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Design and Manufacture of a Main Beam Quadrupole Model for CLIC

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Abstract

The Main Beam Quadrupole (MBQ) magnets represent one of the most populated families of Compact Linear Collider (CLIC) magnets. In total more than 4000 units of 4 different types with the same bore radius of 5 mm and field gradient of 200 T/m but with different magnetic length are needed. An extremely high precision and mechanical stability are necessary in order to fulfill the magnetic and stabilization requirements as defined in the beam optics studies. A magnet design has been proposed and several quadrupole prototypes of different length have been produced targeting a high mechanical precision. Magnetic calculation, constructional design and the first test results are presented.

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Index Terms— Accelerator magnets, resistive magnets.

I. INTRODUCTION

THE Compact Linear Collider (CLIC) is an electron-positron linear collider project for a maximum energy of 3 TeV and very high accelerating gradient of 100 MV/m. In order to optimize the production of sufficient RF power for this high gradient, CLIC relies upon a two-beam-acceleration concept: the 12 GHz RF power is generated by a high current electron beam (Drive Beam) running parallel to the Main Beam. This Drive Beam is decelerated in special power extraction structures (PETS) and the generated RF power is transferred to the Main Beam. This two-beam configuration consists of a repeated modular structure of five different types called “Module”. As concerning magnets installed, the module type 0 has only an accelerating structure for the Main Beam line; module types 1 to 4 contain the Main Beam Quadrupoles (MBQs) of different length but with the same aperture and same nominal field gradient [1]. A schematic layout of the CLIC module types 1-4 is presented in Fig. 1.

Table I summarizes the geometrical and magnetic requirements for the MBQs. The magnet will provide a central field gradient of 200 T/m with a magnetic length of 350 mm, 850 mm, 1350 mm and 1850 mm for MBQ Types 1-4 respectively. The magnet bore diameter needs to be 10 mm and the integrated field gradient quality has to be better than 0.1 % inside a Good Field Region (GFR) of 4 mm radius. The restrictions imposed by the modules layout, limit the maximum overall length of the magnets to 420 mm, 920 mm,

1420 mm and 1915 mm for MBQ Type 1, 2, 3 and 4 respectively.

Fig. 1. Schematic layout of CLIC Type 1-4 modules. Dimensions are in mm.

TABLE I REQUIREMENTS FOR THE MAIN BEAM QUADRUPOLE

Parameter	Value
Family	Type 1/Type 2/Type 3/Type 4
Quantity	308/1276/964/1472
Nominal field gradient	200 T/m
Nominal integrated field gradient	70/170/270/370 T
Magnetic length	350/850/1350/1850 mm
Maximum overall length	< 420/920/1420/1915 mm
Magnet bore diameter	10 mm
Good Field Region (GFR) radius	4 mm
Integrated field gradient error inside GFR	< 0.1%

II. MAIN BEAM QUADRUPOLE MODELS

In 2009 the design and procurement of MBQ Type 1 and Type 4 prototypes were launched. These prototypes will be used to validate the magnet design, to test and prove the active stabilization capability and to develop dedicated magnetic measurement systems for magnets with very small aperture.

Another important aspect to be investigated with this prototype is the achievable mechanical tolerances for an iron yoke with a small aperture.

A. Magnet Design

For practical reasons, a common design (cross-section) was used for all types of the MBQ. Fig. 2 shows the cross-section of the proposed design.

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The magnet yoke consists of four pieces (quadrants) made of solid steel blocks, which permit installation of the coils around each pole. Low carbon steel AISI 1010 was chosen as a yoke material for reason of cost, availability and ease of machining.

The water cooled coils of 17 turns each, were made of hollow copper conductor with a square cross section of 5.6 mm $\times$ 5.6 mm, edge rounding of 1.0 mm and a circular cooling hole with a diameter of 3.6 mm. The main parameters of the MBQ Type1 and Type 4 models are listed in Table II.

Fig. 2. Magnet mechanical layout. Dimensions are in mm.

TABLE II MBQ MODELS MAIN PARAMETERS

Parameter	Type 1	Type 4	Unit
Operating gradient	210	202.2	T/m
Integrated gradient	70	370	T
Magnetic length	333.8	1829.4	mm
Yoke length	332	1827	mm
Total length	420	1915	mm
Magnet bore diameter	10	10	mm
Nominal current	140	128	A
Current density	6.8	6.3	A/mm ²
Windings per pole	17	17	
Conductor height	5.6	5.6	mm
Conductor width	5.6	5.6	mm
Cooling hole diameter	3.6	3.6	mm
Total resistance	48.2	220.3	m Ω
Total inductance	7.2	39.6	mH
Power	0.95	3.61	kW
Cooling circuits/magnet	1	4	
Pressure drop	5.9	6.3	bar
Temperature rise	15	15	K

The magnetic field optimization was performed with Opera-2D/ST and Opera-3D/TOSCA [2]. The 2D code was used to design the pole profile, return yoke cross-section, coil size and coil position.

Due to the quadruple symmetry only 1/8 of the magnet geometry was modeled (see Fig. 3). The boundary conditions were chosen in a way that the flux lines were perpendicular to the horizontal middle plane and parallel to the symmetry axis and the limiting edge of the model. The coils were modeled as square regions; the effects of the cooling holes were neglected. The B(H) curve of Opera “tnten.bh” datafile, which is equivalent to low carbon steel AISI 1010 was used for the simulations.

Fig. 3. Magnetic flux distribution in a 1/8th segment of the quadrupole magnet.

At the initial design study, the hyperbolic pole profile that extended smoothly to the lines at both sides was chosen. However, the precise fabrication of a hyperbolic pole is rather difficult. To simplify the machining of the poles, it was finally decided to adopt a circular contour. The pole profile was optimized at an excitation current of 126 A which corresponds to a nominal field gradient of 200 T/m (see Fig. 4). The obtained pole profile provides a relative central gradient quality of $\Delta G/G_0 < \pm 0.02\%$ inside the good field region as shown in Fig. 5.

