THE DESIGN OF HOMOGENEOUS FIELD SOLENOIDS FOR THE IUCF COOLER SECTION[†]

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Summary

For the electron cooling system three solenoids are designed and under construction. Special attention has been paid to the tolerances to be imposed on the position of the individual turns, the transition between the solenoids and the toroids and the correction for end effects of the solenoids. To measure the field of the combination of toroids and solenoids a special hallprobe assembly with five probes will be used. The procedures to be used for field correction are described.

Introduction

The magnetic field to guide the electron beam will be produced by three solenoids and two 60° toroids. See Ref. 1 for details. The main solenoid produces the actual guide field in the cooling region. The gun-and collector solenoid contains respectively the acceleration column with the electron gun and the deceleration column with the collector. The length of the main solenoid is about 270 cm, the inner diameter is 25 cm. It consists of two layers of 1.65 cm square conductors. Each layer has 31.1 turns of five conductors in parallel. The outer layer is rotated over 36° with respect to the inner layer so that at both ends a conductor of the inner layer meets one of the outer layer. In this way the two times five conductors are electrically connected in series and the water channels are in parallel. There are no splices in the conductors. A current of 1100A is needed to create a field of 0.15T. Each conductor dissipates about 2.8 kW at 0.15T. With a waterflow of 76 ℓ/sec the maximum temperature rise will be about 7°C. Figure 1 shows some details, it also shows the tolerances imposed on each turn and each layer. They are explained in the next section. The given straightness tolerances are average values averaged over five turns. The gun-and collector coils are constructed in the same way. There length is shorter and the diameter is twice the diameter of the main solenoid which means that the tolerances can be larger.

The toroids are existing 60° toroids used in an experimental setup at Fermi-National-Laboratory. To get field lines perpendicular to both ends they have iron plates to define the boundary conditions.

The transition between the toroids and solenoids requires a set of correction coils which are described below. Other correction coils are used to create a homogenious field along the axis of the gun solenoid, to create a required field gradient at the collector and to steer the electron beam. A special set of correction coils may be needed to compensate for field imperfections in the main solenoid.

