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Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC

A. Vorozhtsov^{1*}, M. Modena¹ and D. Tommasini¹

¹ CERN, Geneva, Switzerland

* On leave from JINR, Dubna, Russia

Abstract

A tunable hybrid quadrupole magnet design has been proposed for the final focus in the Compact Linear Collider (CLIC) that is currently under study. The proposed design is a combination of an iron dominated electromagnetic quadrupole with a bore diameter of 8.25 mm with permanent magnet blocks placed between the poles made of soft magnetic CoFe alloy "Permendur". The possibility of using $\text{Sm}_2\text{Co}_{17}$ and $\text{Nd}_2\text{Fe}_{14}\text{B}$ as material for the permanent magnet blocks has been investigated. It is shown that a very high field gradient of 530 T/m ($\text{Sm}_2\text{Co}_{17}$) and 590 T/m ($\text{Nd}_2\text{Fe}_{14}\text{B}$) can be achieved.

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Abstract— A tunable hybrid quadrupole magnet design has been proposed for the final focus in the Compact Linear Collider (CLIC) that is currently under study. The proposed design is a combination of an iron dominated electromagnetic quadrupole with a bore diameter of 8.25 mm with permanent magnet blocks placed between the poles made of soft magnetic CoFe alloy “Permendur”. The possibility of using $\text{Sm}_2\text{Co}_{17}$ and $\text{Nd}_2\text{Fe}_{14}\text{B}$ as material for the permanent magnet blocks has been investigated. It is shown that a very high field gradient of 530 T/m ($\text{Sm}_2\text{Co}_{17}$) and 590 T/m ($\text{Nd}_2\text{Fe}_{14}\text{B}$) can be achieved.

Index Terms— Accelerator magnets, hybrid magnets.

I. INTRODUCTION

THE Compact Linear Collider (CLIC) is an electron-positron linear collider project for a maximum center-of-mass energy of 3 TeV and very high accelerating gradient of 100 MV/m. In order to produce a useful interaction rate with the maximum centre-of-mass energy, extremely small transverse beam dimensions at the collision point are required. This can be achieved with a final focus optics based on very strong magnetic quadrupoles. The most important focusing element is the last quadrupole (QD0) before the interaction point. This quadrupole shall be capable of producing a very strong field gradient to provide the required vertical beam size in the interaction point. A hybrid quadrupole magnet is proposed to provide the very strong field gradient.

II. REQUIREMENTS AND CONSTRAINS

Table I summarizes the geometrical and magnetic requirements for the QD0 quadrupole. The magnet shall provide a central field gradient of 575 T/m with a magnetic length of 2.73 m. A field gradient tunability of 20 % is required to allow energy scan over a limited range. Assuming the thickness of the beam pipe of 0.3 mm, the magnet bore diameter needs to be at least 8.25 mm. The integrated field gradient quality has to be better than 0.1 % inside a good field region (GFR) with radius of 1 mm.

The geometrical boundary conditions for the QD0 magnet depend on the layout of the CLIC interaction region (see Fig. 1). The incoming and outgoing beam lines cross at an

angle of 20 mrad and the outgoing (post-collision) vacuum pipe has a conical shape with a half opening angle of 10 mrad. The distance L^* from the downstream end of the QD0 magnet to the interaction point is 3.5 m [1]. All these facts limit the maximum horizontal dimension of the magnet to 70 mm.

Due to an extremely small vertical beam size of 1 nm r.m.s, any offset between the axis of the magnet and the beam trajectory leads to a displacement of the beam at the interaction point. Therefore, the quadrupole must be actively stabilized in the nm range. To achieve this goal of mechanical stability the vibration induced in and by the magnet itself should be minimized.

TABLE I REQUIREMENTS FOR THE FINAL FOCUS QUADRUPOLE

Parameter	Value
Nominal field gradient	575 T/m
Nominal integrated field gradient	1570 T
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%

Fig. 1. CLIC interaction region layout.

III. MAGNET DESIGN

A. Magnet Description

Fig. 2 shows a cross-section of the proposed design for the QD0 magnet, with the indication of the outgoing beam pipe position at the magnet end, $L^*=3.5$ m.

A conventional iron dominated quadrupole is at the basis of the design. As mentioned in the previous section, the space for the magnet is limited in the horizontal plane, but not in a

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A. Vorozhtsov is with CERN, 1211-Geneva, Switzerland, on leave from JINR, 141980-Dubna, Russia (phone: +41227677329; e-mail: alexey.vorozhtsov@cern.ch).

