Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 36 (2012) 818 – 823

Physics
Procedia

Superconductivity Centennial Conference

Novel ways of heat removal from highly irradiated superconducting windings in accelerator magnets

Erwin R. Bielert[a,b], Arjan P. Verweij[b], Herman H.J. ten Kate[a,b]

[a] *CERN, CH-1211, Geneva 23, Switzerland*
[b] *University of Twente, POB 217, 7500 AE, Enschede, the Netherlands*

Abstract

Novel ideas of heat removal from superconducting windings in accelerator type magnets are investigated with the help of a recently developed and validated thermal model of a magnet cold mass implemented in COMSOL Multiphysics. Here the focus is on how to improve heat removal from the midplane of a superconducting quadrupole magnet, the area exposed to the highest radiation heat load. In addition, this part of the coil windings has the longest thermal path towards the heat sink and several thermal design improvements proposed in the past are not very effective here. It is shown that with minor changes in the geometrical design, the cooling of the midplane conductors can be strongly increased.

---

1. Introduction

For a future luminosity upgrade of CERN's Large Hadron Collider, a substantially higher level of radiation heat load in the coil windings of the next generation inner triplet quadrupole magnets is expected [1]. Two main design choices can be made to guarantee stable magnet operation at this elevated luminosity. An obvious solution is to avoid the high energy deposition levels in the conductors by introducing thicker absorbers in between the beam and the windings, effectively shielding the superconducting cables [2]. To take full advantage of the absorbers, they need to be thermally decoupled

---

[a] Corresponding author.
E-mail address: erwin.bielert@cern.ch

doi:10.1016/j.phpro.2012.06.048

from the cold mass. The implementation of such a solution is, however, not straightforward. The space in the aperture is rather limited. A larger aperture does not come without additional technical challenges [3]. Another solution to reduce the energy deposition by radiation in the superconducting coil windings is by introducing a different layout of the conductors in the cross-section of the magnet. Coil layouts with an open midplane are proposed [4]. With an open midplane, the interaction with the high energy particles takes place in a warm part of the magnet, or in the structural materials of the cold mass, but not in the superconductors. However, the deposited energy still needs to be extracted from the cold mass.

The second design option does not focus on avoiding the volumetric heat load in the superconducting cables, but aims at effectively increasing the heat transfer between the cables and the heat sink. Several design options can be considered, but often competing objectives have to be balanced. Fig. 1 gives examples of an open midplane and the use of absorbers. As a starting point, the nominal design parameters of the LHC Phase-I upgrade for the so-called MQXC inner triplet quadrupole magnet are used [5]. A realistic value for the peak energy deposition in the conductors is about 15 mW/cm^3 when no absorber is used [2]. The beam pipe receives the highest heat load, shielding the conductors in the first and second layers in the windings. The assumption is made that the mass density of collar material and cables is the same, as well as the magnetic field. In this case the spatial energy deposition distribution does not change significantly when the conductors are tilted over a small angle. Furthermore it is assumed that the conductors are only tilted and that the layout of the coil has not changed. To meet the electromagnetic and mechanical specifications, the introduction of an open midplane implies, however, the need for a new conductor layout [6]. The expected steady state distributed heat sources are calculated using FLUKA [7] and can be analytically described by equation 1, where P is the power density in W/m^3, P_0 the peak power density found in the beam pipe, and the two exponential terms describe the azimuthal and radial dependencies. θ is the angle in degrees and θ_0 a fitting parameter, r the radius in m, r_i the inner radius of the coil inner layer also in m and r_0 a fitting parameter.

$$P = P_o e^{\frac{-\theta^2}{\theta_0}} e^{\frac{-(r-r_\mathrm{i})}{r_0}} \tag{1}$$

