FIELD MEASUREMENTS IN THE COOLING SECTION SOLENOID FOR THE RECYCLER COOLER

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Abstract

To increase Tevatron luminosity, Fermilab is developing a high energy electron cooling system [1] to cool 8.9-GeV/c antiprotons in the Recycler ring. Successful cooling of antiprotons requires a round electron beam with a small angular spread propagating through a cooling section with a kinetic energy of 4.3 MeV. To confine the electron beam tightly and to keep its transverse angles $<10^{-4}$ rad, the cooling section will be immersed into a solenoidal field of 50-150G. The requirement to the tolerable electrons angles sets restrictions on the quality of the magnetic field in the cooling section. This paper describes the technique of production of a uniform magnetic field and the results of measurements of the coling section solenoid.

1 COOLING SECTION

The cooling section consists of ten solenoidal modules, gaps between each pair of the modules, longitudinal field correctors (2 per gap) and transverse field correctors (10 pairs per module)[2]. The cooling section is shielded by three layers of the mu –metal. Parameters of the cooling section are given in the table below.

Table 1: Cooling Section Specifications

Parameter	**Value**	**Unit**
Total length of the cooling section	20	m
Length of solenoidal module	190	cm
Solenoidal module ID	15	cm
Gap length	8	cm
Transverse field correctors length	21	cm
Longitudinal field correctors length	3.5	cm
Thickness of the shielding layer	1	mm
Spacing between the shielding layers	1	cm

2 MEASUREMENTS OF THE MAGNETIC FIELD

2.1 Magnetic Field Sensor

While the measurements of the longitudinal magnetic field are done with a Hall probe, the transverse components of the field are measured by a specially designed compass-based sensor. Both Hall probe and the sensor are placed inside a cart that moves through the solenoid with a precision of 1mm, providing a detailed field map [3]. Sensor's work is based on the property of the compass to align itself along the lines of magnetic field (Figure 1).

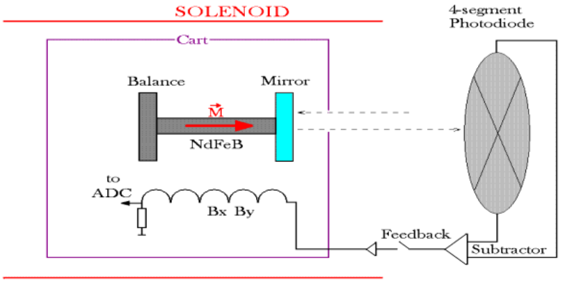

Figure 1: Schematic layout of transverse field measurements (M is the direction of magnetization).

A permanent magnet cylinder (NdFeB) with the mirror attached to its end is suspended in the cart inside the solenoid. It was chosen to use the permanent magnet to increase the returning force on the compass and therefore to reduce random errors. A laser beam that serves as a reference central axis of the cooling section is reflected from the mirror into a four-section photodiode. Compass angular position is controlled by 2 dipole coils (B_x and B_y) so that the reflected beam hits the center of the photodiode. A value of the current generated in these coils gives the transverse component of the magnetic field in the solenoid. These coils are wound around the cart and move along with it.

The measured transverse magnetic field, $B_\perp$, was found to be linear with the longitudinal field component, B_z: $B_\perp=B_z(\alpha+\beta+\delta)+B_0+B_{ext}+\Delta$, here α is the angle between the solenoidal field and the laser beam, β is the angle between the magnetic axis of the sensor and the mirror, B_0 is the component originating from the misbalance of the compass, both δ and Δ represent the time-dependent errors. It was found that δ and Δ do not depend on the longitudinal position of the cart inside the cooling section and basically stay constant during one measurement. And presence of B_{ext} is eliminated by the shielding (Figure 2).

The field to measure and correct is $B_z{\cdot}\alpha$, thus B_0 and β have to be found. It is easy to distinct B_0 by making the measurements for two different B_z. On the contrary, angle β deserves a special treatment. An approach to this problem is the sensor that could be flipped by 180° around its axis. Indeed, for the flipped sensor $B\perp_{flipped}=B_z(\alpha-\beta)+B_0$, and $\beta=(B\perp - B\perp_{flipped})/2$. Besides, the mirror can be adjusted to zero angle β.

