Study of a High Gradient, Large Aperture, Nb_3Sn Quadrupole for the Low-β Insertions of the LHC

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Abstract

The low-β quadrupoles for the LHC must fulfill very severe requirements: magnetic field gradient of the order of 250 T/m with aperture of 70 mm and a field quality substantially better than the lattice quadrupole. Furthermore they must withstand a rate of energy deposited in the winding by radiation of about 30 W per quadrupole. In this paper we study the possibility of using Nb_3Sn technology, with the main aim of increasing the aperture, from the present 70 mm, up to 80-100 mm while keeping the gradient in the same range. Two different techniques: roman arch (or cos2θ) current distribution and rectangular coil block winding, are examined and compared. The limit of the possible gradient are explored as a function of the conductor characteristics (Nb_3Sn at 4.2 K or 1.8 K and NbTi at 1.8 K).

1 INTRODUCTION

In the LHC (Large Hadron Collider) the proton beams are focussed at the IP (Intersecting Point) by an insertion system 300 m long, whose final component is the inner triplet of quadrupoles. These quadrupoles are 5-6 m long and have single aperture larger than the one of the lattice quads (56 mm) and a nominal field gradient around 250 T/m. Their magnetic field must be linear over a *large radius* (β functions are large in the collision mode and the two beams are 5 mm off-axis). Error harmonics must not exceed, at 1 cm radius, 10^{-5} T up to dodecapole and few 10^{-6} T beyond, which is a significant better than the requirements for the lattice magnets. Furthermore they must withstand a considerable amount of heating ($\sim$ 30 w per magnet) due to radiation from the IP that will hit the coils of these magnets.

At present CERN is pursuing a route aimed to explore the maximum performance which can be obtained by using high quality NbTi conductor in conjunction with a novel (compared to the lattice quads) design [1]. A 1 m long model based on this design and built by Oxford Instruments (GB) is to be completed and tested soon [2].

In the frame of a collaboration between CERN and INFN on applied superconductivity, we are looking to a possible alternative design, based on Nb_3Sn conductor. For this technology a design, proposed by Scandale and Taylor [3], based on rectangular coil blocks instead of the more usual roman arch may have some advantages from the point of view of the winding accuracy, at least in the straight section. Moreover the cable would be rectangular instead of wedge-shaped. A preliminary study carried by CERN [4] has resulted in a design, based on flat coils wound with NbTi cable, with a gradient around 220 T/m in a aperture of 66 mm, somewhat 10-15 % less performing that the design with roman arch of [1, 2].

In this paper the performance of the different conductors are discussed together with the different coil designs.

2 CONDUCTORS

The Nb_3Sn technology has been proved in the 10 tesla 1 m-long dipole of CERN-ELIN collaboration, [5] and two high field dipoles models (in the 12-13 tesla range) are under construction in two labs [6, 7].

The advantage of Nb_3Sn with respect to NbTi is the higher critical current density in the wire, basically given by the intrinsic properties of material, and the less amount of copper which can be put in the wire (unless coil stability is in danger).

On the other side, apart from the problems given by reaction at 700°C of the coils (the curvature at the ends asks for wind and react technology), NbTi has two clear advantages:

1. the degradation in the critical current, I_c of the cable is around 3% for NbTi, with a good predictability. Degradation of Nb_3Sn has been intensively studied at LBL and at University of Twente: if cable is properly manufactured can be less than 10% for wedged cable and around 5% for flat cable, the problem being the less predictability of cabling Nb_3Sn . Limiting the compression stress around 100 MPa and impregnation of the coils after reaction are necessary in order to avoid further degradation.

2. the turn to turn insulation can be very thin with NbTi, of the order of 75 μm [2]. For the Nb_3Sn we have selected a glass insulation with an average thickness of 120 μm .

