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Construction of the CERN Fast Cycled Superconducting Dipole Magnet Prototype

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Abstract— CERN is pursuing a small scale R&D on a fast cycled superconducting dipole magnet (FCM) of interest for the upgrade plan of the LHC accelerator complex. The FCM dipole prototype being built has a number of novel features if compared to other magnets for similar applications. In this paper we describe the magnet design, and its expected performance, focusing especially on the novel features (magnetic circuit, mechanical supports, cooling) and on the details of the manufacturing procedure (coil winding and impregnation, joints, instrumentation and quench protection).

Index Terms—Superconducting accelerator magnets, Fast cycled magnets, Superferric magnets.

I. INTRODUCTION

THE Fast Cycled superconducting Magnets (FCM) R&D program that was launched at CERN in 2007 [1] is coming to an end with the construction of a FCM dipole prototype that should be completed by the end of 2011. With a maximal field bore of 1.8 T provided through the pole yoke and with field ramp rates of ± 1.5 T/s the FCM model targets a field range usually held by normal conducting magnets.

The magnet prototype, which features Nb-Ti coils operating at 4.5 K and encased in a warm iron yoke, is a short model of a 3 m-long magnet that was originally designed in the framework of the CERN-PS2 accelerator upgrade study [2]. With estimated overall cryogenic loss around 5 W per meter of magnet, where AC loss have been calculated considering the PS2 operating cycle shown in Fig. 1, the proposed design was shown to be economically advantageous if compared to an option based on conventional normal conducting magnets [2]. The overall cost reduction brought by the superferric option stems from the substantial long-term energy saving during operation.

If compared to other existing superferric magnets, the CERN-FCM has the unique particularity of having a warm iron yoke. This is a huge advantage since the AC loss in the yoke (eddy current and hysteresis losses), which can be significantly large compare to other AC losses, does not add to the refrigerating load. For instance, at the early stage of the development of the GSI SIS-100 superferric dipole, which features comparable magnetic performances than the FCM but

has a 4.5 K iron yoke, the yoke accounted for more than 70 % of the total AC loss [3].

In this paper we discuss design and construction issues that had to be taken into account in order to obtain a technologically feasible, economical to build and operate, and reliable FCM magnet. After a brief description of the magnet design and of its main parameters we will discuss in detail the design of its four main components that are: the coils, the coil support, the thermal screen, and the cryostat.

The goal of the demo magnet is to characterize the performance limits, to address issues such as long term reliability and fatigue, and to prove that this design is an economically viable alternative to normal conducting magnets. To do so, the prototype will be instrumented accordingly and will undergo an extensive test program which will be carried out at CERN in 2012.

Fig. 1. Reference operating cycle used for the estimation of AC losses [2].

II. MAGNET DESIGN AND PARAMETERS OVERVIEW

A. General Considerations

The main parameters of the superconducting FCM prototype model are summarized in Table I.

TABLE I. MAIN PARAMETERS OF THE FCM

Central field	1.8	T
Field ramp rate	± 1.5	T/s
Operating temperature	4.5	K
Nominal current	5.8	kA
Gap height	70	mm
Yoke length	760	mm

The iron yoke, responsible for the strength and homogeneity of the magnetic field in the pole gap, is magnetized by means of two ten-turns superconducting coils that are wound from cable-around-conduit conductor based on Nb-Ti strands. The two coils are installed in a common stainless-steel structure that can withstand the electro-magnetic forces generated in the winding (see Fig. 2). Note that the coil is placed high behind

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the pole in order to reduce its exposure to beam radiation. Around the coils is placed a 50 K thermal screen that will limit the heat radiated from the cryostat. The coil support structure, which is actively cooled at 4.5 K, is attached to the 300 K cryostat by means of eight 8-mm invar rods that are insulated from the support by means of fiber-glass spacers. The heat input brought by conduction through the rods and the spacers is estimated to about 3 W, which represents approximately 60% of the total heat load of the magnet. Finally, the cryostat is encased in a 0.76 m-long and 1.17 m-wide warm iron yoke. Another interesting feature of this magnet is that the beam pipe is completely separated from the 4.5 K environment, thus avoiding thermal loads (beam loss, eddy currents) and allowing direct access even with a cold magnet.

