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Toward a Cold Electron Beam in the Fermilab's Electron Cooler

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Abstract. Fermilab is developing a high-energy electron cooling system to cool 8.9-GeV/c antiprotons in the Recycler ring [1]. Cooling of antiprotons requires a round electron beam with a small angular spread propagating through 20-m long cooling section with a kinetic energy of 4.3 MeV. To confine the electron beam tightly and to keep its transverse angles below 0.1 mrad, the cooling section will be immersed into a solenoidal field of 50-150G. This paper describes the technique of measuring and adjusting the magnetic field quality in the cooling section and presents preliminary results of beam quality measurements in the cooler prototype.

INTRODUCTION

To prepare and test major elements of the electron cooling system, a full-scale prototype has been assembled and commissioned in a separate building outside the Recycler ring. The major differences are shorter beam lines, shorter cooling section (9 solenoidal modules instead of 10), and a lower beam energy (3.5 MeV instead 4.3 MeV). One of the goals for the prototype was to develop a procedure of measuring and minimizing an effective temperature of the electron beam in the cooling section. The subject of the paper is one of the most important components of the effective temperature, a beam centroid motion in the cooling section (CS). The motion may be caused by a non-optimal matching of the beam at the entrance of the cooling section, by a discrepancy between mechanical axis of the cooling section and the solenoid axis, and by imperfections of the solenoid magnetic fields that lead to transverse field components. While the two former can be relatively easily adjusted according to beam-based measurements, the transverse field components have to be measured directly and compensated according to the magnetic field measurements.

The specifics of the Fermilab electron cooler in comparison with existing electron cooling devices is a combination of its low magnetic field in the cooling section, 50-150G, and its high electron energy, 4.3 MeV. As a result, the corresponding Larmour wavelength, 7 -20 m, is significantly larger than a typical scale of changes in the transverse components of the magnetic field, which are about the diameter of the solenoid, 20 cm. Hence, such a short region of the cooling section solenoid can excite the electron transverse motion with an angle of α_x proportional to an integral of transverse field component B_y over this region:

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$$\alpha_x = \frac{1}{(B\rho)} \int_L B_y \cdot dz \,, \tag{1}$$

where $B\rho = 1.6 \cdot 10^4$ G·cm. To keep the contribution of such excitations well below the restriction for the total electron angle, 0.1 mrad, the transverse fields should be compensated down to the level of

$$\int_L B_y \cdot dz \leq 0.3 \text{ G·cm.} \tag{2}$$

For this level of compensation, the magnetic measurements should have a mG-range resolving capability. The sensor used in measurements (see the next section) did have the necessary resolution but lacked a long-term stability. In the final sections of the paper we will discuss possible ways to improve the compensation of the transverse field according beam-based measurements.

MAGNETIC MEASUREMENTS

Design of the Cooling Section

The 20-m long CS consists of ten 2-m long identical solenoid modules separated by instrumentation gaps [2]. The gaps are used for the beam diagnostics instrumentation and vacuum pump connections. The main solenoid in each module is flanked by trim solenoids to preserve the average value of Bz over the gaps. Transverse fields are compensated by 10 pairs (per module) of flexible-circuit dipole coils. A gap between 2 modules is shown in the FIGURE 1, and the CS parameters are listed in TABLE 1.

Each module is equipped by a pair of capacitive pickups used as beam position monitors (BPMs). Transverse positions of the BPMs with respect to each other was calibrated with accuracy of 0.1 mm by using of a wire stretched over the length of the CS. The measured rms BPM noise is 5 μm in the DC beam mode and 100 μm in the pulse mode. The detailed BPM description can be found in [4].

TABLE 1. Cooling Section Parameters.

Parameter	**Value**
Total Cooling Section	
Total length of the CS	20 m
Number of modules	10
Gap length	8 cm
Module Solenoid	
Length / ID / OD (cm)	188.2 / 15 / 20
Magnetic field / current	40 G / 1 A
Trim Solenoid (2 per module)	
Length / ID / OD (cm)	3.5 / 15 / 20
Magnetic field / current	49 G / 1 A
Maximum field/current	0.8 G / 1 A
Dipole Corrector (10 pairs per module)	
Length trim / main	3.56 / 23.28 cm

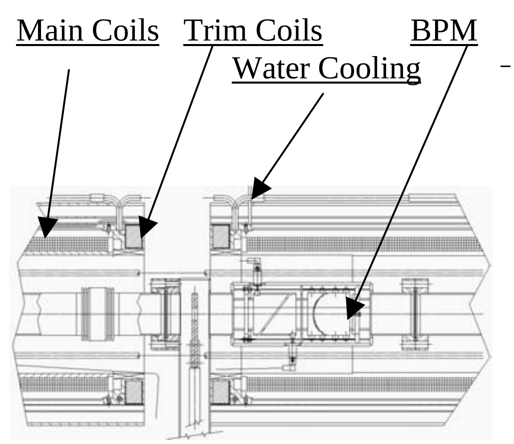

FIGURE 1. Cross-section of Instrumentation gap between two solenoid modules (gap shielding is not shown).

