

DESIGN, ASSEMBLY AND FIRST MEASUREMENTS OF A SHORT MODEL FOR CLIC FINAL FOCUS HYBRID QUADRUPOLE QD0

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Abstract

In the framework of the Compact Linear Collider (CLIC) R&D, a tunable hybrid magnet design has been proposed for the final focus QD0 quadrupole. A short model of the magnet has been realized in order to validate the novel design and its expected performances. In order to achieve extremely high quadrupole gradients (>500 T/m), the magnet design combines: a core structure made in magnetic CoFe alloy “Permendur”, permanent magnet blocks, and air-cooled electromagnetic coils. Relevant aspects of this design are the wide tunability of the gradient range, the compactness and the absence of any vibrations. In this paper a reminder of the magnet design concept is given; then, the procurement and assembly main aspects are presented, followed by the results of the magnetic measurements. Finally, some manufacturing considerations relative to a full size magnet procurement are discussed.

INTRODUCTION

CLIC baseline layout assume an optical scheme with a distance $L^* = 3.5\text{m}$ between the Interaction Point (IP) and the end of the final focusing quadrupole (QD0) on the incoming beam lines, as shown in Figure 1 (not in scale). Due to this small value for the L^* parameter, the QD0 magnet is physically integrated inside the end cover of the experiment detector. This layout is symmetric respect to the IP for the right and left side of the detector.

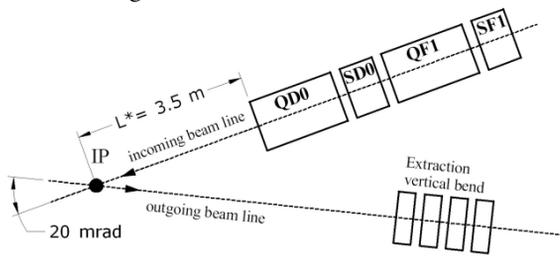


Figure 1: CLIC baseline lattice layout with $L^* = 3.5\text{ m}$

Constraints and Requirements

As a consequence of this tight integration within the detector, QD0 must be as compact as possible in order to limit the space subtracted to the equipment and to minimize the mass of the magnet that needs to be actively stabilized. The integration of the outgoing beam line (post collision line) it is also needed. All these conditions made quite difficult to envisage a superconduction solution for this high gradient quadrupole; therefore, a novel design approach was needed. Table 1 summarizes the magnet main geometrical and magnetic requirements.

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Table 1: QD0 Requirements

Parameter	Value
Nominal field gradient	575 T/m
Magnetic length	2.73 m
Magnet bore diameter	8.25 mm
Good field region (GFR) radius	1 mm
Integrated field gradient error inside GFR	< 0.1%
Adjustment	+0 to -20%

SHORT MODEL DESIGN AND PROCUREMENT

Magnet Design

A QD0 hybrid magnet design was proposed by CERN in 2009, followed by the decision to build a short model to validate the new conceptual design. The main features of the magnet design can be found in [1] and a schematic of the magnet cross-section is shown in Figure 2.

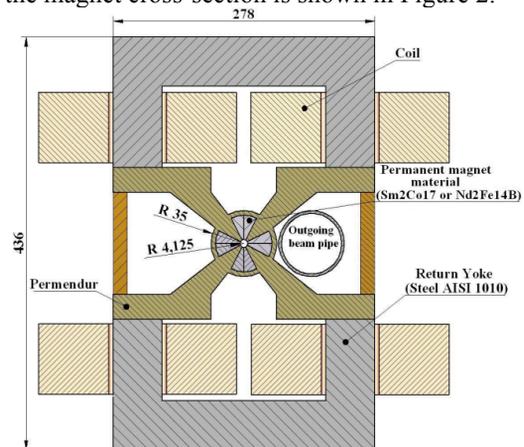


Figure 2: Schematic cross-section of the hybrid design

In function of the chosen permanent magnet (PM) material for the inserted wedges ($\text{Sm}_2\text{Co}_{17}$ or $\text{Nd}_2\text{Fe}_{14}\text{B}$) and of the operating current (Ampere-turns ranging from 0 to 5000 A) the expected maximum gradients, as computed in a 2D (infinite long magnet) finite element analysis, are in the range of 550 to 610 T/m.

Main Components Procurement and Assembly

The procurement of the main components of the prototype (Permendur core part and the PM magnet wedges) was finalized in 2011 (with Vacuumschmelze

GmbH & Co. KG - D), and the coils manufacturing and the prototype assembly was done at CERN. Permendur and PM blocks were produced by Electric Discharge Machining technique (EDM) with a nominal tolerance of $\pm 25\mu\text{m}$. The Permendur core part it is shown in Figure 3. The magnet central part with the PM wedges inserted in the Permendur quadrupolar structure is shown in Figure 4. Coils were manufactured (winding and impregnation) at CERN. The complete prototype is shown in Figure 5.

