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PERFORMANCE OF THE OPTIMIZED MECHANICAL DESIGN OF THE CLIC MAIN-BEAM QUADRUPOLE MAGNET PROTOTYPE

M. Modena and C. Petrone

CERN, Geneva, Switzerland

Abstract

The Main-Beam Quadrupole (MBQ) magnets of CLIC, the Compact Linear Collider understudy at the CERN Laboratory in Geneva, are part of a critical magnet family, considering the industrial production challenges. An R&D program on the MBQ magnets was launched in 2010 for studying and investigating several assembly solutions in order to minimize the procurement cost of a large series of magnets comprising more than 4000 units. In this paper, the performance of the latest configuration is presented, comparing the results of magnetic measurements with previous magnet model variants. Innovative solutions for an efficient and fast fiducialization of the MBQ quadrupoles and alignment with respect to beam trajectory were also studied and developed inside the PACMAN Project, a CERN project supported by the European Union via the 7th Framework Programme Marie Curie actions. The advantages of the mechanical design of the iron yoke and the assembly and alignment procedures are presented and discussed.

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Michele Modena and Carlo Petrone

***Abstract*—The Main-Beam Quadrupole (MBQ) magnets of CLIC, the Compact Linear Collider understudy at the CERN Laboratory in Geneva, are part of a critical magnet family, considering the industrial production challenges. An R&D program on the MBQ magnets was launched in 2010 for studying and investigating several assembly solutions in order to minimize the procurement cost of a large series of magnets comprising more than 4000 units. In this paper, the performance of the latest configuration is presented, comparing the results of magnetic measurements with previous magnet model variants. Innovative solutions for an efficient and fast fiducialization of the MBQ quadrupoles and alignment with respect to beam trajectory were also studied and developed inside the PACMAN Project, a CERN project supported by the European Union via the 7^{th} Framework Programme Marie Curie actions. The advantages of the mechanical design of the iron yoke and the assembly and alignment procedures are presented and discussed.**

***Index Terms*—Electromagnets, magnet design and analysis techniques, magnetic field measurement, linear accelerators.**

I. Introduction

THE Compact Linear Collider (CLIC) is a TeV-scale high-luminosity electron/positron linear collider under study at CERN. Several main project documents were published, including a “Conceptual Design Report” in 2012 [1] and a “CLIC Project Implementation Plan” in 2018 [2]. For optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in stages, at center-of-mass energies of 380 GeV, 1.5 TeV, and 3 TeV, for a site length ranging from 11 km to 50 km. The backbone of the e+/e- linac magnetic structure are the Main Beam Quadrupoles (MBQ), compact normal-conducting magnets with an inner bore diameter of 10 mm and providing a nominal gradient of 200 T/m. Since the magnets will be operated in DC, the iron quadrants are made in solid steel 1010 grade for cost-effective reasons. In the 3 TeV CLIC configuration, the MBQs are more than 4000 units. In 2010 an R&D program was launched in order to procure prototypes and to investigate the optimal procurement for the most critical CLIC magnet families. MBQ was one of these families, and the R&D phase included the optimization of the magnet design and the quadrants high-precision assembly method. Advancement on these aspects was already reported at the MT23 Conference [3]. In this paper, we present the final proposed assembly solution, implementation and report on the tests and measurements done to validate the proposed assembly method. In the last Section VI, a brief introduction to the PACMAN Project, concerning the global assembly procedure for the CLIC linac modules (including the MBQ but also radio frequency and beam position monitor equipment) will also be presented.

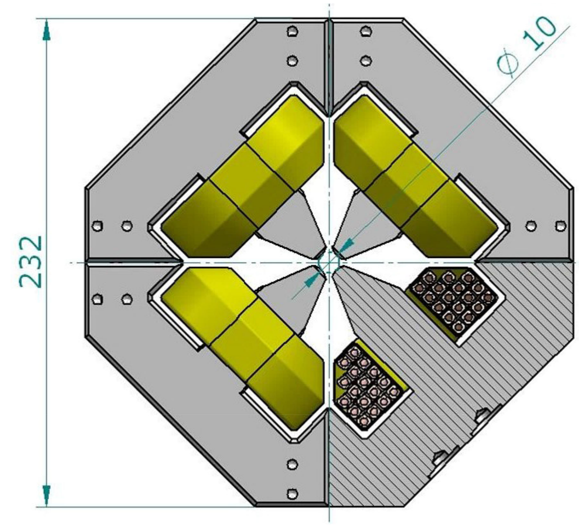

Fig. 1. MBQ Magnet Cross-Section.

