REQUIREMENTS ON SC MATERIALS, STRAND AND CABLE FOR THE FUTURE

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Abstract

This paper discusses a few aspects on magnet design, superconducting materials, filament dimension, strand current density, and topology of cable requested to face the high magnetic field for the future needs of CERN

1. INTRODUCTION

For its future needs, CERN will have to build magnets of various types depending on the domain of applications [1].

1. The most demanding are dipoles and quadrupoles having high field between 10 T and 15 T on the conductor and large aperture bores between 90 mm to 160 mm in lengths of circa 10 m. These magnets have a very high stored energy and are submitted to high energy particle losses inducing possible quenches. The heat deposition linked to beam losses are difficult to calculate but it implies that the operating field could be at 80 % of the maximum field. The temperature margin is a crucial value to be taken into consideration. This paper will consider only the maximum field allowable at the present time.

2. Another domain of application are superconducting accelerator magnets at field of 2 to 6 T but operated in a pulsed mode of 0.5 T/s to 5 T/s. The aperture bores and the lengths are respectively of the order of 100 mm and 10 m.

3. The accelerator application can use very long superconducting magnets at low field of 2 T. These magnets have a low cost but have many corrector winding to compensate the iron saturation. The past experience has shown that the lower cost per Tm can be obtained by using the superconducting material at the max field that the sc material can afford. This paper will not deal with the low field superconducting magnets.

The report will review some aspects of the magnet design and the requirements on the materials, strands and cables.

2. MAGNET DESIGN FOR HIGH FIELD AND LARGE APERTURES

2.1 Generalities on critical current densities.

The maximum bore fields in dipoles is proportional to the cable width and to the overall critical density in the coils. Taking into account the insulation thickness of the cables, it appears that to reach dipolar fields as high as 15 T, critical current densities in the non copper part of the order of 1500 A/mm^2, at 15 T, 4.2 K have to be accessible [2].

2.2 Limits of the layer cos θ magnet design

All the magnet structures, built for accelerators are based on the same general layout, called layer design (Fig. 1). They have been built with success for fields up to 10.5 T with NbTi [3] and up to 11 T and 13 T with Nb$_3$Sn [4, 5]. A design for a 88 mm aperture has been calculated and is presented below [2].

The coil aperture is 44 mm; there is 3 mm space between the two layers. The iron yoke is separated from the coils by an intermediate spacer (collars) of 25 mm thickness and is surrounded by a

28 mm thick stainless steel shrinking cylinder. The inner layer consists of 4 blocks of conductors while the outer is made of 3, adjacent blocks being distant from at least 2 mm. The iron yoke is 350 mm thick.

The critical current density in the non-copper area of the Nb_3Sn strand is assumed to be 1500 A/mm^2 at 15 T, 4.2 K. The copper to non-copper ratio is 1.25. The bore field as calculated is 14.4 T at 4.2 K for a maximum quenching field on the conductor of 15 T taking into account a cable degradation of 10 %. To reach 15 T in the aperture, the magnet has to be operated at 1.9 K.

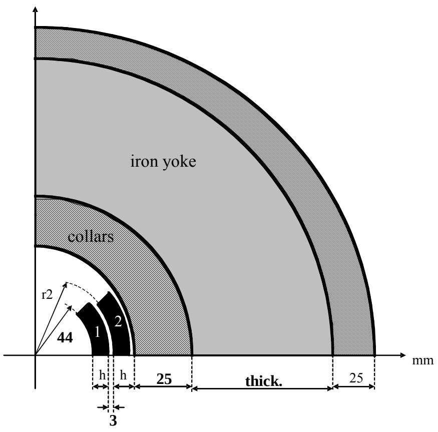

Fig.1 Magnet cross section (layer design)

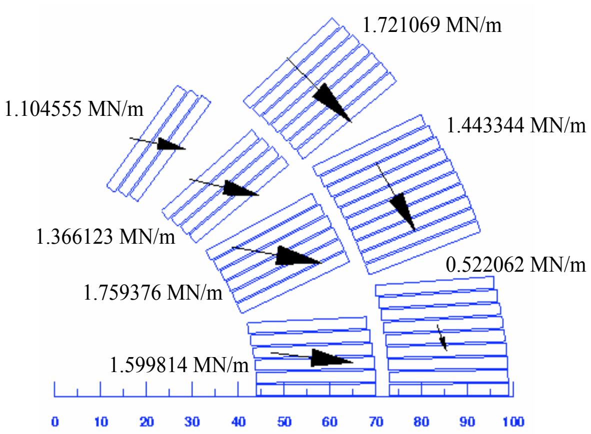

Fig.2 Magnetic force distribution

Fig 2 shows the distribution of the magnetic forces. The axial forces are as high as 1.8 MN for a stored energy of 1.8 MJ/m.