Tolerances imposed on the position of the turns of the main solenoid

Basic formulaes

While the electrons tend to follow the field lines

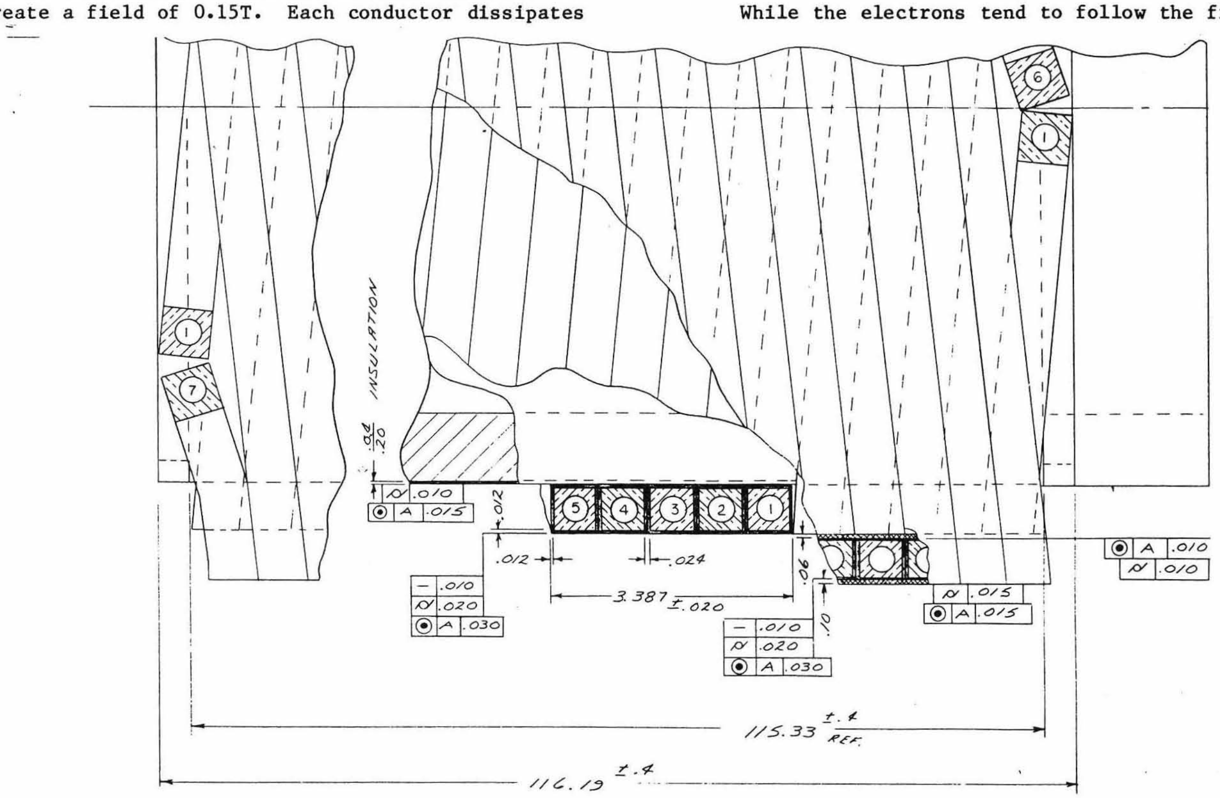

Fig. 1. The main solenoid with tolerances on the position of the individual turns. There are five conductors wound in parallel in each of the two layers.

a radial field component of 10^{-3} times the axial component is equivalent to 0.1 eV transverse energy at 300 keV. The electron beam has a maximum diameter of 2.54 cm. These two statements determine the required straightness of the field axis and the field gradient along the axis.

Formula (1) gives the field distribution along the axis of a single current loop with radius a:

$$H = \frac{I}{2} \frac{a^2}{(a^2+z^2)^{3/2}} \quad \text{A/m.} \qquad (1)$$

In (1) z is the distance along the axis perpendicular to the plane of the loop. I is the current. From (1) one derives an expression for the ratio between H_z and H_r, the radial component, close to the axis:

$$H_r/H_z = 1.5\ rz(a^2 + z^2)^{-1} \qquad (2)$$

H_r/H_z has a maximum at $|z|=a$ where, close to the axis, $(H_r/H_z)z{=}a = .75\ r/a$. At z=a the component H_r is .35 times the maximum values thus:

$$(H_r)_{z=a} = .26(H_z)_{z=0}\ r/a. \qquad (3)$$

In our case at the edge of the electron beam $r/a \approx .1$ The field on the axis of an ultra thin solenoid is easy to derive from (1). If z_1 and z_2 are the coordinates of the ends of the solenoid with a length $z_1 + z_2$, the field on the axis at z = 0 is given by:

$$H = \frac{NI}{2} \left(z_2(z_2{}^2 + a^2)^{-1/2} - z_1(z_1{}^2 + a^2)^{-1/2}\right) \qquad (4)$$

where NI is in amp. turns/m.

Equations (1) to (4) are sufficient to calculate various pertubations on the axis of a thick solenoid coil due to irregularities in the winding. Equation (1) also serves as a starting point to derive a current distribution that compensates a measured field pertubation.

Pertubation due to a small slit between two turns.

Using equation (4) on the two solenoids at both sides of the slit with a width Δ it follows that the relative field change at the position of the slit is equal to Δ/2a. Using (3) the radial field component at the edge of the electron beam, 1.25 cm off axis, will be $H_r/H_z = .013\ \Delta/a$. For a slit of 1mm this gives $H_r/H_z = 10^{-4}$ when a = 125mm. For a repetition of slits due to the insulation between turns, neglecting the pitch, the change in H_z is several orders of magnitude smaller due to the broad distribution given by (1) and in fact the cosine Fourier transform of (1) for the spatial repetition frequency and its harmonics.

It turns out that the insulation between turns following the pitch do not cause a significant radial field component on the axis as long as the pitch is constant.

A sudden change in pitch over one turn can be considered as producing a slit which is tilted over the change in pitch. So in addition to the above mentioned off axis H_r there is on axis H_r given by:
H_r/H_z = (change in pitch/diameter) Δ/2a.

Pertubation due to a small local change in radius.

If one or more turns have a diameter which differs from the rest of the solenoid the field change on the axis can be calculated using (4) for the three subsolenoids. The relative field change just in the middle of the perturbed region with a width w and a small change in radius Δ is equal to (w/2a) x (Δ/a).

So if only a few turns have a small diameter change the effect is smaller than the pertubation due to a slit with the same Δ.

Pertubation due to excentricity of a few turns.

If only one of a few turns are excentric we use (1) to calculate the maximum radial field component on the axis due to displacement Δ.