Fig. 2. 3-D (left) and cross-sectional (right) views of the FCM demonstration dipole magnet.

B. Coils Cooling and Powering Scheme

A schematic view of the electrical and cooling circuit of the FCM coils system is shown in Fig. 3. The two coils are electrically connected in series, but are in parallel from the cooling point of view to decrease hydraulic impedance.

Fig. 3. Electric and cooling circuit for the two coils.

C. Superconducting cables

A superconducting cable, based on the cable-around-conduit concept that was originally developed for the Nuclotron [4], has been further developed for the CERN-FCM magnet. It consists of an internally cooled Cu-Ni pipe featuring inner and outer diameter of 5 mm and 6 mm respectively, around which are twisted 0.6-mm Nb-Ti strands. The strands are held against the pipe by means of a tight Ni-Cr wire wrap. Two cable variants, named FCM001 and FCM002 and made from two different strands that differ from the matrix composition and the diameter of the filaments, were manufactured and successfully tested at CERN [5]. A third cable, named FCM003 and made of a variant of the cable FCM002 built during the development of the cable and featuring 32 strands instead of 33, will also be used for the coils of the FCM. Recently, the AC loss of the cable (hysteresis and eddy current losses) has been characterized at the University of Twente [6]. Table II reports the main cables characteristics. The peak field

in the coil, which is located in the innermost turn of the winding as visible in Fig. 4, has been calculated to 1.08 T. This value sets the magnet working point (5.8 kA, 1.08 T, and 4.5 K) relatively far from the cable critical surface. Indeed, the ratio between the operational current (5.8 kA) and the critical current (defined for a resistivity of 10^{-14} Ω m) is respectively 0.20, 0.29 and 0.30 for the FCM001, FCM002 and FCM003 cables. These comfortable current margins, which translate to appreciable temperature margins, should allow reliable operation of the magnet.

TABLE II. MAIN CHARACTERISTICS OF THE CABLE VARIANTS MANUFACTURED

Cable		FCM001	FCM002	FCM003
Strand $\varnothing$	(mm)	0.6		0.6
Filament $\varnothing$	(μ m)	4		2.6
Matrix composition Cu:CuMn:Nb-Ti	(-)	1.62:0:1	2.39:0.47:1	
Nb of strand	(-)	32	33	32
Cable I_c (4.5 K, 1.08 T)	(kA)	28.8	20.1	19.5
Temperature margin (4.5 K, 5.8 kA 1.08 T)	(K)	3.41	3.02	2.98

Fig. 4. Field in the coil in [T] when the current is set at its maximum value (5.8 kA). The 32 or 33 strands of the cable are modeled here as a ring.

D. Thermal Loads at 4.5 K

The static and dynamic heat loads that add to the refrigeration load are listed in Table III. Dynamic heat loads have been estimated assuming the operating cycle of the PS2 shown in Fig. 1. The total expected loss for the magnet is about 5 W.

TABLE III. ESTIMATED POWER LOSSES IN [W] AT 4.5 K

Cable	FCM001	FCM002	FCM003
Cable hysteresis losses	0.38	0.15	0.15
Cable eddy current losses	0.56	1.05	1.02
Coil support (eddy current)		0.52	
Supporting rods ($\times 8$)		~ 3	
Thermal screen radiation		0.10	
Electric connections ($\times 4$)		0.22	
Total (W)	4.78	5.04	5.01

III. DESIGN OF THE MAIN MAGNET COMPONENTS

A. Coil

The fabrication of the two-layer/five-turn coils for the FCM prototype was done at CERN. In total, nine coils were built out from the three cable variants. Six of them had a fiber-glass insulation scheme, and three had a composite Kapton/fiber-glass insulation. The reason was to reinforce the insulation to better resist wear and tear during winding, as observed on three fiber-glass coils that had shorts during manufacturing.