The progress made by European industry in the last few years on Nb_3Sn performance of commercial wires of suitable length makes advantageous the use of Nb_3Sn at 4.2 K with respect to NbTi at 1.8 K if the peak field is over 9 T. In Fig. 1 the I_c curves for the different materials are reported: the Nb_3Sn wire is from EM-LMI (I) and has 50%

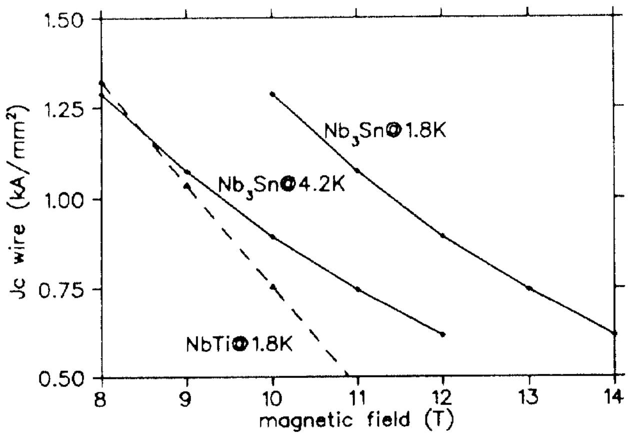

Figure 1: Critical current density vs field for NbTi/Cu and Nb_3Sn/Cu wires. The Cu:non Cu is 1.35 for NbTi and 1.0 for Nb_3Sn . A 3 % cabling degradation for NbTi and 10 % for Nb_3Sn has been taken into account.

copper and a 10% degradation for cabling has been taken into account. The NbTi curves show the measurements on the wire extracted from the cables, manufactured by Outokumpu (F) with 57% copper for the CERN-Oxford quadrupole.

The reported Nb_3Sn has an effective filament diameter of 20 μm (while is less than 10 μm for the NbTi) and the copper content can be lowered, if needed, down to 45%. While the Nb_3Sn performance are very interesting, it should be noted that not so much experience exists in Rutherford cable, so some further 5-10% degradation may be possible, which shifts at 10 T the real crossing point of 4.2 K Nb_3Sn over 1.8 K NbTi.

3 NBTI REFERENCE DESIGN

Two coils configurations, shell and rectangular blocks, have been investigated using as a guideline the CERN-Oxford design. A schematic view of the two quadrupoles is presented in Fig. 2. The aperture is fixed at 70 mm and the radius of the circular iron yoke is R = 79 mm. Two NbTi cables, operating at 1.8 K, are used in order to grade the coils current density; the two inner layers have the same overall current density J_1 and the two outer layers have current density J_2. The critical curve of the coils has been evaluated using the cable presented in section 2 taking into account the proper insulation thickness.

Multipole coefficients and peak field values on the coils have been evaluated analytically (assuming a constant iron permeability $\mu_r = 6$) and with the POISSON code. For completeness we report here the analytical expression of the multipole coefficients for one single rectangular block symmetric respect to the x-axis (r_1, α_1 and x_1, h are the polar and cartesian coordinates of the block inner corner in the upper octant, while r_2, α_2 and x_2, h refer to the

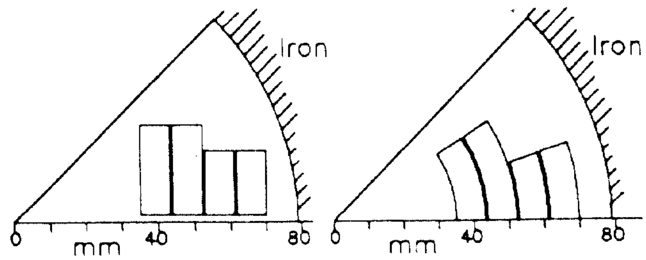

Figure 2: Schematic view of a four blocks quadrupole with rectangular or shell coil geometry. See text for details.

