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Design, Manufacture and Measurements of Permanent Quadrupole Magnets for Linac4

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Abstract

Compact quadrupole magnets are required for the CCDTL (Cell-Coupled Drift Tube Linac) of Linac 4, a 160 MeV linear accelerator of negative hydrogen ions which will replace the old 50 MeV proton Linac2 at CERN.

The magnets, of an overall physical length of 140 mm and an aperture diameter of 45 mm, are based on Sm2Co17 blocks and can provide an integrated gradient of up to 1.6 Tesla. The magnetic field quality is determined by 4 ferromagnetic pole tips, aligned together with the permanent magnets blocks inside a structure made in a single piece. Tuning bars allow to individually trim the magnetic flux provided by each pole, to correct possible differences between blocks and to modify the field gradient intensity within about 20% of the nominal value.

The paper describes and discusses the design, manufacture and magnetic measurements of a first prototype magnet.

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Index Terms—Permanent magnets, quadrupoles, Linac4.

I. INTRODUCTION

THE Linac4 [1] is a linear accelerator for negative hydrogen ions (H^-) which will replace the old 50 MeV Linac2 as linear injector for the CERN accelerators. Its higher energy of 160 MeV will allow to increase the beam intensity in the downstream machines on the way to the LHC.

Linac4 is about 100 m long, normal-conducting, operating at a frequency of 352 MHz.

Its first element is a (H^-) source with extraction energy of 45 KeV. The first RF acceleration (from 45 keV to 3 MeV) is done by a 3 m long Radio Frequency Quadrupole. At 3 MeV the beam enters a 3.6 meter long chopper line. Then, the beam is further accelerated to 50 MeV in a Drift Tube Linac (DTL). The DTL is a 19 m long structure, subdivided into three tanks. The acceleration from 50 MeV to 100 MeV is provided by a Cell-Coupled Drift Tube Linac (CCDTL), made of 21 tanks of three cells each for a total length of 25 meters. The last acceleration from 100 MeV to 160 MeV is done in a π -Mode structure (PIMS), made of 12 tanks of seven cells each for a total length of 22 m.

The quadrupole magnets described in this paper are needed in the CCDTL.

The solution presented here consists of SmCo permanent magnet quadrupoles (PQM) with mechanically adjustable strength. SmCo has been preferred to NdFeBo because of its stability both versus temperature changes and radiations.

To provide the required integrated gradient range, the magnets have been divided into two families, the first consisting of one magnet only (PQM Type I) with an integrated gradient of 1.546 T, and the second consisting of 13 quadrupoles (PQM Type II) with an integrated gradient adjustable from 1.1 T to 1.4 T as shown in Table I.

TABLE I NOMINAL INTEGRATED GRADIENTS OF CCDTL QUADRUPOLES

Magnet Name	Integrated Gradient [T]	Magnet Type
L4C.MQFP.0645	-1.136	PQM Type II Integrated gradient range 1.1-1.4 T
L4C.MQDP.0665	1.137	
L4C.MQDP.0745	1.146	
L4C.MQFP.0765	-1.169	
L4C.MQDP.0465	1.205	
L4C.MQFP.0565	-1.207	
L4C.MQDP.0545	1.208	
L4C.MQFP.0445	-1.229	
L4C.MQDP.0265	1.300	
L4C.MQFP.0365	-1.303	
L4C.MQDP.0345	1.303	
L4C.MQFP.0245	-1.334	
L4C.MQDP.0145	1.377	
L4C.MQFP.0165	-1.546	PQM Type I

The PQMs are positioned outside the RF structure in the limited inter-tank space (Fig.1), their physical length cannot exceed 140 mm and, due to the coupling cell, the outer diameter has to be kept below 200 mm.

Fig. 1. Integration of the PQM in the CCDTL

The list of magnet requirements is completed by a physical aperture diameter of 45 mm and a maximum integrated harmonic content of $\pm 0.5\%$ in a good field region radius of 15 mm. The choice of a design based on permanent magnets appeared the most adequate to meet such parameters, in particular the space constraints.

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II. MAGNET DESIGN

A. Basic features and design parameters

We will describe in detail the design of the prototype, corresponding to a PQM Type I with a higher integrated gradient (trimmeable between 1.67 T and 1.77 T instead of the 1.51 T-1.57 T required for PQM Type I). The design of PQM Type II, allowing a much larger regulation of about 20% but providing a lower gradient, will be briefly introduced as well.

