DEVELOPMENT OF A HIGH-GRADIENT QUADRUPOLE MAGNET WITH A Nb_3Sn CABLE *

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Abstract

In frames of a collaboration between IHEP and FNAL, design of a superconducting high–gradient quadrupole has been carried out at IHEP. The two-layer design implements a Nb_3Sn superconductor with 600 A/mm^2 critical current density at 12 T field and 4.2 K temperature. The quadrupole has maximal field gradient of 220 T/m within 70 mm aperture at 4.6 K operating temperature. Results of optimization of both cross–sectional and end-part geometries aimed at achieving a good quality of integral and edge fields and reducing field overshooting are presented. Arch design was adopted as a more preferable one. Effect of deformations upon current–carrying capacity of the Rutherford–type cable at various angles of keystone has been studied. Results of critical current measurements for original wires and for a 28-wire cable as well as of mechanical performance study of the cable are presented.

1 INTRODUCTION

To increase the luminosity in colliders it is necessary to reduce the β–function in the intersection region. It leads to necessity of augmentation of focusing quadrupole magnet force. The operating temperature has to be diminished down to 1.8 K at application of quadrupoles with NbTi current–carrying element that leads to the complication of a cryogenic system and to the rise of a power consumption. The further increase of the field gradient is possible in going to another SC–material possessing higher values of a critical current. One of the such possibilities is the application of Nb_3Sn compound at 4.6 K temperature.

The design of SC–quadrupole providing the working gradient of 220 T/m at the temperature 4.6 K in 70 mm coil aperture has been developed in IHEP[1]. The tolerances on the lower nonlinearities both central and integral fields at the reference radius of 25 mm must not exceed 1×10^{-4}.

The Nb_3Sn SC–material of MKNOS–08–25531 grade[2] having copper shell was chosen to manufacture the windings. The SC–wire has 0.8 mm diameter, 25531 filaments with the diameter of 1.96 μm, the twist pitch of 10 mm, Cu volume fracture of 36 % and Nb/bronze without Cu ratio of 1:2.38. The critical current density of this wire in the field of 12 T at temperature of 4.2 K equals to 550 A/mm^2 without copper. The S–wire with 10 % more value of critical current will be used for manufacture of the quadrupole, but the magnitude of 550 A/mm^2 has been used in calculations for determination of temperature quench safety margin.

2 THE CROSS–SECTION SHAPE

The calculations on geometry optimization of both the cross–section and the end parts of coils were performed with a help of code HARM-3D[3] in approximation of the infinitely large permeability of yoke having a finite length and an inner cylindrical surface. The real dependence $\mu(B)$ was taken into account with a help of code MULTIC[4] to determine a saturation of iron, its width and so on.

Two type of cross–section geometries were considered at the first stage: the arch design with trapezoid section of cable (Figure 1a) and the geometry with reduced difference between trapezoid bases (weakly keystoned cable) (Figure 1b). It was found after performance of the calculation cycles that the both geometries have practically the same field quality as well as all the rest of magnetic characteristics. The arch design possesses more reliable mechanical properties and has more simple manufacturing methods. However SC–wire in the arch design is deformed very strongly. The deformation value can be determined as $\delta_h = (2d - h_1)/2d$, where d is the SC–wire diameter and h_1 is the smaller base of trapezoid. The value of δ_h reachs about 30 % in the arch design, that can cause the degradation of the critical current.

