# MANUFACTURING AND TESTING OF THE FIRST PHASE SHIFTER PROTOTYPES BUILT BY CIEMAT FOR THE EUROPEAN-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. Its beam will be used in three undulator systems to obtain ultra-brilliant X-ray flashes from 0.1 to 6 nanometres for experimentation. The undulator systems are formed by 5m long undulator segments and 1.1m long intersections in between. They accommodate a quadrupole on top of a precision mover, a beam position monitor, two air coil correctors and a phase shifter. The function of the phase shifter is to adjust the phase of the electron beam with respect to that of the radiation field when the wavelength is changed by tuning the gap. In this context, CIEMAT will deliver 92 phase shifters, as part of the Spanish in-kind contribution to the E-XFEL project. This paper describes the engineering design, the manufacturing techniques and the mechanical and magnetic tests realized on the first prototypes.

## INTRODUCTION

The E-XFEL phase shifter is a permanent magnet device, which will be located in-between the undulators, at the so-called intersections (see Fig.1). The conceptual design and a first prototype were developed by DESY [1], based on the experience gained from TESLA project [2].

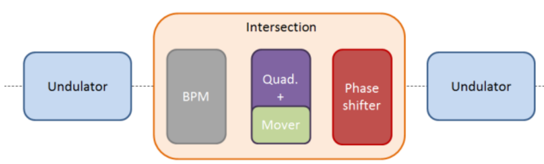


Figure 1: Undulator system intersection layout.

The main specifications [1, 3] that the device currently must satisfy can be found in Table 1. CIEMAT is in charge of the production of 92 units, as part of the Spanish in-kind contribution to the facility.

Table 1: Technical Specifications

| | |
|---|---|
| **Magnetic specifications** | |
| Required min. phase integral for gap 10mm. | 25000 $T^2mm^3$ |
| Max. variation of 1st field integral with gap | +/- 0.004 Tmm |
| Max. variation of 2nd field integral with gap | +/- 67 $Tmm^2$ |
| Phase adjustment accuracy | ± 10º (0.175 rad) |
| **Mechanical specifications** | |
| Minimum gap | 10.5 mm |
| Maximum gap | >100 mm |
| Gap absolute accuracy | Not necessary |
| Gap repeatability in bidirectional movement | ± 50 µm |
| Gap repeatability in unidirectional movement | ± 10 µm |
| Minimum gap speed | 0.01 mm/s |
| Maximum gap speed | 10 mm/s |

*Work partially supported by the Spanish Ministry of Science and Innovation under SEI Resolution on 17-September-2009 and project ref. ICTS-2008-005
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## FIRST CIEMAT PROTOTYPE

### *Engineering Design*

On the basis of the problems detected in the previous prototype developed at DESY, CIEMAT introduces a number of design modifications. A secondary aim is to ease the industrialization of the future series production.

- Several types of non-oriented grain electrical steel were tested to find an alternative to the pure iron, which is relatively expensive and soft. The material choice was not changed because it performed the lowest remnant field or lowest core loses.
- A phosphate coating will be applied to the iron parts to protect them from oxidation.
- The iron yoke thickness is reduced from 30 to 18 mm. This value allows a working point around the maximum permeability of the pure iron (magnetic field from 0.6 to 0.7 T) and a reasonable mechanical stiffness of the yoke. The geometry of the parts has been simplified as well.
- The magnetic modules are redesigned to hold the side magnets against the magnetic forces [4], which otherwise cause friction with the iron yoke. The magnets are confined by a wedge-shaped protuberance.
- A stepping motor will be used instead of a brushless motor to decrease the development time of the control system, since it is similar to that realized by CIEMAT for the quadrupole precision movers in the intersections.
- The movement stage is also updated. A left and a right-hand spindle are joined by a shrinking cylinder to provide opposite and simultaneous movement of the modules. A worm gear unit and a magnetic brake on the stepping motor increase safety measurements under failure. The position feedback is done by an optical encoder placed at one of the magnetic modules, which avoids errors due to clearance or backlash at the gear or the motor.

- Limit switches and hard stops are located at both stroke ends.