II. The CLIC Layout and MBQ Design

The CLIC layout will consist of two head-colliding linear accelerators composed of thousands of 2-m long modules. On each module, the key elements of the linear accelerators (i.e. MBQ magnets and their nano-positioning active systems, radiofrequency accelerating cavities, beam position monitors, etc.) will be installed and pre-aligned [4]. After the installation of the modules in the accelerator tunnel, a final beam alignment will be performed by means of beam-based measurements. The nominal cross-section of the MBQ magnets is shown in Fig. 1. This cross-section was validated, and the magnet performances successfully checked, by several prototypes procured in the previous years (see Section V). The remaining main challenging aspect considering the industrial procurement of a wide series of such magnets would be to identify an efficient and economical (in terms of time and resources) assembly procedure for such small and compact quadrupole magnets. The several thousand magnets to be procured will have the same cross-section but four different lengths (Type 1 to Type 4) from about 0.5 to 2 meter in length. For cost reasons the prototype program was mainly

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The authors are with the CERN, Technology Department, 1211 Geneva, Switzerland (e-mail: michele.modena@cern.ch).

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TABLE I
MAIN DESIGN AND OPERATION PARAMETERS FOR THE MBQ MAGNETS

Parameter	Value	Unit
Nominal current	140	A
Current density	6.8	A/mm^2
Total resistance	48.2	mΩ
Pressure drop	5.9	bar
Temperature rise	15	K
Field gradient (140 A)	200	T/m
Integrated gradient (140 A)	70	T
Good Field Region radius	4	mm
Maximum overall length	420	mm
Magnet bore diameter	10	mm
Yoke length	332	mm

focused on the Type 1. Nevertheless, several quadrants of Type 4 were produced by different suppliers and dimensional qualified, proving no showstopper for the procurement of longer magnet versions.In Table I the main design and operation parameters for the MBQ magnets (Type 1) are summarized.

III. The Assembly Study With the Dummy Sectors

The main aspect investigated was the identification and selection of the most convenient (in term of time) and precise assembly methods for the four steel quadrants. For the first test it was decided to assemble the four quadrants (with the coils installed) utilizing a mounting template based on calibrated pins that were referring to the surfaces of the poles and the magnet bore. We had two manufacturers providing quadrant sets within tolerances of ± 7 μm and ± 10 μm as requested. Magnetic measurements performed on the assembled magnets show errors (in terms of magnetic multipoles) not consistent with the quality of the individual quadrants (in terms of poles surface and mating surface mechanical precision).

It was hypothesized (later confirmed by metrology measurements) of the existence of imitation on this quadrants assembly procedure that were degrading the expected field quality. Therefore, it was decided to evaluate alternative quadrants assembly methods with a set of test on very precise dummy sectors. Following the positive results obtained, it was possible to identify the most promising methods out of the three tested. The method retained was the one with "V" grooves and pins. Based on the performed test and thanks to the high quality of the iron quadrants and "V" grooves machining, it was evaluated that no major advantages should be brought by the use of customized calibrated pins for each couple of "V" grooves matching (1–2 microns variation) [5]. Thus pins with a constant diameter were used.

IV. Quadrants Final Modification

We were interested in performing a test on real magnet quadrants assembled with the method explained in the previous section, so evaluating the improvement eventually provided by the "V" grooves quadrant assembly method in terms of magnetic field quality (being in fact the most important aspect and for which all the process was developed and investigated). The best would have been to evaluate the impact of the new assembly solution on a set of already measured quadrants. This would permit the direct comparison of the two methods by comparing the field quality and preserving the same systematic contribution due to the poles and mating surface machining precision. The choice of modifying an existing set of quadrants would have been cheaper in comparison to produce a full new set of quadrants. This choice was more technically challenging since the existing quadrants would need to be extremely precisely re-positioned on the grinding machine to implement the "V" grooves. Discussing with the manufacturer we were in fact warned that to get the better final precision it is strongly suggested to possibly avoid the iron quadrants dismounting and re-installation during the different machining operation. In fact, normally the machining sequence include several grinding and measurement phases that are done anyway without detaching the iron quadrants from their supports. However, it was decided to take this risk and in order to follow the plan the best-produced quadrants (from DMP-Spain Company) were selected and the manufacturer was asked to re-work them providing "V" grooves with the same geometry as were manufacture and tested in the dummy sectors assembly. The modification was done at the manufacturer premises during 2015, and the metrology acceptance test done at CERN. Fig. 2 shows an iron quadrant after machining the "V" grooves. The quadrants poles and mating surface profiles (already measured at the first manufacturing) confirmed to be within ± 7 μm tolerance (according to ASME Y14.5-2009). The new machined "V" grooves shown to be on average inside a ± 5 μm tolerance but some of them have shown a systematic out of tolerance up to 5–10 μm. This is probably due to the mentioned problematic in the accurate repositioning of the iron pieces on the grinding machine. Since the machining of the grooves was done by grinding the quadrants in the longitudinal direction, there is a very good correlation of the measurements among different longitudinal cross-sections. The magnet was finally assembled following the same procedure tested with the dummy quadrants sectors (i.e. by identical cylindrical pins of 4.000 mm ± 0.5 μm in diameter). The assembled magnet is shown in Fig. 3. Between the mating planes of each couple of quadrants are also visible the new machined "V" grooves.