M. Modena is with CERN, 1211-Geneva, Switzerland (e-mail: michele.modena@cern.ch).

D. Tommasini is with CERN, 1211-Geneva, Switzerland (e-mail: davide.tommasini@cern.ch).

vertical one. Given this constraint, an “8” or “two leaves” structure of the magnet yoke was chosen.

Fig. 2. Magnet mechanical layout.

The main difference in the magnet design as compared to a conventional quadrupole is the presence of rare earth permanent magnet material placed between the iron poles.

This material is oriented to inject magnetic flux into or subtract from each iron pole, as it shown in Fig. 3, where the arrows indicate the direction of the easy axis of the permanent magnet material. It should be noted that the permanent magnets do not directly contribute to the field gradient in the magnet aperture. The magnetic flux due to the permanent magnets is directed to cancel the part of flux produced by the coils which does not contribute to the field gradient in the magnet aperture [2]. This reduces the saturation effects in the iron pole, making it possible to reach a field gradient about 35 % larger than it is available with a conventional quadrupole.

Fig. 3. Central region of the magnet, arrows indicate the direction of magnetization of the permanent blocks.

The central iron part of the magnet is made of a single piece: a ring-like structure links the four poles and the permanent magnet blocks are inserted into the corresponding slots between the iron poles. This design enhances the magnet mechanical rigidity, simplifies the assembly procedure and reduces potential assembly errors and the resulting random multipole errors. A drawback of this ring structure is the short-circuiting of some magnetic flux that causes a reduction of gradient inside the magnet aperture by approximately 4% with compared to the non-ring configuration. In order to achieve higher gradient values, the central part of the magnet is made of “permendur”, a CoFe alloy characterized by a very high saturation level of 2.35 T.

The return yoke consists of two C-shape pieces. Low carbon steel AISI 1010 was chosen as a return yoke material for reason of cost, availability and ease of machining.

The coils are made of square enamelled solid copper wire with the cross-section of 4 mm × 4 mm. Each coil consists of 364 turns (18 layers of 18 turns). To avoid demagnetization of the permanent magnet materials by the opposite field generated by the coils, operation of the magnet is limited to 15.4 A, that corresponds to 5000 A of current-turns product (NI). In operation at maximum current, a current density of 1.0 A/mm² is assumed. This avoids the use of an active water cooling system and allows minimizing the vibration of the magnet.

Varying the current from zero to 15.4 A corresponds to varying the field gradient between 100 T/m to 530 T/m for Sm₂Co₁₇ and 170 T/m to 590 T/m for Nd₂Fe₁₄B that permits a wide tunability of the magnet.

B. Field Computation

Magnetic field calculations of the quadrupole were performed with the Opera-2D/ST and Opera-3D/TOSCA programs [3]. The basic parameter study was performed with the 2D code. The wedge angle of the pole and permanent blocks and yoke cross-section were optimized by this calculation in order to achieve the required field gradient value and field quality.

Due to symmetry only 1/4 of the magnet geometry was modeled (see Fig. 4). The boundary conditions were chosen in a way that the flux lines were perpendicular to the horizontal and the vertical middle planes and parallel to the limiting edge of the model. The coils are modeled as square region with a total applied current density equal to the ampere-turns of the coil divided by the total cross section of the coil. The effect of the spacing between individual conductors was neglected.

Fig. 4. Magnetic flux distribution in a 1/4th segment of the magnet.

The simulations were performed for two types of permanent magnet material: Sm₂Co₁₇ with a remanence B_r of 1.1 T and coercivity H_{CB} of 820 kA/m, and Nd₂Fe₁₄B with a remanence B_r of 1.28 T and coercivity H_{CB} of 990 kA/m.

Fig. 5 gives the curve of field gradient versus (NI) for both types of permanent magnet materials. Since the permanent magnet material preloads the iron poles, the curve becomes asymmetric, allowing much higher field gradient for the positive current than for the negative current.

It is shown that at NI=5000 A the magnet core is close to saturation and further increasing the excitation current is not efficient. Another reason to limit the maximum current is a risk of demagnetization of the permanent magnet as mentioned above.

Fig. 5. Field gradient as a function of current-turns product (NI) for two types of the permanent magnet materials.