Fig. 4. MBQ circular pole profile. Dimensions are in mm.

Fig. 5. Field gradient error [%] at GFR boundary with radius of 4 mm.

The harmonics amplitudes were obtained from the model calculations by Fourier analysis of the radial magnetic field component B_r on a circle with a radius of 4 mm (good field region boundary) (see Fig. 6).

Fig. 6. Normal field components with respect to the main B_2 at 126 A.

In order to check the sensitivity of the magnetic field quality on pole profile mechanical tolerances, some 2D calculations were made. The comparison with an ideal case indicated that a tolerance of only 20 μm had a significant effect on magnetic field quality and the machining precision therefore must be strictly controlled to be within the specified tolerance of 10 μm .

Following a modules layout revision due to the introduction of other elements, the maximum yoke length of the MBQ magnets, was reduced to 332 mm for MBQ Type 1 and 1827 mm for MBQ Type 4. These new yoke lengths are about 4% (Type 1) and 1% (Type 4) shorter than needed to achieve the nominal integrated gradient at the specified magnetic length. Therefore, it was necessary to increase the excitation current in order to compensate the lack of yoke length. The iron length of the magnets determines the new design gradient values of 210 T/m (Type 1) and 202 T/m (Type 4). Fig. 7 gives a curve of the field gradient versus excitation current. It shows that the design gradients of 210 T/m (Type 1) and 202 T/m (Type 4) can be achieved at excitation current of 140 A and 128 A.

Fig. 7. Field gradient as a function of excitation current.

The magnet end termination was optimized with the 3D code. The structure of the MBQ Type 1 with sufficiently long (relatively to the aperture) yoke length of 332 mm was used for that. The 3D model with the field distribution on the surface of MBQ Type 1 magnet is shown in Fig. 8. The 3D simulations were performed at several levels of excitation

current and the field gradient values, agreed with the 2D results at $Z=0$ mm.

Fig. 8. Opera 3D model view.

The contributions from the end sections to the higher harmonics were minimized by introduction of the usual 45° chamfer on the pole ends [3]. A chamfer of $45^\circ \times 1.5$ mm was considered to be sufficient to minimize the dominant systematic harmonics B_6 (see Fig. 9).

The integrated field gradient error stays below $\pm 0.03\%$ inside the good field region in the whole range of excitation current values (see Fig. 10).

Fig. 9. Normal integrated field components with respect to the main $\int B_2 dz$ at $I=126$ A.

Fig. 10. Relative integrated field gradient error [%] at GFR boundary $r=4$ mm for different excitation currents.

B. Models Fabrication and First Test Results

Two MBQ prototype models with yoke lengths of 332 mm (Type 1) and 1827 mm (Type 4) were manufactured. The magnets were assembled from four quadrants each with a pre-assembled excitation coil. The photo of the MBQ Type 4 assembly is shown in Fig. 11.

Fig. 11. The assembled MBQ Type 4.

The quadrants were made from solid iron blocks. After cutting and annealing, as a final process of machining, each quadrant was finished by a fine grinding machining in industry.

The shapes of each yoke quadrant at both ends along the length were measured at CERN Metrology Lab. It was found that the machining accuracy of the pole profile, end chamfers and the reference edges for both sets of the MBQ quadrants were not of the quality contractually agreed and the required tolerances were not fulfilled (see Fig. 12 where an example of the measurements of the pole profile of MBQ Type 1 is shown). Therefore, these prototypes even if fully utilizable for stability and technical tests and representative as concerning the achievable integrated gradient, will be not representative of the expected and needed magnetic field quality.

Since it was anyway planned to procure other 2 magnets Type 1 and Type 4, we expect to get soon more representative quadrants in terms of field quality from a different quadrant production.

Fig. 12. Shape of the pole of MBQ Type 1 measured at CERN. The numbers indicate the shape deviation from the ideal one at the selected points in mm.

The 17-turn excitation coils were manufactured by Tesla Engineering Limited, UK. The coils were wound from one continuous piece of hollow copper conductor with a square cross-section of 5.6 mm × 5.6 mm. The conductor was insulated with glass fiber tape and impregnated with radiation resistant epoxy resin [4]. The manufactured coils were tested electrically and hydraulically at CERN. The tested coils satisfy all design requirements.

The magnetic measurements are currently ongoing. The MBQ Type 1 was magnetically measured with a stretched wire system. The excitation curve of the MBQ Type 1 was obtained by measurements at several levels of the excitation current. The measured curve to compare with the calculated one is plotted in Fig. 13. It is shown, that the measured integrated gradient values are even higher than the calculated and the required integrated gradient of 70 T is achieved at 126 A of excitation current. The measured integrated harmonics reveal the quadrant and pole profiles mechanical out of tolerance

mentioned above and the field quality is evidently degraded by that (see Fig. 14).

Fig. 13. Measured and calculated excitation curves for MBQ Type 1.

Fig. 14. Measured integrated field harmonics at 126 A of excitation current for MBQ Type 1.

III. CONCLUSION

The design of the Main Beam Quadrupole magnet for CLIC and the status of the prototype models were presented. Two quadrupole models were fabricated and measured up to now; other two will be assembled in the next months. Unfortunately, the magnet yokes (quadrants) were not machined with mechanical tolerances specified in the design. The first magnetic measurements done at CERN show, that the needed integrated field gradient was achieved, but in consequence of the mechanical out of tolerance, the magnets are not representative of the expected and required magnetic field quality. The procurement of the 2nd set of quadrants should clarify these aspects.

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