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## Abstract

The IFMIF-EVEDA [1] Linear IFMIF Prototype Accelerator (LIPAc) is a 9 MeV, 125 mA CW deuteron accelerator to validate the technology to be used in the future IFMIF accelerator. The acceleration of deuterons (protons during commissioning phase) will be done through two stages, a Radio Frequency Quadrupole and a Superconducting RF linear accelerator. The matching between both acceleration structures will be done in the Medium Energy Beam Transport line (MEBT). In this section, the transverse focusing of the beam is carried out by five quadrupole magnets with integrated steerers, grouped in one triplet and one doublet. These magnets (MMA01 to MMA05) have been designed by CIEMAT [2] and manufactured by the Spanish company ANTEC S.A. After manufacturing, they were fully characterized at ALBA-CELLS magnetic measurements facility. [3] In this paper we describe the characterization benches used to measure the magnets, the measurement protocol and the alignment procedure, as well as the results obtained.

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# DETAILED CHARACTERIZATION OF MEBT QUADRUPOLES FOR THE LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAc)

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## *Abstract*

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## INTRODUCTION

The compact design of the beamline obligated the integration of steerers into quads. As a consequence, crosstalk was taken into account in the design. For this reason, characterization of MEBT quads was crucial to be sure that the device behaved as expected. Characterization was done using two different techniques. First, magnetic axis deviation, roll angle and the harmonic content were determined through integral field measurements made with rotating coil. Harmonics were extracted for a number of currents in quad and steerer coils, to determine the transfer function of each winding taking into account cross-talk effects due to iron yoke saturation. Second, local field measurements with Hall probe allowed the measurement of the stray field distribution at different quad/steerers currents. In the particular case of magnets with short gap distance this information is relevant because magnets will be placed very close, and therefore the possibility of its cross-talk has to be considered.

## INSTRUMENTATION

ALBA magnetic measurements laboratory is equipped with a rotating coil bench as shown in Figure 1. Its key element is the plate with the coil sensors. The accuracy of measurements depends on coil manufacturing. To this end, ALBA adopted the multi-PCB technology to avoid manufacturing complications and mechanical uncertainties associated with traditional winding of thin wires.

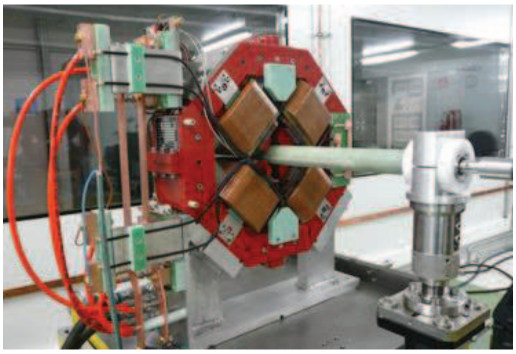

Figure 1: LIPAc MEBT magnet (quad + 2 steerers) on the rotating coil bench at ALBA laboratory.

In the case of the shaft used to measure MEBT quads, the PCB circuit board provides five identical 432-turns radial coils whose output signals can be combined in order to perform analog bucking and compensate both the dipolar and the quadrupolar terms of the measured magnet [4]. The shaft, shown in Figure 2, has an effective length of 0.55 m and a diameter of 44 mm, well adapted to the aperture of the magnets (56 mm) and to the reference radius where multipoles were evaluated ($R_{\mathrm{ref}}$ = 21mm). The bucking ratio obtained for the quadrupolar term is close to 800.

Magnet has been placed horizontal and with the mechanical axis centered with respect to the measurement shaft, according to fiducial mechanical positions and reference surfaces using a laser tracker. In order to calibrate the zero position of the rotating coil, the quadupole has been displaced horizontally relative to the shaft and measurements have been carried out at several transversal positions. An analysis of this set of results allows the simultaneous determination of the zero position of the coil and the roll angle of the magnet with respect to mechanical alignment references. The last is important to avoid skew components in the accelerator.

Regarding measurements with Hall probe, to measure MEBT quads a long L-shaped probe with a usable length of 230 mm has been selected. It allows measuring the full length of the iron yoke plus a sizable portion of the fringe field region. The probe includes three Hall sensors to extract the three components of the magnetic field. Its calibration method takes into account the position of sensitive areas of Hall plates and their deviations from orthogonality, as explained elsewhere [5]. The probe temperature is also kept constant during measurement and recorded for post-acquisition data treatment. The accuracy in the determination of magnetic field is ~10 μT and in the position ~30 μm (*rms* errors).