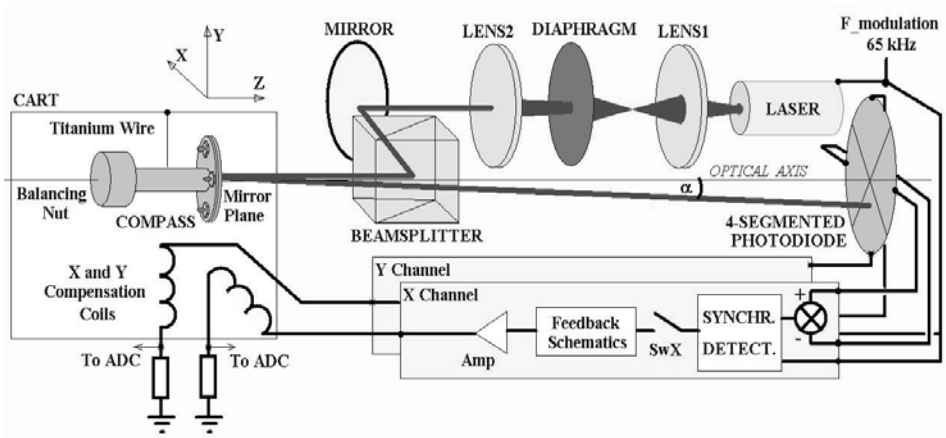

FIGURE 2. The Layout of magnetic measuring system.

Compass Based Magnetic Measuring System

The transverse magnetic fields were measured by a compass-based sensor [3]. The schematic layout of the measuring system is shown in FIGURE 2. A mirror attached to the compass, reflects a laser beam to a 4-segmented photodiode. Using a pair of differential signals from X and Y photodiode segments, two identical electronic feedback systems generate currents in compensation dipole coils, wound around the compass. The fields of the coils rotate the compass until the reflected laser light comes to the center of the photodiode. The value of coil currents in the equilibrium is used as a measure of the solenoid transfer field. The compass and the coils are mounted on a cart, which is pulled through the vacuum chamber.

Measurements have shown that the system has the resolution of 1 mG and linearity better than 1 mG in the range of up to 1 G. Its main problem is slow drifts that may be as high as 10 mG in several hours and 40 mG from day to day.

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Measured Field Maps

To decrease effect of the drifts, the CS fields were measured in two stages. First, the fields were measured with 1-2 cm step that took a week. Second, the cart was passed through the entire CS with measurements taken only in one point per module; this measurement was performed in 2 hours. The results differed from those found in the first run by as much as 40 mG. The differences were interpreted as being caused by drifts in the first measurement and were subtracted from the first set of data in each module. The result of measurements at Bz=100G is shown in FIGURE 3 in light colored curves. Based on these data, the dipole corrector settings for the optimum compensation of fields in the CS were calculated. The expected compensated transverse field in the CS (*Bxy_exp*) is shown in FIGURE 3 in dark color. A simulation of the electron trajectory in these fields predicted the rms value of the electron angles in the CS of 0.03 mrad.