Using (3) and realize that H_z at r = 0 in this formula is only a fraction H_z/H_s of the solenoid field H_s we find:

$$(H_r)_{z=a}/H_s = .26\ (H_z/H_s)\Delta/a.$$

In our case H_z/H_s for one turn is about 3.5% so a shift of 1mm for one turn gives a $H_r \approx 10^{-4}\ H_s$ on the axis.

Influence of the pitch.

We can consider the insulation between the turns as a thin wire coil carrying opposite current. The general formula for the field in any point within this coil is:

$$\bar{H} = \frac{1}{4\pi} \int \frac{\bar{I} \times \bar{r}}{|R|^2} ds.$$

where ds is an element of the wire, |R| is the distance from the point where the field is to be

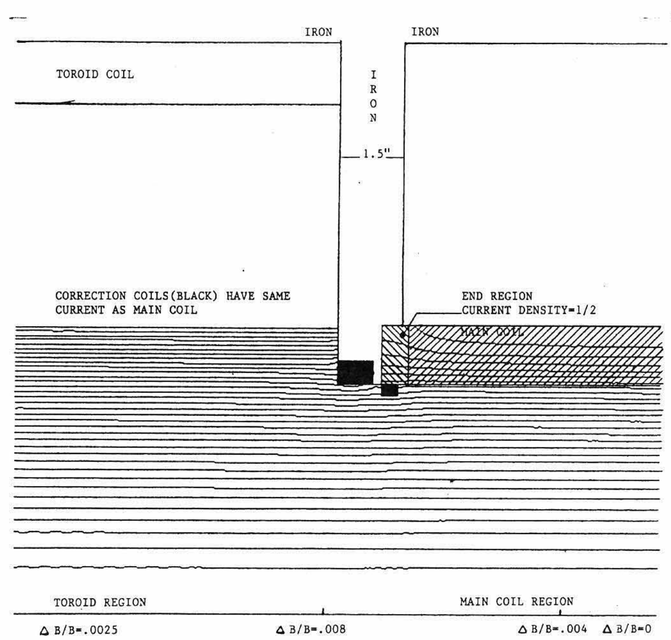

Fig. 2. Poisson calculation for the transition between the main solenoid and the toroid. The toroid is simulated as a coil having cylindrical symmetry. The full black coils are the one and three turns correction coils.

evaluated to ds and r is unit vector along R pointing to ds. For a point on the axis we can add the contributions from elements ds along the length of the solenoid based on symmetry. This shows in our case, assuming 1mm insulation between turns, that the radial field component on the axis is less than 10^{-7} times the axial field if we consider only the contribution of the inner layer. (The outer layer has opposite pitch.)

Transition between main solenoid and toroid.

The toroid field is difficult to calculate because of lack on symmetry. To solve part of the problem in the transition region the toroid was simulated by a coil having rotational symmetry and a Poisson program was used to calculate the field distribution. As can be seen in Fig. 1 the end regions of the solenoid, where the conductors of both layers meet, have a reduced current density. In addition the pitch is there not compensated which causes angular field components. This can be compensated by the iron boundary plate of the toroid using it as a mirror for the current distribution. An additional one turn coil carrying the same current as the solenoid compensates for the reduced current density. The flux leaking away via the iron plate is compensated for by a three turn coil inserted into the iron plate and connected in series with the solenoid. The result of the Poisson calculation is shown in Fig. 2. It shows the field density, rB, and the resulting field change on the axis.

The same kind of correction is used for the transition between the gun-and collector solenoid and the toroid. There the one turn compensation coil is laid on the outside of the solenoid (see Fig. 3).

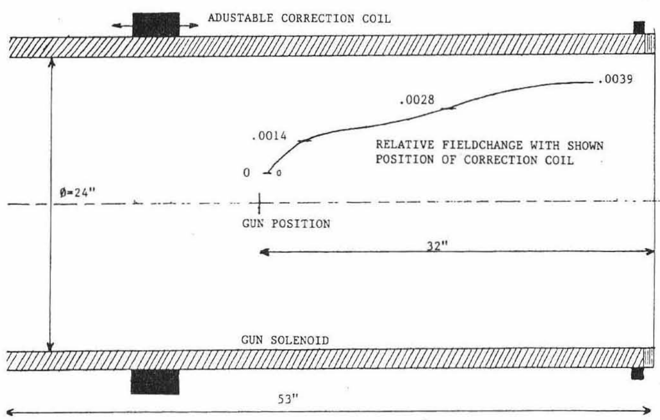

Fig. 3. The gun solenoid with movable correction coil to correct for the open end. The field distribution is shown from gun to toroid with the given position of the movable coil.