outer corner)

$$B_1 = -\frac{\mu_0 J}{\pi}\left[(\alpha_2 x_2 - \alpha_1 x_1) + h\, ln\left(\frac{r_2}{r_1}\right)\right]$$

$$B_2 = -\frac{\mu_0 J}{\pi}(\alpha_1 - \alpha_2)$$

$$B_n = \frac{-\mu_0 J}{\pi(n-2)(n-1)}\left[\frac{sin[(n-2)\alpha_1]}{r_1^{n-2}} - \frac{sin[(n-2)\alpha_2]}{r_2^{n-2}}\right]$$

the contribution of a circular yoke of radius R assuming infinite permeability is:

$$B_n = \frac{-\mu_0 J}{\pi}\left[\frac{r_1^{n+2} sin[(n+2)\alpha_1] - r_2^{n+2} sin[(n+2)\alpha_2]}{(n+2)(n+1)R^{2n}}\right]$$

In the shell configuration the compensation of the B_6 component can be reached modulating the aperture of the inner two layers around the value $\alpha = 30°$ (B_6=0). For the rectangular block this kind of compensation is actually impossible since it requires a height of the inner block which makes very difficult the winding of the coil ends.

The compensation of the B_6 component asks for the insertion of a shim (4 mm thick in this configuration) at the symmetry planes. This reduces the efficiency of the quadrupoles but in this specific case can be an advantage because can reduce the radiation heating problem.

The main characteristics of the two configurations are presented in table 1. The rectangular block quadrupole has a gradient 10 % lower than the shell quad. (224 T/m vs 241 T/m) with the same total current and the same margin, in term of J/J_{max} evaluated on the load line, on both cables. The multipole coefficients B_6 and B_{10} are in both cases at reasonable levels (less than 10^{-5} T) and no attempt has been made to reduce them further.

It seems possible to increase by 3-5 % the gradient, with the same margin on the cables, by grading the second layer of the shell configuration (as well as for the rectangular block case) as designed in the CERN-Oxford quadrupole.

4 NBSN QUADRUPOLE

To explore the possibility offered by the use of Nb_3Sn on the main quadrupole characteristics (aperture and gradient) we have used simple scaling laws starting from the basic design previously discussed. The aim of this study

Table 1: Reference designs characteristics.

Coils	rect.	shell
B2 (T at 1 cm)	2.24	2.41
B6 (T at 1 cm)	$-6.0\ 10^{-6}$	$2.8\ 10^{-6}$
B10 (T at 1 cm)	$-2.5\ 10^{-6}$	$-2.4\ 10^{-6}$
J_1 (A/mm^2)	460	460
J_2 (A/mm^2)	700	660
B_{max} cable 1 (T)	9.57	9.51
B_{max} cable 2 (T)	7.48	8.19
J_1/J_{max}	93 %	93 %
J_2/J_{max}	89 %	89 %
NI (kA/octant)	395	393

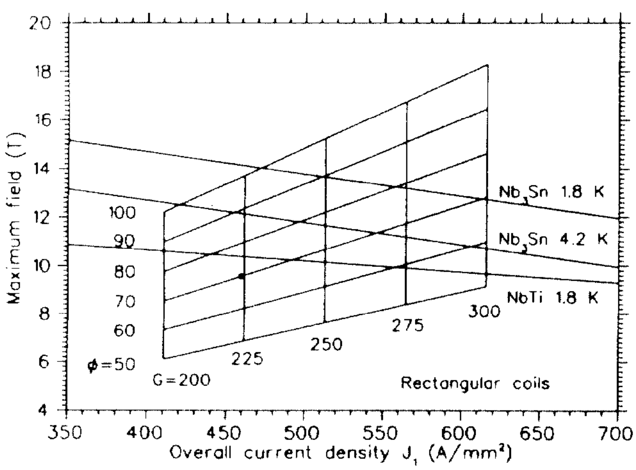

Figure 3: Quadrupole gradient G (T/m) and aperture ϕ (mm) as a function of current density and peak field in the inner blocks. Critical current curves for Nb_3Sn and NbTi cables are also shown. The dot indicates the reference design.

is to see which apertures and gradients are possible using Nb_3Sn at 4.2 K or 1.8 K, and to evaluate Nb_3Sn vs NbTi. Quadrupole configurations were obtained from the basic design by changing proportionally all the current densities to vary the gradient, and/or scaling all coils and iron dimensions, to vary the aperture. The iron has ben assumed to have a constant average permeability $\mu_r = 6$.