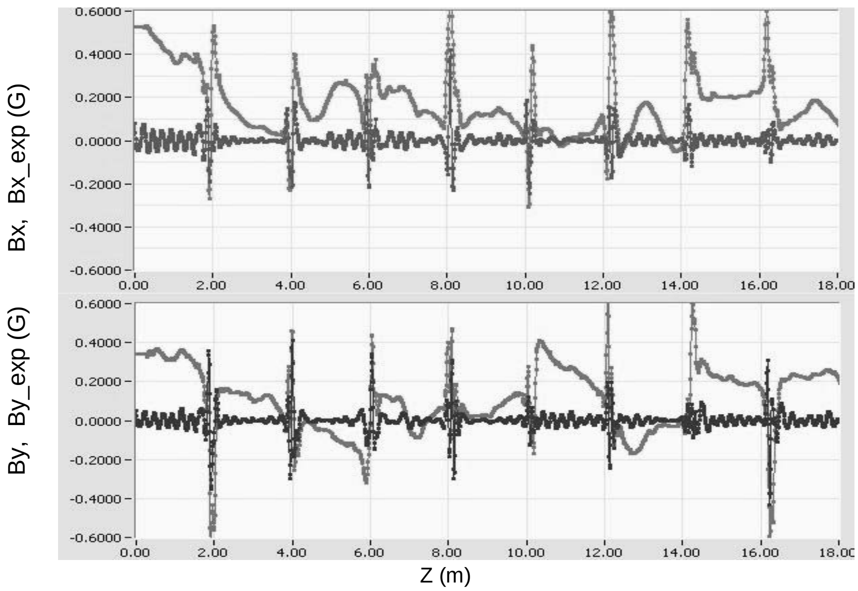

FIGURE 3. Transversal Magnetic Field in CS at Bz=100G (light color – Initial with compensation coils off, dark color – after compensation by dipole correctors).

FIELD ADJUSTMENT BY BEAM TRAJECTORY

Field Compensation And Beam Angles

The transverse field components at 100G of the longitudinal field were compensated by dipole correctors ($I'xy_{n,m}^{100G}$, n – solenoid, m – corrector). The trajectory of the beam, corresponding to initial compensation was measured by BPMs. The trajectory could be represented as a sum of Larmor oscillations and the drift, caused by an error in determination of the average angle of cooling section solenoids. The drift was eliminated by the simultaneous change in the currents of all dipole correctors. The Larmor oscillation, caused by the beam angle at the entrance of CS, was suppressed by two sets of external (to the CS) upstream steerers.

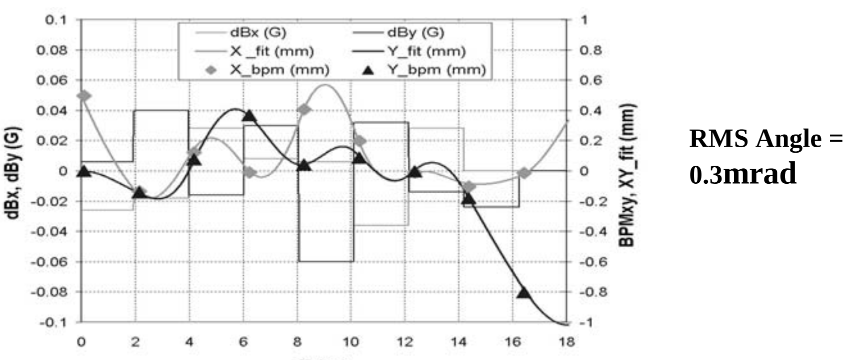

FIGURE 4. BPM readings (dots) & their fits (solid curves) at Bz=100 G after altering the field dBx, dBy (thin lines).

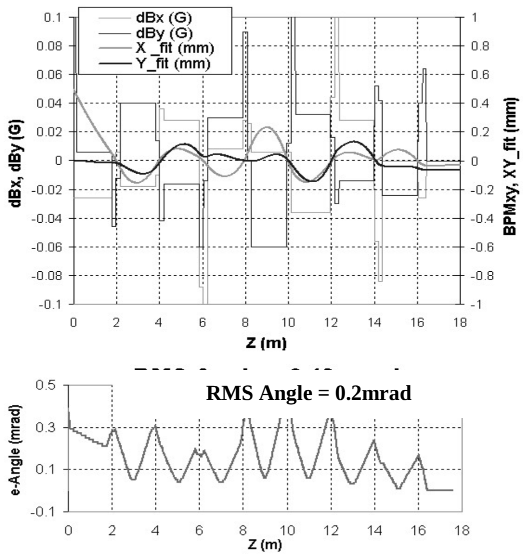

FIGURE 5. Simulation of beam trajectory and angle improvements after field correction in the gaps by trim dipoles only.

After that the trajectory looked as shown in FIGURE 4. Let us assume that the modules were measured with the errors (dBx and dBy) with respect to each other. Then one can fit the measured points with the curve, simulating the electron's trajectory in the measured magnetic field (FIGURE 4). The parameters of the fit are dBx and dBy. The RMS angle obtained from this simulation is 0.3 mrad.

It is clear, that applying the same additional current to each of 10 dipole correctors wound on each 2m-long modules, trying at the same time to zero the closest downstream BPM reading, we could compensate the field up to the achievable beam angle limit 0.03 mrad (for more detail explanation see below). But even in a worst case, when further BPM zeroing is done with trim dipole correctors only (see field spikes in FIGURE 5), the estimation gives 0.2 mrad for RMS angle, i.e. improving the angles by 30%. Settings for dipole currents in the file after such adjustment can be updated as following:

$$Ixy_{n,m}^{100G} = I'\,xy_{n,m}^{100G} + dIxy_{n,m}^{GAP} \quad for \quad any \quad solenoid \quad n, \quad but \quad m = 0{,}9 \quad only \tag{3}$$

Compensation Procedure for Different Longitudinal Fields

We verified the assumption, that the gap regions are the main sources of constant components in transversal field, calculating the dipole settings at different longitudinal fields (the initial data used in recalculation was settings at *Bz=100G*, denoted as $Ixy_{n,m}^{100G}$ [A] where *n* – solenoid number, *m* – dipole corrector number).

