BEAM-BASED FIELD ALIGNMENT OF THE COOLING SOLENOIDS FOR FERMILAB'S ELECTRON COOLER*

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Abstract

The cooling section of FNAL's electron cooler (4.3 MeV, 0.1 A DC) [1] is composed of ten (10) 2 m-long, 105 G solenoids. When it was first installed at the Recycler ring, the magnetic field of the cooling solenoids was carefully measured and compensated to attain the field quality necessary for effective cooling [2]. However, the tunnel ground motion deteriorates the field quality perceived by the beam over time. We have developed a technique which uses the cooling strength as an indication of the relative field quality and allowing us to re-align the longitudinal magnetic field in the successive solenoids of the cooling section assuming that the transverse component distribution of the field within each solenoid has not changed.

INTRODUCTION

For electron cooling purposes, a cold (i.e. with low transverse velocities, or angles in the lab frame) electron beam must be generated, transported to the cooling section (CS), where electrons interact with the particles that need cooling, and must remain cold until the beam exits the CS. While there are many sources contributing to the total rms angle in the beam [4], having a magnetic field in the CS with a large transverse component would prevent any efficient cooling. Assuming that all solenoids were perfectly aligned, we estimated that the field quality achieved for the compensated magnetic field lead to a total rms angle of 50 μrad for the electron beam [2]. However, we observed its deterioration over time, which needed to be corrected.

In this paper, we present our observations of the field degradation, and described the procedure we developed to correct it (different in nature than the one proposed in Ref. [3]), using the cooling strength as a diagnostic for the 'straightness' of the field. Results of this method are discussed.

OBSERVATIONS

Once the compensation of the magnetic field has been optimized and set, the electron beam trajectories in the cooling section should remain the same for fixed initial conditions of the centroid. However, over several months, we find that the trajectories get perturbed. This is illustrated in Figure 1, which shows the difference of trajectories taken a few months apart, and where one set of trajectories was obtained after the field had been re-aligned for the first time using the procedure we will describe. Beam position monitors (BPM) are located between each solenoid, with the first BPM being at the entrance of the first solenoid. On Figure 1, '0 cm' is a reference point outside of the first solenoid.

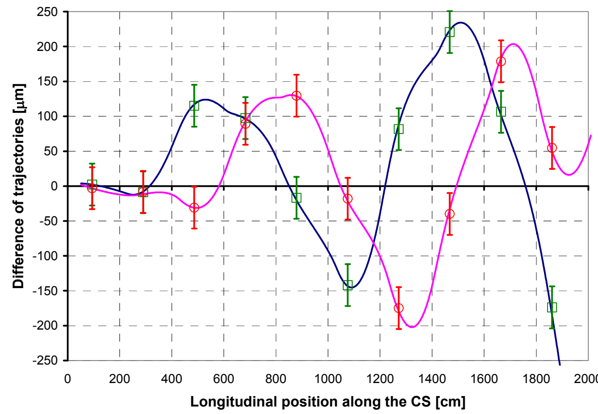

Figure 1: Difference of trajectories taken 3 months apart. Green squares: Horizontal; Red circles: Vertical. I_b = 100 mA, on-axis. The solid lines are fitted trajectories using the measured magnetic fields and solenoid-to-solenoid magnetic offsets as fitting parameters.

Note that the trajectories are taken for the same beam current (100 mA) and initial conditions where the beam is so-called 'on-axis', meaning that, ideally, trajectories coincide with the antiprotons central orbit. Moreover, the beam position monitors (BPM) are calibrated such that the antiprotons central orbit corresponds to zero position after the calibration procedure. The BPMs typically move, randomly from BPM to BPM, by 50 μm rms for all BPMs (100 μm in the worst BPM) over one year [5]. On the other hand, the electronic drift is <3 μm rms for all the BPMs (± 10 μm peak-to-peak in the worst BPM) over several weeks [5]. Both sources of error are about 5 times (or more) smaller than the effect shown on Figure 1.

PRINCIPLE OF THE METHOD AND PROCEDURE

The reason for the beam trajectories to change with time is likely because of ground motion in the tunnel, which moves the solenoids independently to one another, so that they appear inclined to a beam going through (Figure 2). Because each solenoid behaves like a rigid object [6], we can assume that the transverse component distribution of the magnetic field within each solenoid does not change. Hence, as illustrated in Figure **2**, the beam experiences a transverse magnetic field, $B_\perp$, when it travels from one solenoid to the next and oscillates in a fashion consistent with the trajectories shown in Figure 1.

