MAGNETIC CHARACTERIZATION OF FAST-PULSED QUADRUPOLE MAGNETS FOR LINAC4

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Abstract

Linac4, currently being built at CERN, includes 24 quadrupole magnets characterized by narrow apertures and fast excitation cycles which make accurate magnetic measurements challenging. This paper describes the method used for the measurement, which is a combination of techniques based on stretched wire, rotating and fixed search coils. We show how these different instruments can be used in a complementary way to derive information on different aspects of the magnetic behaviour, such as the impact of hysteresis and dynamic eddy current effects. We summarize the results of the series measurement campaign, which include field strength, harmonic components, and the offset and orientation of the magnetic axis. Finally, we discuss the relevance of these measurements as their impact to the operation of the linac.

INTRODUCTION

This paper is mainly concerned with a series of 24 electromagnetic quadrupoles (EMQ), currently being installed in the inter-tank regions of Linac4 at CERN (see Fig. 1 and Table 1) [1, 2]. Due to their small size these magnets must be air-cooled, which entails cycling with fast ~5 ms pulses. The combination of a small aperture and possible large dynamic effects due to eddy currents and iron hysteresis makes the measurement a challenge. In the following, we discuss the measurement method and the main results obtained. More details are given in [3].

Table 1: Main Intertank EMQ Parameters

Parameter	Value
Aperture ∅ (mm)	54
Good Field Region ∅ (mm)	36
Nominal peak current (A)	67.4
Nominal integrated gradient (T)	1.83
Integrated gradient tolerance	±0.5%
Stable flat-top duration (μs)	400
Harmonic error tolerance ($\lvert c_n \rvert$, n=3 to 10)	1%
Axis offset radial tolerance (mm)	0.1
Roll angle tolerance (mrad)	1
Yaw and pitch tolerance (mrad)	2

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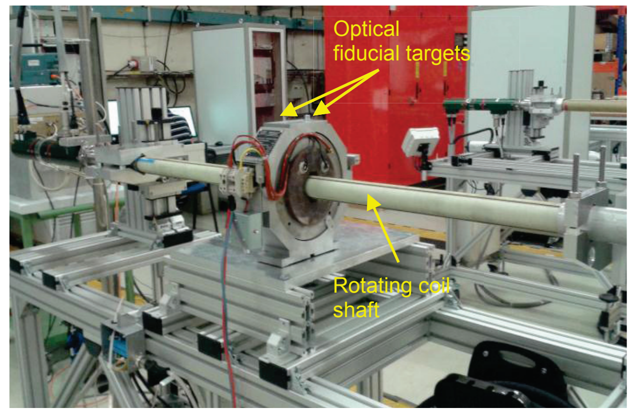

Figure 1: An EMQ on the rotating coil bench.

MEASUREMENT SETUP

Since no single instrument is available at CERN to measure all field parameters, we combined different measurement techniques. We used primarily a single stretched wire (SSW) system [4] as our established reference, together with a LEICA laser tracker LTD500, for magnetic axis fiducialization and integral field strength of the whole series in AC excitation mode at 12 A. A rotating coil system [5], more accurate but more resource-intensive, was used on a few sample units to check harmonic field content in nominal (dynamic) conditions and at 20 A DC, that is the maximum allowable for short periods. The coil shaft was kept fixed to measure dynamic effects with a fast National Instruments 6366 USB DAQ and to check the correlation with SSW in AC mode. Finally, a so-called AC mole [6] was used to measure the pitch and yaw angles. Nominal excitation was achieved using a CERN-developed prototype MAXIDISCAP capacitive discharge power supply [7].

EDDY CURRENT EFFECTS

The very high peak $\dot{B} \approx 300$ T/s in the iron yoke might give rise to substantial eddy current effects, in spite of the 0.5 mm thin laminations. These effects have been measured as explained in [8] by means of a fixed integral coil. The results are given in Fig. 2, which shows the profiles of the excitation current and of the integrated gradient, scaled to coincide at the end of the flat-top. The gradient has been corrected for integrator drift due to input voltage offset. Their difference ΔI, which is representative of the non-linearities, shows clearly an

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exponential decay with a time constant $\tau_e = 0.5$ ms and an

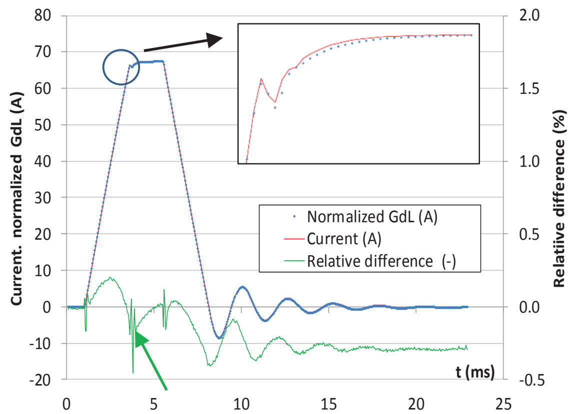

Figure 2: Current and normalized field integral profiles showing the exponential transient due to eddy currents. (highlighted by the green arrow). The insert shows the current overshoot at the end of the ramp-up.