During the magnetic measurements in the CS we were convinced that the magnetic shield suppresses completely the external fields with magnitudes up to 2 G inside of each 2m-long module. So the only residual Bz-independent (or constant) component is present in the gaps (more detailed about measured components see in [3]). An indirect

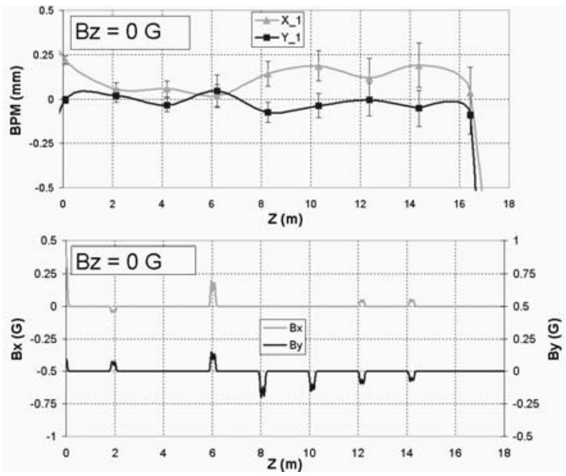

FIGURE 6. BPM readings (dots) & their fits (solid curves) after field correction made by trim dipoles Bx, By (bottom plot).

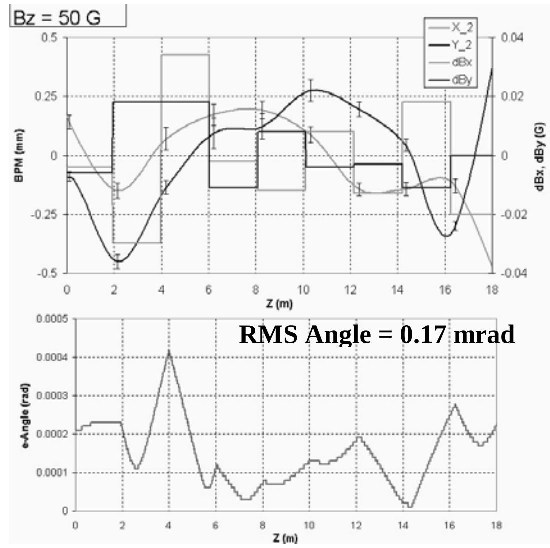

FIGURE 7. BPM readings (error bars) & their fits (solid curves) after dipole settings were recalculated for Bz =50G. Beam angles and offsets at the CS entrance: θx=-0.2mrad, θy =-0.1mrad, X0=0.15mm, Y0=-0.1mm.

determination of this field was performed by passing the beam through the CS at Bz=0G. The closest downstream BPM readings were zeroed with adjustment of the currents in trim dipoles. The resultant beam trajectory and the corresponding transverse fields are shown in FIGURE 6 on top and bottom plots respectively. Lets denote the corresponding dipole settings as $Ixy_{n,m}^{0G}$ [A]. Then the settings for any longitudinal field Bz can be calculated by formula:

$$Ixy_{n,m}^{Bz} = \frac{Bz}{100G} \cdot (Ixy_{n,m}^{100G} - Ixy_{n,m}^{0G}) + Ixy_{n,m}^{0G} \tag{4}$$

where n – solenoid and m – dipole numbers. The result for the beam trajectory recalculated at Bz=50G, is shown in FIGURE 7. the beam's rms angle, equal to 0.17 mrad, is quite close to the original value that beam angle had at Bz=100G.

Estimations of the achievable angle in the CS

The estimation of the angle of the beam can be made from the following consideration. Suppose that the transverse field $B_{\perp}(z)$ in the cooling section was set with some error. And therefore the beam has an angle θ with respect to the axis of the CS. The trajectory of the beam is also displaced from the axis of the CS. The displacement of the beam in every BPM can be zeroed by the introduction of an additional transverse field ($B_{\perp add}$) into the cooling section. This procedure can also suppress the angle θ significantly, provided $B_{\perp}(z)$ satisfies the conditions that will be found below.