Changing currents in all correctors in a solenoid by the same amount creates a nearly constant dipole field

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offset $\Delta B_\perp$, equivalent to tilting the solenoid. Hence, the goal of the procedure is to find and apply the proper $\Delta B_\perp$'s that will cancel out $B_\perp$'s. The first and most challenging step of the procedure is to align the field in the first solenoid, i.e. to make sure that the beam enters and exits on-axis with a zero angle with respect to the longitudinal magnetic field, B_{z0}. Then, merely zeroing the position in the remaining BPM's of the CS one by one by adjusting $\Delta B_\perp$ ensures that the accompanying field is straight.

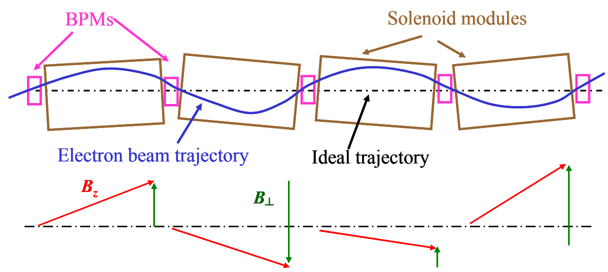

Figure 2: Illustration of the CS with inclined solenoids and corresponding 'transverse dipole offsets'.

To align the field in the first solenoid, we rely on the sensitivity of the cooling force to the electron angle. To first order, the cooling force is proportional to $1/\alpha^2$, where α is the total rms angle of the electron beam. We then assume

$$\alpha^2(z) = \alpha_T^2 + \alpha_D^2(z) \tag{1}$$

where α_T is the non-coherent, temperature-like component of the angle and α_D, the component resulting from the solenoid tilts. If the positions at the entrance and the exit of the solenoid are fixed to zero (by a dedicated control program using upstream correctors), the trajectory within the solenoid is close to parabolic and, in this approximation, we can analytically calculate the average cooling force, <F>, and express the ratio

$$\frac{<F>}{F_{Max}} = \frac{\arctan(\alpha_0/\alpha_T)}{\alpha_0/\alpha_T} \tag{2}$$

where α_0 is the initial angle of the beam w.r.t. B_{z0} and F_{Max} is the maximum cooling force (when the initial angle is zero). Using Eq. (2), if we estimate that α_T = 100 µrad and that changes of the cooling force of the order of 10% can be resolved, we can expect to reduce α_0 to 50-60 µrad. This is of the same order as our best estimate for perfectly aligned solenoids [2], which would imply that the total angle resulting from field imperfections would be of the order of 70 µrad (angles added in quadrature).

We can use two types of measurements to evaluate the cooling force while varying α_0 (i.e. varying $\Delta B_\perp$): cooling rate measurements [7] or drag rate measurements by the voltage jump method [4]. But, since the goal of these measurements is to maximize the cooling force in the first solenoid only, a preliminary step is to adjust the beam trajectory such that the solenoids downstream of the first one do not contribute to cooling. This is achieved by using the first few correctors of the second solenoid to kick the electron beam away from the axis by 3-4 mm. Then, evaluation of the cooling force is carried out for one direction at a time (i.e. first vary the dipole correctors in the horizontal direction, find the optimum, then repeat in the vertical direction). We typically go through two iterations, the second one with smaller steps for the dipole setting offsets.

SAMPLE MEASUREMENTS

With the Cooling Rate Method

For the cooling rate method [7], the momentum spread as a function of time is measured for various dipole corrector settings. The slope of a linear fit to the data is what defines the cooling/heating rate. Figure 3 shows the longitudinal cooling/heating rate measured as a function of the dipole correctors offset in the vertical direction. The momentum spread is measured using a 1.75 GHz Schottky detector, and each slope is determined after staying 15 minutes at a fixed corrector set point.

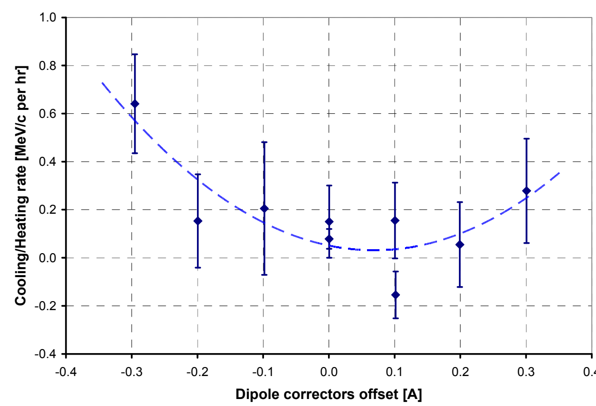

Figure 3: Cooling/heating rate as a function of the dipole correctors offset for the first solenoid (vertical, i.e. horizontal field). I_b = 200 mA, on-axis. N_p = 44×10^{10}, 6.1 µs bunch. Error bars are the statistical errors of the fit (1σ) when extracting the slope from the raw data. The dashed line is an arbitrary polynomial fit (2nd order).

