Design of SC solenoid with high homogeneity [*]

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Abstract: A novel kind of SC (superconducting) solenoid coil is designed to satisfy the homogeneity requirement of the magnetic field. In this paper, we first calculate the current density distribution of the solenoid coil section through the linear programming method. Then a traditional solenoid and a nonrectangular section solenoid are designed to produce a central field up to 7 T with a homogeneity to the greatest extent. After comparision of the two solenoid coils designed in magnet field quality, fabrication cost and other aspects, the new design of the nonrectangular section of a solenoid coil can be realized through improving the techniques of framework fabrication and winding. Finally, the outlook and error analysis of this kind of SC magnet coil are also discussed briefly.

Key words: nonrectangular section coil, SC magnet, active shimming, linear programming

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1   Introduction

The development of SC solenoids is of great importance in accelerator technology. SC solenoids are also applied in MRI technology, high power microwave klystron systems and high precision detectors in astronomy [1–4]. Different kinds of magnetic requirements and performance goals make SC magnets very complex and huge. As we know, homogeneity restraints of a magnetic field is one of the most common requirements in electromagnetic design. In this paper, we first introduce the linear programming method of calculating the current density from the magnetic field homogeneity requirement, then traditional coils and nonrectangular section coils are compared. In the end, through bettering the skeleton and winding techniques, a nonrectangular section solenoid can be designed.

2   Magnetic field requirement

There is a linear relation between the magnetic field and the charging current according to the Bio-Savart law. Linear programming principle can be applied to obtain the magnet current density distribution if the magnetic requirement is given [3, 5]. For example, a solenoid with the warm bore diameter 60 mm and the length 200 mm is supposed to produce a central magnetic field 7 T with a homogeneity of several ppm on 30 mm DSV (the diameter of spherical volume). The current density distribution cloud picture, as Fig. 1 shows, can be obtained through the linear programming method.
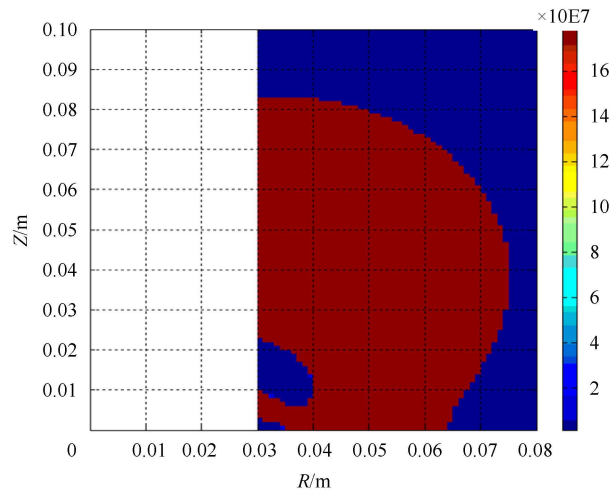

Fig. 1.   (color online)The current density distribution of SC solenoid.

Figure 1 shows a quarter SC solenoid current density distribution. The original point stands for the center point of the SC solenoid, the horizontal and vertical axis

means the radial and axial direction respectively, and the right color bar expresses the current density with unit A/mm². Because the linear programming target function is set as the volume of the coil, the current density almost has two values: the maximum 180 A/mm² and the minimum value zero. In the inner side of the coil, the current zone shape shows an irregular form. In the outer side of the coil, the current zone border presents a ladder or step profile. This is because the feasible region is meshed by a rectangular grid. It is clearly seen that the current zone is a close continuous shape. This feature means the SC solenoid can be fabricated as a whole without layering.

3   Electromagnetic design

Spherical coils for MSS (the magnetic surgery system) have been successfully designed and developed [6]. This type of coil, which can produce a linear gradient field in a large spherical volume, is quite different from the nonrectangular section solenoid coils to be discussed here. Two designs are analyzed to produce a central field up to 7 T with a field homogeneity of several PPM. One is the traditional solenoid coil; the other is the nonrectangular section coil. The two different designs are compared in detail in many aspects.

3.1   Traditional design

It is well known that a single traditional solenoid coil cannot provide a high quality magnetic field. In order to produce 7 T with a homogeneity of several PPM, a notched solenoid within a volume of $\phi160$ mm×200 mm whose inner diameter is 60 mm, the outer diameter is 134 mm, the length is 160 mm and the current density is 133 A/mm², can provide the 7 T central field. Fig. 2 shows the typical rectangular section coil model and Fig. 3 shows its magnetic field calculation.
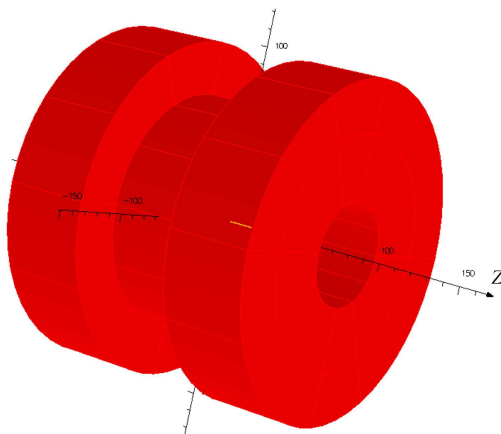

