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Magnetic Qualification of Permanent Magnet Quadrupoles for CERN's Linac4

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Abstract

This paper summarizes the results of the magnetic measurements done to qualify prototypes and series permanent-magnet quadrupoles for the new Linac4, currently in construction at CERN. The results, obtained with a combination of stretched wire and rotating coil techniques, include the individually tuned integrated field gradient, multipoles, magnetic axis and field direction. These magnets are characterized by a challengingly small 22 mm aperture diameter and we illustrate the methods adopted to guarantee instrument calibration, along with the estimated accuracies of the measured quantities and their impact on beam optics.

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Abstract—This paper summarizes the results of the magnetic measurements done to qualify prototypes and series permanent-magnet quadrupoles for the new Linac4, currently in construction at CERN. The results, obtained with a combination of stretched wire and rotating coil techniques, include the individually tuned integrated field gradient, multipoles, magnetic axis and field direction. These magnets are characterized by a challengingly small 22 mm aperture diameter and we illustrate the methods adopted to guarantee instrument calibration, along with the estimated accuracies of the measured quantities and their impact on beam optics.

Index Terms—Magnetic measurement, harmonic coil, Halbach array, permanent magnet quadrupole, stretched wire, in-situ calibration.

I. INTRODUCTION

THIS paper concerns the magnetic performance of prototype and series Permanent Magnet Quadrupoles (PMQ) for the first drift tube tank of Linac4, a new 160 MeV H^- injector currently in construction at CERN [1]. The PMQs will be electron welded inside the copper drift tubes, alignment being provided by the outer cylindrical surface and radial pins. Permanent magnets have been chosen as the best practical way to provide the required high gradient within the small volume available inside the high-frequency accelerating structure. Additional advantages include simple fixed-optics operation and no heat losses [2].

The PMQs are arranged in a FOFODODO layout and must be tuned in F/D pairs to the same integrated gradient $\int Gdl$, generally decreasing along the linac. The tuning is done by the manufacturer and is checked at CERN, based on a common measurement reference, as a part of the acceptance tests of each magnet. Since the drift tubes are not adjustable in any way, corrective interventions on assembled tanks would be very costly and must absolutely be avoided. For this reason, all magnets shall be re-tested once mounted in their respective drift tube paying attention in particular to the field polarity, the centering of the magnetic axis with respect to the mechanical axis and any deterioration due to welding-induced heating.

The magnetic performance of the very first prototypes and pre-series units, made and tested by various manufacturers and cross-checked at CERN, has already been discussed in a

previous paper [3]. Here we focus mainly on the batch of 39 PMQs made by Aster Enterprises, Acton, MA, for the lowest energy drift tube tank, which have been recently accepted and are at present scheduled for installation in the tanks. In the following sections we first discuss the design of the magnets and then we describe the measurement method, emphasizing some aspects linked to calibration. Next, we report a detailed statistical summary of the test results and finally we give our conclusive comments.

II. MAGNET DESIGN AND PROTOTYPING

The design of the PMQ is based on a modified Halbach array [4] as shown in Fig. 1a. The main parameters are listed in Table 1. The field is generated by 16 rectangular permanent magnet blocks, all magnetized to the same remanent magnetization B_r along the appropriate direction, housed in slots cut at different radial positions to adjust coarsely the gradient. The blocks are held in place by a set of 32 radial silver-plated screws and the gradient can be fine-tuned over a 0.5% by adding up to 25 μm of stainless steel shims at the inboard. (Optimization of the harmonics would be also possible with this design, but was not necessary.) The material selected is $\text{Sm}_2\text{Co}_{17}$, which has a high maximum $B_r \approx 1.2$ T and, most importantly, the best long-term stability against neutron-induced degradation and temperature effects, with a dB_r/dT about $-3 \cdot 10^{-4} \text{ K}^{-1}$. The housing is made of a special grade of austenitic steel 316 LN, originally developed for the LHC, with very low magnetic permeability ($\mu_r \leq 1.003$) as needed for the fields of the blocks to superpose linearly. Stainless steel matches well copper in terms of thermal expansion and galvanic potential, and its low thermal conductivity protects the magnets against accidental overheating during welding.

