MAGNETIC CHARACTERIZATION OF THE PHASE SHIFTER PROTOTYPES BUILT BY CIEMAT FOR E-XFEL*

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Abstract

The European X-ray Free Electron Laser (E-XFEL) will be based on a 10 to 17.5 GeV electron linac that will accelerate the beam used in the undulator system to obtain ultra-brilliant X-ray flashes for experimentation. The so-called intersections are the transitions between undulators, where a quadrupole on top of a precision mover, a beam position monitor, two air coils and a phase shifter are allocated. CIEMAT participates in the development of the phase shifters (PS), as part of the Spanish in-kind contribution to the E-XFEL project. The updated design of the phase shifter is presented here to improve its behaviour as a result of the measurements on the first prototype, which did not fulfil the first field integral specification. This paper describes the magnetic measurements carried out on the last two prototypes in the test bench at CELLS, together with the tuning process to decrease the field integral dependence with gap.

INTRODUCTION

The E-XFEL phase shifter will be located at the intersections in-between the undulators (Figure 1). The role of the phase shifter is to adjust the phase of the electron beam and the radiation when entering into an undulator according to different required beam energies and wavelengths. The main specifications [1, 2] that the device must currently satisfy can be found in Table 1.

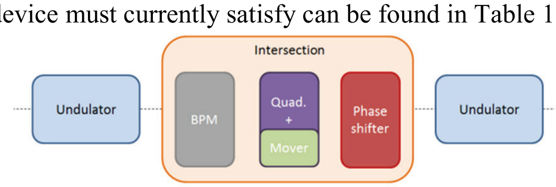

Figure 1: Undulator system intersection layout.

Four magnetic modules in a hybrid Halbach array produce a double sinus magnetic field in the mid-plane. The magnetic modules are surrounded by a pure iron yoke to enhance the phase integral value and weaken the fringe fields at nearby elements (Figure 2). The variation of the magnetic field strength is obtained by approaching or moving further the magnetic modules. Upper and lower modules move simultaneously with a unique spindle.

DEVELOPMENT OVERVIEW

The conceptual design and a first prototype were developed by DESY [1], based on the experience gained from TESLA project [3]. Up to now, CIEMAT has developed three prototypes in collaboration with industry, as part of the Spanish in-kind contribution to the facility. The first CIEMAT prototype design [4] was based on the previous DESY prototype. Some design modifications were already introduced, agreed with the E-XFEL counterparts, in order to ease fabrication and assembly. That prototype fulfilled all the specifications, except the most challenging one, the variation of the first field integral with the gap (DESY prototype had failed as well).

In agreement with the E-XFEL, CIEMAT had developed a magnetic measurement bench based on a moving long coil connected to an analog integrator [5]. However, there are still some problems to get the required accuracy, incompatible with the project timeline.

Table 1: Technical Specifications

Magnetic specifications	
Min. phase integral at gap 10.5 mm (21ºC)	23,400 $T^2 mm^3$
Max. variation of 1st field integral with gap	± 0.004 T·mm
Max. variation of 2nd field integral with gap	± 67 T·mm^2
Mechanical specifications	
Gap	10.5 to 100 mm
Gap repeatability in bidirectional movement	± 50 µm
Gap repeatability in unidirectional movement	± 10 µm
Gap speed	0.01 to 10 mm/s

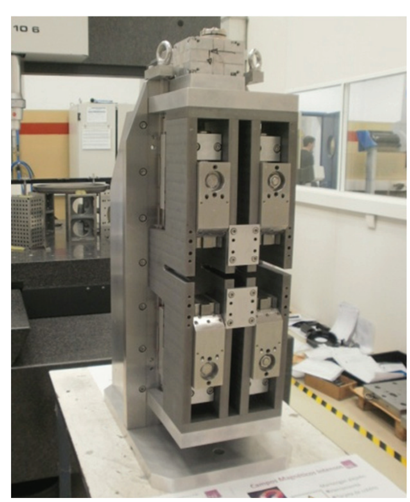

Figure 2: Third CIEMAT prototype

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As a consequence, in November 2011, the E-XFEL organized an external panel review to assess the problem. The main recommendations of the panel review were: 1) trying to relax by all means the first field integral specification, and 2) the use of standard methods for the magnetic measurements. On the one hand, the E-XFEL revisited the first field integral specification [6]: it can be up to 0.018 T·mm for gaps below 16 mm, but still below 0.004 T·mm for larger gaps. However, the mechanical reproducibility is stricter, only a 10 µm deviation in bidirectional movements is allowed. E-XFEL discarded the possibility to use the nearby air coil correctors to compensate the first field integral variation provided by the phase shifters. On the other hand, CIEMAT decided to characterize the devices at the CELLS test-bench [7, 8], which is based on flipping coil and Hall probe techniques (Table 2), for the field and phase integral measurements, respectively. It is worth to highlight that the flipping coil bench accuracy is the state of the art (the bench is produced by ESRF, Grenoble), but still close to the specification for the E-XFEL phase shifter.