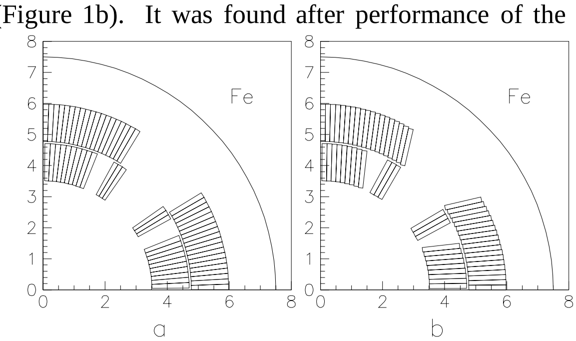

Figure 1: *Quadrupole cross–section; a — the arch design, b — the design with weakly keystoned cable.*

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3 SC–CABLE AND SC–WIRES

Three samples of cables with the various δ_h have been made for investigation of wire deformation influence on the current–carrying characteristics. The first sample had a rectangular shape with dimensions 11.2 mm×1.6 mm and zero wire deformation. Two other cables were formed in a trapezoid shape with 12 mm height and bases of 1.28 mm, 1.426 mm for 20 % wire deformation and 1.126 mm, 1.579 mm for 30 % wire deformation. The cable samples, extracted wires and the initial non–deformed wire were exposed to simultaneous thermal diffusion annealing to form SC–compound Nb_3Sn. The measurements of the current–carrying capability of both cables and single wires were carried out in the magnetic field of solenoid with 15 T maximal field at 4.2 K. The dependences of the critical currents versus magnetic field for initial wire (1) and wires extracted from cables with $\delta_h = 20$ % (2) and 30 % (3) are presented on Figure 2a. The critical current degradation for the wire with 30 % deformation against the magnetic field is shown on Figure 2b. Here the value of degradation is $\delta_I = (I_{30} - I_0)/I_0$, where I_{30} is the critical current in deformed wire and I_0 is the critical current for initial wire. The drop of current–carrying capability at 9 T constitutes approximately 5 % for extracted wire from cable with deformation of 30 % compared with the initial wire.

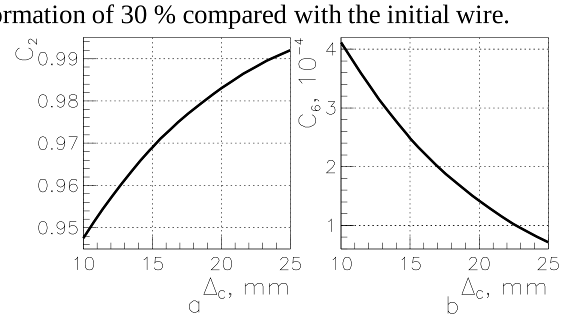

Figure 2: *Critical current dependences for the wires with various deformation (a) (1 — 0 %, 2 — 20 %, 3 — 30 %) and critical current degradation in wire with 30 % deformation versus magnetic field (b).*

The complete results of current–carrying capability study for both wires and cables based on Nb_3Sn were presented in [5] where it was shown that the magnitudes of critical current degradation in cable do not exceed the corresponding values in wire at all other conditions being the same. The critical current degradation of 5 % is fully acceptable so the arch design has been chosen as a basis.

The cable width along the middle line was measured at the stage of cable fabrication during forming and after thermal treatment under pressure up to 70 MPa. The results of these measurements as well as the results of height measurements of stacks, which consist of 10 cable pieces, showed that the cable width is changed in the process of the thermal diffusion annealing. The variation of the cable width before and after annealing equals to 13.5 μm for the cable with $\delta_h = 20$ % and about 11 μm for the cable with $\delta_h = 30$ %. These deviations must be taken into account during design of windings.

4 CROSS–SECTION OPTIMIZATION

Two layer winding allows to get the necessary field gradient and satisfies all other requirements.

Further we will use the following standard field representation in the magnet aperture:

$$B_y + iB_x = B_0 \sum_{n=1}^{\infty} W_n \left(\frac{r}{r_0} e^{i\Theta}\right)^{n-1}, \tag{1}$$

where $B_0 = G_0 r_0$ is the field on the reference radius $r_0 = 25$ mm, B_x, B_y are the field components, G_0 is the field gradient in the magnet center and $W_n = C_n + iS_n$ are the nonlinearities of order $n-1$. For normalization it is convenient to choose G_0 at the infinitely large magnetic permeability of iron, then the difference $1 - C_2$ will characterize the value of iron saturation.