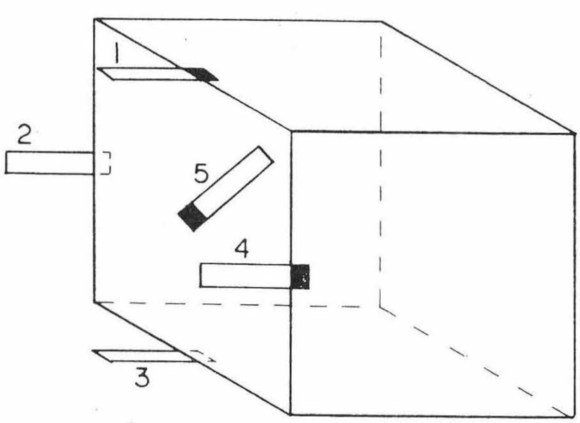

Fig. 4. The hallprobe assembly. The five hallprobes are mounted against five faces of precision glass-cube with mirror coating.

Compensation of the open end effect for the gun solenoid.

To keep the gun solenoid as short as possible a correction coil is used to create a homogeneous field from the gun down along the acceleration column. It turns out that the position of this coil for optimal correction is rather critical. For the present dimensions it has to be positioned within 5mm, being one third of the conductor cross section. In addition the influence of the iron return path is somewhat uncertain. For these reasons it is decided to have the position of this coil adjustable as shown in Fig. 3.

Fringe field of the toroid in the solenoid.

The field density in the toroid has a 1/r dependence where r is the distance to the top angle of the toroid. This means that the field matches only at one value of r to the field of the solenoid. As a result the solenoid field is pushed outwards. The extent of this fringe field region is limited by the size of the hole, but it means that one loses the end regions of the main solenoid for the cooling. This can be compensated at least partly by a short dipole coil giving a horizontal field component with a matched decay along the solenoid. In fact the horizontal field component in the transition region does not seem to be harmful in heating up the electron beam for the change in field direction is slow enough to allow the electrons to follow the field lines adiabatically. Gradient coils can be used to smooth the field gradient. See Fig. 6.

Field Mapping

In order to get a field map the main solenoid and the toroids will be mounted together.

A computer controlled mapping table is available on which a 4m ceramic arm will be mounted to support the hallplate assembly. This assembly consists of five hallplates mounted against five faces of a precision glass mirror cube as shown in Fig. 4. Hallplate 5 measures the longitudinal field component, the other four measure radial components. In this way it might be easy to decide on symmetry of the field, to find the axis and decide about its straightness. The direct measurement of H_r gives at the same time the field gradient along the axis in comparison with the point to point measurement of H_z. The hallplate assembly will be tracked with an autocollimation telescope looking to the front face of the cube (opposite face 5). The configuration makes it rather easy to find the effective angle the hallplates 1-4 make with the mounting face, and the value of the transverse hall effect. To do this the whole assembly will be placed in a homogeneous field magnet with the field vertical and parallel to the faces 1-4. By rotating the cube along a vertical axis over 4 x 90° and aligning the faces with a telescope in autocollimation the angle over which the hallplates 1 to 4 are rotated along an axis parallel to face 5 can be determined. In addition the transverse hall effect is found by reversing the field.

The mentioned offset angles are the most important ones in scanning the solenoid. The offset angles along a line perpendicular to face 5 can be found in the same way by rotating the assembly while the field is parallel to face 5.

Field corrections in the main solenoid.

The first point of concern is to find out if the solenoid field has an axis which is straight within .3 mrad. Pertubations due to a sudden variation in pitch, a equivalent to tilted turns, or excentric turns can be distinguished by the pecularities of the resulting H_r distribution. If they occur only at a few spots the variation in pitch can be corrected by means of a short dipole and the pertubation due to excentric turns by correction turns placed excentric over half the width of the conductor. After this is done it is not unlikely that we are left with field gradients along the axis. This can be corrected by means of a compensation coil inside the main solenoid for which the current distribution can be determined with the aid of the fourier transform. If the desired correction field distribution in generated by a number of turns then the field is given by:

$$H_z = \sum I(k)\ P(z-k)$$

where I(k) is the current density at the k^{th} turn and P is the profile function given in (1). The sum is nothing more than the convolution between I and P. Then the fourier transform reads: $H(\omega) = I(\omega) \times P(\omega)$, so the required current distribution is given by the reverse fourier transform of $H(\omega)/P(\omega)$ where $H(\omega)$ is the fourier transform of the opposite of the measured field pertubation along the axis. To get useful results it is necessary to smooth the data before the fourier transform is applied and to use a kind of cesaro summation in the reverse fourier transform to take care of dividing the $H(\omega)$ data by small numbers in the high frequency content of $P(\omega)$.