The salient features of the design, schematically represented in Fig.2, are:

- the use of an aluminium alloy structure wire-cut in a single piece. This structure centers the permanent magnets and the ferromagnetic pole tips between each other and with respect to the return yoke;
- the location of the permanent magnet blocks, which coupled to the pole tips form the magnetic poles;
- the use of ferromagnetic pole tips glued on the permanent magnets. This solution allows to minimize the effect of slight imperfections of the direction of magnetization (easy angle) of the permanent magnet blocks, thanks to the fact the direction of the flux lines at the exit of the pole tip in the aperture is basically perpendicular to the pole tip surface;
- the adjustment of the magnetic reluctance on each individual pole, performed by tuning blocks;
- the use of $\text{Sm}_2\text{Co}_{17}$ permanent magnet blocks, which provide less energy product than NdFeBo but are radiation and corrosion resistant and their magnetic properties (reversible temperature coefficient) are acceptably stable with temperature. The selected material was “RECOMA 30S”, by “Arnold Magnetic Technologies” [3], having a maximum energy product of 29.5 MGOe, a remanence $B_r = 1.1$ T, and a reversible temperature coefficient of B_r of about -0.035% /°C.

Fig. 2. Schematic features of PQM Type I. (1) tuning block (2) return yoke (3) aluminium structure (4) pole tip (5) permanent magnet $\text{Sm}_2\text{Co}_{17}$

The main design requirements are summarized in Table II.

TABLE II MAIN DESIGN PARAMETERS OF PQM TYPE I

Description	Value	Unit
Magnet height x width x length	164 x 164 x 100	mm ³
Physical aperture diameter	45	mm
Integrated field gradient (min/max)	1.51 / 1.57	T
Good field region (GFR) radius	15	mm
Magnetic length	110	mm
Material of permanent magnet blocks	$\text{Sm}_2\text{Co}_{17}$	
Material of ferromagnetic parts	AISI 1010	
Harmonic content at GFR radius	<0.05	

B. Magnetic design

The magnetic cross section looks like a classical quadrupole electromagnet where the coils have been replaced by permanent magnets blocks integrated in the poles (Fig.3). In addition to the pole tip shape, field accuracy depends on the uniformity of the easy axis orientation and field strength of the blocks. To compensate possible inequalities and to set the field gradient, a mechanical trimming can be performed by acting on tuning blocks, rectangular shaped independently movable on each pole.

The magnetic field optimization was performed with Opera-2D/ST and Opera-3D/TOSCA [2], using the material properties of AISI 1010 for the pole tip, tuning block and return yoke, and the supplier's ones for the permanent magnet.

Due to symmetry, only 1/8 of the magnet geometry was modelled (see Fig. 3).

Fig. 3. 2D magnetic field distribution

The pole tip profile (Fig.4) is an arc with the radius of 23 mm and angular span of 25° with respect to the pole axis, two arcs with the radius of 30.8 mm and angular span of 12° at both sides are extended smoothly to the tangential lines. These lines act as a shim to increase the gradient at the end of the good field region.

Fig. 4. Pole tip profile

The harmonics amplitudes expressed in units (parts in 10^{-4} of the field gradient) (Fig.5) were obtained from the model calculations by Fourier analysis of the radial magnetic field component B_r on circle with a radius of 15 mm (good field region boundary). Being the model symmetric, only “allowed harmonics”, in particular the dodecapole component $n=6$ and the twenty-pole component $n=10$.

Fig. 5. Field gradient harmonics computed in 2D.

The results are extremely low values, confirming the validity of this simple design.

As the permanent magnet blocks are placed directly in the poles, a concern are possible errors in the easy axis of the magnetization. To study this effect we considered two cases with angular deviations of up to 2° (Fig.6), representing an upper limit according to the permanent magnet blocks manufacturer.

Fig. 6. Configurations of easy axis direction errors

The relevant results are shown in Fig.7 : thanks to the effect of the ferromagnetic pole tips the design is well tolerant to small errors in the direction of the magnetization axis of the permanent magnets blocks.

Fig. 7. Effect of an error in the magnetization angle

Since the magnet has a relatively small length with respect to the aperture, we decided to explore already at a design stage the correction of the integrated field gradient harmonics by chamfering the pole tips at the magnet extremities according to the scheme in Fig.8.

Fig. 8. Pole tip with 45° chamfer

All 3D computations were performed using Opera 3D. The 3D field map in Fig.9 shows that the field concentration on the pole edges at the magnet extremities is still within an acceptable extension.