High field quality is reached by corresponding choice of layer angles, that suppress the nonlinearity C_6. For suppression of the nonlinearity C_{10} it is necessary to insert the interturn spacer in the first layer From manufacturing reasons the angle of the second layer must be less than the angle of the first one. It was shown by calculations that it is sufficient to have 28 wires in the cable for provision of the necessary temperature quench safety margin.

Collar width Δ_C determines the distance between the outer radius of the outward layer and the inner surface of the iron. The dependences of C_2 and C_6 against Δ_C are shown on Figure 3. One can see from this picture that the minimal width of Δ_C must be 25 mm for high field quality at all levels of the working current.

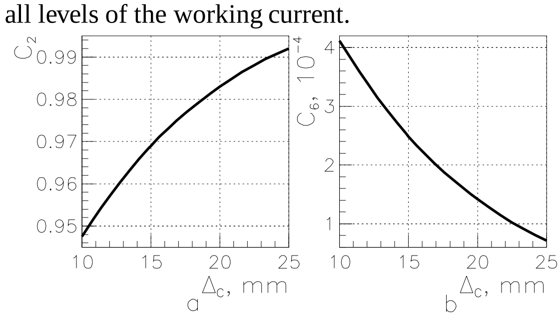

Figure 3: *Dependences C_2 (a) and C_6 (b) versus collar width.*

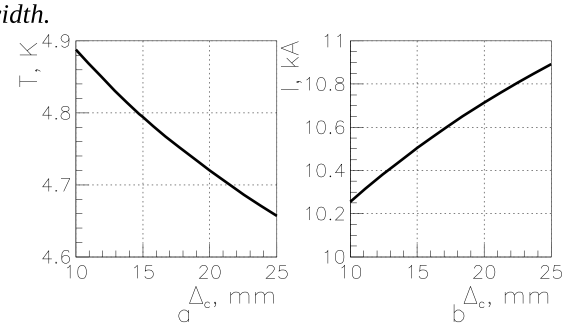

Figure 4: *Dependences of temperature quench safety margin (a) and turn current (b) versus collar width.*

The calculations of mechanical collar strength also showed that the minimal collar width must be 25 mm. On the other hand moving away magnetic circuit from windings, we reduce its contribution in the field gradient that causes the increment of turn current and thus the temperature quench safety margin has a drop as it is shown on Figure 4. It follows from Figure 4 that the maximal collar width must not exceed 25 mm to provide the operating temperature of 4.6 K. So the collar width was chosen 25 mm.

It was shown by the calculations of magnetic characteristic dependences versus magnetic circuit width that its minimal value must be 80 mm.

5 GEOMETRY OF THE END PARTS

Each current layer on the end parts is divided into three blocks by interblock spacers in order to diminish the cable deformation. The middle turn is placed like a shape of constant perimeter and neighbouring ones are fit snugly to it and so on. The turns are aligned with the upper generating line of the cylinder in the longitudinal direction (Figure 5). From manufacturing reasons both layers must be matched by their total lengths. The spacer widths in the first layer are chosen from condition of suppression of the lower edge nonlinearities C_6 and C_{10}. The additional condition of magnetic length gain was taken into account during definition of the first spacer position. Here and further the spacers are enumerated from the magnet end. The second spacer was as a continuation of interturn spacer suppressing the field nonlinearity C_{10} in the cross–section.

