STABILITY OF A NbSn LOW-BETA QUADRUPOLE IN THE LHC RADIATION ENVIRONMENT

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Abstract

Use of Nb_3Sn coils can significantly improve the performances of the $low\ \beta$ quadrupoles of hadron colliders. In this paper we report the results of a study to evaluate the average and the peak power deposition on the Nb_3Sn coils of a quadrupole for the second generation of the $low\ \beta$ insertion for the LHC. The power release into the coils by radiation escaping from the interaction point has been investigated, by means of FLUKA code, as a function of different gradient–aperture combinations (the basic values being 300 T/m – 70 mm). Consequently the superconducting stability of the impregnated coils has been evaluated both at 2 and 4.2 K operation temperatures of the magnet.

1 INTRODUCTION

In the frame of the CERN-INFN collaboration on superconducting magnets for the LHC, a study of a very high performance quadrupole for a second generation of inner triplet of the $low\ \beta$ insertions is under way at LASA lab of INFN-Milan. This type of quadrupole needs to reach very high magnetic field gradient, beyond 235 T/m in the machine, in a single aperture bore of 70 mm [1].

CERN has designed and built, in collaboration with Oxford Instruments (GB) [2], a full section 1.3 m long model of a novel design quadrupole, that has been successfully tested up 93% of the I_{max} reaching 245 T/m [4]. This quadrupole model makes use of very high performance NbTi cable with all kapton insulation.

To break the barrier of 250 T/m in 70 mm coil aperture we have designed a quadrupole, based on Nb_3Sn conductor, whose schematic cross section is reported in fig. 1. Nb_3Sn has very high performance in term of I_c characteristic vs field but suffers of serious drawbacks, namely the necessity of high temperature reaction (650 °C or more) and a brittleness that makes coil handling hazardous.

Brittleness of the Nb_3Sn and its I_c degradation vs transverse stress in case of bare cable requires the coils be fully impregnated under vacuum after reaction. Full impregnation of the coils raises a concern about coil stability due to lack of direct cooling.

The main points on stability in our design are:

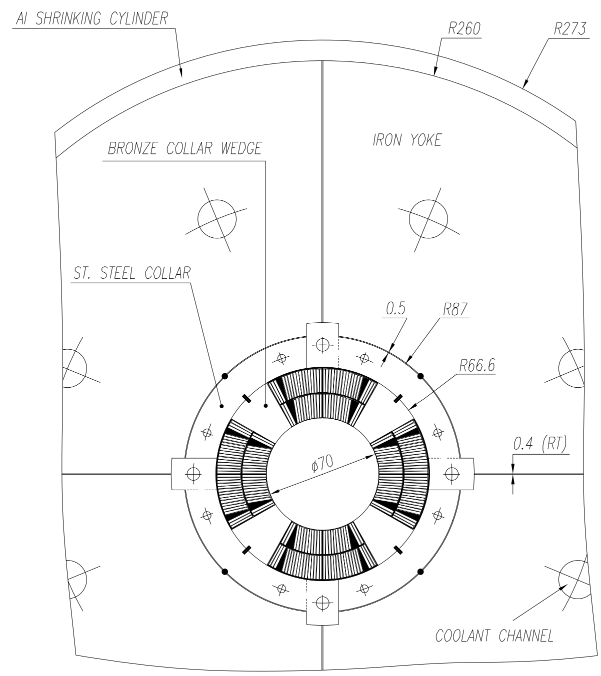

Figure 1: Schematic cross section of the Nb_3Sn quadrupole.

- the peak field on the coil, 11.5 T at 300 T/m, imply large operating stress in the coil, over 100 MPa in the high field region;
- impregnation of the coil will help mechanical stability on the coil head; this point is sometime neglected but it has been proved very important in the main dipole magnet [5], such that now is part of the design of the LHC dipoles;
- when working at 1.8 K, the disadvantage of specific heat, lower than at 4.2 K, is not balanced by the advantage of better heat transfer;
- the stability margin can be compromised by a considerable heat deposition into the coil due to radiation which can increase significantly the operating temperature.