Fig. 9. 3D field map (Bmod in Tesla) of the magnet with chamfered pole tips

We explored 45° chamfers with different cut amplitudes: the relevant results are shown in Table III.

The integrated harmonics amplitudes were obtained from the model calculations by Fourier analysis of the radial field component B_r integrated on a cylindrical surface with radius 15 mm (GFR boundary) over a length $L=300$ mm.

TABLE III REDUCTION OF INTEGRATED DODECAPOLE BY CHAMFER

n	no chamfer	4 mm chamfer	5 mm chamfer	6 mm chamfer
2	1	1	1	1
6	$-2.8 \cdot 10^{-3}$	$-4.4 \cdot 10^{-4}$	$-1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
10	$3.6 \cdot 10^{-5}$	$-8.0 \cdot 10^{-5}$	$-7.4 \cdot 10^{-5}$	$-7.3 \cdot 10^{-5}$
14	$-1.3 \cdot 10^{-5}$	$-1.3 \cdot 10^{-5}$	$-1.3 \cdot 10^{-5}$	$-1.3 \cdot 10^{-5}$

On the prototype magnet we choose to implement a 5 mm chamfer.

III. PROTOTYPE: MANUFACTURE AND MEASUREMENTS

The assembly of the prototype magnet was performed at Arnold Magnetic premises.

The $\text{Sm}_2\text{Co}_{17}$ blocks were built in 50 mm long units, machined at the correct size and thereafter glued to the pole tip thus constituting a unique pole unit. Once magnetized, the 4 pole units were inserted in the aluminium frame (Fig.10)

Fig. 10. Inserting the pole elements in the aluminium frame

The ferromagnetic yoke was thereafter placed around the aluminium frame and blocked with side pins. Finally, the tuning blocks were set at their nominal position.

The magnetic measurements were carried out with a rotating coil at a radius of 17 mm. The absolute measured value of the integrated gradient, scaled at a reference radius of 15 mm, was 1.770 T, very close to the computed one of 1.774 T.

The field harmonics, also scaled at 15 mm, are shown in Table IV.

TABLE IV INTEGRATED FIELD HARMONICS

n	Computed b_n	MEASURED b_n	a_n
2	1		1
3	0	$-5.2 \cdot 10^{-4}$	$8.5 \cdot 10^{-4}$
4	0	$6.1 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
5	0	$-0.3 \cdot 10^{-4}$	$-1.3 \cdot 10^{-4}$
6	$-1.1 \cdot 10^{-4}$	$-2.2 \cdot 10^{-4}$	$0.8 \cdot 10^{-4}$
7	0	$0.1 \cdot 10^{-4}$	0
8	0	0	0
9	0	$-0.1 \cdot 10^{-4}$	$0.1 \cdot 10^{-4}$
10	$-0.7 \cdot 10^{-4}$	$-0.6 \cdot 10^{-4}$	$0.1 \cdot 10^{-4}$
11	0	0	0
12	0	0	0
13	0	0	0
14	$-0.1 \cdot 10^{-4}$	0	0

The measured field harmonics are as expected very low for a permanent magnet. The presence of “non allowed” harmonics such as the sextupole and the octupole, remains well below the allowed limits given in Table II, so that it was not required to perform any adjustment with the tuning blocks. However, it was experimentally verified that the range of adjustment of the gradient corresponds to the computed one, between 1.66 T and 1.77 T.

IV. NEXT STEPS

Considering the excellent results obtained on the prototype, we decided to use it in Linac 4 as a PQM Type I of Table I. The required reduction of the integrated gradient is obtained by a modification of the tuning blocks and the return yoke,

adding an additional non magnetic spacer as shown in Fig. 11.

Fig. 11. Transformation of the prototype into a PQM type I quadrupole.

Concerning PQM Type II, we completed a design regulating the field gradient by 20% and providing an integrated gradient of up to 1.4 T @ $R=15$ mm. Compared to Type I, while still keeping the same external dimensions, this magnet uses larger tuning blocks and smaller permanent magnet blocks (Fig.12).

Fig. 12. Detail of PQM type II quadrupole.

V. CONCLUSION

The design of the permanent magnet quadrupoles for Linac4 incorporate a number of interesting features, such as a non magnetic frame made from a single piece, ferromagnetic pole tips, tuning blocks which provide a high quality result with a simple and relatively cheap construction. The measured results on a prototype confirm all aspects of design principles.

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