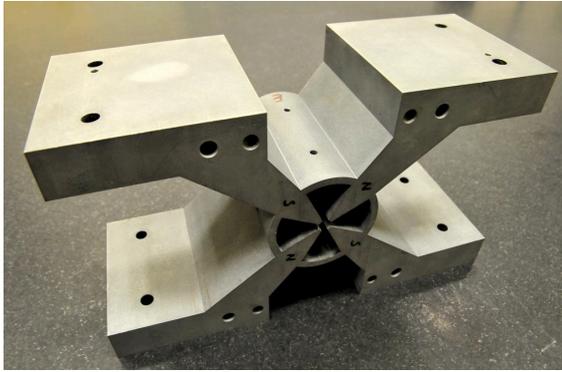


Figure 3: Core element in Permendur of QD0.

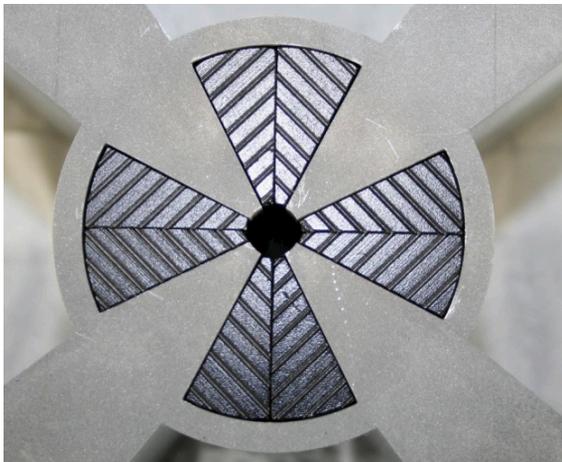


Figure 4: Detail of the magnet central part.

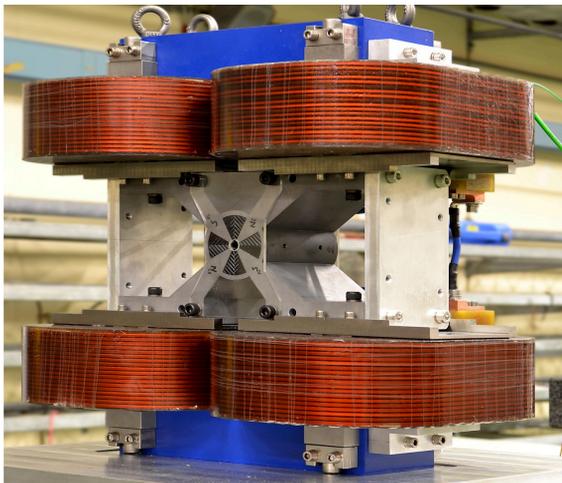


Figure 5: The fully assembled prototype

MAGNETIC MEASUREMENTS

The QD0 prototype was magnetically measured in January 2012. Measurements were focused on gradient, magnetic axis and harmonic content [2].

The classical “single-stretched wire” [3] method was used to determine the field strength (integrated gradient). A second method, the “vibrating wire”, based on the displacement due to the Lorentz forces of the wire fed by an alternating current at the wire’s resonance frequency, was used to determine the magnetic axis, where the vibration amplitude takes its minimum [4,5].

High-accuracy measurements of the harmonic coefficients, usually denoted as field multipoles, are prevalently based on rotating coils. This method yields a measurement of the magnetic flux linked with the coil as a function of its angular position. Evidently, small-aperture magnets are very challenging for multipole measurements with this method. A new rotating coil system with diameter of only 7.7 mm (Figure 6) is under commissioning at CERN but was not yet fully available for these measurements. For this reason a new wire method, the “oscillating wire”, was used instead. The wire is positioned step-by-step on the generators of a cylindrical domain inside the magnet aperture and is powered by a sinusoidal current. The amplitudes of the wire oscillations are measured and related to field harmonics by a suitable analytical model [6]. The multipole field errors were measured at a reference radius (r_{ref}) of 3 mm after centring better than 0.01 mm (by means of “vibrating wire” method). In Tables 2 and 3 the relative normal and skew multipoles components are given for different excitation currents in units of 10^{-4} . The repeatability of the oscillating wire measurements was found to be better than 5 units.



Figure 6: Rotating coils measuring system (7.7 mm diameter) under commissioning at CERN.

Table 4 shows the measured integrated gradients as a function of excitation; in Figure 7 are reported the measured central gradient (red dots), and model results for a full size magnet (longer than 300 mm) and for the short prototype (100 mm).

Table 2: Normal relative multipoles in units of 10^{-4} as a function of the magnet current at $r_{ref} = 3$ mm.

