Design of an asymmetric superconducting magnet for a Penning trap *

BIAN Wen-Long(卞文龙)[1,2;1)] MA Li-Zhen(马力祯)[1;2)] WU Wei(吴魏)[1]
YAO Qing-Gao(姚庆高)[1] GUAN Ming-Zhi(关明智)[1] DU Jun-Jie(杜俊杰)[1]

[1] Institution of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: A new 7.0 T asymmetric active shield superconducting magnet for Penning traps is proposed in this work. The magnet has two field regions whose homogeneity is better than 0.5 ppm. Linear and nonlinear methods are used for the asymmetric electromagnetic optimization. Stress analysis, mechanical design and a quench protection system design are also introduced in this paper.

Key words: Penning trap, superconducting magnet, asymmetric, active shield

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1 Introduction

Penning traps are one of the most accurate tools available for mass measurement [1]. The magnet system is a critical component of the Penning trap as the homogeneity, strength and stability of the magnetic field strongly affect the accuracy and the sensitivity of the Penning trap system.

Generally, a symmetric magnet design is used, in which the magnet consists of a set of symmetric solenoid coils [2]. The magnet will produce about 0.5 ppm in a 1 cm^3 region with active and passive shimming methods [3]. One distinct disadvantage of the symmetric magnet is its huge size. Taking the Lanzhou Penning trap as an example, the length of the magnet is almost 1 m while the diameter of the outer coil is 0.8 m. This size is not convenient for detector installation.

Recently, asymmetric magnets have been developed as an alternative to symmetric magnets [3, 4]. The asymmetric design can give a larger warm bore for the magnet and better usage of superconducting wire. The superconducting magnet design is a complex physics issue, which needs to make a trade-off between different approaches, considering magnet structure and bore size; sometimes, an asymmetric design will be the best choice [5].

In this paper, a new asymmetric type of 7 T Penning trap is designed using both linear and nonlinear methods. The parameters of such a 7 T Penning trap are shown in Table 1.

Table 1. Specification of a superconducting magnet.

item	value
central field/T	7
homogeneity	3×10E-7 within 1 cm^3
5 Gauss stray field contour/m	3.0
magnet length/m	<0.8
bore size/mm	156

2 Coil design

The goal of the asymmetric coil design is to optimize the magnetic field homogeneity while achieving a low stray field [6, 7]. As shown in Fig. 1, the feasible coil section was divided into several sections with the target region a constraint for the linear solution. For the asymmetric design, the target region is asymmetrically distributed with the center of the region closer to one side of the current section than the other. Linear programming was used to get the rough design for the asymmetric superconducting coil with Target Region 1 including two homogenous regions as required by the Penning trap. In order to get a better result, Target Region 2, which is larger than Target Region 1, was set as another constraint for linear programming. In order to meet the requirements for the stray field, the target field was set as a 5 Gauss region. The linear programming solution is shown in Fig. 2. Non-linear programming was then used to achieve rectangular coils, as shown in Fig. 3. By optimizing the radial and axial dimensions of each

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1) E-mail: bianwenlong@impcas.ac.cn
2) E-mail: malz@impcas.ac.cn

Table 2. Specification of an asymmetric superconducting magnet.

coil No.	coil1	coil2	coil3	coil4	coil5	coil6
turn/layer	96	52	65	60	99	144
layer	60	48	44	50	64	20
wire length/m	5296	2209	2511	2684	5890	6401
SC wire/mm	1.28×0.83	1.28×0.83	1.28×0.83	1.28×0.83	1.28×0.83	1.28×0.83
max field/T	8.39	7.48	7.27	7.43	8.36	2.97
iop/A	250	250	250	250	250	250
iop/I_c	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
radial force/Ton	293	140	154	147	276	113
axial force/Ton	121	3.04	−1.97	−1.55	−125.33	10.13

coil, we could get the final electromagnetic design of the Penning trap. Before nonlinear optimization, the superconducting wire was chosen based on the linear results, selecting NbTi wire manufactured by Western Superconducting Technologies in China, with I_c=600 A at 7 T.