Table 2: Main specifications of the CELLS test-bench

Hall probe test bench main specifications	
Field absolute accuracy	0.5 Gauss
Field integral accuracy	About 0.01 T·mm
Minimum step size	20 µm
Flipping coil main specifications	
Field integral absolute accuracy	0.001 T·mm

Finally, the phase shifter design was reviewed to improve the magnetic behaviour and, at the same time, to correct small mechanical problems. CIEMAT decided to produce two units, in order to check the first field integral variation and to validate the design for the industrial production of 91 units.

MAGNETIC ADJUSTMENT

The design of the phase shifter allows regulating the vertical position of the lateral magnets and also the vertical position and transverse orientation (tilt angle) of each pole by means of screws (Figure 3).

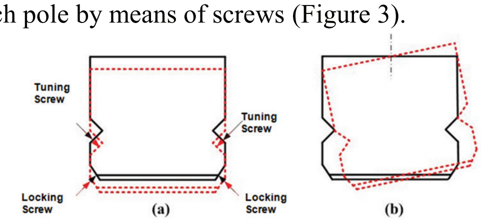

Figure 3: Pole adjustment: height (a) and tilt (b) shifts [9]

The effect of those movements on the first field integral can be noticed as follows:

- Lateral magnet vertical position: the vertical field is enhanced when the magnet is moved towards the middle plane.
- Pole vertical position: the vertical field is enhanced when the pole is moved towards the middle plane.
- Pole tilt: the horizontal field is enhanced in the direction of the tilting.

Besides, shims of different magnetic materials can be used for additional magnetic calibration. They must be placed symmetrically to affect only the horizontal or vertical field component.

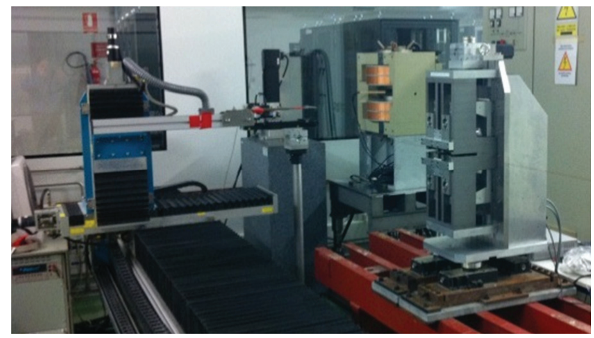

Figure 4: 3rd CIEMAT prototype at CELLS test-bench

MAGNETIC MEASUREMENTS AND ANALYSIS

It is worth to mention that the reproducibility of the flipping coil bench measurement of the first field integral is better than 0.001 T·mm, although there is an uncertainty about the absolute value, because the phase shifter is 200 mm long but the flipping coil length is 4 m. The iron yoke shields partially the ambient field. When no phase shifter is present, the first field integral is -0.018 T·mm in the horizontal direction, and -0.157 T·mm in the vertical one. They are due to the Earth field and the synchrotron storage ring contribution, being constant during the measurements. When the phase shifter is present and open at maximum gap, the first integral of horizontal field is -0.024 T·mm (second prototype) and -0.021 T·mm (third prototype), while -0.153 T·mm and -0.157 T·mm for the vertical component. We have assumed -0.020 (horizontal) and -0.153 (vertical) T·mm as a fair value for the reference value, with a confidence margin of ± 0.002 T·mm. Further studies are ongoing to fix this value with more accuracy.

Second CIEMAT prototype (PS2)

Figure 5 depicts the variation of the first field integral with the gap. The vertical one is within specifications (± 0.004 T·mm for gaps above 16 mm, ± 0.018 T·mm for gaps below 16 mm), but not the horizontal one. It was not possible to decrease the horizontal field integral, neither with shims nor tilting the poles. A weak remnant magnetization is present in the horizontal direction, but it is very difficult to correct it with external coils.

The most likely explanation is coming from the problems found during the assembly of this particular unit. The dowel pins which placed the iron yoke on the support plate were wrongly machined, and hence the iron was finally positioned without dowel pins. Since the magnetic modules have been assembled and disassembled several times, some residual magnetization of the yoke may take place.

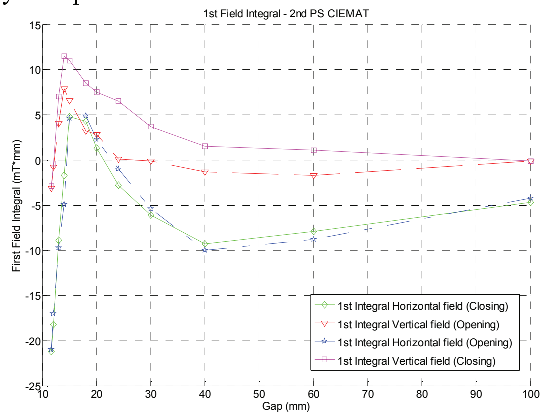

Figure 5: Measured first field integral dependence with gap (second CIEMAT prototype).