I (A)	b3	b4	b5	b6	b7	b8	b9	b10
0.0	26.6	55.8	-13.6	414.5	6.6	20.7	-9.2	-118.3
3.1	19.8	46.4	-11.8	307.6	3.8	16.1	-6.6	-131.9
6.2	7.2	32.9	-7.7	75.1	2.9	8.7	-5.5	-143.0
7.6	6.7	32.9	-6.1	1.5	4.6	3.9	-1.3	-128.8
15.5	2.1	30.2	-8.5	-58.6	4.9	2.4	-2.6	-87.4
18.6	3.0	31.3	-7.3	-57.0	4.2	0.4	-1.8	-83.7
15.5	3.0	31.1	-7.8	-57.3	3.7	3.0	-1.5	-84.7
7.0	10.0	31.9	-7.1	27.1	5.6	7.9	-1.3	-132.2
6.2	9.5	32.2	-5.7	69.6	4.7	7.9	-3.5	-143.2
3.1	21.2	46.0	-12.1	302.3	8.5	15.0	-8.6	-133.2
0.0	25.0	56.9	-15.3	412.7	6.1	20.9	-8.2	-118.2

Table 3: Skew relative multipoles in units of 10^{-4} as a function of the magnet current at $r_{ref} = 3$ mm.

I (A)	a3	a4	a5	a6	a7	a8	a9	a10
0.0	27.6	3.8	-36.8	-20.5	4.8	-7.1	-3.6	16.2
3.1	2.9	4.8	-24.7	-9.0	6.3	-0.2	-6.4	11.4
6.2	0.1	0.2	-15.2	7.0	0.7	-3.1	-5.6	16.6
7.6	-2.7	2.3	-14.5	9.4	3.3	-1.3	-5.2	14.6
15.5	12.0	-3.6	-11.0	13.3	-1.2	-1.8	-3.2	12.3
18.6	9.6	-3.2	-13.1	13.1	0.3	-3.3	-2.1	10.9
15.5	12.5	-2.7	-11.9	11.8	0.0	-2.2	-1.3	10.0
7.0	1.5	2.8	-15.0	8.3	0.9	-4.9	-1.8	15.9
6.2	-0.7	2.1	-11.9	6.2	3.4	-3.2	-3.9	17.6
3.1	5.9	2.5	-25.3	-14.5	4.7	-7.6	-6.8	16.1
0.0	27.4	3.4	-30.6	-19.8	4.9	-7.0	-6.2	16.4

Table 4: Measurement of the integrated gradient versus current after correction from the multipole content.

I [A]	GdL x [T]	GdL y [T]
0	-14.971	14.970
3.1	-18.286	18.281
6.2	-32.769	32.777
7.6	-39.092	39.097
15.5	-52.489	52.498
18.6	-52.952	52.960
15.5	-52.496	52.506
7	-36.784	36.797
6.2	-32.994	33.007
3.1	-18.432	18.432
0	-14.913	14.914

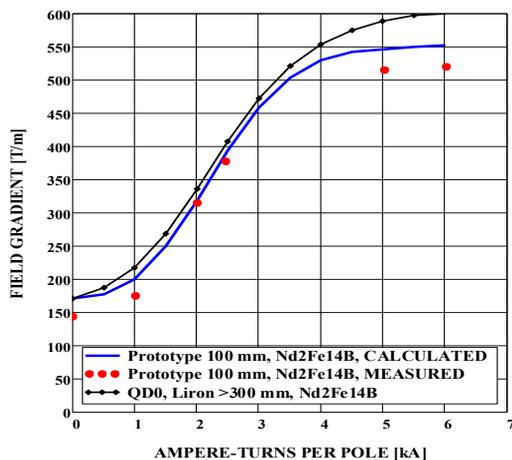


Figure 7: Computed and measured central gradients as function of ampere-turns.

Some first comments to these results: the measured field quality is very close to the required 10 units (of 10^{-4}) in all the operating range, a very positive result for such short “validation” prototype; the 6% of discrepancy between measured and computed maximum gradient is probably due to the tolerances (angles and modules) on the PM block magnetization. New measurements with the second set of PM blocks are ongoing.

CONCLUSION AND CONSIDERATIONS TOWARD A FULL-SIZE DESIGN

The measurements of the short prototype show the validity of the new design concept towards the achievement of (i) very high quadrupole gradients, (ii) wide gradient tunability, and (iii) good magnetic field quality.

A magnet of nominal length (2730 mm, see Table 1) will imply that a “modular” construction must be envisaged for the core-elements (i.e. the quadrupolar structure in Permendur and the PM blocks). The low-carbon steel “C”-shape return yokes must instead have the full length and will guarantee the precise assembly and alignment of the core modular elements.

CERN plans to manufacture in a due time a longer prototype to investigate: (i) the maximum feasible length for the core modular elements, (ii) the precise assembly technique for the modular elements and (iii) the global performance in terms of geometry, magnetic field quality and achieved gradients. The decision to procure a longer prototype will also depend by the future evolution of CLIC parameters in the R&D phase.

ACKNOWLEDGMENT

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