# DESIGN, MANUFACTURING AND TESTS OF CLOSED-LOOP QUADRUPOLE MOVER PROTOTYPES FOR EUROPEAN XFEL*

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*Abstract*

In this report the development of a quadrupole mover with submicron repeatability is reported, which will be used in the intersections of the Undulator Systems of the European XFEL (EXFEL) [1]. It is part of the Spanish in-kind contribution to this facility. The main specifications include submicron repeatability for a 70 kg quadrupole magnet within compact dimensions and a ±1.5 mm stroke in the vertical and horizontal direction. Compact linear actuators based on 5-phase stepping motors have been chosen. Vertical actuator works in a wedge configuration to take mechanical advantage. A closed-loop control system has been developed to achieve this repeatability. For the feedback, one LVDT sensor for each axis was used. Mechanical switches are used to limit movement. In addition, hard-stops are included for emergency. Prototyping stage is done and a serial production of more than 90 devices is expected, so intense work has been done to achieve a reliable industrial production and validation. In this report, results of mechanical measurements including reproducibility, tests of different operation strategies and critical situations will be reported.

## SPECIFICATIONS

The main specifications for these quadrupole movers are included in Table 1.

Table 1: Main Specifications for Movers

| Concept | Value | Details |
|---|---|---|
| *Dimensions* | 340x220x175 mm | Long, wide, high |
| *Axes* | 2 (Horizontal and Vertical) | ±1.5 mm min. stroke |
| *Load* | 70 kg | |
| *Repeatability* | < 1 μm | |
| *Control device* | LVDT closed-loop | Electromagnetic brakes |
| *Ranges* | Max ±1.7 mm Limit switches | Max. ±1.8 mm Hard stops |
| *Alignment angles* | 0±3 mrad | Yaw & Pitch |
| | 0±0.6 mrad | Roll |
| *Control system* | Beckhoff Compatible | Independent control of axes |

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## DESIGN: KEY ASPECTS

A robust and compact mover is required according to previous specifications; therefore concept design includes the following important features.

High-precision compact linear actuators have been selected for both axes. A direct approach for the vertical movement of a 70 kg load is not straightforward in terms of compactness and dimension specifications. Therefore, a wedge design was chosen based on a previous development [2].

The wedge design, illustrated in Fig. 1, has a 5:1 slope so the force needed to lift the load is about 5 times lower than the direct weight of the load.

At same time, diagonal movement instead of a vertical one results in a finer resolution for vertical axis.

On the other hand, as in-plane positioning is expected (horizontal and vertical axes shall move to meet the required quadrupole position), amplified crosstalk effects could arise from this movement. Because of that, a high rigidity slide unit is added to keep independent axis behaviour.

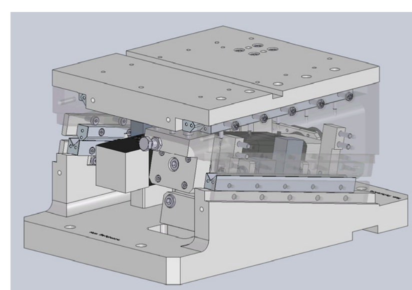

Figure 1: General design.

A closed-loop control system is implemented in order to achieve submicron repeatability. Two LVDTs are placed inside the mover to get a continuous measurement of each axis absolute position. Each LVDT has been arranged to measure just one axis at a constant contact point, which means that the LVDT and the measurement surface have no relative movement apart of the measured in-axis separation.

Limit switches were added at the ends of movement of both axes to ensure that even under a failure of the LVDT sensors the mover would reach a safe stop position.

Moreover, mechanical barriers have been implemented to exclude any possibility of overtravelling which could damage the beam pipe.

## CONTROL SYSTEM

The mover is controlled with a PC running *Twincat* PLC, a software by *Beckhoff* that will be used in E-XFEL. The software has been coded in Structured Text, following the IEC 61131-3 standard. It was decided that both motors be independent, so that a motor will not move when given a command until the other motor is stopped. This choice has been validated by extensive testing. Motors are configurable: the operator can set over 20 parameters to adjust backslash control, brake delay time, operation mode and dead-band position, among others. According to specifications, the strategy of the control system includes some important clues for the movements:

- As a closed loop control system is developed, the movement will not stop until command position is considered reached in both axes.
- When LVDT position differs from SetPoint less than a parametric value, the mover stops and the electromagnetic brake holds this position.
- When actual position differs from command position, an autocorrecting movement will start even if command position remains constant.
- Sequential movement of axes
- Settling time of seconds for micrometric movements
- Settling time for millimetric movements up to one minute.

## PROTOTYPE PRODUCTION

Two prototypes have been produced for the time being. The first one was assembled and tested at Ciemat, with a manual control system to measure repeatability for each axis separately. The second prototype was already produced in collaboration with the industry. It was tested with an automatic system. A *LabView* GUI, developed in-house, communicates with the PLC program and the *Heidenhain* Digital Readouts and stores the data to perform the tests described in the next paragraphs.

## REPEATABILITY TEST SET-UP

The repeatability is the most challenging specification of the movers, as submicron level must be reached.

The testing set up is displayed at Fig. 2. The mover is holding a prototype quadrupole while magnetic axis position is measured at both axes with external reference gauges.

Repeatability is a way to evaluate how small this deviation value is. The positioning to a certain LVDT position reaches always exactly the same actual position from external references in a perfect repeatable system. Repeatability does not mean in any sense accuracy, so this fact should be taken into account when evaluating results.

For cycles involving the repetition of the same *setpoints*, the repeatability (Eq. 2) graph is calculated from deviation data (Eq. 1), for $j$ cycles of $i$ steps each one. Root Mean Square value of repeatability is calculated by (Eq. 3), so a repeatability value is calculated for each set of movements.