We do not know the limits of the layer cosθ magnet design. They offer a good field quality in large apertures but can be limited by compressive stresses that are maximum at the mid-plane of the layer. At 15 T, j=1500 A/mm^2, the magnetic compressive stresses are 150 MPa on the inner layer and 160 MPa on the outer layer in a 88 mm bore dipole. To the magnetic stresses, it has to be added the stresses due to the mechanical structure deflection under the main horizontal forces that vary from 7 MN/m to 15 MN/m when the field goes from 12 to 15 T. To keep the contact between the conductor and the mechanical support structure at the upper angle of the coil layer, a coil pre-stress of the order of 50 MPa has to be added during the magnet assembly and stays on the mid-plane conductor. It is known that the critical current density in the Nb_3Sn material is sensitive to stresses and degrades for stresses higher than 200 MPa. For the layer design, when the aperture goes from 88 mm to 130 mm and 160 mm, the maximum compression stress due to magnetic forces goes from 150 MPa to 215 MPa and 255 MPa. It seems that, with the high critical current densities in Nb_3Sn superconducting cables, the cos θ layer design could be limited to apertures of circa 90 mm if the degradation process is well understood and perhaps overcome.

2.3 Motor type design

In this design, the rectangular conductors are located in notches machined in a metallic structure (Fig. 3). The winding is performed by inserting the cables in the metallic structure, positioned horizontally with the notches open vertically.

The ends are rather difficult since the cable sees a hard bending. Passing from one notch to the other will take place in the ends where the conductor from the top of a notch goes to the bottom of the other notch.

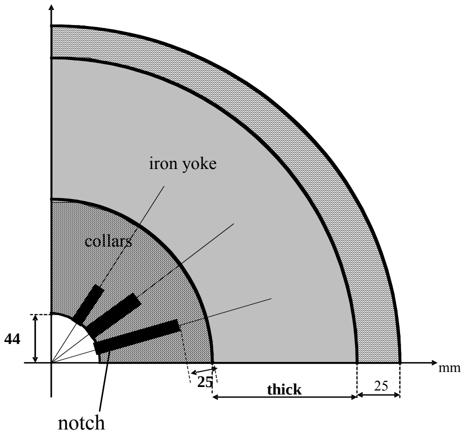

Fig. 3 Magnet cross section (motor type design)

This kind of winding in an open structure and not on a mandrel has already been made at LBNL (Isabelle) for a single layer design. A magnet using the slot design type has already been built at CEA Saclay [6] using a NbTi cable. Figure 4 shows a model magnet investigated at CEA Saclay. It needs a good and clever tooling. This type of approach could be made with the Nb_3Sn cables, which seems to be less "nervous" than the NbTi cables. After winding, the reaction and the impregnation could be performed in the same metallic structure, which becomes a mechanical support for the electro-magnetic forces. Due to the expansion of the Nb_3Sn at reaction, the conductor, located in the closed volume of the notch could need less pre-stress at assembly. Bladders could be incorporated in the notches to put a pre-stress if needed.

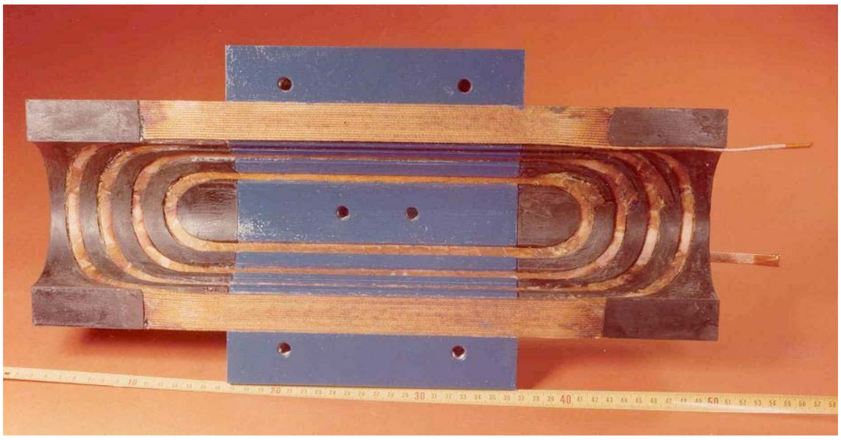

Fig.4 Model magnet built at CEA Saclay

The external mechanical structure would be the same as for the layer design. The two poles are associated by a lateral welding. The yoke is split horizontally and contained in a shrinking cylinder. Cooling of the deepest conductors could be made with copper drains.