Let's consider the motion of an electron in the module consisting of a regular part of one solenoid and one gap. This module corresponds to the region between two BPMs. It can be shown that the measured longitudinal magnetic field $B_z(z)$ in CS can be substituted by its average value B_z in the equations of motion. The relative error in the calculated angle resulting from such a substitution does not exceed 1%. Thus the equations of motion are:

$$\begin{cases} r' = \theta \\ \theta' = i \cdot k \cdot (-\theta + \dfrac{B_\perp(z)}{B_z}) \end{cases} \tag{5}$$

where $k = -\dfrac{q \cdot B_z}{p_z \cdot c}$, $r=x+iy$, $\theta=\theta_x+i\theta_y$, $\theta_{x,y}=p_{x,y}/p_z$, $B\perp=B_x+iB_y$, q is the charge of an electron, p_x, p_y, p_z are x, y and z projections of the electron's momentum and an apostrophe denotes the differentiation over z. the solution of (5) is

$$\begin{cases} r = \dfrac{1}{B_z} \cdot \left(I_\perp - e^{-ikz} \cdot I\right) \\ \theta = \dfrac{i \cdot k}{B_z} \cdot e^{-ikz} \cdot I \end{cases} ; \; I_\perp = \int_0^z B_\perp(\xi) d\xi \;, \quad I = \int_0^z e^{ik\xi} B_\perp(\xi) d\xi \tag{6}$$

Here an assumption that the electron has a zero displacement and zero angles at the entrance of the module was made. Suppose that r at the exit of the module is zeroed by the introduction of the transverse field, constant over the whole length (L) of the module, i.e. $B_{\perp add}(z) = const$ for $0 \le z \le L$.

$$\begin{cases} r(L) = 0 = \dfrac{1}{B_z} \cdot \left(I_\perp - e^{-ikL} \cdot I\right) - \dfrac{B_{\perp add}}{B_z} \cdot \dfrac{i(1-e^{-ikL}) + kL}{k} \\ \theta(L) = \dfrac{i \cdot k}{B_z} \cdot e^{-ikz} \cdot I - \dfrac{B_{\perp add}}{B_z}(1 - e^{-ikL}) \end{cases} \tag{7}$$

It follows from (7) that $\theta(L) = 0$ if integrals of the transverse field over the module satisfy the following condition (8):

$$I_\perp = I \cdot \frac{kL}{2} \cdot \frac{e^{-ikL} + 1}{\sin(kL)} \tag{8}$$

Of course, an ideally compensated transverse field satisfies (8). In a case if equality (8) is not fulfilled precisely it allows estimating the angles at the exit of the module as well as the angles inside the module (one has to substitute L with z for the latter).

The formula (8) replaces the estimations of the angle with the estimations of the errors in compensation of the transverse field. The upper limit of the possible error in the compensation of transverse field $\Delta B_\perp(z)$ in the CS was found from the analysis of magnetic measurements. This error can be separated in two parts. The first part is $\Delta B_\perp(z) = b_\perp \cdot z$, where $b_\perp \cdot z = 30mG$ at maximum for the module of 2m length. The second part is due to the fact that the solenoid and gap in the same module may be compensated with different constant errors $\Delta B1_\perp$ and $\Delta B2_\perp$ with $\Delta B_\perp = \left|\Delta B1_\perp - \Delta B2_\perp\right| = 50mG$ at maximum. Finally, it was found that zeroing the displacement in every BPM_n by the introduction of transverse field $B_{\perp add}(z) = B_n = const \quad z \in [0, L]$ in the respective module #n would result in the rms angle $\theta \le 0.09\ mrad$.

CONCLUSION

Transverse fields in the cooling section prototype were measured by a compass-based system, and their integrals were compensated by a set of dipole correctors according to the results of the measurements. The entrance beam angle and position were adjusted to minimize scalloping in the compensated field, caused by the entrance mismatch. The BPM readings recorded for this optimum case, were used to simulate the beam trajectory under an assumption that the remaining beam deviations in BPMs are caused by an incomplete correction of long-term drifts in magnetic measurements. The simulation gives an estimated value of the trajectory rms angle of 0.3 mrad. Estimations and preliminary measurements show that the scalloping may significantly decreased further by adjusting average transverse fields in separate modules according to BPM readings.

Several improvements are foreseen by the time of installing the setup in the Recycler ring in the fall of 2004. First, we hope to improve the stability of magnetic measurements. Second, the antiproton beam trajectory, which is a straight line inside the cooling section, will be used as a reference to calibrate BPM mechanical offsets with a 30 μm precision. Finally, the proposed procedure of using BPM readings for adjusting the solenoid field should provide the necessary field quality.

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