For the case of rectangular blocks quadrupoles the constant gradient and constant aperture lines are plotted in Fig. 3 as a function of critical current density and coil peak field together with the I_c curves of NbTi and Nb_3Sn windings. The use of Nb_3Sn cable at 4.2 K allows to increase the aperture by 20 % (85 mm), with respect to NbTi, keeping the same gradient (225 T/m) or to increase the aperture by 40 % (100 mm) reducing the gradient to 200 T/m.

Better performances can obviously be obtained with Nb_3Sn cable operating at 1.8 K; it seems possible to obtain the design gradient (250 T/m) with 85 mm aperture or the maximum considered aperture (100 mm), with a 225 T/m gradient.

Although deduced from simple scaling rules, the prediction of quadrupoles performances vs cables characteristics should have accuracy of the order of 10 % and therefore be useful for a first selection of the parameters.

Similar results holds also for the shell configuration; the relative advantage (respect to the rectangular blocks) is about 10% in the gradient with the same J/J_{max} margin.

5 CONCLUSION

The comparison of the two reference design, shell or rectangular block, indicates that about 10 % higher gradient can be achieved with the shell configuration. On favor of the rectangular type there is the "natural" existence of a shim of the order of 4 mm at the symmetry planes useful to cope with the radiation heat deposition.

The use of Nb_3Sn cable, at 4.2 or 1.8 K, allows to obtain the nominal gradient with aperture increase respectively of 20% (85 mm) or 40% (100 mm). It is not yet clear how much an increased aperture of the quadrupoles reduces the radiation problem and the effective benefit of the midplane shims.

Of course the best will be to use Nb_3Sn at 1.8 K which is by far more advantageous. A preliminary evaluation of the stability problem of the coils at 1.8 K with a heat peak deposition by radiation of 2.7 mW/cm^3 indicates that impregnated coils will have a sound margin of stability even if the heat conductance is reduced and the heat capacity is very small. Both solution (4.2 or 1.8 K) will be taken into consideration for the magnetic design.

6 REFERENCES

[1] T.M. Taylor, R. Ostojic, "Conceptual Design of a 70 mm Aperture Quadrupole for the LHC Insertions", CERN AT/92-24(MA), LHC note n.202 and Proc. of Applied Superconductivity Conf., Chicago 1992.

[2] R. Ostojic, T.M. Taylor, G.A. Kirby, " Design and Construction of One-Meter Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions", CERN AT/93-36(MA) LHC note n.245 and Proc. of MT-13 Conf., Victoria B.C. 1993.

[3] W. Scandale and T.M. Taylor, "A Design Concept for the LHC Insertion Quadrupoles", CERN AT-MA/91-04, LHC note 145 and Proc. of PAC, San Francisco 1991.

[4] T.M. Taylor, CERN AT/MA, private communication and unpublished internal note of N. Galante and T.M. Taylor.

[5] A. Asner, R. Perin, S. Wenger, F. Zerobin, "First NbSn 1m Long Superconducting Dipole Model Magnets for LHC Break the 10 Tesla Field Threshold", Proc. of MT-11 Conf., Tsukuba (J) 1989, pag.36.

[6] D. Dell'Orco, R. Scanlan and C.E. Taylor, "Design of the Nb_3Sn Dipole D20", LBL-32072, UC-414 and Proc. of the Applied Sup. Conf., Chicago 1992.

[7] A. Den Ouden, H.H.J. ten Kate, S. Wessel and E. Krooshoop, "An Experimental 11.5 T Nb_3Sn LHC Type Dipole Magnet", Proc. of Mt-13 Conf., Victoria B.C., 1993.