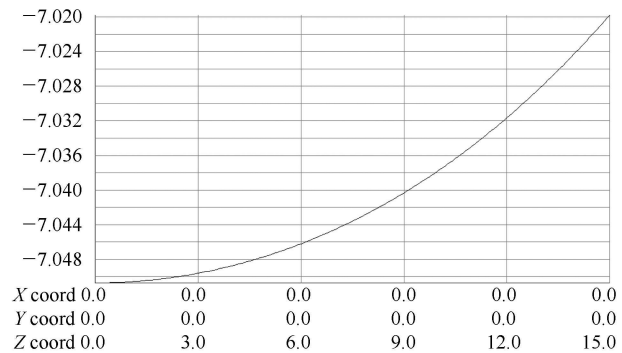Fig. 2.   (color online) The traditional solenoid model.

Fig. 3.   (color online) The magnetic field distribution of the traditional solenoid.

It could be seen that although a single coil can produce a magnetic field up to 7 T while Bmax is 7.08 T，the homogeneity is only about 4.43×10^{-3}. The energy of the solenoid is about 59 kJ and the inductance is about 1.6 H. To produce a field up to 7 T, about 30 kg SC wires are employed. Generally, in order to get a better homogeneity requirement, notched coils with compensating coils may be designed to have the error coefficient to zero [7]. A complex shimming system is needed for the higher homogeneity demand. A typical shimming system not only includes several layers of active shimming coils, but also includes soft magnetic material passive shimming technology. All these make the high homogeneity SC magnet system complicated and not easy to be developed.

3.2   Nonrectangular section solenoid design

In theory, magnetic field can only be generated by current (as magnetic monopole is not found yet), so if the wire section could be changed to a desirable shape, all kinds of magnetic field distributions could be obtained. This method means that the SC magnets design is simplified to the SC wire design. For conventional water-cooled magnet, it is possible to make the whole conductor (usual copper) into a desirable shape. However, an SC cable (NbTi or Nb_3Sn) usually consist of multiple superconducting filaments inside and a Cu stable base material outside. After stretching repeatedly, a thin SC filament with a diameter of about μ m can be manufactured. This means SC cables are not easily improved. Moreover, another crucial question in cable improvement is the huge current charging if the cross-section area is enlarged. Another way of making a nonrectangular section magnet is still employing traditional SC multifilament cable. This method needs the improvement of skeleton and winding techniques. Figs. 4 and 5 show the nonrectangular section solenoid coil model and its rough manufacturing conception.

The new skeleton is designed to hold the nonrectangular section coils. A feasible measure is cutting the
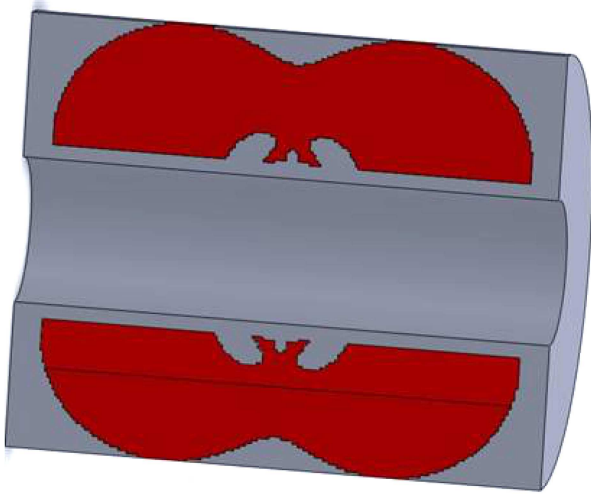
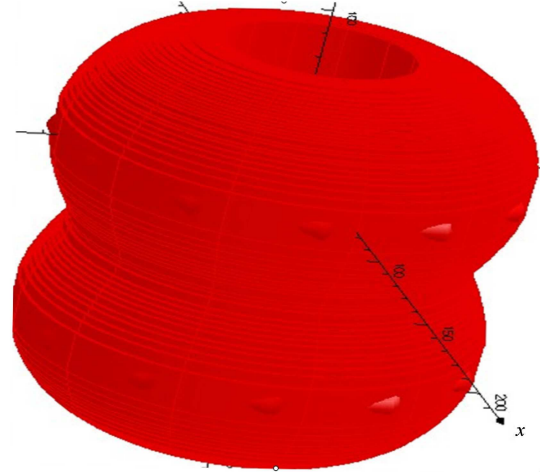Fig. 4.   (color online) The nonrectangular section solenoid model.