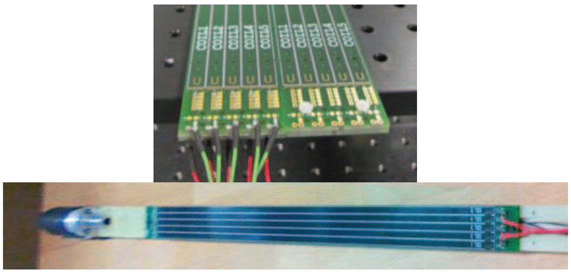

Figure 2: Multilayered PCB with radial coils developed at ALBA outside (*top*) and inside (*bottom*) the shaft used for doing integral measurements of multipole magnets

## MEASUREMENTS

### *MMA01 Magnet*

For the MMA01 quad, an exhaustive characterization including integrated (rotating coil) and local (Hall probe) measurements has been carried out.

Horizontal fieldmaps at the mechanical midplane have been acquired for different powering combinations of the quad/steerers windings. Figure 3 shows the resulting field distributions for some selected configurations.

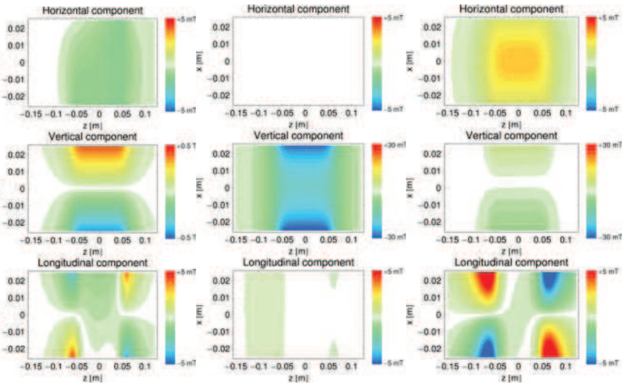

Figure 3: Horizontal fieldmaps at mechanical midplane of MMA01 with quad powered at 120A and steerers off (*left*), with quad off and horizontal steerer at 20A (*center*), and with quad off and vertical steerer at 20A (*right*).

Field maps over the surface of a cylinder of radius 17.5mm (for larger radius the probe would interfere mechanically with the poles) have also been acquired in order to determine the longitudinal distribution of the harmonics. An example of the obtained harmonics from $C_2$ up to $C_{10}$ extrapolated up to the reference radius $R_{\text{ref}}$=21mm is shown in Figure 4.

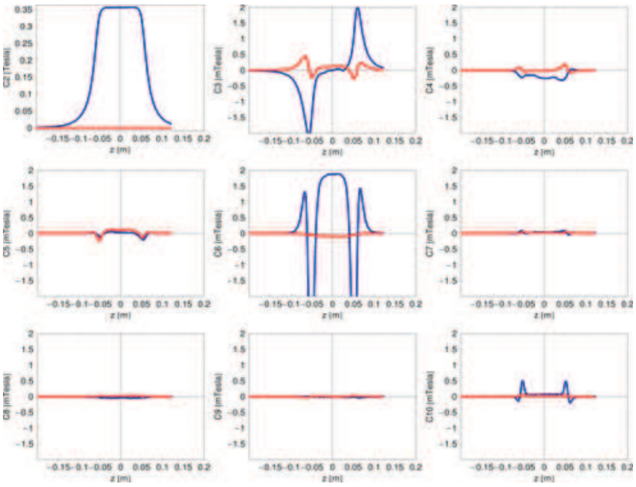

Figure 4: Harmonics from $C_2$ up to $C_{10}$ (*blue*: normal, *red*: skew) at $R_{\text{ref}}$ = 21mm along the quad axis from Hall probe data on the MMA01 @ 120A with the steerers off.

Figure 5 shows a comparison between the integrated field harmonics extracted from numerical integration of Hall probe data and rotating coil measurements. This plot illustrates that there exists a good agreement between the two experimental techniques, with differences for individual harmonics not larger than 1unit.

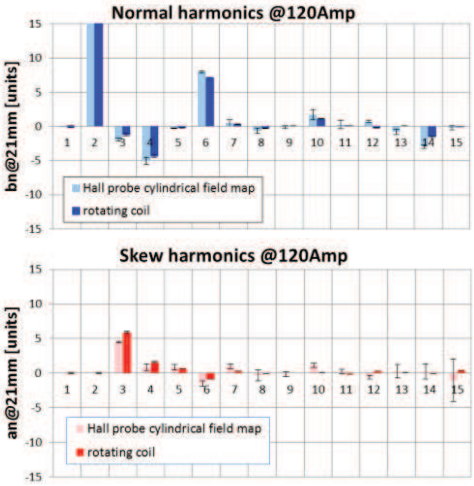

Figure 5: Comparison in units ($c_n$ [units] = $C_n/B_2\times10^4$) between integrated field harmonics determined on the MMA01 magnet using Hall probe and rotating coil.

