Краткие сообщения ОИЯИ № 4[67]-94 *JINR Rapid Communications No.4[67]-94*
УДК 621.384.634.5

ACTIVELY SCREENED SC MAGNETS

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The concept of new actively screened SC magnets without a steel yoke for high energy accelerators is proposed, and their main features are discussed.

The investigation has been performed at the Laboratory of High Energies, JINR.

Активно экранированные СП магниты

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Предложена новая концепция активно экранированных СП магнитов без железного ярма для ускорителей высоких энергий и обсуждаются основные их свойства.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Introduction

In modern SC magnets the field strength and its quality are determined by a SC coil and its shape. Nevertheless, a cold steel yoke constitutes 80% and more of the magnet weight what significantly increases the magnet cost and time and cost of its cool-down and warm-up [1]. The steel yoke increases the magnet field only by 20—25%, and its main role is to shield stray fields. This task can be successfully resolved by an additional SC coil that only slightly increases the superconductor volume but drastically reduces the total magnet weight and its cost, and permits one to avoid such unpleasant features of the cold yoke as an additional energy losses due to steel magnetization in a pulse mode and nonlinearities with steel saturation at high fields.

We consider analytically the field of a shielded magnet and show how the volume of a superconductor should be increased to get a complete active shielding.

1. Ideal Magnet

Dipole and quadrupole fields required in high energy accelerators are produced by SC coils of two shapes [2]: overlapping ellipses and $\cos\theta$ for a dipole field and crossed elipses or $\cos 2\theta$ for a quadrupole one which provide ideal fields. We consider overlapping ellipses, and it may be shown that cos θ coil is the limiting case of the latter.

The coil shape can be deduced using a straight cylindrical infinitely long conductor with a uniform current density j. If the conductor cross section is an ellipse with axes a and b ($b < a$), then its field H in complex form can be written as [3]

$$H = H_y + \mathrm{i}H_x = \frac{0.4\pi j}{a + b}(bx - \mathrm{i}ay) \tag{1}$$

inside the conductor and

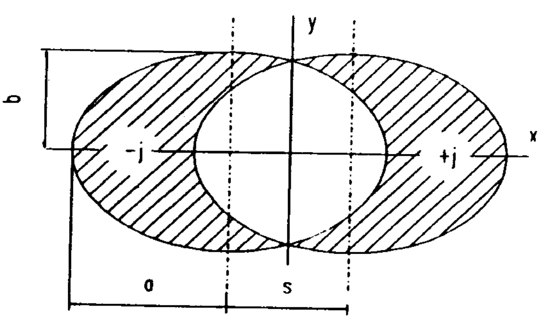
$$H = \frac{0.4\pi jab}{z + \sqrt{z^2 - c^2}} \tag{2}$$

outside it. Here $c^2 = a^2 - b^2$, $z = x + \mathrm{i}y$, $\mathrm{i} = \sqrt{-1}$ and the origin of the coordinate system coincides with the conductor center. The field is in G if the current density is expressed in A/cm^2 and all linear dimensions in cm.

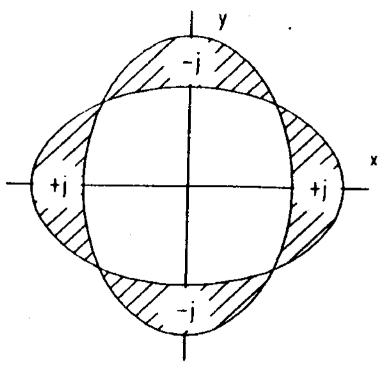
Two such conductors overlapped at a distance s between their centers and carrying the same current densities but of opposite signs produce a pure dipole field

$$H_y = \frac{0.4\pi jsb}{a + b}, \quad H_x = 0 \tag{3}$$

inside the overlap region that is free of current. Two crossed similar conductors create a pure quadrupole field inside the aperture



a)



b)

Fig.1. Coil cross sections of an ideal dipole a) and quadrupole b)

$$H_x = Gy, \quad H_y = Gx, \quad G = -\,0.4\pi j \,\frac{a-b}{a+b}. \tag{4}$$

These two cases are shown in Fig.1. Dimensions of the ellipses have to be chosen such that to provide the required field strength or gradient at a given current density and to leave enough a current free space between them to place there a vacuum chamber for an accelerating beam. Evidently, the outside fields of the magnets are not equal to zero.

2. Screened Magnet

Let us consider now a similar elliptical conductor immersed into a bigger or screening one with axes a_s, b_s and a current density j_s as shown in Fig.2.

The magnetic field outside this pair of conductors is equal to

$$H_{out} = 0.4\pi\left(\frac{jab}{z+\sqrt{z^2-c^2}} + \frac{j_s a_s b_s}{z+\sqrt{z^2-c_s^2}}\right). \tag{5}$$

The last equation shows that the outside field is zero if the following two conditions are fulfilled

$$jab = -j_s a_s b_s, \tag{6}$$

$$c = c_s. \tag{7}$$

Eq.(6) means that the total currents in both conductors are the same but of opposite directions, and from eq.(7) it follows that the focuses of both elliptical conductors coincide.