In this design, the magnetic forces (Fig. 5) in each slot are radial and are better distributed on the external mechanical structure. The cable is submitted however to an hard bend in the ends of the winding, which is can be conceivable for large aperture dipole magnets. The maximum compressive stress due to magnetic forces stays in the vicinity of 140 MPa for apertures varying from 88 to 160 mm. This magnetic design is less efficient than the layer design. It leads to 13.8 T in the bore for a maximum quenching field of 15 T on the conductor.

A difficulty could be the quench protection for long magnets, which would require quench heaters incorporated in the notches. In this design, the inter-strand losses are reduced since the field is ~ parallel to the broad face of the cables. The quench back effect is then reduced except if the adjacent resistance between the strands of the cables is small.

The advantages of the motor-type design compared to layer design are: more free space on the mid-plane, and about twice more margin on the block closest to the mid-plane with respect to the upper block as in layer magnets, which could be interesting for beam losses.

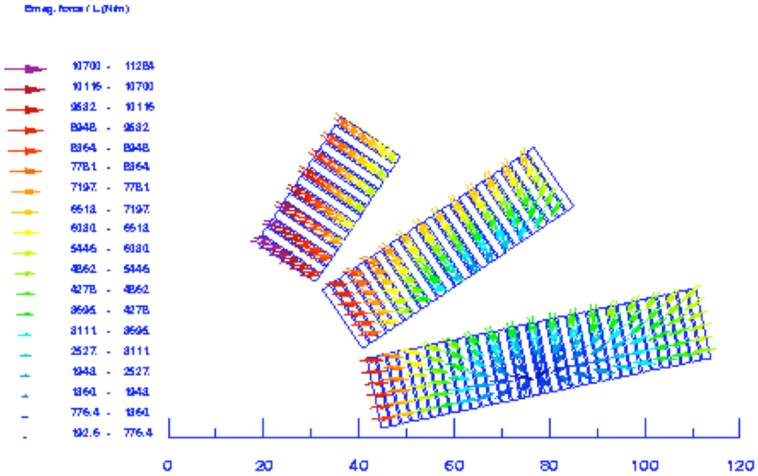

Fig 5 Magnetic forces in a motor-type dipole of 88 mm

2.4 Compensation of the field harmonics due to the filament size

The Nb3Sn filaments have an effective diameter larger than 50 μm leading to high magnetization effects at low field. The field components inside the winding are expressed by:

$$Br=[B_1+B_0(r_2-R/r_2-r_1)+B_0(R^3-r_1{}^3/3R^2(r_2-r_1)]\sin\theta$$

$$B_\theta=[B_1+B_0(r_2-R/r_2-r_1)-B_0(R^3-r_1{}^3/3R^2(r_2-r_1)]\cos\theta$$

where $B_1$and B_0 are respectively the iron contribution and the coil contribution to the main field, R is the radial coordinate. It can be seen how the field varies inside the winding. By inserting a paramagnetic material inside the coil winding, currents will be generated inside the material according to:
$j'z=dM_\theta/dr - dMr/d\theta$

These currents will create field components in opposition to the field components created by the sc diamagnetic currents. At 5 T, an iron wedge in the inner layer of the 15 T magnet will still generate a sextupole of 25 units [2] (Fig. 6).