A study of the power deposition has been carried out by CERN [6] with a simplified model and the power deposi-

Table 1: main features of quadrupole design

coil aperture (mm)	85	70
gradient (T/m)	250	300
operating temperature (K)	1.8	
superconductor	Nb_3Sn Int.Tin Diffusion	
J_c non Cu (A/mm^2)	1500 at 12 T, 4.2 K	
α=Cu:non Cu	1:1	
cable composition	36 strands, ϕ=0.825 mm	
cable size (mm)	1.34–1.60×15.0	
operating current (kA)	15.1	17.9
$J_{overall}$ A/mm^2)	565	670
peak field on coils (T)	12.1	11.45
insulation type	R-glass+epoxy	
insulation thickness (mm)	0.125 azim., 0.250 rad.	
midplane shim (mm)	2 ×0.3mm	
temperature margin (K)	3.9	2.8
hot spot temperature (K)	$\leq$ 120	$\leq$ 130

tion has been found to 6 W/m (30 W per magnet). This point must be very carefully evaluated for coils which are almost adiabatic, especially because the power deposition into the coils –a substantial fraction of the total power– is strongly peaked at the coil midplanes.

2 QUADRUPOLE CHARACTERISTICS

We examined two designs with the same conductor: one that should generate 250 T/m in a 85 mm coil aperture [7] and the latest that aims to generate 300 T/m with 70 mm useful bore. The design stability margin is given by operation at 93-94 % of the I_{max} as given by short sample measurements.

The main paramenters are reported in table 1.

The load line for the 300 T/m – 70 mm case together with the $J_{c\,ov}$ at 4.2 and 1.8 K for the Nb_3Sn winding are reported in fig. 2, where for comparison is reported the $J_{c\,ov}$ characteristic of the NbTi CERN-Oxford quadrupole.

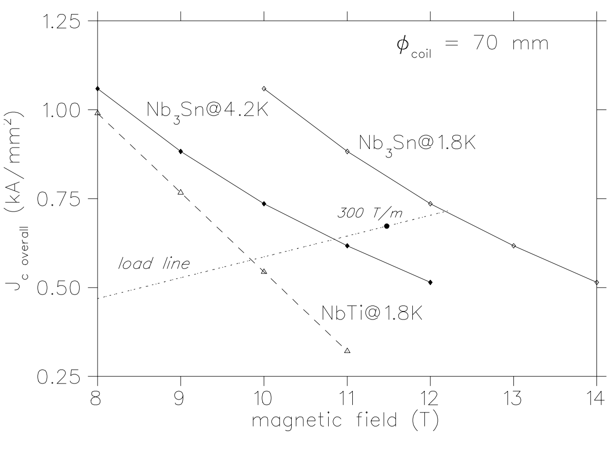

Figure 2: Coil J_c for our Nb_3Sn and for NbTi and magnet load line.

3 POWER DEPOSITED BY RADIATION

The source of the radiation power escaping from the interaction point (I.P.) has been evaluated by taking few hundreds of the 7+7 TeV events from DTUJET code. The interesting events are the inelastic and the single diffractive ones, whose cross sections are $\sigma_{in} = 60$ mb and $\sigma_{sd} = 12$ mb respectively. The neutral particles released in the interactions were directly processed by FLUKA [9], while the charged ones were transported along the beam pipe though the detector field and through the inner quadrupole triplet of the $low\,\beta$ insertion. Low energy neutrons have been neglected. Whenever a charged particle hits the beam line structure it was processed by FLUKA as a single event.

The inner triplet starts with Q_1 placed at 23 m from I.P., with a free space of 2.5 m between Q_1 and Q_2, 1 m between Q_2 and Q_3, 2.3 m between Q_3 and Q_4. Between the I.P. and Q_1 a ϕ_{in}= 30 mm, 1.8 m long, copper collimator is placed at 19 m from I.P. Moreover the effect of four stainless steel absorbers inside the beam pipe along the quadrupoles has been evaluated. The thickness of the absorbers is 5 mm [8].

The results of the calculation for the nominal luminosity of 10^{34} cm^{-2} s^{-1} are summarized in table 2 where data refers to Q_2 that is by far the hottest quadrupole.

The peak power deposited into the coils ranges from 1.3 (for 250 T/m - 85 mm) up to 2.1 mW/cm^3 (for 300 T/m - 70 mm). We think that the grid used is too wide (about 1×1×50 cm^3) and these should be regarded as minimum values. For these reasons and to be conservative we preferred, in thermal analysis, to concentrate the whole power released in the coils near the midplane. In this way, in case of 300 T/m – 70 mm, the power density along the midplane for the hottest coil becomes 5.8 mW/cm^3.

The results so far obtained are very preliminary but sufficient to evalute the stability of the Nb_3Sn coil. More accurate calculation, with bigger statistic and higher number of events is underway.

