FIELD STUDY OF THE 4 T SUPERCONDUCTING MAGNET FOR RAPID CYCLING HEAVY ION SYNCHROTRONS*

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Abstract

The problem of the magnetic field optimization of a 4 T dipole magnet with circular aperture of 100-110 mm for rapid cycling synchrotron is considered. The use of a single layer low inductance coil made of high current hollow superconducting cable operating at 30 kA is proposed. The magnetic field ramp rate up to 4 T/s should be achievable. Mathematical method to minimize sextupole and higher order non-linearities to the tolerable values by variation of angular position of the coil turns is developed. The results of numerical simulation of 2D magnetic field are presented. The further possibilities to improve the field quality for similar magnets and their application for heavy ion and proton synchrotrons and boosters are discussed.

INTRODUCTION

Fast cycling dipoles of a "window frame" type operating at B_{max} = 2 T, dB/dt = 4 T/s and f = 1 Hz were designed and tested in the frames the Nuclotron construction at JINR in Dubna [1]. Coils of the dipoles are made from hollow superconducting NbTi cable cooled with two-phase helium flow at temperature of T = 4.5 K. The iron yoke is also cooled up to liquid helium temperature.

During the last three years R&D works on improvement the Nuclotron dipole are carried out by the JINR/GSI collaboration [2]. The main research goal of the collaborative works is to construct fast-cycling superconducting 2 T, and 4 T/s dipole for heavy ion synchrotron SIS100 [3]. It was experimentally achieved a reduction of the dynamic heat losses by a factor of 4 in comparison with the original Nuclotron lattice dipole. It is possible to obtain the further reduction of AC losses in the magnet with the using of new SC cable based on the new NbTi wire with a filament diameter of 3.5 - 4 μm instead of 6 μm in the reference [1].

Considerable progress that have been achieved in the design and study of a fast cycling 2 T magnets based on a hollow superconducting cable makes very promising application of the described approach for heavy ion and proton synchrotrons with the field ramp of 4 T/s and peak magnetic field up to 4 T and higher.

The conceptual design of the rapid cycling superconducting magnet with a field up to 4 T, using hollow NbTi cable, has been presented at [4]. The single layer winding is made by the hollow NbTi cable with coil turn number of 2N = 12 – 16. The maximum operating current in the winding is 30 kA. In this paper we study magnetic field of the low turn winding dipole with circular aperture of 160 mm. One fourth part of the dipole magnet cross section is shown in Fig. 1.

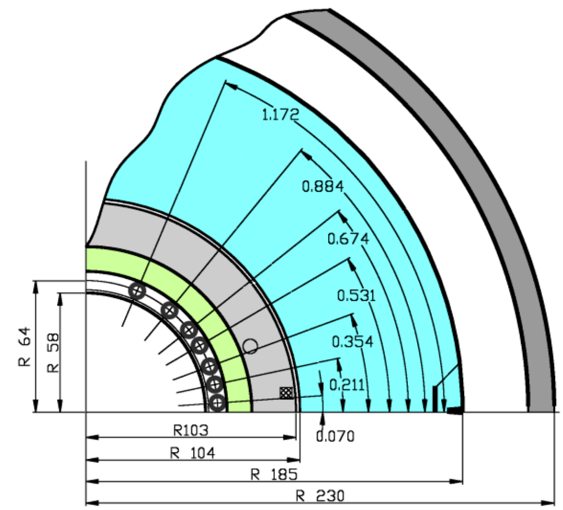

Figure 1. 1/4 cross section of the rapid cycling superconducting magnet.

COMPUTER SIMULATION METHOD

Let us examine the optimization problem of the two-dimensional magnetic field distribution with the aid of the variation of the current winding position, without a change of the iron screen configuration. Basic purpose consists in obtaining of the field with the assigned uniformity in an operating region of magnet, which has the form of the circle of radius *r*. There are 2N current turns, whose centers are located on the circle of radius *R*. Position of the each *i* - winding is characterized by the angle ϕ_i. We will solve optimization problem by variation of the angles.

The expansion of the magnetic field components in Fourier series is one of the most convenient methods for estimation of the field distribution quality. The complexity of the task consists in the fact that it is necessary to obtain field uniformity for the broad range of a current change.