A number of prototypes made by different manufacturers were tested at CERN. The main designs include:

- Round magnet bars (Fig. 1b): the field is generated by two arrays including 27 transversally magnetized bars. Tuning the $\int Gdl$ is achieved by adding iron washers at the ends. The major drawback is poor field quality with respect to the final design, with low-order harmonic errors about twice as high.
- High gradient (Fig. 1c): this is a classic Halbach array with 16 trapezoidal sectors, filling almost completely the volume available and hence providing almost double the gradient for the same magnetization. Apart from the higher gradient being unnecessary, with this design the $\int Gdl$ can be tuned only by changing the magnetization of the blocks or by enlarging

mechanically the bore, both options being impractical.

- c) Low gradient (Fig. 1a): this is the final design with 16 segregated blocks. The aluminum frame used initially was found to react electrochemically with the copper drift tube even in the presence of minute amounts of air moisture during the installation, leading to corrosion. A titanium frame was tested as a possible alternative, however its cost is four times higher than steel with no measurable advantage. Field harmonics of Al- and Ti-frame units, plotted in Fig. 3, do not differ significantly from those of steel-frame ones.

Fig. 1. (a) 45mm long PMQ for Tank I; (b) schematics of 27-round bar prototype; (c) high-gradient prototype with standard Halbach blocks

TABLE 1 PMQ PARAMETERS

Parameter	Value
Peak gradient [T/m]	23.6 – 58.4
Integrated gradient [Tm/m]	1.0-2.5
Length [mm]	45-80
Bore diameter [mm]	22
reference radius r_{ref} [mm]	7.5
Outer diameter [mm]	60

III. MEASUREMENT AND CALIBRATION PROCEDURE

A. Measurement method

In general, measurement of magnets as small as the PMQs is a challenging task. Considering e.g. a rotating coil inside a bore of radius r , the maximum number of coil turns that can be wound with a conductor of given gauge is proportional to r^2 ; therefore, the signal corresponding to the harmonic of order n scales as r^{n+1} . In addition, the measured field coefficients C_n are inversely proportional to the geometrical coil sensitivity factors κ_n , which in turn scale as r^n [5], so that the relative impact of radial mechanical tolerances and calibration errors δr is $\delta C_n / C_n = n \delta r / r$. In the end, measurement uncertainties can be expected to be one to two orders of magnitude larger than in typical synchrotron magnets having $r \approx 50$ -100 mm.

The measurement method developed for the PMQs makes combined use of two instruments, i.e. a) a single stretched wire system, originally developed by FNAL for LHC quadrupoles [6] and b) a rotating coil system developed at CERN, based on a 200 mm long, $\varnothing 19$ mm quadrupole-compensated coil array [7]. The stretched wire works by integrating the flux swept by the wire during a micrometer-

precise translation of its extremities, thus providing the integrated gradient $\int G dl$ with the highest accuracy. This system could be used to measure the position of the magnetic axis, however that would require the use of additional optical retro-reflector targets, for which there is little room. The rotating coil system provides all the main required quantities i.e. the integrated field gradient, direction, center and harmonics, albeit with the limitations explained below. We recall that the specifications of the PMQs also include the pitch and yaw of the magnetic axis, which should be aligned to the beam within 2 mrad to maximize beam acceptance. For such short magnets both instruments have poor sensitivity to misalignment, so in this case it was decided to rely solely upon mechanical tolerances.

B. Calibration issues

The coil currently in use is affected by mechanical imperfections leading to longitudinal non-uniformity of width and radius by about 0.6%. When measuring a magnet shorter than the coil, such variations imply that the usual calibration of the average geometry is practically useless. To overcome this drawback we have developed an *in-situ* cross-calibration procedure which makes extensive use of the advantage inherent in small magnets, that is the possibility to flip them easily around all axes. By making suitable averages of the results one can compute and correct the systematic offsets affecting the measurement, thus gaining back most of the lost accuracy, as explained in another paper [8].

