A 300 T/m NbSn QUADRUPOLE FOR THE LOW-BETA INSERTIONS OF THE LHC

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Abstract

The NbTi quadrupoles for the LHC insertions have a design gradient of 250 T/m at 1.8 K with a 70 mm aperture. We are exploring the use of the Nb_3Sn technology for second generation $low\ \beta$ quadrupoles for LHC. A conceptual design of a Nb_3Sn quadrupole operating at 1.8 K with 300 T/m gradient and 70 mm aperture is presented. Cable performance, winding technique,magnetic design, mechanical structure and magnet protection are discussed.

1 INTRODUCTION

In the LHC (Large Hadron Collider) the proton beams are focussed at each side of the IP (Interaction Point) by a set of four quadrupoles, series connected, forming the inner triplet. These quadrupoles, 5.5 m long, have single aperture (70 mm) and a design gradient of 250 T/m at 1.8 K.

A 1.3 m long model using an high quality NbTi conductor and a novel design [1] has been built by a CERN -Oxford Instruments (GB) collaboration and has reached a gradient of 245 T/m.

In the frame of a collaboration between CERN and INFN on superconducting magnets we have looked to alternative design using Nb_3Sn conductor. An initial investigation [2], based on simple scaling laws and assuming as a reference the CERN-Oxford design, has explored various layout (shell or rectangular block) and different bore apertures (70 or 85 mm) indicating the possibility to reach with the Nb_3Sn technology the 300 T/m with the small aperture or 250 T/m with the large bore.

A more detailed study [3], including the mechanical structure and magnet protection, has been completed for a large aperture (85 mm) quadrupole. Finally the choice has been made to maintain the nominal aperture (70 mm) and to aim at gradient of 300 T/m. In this paper the conceptual design of this quadrupole is presented and the relevant aspects are discussed in detail.

2 CONDUCTOR

We plan to use a conductor manufactured by Europa Metalli (Florence) with the Internal Tin Diffusion method. It has 37 islands embedded in a copper matrix. Each island, which has a Sn core and 190 Nb filaments, is enclosed by a Nb barrier, whose thickness is about 20 μm, to prevent poisoning of the pure copper during heat treatment. The barrier is partially reacted into Nb_3Sn : this helps to obtain very high I_c values but is detrimental for the effective filament diameter that ranges from 20 to 30 μm, depending on the layout [4].

Table 1: Superconducting cable.

superconductor	Nb_3Sn - Int. Tin Diffusion
barrier	niobium
effective ϕ_{fil}	20-30 μm
ϕ strand	0.825 mm
α=Cu:non Cu	1
heat treat. temp.	up to 650°C, 350 hours
J_c non Cu	1500 A/mm^2@ 12 T, 4.2 K
n. of strands	36
cable size	$1.34 \div 1.60 \times 15.0\ mm^2$

The Nb_3Sn critical current density measured in virgin wires at 4.2 K vs applied magnetic field is reported in Fig 1 together with the scaling to 1.8 K. Also shown, for comparison, is the NbTi curve of the conductor used in the CERN-Oxford quadrupole. The cable characteristics are reported in Table 1.

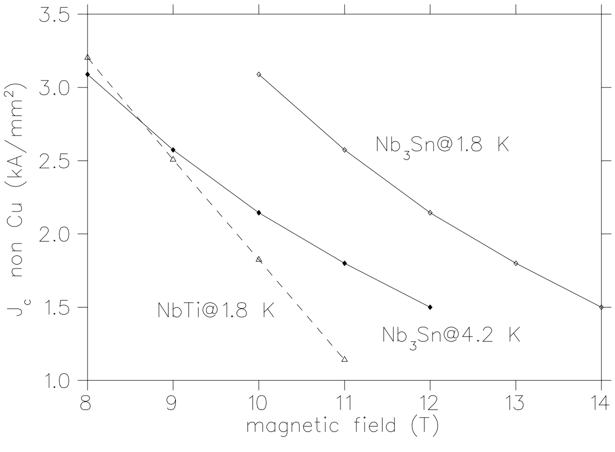

Figure 1: Non copper critical current density for Nb_3Sn and NbTi in virgin wires.

Disadvantages of Nb_3Sn technology with respect to the more standard NbTi one have been extensively described in [3]. In the meanwhile we have investigated I_c degradation due to cabling. In a prototype cable, 150 m long and with 7% lower current density, degradation after cabling (measured on wires) was found about 5%, very near to the standard 3% for good NbTi cable. Also the I_c degradation vs transverse compression, a key factor for this type of magnet, will be soon measured.