Finally, for the test of the magnet we dispose of three sets of two coils built from the three cable variants.

For practical considerations, the coil is wound started from the outermost layer so that the cable entrance and exit are both located on the outer side of the coil. Fig. 5-left shows the coil during the winding. The mechanical stiffness of the winding is then obtained by impregnating the coil with the Epoxy resin CTD-101. This resin was chosen for its high fluidity which allows a good penetration of the resin inside the coil, and also for its good radiation and cryogenic temperature resistance. Note that during the winding it was observed that the FCM002 cable, which is made of 33 strands, had more mechanical elasticity than the two other cables that feature 32 strands, thus making the winding more difficult.

The coil is 1300 mm long, 600 mm wide, and has a cross-sectional area of $45 \times 20 \text{ mm}^2$ (see Fig. 6). In Fig. 5-right it is shown the coil in the mould (left) and after impregnation (right). Note that the positioning of the conductor in the coil does not need to be well controlled since the field is provided through the yoke.

Fig. 5. Left: manufacture of the coil. Right: FCM's coil in the mould (left) and after impregnation (right).

Fig. 6. Cross-sectional view of the FCM's dummy coil. Irregularities visible on the contour are due to impregnation mould-related issue. They are not present on the superconducting coils manufactured afterward.

B. Coil Support Structure

For simplicity and flexibility reasons it was decided to decouple the magnetic design of the magnet from the mechanical one. This implies that the electromagnetic forces that arise in each leg of the coil, and that can be as large as 1.26 ton in the horizontal plane and 0.6 ton in the vertical one, have to be entirely taken by the coil support structure. The ideal material for the coil support would be a very resistant composite material (e.g. carbon fiber-based composite) which would provide the required stiffness but avoid eddy currents that are driven by the field changes in the proximity of the coil. However, for economical and time constraints reasons we have chosen 316 LN stainless-steel. Consequently, the design of the coil support had to satisfy conflicting requirements of mechanical rigidity and low heat generated in its core by the time varying magnetic field. The final design of the coil support is shown in Fig. 7, and a picture of one leg being fabricated is shown in Fig. 8 (middle). The maximum

deflection of each leg of the coil support is 0.7 mm (1.4 mm in total as shown in Fig. 7), and the energy dissipated due to eddy current over a period is estimated to 0.52 W. The latter is removed by means of a 4.5 K cooling pipe welded to the structure. Electric insulation sheets placed in between all the different parts that compose the support prevent eddy current from running in a close loop along the steel structure. Without them, the average dissipated power would be as large as 570 W. Note that the holes drilled in the structure and visible in Fig. 7 do not aim at reducing the power dissipated but have been implemented to reduce the thermal mass to be cooled-down at negligible loss of mechanical rigidity.

Fig. 7. Deformation of the coil support due to Lorentz forces and at 5800 A. The center of the left leg is taken as reference for the displacement.

C. Thermal Shield

The 50 K thermal shield is placed in between the cryostat and the coil so to shield the coil against heat radiated from the cryostat. Like for the coil support, the choice of the material for the thermal shield has conflicting requirements. Indeed, on one hand a good thermal conductivity is needed to have a uniform temperature of the thermal screen, while on the other hand a low electric conductivity would lead to large eddy currents and large electromagnetic forces that would weaken the magnet reliability over time. Stainless-steel was chosen because of its large electric resistivity compare to materials like Cu and Al. As for the coil support, the thermal screen is made of several pieces insulated from each other so to break eddy current from running in a close loop around the pole. Fig. 8-left is shows the parts of the thermal shield being fabricated.

Fig. 8. Some elements of the FCM magnets (left: central part of the cryostat, middle: element of the coil support, right: elements of the thermal screen).

