TOPOLOGY OPTIMIZATION FOR A SUPERCONDUCTING CYCLOTRON MAIN MAGNET*

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Abstract

Main magnet is the heaviest component in a superconducting cyclotron, which occupies a large amount of cost. Topology optimization method is implanted to minimize the weight of main magnet while keep the field performance, which will make significant economic benefit. Due to the powerful superconducting coils, the main magnet is driven into saturation, and the nonlinear effect of the material must be considered. If the ordinary standard density method is used for the main magnet structure optimization, the nonlinear B-H relation have to be interpolated and the sensitivity analysis is very complicated. In this paper, a proper 2D model is established and the optimization formulation is given using standard density method. Then, the optimized topology of the main magnet for a 250MeV superconducting proton cyclotron is designed.

INTRODUCTION

A superconducting cyclotron is underdevelopment in Huazhong university of science and technology for proton therapy [1]. The extraction energy of the proton beam from this cyclotron is 250 MeV. Main magnet is the heaviest component in a superconducting cyclotron, which occupies a large amount of cost. And the average magnetic filed of 2.4 T is designed in the central region. Thus, the main magnet operates with the iron saturated.

In this paper, a new yoke shape is designed to minimize the weight of main magnet while keep the field performance inside the cyclotron using topology optimization method. Before optimization, a 2D model is established using the pseudo material to reflect the 3D structure of the pole in the main magnet. On basis of the 2D model, the constrain and object function is given, the result shows that the new yoke saves about 25% weight of the original one with the same magnetic energy storage in the gap of the poles.

2-D MODEL OF THE MAIN MAGNET

The main magnet consists of 3 parts: poles, yoke and superconducting coil. The cross section is shown in Fig. 1, in which the yoke and superconducting coil can be described using two-dimensional (2D) rotation symmetry model. While the pole contains four spiral sectors, thus, only three-dimensional (3D) model can reflect the structure of the pole. Like most topology optimization methods, the 3D model should be reduced to a 2D problem.

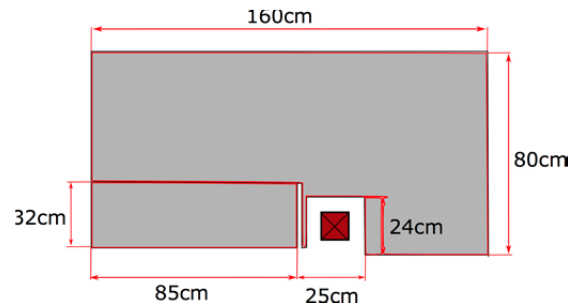

Figure 1: Cross section of the main magnet.

To establish the 2D model for optimization, a uniform surface current distribution is assumed to describe the coil. B-H curve is used to describe the nonlinear property of the soft iron for the pole and yoke. In this paper, a homogeneous mixed air and soft iron material is used to describe structure of the hills and valleys, that the magnetic pole is equivalent to a two-dimensional axisymmetric model, this approximation is often used to calculate the radial distribution of the average magnetic field [2], the magnetic induction intensity B' and the magnetic field strength H of the pseudo material satisfy the following formula

$$B' = \mu_0 H + k\left(B - \mu_0 H\right) \qquad (1)$$

B in the right side can be obtained by B-H curve of the normal soft iron, k is the width ratio of the hill. B-H curve of the pseudo material with different width ratio of the hill is shown in Fig.2. The saturation field strength increases with the width ratio k, while the slope of the B-H curve converges to μ_0.

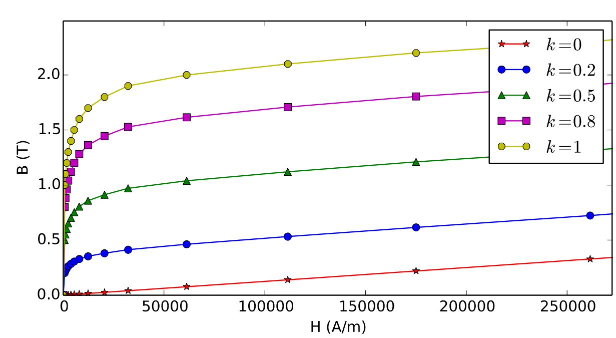

Figure 2: B-H curve of the pseudo material with different width ratio of the hill.

On assumption of the pseudo material, the two-dimensional model of the main magnet is established in the finite element software Comsol. The distribution of the magnetic flux density is shown in Fig. 3. It can be seen from the figure that the magnetic field strength

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reaches the maximum value in the pole region, while in the vicinity of the axis of symmetry and in some corners there appears low magnetic field strength areas, in these areas, soft iron material utilization is low in these regions.

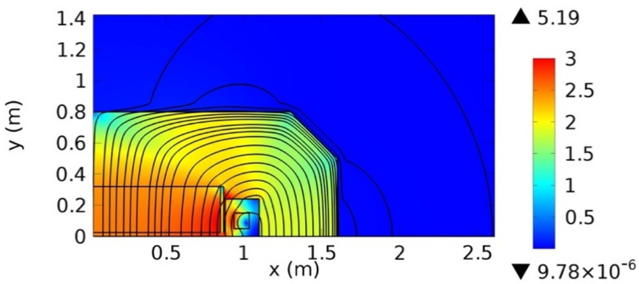

Figure 3: Distribution of the magnetic flux density.