To avoid degradation of the outer copper quality and possible flake off of the barrier during heat treatment due to oxygen contamination through the thin copper layer, our conductor must be treated under vacuum or inert atmosphere during all the stages of reaction.

3 INSULATION AND WINDING

The coils are wound and then reacted. So far we have tested for insulation three different materials: R-glass tape, mica-glass tape from Isovolta (A) and a ceramic-glass composite foil from Toshiba (J). Each insulation has been treated at high temperature (700 °C) in Ar atmosphere and under vacuum in shape of tape or foil and then the insulation resistance has been measured up to 1 kV under a pressure of over 50 MPa.

Results have been very positive for the mica-glass tape and for the ceramic-glass foil, with R $\geq$ 10 MΩ at 1 kV and $\geq$ 1 GΩ at 500 V. The R-glass tape has shown,after a special chemical treatment [5] to remove the sizing agent,insulation resistance of typically 1 MΩ at 1 kV and $\geq$ 1 GΩ at 500 V. It should be mentioned that resistance on glass samples occasionally is much lower and that the chemical process is not yet tested on a real coil. We rely also on the fact that continuity of the insulation should be assured by proper impregnation of the coil under vacuum. For the time being we keep as interturn insulation a R-glass tape, that is easy available in different dimensions,butt-lap wrapped around the cable and enclosing, on one side only of the cable, a further glass tape. In this way the turn to turn gap is 240 μm .

The alternatives under study are:

i) use of glass tape wrapped around the cable and enclosing a mica-glass tape (probably it is the best solution for insulation),

ii) ceramic-glass tape used only as a spacer, if it will be available in the proper dimension. In this way the turn to turn distance is 150 μm .

The ceramic-glass tape is more robust than R-glass and more flexible than mica-glass but unfortunately the minimum available thickness is 150 μm while R-glass is 80 μm thick and mica-glass is 100 μm .

The coils are wound in double pancake technique to avoid the joint between the inner and outer layer of each pole which is normally a weak point of the magnet and can limit the performance.

4 COIL LAYOUT

The double pancake technique prevents the possibility of grading ; we point out however that the grading is less effective in Nb_3Sn coils respect to NbTi because of the reduced slope of the Jc vs B line (see fig 1). No specific cable optimization has been pursued ; we selected actually strand diameter, cable size and keystone angle corresponding to the outer layer of the LHC dipole in order to avoid any cabling development.

Table 2: Quadrupole characteristics.

Operating gradient	(T/m)	300
Load line margin		94%
Peak field in conductor	(T)	11.5
Operating current	(kA)	17.9
$\lvert b_6 \rvert$,$\lvert b_{10} \rvert$	(10^{-4} units)	< 0.01
No. of turns per coil		12+17
Inner/outer coil diameter	(mm)	70/132.2
Inner/outer yoke diameter	(mm)	174/520
Stored energy	(kJ/m)	453
Inductance	(mH/m)	2.8

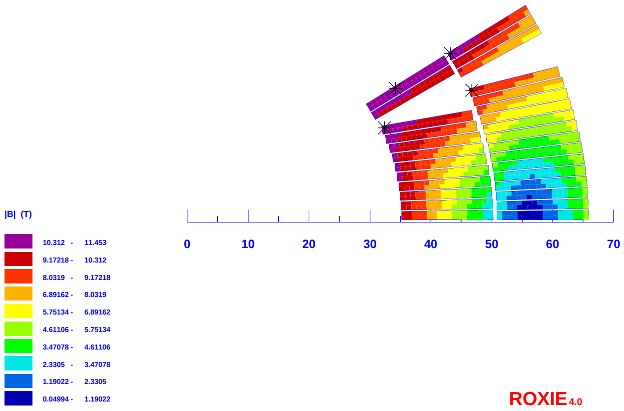

Figure 2: Coil layout (one octant) with field distribution. Peak field locations for each block are indicated.

The cable layout, calculated with ROXIE [6], is presented in fig 2 and the main parameters of the magnet design are given in Table 2. The 300 T/m gradient corresponds to 94% of the load line; so far no degradation for the azimuthal stress (110 MPa) has been considered pending measurements. The iron yoke is placed at 20 mm from the coil in order to have a rigid collars; an iron closer to the coils, 10 mm, gives only 1.4% increase in gradient. The operating current is large, 17.9 kA, but still manageable, to get the advantage of a low inductance which makes the protection of the magnet easier.