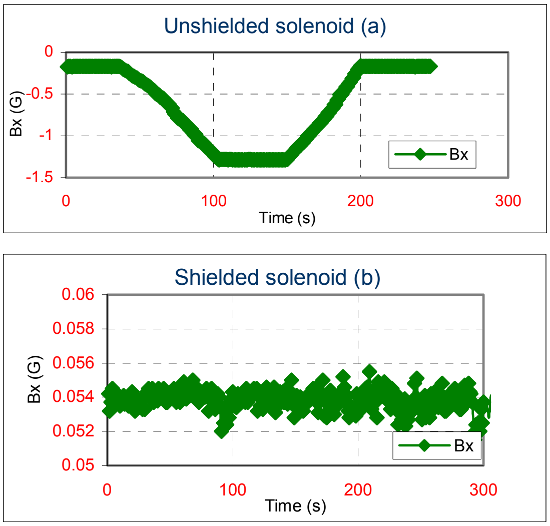

Figure 2: a.) External field is 1.4 G, the solenoid is unshielded; b.) external field of 2 G is shielded by 3 layers of 1mm thick mu-metal. Shielding coefficient is better than 1000.

2.2 Stability of the Measurements

Initially, a long-term reproducibility of the measurements of an angle α was observed to be about 1 mrad. The following factors make the measurements unrepeatable: mechanical instabilities of the sensor, temperature instabilities, and an azimuthal rotation of the cart with respect to the solenoid.

Sensor's instabilities were caused by random shifts of the point of a compass suspension and by spontaneous changes in the angle between the mirror and the permanent magnet. In a redesigned sensor the new methods of suspension and mirror fastening were used and both of the problems were eliminated.

The change in temperature causes a change in the air refraction index and thermal deformations of the suspension wire in the sensor. The sum effect of the thermal instabilities was estimated to be 1mrad/10°C. To reduce the thermal effects, an optic table as well as the space between the table and the vacuum tube were covered and isolated.

The factor of cart's rotation is related to an angle that the cart acquires when it moves in the cooling section. Figure 3 explains how this angle leads to the coupling of B_x and B_y transverse fields and therefore to the error up to 0.1mrad.

To measure the cart rotation, a set of measurements had to be done. Namely, producing various transverse fields using transverse correctors, wrapped around a solenoid, one can determine the coupling between B_x and B_y. As it was said, B_x and B_y are measured by the dipole coils wound around the cart, thus B_x-B_y coupling gives the rotation of the cart.

At present, measurement's repeatability of 0.2 mrad was achieved. Please notice, that angle α gives the direction of magnetic lines with respect to the axis of the cooling section, while the angle of electrons is given by integration of the field's transverse component (see Sec. 3).

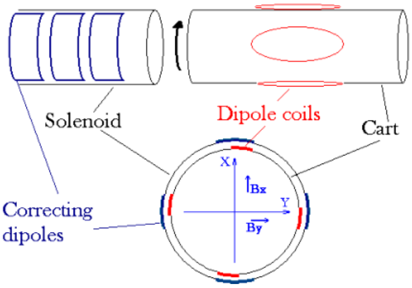

Figure 3: If the cart has an asimuthal angle with respect to the solenoid then measured B_x and B_y fields are coupled.

3 THE METHOD OF FIELD CORRECTIONS

The quality of the field in the prototype cooling section consisting of two solenoidal modules and the gap between them was examined. Below the graphs of uncorrected longitudinal and transverse magnetic fields are shown.

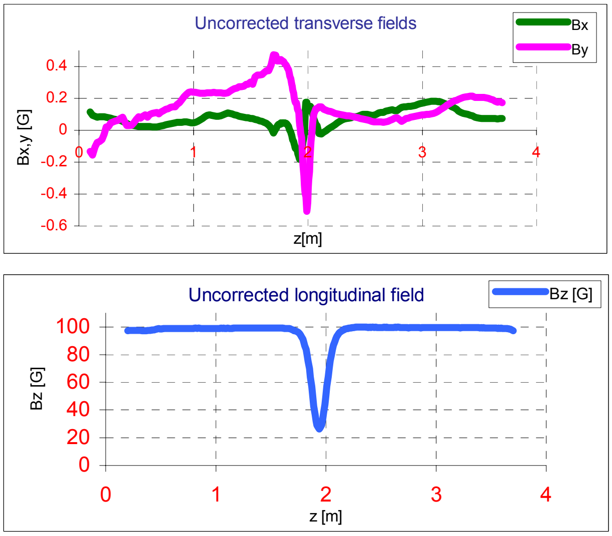

Figure 4: Uncorrected transverse and longitudinal magnetic fields in the prototype section.