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 1 mm (good field region boundary) (see Fig. 6). The field gradient error stays below $\pm 0.01\%$ inside the good field region (see Fig. 7).

Fig. 6. Normal field components with respect to the main B_2 for two types of the permanent magnet materials.

Fig. 7. Field gradient error [%] at GFR boundary with radius of 1 mm.

The OPERA-3D model with the field distribution on the surface of magnet is shown in Fig. 8 and Fig. 9. In the model, the yoke has only a length of 300 mm, compared to the actual yoke length of 2730 mm, because it is mainly used to study the end effects. The simulations were performed at 5000 A of (NI) for two types of the permanent magnet materials $\text{Sm}_2\text{Co}_{17}$ and $\text{Nd}_2\text{Fe}_{14}\text{B}$.

The field gradient values at $Z=0$ mm, obtained from 3D model, agree with the 2D results. The field gradient distribution along the z -axis is shown Fig. 10. The integrated harmonic amplitude values were obtained from the model calculations by Fourier analysis of the radial field component B_r integrated on a cylindrical surface with radius of 1 mm and a length $L=500$ mm ($-250 \text{ mm} < z < +250 \text{ mm}$) (see Fig. 11). The integrated field gradient error stays below $\pm 0.03\%$ inside the good field region (see Fig. 12).

Fig. 8. Opera 3D model view.

Fig. 9. Opera 3D model view (central part). The arrows indicate the field direction.

Fig. 10. Field gradient distribution along the z -axis at $\text{NI}=5000$ A.

Fig. 11. Normal integrated field components with respect to the main $\int B_2 dz$ for two types of the permanent magnet materials at $\text{NI}=5000$ A.

Fig. 12. Relative integrated field gradient error [%] at GFR boundary $r=1$ mm.

IV. MODEL CONSTRUCTION AND FIRST TEST RESULTS

In order to verify the conceptual design, tolerances on integrated field strength and to study the assembling procedure, a prototype model with full-scale cross-section, working at nominal conditions, but with much shorter yoke length of 100 mm, has been designed and is currently under construction. The mechanical layout of the prototype is shown in Fig. 13.

Fig. 13. QD0 prototype mechanical layout.

The hybrid quadrupole prototype needs four permanent magnet assemblies of 100 mm length; each consists of four permanent blocks of 50 mm length glued together. The permanent magnets blocks made of VACOMAX 225HR ($\text{Sm}_2\text{Co}_{17}$) and VACODYM 655HR ($\text{Nd}_2\text{Fe}_{14}\text{B}$) were supplied by Vacuumschmelze, Germany [4].

The permendur part of the quadrupole structure was machined by wire EDM to a tolerance of $\pm 25 \mu\text{m}$. The selected material for this part was VACOFLUX 50 by Vacuumschmelze [5].

The permanent magnet assemblies were inserted between the iron poles. A specific assembly device to guide the permanent magnets into the corresponding slots was designed and built.

The magnetic properties of the permanent magnets blocks as well as the $B(H)$ curve of the VACOFLUX 50 were measured by the supplier and found consistent with the properties as listed in the technical documentation.

The production of the 4 coils is under completion at CERN and the magnet will be fully assembled in the next months.

The magnet was magnetically measured by stretched wire system in the configuration with only the central part of the structure assembled as shown in Fig. 14. In order to compare the measured and calculated results, the OPERA 3D model of this partial assembly was also computed (see Fig. 15).

Fig. 14. The central part of the quadrupole (permendur) with the permanent magnet $\text{Sm}_2\text{Co}_{17}$ inserts.

The measured results compared with the calculation are plotted in Fig. 16. It was shown that the measured integrated field gradient and the integrated field harmonics are in good agreement with the computed values.

Fig. 15. OPERA 3D model showing only central part of the magnet assembly.

Fig. 16. Measured and Calculated results of the central part of the magnet assembly.

V. CONCLUSION

The design of the final focusing quadrupole magnet for CLIC and the status of the prototype model were presented. The magnet design was verified by the FEM calculation, which showed that the required field gradient value can be achieved using the permanent magnet material $\text{Nd}_2\text{Fe}_{14}\text{B}$ and about 45 T/m less than the required value with the $\text{Sm}_2\text{Co}_{17}$. However, the $\text{Sm}_2\text{Co}_{17}$ could be more favorable due to its radiation hardness and weaker temperature dependence. The final decision concerning the permanent magnet material type will depend on final lattice design retained for the final focus and on technical reasons.

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