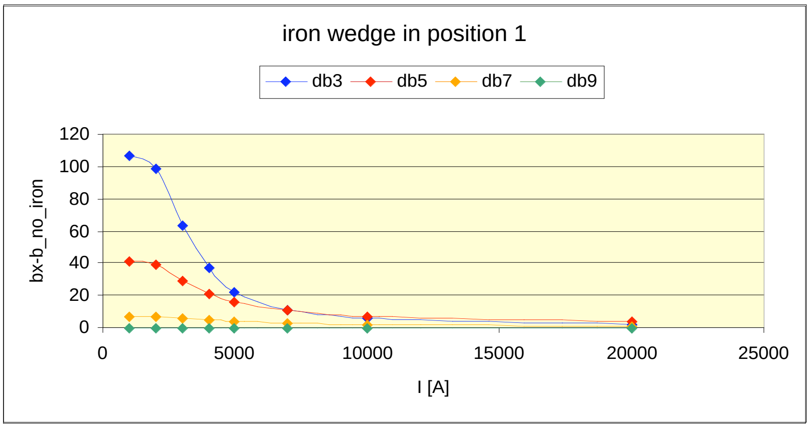

Fig. 6 Multipoles due to iron wedge to compensate the diamagnetic effects

3. SUPERCONDUCTING MATERIALS,STRANDS AND CABLES

A kind of axiom is that it is feasible to build a good magnet at a field X when a current density between 1000-2000 A/mm^2 is obtainable at the field X.

3.1 Superconducting materials

The values of critical current densities in the non copper part can be seen in a plot from S.Gourlay [7] (figure 7).

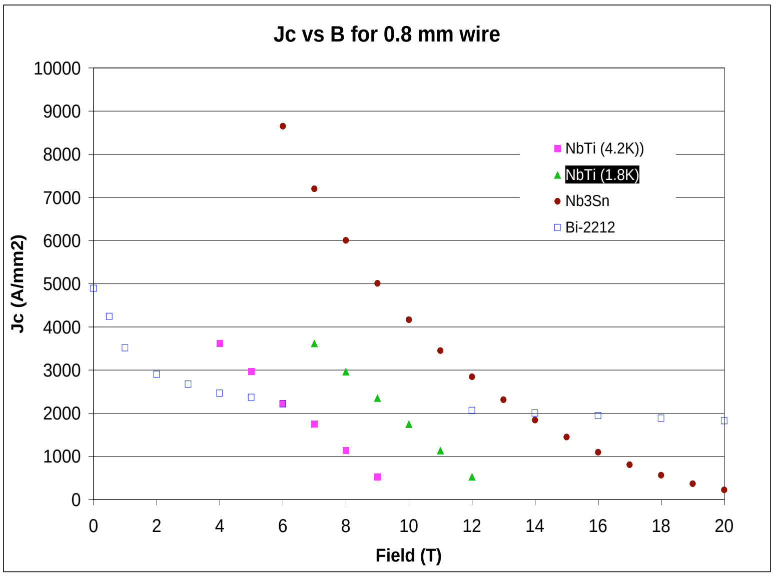

Fig.7 Critical current densities in non copper

From this graph, the following values can be kept in mind:

NbTi	1200 A/mm^2 at 11 T, 1.9 K (obtained)
NbTiTa	1200 A/mm^2 at 12 T, 1.9 K (to be proven)
Nb_3Sn	1500 A/ mm^2 at 15T, 3000 A/mm^2 at 12T and 4.2 K (under development).
Bi-2212	2000 A/mm^2 at 20 T, 4.2 K

Working at 1.9 K with Nb3 Sn could bring a field increase of 0.7 T for the same critical current density.

With the Bi-2212, no accelerator magnet has been built and tested yet.

To build accelerator magnets in the range of 15 T, the Nb_3Sn is the usable superconducting material that is today in an advanced phase of development. For magnets in the vicinity of 10 T, NbTi material at 1.9 K stays the preferable material.

3.2 Filament size, matrix material, strand diameter

The requirements on the filament size are governed by the flux jump stability, the diamagnetic losses and the effect on the field harmonics at low field.

For the NbTi, filament diameter of 6-7 μm are obtained industrially in a copper matrix on a large scale, like for LHC, thanks to the introduction of a Nb barrier around the NbTi bars. The strand diameter is around 1 mm for a current of 500 A at 10 T. Filament size of the order of 3.5 μm can even been obtained in a copper matrix. Below 3 μm, a matrix of CuNi or CuMn has to be used. If the filament size has still to be reduced, the strand diameter will be smaller than 0.5 mm. In this case, the cabling with a high number of strands to fabricate a high current cable needed for the accelerator magnets can be challenging.

With the Nb_3Sn present technology used to reach high critical current density, the filament size is today close to 100 μm but should be reduced to less than 50 μm in the future.