It is required to keep electron angle in the cooling section below 10^{-4}rad. In our case the wavelength of cyclotron oscillations ρ is at least 6m. The regions of a disturbed magnetic field are much smaller then ρ. Thus conditions the field to satisfy are formulated as follows [4]: the longitudinal field B_z at any point in the cooling section shouldn't differ too much from the field averaged over the whole cooling section

$$\left| \frac{B_z - \langle B_z \rangle_{over\ solenoid}}{\langle B_z \rangle_{over\ solenoid}} \right| < 3 \cdot 10^{-3} \qquad (1),$$

$$\int \left| \frac{B_z - \langle B_z \rangle_{over\ solenoid}}{\langle B_z \rangle_{over\ solenoid}} \right| dz < 2\,\text{cm} \qquad (2),$$

and an integral of the transverse field $B_\perp$ should be kept below 1[G·cm] at any point inside the cooling section

$$\int_{z_{in}}^{z'} B_\perp dz < 1\ G\,\text{cm} \qquad (3),$$

for any z' in the cooling section (z_{in} is the initial coordinate of the cooling section). The fields shown in Figure 4 were found unsatisfactory and should be improved. On this account the following algorithm was suggested:

1. A rough mechanical alignment of all solenoids with respect to each other is done.
2. The average longitudinal fields in solenoids are set equal to each other with the accuracy of $6 \cdot 10^{-3} < B_z >$: $\langle B_z \rangle_{oversol\ \#1} = \langle B_z \rangle_{oversol\ \#2} = \ldots = \langle B_z \rangle_{oversol\ \#10}$.
3. Longitudinal correctors (short solenoids attached to both ends of each module) correct the longitudinal field component in the gaps between solenoidal modules, so that the integral (2), taken over the gap, is less than 0.1 cm.
4. A precise mechanical adjustment of each of the modules is done. This step eliminates an average angle that each solenoid has with respect to the axis of the cooling section i.e. an average transverse fields in the solenoids.
5. Local disturbances of $B_\perp$ are suppressed by transverse correctors (dipole coils wound around the module).
6. The final step is to set integral (3) over the gap equal to zero. It was found that having a good shielding, the only source of transverse fields in the gap is the misalignment of two solenoids with respect to each other. Such fields can be corrected by the dipole coils installed at the ends of the solenoidal modules.

The algorithm described above was tested in two solenoidal modules. The results of its application are shown in Figure 5. All the discussed conditions are satisfied for the whole length of the section but the gap region that corresponds to z=1.8-2.0m. This fact is confirmed by a simulation of the motion of an electron in the corrected magnetic field (Fig 6). The angle acquired by the electron is less than 10^{-4}rad everywhere but in the gap between two solenoidal modules.

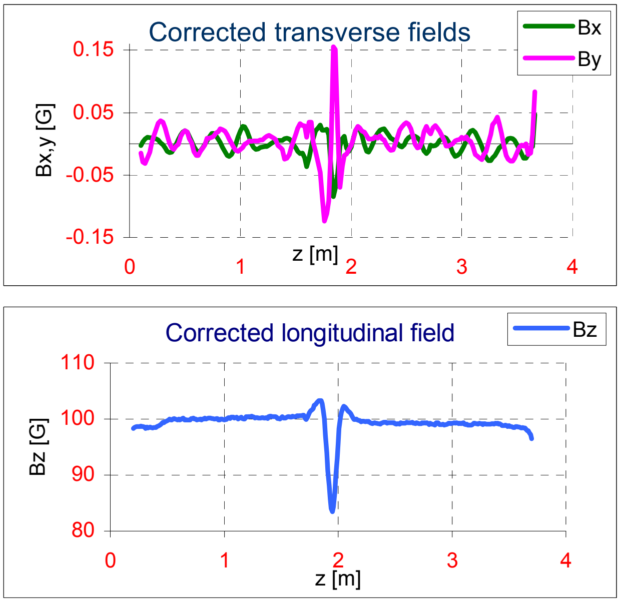

Figure 5: results of the field's corrections.

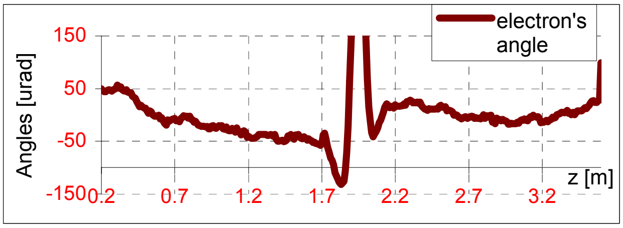

Figure 6: motion of an electron in the magnetic field from Figure 5.

4 CONCLUSION

The method of the correction of the cooling section's magnetic field was worked out. The field in the prototype cooling section was measured and corrected to satisfy requirements of the effective electron cooling. At present, the full length cooling section has been installed and will be measured in the nearest future.

5 REFERENCES

[1] S. Nagaitsev et al., NIM A441(2000), 241

[2] J. Leibfritz et al., "Fermilab Electron Cooling Project: Engineering Aspects Of Cooling Section" PAC'01, Chicago, July 2001.

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[4] S. Nagaitsev et al., "Fermilab Electron Cooling Project: Estimates For The Cooling Section Solenoid" Fermilab-FN-689, April 2000.