Cooling Section Solenoid for the 5 MeV Fermilab Electron Cooling Project

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Abstract

The proposed electron cooling section solenoid will consist of ten 2-m long modules with a common ferromagnetic shield. Each module is a solenoid with a maximum longitudinal field of 150 G, flanked by 8-cm gaps for diagnostics, pump-out ports and correction coils. This paper discusses requirements on each module as well as the design criteria that would allow to keep transverse electron angles in the cooling section below 70 μrad.

1 INTRODUCTION

A final goal of the Electron Cooling R&D efforts is a round electron beam with a kinetic energy of 4.3 MeV propagating through a solenoidal cooling section with transverse angles below $1\cdot10^{-4}$ rad [1]. The latter requirement is important because electrons with angles above this critical value have a reduced cooling ability. Electron angles in the cooling section largely depend on the magnetic field quality.

The restrictions for the Fermilab cooling section solenoid field quality are quite different from those for traditional low-energy electron coolers (e.g. [2]). The fundamental distinction is based on a simple fact that excitation of an electron velocity, transverse to magnetic lines, by a perturbation in a solenoidal field is maximal when the length of the perturbation, L_p, is about the Larmor period, $\lambda=2\pi\cdot\rho_L= 2\pi\cdot\gamma\beta mc^2/eB_0$. As a rule, a typical L_p value is close to the solenoid diameter.

Having the solenoid diameter of 30–50 cm and λ~1–3 cm << L_p, low-energy coolers maintain the effective transverse beam temperature low because of the adiabaticity of the electron motion. In this case, the excitation of transverse electron velocities is suppressed dramatically with the increase of both the magnetic field and the solenoid diameter, and by the decrease of the electron energy. Electrons strictly follow the magnetic field lines so that deviations of their trajectories from straight lines are determined by local values of the transverse components of the magnetic field.

In contrast, the worst case for the Fermilab's cooler, with the solenoid diameter of 15 cm and λ~6-20 m >> L_p, is at the maximum value of the longitudinal field. Electron angles are formed by the integral of transverse magnetic field components so that averaging of them along the axis is essential. Only the mean winding density must be the same in the solenoid to keep the angles below the critical value. The low strength of the magnetic field makes it possible to drastically decrease the size of the wire, which improves the precision of winding and averages out winding errors better because of an increased number of turns.

The proposed cooling section [3] consists of ten modules equipped with identical solenoids. Some parameters of a solenoid module are shown in Table 1.

Table 1: The basic parameters of the cooling section solenoids.

Parameter	Symbol	Value	Units
Solenoid length	l_s	192	cm
Solenoid ID	2*a*	15	cm
Magnetic field	B_0	50 - 150	G

Neighbouring solenoids are divided by a gap where a vacuum pump port, scrapers, and BPM feedthroughs are placed. Effects of magnetic field perturbation because of gaps and because of winding errors in the homogeneous part of solenoids are considered separately in Sections 2 and 3, respectively.

In this paper, we assume that an angle acquired by an electron because of passing through a specific perturbation has to be below $2\cdot10^{-5}$ rad while an angle inside a perturbed region should be kept under $7\cdot10^{-5}$ rad. In this case, full electron angles might be under boundary of ineffective cooling ($1\cdot10^{-4}$ rad).

All calculations were performed for the magnetic field strength of 150 G and the initial electron radius of r_0=5 mm. Numerical simulations of magnetic fields and single particle motion were done by the computer code SAM 3-0 [4].

2 EFFECTS OF GAP

2.1 General Considerations

First, we consider the effects of longitudinal field variations caused by a gap between solenoids. Two separate effects can be distinguished.

First of all, after passing the gap region, an electron can acquire an angle θ_{out} more than the critical value of $2\cdot10^{-5}$ rad. For the magnetic field given by Table 1, the electron Larmor oscillation period, λ, in the cooling section is 6.3 – 20 m while the gap size is much smaller (6 - 10 cm). The gap between solenoids can generate an angular perturbation similar to that of a thin lens. A radial angle θ_{out} acquired while traversing the gap can be found from the equation of the particle motion in an axially symmetric magnetic field [5]:

$$\frac{d^2r}{dz^2}-\left[\frac{r_0^4}{r^4}-\frac{B^2(z)}{B_0^2}\right]\cdot\frac{r}{4\rho_L^2}=0\,, \qquad (1)$$

where r is the electron's radius, $\rho_L = \beta\gamma mc^2/eB_0$ is the Larmor radius, γ and $\beta=v/c$ are the usual Lorentz factors, $B(z)$ and B_0 are magnetic fields inside the gap and in the homogeneous part of the solenoid, respectively.