3.3 Strands

Long length accelerator magnets are operated at high current, close to 20 kA, to have a small self-inductance and a reliable quench protection. The usual strand diameter is in the range of 1mm to have cables made of ~40 strands. The copper amount requested for the magnet protection in case of quench has to be calculated for each magnet design. A copper to non-copper ranging between 1.1 and 1.3 can be used for Nb3Sn magnets whereas a ratio of 1.5 to 1.8 is recommended for NbTi magnets. The total amount of copper in Nb3Sn conductor can be reduced in compression with NbTi, since the enthalpy of the bronze helps to reduce the temperature in case of a quench.

4. INTER-STRAND RESISTANCE

There is an electrical resistance (Rc) between the strands of the 2 layers of the cable and a distributed conductivity along the length of the 2 adjacent strands. The inter-strand resistance Rc has a major impact on the ac losses. The cable losses vary with the square of the cable aspect ratio and are very significant for wide flat cables (e.g 26 mm for a 15T magnet designed with 2 layer coils). The values of Rc are governed by the coating material, the strand deformation, the coating rugosity and the local pressure at cabling.

4.1 Coating Materials and Rc values

Table 1 indicates some values of Rc obtained in Rutherford type cables. SnAg is used for LHC. Without coating, the Nb3Sn strands have a tendency of sintering at the reaction temperature of 700 °C. Cr is used for ITER but is difficult in cabling Rutherford type cables requested for accelerator magnets of the layer design.

Table 1 Some values of the inter-strand resistance

Material	Rc(μΩ)	Comments
SnAg	10-50	after a cable heat treatment at 200 °C, not usable at 700 °C
Sn Ni	100-500	not usable at 700° C(?)
Ni	500	-diffuses in Cu at 700 °C(?) -suffers from environmental constrains
Cr	700-1000	-usable at 700 °C -depends strongly on the deposition process

4.2 Cored Cables with a Stainless Steel or Ta core

Another possibility to cut the inter- strand currents is to introduce in the cable between the 2 layers of strand a foil made of stainless steel or Ta as proposed by L.Krempasky and M.Wilson (Fig. 8). The thickness of the foil is in the range of 25-50 µm. The values of Rc are around 1 Ω for cored cables. During the LHC cable R&D phase, M.Wilson has proposed to improve the cable electrical stability, by soldering the adjacent strands.

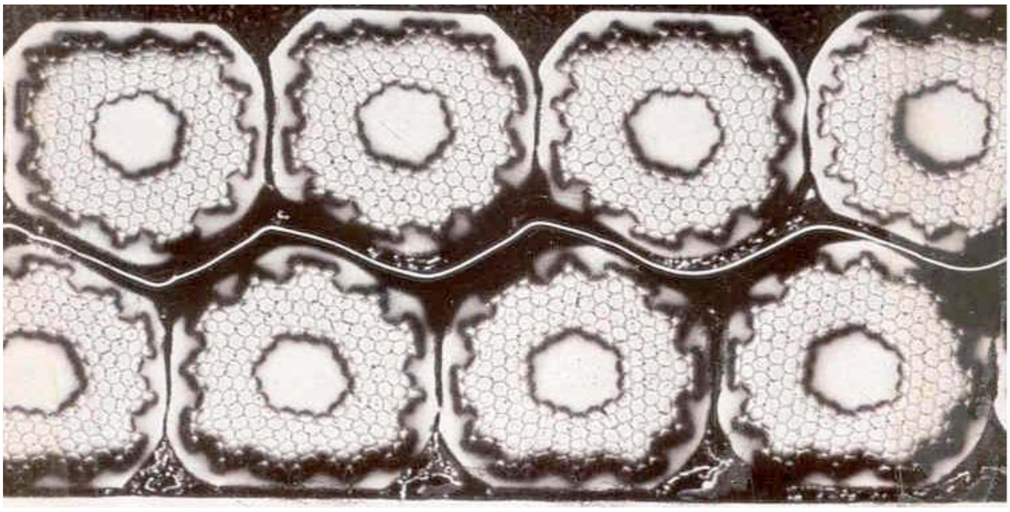

Fig. 8 A cored cable

4.3 Materials for strand coating

In the frame of the LHC programme, many materials have been looked and measured. The values reported in Table 2 are normalised in µΩmm^2, product of the resistance times the contact area.

