THE MAGNETIC FIELD INTEGRAL HYSTERESIS ON THE EUROPEAN XFEL GAP MOVABLE UNDULATOR SYSTEMS

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Abstract

Magnetic field hysteresis effects between opening and closing the gap of an undulator or phase shifter of the Undulator System of the European X-ray FEL may have an impact on the radiation properties. Using the moving wire technique the hysteresis between opening and closing the magnetic gap has been measured with high accuracy. Within the measurement accuracy undulator segments show negligible magnetic hysteresis between opening and closing the gap so that no effect on beam operation is to be expected. In contrast, about 2/3 of the phase shifters show a small hysteresis of the first field integrals of a few G.cm. In one direction of the gap movement they exceed field integral specifications. However the hysteresis is very reproducible. All phase shifters are magnetically tuned so that they fully satisfy magnetic specifications for beam operation when the gap is opened.

INTRODUCTION

The European XFEL (XFEL.EU) is designed to use three gap movable SASE Undulator Systems to produce FEL radiation tunable from 0.05 to 5.2 nm and pulse lengths of less than 100 fs [1,2]. The radiation wavelength can be tuned while selecting the e-beam energy between 8.5 to 17.5 GeV and / or changing the gap of the undulator systems. A total of 91 so called undulator cells are built and each is composed of a 5-metre long undulator segment equipped with two horizontal/vertical air coil correctors on both ends and a 1.1-metre long intersection unit containing a phase shifter (PS), a quadrupole mover with quadrupole magnet, the vacuum system and the beam position monitor. All undulator segments and phase shifters [3] for the XFEL.EU are built using NdFeB hard magnets. All devices were magnetically tuned to tight specifications in order to optimize the SASE effect (see Table 1).

The quality of the produced SASE radiation is essentially influenced by the global electron trajectory while traveling through the whole SASE System. At either end of an undulator segment there might occurs entrance and exit kicks, which are related to imperfections in the magnetic structures. They are compensated by using the air coils correctors. Similarly, small field integrals in the phase shifters [4] are required to guarantee minimum FEL power loss and no beam wander in between undulator segments. While tuning the wavelength and changing the gaps of the permanent magnet undulator systems, the presence of hysteresis effects on the magnetic field integrals while opening or closing the gaps may result in uncorrected compensation for the end kicks or mismatch of the e-beam phase between undulator cells. As a consequence the global trajectory of the electron beam and the quality of the produced SASE radiation is deteriorated. These considerations gave the motivation to investigate and monitor the presence of hysteresis of magnetic field integrals on undulators and phase shifters during the serial production.

Table 1: XFEL.EU Magnetic Specifications

Undulators	**SASE1-2**	**SASE3**
# of Segments	35	21
K-parameter @10mm	≥ 3.9	≥ 8.0
End kicks By and Bz (T.mm)	$\lvert \leq 0.15 \rvert$	$\lvert \leq 0.15 \rvert$
RMS Phase jitter (degrees)	≤ 8	≤ 8
Phase shifters		
# of Phase Shifters		95
Magnetic Field at gap = 10.5 mm		≥ 1.26 T
Phase Integral at gap = 10.5 mm		≥ 25000 T^2m^3
First Field Integrals (T.mm or 10^3 G.cm)	Gap (mm)	±Tolerance
	16	±0.004
	15	±0.007
	14	±0.009
	13	±0.012
	12	±0.014
	11	±0.017
	10.5	±0.018

EXPERIMENTAL METHODS AND FIELD INTEGRAL PROPERTIES

Direct field integral measurement techniques provide much higher accuracy [5–7] than Hall sensor measurements for the evaluation of total first and second field integral properties. The stretched wire (SW) method [5] was chosen and two dedicated moving wire (MW) systems [8] were built. The first, so-called "short MW", is designed to measure first field integrals in short devices such as phase shifters or air coils with sub-G.cm accuracy. The "long MW" system is focused to measure both first and second field integrals of the 5-metre long undulator segments and to determine the end kicks and their respective compensations. In both systems the first and second

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field integrals are calculated based on the integrated induced voltage $V(t)$ over a time t when the N strand wire moves by Δx as follows:

$$I_{1y,z} = \frac{\Delta\Phi_1}{\Delta x} = \frac{\int_{t1}^{t2} V(t)dt}{N\Delta x} \quad \text{(parallel motion)} \quad (1)$$

and

$$I_{2y,z} = \frac{L}{2} I_{1y,z} - \frac{L\int V(t)dt}{2N\Delta x} = \frac{L}{2} I_{1y,z} - F_{2y,z}$$
$$\text{(anti-parallel motion),} \quad (2)$$

where the so-called measured integrated voltage $F_{2y,z}$ is obtained while performing anti-parallel movements of the stretched wire ends [5,8]. Therefore, the second field integrals $I_{2y,z}$ are estimated from direct measurements of magnetic flux when moving the stretched wire in parallel and anti-parallel directions.