Figure 2: Repeatability tests set up.

$$\text{Dev}_{i,j} = \text{LVDT.Meas.}_{i,j} - \text{Ext.Ref.}_{i,j} \quad (1)$$

$$\text{Rep.}_{i,j} = \text{Dev}_{i,j} - \text{Mean Value}\left(\text{Dev}_{i,\forall j}\right) \quad (2)$$

$$RMS\ \text{Rep.} = RMS\ \text{Value}\left(\text{Rep.}_{i,j}\right) \quad (3)$$

Fig. 3 shows an example of how repeatability is calculated from one set of measurements.

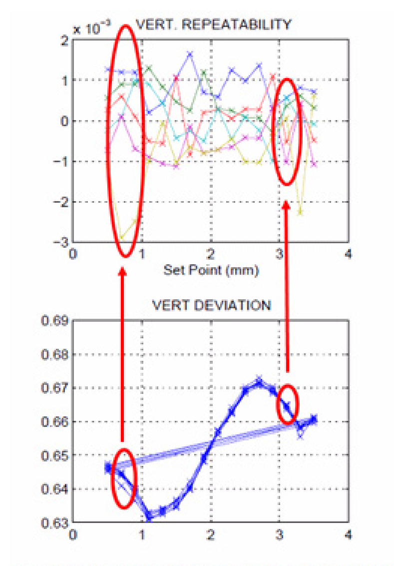


Figure 3: Repeatability graph example. *RMS* Value is 0.9 microns for this set of measurements.

The sets of measured movements are:

- 0.2 mm steps along the vertical axis for the whole movement range while keeping horizontal axis at 3 different positions.
- 0.2 mm steps along the horizontal axis for the whole movement range while keeping vertical axis at 3 different positions.
- Cyclic random movements in both axes inside a range of ±50 microns from central position

## REPEATABILITY TEST RESULTS

Results for direct movements from a given position have been found to have very high repeatability. Design has showed also a high ability to keep position under certain possible conditions, like for example small constant lateral forces or surroundings vibrations [4].

For sequential arbitrary movements in the XY plane, best results are found when some backlash compensation strategy is applied, including micrometric correction movements [3].

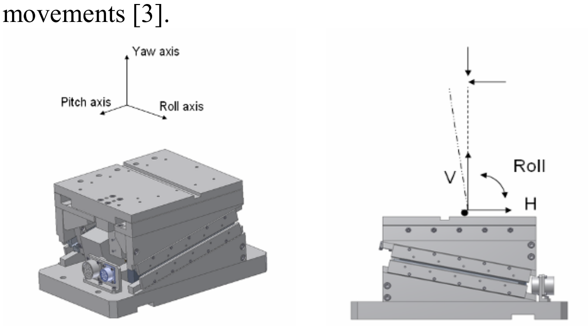


Figure 4: Platform alignment angles and beam position.

The backlash measured is mainly caused by the platform angle variations resulting from dynamic behaviour. Very little changes on this angle can produce micrometric variations at beam axis position. In fact, variations of less than 0.05 mrad have been measured, much less than the 0.6 mrad specification, but large enough for backlash effect due to the inherent limitation of positioning the quadrupole field centred with the beam axis with a measurement inside the mover.

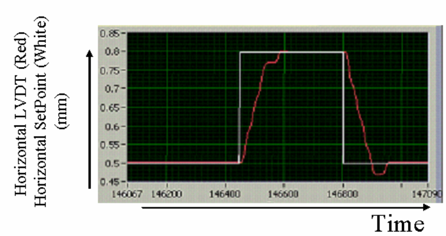


Figure 5: Backlash compensation strategy at positioning.

Backlash compensation have been optimized at about 0.03 mm, large enough to make positioning independent of the previous movement done while small to be carried in a few seconds without large displacement from command position. A simple picture is displayed in Figure 5 to show how this compensation is achieved.

Under such conditions, *RMS* repeatability is below 1 micron at every set of movements for both axes.

One more test has been carried out; the evaluation of deviation differences between non-repeated random movements around central position. Although this is not a kind of repeatability, great results of less than 1.5 microns for both axes have been found.

## OTHER VALIDATION TESTS

Each mover will need some tuning after assembly prior to be used with the quadrupole because it would be very difficult to get such a device adjusted from industrial processes.

Latest information available about components interacting with this mover has been taken into account, including alignment and mounting procedure of adjacent components.

This step is in fact very important as without proper tuning and assembly specification, any offset or cumulative errors from the whole assembly would pose serious risk for the vacuum chamber integrity as quadrupole magnet could touch against it.

Moreover, since the mover should be tuned prior to its final installation at the intersection, some points will be checked: nominal travel related to the ground, fine tuning of limit switches, LVDTs and hard-stops.

## CONCLUSIONS

This quadrupole mover for E-XFEL intersections has been evaluated in several tests getting good results. The preserial production is ready to be produced, but official validation is pending. It is expected to supply 92 units according to E-XFEL schedule, as part of the Spanish in-kind contribution to this facility

## ACKNOWLEDGMENTS

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## REFERENCES

[1] M. Altarelli, Editor, “The European X-Ray Free-Electron Laser, Technical design report”, DESY (2007).

[2] F. Toral et al., “Design, Manufacturing and Tests of a Micrometer Precision Mover for CTF3 Quadrupoles, EPAC’08, Genoa (2008).

[3] J. Munilla, “Closed loop control system evaluation of the E-XFEL quadrupole mover prototype”, CIEMAT Internal Report, May 2011, Madrid.

[4] S. Karabekyan, “Result of the measurements to determine the influence of the horizontal force on the quadrupole-fixing-platform of the quadrupole mover”, June 2010. E-XFEL Report, Hamburg.