A Conduction Cooled High Temperature Superconductor Quadrupolar Superferric Magnet, Design and Construction

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Abstract. The paper presents the prototype of an YBCO superferric quadrupolar magnet for high gradient magnetic field generation, design and construction. The temperature of the superconducting coil has to be kept within safe limits or the HTS would exit the superconductive state. Of particular concern is the „warm” beam tube that passes through the magnet. Cryogenic conduction cooling with a closed cycle G-M Cooler may ensure the removal of the ambient heat influx. Numerical simulation results on the magnetic field and heat transfer problems are then discussed. The computational domain is abstracted out of the CAD design of the system. The design solution is presented and compared with the numerical simulations results.

1. Introduction

Recently, superferric magnets are considered for replacing the copper coils with superconductor windings, a technology is used more and more in the fabrication of high-energy particle accelerators such as dipoles and quadrupoles especially. In particular, quadrupoles have a specific task in shrinking the particles beam size. Usually either NbTi or Nb3Sn superconductors are used, but they have to be cooled by liquid helium to 4.2 K or even lower. The advantages of the HTS coated conductors, like YBCO tape, are the high critical current density at higher magnetic field while operating at a higher temperature (30-77 K). These features recommend their usage in the construction of magnets for either high magnetic field density or high magnetic field gradients.

On the other hand, the increased performances of the closed cycle cryocoolers make them sound solutions for the cooling of the superconducting field windings even the entire magnet, avoiding thus cryogens consumption. In this respect, the HTS coil – cryocooler combinations may provide for a new promising architecture of the magnets for particle accelerators.

From the designer perspective, the use of high temperature superconductors (HTS) in particle accelerators of higher energy raises concerns addressable, in the conception phase, through mathematical modeling and numerical simulation. This approach may unveil the magnetic field quality and the heat transfer paths within the structure. Along this line, the present work presents a quadrupole superferric magnet (QSM) prototype for high gradient magnetic field (~30 T/m in the central zone). The HTS coils are made of coated YBCO tape in double pancake design. The end parts
of the coils are racetrack shaped. The profile of the iron yoke is optimized for the magnetic field quality at required field gradient. The superconducting coils are cooled with a Gifford – McMahon cryocooler (GMC) [5]. Numerical simulation is used to solve for the magnetic field and the thermal transfer under steady state operation. The main outcomes are the magnetic field profile and quality and to evaluate accurately the thermal loads for the cryocooler. At this stage we report only design results used in the construction phase. Experimental validation makes this object of a future report.

2. The Quadrupolar Superferic Magnet System – Design and Construction

The first design concern is the magnetic field gradient. Mathematical modeling and extended numerical simulations were performed to optimize the pole profile with the aim to produce high quality field gradient in the central bore of the magnet. The magnetic field is produced by two HTS double pancake racetrack shaped coils per pole. The second objective is the thermal optimization to ensure adequate working conditions for the superconducting coils [1, 2]. A thorough thermal optimization of the system is needed because of the limited power of the cryocooler.

A simplified CAD geometry (Figures 1, 2) was used as computational domain. The HTS coils are made of YBCO tape [3]. Table I summarizes the main parameters of the tape and the magnet system.

| HTS tape | QSM system |
|----------|------------|
| Value    | Value      |
| Units    | Units      |

| HTS tape  | Value | Units |
|-----------|-------|-------|
| Width     | 4     | mm    |
| Thickness | 0.11  | mm    |
| Critical current | 120  | A     |
| Critical bend diameter | 11   | mm    |
| Overall size            | 280 × 450 × 630 | mm |
| Magnetic field gradient | 33.97 | T/m |
| Coils dimensions:       | 144 × 54 × 12 | mm |
| - turns per pancake     | 30    | -     |
| - field current         | 90    | A     |

The current leads – a copper / HTS combination – are thermally connected to the first stage of the cryocooler (50 K) [2, 8]. The estimated cryogenic heat loads are summarized in Table II.

| Heat flux rates [W] | 1\textsuperscript{st} stage | 2\textsuperscript{nd} stage |
|---------------------|-----------------------------|-----------------------------|
| Conduction heat transfer in the current leads | 18.5 | 1.26 |
| Heat conduction through measurement wires | 0.31 | 0.12 |
| Heat conduction through mechanical supports | 2.0 | 3.5 |
| Heat transfer through radiation | 16.5 | 0.1 |
| Total thermal load | 37.31 | 4.98 |

The magnetic yoke of the magnet is made of bulk iron (99.08 % iron content by atomic spectroscopic analysis), machined to the shape shown in Figure 4. The inner diameter is 40 mm, the outer diameter is 160 mm, and it weights ~10 kg. Total losses for this type of iron were 0.34 W/kg measured at 2 Hz, so this contribution to the heat load of the cryocooler is small enough. However, in this study we are concerned with the steady state only (DC operation of the magnet), which is consistent with a slow ramping operation. The cryostat, made of stainless steel, is T-shape to meet two main conditions: magnetic field structure and access to the warm bore, and magnet thermal stability.
3. Mathematical and Numerical Modelling of the Magnetic Field and Heat Transfer

In the superconducting state the Joule effect is null therefore the magnetic field and heat transfer problems are uncoupled, and they may be solved separately.