Typical results for the first field integral measurements of a batch of 31 phase shifters are shown in Fig. 1A. First and second integrals of a representative undulator segment with air coil correction are shown in Fig. 1B. The gaps were moved from closed to open for these measurements. Figure 1A demonstrates that the field integrals of all phase shifters are well within inside XFEL.EU specifications and Fig. 1B shows that the field integrals of an undulator segment can be properly compensated by the air coil correctors. Very similar results are obtained for all phase shifters and undulator segments of the serial production.

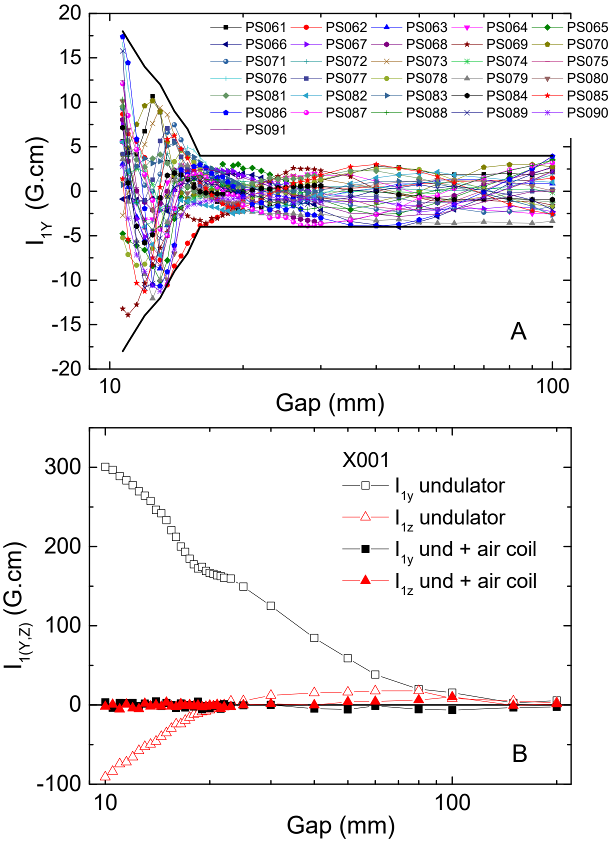

Figure 1: First field integrals of a Phase shifter batch (1A) and of an undulator segment (1B).

Hysteresis effects were measured by first carrying out measurements when the gaps are opened followed by measurements when the gaps are closed. The measurements ranged between 10.0 and 200mm gaps for the undulator segments and between 10.7 and 100mm for the phase shifters.

HYSTERESIS IN UNDULATORS

Hysteresis measurements were made on several undulator segments. The gap dependent vertical first field integrals taken for gaps closed → open → closed for two representative segments are shown in Fig. 2A. Curves coincide within linewidth. No clear evidence of magnetic hysteresis is observed.