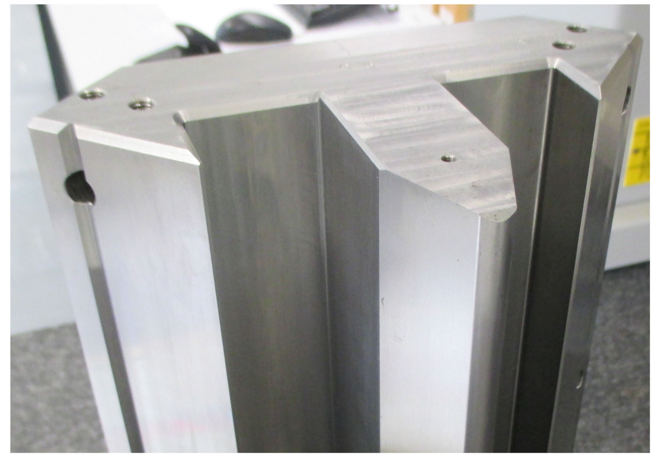

Fig. 2. MBQ quadrant details.

V. The Magnetic Measurements

The oscillating wire is the magnetic measurement method chosen because it proved to be particularly suitable for small

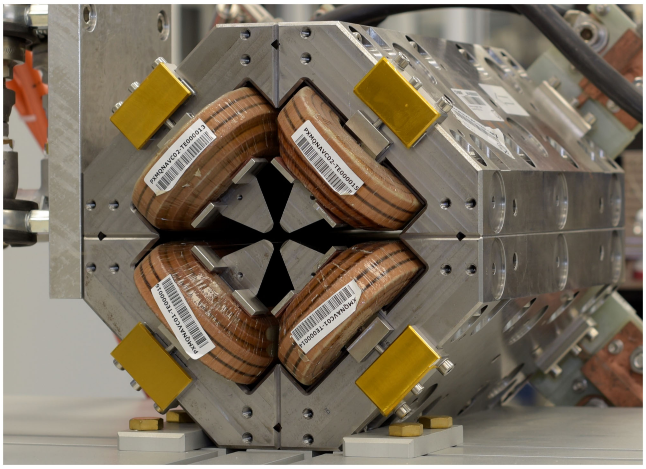

Fig. 3. MBQ magnet assembled.

aperture magnets [6]. The transverse field harmonics are obtained positioning the wire step by step on K positions ($k = 1 \dots K$) on a cylindrical domain (φ_k) inside the magnet bore as discussed in [7]. The radius r_0 of the circular trajectory is centered in the magnetic axis found by vibrating wire technique [8]. At each k position, based on the Lorentz force, the wire displacements $d_x(r_0, \varphi_k)$ and $d_y(r_0, \varphi_k)$, in x and y directions are proportional to the integral field as described in the following equation

$$\delta_y(r_0, \varphi_k) = \lambda_y \int_0^L B_x(r_0, \varphi_k) \mathrm{d}z \,, \qquad (1)$$

where λ_y is considered constant for every φ_k [7].

A. Magnetic Measurement Setup

For these measurements campaigns, a Cu-Be wire of 0.1 mm in diameter and 1510 mm in length is stretched in the magnet bore at 6.8 N. In the setup process, particular attention is given to the parallelism of the wire supports to keep a constant wire response along the trajectory. Nevertheless, the tension stability is controlled at every k position and eventually adjusted. $K = 256$ angular positions sample the circular trajectory of 4 mm in radius (r_0). The sinusoidal wire driving current is 8 mA at 30 Hz, well below the natural wire frequency of 79 Hz. The linear range of the oscillation-voltage transducer used (photo-transistors technology) guides the choice of the wire-current parameters at a given magnetic field level. The correctness of the measurement results depends strongly on the wire-current parameters for a given setup. In order to find the magnetic axis as multipole measurement starting point, the wire current excitation frequency was chosen closer to the natural wire frequency of 79 Hz to gain sensitivity in the transducer working range. The magnetic axis finding is based on acquiring the wire amplitude in several horizontal and vertical position on a linear trajectory in the magnet bore. The data fitting allows to position the wire on the magnetic axis with a precision of a few μm.