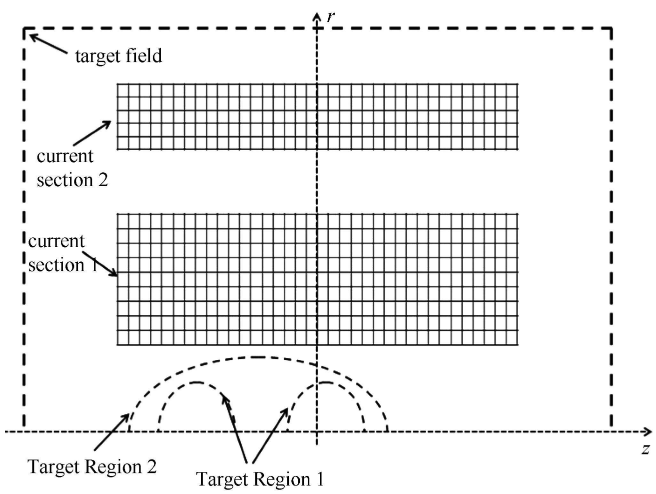

Fig. 1. The multi-section feasible coil space with numerical grid.

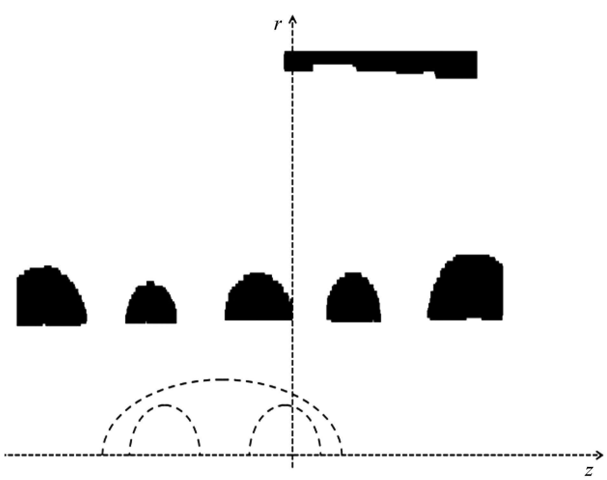

Fig. 2. Coil position of linear program.

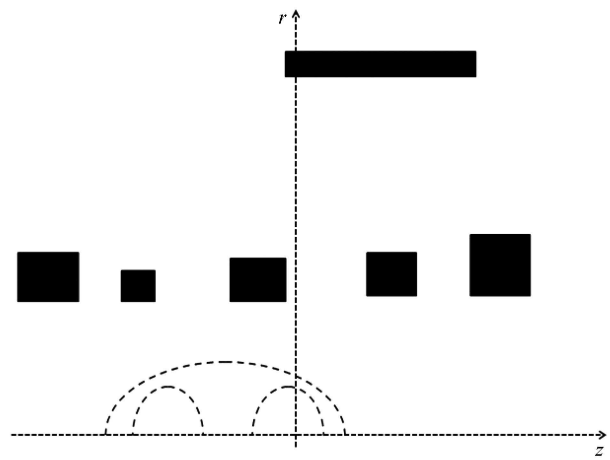

Fig. 3. Coil position of nonlinear program.

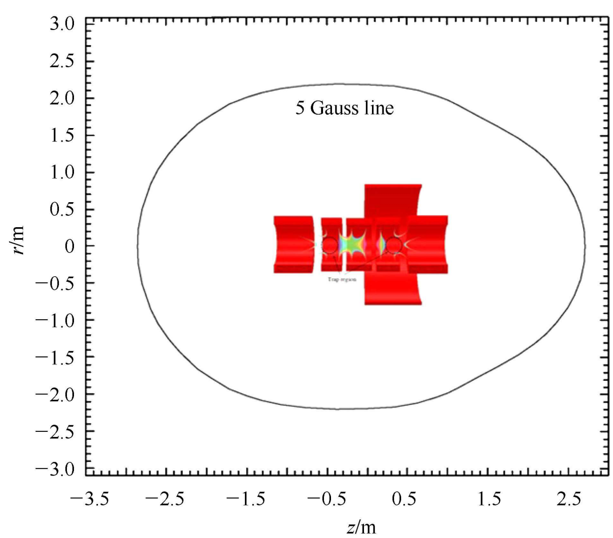

Fig. 4. Stray field contour of the magnet.

The specifications of the asymmetric Penning trap magnet are presented in Table 2. The magnet consists of 6 coils and the superconducting wire use ratio is less than 50%. The two trap regions are clearly shown in Fig. 4. The stray field is limited to 3.0 m with the help of the bulking coil of the opposite current; because of the asymmetric design, the stray field at the bulking size is less than 2.5 m.