Table 2 Materials for coating

µΩmm^2	material	Comments
10	SnAg	soft coating, creeps
100	SnNi	
500	Ni, ZnNi	hard coating, cracks occurred Ni oxidized preferentially to Zn
1000	Ni+NiP Zn	thick oxide layer
10^4	passived Zn	Oxide layer
10^6	Oxidized Cu	

4.4 Strand deformation and coating surface topology

The coating roughness and the local pressure at cabling play a role since the inter-strand currents are passing through small local contacts squeezed at cabling. Figures 9 and 10 show the deformed contact surface after cabling and the surface local irregularities through which the inter-strand currents are passing. These figures have been obtained by measurements on the LHC strands and cables made by J M Depond at CERN.

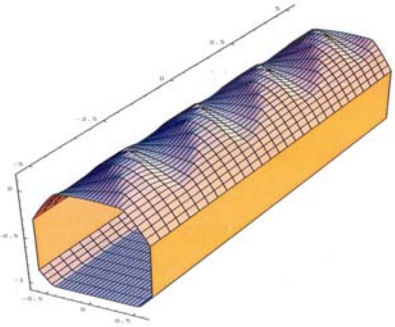

Fig. 9. Strand deformation at cabling

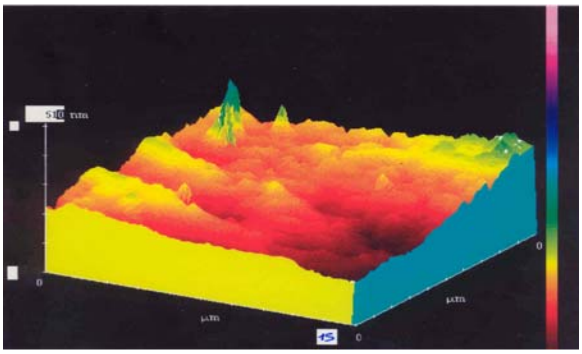

Fig. 10 Rugosity of the coated strand

5. CABLES

Cabling requires special machines and dedicated tools (mandrels and rollers) of high mechanical precision. The geometrical dimensions of cables are obtained after trials. They have to insure a good mechanical stability for winding. In case on the Nb_3Sn cables, degradation due to cabling has to be measured. The relations given here are based on the work made at LNBL [8] for Nb_3Sn and at CERN for NbTi. The expressions that are for strands of diameter around 1mm give the relations for the thin edge ($width\_inner$), the thick edge ($width\_outer$) versus the strand diameter and the number of strands.

for keystoned cable:

$$height = 1.04 \frac{nbr\_str}{2} \phi_{str} \; ; \; width\_inner = 2 * 0.87 \phi_{str} \; ; \; width\_outer = 2 * 0.95 \phi_{str}$$

where ϕ_{str} is the strand diameter and nbr_str the number of strands in the cable;

for rectangular cable:

$$height = 1.04 \frac{nbr\_str}{2} \phi_{str} ; \; width = 2 * 0.87 \phi_{str}$$

The geometrical dimensions of NbTi cables are as following for keystoned cables:

$$height = 1.015 \frac{nbr\_str}{2} \phi_{str} \; ; \; width\_inner = 2 * 0.82 \phi_{str} \; ; \; width\_outer = 2 * 0.95 \phi_{str}$$

The edges of the cables must not be sharp and be free of burrs to avoid problems of electrical insulation.

6. MAGNETS

The following paragraphs comment the feasibility of magnets for the various applications.

6.1 AC magnets in the range of 5 T and 0.2T/s

The superconducting material is NbTi operated at 4.2 K in a circulating sub-cooled helium. These magnets can be like the TEVATRON magnets. At FNAL, the cables were of the Zebra type (one copper strand adjacent to an oxidised strand). At CERN a magnet using a Rutherford cable impregnated with SnIn alloy to reduce the cable losses has been built and can produce 5 T in 25 sec. The magnet technology is well known.

6.2 AC magnet in the range of 5 T and 5 T/sec.

An example of this type of magnet is the GSI project. The superconducting material is NbTi at 4.2 K. The strand diameter is ~0.8mm. The filament size is 3 µm in a copper or a CuMn matrix. The diamagnetic losses in the NbTi filaments are dominating at field ramp since the cables have a stainless steel core. The filament twist pitch is in the range of 6-10 mm.

The conductor cooling is realized by making holes in the insulation. During the GESS collaboration (CEA-Saclay, Karlsruhe, Rutherford Lab) magnets of these field ramp characteristics have been built in 1974. Some magnets had Cu drains for cooling.

For a long chain of magnets in series, high current (10-20 kA) are preferable to reduce the self-inductance and then the impact on the electrical mains at the machine ramp. The magnet technology is known.