Measurements with the rotating coil bench have been useful to determine the influence between the quad and the steerers. As an example, Figure 6 shows the transfer functions for the horizontal/vertical steerers for different settings of the quad. In a similar way, Figure 7 shows how the strength of the dipole generated by the correctors at a fixed current changes with the current setting of the quad. Both figures illustrate that for quad currents higher than 150 A the correctors lose efficiency as a result of the iron yoke saturation, as expected from simulations. The steerers work as expected, and the current to be applied to obtain a given beam correction depending on the quad working point can be determined from measured data.

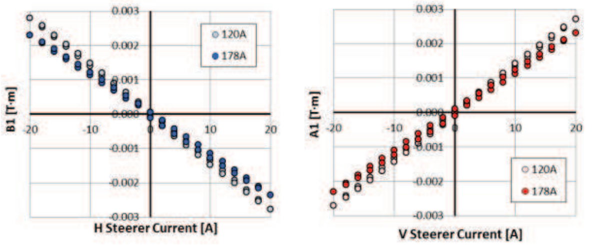

Figure 6: Transfer function of horizontal/vertical steerers for different settings of the quad, determined for the MMA01 magnet with the rotating coil bench. Some hysteresis is present, but this is within tolerances.

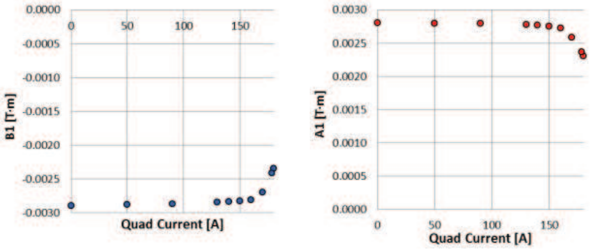

Figure 7: Integrated dipole strength at fixed corrector current (20A) as a function of the quad current for the horizontal (*left*) and vertical (*right*) corrector.

### *Series Magnets*

The remainder magnets have only been characterized with rotating coil. Figure 8 shows a comparison between the transfer functions for the five MEBT quads with the steerers switched off. The *rms* relative dispersion of the integrated quadrupole ($B_2$) is $16 \cdot 10^{-4}$ at maximum current (178A) and $5 \cdot 10^{-4}$ at nominal current (120A).

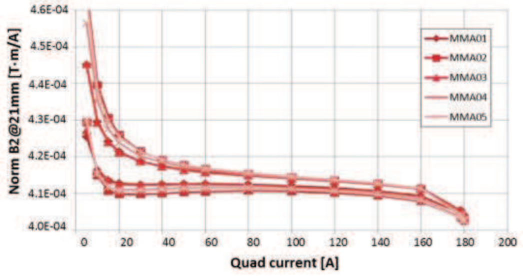

Figure 8: Comparison between the transfer functions for the quadrupolar term for the five analyzed magnets.

Figure 9 shows a comparison between the harmonic distributions at nominal current for the series of quads. It can be seen that, apart from the accepted systematic harmonics ($b_6$, $b_{10}$, $b_{14}$ and so), some of the magnets display random harmonics with values larger than expected. In particular, in some cases normal sextupolar and octupolar terms ($b_3$ and $b_4$) have been found to be beyond the specified tolerance level (±10 units). Further studies have shown that such deviations were due to a lack of symmetry in the assembly of the four quadrants of the magnets, and corrective measures have been introduced where required. A detailed discussion is out of the scope of this paper and will be presented elsewhere [7].

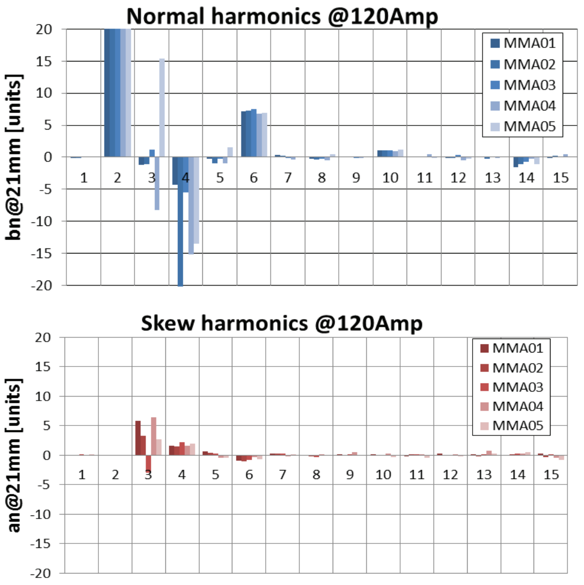

Figure 9: Harmonic distribution for quad powered @120A and the steerers off for all 5 MEBT quads.

## CONCLUSIONS

ALBA rotating coil and Hall probe benches have been used to characterize five IFMIF-EVEDA MEBT quads. Axis deviation, roll angle, harmonic content, cross-talk effects and stray field distribution have been measured, obtaining relevant data for accelerator operation.

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