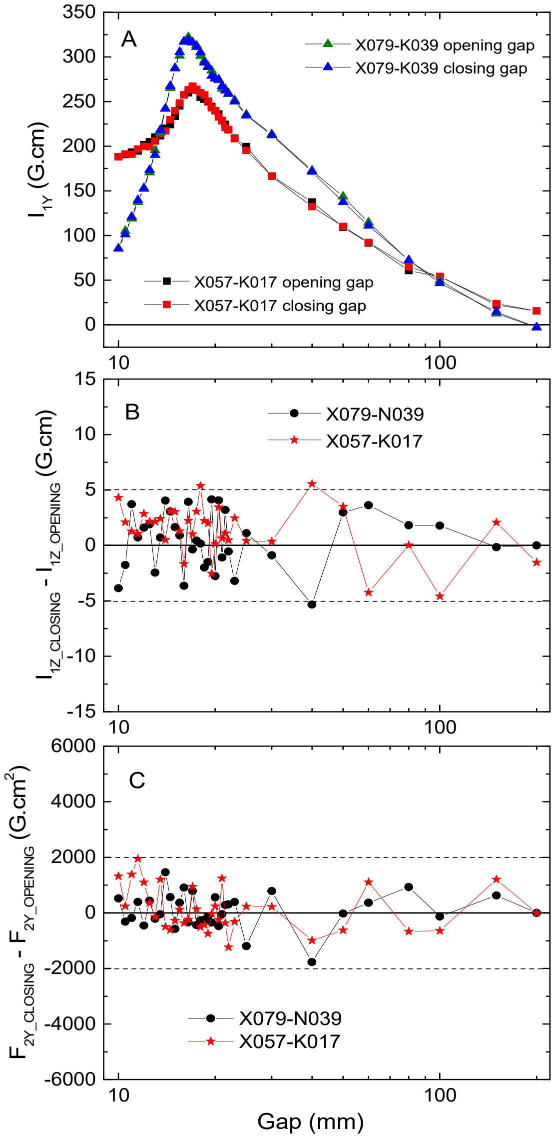

Figure 2: The vertical first field integral for two undulator segments (2A) and differences between closing and opening gap measurements (2B) and (2C).

The differences between the open and close direction measurements, for the horizontal first integral and the vertical F_{2y}, are shown in Fig. 2B and Fig. 2C. Within measurement accuracy no magnetic hysteresis is seen. The differences seen in Fig. 2B and Fig. 2C are determined by the accuracy of the first and second field integrals of 5 G.cm and 2000 G.cm^2, respectively. Based on these magnetic measurements it is assumed that within measurement accuracy the undulator segments can be operated equally well in both directions.

HYSTERESIS IN PHASE SHIFTERS

The vertical field integral of a phase shifter when measured in open, close, and again open direction is shown in Fig. 3A. A clear magnetic hysteresis between opening and closing the gaps is seen. Such characteristic closed loop behaviour has been seen in about 60 out of a total 95 phase shifters of the serial production. This was also observed in prototypes where no mechanical hysteresis was present [9,10] and in electromagnetic phase shifters [11]. The difference between opening and closing the gap (Fig. 3B) amounts 10-20 G.cm and exceed the specifications by about 10 G.cm. This hysteretic behaviour is very reproducible and open direction measurements agree well (Fig. 3A and Fig. 3B).

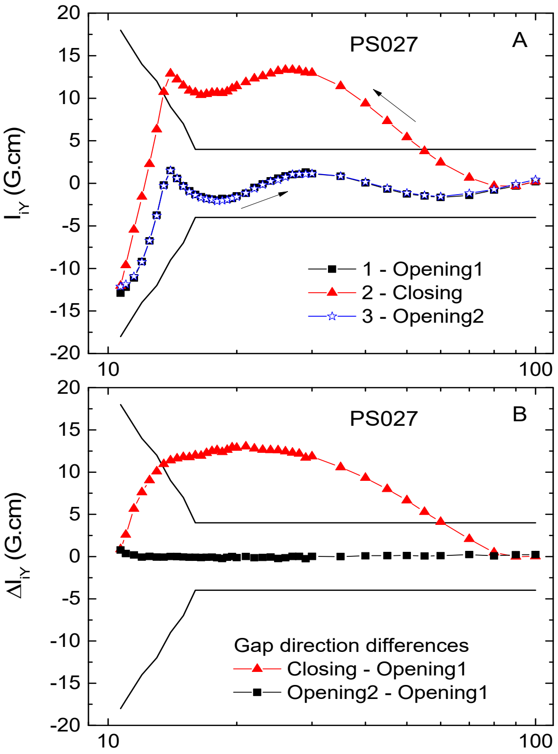

Figure 3: One representative closed loop magnetic hysteresis of the vertical integrals as seen for 60 phase shifters. The close → open direction is outside the XFEL.EU specification window.

On the other hand, magnetic hysteresis is not observed in horizontal field integral (not shown here) due to the much smaller magnetic fields in this direction. Nevertheless, we emphasize that all 95 phase shifters which were built for XFEL.EU are tuned inside the specification window on the close → open direction.

The hysteretic behaviour on the phase shifters is explained by a small remanent magnetization of the iron yoke which encages the permanent magnet components and reduces fringe fields [3]. Although only a selected iron grade was used and magnetic annealing at 850°C after machining was applied a small remanence was still observed. Without the magnetic annealing the effect would be significantly larger.

SUMMARY AND CONCLUSION

The magnetic hysteresis of the field integrals of the undulators and phase shifters for the XFEL.EU were investigated using the moving wire method.

Within the measurement accuracy of about 5 G.cm and 2000 G.cm^2 for the first and second field integrals, respectively, the undulator segments were found to have no magnetic hysteresis.

A closed loop hysteresis is found on the vertical field integrals of 60 phase shifters of the serial production. It is, however, very reproducible. The open direction of gap movement is well within specifications, while the close direction may exceed specs by up to 20 G.cm. Therefore for the best performance with lowest field integral errors the phase shifters should be operated when the gap is opened.

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