The most critical step in the coil calibration procedure is the calculation of the effective width and radius so that $\int G dl$ is forced to match with the stretched wire-measured value, taken as the reference. Initially, this was done only on a set of two special reference magnets chosen as a common calibration reference for both CERN and the manufacturer, to be kept one at each site. These magnets were deliberately given high multipole field errors, about 3.5% of the main field in total, to facilitate the comparison of harmonic measurements. However, a more detailed analysis showed that in case of large multipoles the accuracy of the reference stretched wire measurement itself can be affected. For instance, if we call $\int G_x dl$ and $\int G_y dl$ the results of measurements done while translating the wire, initially centered, by an offset Δ along the x and y axis respectively, we find that:

$$\begin{cases} \frac{\int G_x dl}{\int G dl} = 1 + \frac{1}{2} \left(\frac{\Delta}{r_{ref}} \right)^2 \frac{b_4}{10^4} + \frac{1}{3} \left(\frac{\Delta}{r_{ref}} \right)^4 \frac{b_6}{10^4} + \frac{1}{4} \left(\frac{\Delta}{r_{ref}} \right)^6 \frac{b_8}{10^4} + \dots \\ \frac{\int G_y dl}{\int G dl} = 1 - \frac{1}{2} \left(\frac{\Delta}{r_{ref}} \right)^2 \frac{b_4}{10^4} + \frac{1}{3} \left(\frac{\Delta}{r_{ref}} \right)^4 \frac{b_6}{10^4} - \frac{1}{4} \left(\frac{\Delta}{r_{ref}} \right)^6 \frac{b_8}{10^4} + \dots \end{cases}$$

i.e. the measurement error is proportional to each multipole and tends to diverge as Δ is made larger, which is normally the case in order to maximize the measured signal level. As a consequence, the PMQs in the first tank have been tuned systematically 0.9% lower than the original specification. This remains within optically acceptable limits (i.e. a 0.5% RMS emittance increase) provided that the beam is re-matched from the MEBT. To prevent such errors occurring again we have now selected the magnet with the best field quality (all

harmonics lower than 0.2%) as the new reference and, in addition, we have reduced Δ from 10 mm to 7.5 mm, i.e. the lowest value compatible with a reasonably high signal level. As a further safeguard, we also plan to double-check the integrated strength of all magnets with the stretched wire.

IV. SUMMARY OF TEST RESULTS

A. Integrated strength

The relative difference between the coil-measured and nominal $\int Gdl$ is summarized, along with all other results, in Table 2 and is plotted in Fig. 2. After re-matching of the optics, we find that the RMS spread of the values is 0.13% (one sigma), well below the 0.5% tolerance. This figure reflects essentially random measurement errors on a magnet-to-magnet basis, since it is virtually identical to the spread between coil and wire measurements at CERN (0.12%) and to the spread between measurements done at CERN and at the manufacturer's (0.11%). It should be noted that the repeatability of the $\int Gdl$ measurement, defined as the standard deviation over at least 3 consecutive takes, is much smaller, about 0.03% for both instruments.

Fig. 2. Integrated gradient error relative to specification (rematched optics).

B. Field quality (harmonics)

The measured field harmonics up to order $n=10$, expressed in a rotated reference system where the field is purely normal, are plotted in Fig. 3. In all cases the norm of the harmonic is below the tolerance, i.e. 1% of the main field at $r_{ref}=7.5$ mm. The harmonics of the best and worst PMQ, so defined in terms of the field error upper bound $\sum_n |c_n| = 0.7\%$ and 1.9% respectively, are plotted in Fig. 4. In some PMQ the harmonic $n=6$, mainly due to the anisotropy of the permeability in the permanent magnets, stands clearly out; however, in the majority of cases the field error is dominated by the sextupole, the octupole etc. in decreasing order, which seem to point to construction tolerances (e.g. geometry of the pieces, direction and uniformity of the magnetization vector) as the main error source. We must mention that almost one half of the total number of magnetized blocks, all inspected individually during fabrication, was rejected and replaced because they were out of specifications, which explains the good field quality achieved. We have also tentatively measured very high

order harmonics which should be present according to the number and shape of the magnetized blocks [4]. Indeed, in some magnets we find a level around 0.2% of harmonics of order $n=22, 36, 58$ and higher. However, random measurement errors on these harmonics are comparatively high and considering that they have little influence on the beam no further investigations have been made.

Due to mechanical tolerances of the rotating coil, systematic errors up to 0.06% are expected for the harmonics up to $n=10$. While these errors have in principle been calibrated out, we have compared all of our results with those obtained at the manufacturer's, finding no systematic effects and random differences about 0.04% RMS. In addition, we have been making harmonic measurements with a completely independent new instrument being developed for CLIC magnets and based on a vibrating stretched wire [9]. A preliminary comparison gives a RMS difference about 0.05%, in line with the previous result.