B. Magnetic Measurements Results

The measurement starts with a degaussing process followed by three current cycles from 0 up to 180 A, to set the magnet in a reproducible state. The magnet transverse field harmonics (multipoles) have been measured at three different current levels 80, 126, and 140 A. Table II lists the transverse field harmonics measured at the three different current levels expressed in units ($1 \text{ unit} = 1 \cdot 10^{-4}$ of the main quadrupole field B_2). Figs. 4 and 5 show the comparison of the normal coefficients b_3 (i.e. $b_3 =$ 3th order), b_4, b_5 and b_6, and skew a_3, a_4, a_5 and a_6 between the old and the final magnet assembly. The measurement precision performed on five repetitions at 1σ is 3 units for the 3th and 4th multipole orders and 1 unit for the higher orders.

The final assembly process shows a multipole amplitude reduction compared with the multipoles on the previous assembly reported in [3] and listed in Table III for convenience. The field gradient has been measured by the single stretched wire method

TABLE II
NORMAL AND SKEW MULTIPOLES - NEW ASSEMBLY

I	Multipoles in Units @ r_o = 4 mm							
A	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}
80	-12.3	6.4	-3.2	-2.1	-2.3	-0.9	-1.0	0.6
126	-18.5	11.0	-4.5	-1.3	0.0	0.6	-1.1	1.0
140	-20.9	12.4	-3.9	-1.2	-1.2	-0.2	-0.1	0.4
A	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
80	-2.8	2.9	-0.8	-2.3	0.1	1.0	0.9	1.2
126	-2.6	3.1	0.1	-1.6	-0.9	1.1	-0.5	0.1
140	-2.7	3.6	0.2	-2.5	0.7	0.7	0.4	0.6

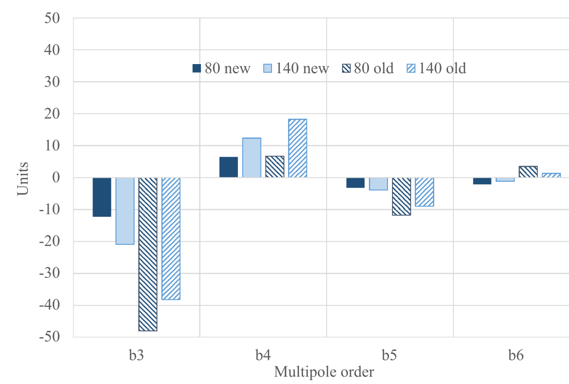

Fig. 4. Normal multipoles old and new assembly comparison.

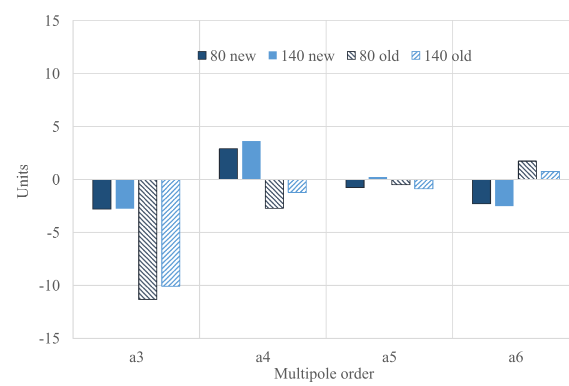

Fig. 5. Skew multipoles old and new assembly comparison.

TABLE III
NORMAL AND SKEW MULTIPOLES - OLD ASSEMBLY

I	Multipoles in Units @ r_o = 4 mm							
A	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}
80	-48.0	6.7	-11.8	3.5	-1.3	0.2	2.1	1.2
126	-39.3	16.1	-12.2	0.5	-0.4	3.4	0.8	0.4
140	-38.2	18.2	-9.0	1.3	-1.8	2.1	1.7	0.4
A	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
80	-11.3	-2.7	-0.5	1.7	-0.8	0.5	0.2	-1.2
126	-11.1	-0.6	-0.7	2.4	-0.3	-1.4	1.0	-1.2
140	-10.1	-1.2	-0.9	0.8	-1.2	0.0	0.3	-1.0