5 MECHANICAL STRUCTURE

The main characteristics of the mechanical structure,schematically shown in fig 3 are:

i) a 20 mm stainless steel collar ring and four bronze wedges in the pole regions;

ii) an iron yoke, 174 mm thick, cut in four parts and in contact with the collar only near the coil midplanes;

iii) an aluminum shrinking cylinder 13 mm thick.

The mechanical structure has been designed to minimize the transverse compression in order to reduce the critical current degradation. The mechanical separation of the pole wedge from the ring collars allows to keep the wedge always in position from winding to yoking. The collar wedges are made out of bronze to fit the thermal contraction of the coil during the cooldown. Materials with a lower thermal contraction, like Ti alloys, give a further prestress during cooldown, and also longitudinal stress on coil heads, but they cause an elliptical deformation of coils increasing the peak stress during magnet excitation. Material and thickness of the collar ring have been designed to withstand the magnetic forces with negligible deformation.

Almost all coil prestress is given during collaring and the force nedeed is about 500 ton/m using a dipole type press. Two collaring techniques are under study: the first using a special press[3] acting simultaneously on X,Y planes, the second using clamps for the precollaring and then a dipole type press acting alternatively on the two planes and inserting pinning rods of increasing diameter. This last technique requires an expandable collaring mandrel.

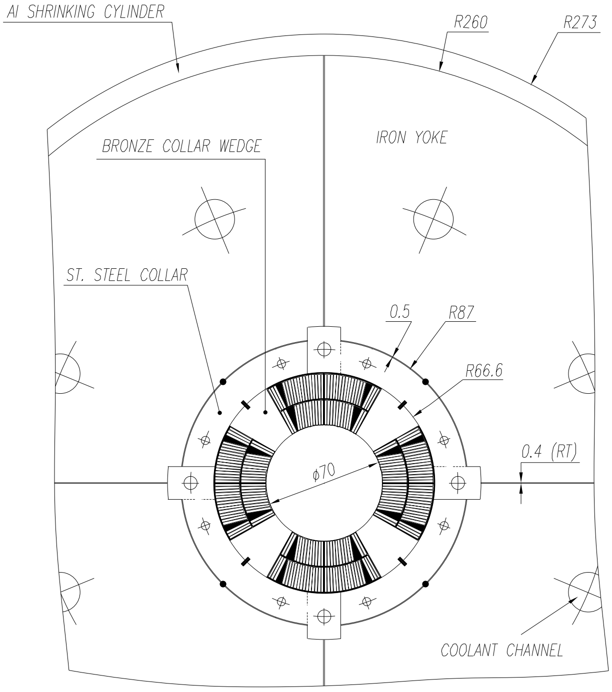

Figure 3: Cross section of the magnet

The yoke and the shrinking cylinder have been designed in order to minimize the coil stress and the coil deformation at full magnet excitation. In the first studies, trying different collar materials and thicknesses, the peak pressure in the coils was always found in the midplane at the inner side of the first layer (as usual in this type of magnet) with values between 140 and 160 MPa. This peak was due to the e.m. forces (F_r= 93 ton/m, F_θ= -289 ton/m in each octant) and to a deformation of the collar that give a 0.06 mm deformation of the inner edges of the coils.

In this design the shrinking cylinder gives after coldown a force of 100 ton/m for octant that the yoke transfers to the collar only on the midplanes, causing an opposite deformation. In this way when the magnet is at maximum excitation this deformation is almost all compensated, the peak stress value (123 MPa) is still on the midplane but on the outer edge of the coil (where the field is much lower) while on the inner edge the peak stress is less than 110 MPa.

6 STABILITY AND PROTECTION

A preliminary evaluation [7] of the stability problem of the coils at 1.8 K with a peak power deposition by radiation of 2.1 mW/cm^3 indicates that impregnated coils will have a sound margin of stability, 1.9 K above the operating temperature.

The magnet can be protected with an active heaters system, as in the LHC dipoles. A passive system based on a dumping resistor can be used for a 1 m long model[3]. The extension of the passive system to a full length magnet is under investigation.

7 CONCLUSION

A 70 mm bore Nb_3Sn quadrupole with a gradient of 300 T/m at 1.8 K seems feasible with the present state of the art and without major cable improving.

A proposal will be submitted to INFN 1n 1996 to build and test a 1 m long model.

Test on insulation and critical current degradation under stress are under way . A small racetrack coil (12 turns, 0.4 m long) is under construction to verify all technical aspects of insulation, winding and impregnation.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

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