The constant permeability models work quite well for low field. It is possible to use a constant (sufficiently high) value of magnetic permeability μ in iron yoke for this range The advantage of this model over the rests consists in the possibility to obtain magnetic field as a linear vector function of the winding current This fact allows to reduce the computational time at the optimization of the magnetic field substantially.

Let *G* is region, filled with iron, *B(x)* – magnetic field,

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H(x) – tension, *M(x)* - magnetic moment, $\mu = \mu(x)$ - magnetic permeability, $H^S(x)$ - field of the current elements. The integral formulation of the problem in the three-dimensional space is given in [5]

$$H(a) = H^S(a) + \frac{1}{4\pi}\nabla_a \int_G \left(M(x), \nabla_a \frac{1}{|x-a|} \right) dV_X \quad (1)$$

The values *B(x), H(x)* and *M(x)* are connected by the next relations

$$H(a) = \frac{B(a)}{\mu(|B(a)|)\mu_0}, \quad M(a) = \frac{B(a)}{\mu_0} - H(a) \quad (2)$$

The tension of magnetic field $H^S(a)$ from current source in (1) is determined by Biot-Savart low

$$H^S(a) = \frac{1}{4\pi}\sum_{i=1}^{N}\int_{\Omega_i}\left[\nabla_a \frac{1}{|x-a|} \times J_i^S(x)\right] dV_X \quad (3)$$

where $\{\Omega_i,\ i = 1, N\}$ are current windings; $J_i^S(x)$ is current density in *i*-th winding.

For 2D task equation (1) is reduced to the next one:

$$H(a) = H^S(a) + \frac{1}{2\pi}\nabla_a \int_G (M(x), \nabla_X \cdot \ln|x-a|) dS_X \quad (4)$$

The tension $H^S(a)$ is estimated by the next formulas:

$$H^S(a) = \frac{1}{2\pi}\sum_{i=1}^{N}\int_{\Omega_i}\left[\nabla_X \cdot \ln|x-a| \times e_0 J_i^S(x)\right] dS_X \quad (5)$$

e_o is unit vector, orthogonal of the plane.

In the case of a constant magnetic permeability μ equation (4) is transformed to the boundary integral equation

$$H(a) = H^S(a) + \frac{1}{2\pi}\nabla_a \oint_{DG} (M(x),\ n_x) \cdot \ln|x-a|) dl_X \quad (6)$$

For $x \in DG$ the function $\sigma(x)$ is $\sigma(x) = (B(x), nx)$. Then from (2) and (6) we obtain [6]

$$\frac{\sigma(a)}{\mu} = \mu_0 (H^S(a), n_a) + K(a) \quad (7)$$

where $H^S(a)$ and *K(a)* are

$$H^S(a) = \frac{1}{2\pi}\int_{\Omega_i}\left[\nabla_X \cdot \ln|x-a| \times e_0 J_i^S(x)\right] dS_X$$

$$K(a) = \frac{1}{2\pi}(1 - \frac{1}{\mu})(n_a, \nabla_a \oint_{DG} \sigma(x) \ln|x-a| dl_X)$$

$\sigma(a)$ of (7) is equal

$$\sigma(a) = \sum_{i=1}^{N}\sigma_i(a) \quad (8)$$

where $\sigma_i(a)$ is the solution

$$\frac{\sigma_i(a)}{\mu} = \mu_0 (H_i^S(a), n_a) + K_i(a) \quad (9)$$

For a constant magnetic permeability μ field from several windings can be obtained as sum of the fields from each winding individually. The obvious consequence of this fact is possibility to calculate the Fourier coefficients for the magnetic system as their sum for each winding individually.

Let us examine the procedure of the optimization of field distribution. One can designate $\{f_i,\ i = 0; L\}$ and $\{g_i,\ i = 0; L\}$ as the first (L+1) – harmonic number of the component of magnetic field B_x and B_y respectively. A functional F corresponding to the uniformity of the magnetic field is determined as

$$F = F(\phi_1, \phi_2, ..., \phi_N) = \sum_{i=0}^{L}\left(\frac{f_i}{g_0}\right)^2 + \sum_{j=1}^{L}\left(\frac{g_i}{g_0}\right)^2 \quad (10)$$

For minimization of the functional it was used the method of gradient descent. It should be noted that the uniformity of the field with the low values does not guarantee uniformity with the great significances of induction because of the strong nonlinear dependence of field on the current in the windings.