TABLE IV
INTEGRAL GRADIENT FIELD MEASURED

Current	Field $\pm$ 1σ	Transfer function
A	T	T/A
20.0	11.392 $\pm$ 0.013	0.5696
40.0	22.701 $\pm$ 0.011	0.5676
60.0	33.867 $\pm$ 0.013	0.5645
80.0	44.807 $\pm$ 0.013	0.5601
100.0	55.334 $\pm$ 0.017	0.5533
120.0	64.248 $\pm$ 0.013	0.5353
126.0	66.318 $\pm$ 0.014	0.5263
140.0	70.234 $\pm$ 0.011	0.5017
160.0	74.071 $\pm$ 0.011	0.4629
180.0	76.721 $\pm$ 0.021	0.4262

performing the complete hysteresis loop using 180 A as maximum current level. Table IV lists the integral field averaged from ramping the current up and down including the measurement precision given at 1σ performed on five repetitions. Due to the small effect of the multipoles, no correction is required on the gradient field measurement, see reference [9].

VI. THE PACMAN PROJECT

The PACMAN[1] project (the acronym stands for "Particle Accelerator Components Metrology and Alignment to the Nanometer-scale") investigated an innovative method to fiducialize the reference axes of accelerator components using a stretched wire. For the fiducialization of each main components in the pre-alignment phase, an accuracy of ± 5 μm is budgeted, while for the modules alignment in the tunnel an overall accuracy of 5 μm along 200 m long sliding window is required. PACMAN developed methods and tools allowing the fiducialization of different types of accelerator components simultaneously inside the environment of a 3D coordinate measuring machine (CMM). Figure 6 shows a view of the Final PACMAN Alignment Bench with several subsystems assembled (MBQ quadrupole, magnet nanopositioning system, stretched wire, etc.) in the CERN metrology environment [10].

Methods to precisely locate the magnetic axis of the MBQ quadrupole and the electromagnetic zero of a BPM and accurately refer them to the module global alignment system have been successfully demonstrated [4]. An improvement in the efficiency and accuracy of the fiducialization/alignment process

[1]The PACMAN project has received funding from the European Unions 7^{th} Framework Programme Marie Curie actions (grant agreement PITN-GA-2013-606839).

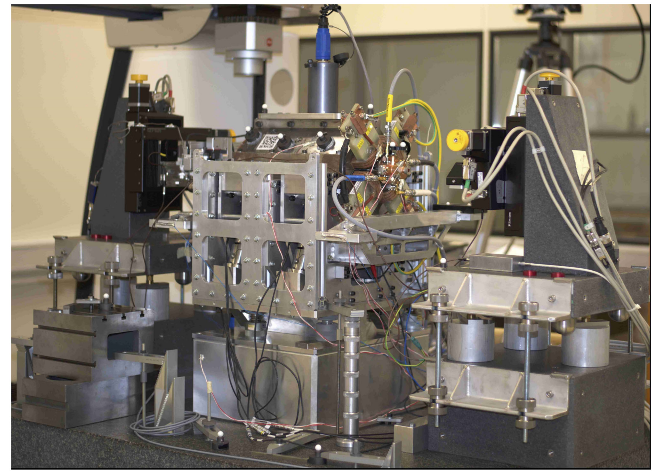

Fig. 6. The final PACMAN alignment bench during metrology measurements.

like the one proposed would be critical for a successful industrial program aiming to the procurement and high-precision assembly of a huge number of components as needed for CLIC. The program started in September 2013, and had a four years duration. The studies and research brought seven Ph.D. fellows to obtain their doctorate successfully.

VII. CONCLUSIONS

The results of the final action for the R&D phase of the MBQ magnets of the CLIC accelerator Project was reported. This magnets family would be the backbone of the two linacs of the CLIC complex, and in the 3 TeV collision energy configuration more than 4000 MBQ units would be needed. Thanks to the development and procurement of a few prototypes, it was possible to select a magnet design and assembly methods convenient for the potential large procurement. The presented field quality results show the improvement provided by the final assembly method. The MBQ magnet is also one of the main accelerator components studied in the PACMAN project ("Particle Accelerator Components' Metrology and Alignment to the Nanometer-scale"). The project, that took place at CERN between 2013 and 2017, was briefly described. The project main target was the development of novel methods and tools to allow the parallel fiducialization of accelerator components, with the aim of defining innovative and efficient techniques for the procurement and fiducialization of a large numbers (more than 2000) accelerator modules.

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