D. Demountable Electrical Connections

The need for flexibility and rapidity to test the different coils in the magnet led to the development of a demountable electrical connection with low resistivity for cable-around-conduit conductor. The main component of the connection is a piece of copper that fits to the round cable and that provides a

flat surface on one side. Fig. 9 shows a connection prototype. It is composed of two cable/copper piece assemblies clamped together and separated by a thin indium foil. The difficulty to provide connection with a resistivity that approaches the theoretical value of $2.5 \text{ n}\Omega$ was to make a good soldering joint between the cable and the copper piece (no air bubbles, no flux residuals). The soldering process has been continuously improved, and we have presently reached reproducible connections with $4 \text{ n}\Omega$ resistance at 5 kA and 4.2 K , which is appropriate for the magnet test conditions.

Fig. 9. Left: demountable electrical connection developed for cable-around-conduit conductor (a former version of copper pieces is used here). Right: cross-sectional cut of the final connection.

IV. QUENCH PROTECTION SYSTEM

The main issue in protecting fast-ramped superconducting magnets lies in the difficulty to detect the voltage rise due to a quench, typically a few 100 mV , in a large induced background voltage. In our case, the voltage induced across a coil during a field ramp of 1.5 T/s is as large as 4.3 V . The quench detection method we are considering for the FCM prototype consists in balancing the induced voltage by means of a co-wound wire made of copper that will see the same flux variation as the superconducting coil. The co-wound wire is visible in Fig. 5. A quench analysis study for this magnet had already been performed with the THEA code [7]. In order to keep the hot spot temperature in safe limits, typically within 100 K , the detection time has to be smaller than 0.07 ms and the current dump time constant has to be of the order of 0.3 s [8]. This has been found to be possible with a realistic detection threshold set to 300 mV , and with a compensation of the inductive voltage to better than 1% , which should be easily reachable using the co-wound wire.

V. MAGNET INSTRUMENTATION AND TEST PROGRAM

The FCM prototype will be extensively tested with a dedicated test station, presently being fabricated at CERN, starting by the end of the current year. For that purpose the FCM will be instrumented with thermometers, voltage taps, strain and displacement gauges. The temperature of the supercritical He at the entrance of the each coil will be controlled by means of heaters. The goal of the test campaign is to characterize the magnet performance limits, measure heat load, and to assess its reliability over time.

The tests will start with zero current measurement so to measure the static heat load. Then, measurements performed with DC current will be carried out to characterize the quench current as a function of the temperature (4.5 K to 6 K). Subsequently, AC measurements will be performed in order to

characterize the quench current versus the current ramp rate (0 T/s to 10 T/s) and AC loss.

Once the performance limits of the magnet are characterized, the plan is to do a cycling test to assess the reliability of the magnet over time. Consequently, the FCM will be pulsed $\sim 5 \times 10^5$ times following the operating cycle of the PS2 accelerator. After this test the magnet will be disassembled for visual inspection of the magnet components.

Even if it is not the main purpose of the tests, the magnetic field in the magnet aperture will be measure both in DC and AC conditions to provide a benchmark for the design.

VI. CONCLUSION

A prototype of FCM magnet is being built at CERN as a technology demonstrator of a low-loss superferric dipole. The model will be equipped with Nb-Ti coils made of a novel cable-around-conduit conductor that was successfully tested and validated at CERN

The continuous improvement of the coil winding process and of the conductor insulation scheme led to the manufacture of a total of three sets of two coils, based on three cable variants, which will be tested in the magnet.

A number of design choices have been made for the design of this magnet: the cooling of the magnet is achieved with a forced flow of supercritical He at 4.5 K , the iron yoke is warm, the mechanical and magnetic design are decoupled, and the quench detection system is based on a co-wound wire that will balance the induced voltage across the coil. The advancement of the components fabrication, in line with the initial schedule, confirms the design choices for manufacturing.

The testing of the magnet, which should start by the end of 2011, should lead to interesting results in the following six month. If the energy-efficiency and reliability of this magnet is demonstrated, then FCM magnets will be a serious option for a future upgrade of the CERN injector complex.

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