An important point in the whole procedure is that we are allowed to make errors. If we like to correct field pertubations of a few times 10^{-3} down to a few times 10^{-4} we can make errors of at least 10%.

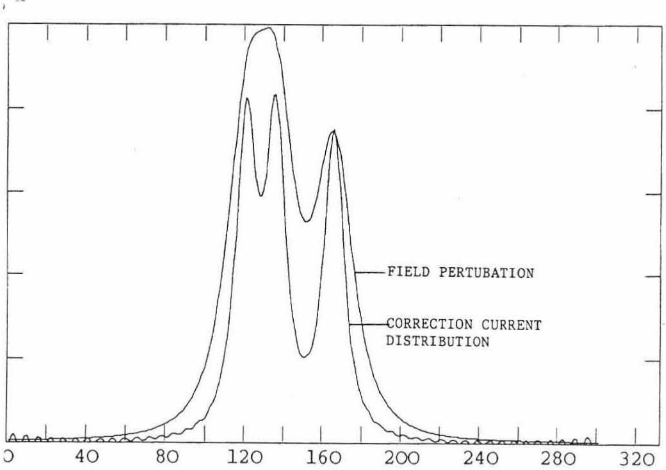

Fig. 5. The current distribution needed to generate the given field pertubation. The pertubation is simulated by three single turns with a diameter equal to the main solenoid diameter. The correction coil is supposed to have a continues current distribution, and a smaller diameter. The current distribution is obtained by the Fourier transform method.

Fig. 5 shows a simulated field pertubation using three current loops at position 120, 135 and 165 cm with a radius of 15 cm. The correction coil is supposed to have a radius of 8.5 cm. The frequency spectrum of $H(\omega)/P(\omega)$ was truncated with a square cutoff function to remove high frequencies where $P(\omega) < 10^{-3}$ times P(o). The resulting oscillations due to this cutoff, Gibbs phenomenon, care clearly visible.

Conclusion

The solenoids are presently under construction at Sigmaphi in Paris, France.[2] The design tolerances are chosen such that the field should meet the requirements and that they can be met using standard techniques. Field measurements will be done using 5 Hallprobes of type BH205, manufacturer F.W. Bell, mounted on the faces of a precision mirror cube. Most of the field correction probably has to be done in the transition region between the toroids and the main solenoid in order to make the effective cooling length as large as possible. The given examples indicate that standard techniques to wind the solenoid are quite sufficient to realise the required field homogeniety.

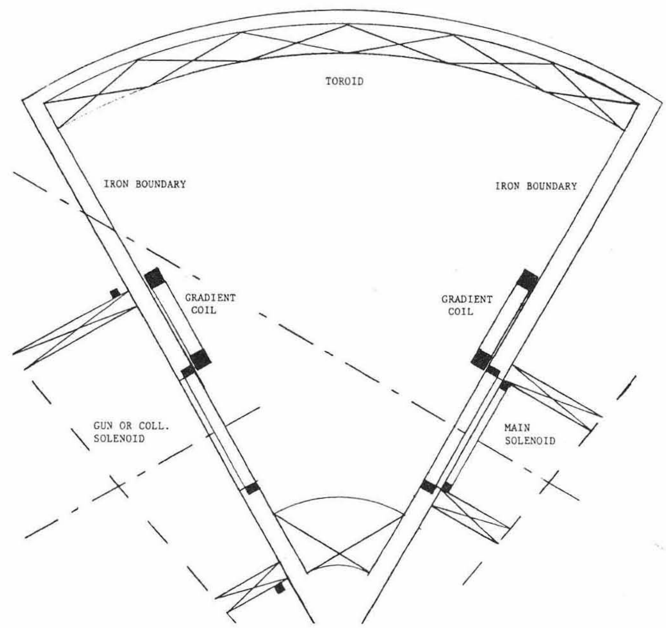

Fig. 6. Correction coils for the transition between solenoids and toroid. Next to the coils shown in Fig. 2 there are two gradient coils planned to smooth the change in the radial field component due to the fringe field of the toroid.

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