In a case of a paraxial motion and a thin lens approximation ($r \approx r_0$ inside the gap), the acquired angle is

$$\theta_{out}=\frac{r}{4\rho_L^2}\cdot\int\limits_{gap}\left(1-\frac{B^2(z)}{B_0^2}\right)dz\,. \qquad (2)$$

After passing through the gap an electron begins to spiral so that the total transverse velocity is constant. To correct this angle, we added short corrector solenoids on both sides of the gap (Fig. 1) so that

$$\int\limits_{gap}\left(1-\frac{B^2(z)}{B_0^2}\right)dz=0 \qquad (3)$$

and the total angle is zero inside the next downstream homogenous part of the solenoid. In the practically interesting case of a low field perturbation, to attain the requirement (3) one needs to keep average density of Ampere-turns in the gap equal to that of the regular part of the solenoid. This determines the current in the corrector solenoids.

The second harmful effect of a gap is an azimuthal angle, θ_φ, which electrons have inside the gap. If $\Delta B \equiv |B(z)-B_0| << B_0$,

$$\theta_\varphi=\frac{r}{2\rho_L}\cdot\frac{\Delta B}{B_0}\,. \qquad (4)$$

The angle θ_φ exists inside the perturbed region only and disappears when $B \to B_0$. It can not be set to zero in the gap, and the critical value of $7\cdot10^{-5}$ rad determines the length, L_g, of a region around the gap where the cooling is ineffective because of large azimuthal velocities.

2.2 Corrector solenoids design

There are a number of possibilities one can use to minimise the detrimental effects of the gap [3]. We have chosen to employ the one that simplifies the overall design: a pair of correction coils with a magnetic shield (Fig. 1). While for a given gap size δ the current value in these coils is fixed by Eq. (3), the length d of the shield protrusion is the parameter which can be varied to minimise the length L_g of the ineffective cooling region (azimuthal angle $>7\cdot10^{-5}$ rad at the 5 mm radius).

Particle trajectory simulations were performed to choose the optimal values for the correction currents and the length d for various gap sizes. We have chosen the gap size to be 8 cm. This allows to have a sufficient room for vacuum chamber penetrations, while the perturbation length L_g ($\approx$ 8 cm) remains much smaller than the full length of the module (2 m).

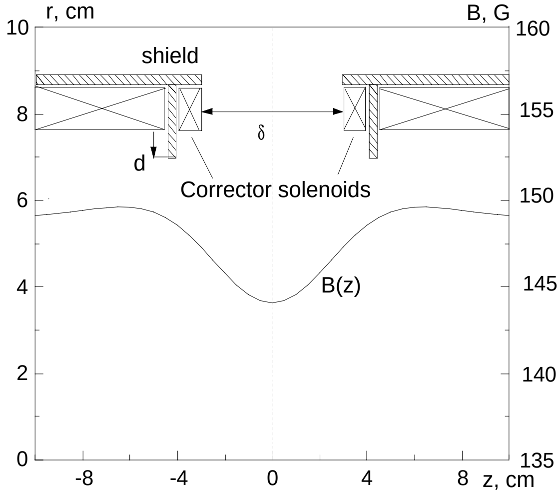

Figure 1: The simulated geometry of the gap effect compensation by a pair of coils and a magnetic shield.

3 SOLENOID MODULE DESIGN

The solenoid module will be manufactured as a single coil. Some of its parameters are listed in Table 2.

Table 2: Proposed parameters of the module solenoid.

Number of layers	6
Number of turns in one layer	~980
Wire size (square AWG13)	1.88 mm
Current for B_o=150 G	4 A
Total weight	250 kg
Power	240 W

It is proposed to wind the solenoid around a 15-cm diameter aluminium tube with a 1.9-mm size square copper wire. The low wire size helps to maintain a good precision of winding; moreover, an increased number of turns averages out field errors caused by deviations of wire positions from an ideal spiral. The chosen wire size is a compromise, which gives an acceptable total voltage drop over ten solenoids connected in series. We prefer to make an even number of layers to avoid problems with a current return path.