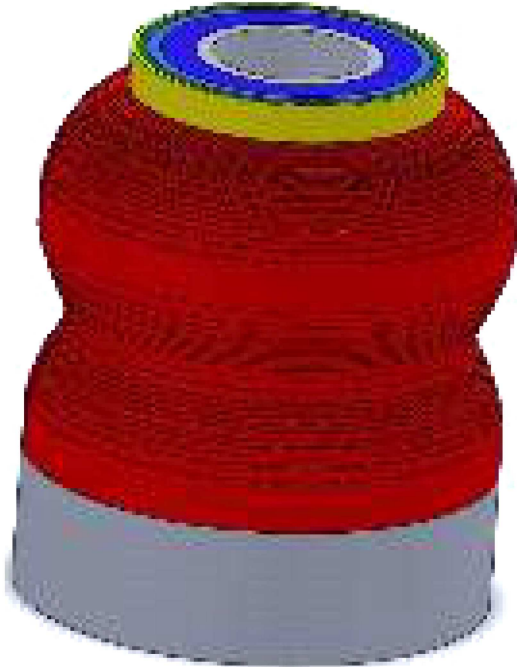Fig. 6.   (color online) The norectangular section solenoid coil.

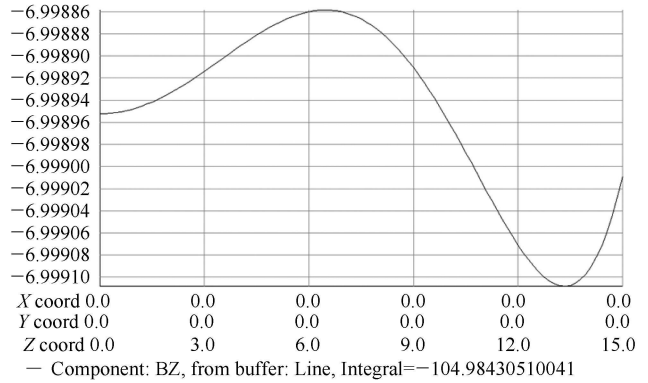Fig. 5.   (color online) The nonrectangular section solenoid assembly.

Fig. 7.   (color online) The nonrectangular section solenoid magnetic field distribution.

60 mm, outer diameter of 150 mm and a total length of 166 mm.

More than that, the total energy of the nonrectangular section coil is about 21 kJ with inductance 0.65 H. The Bmax is about 7.18 T in the coil while the SC cable mass is about 16.23 kg. Compared with a complex homogenous magnet, it is also easier to fabricate and develop.

3.3   Comparison of the two designs

The nonrectangular section coils have many advantages compared with traditional coils. First and foremost, the magnetic field distribution is much better than traditional coils. Second, if the nonrectangular solenoids have a similar volume size, SC cables are more fully used to produce the same magnetic field. Third, the nonrectangular section coils are easy to extend to other SC magnet domains, as long as a linear programming method is used to calculate the coil current distribution. Furthermore, the nonrectangular section coil can be applied in

skeleton into slices: sliced framework can be installed before the winding process. The next sliced framework is installed after the previous layer SC cable winding. Each sliced skeleton corresponds to the layered coil in height and width. As to the central hollow space, similar treatment can be employed. The magnetic field distribution generated by the current density distribution zone in Fig. 1 can be computed in OPERA3D. Figs. 6 and 7 show that the homogeneity can only be boosted to 3.43×10^{-5} at the axial distance of 30 mm for a nonrectangular section solenoid with an inner diameter of

HTS (high temperature superconducting) pancake coils. The cost of economical cables or tapes may contribute to the increased skeleton fabrication and winding.

The main parameters of the two solenoid designs are listed in Table 1. The nonrectangular section solenoid has a smaller energy and inductance. This means the coil is safer when quench happens. Other parameters have the same order of magnitude. Of course, the latter's homogeneity is much better than that of the traditional one.

Table 1.   Comparison of the two designs.

parameters	traditional coil	nonrectangular section coil
B_0/T	7	7
homogeneity	4.3×10^{-3}@30 mm	3.43×10^{-5}@30 mm
bmax/T	7.08	7.18
energy/kJ	59	21
current Margin	0.41	0.58
inductance/H	1.6	0.65
SC wire mass/kg	30.1	16.2

4   Conclusion

Nonrectangular section coils have a positive influence on SC magnet design. As to stray field desirement, linear programming can be applied in a similar way. So nonrectangular section coils have a very large applied range and deserve to become popular. The calculated magnetic field and actual measurement may produce error. There are three sources:

(a) Ring current silk is very accurate when the current zone is meshed in a small grid, however, the magnetic field calculation is the simplification of the Biot-Safar's law. The error is small, but still exists.

(b) The current density contour is obtained by a linear programming method. In fact, there is a very small current zone whose current is not the maximum and zero, but medium. The smaller values are disposed as zero and bigger values maximum. This will bring a computational mistake into the magnetic field calculation.

(c) There are inevitable mismatching tolerance in the actual fabrication process: scale error, geometric tolerance technical control and so on.

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