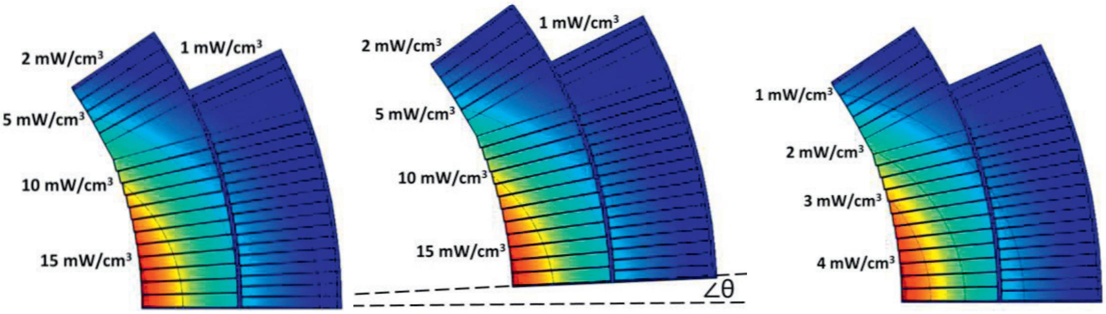

Fig. 1. (Left) Cross-section of the winding pack in the so-called MQXC quadrupole magnet, showing one eighth of the coil windings. Contour lines indicate the size of the distributed heat source. (Middle) The same energy deposition distribution in the case of an open midplane with an angle θ of 2.5 degrees, lower peak heat source in all conductors. (Right) The use of absorbers reduces the energy deposition in the cold mass, in this example with 71%.

A new design featuring an increased heat transfer instead of decreased energy deposition is favourable since the thermal analysis can be partially decoupled from the electromagnetic and mechanical design. With the introduction of additional heat removal channels in previously closed parts of the insulation, helium can more easily reach the conductors and cool them more effectively. Many years are spent to better understand the heat transfer through the cable insulation. This main thermal barrier between the superconducting cables and the heat sink has been thermally optimized, which has resulted in the so-called Enhanced Insulation [8]. Micro-channels filled with superfluid helium are introduced such that the effective thermal conductivity of the cable insulation is strongly increased. Improvements of the heat transfer can also be introduced by changes in the ground insulation plane [9] and the annular space between the inner layer of the coil and the beam pipe, as well as by decreasing the packing factor of the collar and yoke laminations [10]. Here, the focus is on removing heat from the midplane area, where in fact the highest radiation heat load occurs. Additionally, this part of the coil has the longest thermal path towards the heat sink. The thermal improvements mentioned before only partially help reducing the temperature excursions in the midplane conductors. However, also here improvements of the thermal design are possible, without interfering with the electrical, magnetic or mechanical design.

At a homogeneous bath temperature, the temperature margin of the midplane conductors is about 0.70 K higher than the margin of the pole conductors at an operating current of 12.6 kA, since the magnetic field peak value is located at the pole, see Fig. 2. The conductors are numbered from the midplane to the pole for each layer. The inner layer has 17 conductors, the outer layer 19. For low energy depositions in the coil windings, the assumption of a homogeneous bath temperature is correct. However, when higher energy depositions are taken into consideration, an inhomogeneous temperature distribution arises. The position of the conductor with the smallest temperature margin will depend on the distribution of the energy deposition as well as on the heat transfer within the coil windings, in combination with the magnetic field distribution. The energy depositions shown in Fig. 1 are used in combination with a cable insulation consisting of polyimide without micro-channels to show the importance of the cable-insulation. When the heat is extracted to the helium bath by solid conduction through a 169 μm thick layer of solid Kapton (~6×10^{-3} W/mK at 1.9 K), results show much smaller temperature margins for all conductors. From Fig. 2 it also becomes clear that 15 mW/cm^3 is present in the critical range for the LHC MB insulation, the advantage of the superfluid helium decreases strongly at depositions of 20 mW/cm^3 and higher because the temperature of the cable and of the helium in the micro-channels has reached the lambda transition temperature of 2.16 K. The enhanced insulation allows much higher energy depositions, if the small edges of the cable are in direct contact with a helium bath. This is not the case for the outer layer conductors, and only valid for one thin edge of the inner layer conductors.