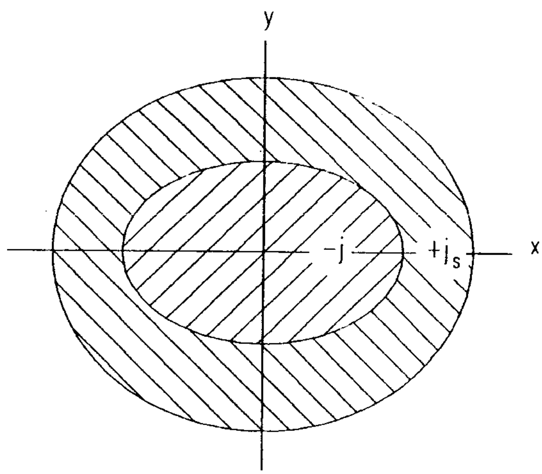


Fig.2. A screened elliptical conductor

Now suppose that

$$a_s = ka \quad \text{and} \quad k > 1. \tag{8}$$

Then according to eq.(7) and (6), we find

$$b_s = \sqrt{b^2 + (k^2-1)a^2}, \tag{9}$$

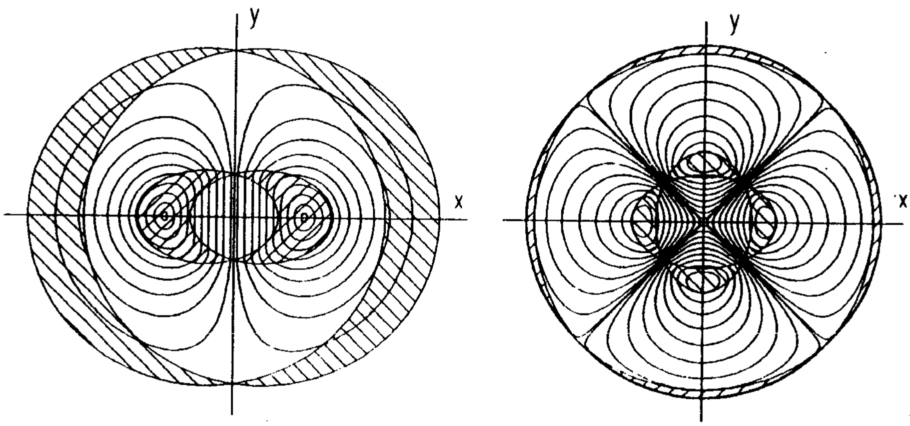


Fig.3. Computer plot of the magnetic fields in a screened ideal dipole, on the left hand, and a quadrupole, on the right hand, for $k = 2.5$

$$j_s = -j \frac{b}{k\sqrt{b^2 + (k^2 - 1)a^2}} \approx -\frac{j}{k^2}. \qquad (10)$$

The last approximation is valid if $a \approx b$ and $k >> 1$. This pair of screened conductors is used lower to construct ideal magnets as one eliptical conductor was used above.

If we now take another pair of similar conductors with as opposite currents as before and overlap (or cross) them, we shall get an ideal dipole (quadrupole) magnet without stray fields (Fig.3). Then the dipole field of the screened magnet is equal to

$$H_{ys} = -\frac{0.4\pi jbs}{a + b}\left[1 - \frac{a + b}{k(ka + b_s)}\right] = H_y(1 - h), \quad H_{xs} = 0. \qquad (11)$$

The gradient G inside the wholly screened quadrupole lens equals

$$G_s = -0.4\pi j \frac{a - b}{a + b}\left[1 - \frac{b}{kb_s}\left(\frac{a + b)}{a_s + b_s}\right)^2\right] = G(1 - g). \qquad (12)$$

Here dimensionless values of h and g show how much the field and gradient of screened magnets differ from the same value of unscreened coils. Evidently, a minimal value of k is $1 + s/a$. If we choose larger k, then there will be enough a current free space between screening conductors and a main coil to place there force collars that constrain coil motion to negligible levels. The area S of the main dipole coil is equal to

$$S = 2ab\left(\arcsin\frac{s}{2a} + \frac{s}{2a}\sqrt{1 - \frac{s^2}{4a^2}}\right) \approx 2bs\left(1 - \frac{s^2}{24a^2}\right). \quad (13)$$

The total current in this coil or its ampere-turns Iw are then $Iw = jS$. From this equation and eq. (10) it follows that the same value for the screening coil Iw_s is

$$Iw_s \approx \frac{Iw}{k}. \quad (14)$$

The field strength at the screening coil is very low, and so the critical current density in it is 3—5 times higher the in the main coil. Therefore, the total additional volume of the superconductor in this coil needed for a wholly screening is of the order of 10% of the superconductor in the main coil if k is equal to 2.5 and more.

A SC volume needed to screen a quadrupole lens is even lower. The cross section area S_m of its main coil equals

$$S_m = 2ab\left(\arccos\sqrt{\frac{1 - e^2}{2 - e^2}} - \frac{\pi}{4}\right) \approx \frac{c^2}{2}\sqrt{1 - e^2}, \quad (15)$$

where $e = ca^{-1}$ is the coil eccentricity. The area S_s of the screening coil is

$$S_s \approx \frac{c^2}{2}\sqrt{1 - \frac{e^2}{k^2}} \quad (16)$$

or almost the same as the main coil area. Therefore, eq. (14) in the case of a quadrupole lens takes the form

$$Iw_s \approx -\frac{Iw}{k^2}. \quad (17)$$

It reflects the fact that a field outside a dipole drops with a distance r as r^{-2} and a quadrupole r^{-3}. So the additional SC volume for screening a quadrupole coil is lower than in the case of a dipole.

Conclusion

As is shown above, SC magnets without stray fields can be constructed at least in the two-dimensional case. The total additional volume of the superconductor in actively screened dipole magnets is 30—35% higher than in magnets with iron shielding but their weight 5—8 times lower.

Stray fields at the magnet ends need three-dimensional computer calculations. It is evident a priori that the screening will not be so wholly there as in considered case, but end stray fields will be much lower, and these low fields can be effectively shielded by soft steel walls of a warm vacuum vessel of a LHe cryostat. The walls are far enough from SC coils because between them there are one or two thermal screens.

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Received on September 1, 1994.