4 2-D THERMAL MODEL

A 2-D thermal analysis was carried out by means of ANSYS code on an octant. Main features of the thermal model are:

1. steady state;
2. linear analysis, i.e. material properties are constant at the initial temperature. This hypothesis is confirmed a posteriori by the very small temperature increase;
3. regions are (iron is neglected since is thermally separated):
   (a) two coil shells, each one containing a longitudinal copper wedge, where the material properties are the effective values of the conductor unit cell; typical mesh dimension in the coil is 2×2 mm^2;

Table 2: heat deposition (four poles) and coil temperature rise above 2 K

apert.×grad. (mm×T/m)	power into coils (W/m)	hottest coil (W/m)	power in th. calc. (mW/cm^3)	ΔT_{max} coils (K)	total power into cold mass (W/m)	power into adsorber (W/m)
70×250	1.27	0.36	4.7	0.42	3.84	2.31
70×300	1.44	0.44	5.8	0.50	4.30	2.56
85×250	1.27	0.35	4.6	0.42	3.98	2.42

Table 3: stability margin of the coils (without radiation)

apert.×grad.	T_{bath} (K)	ΔT_m (K)	ΔH_m(kJ/m^3)
70×300	2.0	2.8	5.24
70×300	4.2	2.4	11.3

   (b) radial insulation regions on the inner coil radius, between two coil shells and between outer coil radius and collar;

   (c) pole wedge in bronze and, separated, the insulation between pole wedge and coils;

   (d) stainless steel ring collar;

4. no heat exchange at midplane and along the 45°boundaries (symmetry conditions); convective heat exchange with cryogen, HeII or LHe, at fixed temperature: a conservative heat transfer coefficient of 100 W/m^2-K has been taken.

5. the total power released into the coil has been concentrated in the mesh elements along the midplane; computation has been done for the coil with the biggest heat deposition;

The inner bound insulation region has been magnified in radial dimension to be properly described and consequently its thermal conductivity amplified by the same factor.

The results of this preliminary analysis, computed at 2 K where the thermal conductivity are worse than in the case of 4.2 K, are summarized in the table 2.

The heat flow to the helium is very low, with a peak of about 17.7 W/m^2, generating a temperature rise of 0.17 K at the coil to helium interface.

5 STABILITY ANALYSIS

The numbers reported in the previous table must be compared with the stability margin for the coil operation. The stability can be reported as temperature margin, ΔT_m, or enthalpy margin (against distributed continuous perturbation), ΔH_m. These values are reported in table 3 without taking into account the radiation heat.

It can be seen on the temperature margin that the 0.5 K of temperature increase due to heat deposition, see table 2, has a small effect on the coil stability. Actually the first 0.5 K above 2 K gives negligible contribution to enthalpy margin which decreases from 5.24 down to 4.8 kJ/m^3. The situation is even better at 4.2 K where the residual 1.9 K temperature margin corresponds to a more comfortable 9.8 kJ/m^3 enthalpy margin.

6 CONCLUSIONS

This preliminary calculation shows that Nb_3Sn technology can be employed for these very demanding magnets. From the point of view of stability the heat deposition by radiation is acceptable without endangering the $low\ \beta$ quadrupole operation also at superfluid temperature.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] LHC - conceptual design, edited by P. Lefèvre and T. Pettersson, report CERN/AC/95-05(LHC), 1995.

[2] R.Ostojic, T.M.Taylor, G.A.Kirby, “Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions”, Proc. of MT-13,Vancouver B.C. 1993, pag 1750.

[3] G. Ambrosio, G. Bellomo and L. Rossi, ”Study of a High Gradient, Large Aperture, Nb_3Sn Quadrupole for the $low\ \beta$ Insertions of the LHC”, Proc. of EPAC94, London, pag 2268.

[4] T. Taylor, CERN-LHC div., private communication, 1996.

[5] M.Bona, R.Perin, E.Acerbi and L.Rossi “Assessment of the Test Results of the Two CERN-INFN 10 m Long Superconducting Dipole Prototypes for the LHC” Proc. of MT-14 Conf., Tampere (Finland) 1995.

[6] A. Morsch, R. Ostojic and T.M. Taylor , “Progress in the System Design of the Inner Triplet of 70 mm Aperture Quadrupoles for the LHC Low-β Insertions”, Proc. of EPAC94, London, pag 2274.

[7] G. Ambrosio et al., ”Preliminary Proposal of a Nb_3Sn Quadrupole Model for the $low\ \beta$ insertions of the LHC”, report INFN/TC-95/25, 1995.

[8] R. Ostojic, CERN-LHC div., private communication.

[9] A. Fassò, A. Ferrari, J. Ranft and P. R. Sala, “FLUKA: present status and future developments”, Proceedings of the IV International Conference on Calorimetry in High Energy Physics, La Biodola (Elba), September 19-25 1993, A. Menzione and A. Scribano eds., World Scientific, pag 493 (1994).