3 Stress analysis

The stress distribution of the coils was investigated by considering pre-tension, cooling expansion and coil charging. The coils are wound on a 304L stainless steel former with a pre-tension of 5 kg, with 4 layers of aluminum over-binding on coil1 and coil5 with a pre-tension of 10 kg. The magnetic force distribution of the coils is shown in Fig. 5. The finite element method was used for stress analysis, with three steps in the analysis: the winding pre-tension was first loaded, then the wire cooled down to 4.2 K, and finally the magnetic force was loaded on the node at the wire position by reading the magnetic force matrix. The radial stress of the coil is shown in Fig. 6. The maximum stress of the coil is 14.8 MPa. The radial stress at the innermost layer was just 1.4 MPa, which is a safe stress level for the coil [8].

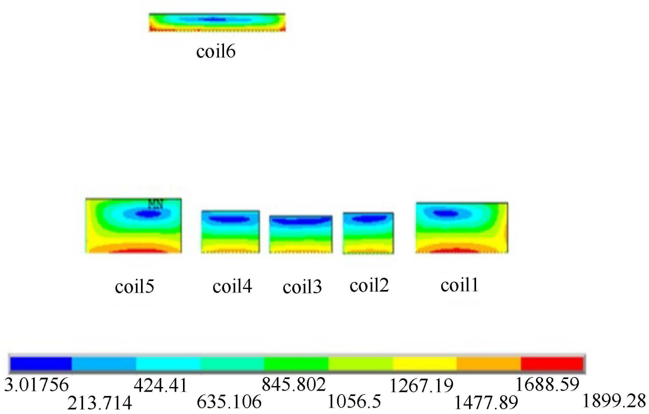

Fig. 5. Magnetic force distribution in coils.

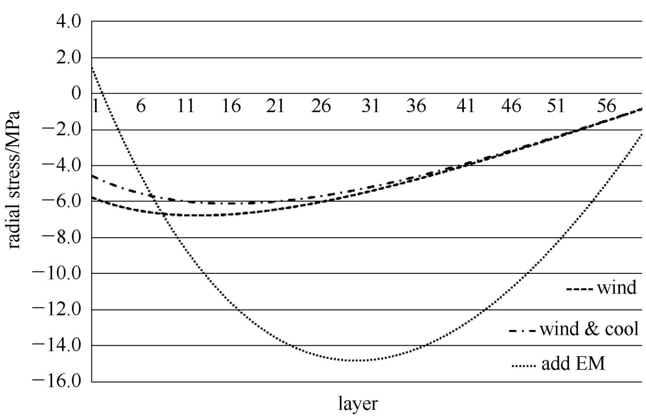

Fig. 6. Radial stress inside coil1.

4 Mechanical design

The configuration of the cryostat is shown in Fig. 7. The main coils are wound on a high strength former made of 304L stainless steel, which is widely used in cryogenics. The bulking coil is wound on the former, which is welded to the end plate of the 4 K vessel. 12 triangular type 304L supports, including supports for bulking coil, are used to prevent coil deformation after winding and cooling. With this design, there is enough space for a quench protection circuit (not shown in this figure). The 4 K superconducting magnet is supported by 8 carbon fiber rods. Two HTS (high temperature superconductivity) current leads are used in the magnet to decrease heat leak during ramping, with the top side of the HTS leads connected to the first stage of the cryocooler to make sure that the top temperature is below 70 K. The total length of the magnet is less than 0.8 m, the diameter of the 300 K vessel is 0.95 m, and the diameter of the 4 K vessel is 0.75 m.

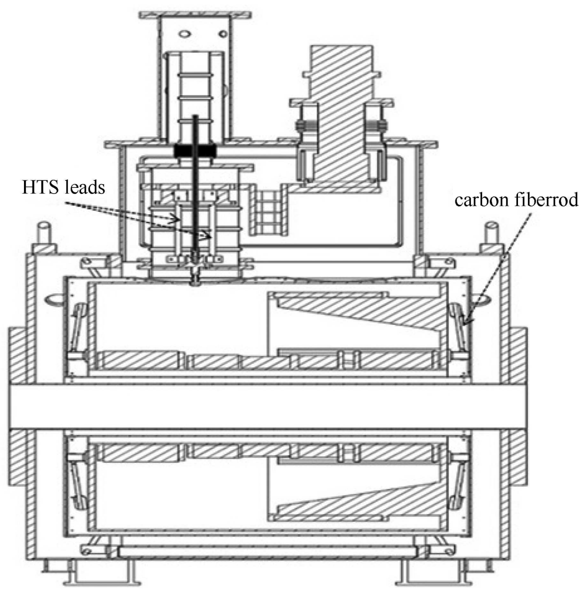

Fig. 7. Mechanical design of the magnet.