6.3 DC high field magnets- up to 10.5 T

The superconducting material is NbTi working at 1.9 K. The critical current density Jc reaches 1100 A/mm2 at 11 T. The strands are made of 10'000 filament having a diameter of 5-7 µm embedded in a copper matrix with a Cu to Superconductor ratio of 1.6-1.8.

The cable compaction ranges between 88 to 90 % allowing a content of 3 % of helium II that participates to the enthalpy. At superfluid helium, beam losses in the coils up to the equivalent of $10 mW/cm^3$ should not induce a quench in the magnet where the cables are insulated by a double wrap and polyimide ribbon.

The magnet construction uses a known technology applied on an industrial scale for LHC (1248 dipoles, 15 m long). A bore field of 10.5T has been reached in magnets of this type like MFISC [3] and MFRESCA [9] that is in operation at 10.3 T for many years at CERN.

6.4 DC High field magnet up to 11 - 11.5 T

The superconducting material candidate is NbTiTa at 1.9 K that has to be developed. The raw material must have, more particularly, a high homogeneity, a small grain size. Unfortunately, even if Bc_2 is increased by 1 T at 1.9 K, high critical current densities have not been reached. No real systematic attempt has been conclusive to obtain high Jc (after the work made by Mc Inturff & Larbalestier for the construction of quadrupoles) The development of the NbTiTa alloy would permit an increase of the magnet field by 1 T. The technology for the magnet construction is known and is similar to the NbTi technology working at 1.9 K.

6.5 DC high field magnet at 4.2 K in the range of 15-16 T

The superconducting material is Nb_3Sn made by the processes called Internal Tin Diffusion (ITD), and Powder In Tube (PIT). Another technology called Bronze Route has allowed building magnets up to 9.4 T in the aperture, but is not able to reach the critical current densities required for magnets of 15 T. With the ITD and the PIT process, critical current densities of 1500 A/mm^2 at 15 T and 3000 A/mm^2 at 12 T are close to be reached on an industrial scale thanks to the development made in USA.

Development is starting as well in Europe via the NED project [10]. Up to now, the equivalent filament size, defined by magnetisation measurements, is in the range of 80 – 100 µm, still too thick for accelerator type magnets and to avoid flux jumps. The R&D work is concentrated now on the aim of high critical current densities with filaments in the range of 30 to 50 µm. For a magnet designed to quench at 15 T, the temperature margin would be 1.4 K at 13 T and 2.6 K at 12 T. To reach higher dipole fields, the magnet must be operated at 1.9 K.

The technology of construction for accelerator magnets consists in making the reaction at ~650 °C after the winding of the coils. The creation of the Nb_3Sn phase creates a volumic expansion in the strand of ~30 % that could lead to a change in strand dimensions of ~3 % transversally and ~3% longitudinally. However, at Fermi Lab, it has been reported that the strand diameter expansion in the range of 2 to 3 % depends on the process of fabrication and the cable length contracts during reaction. There is an experience of construction of short models but the construction of long magnets is still challenging.

7. CONCLUSIONS

The conclusions refer to the quenching magnet field. The operation field has to take into consideration other factors like beam losses and the temperature margin. The calculation tools and the expertise exist for the design of magnets for the future needs. The calculation tools and the expertise exist for the calculations of the strand and cable characteristic effects on the magnets.

The superconducting NbTi material is well known and is usable for long magnets up to 10.5 T, in DC mode or 6 T in AC mode up to at least 5 T/s.

The superconducting NbTiTa material needs development to gain 1 T in the bore field. The technology of construction is known but the development effort has to be balanced with the small gain of 1 T.

The Nb_3Sn has made enormous progress thanks to the efforts in USA. A field up to 16 T has been reached in a small gap dipole by the group of LBNL. The development of the Nb_3Sn conductor has to be pursued. We must be able to build large bore magnets with Nb_3Sn in the range of 12-16 T following the wind and react route. The construction of long magnets is still challenging.

ACKNOWLEDGEMENTS

The construction of superconducting magnets for accelerators has an history of more than 35 years. During all this years, many contributors and many laboratories have developed the strand, cable, and magnet technology so that many of their ideas seem to be in the public domain. It is impossible to mention here, in the references, all the authors. They are well known in the superconducting community for accelerators magnets. The author wish to thank all the persons at CERN and in the other laboratories for their contribution in the topics mentioned inside this paper and present his excuses for those, very numerous, who are not named in the references.

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