TABLE 2 FIELD QUALITY SUMMARY

Parameter	Tolerance	Average	Standard Deviation
$\int Gdl$ [% of nominal]	0.5	0.00	0.13
$ c_3 $ [% of C_2 @ 7.5 mm]	1	0.37	0.16
$ c_4 $ [% of C_2 @ 7.5 mm]	1	0.30	0.13
$ c_5 $ [% of C_2 @ 7.5 mm]	1	0.17	0.09
$ c_6 $ [% of C_2 @ 7.5 mm]	1	0.26	0.11
Field direction (F) [mrad]	1	0.27	1.11
Field direction (D) [mrad]	1	-0.74	1.34
Magnetic center x [mm]	0.1	-0.01	0.04
Magnetic center y [mm]	0.1	-0.01	0.03

Fig. 3. Norm of the field harmonics of all tested PMQs. The continuous lines represent the upper and lower bound of the 3σ spread of the series units.

Fig. 4. Norm of the field harmonics of the best and worst PMQ.

C. Field direction

Each PMQ has two pin holes 90° apart that allow installation inside a drift tube in either F or D configuration (corresponding to a positive or negative normal quadrupole). The pins define the x and y directions of the mechanical reference system of the magnet. In this reference we define the field direction as $\alpha = -\frac{1}{2}\tan^{-1}(A_2/B_2)$ where A_2 and B_2 are the skew and normal quadrupole components. The mechanical reference system is offset by $\Delta\alpha$ with respect to the natural reference system of the rotating coil, i.e. a system with x axis parallel to the coil at the time when flux integration starts. The offset $\Delta\alpha=3.4$ mrad is measured by flipping the magnet around a vertical axis and averaging the results. Its spread, about 0.4 mrad, gives an estimation of the uncertainty of angular measurements and can be tracked as an indicator of the mechanical stability of the system.

The field direction has been measured in both F and D configurations and is plotted in Fig. 5, where we can see that almost one half of the magnets exceed the nominal ± 1 mrad tolerance by up to almost 3 mrad. Nonetheless, the averages remain within tolerance and the errors can be accepted by beam optics. The orthogonality error of the pins, measured magnetically, averages about 1.0 mrad with a standard deviation of 0.9 mrad and is not found to correlate with the field direction error.

Fig. 5. Field direction for the two possible configurations of each PMQ. The orthogonality error between the pins is the difference of the two values.

Fig. 6. Magnetic center of all series PMQs respect to the mechanical center (axis of the external cylindrical surface). The circle represents the tolerance.

A. Magnetic axis

The position of the magnetic axis, measured by flipping the magnet about the horizontal and vertical axes and averaging the results, is plotted in Fig. 6. For all the PMQs the axis is well within the 1 mm nominal tolerance. Also in this case, the systematic offset between the rotating coil axis and the magnet support is recalculated each time and its spread, which is about 0.02 mm, gives an indication of the uncertainty of the results.

B. Fringe field

The radial fringe field of the strongest PMQ has been mapped with a Hall probe to assess the possible deflection of the electron beam used for welding. The level is about 8.2 mT at $r=30.5$ mm, i.e. about 1.5% of the peak field within the aperture. The leaking field has quadrupolar symmetry and decreases as $1/r^2$, meaning that it drops below ambient background level at a $r \geq 55$ mm. We remark that the relative leakage level for the regular Halbach design unit tested has been found to be about 3.1%, owing to the magnetized blocks being radially larger. It is interesting to note that the decay rate for an infinitely long 16-block Halbach quadrupole should be in theory much higher, namely $1/r^4$ or higher. The low rate observed may be ascribed to the low longitudinal aspect ratio.

V. CONCLUSIONS AND OUTLOOK

All measured PMQs have been accepted and sorting seems to be unnecessary to meet optics requirements. We are now preparing to measure assembled drift tubes and 80 mm PMQs for the remaining tanks. The rotating coil system is presently being upgraded with new coils with improved geometry, up to 400 mm long and with diameters from 8 mm to 19 mm, which will enable us to apply the experience acquired with the sophisticated calibration techniques needed to other linear accelerators in the future.

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