5 Quench analysis

The magnet inductance is more than 40 H, which means there is more than 1 MJ of energy stored in the magnet. A quench circuit was designed to protect the magnet from being destroyed during a quench. The quench simulation was carried out using OPERA-3D QUENCH program. It is assumed that the quench starts on coil1 and the quench time is between 0 and 0.1 s, and no protection circuit was considered at first. Fig. 8 shows the maximum quench voltage can reach as high as 1500 V without the quench protection circuit. The protection circuit was then added to the simulation. Fig. 9 shows

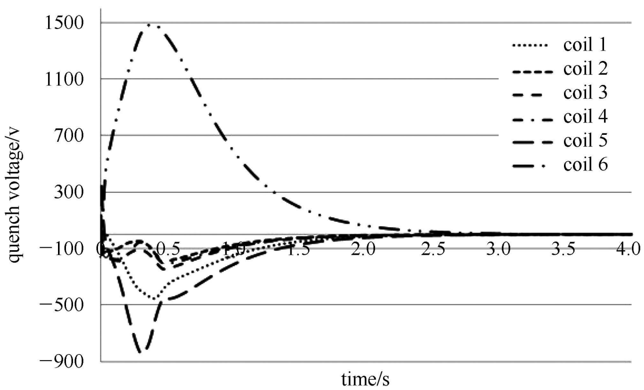

Fig. 8. Quench voltage without protection circuit.

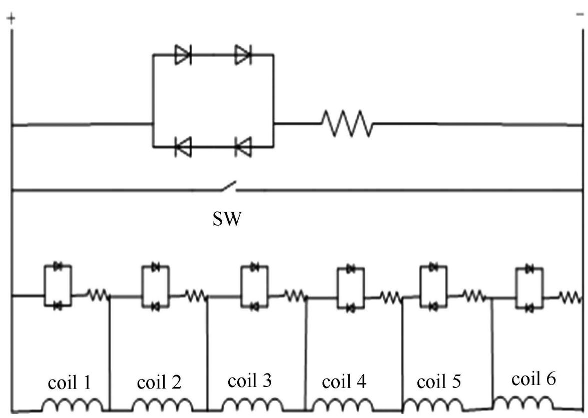

Fig. 9. Protection circuit.

the quench protection circuit of an asymmetric extremity magnet: each of the coils in the system is wired in parallel with a dump resistor and back to back diode, with the right dump resistors chosen to ensure the quench safety and protection of the magnet [9]. With the protection circuit, the maximum voltage decreases to 350 V, as shown in Fig. 10. Fig. 11 shows that the current in

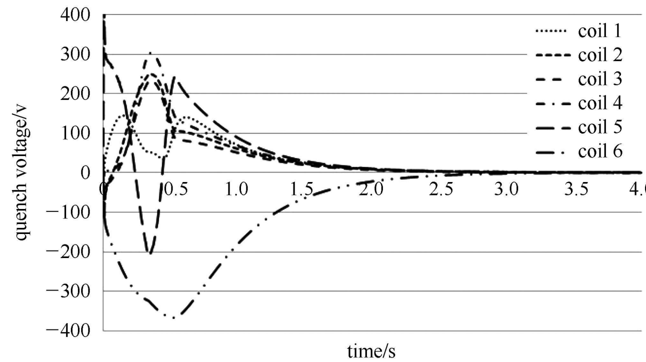

Fig. 10. Quench voltage with protection circuit.

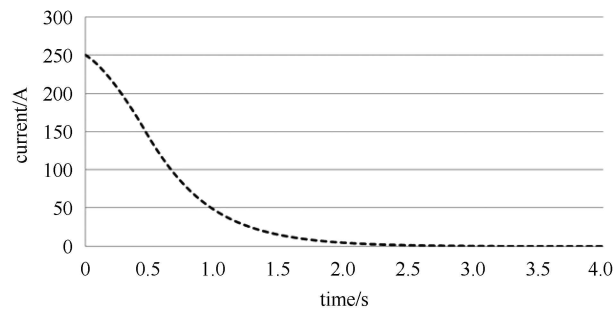

Fig. 11. Current decay curve during quench.

the magnet decreases from 250 A to 0 A in 2.5 s during a quench.

6 Conclusion

An asymmetric Penning trap has been designed using linear and nonlinear programming to show that the magnet has two qualifying trap regions. Stress analysis and quench analysis show the feasibility of the design. The mechanical design shows the benefits of the asymmetric design, as the magnet has a compact size and leaves enough room for a quench protection circuit.

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