Therefore for the selected configuration of windings the solution of integral equation (4) makes it possible to consider the effects of saturation of iron with large fields.

RESULTS OF SIMULATIONS

The calculations of dipole component showed the required induction of the magnetic field of 4 T to be realized in the magnet with 7 turns in the half winding with the current 30 kA. The diameter of external cable was selected with 9 mm. For 6 turns the induction of field with the current 30 kA is 3.5 T. The computer simulation results are presented in Fig. 2, 3 and in the Table 1.

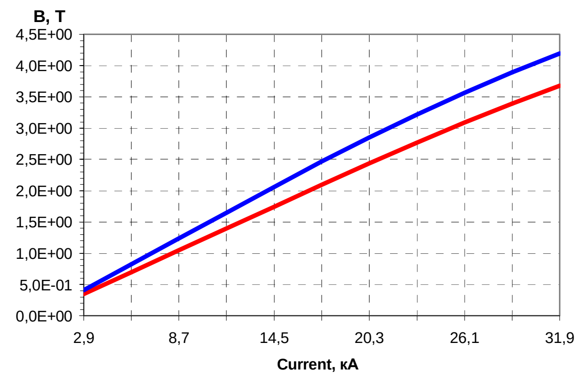

Figure 2. Dipole magnetic field as a function of operating current for 6 and 7 turns in half winding (lower and upper curves respectively).

Angular coordinates of the turns were determine to minimize the amplitudes of the odd harmonics from the third and higher. The optimized angular positions each of 7 turns in the half winding are shown in Fig. 1. The values of the non-linearities of magnetic field were calculated for B = 4 T and r = 40 mm.

For example the values of nonlinearities presented in the table would lead to grow of beam betatron tune spread of 0.03 in the case of Nuclotron. It is not so dangerous at heavy ion acceleration. The difficulties would arise at the beam slow extraction. Such distortions will cause partial stabilization of the betatron amplitudes at crossing of the resonance band [7].

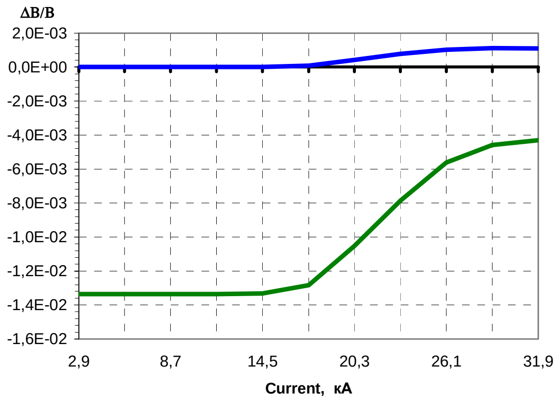

Figure 3. The relative values of the sextupole field component before and after optimization (lower and upper curves respectively).

Table 1. The relative values of the highest harmonics at B = 4 T.

Number of harmonics	N=7 (before optimization)	N=7 (after optimization)
3	$4.31\ 10^{-3}$	$1.1\ 10^{-3}$
5	$-1.29\ 10^{-3}$	$3.01\ 10^{-5}$
7	$5.93\ 10^{-3}$	$-2.28\ 10^{-5}$
9	$1.29\ 10^{-3}$	$-6.81\ 10^{-6}$

Unfortunately we could not decrease the relative value of sextupole non-linearity up to magnitude order of 10^{-4} optimizing the azimuth position of turns only.

Therefore further optimization assumes the modification of the iron screen form and (or) arrangement of additional correcting windings.

CONCLUSION

R&D of the superconducting rapid cycling dipole magnet with field of 4 T, based on the superconducting hollow cable, is continued. The optimization of magnetic field in the operating region by means of the angular coil distribution was carried out at this stage. The obtained results are acceptable for the rapid acceleration of ions, for example, for boosters.

We connect further improvement of the field quality with the optimization of the magnetic screen form and active correction of sextupole component.

The next step will be development of a quadrupole lens with low turn windings made from hollow superconducting cable.

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