OPTIMIZATION OF THE YOKE

In the optimization process, the optimization objective is to reduce the weight of the yoke in the case of ensuring the magnetic field strength between the magnetic gap of the poles, the model for optimization is shown in Fig.4. It contains 5 regions: coil, pole region with pseudo material, fixed yoke region with normal iron material, optimization region, and the integral object region in the gap. The iron distribution in the optimization should be adjusted to find the maximum magnetic field energy in the integral region.

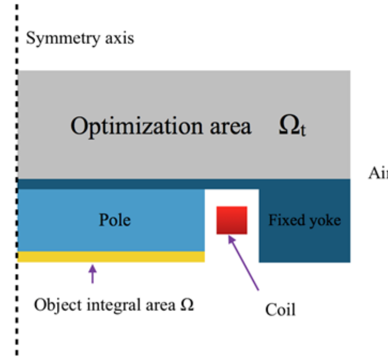

Figure 4: Model of the optimization.

The control variable is the iron density ρ. Objective function is given as,

$$Maximize\Big|_{\rho_{design}} : E(\rho) = \iint_{\Omega_t} B \cdot H \, d\Omega \quad (2)$$

where Ω is the object region. The iron density satisfies 0< ρ<1. To reduce the volume of the yoke, iron density ρ is constrained by

$$0 \le \int_{\Omega_t} \rho \, d\Omega \le \gamma A \quad (3)$$

where A is the area of the optimization region，γ is the reduced ratio of the yoke. Material property satisfies,

$$B' = \mu_0 H + \rho^p \left(B - \mu_0 H \right) \quad (4)$$

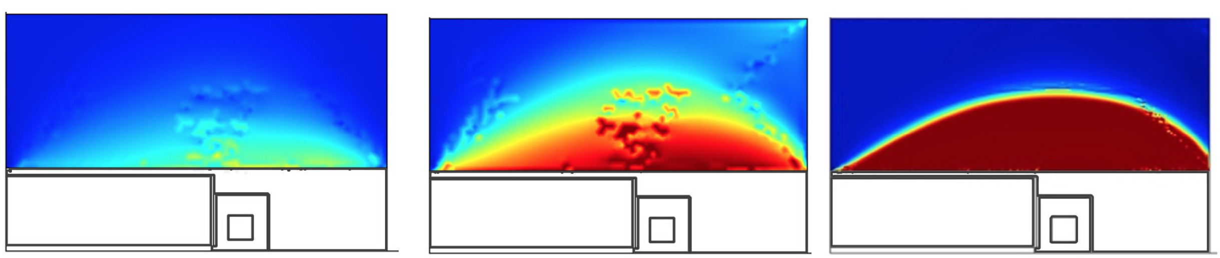

Figure 5: Iron density distribution during the iteration.

it is similarity to the expression of the pseudo material used to describe the pole. A Penalty factor p is used to ensure the continuity of the topology [3][4].

RESULTS AND DISCUSSION

Using the above method with the penalty factor of 2.4, target volume is reduced to 0.75 of the original volume, and the initial condition of the iteration is set to the constant density of 0.75. The process of the iteration is shown in Fig. 5. With the process of iteration, the material density tends to be binarized, eventually converging to a smooth continuous region.

The 2D model with the new yoke is evaluated by the finite element analysis software Comsol. Fig.6 shows the magnetic field distribution of the new 2D model. The distribution of the magnetic field in the yoke is relatively uniform than that in Fig. 3, the area of the low field region is reduced, and the weight of the magnet is 0.75 of the original model. The axial component of the magnetic field B_z along the radius is shown in Fig.7. In the model with the optimized yoke, the axial component of the magnetic field B_z is lower than that in the original model in the central region, but it is higher in the extraction region, this can be compensated by the width of the hill.

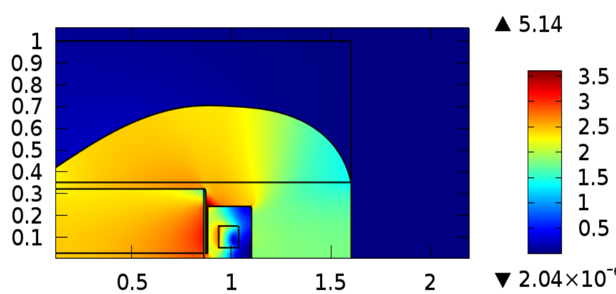

Figure 6: Magnetic flux density in the optimized yoke.

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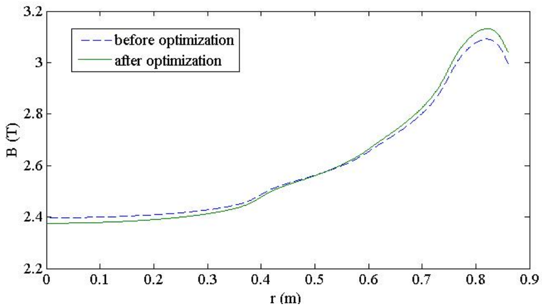

Figure 7: B_z along the radius before and after the optimization.

CONCLUSIONS

In this paper, a 2D model of the main magnet of the superconducting cyclotron is established using the pseudo material. On the basis of the 2D model, a new algorithm of magnet topology optimization is proposed. After the optimization the magnetic field energy storage in pole gap is close to that of the original model. But the new model saves about 25% material. This method provides a general algorithm for the optimization of the yoke of the superconducting cyclotron.

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