On the other hand, a slight hysteresis has been measured in the vertical component, with a maximum of 0.006 T·mm at a gap of 24 mm. A careful study of the operation strategy must be done to conclude if it can be a problem for the undulator performance. It was checked that no mechanical hysteresis (backlash) was present.

The second field integral is well below the requested tolerances (67 T·mm^2) for all gaps: ± 8 T·mm^2 for the vertical component and ± 4 T·mm^2 for the horizontal one.

The phase integral calculated from the measurements of the field profile in the middle plane at 10.5 mm gap is 23,702 T^{2}mm^3 (at 21ºC).

Third CIEMAT prototype (PS3)

Figure 6 depicts the variation of the first field integral with gap. In the opening movement, both field components are within specifications. When a bidirectional movement is considered, in the case of the vertical field, hysteresis is present again, with a maximum of 0.010 T·mm at gap 20 mm. At this point, one can conclude that the hysteresis is inherent to the existing design, because measurements also match numerical simulations with FEM when modelling real materials. No mechanical hysteresis (backlash) is present.

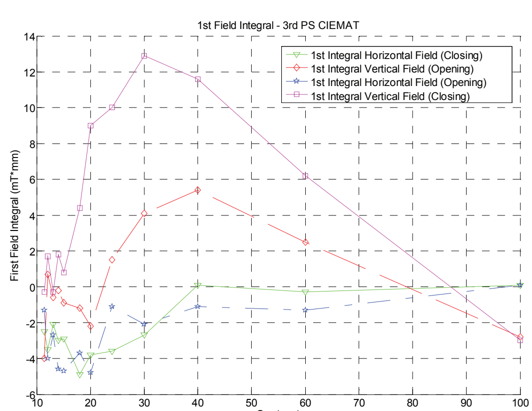

Figure 6: Measured first field integral dependence with gap (third CIEMAT prototype).

The second field integral is well below the requested tolerances (67 T·mm^2): ± 4.4 T·mm^2 for vertical and horizontal components and all gaps.

The phase integral calculated from the measurements of the field profile at 10.5 mm gap is 23,478 T^{2}mm^3 (at 20ºC).

CONCLUSIONS

CIEMAT is contributing to the E-XFEL with the phase shifters for the undulator intersections, among other components. For the PS, the most challenging specification is the variation of the first field integral with gap. The design has been revisited after the first prototype characterization. As consequence, for the next two prototypes, the first field integral variation has been reduced. Specifically, the last one is about the allowed limits. Besides, a small magnetic hysteresis has been measured in the vertical component. That effect is inherent to the existing design and the magnetic materials available in the market for industrial production. CIEMAT prototypes have successfully complied with the rest of specifications.

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REFERENCES

[1] J. Pflueger, Y. Li, H. H. Lu "The permanent magnet phase shifter for the European X-ray free electron laser", Nucl. Instr. and Meth. A605,(2009) 399-408

[2] M. Altarelli, Editor, "The European X-Ray Free Electron Laser Technical Design Report", ISBN 3-935702-17-5.

[3] J. Pflueger, M. Tischer, "A prototype phase shifter for the undulator system at the TESLA X-ray FEL", TESLA-FEL 2000-08, 2000; http://flash.desy.de/ reports_ publications/

[4] I.Moya, et al, "Manufacturing and testing of the first phase shifter prototypes built by Ciemat for the European-XFEL", IPAC 2011, THPC174.

[5] S. Sanz et al., "Development of a Test Bench for Magnetic Measurements on E-XFEL Phase Shifters", IEEE Trans. App. Superconductivity, Vol. 22, June 2012.

[6] Y. Li, J. Pflüger, "New Assessment of Field Integral Tolerances for the EXFEL Phase Shifters", E-XFEL WP71 Report, WP71/2012/03, February 2012

[7] J. Campmany, J. Marcos, D. Einfeld, "Characterization of ALBA storage ring bending magnets using a high precision hall probe bench", IMMW16, October 2009

[8] D. Beltran, J. Bordas, J. Campmany, A. Molins, J.A. Perlas, M. Traveria, "An instrument for precision magnetic measurements of large magnetic structures", Nuclear Instruments and Methods A, 459 (2001) 285.

[9] H.H. Lu, J. Pflueger, S. Sanz, "First Experience and Magnetic Measurements on the first Phase Shifter Prototype made by CIEMAT", E-XFEL WP71 Report, WP71/2010/13, March 2011.

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