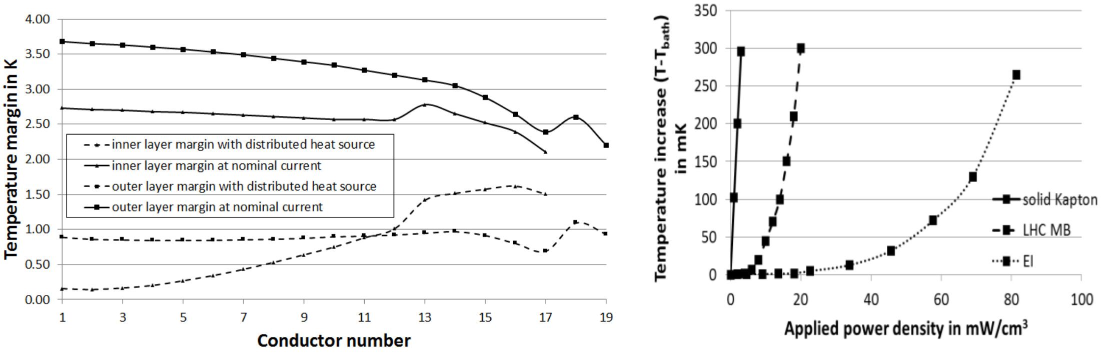

Fig. 2. (Left) Temperature margins for the inner and outer coil layer conductors for no heat load and distributed heat, when solid polyimide cable insulation with a thickness of 169 μm is used. (Right) Temperature increase versus applied power density for three different cable insulations.

2. Thermal model

Present inner triplet quadrupole magnets at the LHC are wound with Nb-Ti Rutherford cables. The critical surface of Nb-Ti introduces limits on the design of magnets. For high-current density, high-field applications, as is the case for high energy physics accelerator magnets, the temperature must be close to 2 K. At this temperature, superfluid helium (or rather He II) is used as a coolant. The extraordinary high thermal transport properties of He II allow fairly high energy depositions in the superconducting coil, without large temperature excursions arising. The thermal properties are strongly non-linear. The properties of superfluid helium are implemented in our thermal model using the Gorter-Mellink law for turbulent heat transport in Tisza's two-fluid model [11]. From this relation it becomes clear that the effective thermal conductivity of He II depends on the heat flux, see equation 2

$$q = -\left(\left(\frac{1}{|f(T)|}\right)^{\frac{1}{3}}\left(\frac{1}{|\nabla T|}\right)^{\frac{2}{3}}\right)\nabla T \qquad (2)$$

where q is the heat flux in W/m^2, $1/f(T)$ is the heat conductivity function in W^3/m^{5}K and T is the temperature in K. Therefore higher energy depositions decrease the heat extraction capabilities through superfluid helium and can cause temperature rises up to the lambda temperature. Once the lambda temperature is reached, helium will lose its almost perfect transport properties.

A thermal model including channels filled with superfluid helium is implemented in COMSOL Multiphysics [12]. Effective thermal conductivities are extracted from measurements of the so-called MB insulation, which is applied in LHC's main bending dipole magnets and the so-called Enhanced Insulation mentioned before. This insulation allows superfluid helium to penetrate into the micro-structure. All thermal barriers, which are introduced in the magnet design due to magnetic- , electric- or mechanical design criteria have to be minimized. However, because of these same criteria, the thermal design window is rather limited. Channels with cross-sections in the order of μm to mm can be introduced without interfering significantly with the electromagnetic and mechanical design.

3. Influence of midplane cooling on the temperature margin

To guarantee stable magnet operation, the temperature of the conductors needs to stay well below the current sharing temperature. The conductors in the inner coil layer are effectively cooled at the small edge face at the side of the beam pipe. The other small edge face is most often blocked by a quench heater, which is made of a stainless steel strip in between two sheets of Kapton. This means that there is no direct helium path between the coil inner and outer layers. With a closed ground insulation plane, an almost closed volume is formed for the coil outer layer. Besides opening the ground insulation and making use of a meandering quench heater [9], adding helium channels at the midplane of the coil can reduce the peak temperatures. Table 1 summarizes the twelve cases which are explored in this work.

Table 1. Cooling cases anaylzed

Cable insulation	Energy deposition	Midplane cooling
Solid Kapton	Nominal/2x Nominal	Yes/No
LHC MB	Nominal/2x Nominal	Yes/No
EI	Nominal/2x Nominal	Yes/No

Possible solutions include the introduction of a copper cooling fin, consisting of a fine structure to avoid induced currents or the addition of channels allowing helium to penetrate into the coil more easily. Here, a thin fishbone structure is proposed, which consists of a strip of G10 of 0.20 mm thickness. When it is machined such that the surface contains crossing channels of 0.10 mm deep and 1.00 mm wide every 3.00 mm, a 15% open structure is realized, which thermally connects the coil outer layer to the helium bath at the annular space between coil and beam pipe. Introducing midplane cooling should therefore always lead to an increased temperature margin of the midplane conductors in the coil's outer layer.

