measurements must be made four times between each pair of adjacent magnetic structures.

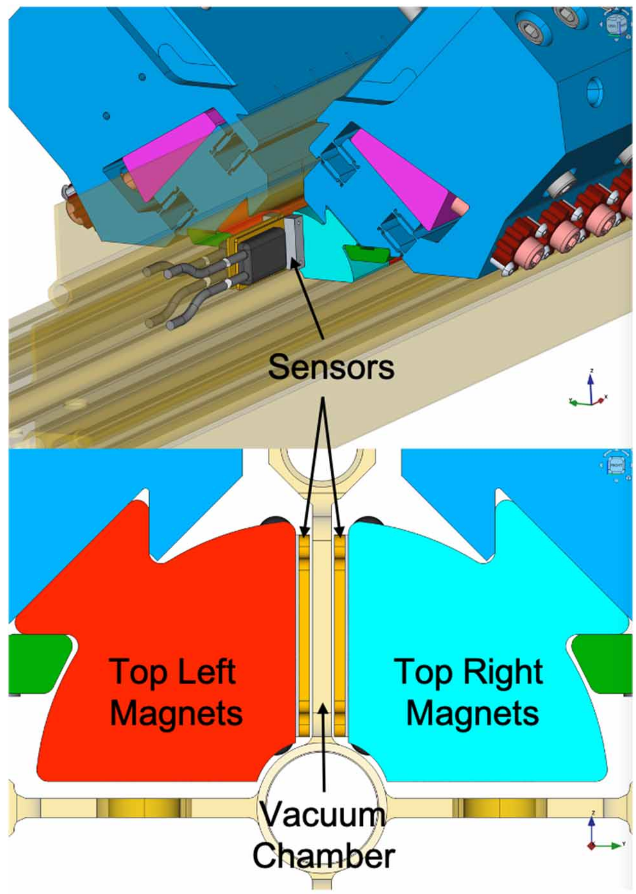

Figure 3: Isometric (top) and frontal (bottom) views of the gap measurement setup.

Shift Measurements

To perform reference measurements in the longitudinal direction, it is proposed to use an aluminum reference object rigidly mounted on a vacuum chamber. The end of the vacuum chamber to which the reference object is attached is rigidly connected to the undulator frame. Thus, the reference object is rigidly attached to the undulator frame and its surfaces serve as reference planes. This object is fixed at a distance of about 2 mm from the front plane of the magnetic structure. A double-sided capacitive sensor is inserted into this gap (see Fig. 4). The idea is again that the sum of the two measurements remains constant even if the sensor deviates relatively from the measured surfaces

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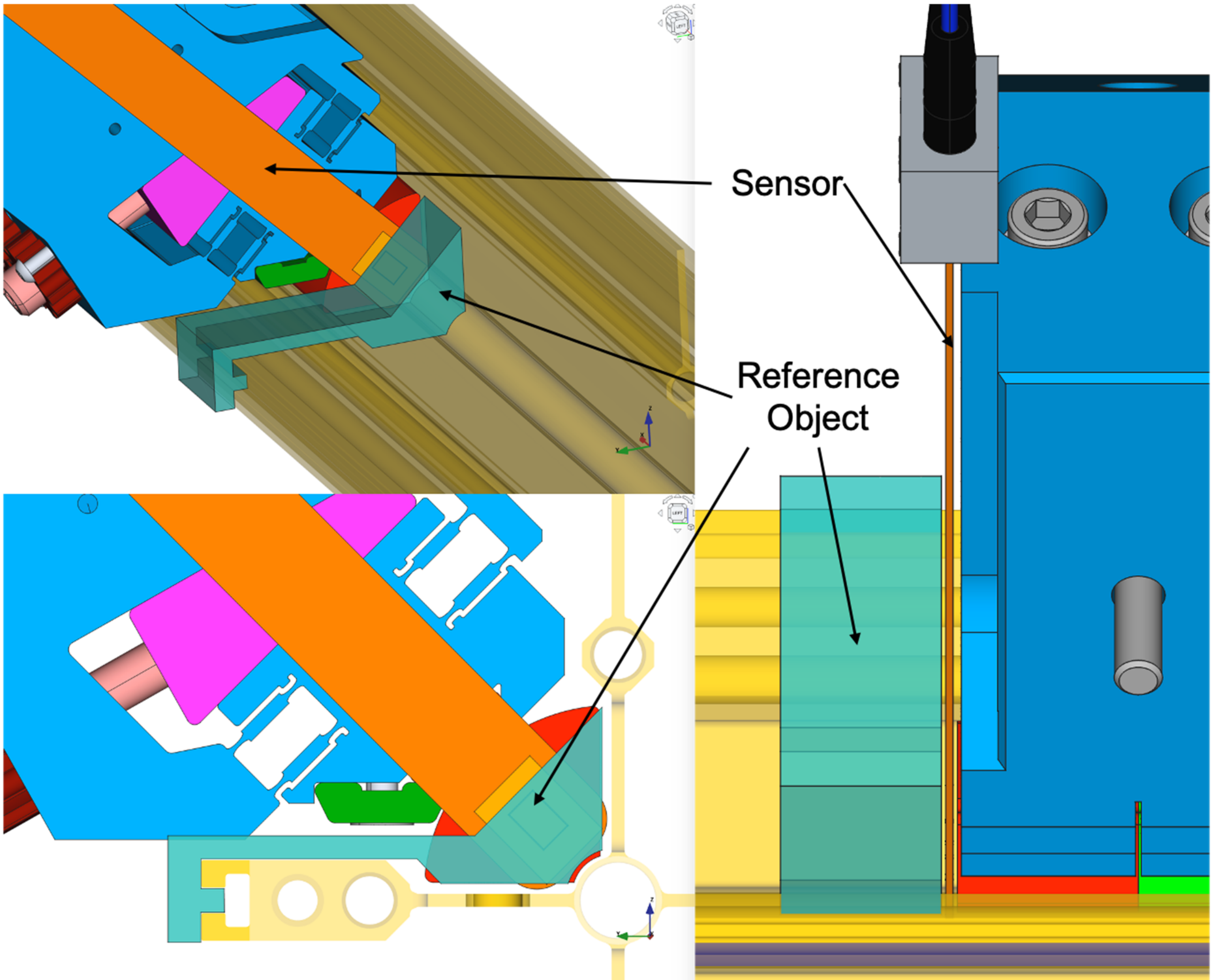

Figure 4: Isometric (top left) frontal (bottom left) and top (left) views of the shift measurement setup.

CONCLUSIONS

First, a reference gap measurement method for planar undulators presented in this paper. This method has shown sub-micrometric reproducibility of measurements, which can be used when encoders fail and need to be replaced. It was used in the European XFEL for the reference gap measurements for 91 planar undulators and 88 phase shifters.

The two other methods for performing reference measurements of gap and shift of helical APPLE-X undulators are also presented. These measurement methods are planned to be carried out after the installation and thermal stabilization of the undulators in the tunnel.

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