The main parameter determining solenoid quality is the magnitude of transverse components of the magnetic field. An electron propagating through a short region with a dipole field $B_\perp$ acquires an angle θ_d:

$$\theta_d=\frac{1}{B_0\rho_l}\cdot\int B_\perp dz\ . \qquad (5)$$

The shortest scale of dipole field variations is the solenoid diameter, which is much larger than the beam size. Therefore, the field effects are nearly identical for all electrons in the beam, and we can consider only the motion of an electron entering the solenoid on axis.

The restriction to such perturbations is the same as was discussed above, namely, an electron angle should never exceed $7\cdot10^{-5}$ rad. For an electron with kinetic energy of 4.3 MeV, this angle corresponds to an integral of the dipole field of 1 G·cm. All perturbations exceeding this level should be corrected by dipole coils placed over the solenoid body. Note that this scheme assumes that angles at the entrance and exit of every module are low. Analogously, the limit for the angles is taken equal to $2\cdot10^{-5}$ rad.

One of the dangerous perturbations for the future electron cooling device is a time-dependent magnetic field from the Main Injector current buses and quadrupole magnets. A typical size of the fringe fields is several meters and its amplitude is about 5 G. To preserve electron angles, resulting from these fields, under $2\cdot10^{-5}$ rad, the cooling section should be magnetically shielded with restriction for a residual field value of about 1 mG. We intend to use a two-layer magnetic shield with a shielding factor of more than 3000. The prototype shield has been manufactured and tests are underway.

Below we summarise various restrictions on the solenoid design and ways to correct the field non-uniformities.

1. Perturbations because of module-to-module misalignments seem too severe for a mechanical alignment of the axes. Correction dipole coils will be used in conjunction with in-situ sensitive transverse field measurements [6] to correct both the module incline and its radial displacement.
2. The mechanical distortion of the module because of its weight will be compensated by dipole correctors placed along the solenoid. The expected sag in the middle of a 2-m long module is 0.4 mm. At 150 G this corresponds to a maximum vertical magnetic field of 0.12 G. Four vertical correctors was found to be sufficient to compensate for this error.
3. Winding errors, or deviations of winding from an ideal spiral, seem to be the most fundamental factor determining the solenoid field quality. We have simulated these errors by representing the solenoid by a set of identical thin closed-loop round coils with current equal to the solenoid current. Three types of errors were investigated: random shifts of coils in the transverse direction, their random tilt, and a non-uniformity of the coil distribution along the solenoid. We found [3] that the winding precision of ±0.6 mm with 8 correctors and ±0.2 mm without any correctors would result in a suitable transverse field magnitude. The winding precision of 0.2 mm has been already demonstrated on a solenoid prototype, which is being manufactured at Fermilab.
4. The difference in a number of turns between modules will be corrected by shunt resistors to adjust the longitudinal magnetic field in the solenoid to within ±0.2%.

4 CONCLUSIONS

1. For the proposed solenoid parameters, listed in Table 1, the harmful effects of the gap between solenoids can be compensated by one pair of coils and a disk-shaped magnetic shield.
2. The length of the region of ineffective cooling caused by a gap can be made less than 5% of the total solenoid length if the gap length is 10 cm or lower.
3. The magnetic field quality in the homogeneous part of a module is determined mainly by mechanical distortions of the solenoid body and by possible inclinations of individual turns. Using 8 pairs of dipole correctors per 2 m module, we can achieve the desired magnetic field quality with the precision of wire positioning of ±0.6 mm.
4. The corrector adjustment has to decrease the transverse field integral under every corrector to below 0.3 G·cm to keep the electron angle change less than $2\cdot10^{-5}$. With the corrector length of 25 cm, this value of the integral corresponds to about 12 mG of an average transverse field. The necessary precision of transverse field measurements should be lower by several times, or about 3×10^{-5} of the longitudinal field.
5. The proposed solenoid design looks doable and less expensive than solenoids of low-energy coolers (per unit length).
6. The prototype module is being manufactured and will be tested in the summer of 2000.

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