Figure 3 gives an overview of the numerically obtained results of the temperature margin for the cases defined in Table 1. Each of the plots shows a comparison between the different cable insulations and the impact of midplane cooling on the temperature margin. Dashed lines indicate the situation with midplane cooling, the full lines without. For clarity, the margins for the conductors in the coil inner layer and coil outer layer are split into two plots (top plots inner layer and bottom plots outer layer). Furthermore as indicated in Table 1, two levels of energy depositions are compared. The nominal energy deposition if no absorber is used (left plots) and the situation where the energy deposition is two times this value (right plots). Notice that some curves are hard to distinguish from another because they are overlapping. The reference at 12.6 kA shows the theoretical maximum margin without energy deposition (or infinite heat transfer), where the total structure is maintained at the bath temperature of 1.9 K.

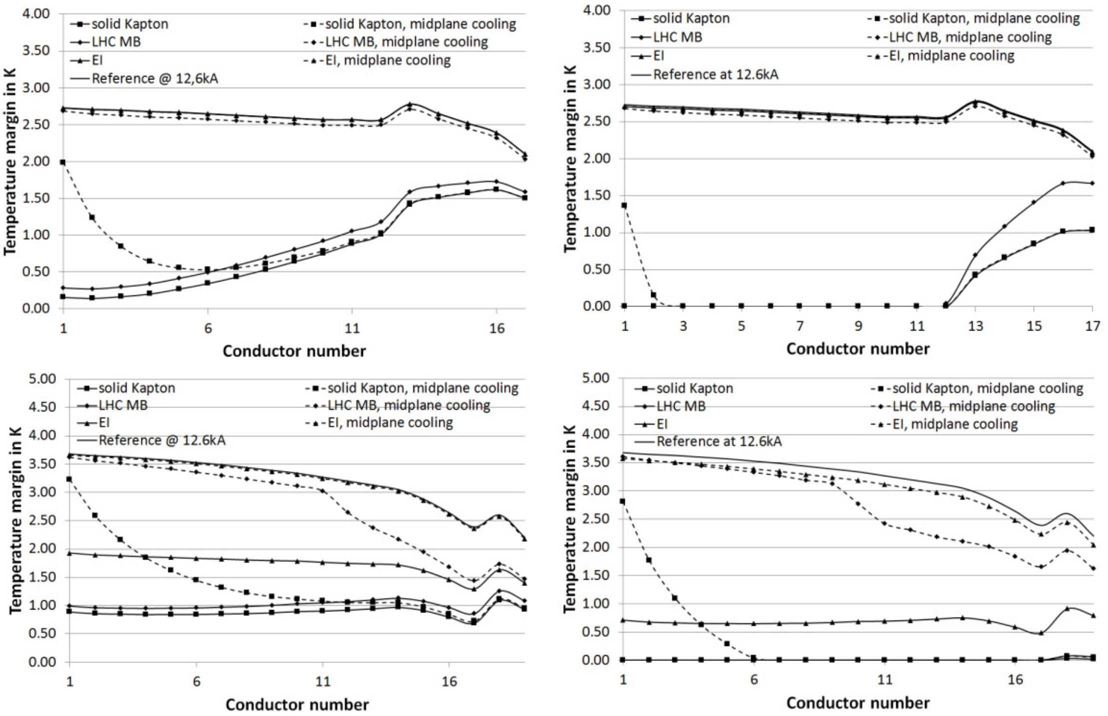

Fig 3. Overview of temperature margins. (Top left) Inner layer, nominal energy deposition. (Top right) Inner layer, 2x nominal energy deposition. (Bottom left) Outer layer, nominal energy deposition. (Bottom right) Outer layer, 2x nominal energy deposition.

As becomes clear from Figure 3, the combination of energy deposition, cable insulation and midplane insulation leads to quite different temperature distributions and thus temperature margins. In the top left plot it is shown that for nominal energy deposition, midplane cooling has a strong impact in the case of the LHC MB cable insulation. Midplane cooling allows all the coil inner layer conductors to stay more or less at the bath temperature, but without midplane cooling, the margin for the first six conductors drops below 0.50 K. For higher energy depositions (top right plot), without midplane cooling, the LHC MB cable insulation is not good enough as several inner layer conductors completely have lost their margin. With midplane cooling, the LHC MB insulation seems to be good enough, again increasing the margin to the maximum possible one, with the conductors at the bath temperature.