amplitude of 0.2% at the end of the ramp-up. This means that the entire flat-top is stable enough for the passage of the beam. A small overshoot at the end of the ramp-up mitigates the amplitude of the transient. The final offset of about 0.3% between the initial and final value of the field can be attributed to remanent field. Since the magnet was subject to several pre-cycles, it was supposed to be on a stable hysteresis cycle and hence remanent field was not expected. However, the current oscillations at the end of each pulse are not controlled, and this may have an impact on the reproducibility of the magnetic behaviour.

This result is also necessary to establish the integration limits needed to measure accurately the field level corresponding to DC conditions. Measurements carried out in two magnets give consistent results, which can be confidently extended to the whole series as they depend essential upon the resistivity of the laminations, their insulation, and the overall geometry.

MAGNETIC AXIS

The single-stretched wire system works by aligning with μm resolution a CuBe wire on the average magnetic axis of the quadrupole. The ends of the wire, which were in this case about 1.5 m apart, are then surveyed and related to the two fiducial targets on the magnet. Initially, DC measurements were found to be sensitive to interference from background fields as low as 1 G, so we switched to AC magnet excitation at low current (12 A) and low frequency (8 Hz), which in our experience preserves well pole symmetry and guarantees immunity from DC offsets.

The results obtained are shown in Fig. 3. The average and standard deviations are 2±106 μm and 17±34 μm along x and y, which is consistent with the specified mechanical tolerances. The systematic horizontal error could be easily estimated by turning the magnet by 180° around their vertical axis; we assume vertical errors to be statistically of the same order (a few μs of wire sag have been accounted for separately). Wire position repeatability over 3 measurements is about 35 μm, while the nominal uncertainty of the optical survey is 20 μm. Only four quadrupoles are significantly out of spec; these will be corrected by adding shims on the final supports.

On magnets of such short length, the SSW technique gives reliable information on the average transversal position of the axis but cannot be trusted for pitch and yaw angles, which have been shown by beam simulations to play an important role for these magnets. Pitch and yaw angles have been measured on a sample of seven units with an AC mole, which is able to measure field strength and axis averaged over a longitudinal distance of 100 mm rather than over the full field integral. We get an average and standard deviation of -1.1±0.5 mrad and 0.1±1.3 mrad for the pitch and yaw respectively, which are within the tolerance.

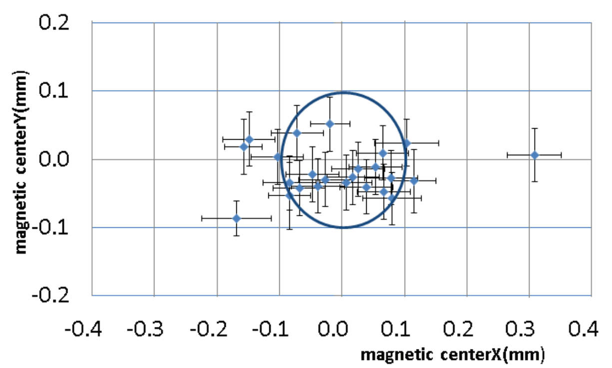

Figure 3: Summary of magnetic axis offset w.r.t. the nominal mechanical axis.

INTEGRATED GRADIENT

For practical reasons, the integrated gradient of the whole series was measured with AC mode SSW. The impact of eddy currents and of lower-than-nominal excitation was investigated thoroughly on a sample of several units, which provided consistent results. As an example, we show in Fig. 4 a comparison of the dynamic transfer function, i.e., the ratio of the instantaneous integrated gradient to the excitation current. This has been measured with a fixed integral gradient coil, obtained by connecting in series opposition two equal and parallel coils of a regular quadrupole-compensated rotating coil array. This configuration provides gradient measurements about 0.7% higher than the reference harmonic measurement, due to a combination of errors coming from calibration and higher harmonic content of the measured field; however, this does not impact the following considerations on the relative scaling between the three methods. The results obtained show a good linearity of the quadrupole up to the nominal current, with as little as 0.2% saturation and 0.4% of hysteresis in spite of the eddy current losses. The peak-to-peak AC transfer

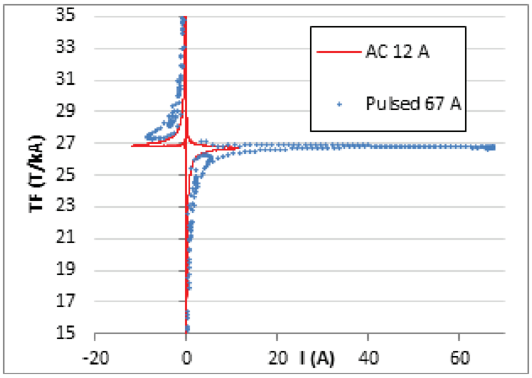

Figure 4: Dynamic integrated gradient transfer function in pulsed and AC excitation modes.