### *Control System Design*

A control system [5] was developed following E-XFEL requirements, which implies the use of Beckhoff automation system. It is controlled with a PC running Twincat PLC. The software has been coded in Structured Text, following the IEC 61131-3 standard. The motor control is configurable: the operator can adjust backlash control, brake delay time, operation mode and dead-band position, among others.

### *Manufacturing and Assembly*

The yoke material is unalloyed iron (min. 99.85% Fe, max. 0.02 C, max 0.015 S), commercialized under the brand ARMCO. To obtain the best magnetic properties, annealing is mandatory. This treatment consists of heating the parts at 950ºC during 45 minutes in pure dry hydrogen or under vacuum, followed by cooling at 180°C/h in the same atmosphere. To reduce the treatment time, cooling could be performed in air below 200ºC. The iron parts shall be in contact with refractory stainless steel inside the furnace; graphite is not used to avoid the diffusion of carbon into the pieces.

The flatness tolerances of the yoke plates are very tight (+/- 0.02 mm), due to the small gap between the magnets and the iron (0.1 mm minimum). A large gap will decrease the phase integral, while a non-uniform gap will increase the variation of the first field integral as a function of the gap between the modules.

Several tests were performed to check if the annealing could be done after the machining. They failed, due to the induced deformation, in spite of the special procedures:

- A stress relieve treatment at 650ºC was done before machining.
- The pieces must be placed in the furnace laying on one of the narrow faces, to enhance the temperature uniformity.

It was decided to add a last step of machining after annealing, but keeping the previous recommendations in any case.

It is also important that the iron yoke is not magnetized before assembly, because partial magnetization of the yoke will produce asymmetric magnetic fields, which will make difficult to achieve low field integrals. The straightforward technique to achieve the required flatness of the iron parts is grinding, but the pieces are usually held by magnets in the machine. Several tests of demagnetization were performed without satisfactory results. It was decided to request the fixation of the parts by mechanical means or by vacuum.

### *Mechanical Tests*

First of all, several critical dimensions are checked for validation:

- The iron yoke mid-plane must be at 400 mm from the base, with a tolerance of +/- 0.1 mm. The measurement yielded 400.2 mm.
- The tolerance of the position of the magnetic modules respect the mid-plane is +/- 0.1 mm (see Table 3). It is worth to notice that the relative misalignments between them are close to zero.

Table 3: Error in the positioning of the modules

| Left side | Error | Right side | Error |
|---|---|---|---|
| Up | 0.05 mm | Up | 0.05 mm |
| Down | 0.04 mm | Down | 0.04 mm |

- The limit switches and hard stops were difficult to adjust with precision. The lower limit switch support was not rigid enough and the activation of the limit switch was in a band of 0.3 mm.

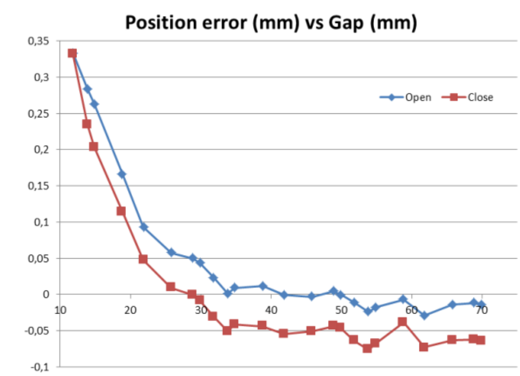


Figure 2: Mechanical hysteresis measurements.

- The clearance between the magnetic modules and the iron yoke must be at least 0.05mm, but light friction was detected at some points.
- The magnetic module movement must be characterized to measure the hysteresis, precision and repeatability. A LabView GUI, specifically developed in-house, communicates with the PLC program and the Heidenhain length gauges and stores the data. The deformation of the module support for small gaps (about 0.15 mm) is larger than foreseen in the simulations (0.03 mm). It is due to a deficient fixation of the support beam and the deformation of the linear guides. The unidirectional movement fulfils the specification, but the bidirectional movement has an average error of 57 µm (Fig. 2), slightly above the requirement (50 µm).