Although the energy deposition in the coil outer layer is much less than in the coil inner layer, the outer layer might still be critical in the thermal design, since the cooling is worse. The bottom left plot of Figure 3 shows that without midplane cooling the Enhanced Insulation can extract the energy from the cables quite effectively, the temperature margin of all coil outer layer conductors has decreased about

1 K, but the margin is still more than 1 K. Additional midplane cooling keeps all conductors at the bath temperature. When the LHC MB insulation is used in combination with midplane cooling, some of the conductors close to the pole are heated enough to reach the lambda transition temperature and therefore local heat transfer decreases strongly. A profound kink can be seen in the obtained margin curve. Without midplane cooling the temperature margin is about 1 K for all outer layer conductors.

The bottom right plot in Figure 3 shows the margins when the energy deposition is again increased a factor of two, but now for the outer layer conductors. In the case of LHC MB cable insulation, the margin of all conductors of the coil second layer is zero. Using the EI the average temperature margin is about 0.5 K. The influence of midplane cooling is clear: the heat transfer capabilities of the LHC MB insulation allow effective cooling of the midplane conductors, but the conductors positioned closer to the pole still see a temperature rise and again a kink is visible in the margin curve. Combining midplane cooling with the EI, also the conductors of the coil outer layer are kept close to the bath temperature.

4. Conclusion

From the presented results it has become clear that midplane cooling has the highest impact if the cable insulation is not permeable for superfluid helium, which implies that midplane cooling is an interesting cooling option for impregnated coils. It must be noticed that midplane cooling in the way it is proposed, only works when the annulus is maintained at the bath temperature.

Depending on the heat transfer properties of the cable insulation, a larger number of conductors can be cooled effectively by midplane cooling. If a solid Kapton insulation is used, only the first couple of conductors, counted from the midplane, have an increased temperature margin due to midplane cooling. In the case of using the enhanced (more open) cable insulation, almost all conductors are more effectively cooled by additional midplane cooling, because the micro-channels in the cable insulation itself are in more direct contact with the helium bath.

The coil should always be as open as possible to superfluid helium. Midplane cooling should be combined with other thermal improvements in the magnet design, like the enhanced cable insulation, open ground insulation, meandering quench heaters and the annular space between the inner layer conductors and the beam pipe must be left open. The same idea can also be applied next to the wedges to have a larger effective cooling surface of the cables in those parts of the coil windings as well.

References

[1] Rossi, L. LHC upgrade plans: options and strategy. *IPAC 2011,* San Sebastian, Spain, to be published

[2] Baglin, V., Ballarino, A., Cerutti, F., Denz, R., Fartoukh, S., Fessia, P. et al., *LHC Project Report* 1163; 2008.

[3] Rossi, L. Todesco, E. Electromagnetic design of superconducting quadrupoles. *Physical Review Special Topics-AB* 2006; **9.**

[4] Gupta, R., Anerella, M., Harrison, M., Schmalzle, J., Mokhov, N. Open midplane dipole design for LHC IR upgrade, *IEEE Transactions on Applied Superconductivity;* **14,** 2: 259-262.

[5] Russenschuck, S., "Parameter list for the MQXC quadrupole for the LHC inner triplet upgrade", https://espace.cern.ch/MQXC/Shared%20Documents/MQXC_Parameters.pdf,date accessed, Jan, 2011.

[6] Bruer, J. Open midplane designs based on sector coils in superconducting dipole magnets, 2008.

[7] Hoa, C., Mokhov, N., Cerutti, F., Ferrari, A. *LHC Project Note* 411, 2008.

[8] Granieri, P., Richter, D. Tommassini, D. Thermal Characterization of the Cable Insulation for the Nb-Ti HL-LHC Inner Triplet Model, *MT22*, Marseille, France, to be published

[9] Bielert, E.R., Ten Kate, H.H.J., Verweij, A.P., New 2D thermal model applied to an LHC inner triplet quadrupole magnet. *Proc. 23rd Int. Cryo. Eng. Conf.*, Wroclaw, Poland, 2011, pp. 1065–1070.

[10] Bielert, E.R., Ten Kate, H.H.J., Verweij, A.P., Effect of superfluid helium at the inner coil face on cooling and stability in superconducting accelerator magnets, *Adv. in Cryo. Eng.*, to be published.

[11] Van Sciver, S.W., *Helium Cryogenics*, New York: Plenum; 1986, p. 166-182

[12] COMSOL Multiphysics. Available: http://www.comsol.com