The magnetic field problem is defined through

\[ \nabla \times \mu_0^{-1} \nabla \times A = J_z^e, \]

where \( A \) [T/m] is the magnetic vector potential, \( J_z^e \) [A/m^2] is the external electrical current density (in the windings), \( \mu_0 = 4\pi \times 10^{-7} \) H/m is magnetic permeability of vacuum, and \( \mu_r \) is the relative permeability. Magnetic insulation boundary conditions (BCs) close the problem. The problem was FEM solved [6]. The total current, \( I_0 \), is an input parameter (10…400 A). Figure 8 shows the magnetic flux density and the relative permeability in the iron yoke for the optimal external current \( (I_0 = 90 \text{ A}) \). Figure 9 depicts the magnetic flux density versus \( I_0 \), 15 mm away from the center.

Conduction heat transfer is governed by

\[ \nabla \cdot (-k \nabla T) = 0, \]

where \( T \) [K] is the temperature, and \( k \) [W/(m·K)] is the thermal conductivity. The BCs are as follows: \( -n \cdot (-k \nabla T) = h(T_{inf} - T) \), where \( h \) [W/m^2K] is the convection heat transfer coefficient for the shell (convection to the ambient) and \( T_{inf} \) [K] is the ambient temperature; \( -n \cdot (-k \nabla T) = 0 \) for the symmetry plane (adiabatic); \( T = T_0 \), \( (1 - \varepsilon)G = J_0 - \varepsilon \sigma T^4 \), where \( \varepsilon \) is the surface emissivity [1, 2, 7], for the shields, \( T_0 \) [K] is the mutual surface temperature, \( \sigma = 5.67 \times 10^{-8} \) W/(m^2K^4), \( G \) [W/m^2] is the incoming radiation heat flux, or irradiation, and \( J_0 \) [W/m^2] is the surface radiosity. Surface-to-surface radiation conditions were set for
different temperature surfaces that can “see” each other. Insulation conditions were set for negligibly small areas, e.g. the rims. The temperature of the cooling heads was set at 65 K for the first stage and 10.2 K for the second stage, in compliance with the cold head capacity map of the crycooler.

4. Results and Conclusions

Numerical simulations reveal the magnetic field and the heat transfer paths within the quadrupolar HTS-YBCO superferric magnet for particle accelerators prototype that we designed and fabricated. The results compare well with preliminary available experimental data: the magnetic flux density gradient obtained for optimal current, of 90 A, is 30 T/m, and the peak value in the iron yoke is 1.6 T; the heat loads to the G-M crycooler resulting from numerical simulations are ~5 W for the second stage and ~37 W for the first stage. It may be concluded that the cooling system will keep the coils at 10 K and the thermal shield at 65 K. In this stage the magnet is built. Cooling and functional tests are planned in the next period of time.

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References

[1] A.M. Morega, I. Dobrin, and M. Morega, “Thermal and magnetic design of a dipolar superferric magnet for high uniformity magnetic field”, Proceedings of The 7th International Symposium on Advanced Topics in Electrical Engineering – ATEE, May 12-14, Bucharest, pp. 589-592, 2011, IEEE no: CFP1114P-PRT, ISBN 978-1-4577-0507-6.
[2] A. M. Morega, I. Dobrin, A. Nedelcu, M. Morega, „A Quadrupolar Superferric Magnet”, Proceedings of The 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 24-26 May 2012, Brasov, Romania, ISBN 978-1-4673-1653-8/12. IEEE Xplore.
[3] SuperPower Inc., http://www.SuperPower-Inc.com
[4] J. Shi, Y. Tang, et al., “Development of Conduction Cooled HTS SMES”, IEEE Trans. on Applied Superconductivity, vol. 17, pp. 3846-3850, 2007.
[5] Sumitomo Inc., http://www.shicryogenics.com
[6] Comsol Multiphysics AB, Sweden, v. 3.5a (2010), v. 4.2a (2012), v. 4.3 (2013).
[7] A. Bejan, Heat Transfer, John Wiley & Sons, Inc., N.Y., 1993.
[8] HTS-110 Co, http://www.hts-110.nz/current_leads