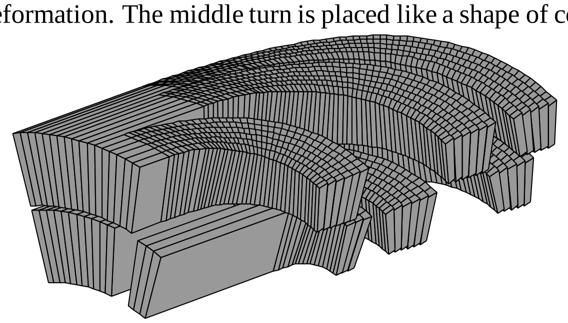

Figure 5: *General view of the optimized end parts of quadrupole.*

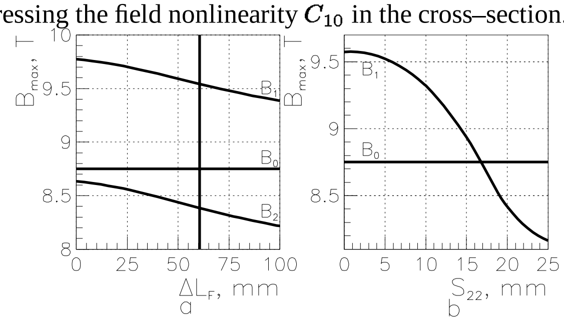

Figure 6: *Dependences of the maximal fields at the end parts versus iron shortening (a) and versus the second spacer width in the second layer (b); B_1, B_2, B_0 are the maximal fields at the end parts of the first and the second layers and in the cross–section.*

The spacers in the second layer were used for minimization of the magnetic field enhancement at the end parts. The maximal field at the end parts of the first layer after setting of spacers, which suppress the lower edge nonlinearities C_6 and C_{10}, is more by 12 % than the maximal field in the central cross–section in the geometry with zero spacers widths in the second layer and the iron length equal to the total windings length. As one can see from Figure 6a, these values can not be equalized completely by an iron shortening. The boundary of the minimal straight lengths of the blocks is shown by the vertical line on this picture. For further reduction of the field enhancement it is the most efficient to increase the width of the second spacer in the second layer S_{22}, where the first index denotes a layer number and the second index labels a spacer number. With the width of this spacer $S_{22} = 17$ mm the maximal field magnitude B_1 at the end parts of the first layer equals to the maximal field value B_0 in the cross–section as it is shown on Figure 6b. The field at the end parts of the second layer is always less than B_0. The results presented on Figure 6b were got with the iron length equal to the minimal straight part length of winding blocks, the spacer width $S_{21} = 4$ mm and the suppressed lower nonlinearities of the edge field.

6 CONCLUSION

As a result of optimization of the geometric parameters influencing on the field quality, the design of the SC–quadrupole with the nominal gradient 220 T/m has been developed. The windings use the SC–wires based on Nb_3Sn with the critical current density $j_c = 550$ A/mm^2 without copper in the field 12 T at the temperature 4.2 K. One can rely on the gradient rise up to 250 T/m taking into account a possibility of gain in j_c. The mechanical strength of the quadrupole is provided by the shape of the arch design and by the choice of the sufficient width of the stainless steel collar. The optimal turns distribution in the central cross–section and at the end parts of windings suppresses the lower nonlinearities both the field and the integral field and minimizes the field enhancement at the end parts. A possibility of magnetic length gain were taken into account during the end parts optimization. The development was carried out taking into account the existing production potentialities of the SC–quadrupole manufacturing in IHEP.

7 REFERENCES

[1] I.V. Bogdanov et al. ”Geometry Optimization of a High Gradient Quadrupole Magnet”, Proc. of XV Conf. on Magnet Technology, Bejing, China, 1997.

[2] I. Davidov et al., ”Development and Investigation of Multifilamentary Nb_3Sn Conductors to be Used in the ITER,” IEEE Trans. Magn., vol.30, No.4, p.2316, July 1994.

[3] S.V. Purtov, L.M. Tkachenko, ”HARM–3D — a Code to Calculate Magnetic Characteristics of Superconducting Magnets,” Proc. of XV Conf. on Magnet Technology, Bejing, China, 1997.

[4] L.M. Tkachenko, ”Codes MULTIC2 and MULTIC3,” In ”Computer Codes in Accelerator Domain”, Internal Report, DESY M-92-07, p.40-41. Nov., 1992.

[5] I.V. Bogdanov et al. ”Study of the Nb_3Sn Cable Characteristics for SC–Quadrupole with High Gradient,” Proc. of XV Conf. on Magnet Technology, Bejing, China, 1997.