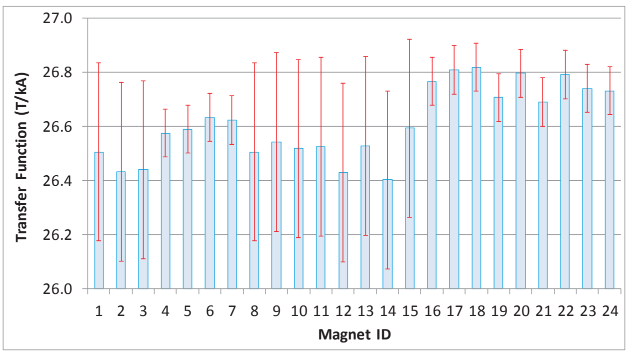

Figure 5: Summary of integrated gradient.

function at 12 A is within a few 10^{-4} from the nominal value, which confirms that both eddy current losses and residual field effects have a negligible impact.

The series results are summarized in Fig. 5. We get an average of 26.6 T/kA, about 1% higher than nominal, and a standard deviation about 0.5%. Nine EMQs exceed the tolerance, which does not represent an issue since magnets are powered individually. The measurement uncertainty is ranges from 1.3% to 0.3%, higher values being due to background interference with the return wire of the SSW.

FIELD QUALITY

Harmonic field quality has been measured on three quadrupoles at nominal current with a newly developed pulsed/stepwise rotating coil mode, which gives results essentially consistent with a standard DC measurements at 20 A. An example of the results, which are all similar, is given in Fig. 6. The only significant components are, as expected, b_6 and b_{10}. The total error is two orders of magnitude below tolerance and can be neglected.

FIELD DIRECTION

The field direction (roll angle) has been obtained as a by-product of the SSW AC tests, which measure the gradient along the vertical and the horizontal directions (see Fig. 7).

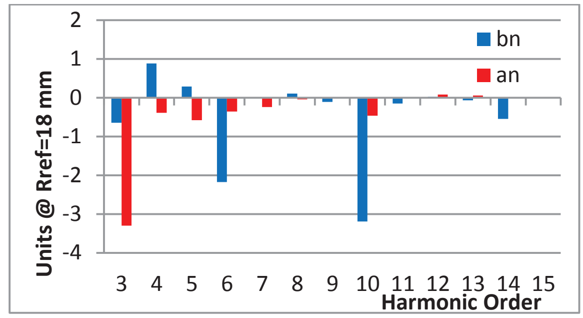

Figure 6: Field harmonics of EMQ 018 at 67.4 A in units of 10^{-4} w.r.t. the main component.

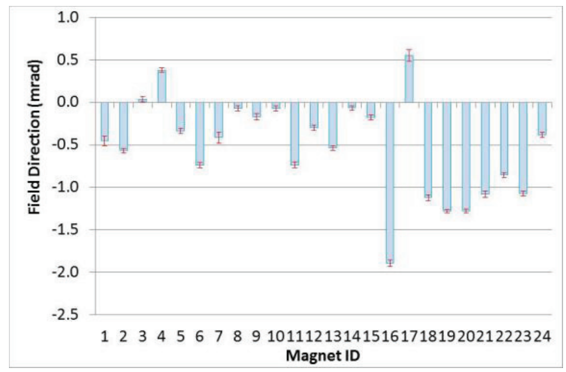

Figure 7: Summary of field direction results.

We have on average 0.5±0.6 mrad, which is within the RMS specifications. The uncertainty takes into account the systematic errors obtained by comparison of different SSW systems and can be partially attributed to the flatness error of the top fiducial support surface, which was not initially designed for this purpose since the roll reference is given by the bottom support.

CONCLUSION

All the quadrupoles have been accepted and are currently being installed, with only a few being in need of transversal axis offset adjustment.

The impact of eddy currents and hysteresis on the integrated field has been measured to be negligible. However, these effects depend in a critical manner upon certain details of the excitation cycle, such as the level and duration of the overshoot at the end of the ramp-up and the reproducibility of the oscillations at the end of the ramp-down. When the production version of the MAXIDISCAP power supply will be available, further tests will be carried out.

The combination of techniques validated in this campaign will be used to test the upcoming series of transfer line EMQs.

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