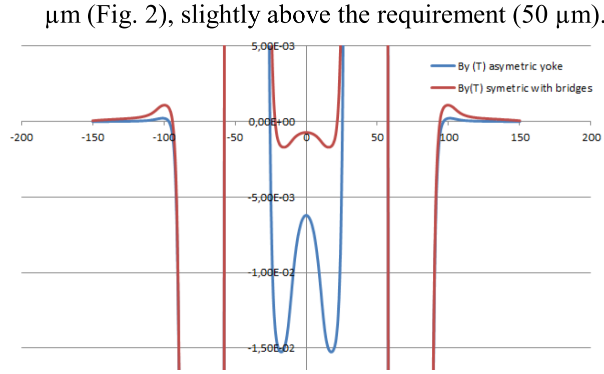


Figure 3: Vertical magnetic field along the gap.

### *Magnetic Tests*

A magnetic measurement system has been developed at CIEMAT, specifically designed to be able to measure the extremely small values of the field integrals. It is based on the integration of the voltage induced in a long coil that slips along the gap [6]. The first measurements on the vertical field showed an asymmetry in the stray fields of the side and central yoke plates, which was not detected in the design stage. It was checked with a numerical simulation (see Fig. 3). It was repaired with two iron bridges screwed to the rear of the central plates.

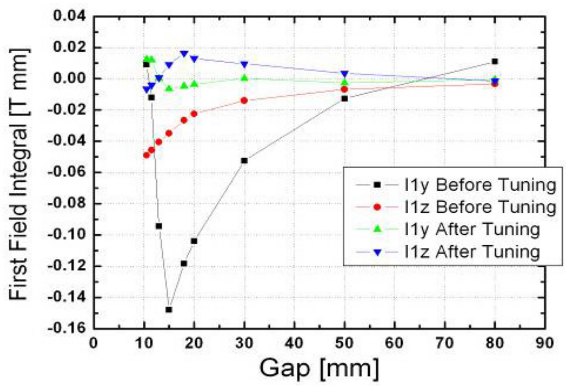


Figure 4: First field integrals vs. gap.

CIEMAT test bench was not properly calibrated when the first CIEMAT prototype was finished, so it was sent to E-XFEL test facility for final tuning [7]. The improvement due to tuning is significant. Finally, the variation of the first integral of vertical field for different gaps was +/- 0.01 Tmm, and -0.01 to +0.015 Tmm for the horizontal one (see Fig. 4). A likely explanation could arise from the fact that the return flux is not exactly the same in the side and the repaired central iron plates.

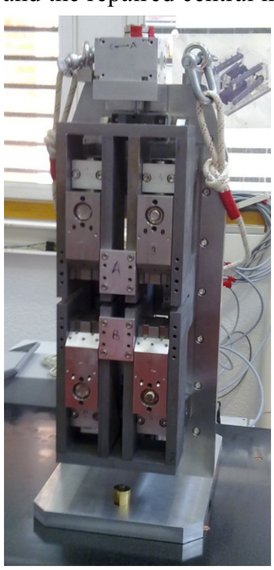

Figure 5: Second CIEMAT prototype.

## SECOND CIEMAT PROTOTYPE

A second prototype has been recently produced (Fig. 5). The design modifications respect the first one are:

- The magnet confinement is done by square-shaped protuberances and the clearance between the modules and the yoke is increased to guarantee the absence of friction.
- Stiffer limit switches and hard stops with fine adjustable position (+/- 10 micron).
- New stepping motor with five phases and micro-stepping for enhanced resolution.
- The support beam of the magnetic modules is reinforced to diminish deformation at small gaps.

The mechanical deficiencies detected in the first prototype have been overcome. Magnetic measurements are on-going.

## CONCLUSIONS

Two phase shifter prototypes have been produced at CIEMAT, as preparation of the future series production for E-XFEL. The mechanical and magnetic tests on the first prototype showed some deficiencies which are on the way to be solved in the second prototype, presently being tuned and calibrated. The most challenging one is the variation of the first field integral with the gap.

## ACKNOWLEDGEMENTS

The authors want to thank valuable discussions with J. Pflueger and S. Karabekyan (E-XFEL), and fruitful suggestions from the Spanish companies involved in the fabrication process.

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