This method proved to have several drawbacks. First, the results are very noisy and the determination of the cooling/heating rate (i.e. the slope) has large uncertainties. In addition, since the cooling rate in a single solenoid is quite weak, this measurement is very sensitive to diffusion, which depends on several factors such as emittances and details of the momentum distribution, just to name a couple, all of which may vary over the length of the measurement. Then, at a minimum of 15 minutes per step, the whole procedure takes a lot of time to complete.

With the Drag Rate Method

The procedure for drag rate measurements is the same as described in Ref. [4]. Starting from an equilibrium, $\Delta B_\perp$ is changed before each measurement and the corresponding drag rate recorded. Figure 4 shows the drag rate as a function of dipole correctors offset in the vertical direction.

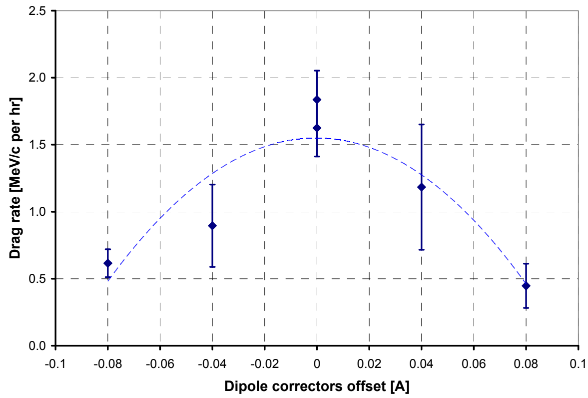

Figure 4: Drag rate as a function of the dipole correctors offset for the first solenoid (vertical i.e. horizontal field). I_b = 100 mA, on- axis. Voltage jump is 2 kV. Error bars are the statistical errors of the fit (1σ) when extracting the drag rate from the raw data. The dotted line is an arbitrary polynomial fit (2nd order).

The drag rate method has several advantages over the cooling rate method. First, the signal-to-noise ratio is more favorable which allows for speeding up the data acquisition. Each measurement (one corrector setting step) takes only 3-5 minutes. In addition, after each step, the antiproton beam is returned to its original conditions (i.e. an equilibrium), which makes the measurements more consistent over time. Moreover, for the low rate measured with a single solenoid, the drag rate measurements are less sensitive to the momentum distribution details and the momentum spread of the antiproton beam. We also have automated the data taking sequence, which helps both with the speed of the procedure and maintaining fixed initial conditions. On the other hand, this method is sensitive to the electron beam energy variations which could be non-negligible in respect with the energy offset from the voltage jump itself and to the transverse emittance of the antiproton beam [8].

RESULTS AND DISCUSSION

Although the uncertainties are quite large for both methods, one can extract an optimum value for the corrector dipole settings. For the measurements carried out in March 2007, using the drag rate method, we found that the corrector settings in the horizontal direction should be changed by -35 mA (i.e 28 mG) and remain unchanged in the vertical direction. This corresponded to a 0.13 mrad angle correction for the electron beam in the first cooling solenoid and presumably to a vertical tilt correction of 0.25 mrad of the 2-m solenoid.

After the rest of the cooling section magnetic field was aligned standard cooling rate measurements were performed accordingly to the procedure detailed in Ref. [7]. We find that the longitudinal cooling rate increased by 12%, while the transverse cooling rate increased by 35%.

A couple of reasons can be brought forward to explain the large uncertainties of the measurements presented in Figure 3 and Figure 4. First, we have recently found that the drag rate and cooling rate depend greatly on the transverse emittance of the antiprotons [8]. In neither case was the transverse emittance controlled to the level needed to ensure that even without changing dipole corrector settings, the cooling or drag rates were stable. Also, one of the assumptions for this method is that the rms angle of the electron beam is incoherent except for the dipole component resulting from the tilt of the solenoid. If the rms angle of the electron beam is dominated by envelope scalloping then the distribution of angles is such that there is overall a region of good cooling (where the angles are low) and a region of bad cooling (where the angles are high). By adding a transverse magnetic field dipole, one merely shifts this distribution of angles [1], so that, the change in the cooling rate can not necessarily be linked to an improvement of the straightness of the field. The shape of the electron beam recently observed on a scintillator screen at the exit of the CS certainly points toward high coherent angles [8].

CONCLUSION

The straightness of the magnetic field in the cooling section degrades with time. We presented a procedure that uses measurements of the cooling force using only the first solenoid to re-align the magnetic field.

Although the data obtained for both methods shown (cooling rate and drag rate methods) have large uncertainties, they have been successful and resulted in an immediate improvement of the cooling efficiency.

ACKNOWLEDGMENTS

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