ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAF056

THE CERN-ELENA ELECTRON COOLER MAGNETIC SYSTEM

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Abstract

Phase space compression of the antiproton beam in ELENA will be performed by a new electron cooler, the performance of which is greatly influenced by the properties of the electron beam. Careful design of the electron gun electrodes, the efficient recuperation of the electrons in the collector and the quality of the guiding magnetic field ensure an optimal performance of the cooler.

The ELENA cooler is a compact device incorporating an adiabatic expansion to reduce the electron beam temperature as well as electrostatic bending plates for efficient collection of the electron beam. The transverse components of the longitudinal field in the cooling section must be kept small ($B_{\perp}/B_{\parallel} \leq 5\mathrm{x}10^{-4}$) to ensure a minimal perturbation to the electron beam transverse temperature. The longitudinal field itself needs to be as low as possible such that the distortion to the closed orbit of the circulating ion beam due to the short 90° toroids is kept as small as possible.

We present the solutions chosen to design and construct a magnetic system within the above constraints as well as the setup used to measure and optimise the magnetic field components.

INTRODUCTION

Electron cooling will be central to the success of the ELENA project [1] which aims to increase by a factor of up to 100 the number of antiprotons available for the trap experiments.

Figure 1: Location of the cooler in ELENA.

The cooler has been installed in long straight section 4 of ELENA (Fig. 1) taking up almost half the available space. The rest of the section accommodates the orbit correctors and the compensation solenoids of the cooler.

Figure 2 shows the mechanical layout of the electron cooling device. The magnets, incorporating the vacuum system, are mounted on a base frame which is placed on three jacks for alignment. The supporting frame also holds two standard machine orbit correctors.

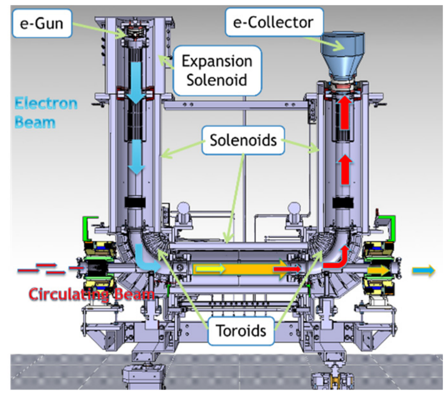

Figure 2: Mechanical layout.

The vacuum level in the cooler must be the same as for the rest of the ring: $3\mathrm{x}10^{-12}$ Torr. All the chambers are made of 316LN stainless steel and NEG coated where possible. At the gun and collector, special chambers incorporating NEG strips have been designed. This increases the pumping speed by a factor of 10 in these regions where the gas load is the highest.

THE MAGNETIC SYSTEM

The magnetic system of the electron cooler consists of:

- An expansion solenoid to increase the magnetic field around the electron gun which is needed for the adiabatic expansion of the electron beam.
- Three main solenoids for the gun, drift and collector.
- Two toroid sections each made up of 9 racetrack coils.
- A squeeze coil placed at the collector entrance to ensure that the electrons are focussed as they are decelerated by the repeller electrode.
- Two orbit correctors at the cooler entrance and exit to compensate the horizontal kick experienced by the circulating beam in the toroids.

The toroid coils come in 3 different sizes; two medium sized coils near the drift solenoid, three large coils to allow access by the antiproton beam as well as access for pumps etc. and finally four small coils near the gun and collector solenoids, respectively. To compensate for the larger size, the two outer large coils have 1 extra turn whilst the centre large coil has 2 extra turns.

To guide the electron beam through the solenoid magnets and toroids, steering coils have also been integrated into the magnets. These will provide a small deflection such that the electrons can be aligned to the circulating ion beam and steered correctly into the collector.

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The complete setup of the main magnetic components can be seen in Figure 3.

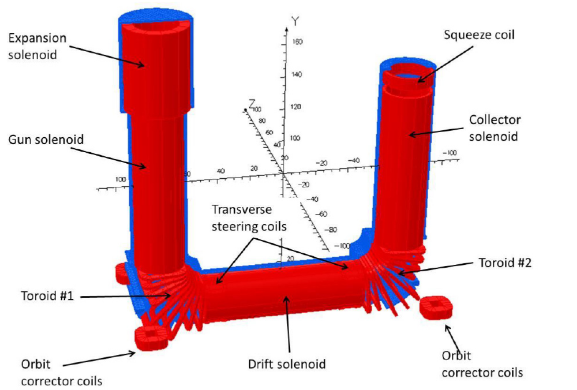

Figure 3: OPERA model of the ELENA cooler magnet system. Only half of the shield is shown to allow visualisation of the coils.

Electromagnetic modelling of the magnetic system was made prior to the production of the magnets [2,3]. The theoretical characteristics of each component were calculated and the sensitivity of the field to possible construction errors (winding errors, layer jumps, coil misalignment, misalignment of the shielding, tilt in shielding axis etc.) was studied. This showed that to reach the good field region requirement of $B_\perp/B_\parallel < 5\times10^{-4}$ over at least 65 cm in the drift solenoid, additional field correction and fine-tune coils had to be integrated in the solenoid design. A set of circular coils are placed close to the central region with the aim to ensure that $B_\perp/B_\parallel < 5\times10^{-3}$ over a maximum length. Saddle coils are installed at each end of the drift solenoid to compensate for the B field leaking into the drift solenoid from the toroids and the vertical solenoids. In addition, 24 fine-tune coils are inserted into the centre of the drift solenoid and can be powered individually to further reduce the transverse component of the magnetic field.

MAGNETIC MEASUREMENTS

To measure the transverse magnetic field with the required accuracy, a special measurement stand was set up (Fig. 4). A Hall probe (Lakeshore model 460 Gaussmeter with a 3-axis HSE probe) having a 1 mG resolution in the range of 300 G was placed in a carrier with a mirror glued to the front. The mirror is used with an autocollimator to measure the tilt angle of the probe. The probe carrier was mounted at the end of a counterbalanced 50 mm diameter carbon fibre tube with three mounting points that, when mounted in its four possible rotational positions, coincide with the nine measurement positions.

The use of a counter balanced carbon fibre tube produces a rigid system that has minimal deflection caused by the weight of the probe and settles into its equilibrium position in as short a time as possible after being moved. The time required for oscillations to be damped to an acceptable level was determined by experimentation. The angle of the probe arm is adjustable so that its deflection under its own weight can be countered so that the probe remains horizontal.

The probe carrier and carbon fibre tube were driven and positioned down the solenoid bore with a CMM arm. This allows the probe to be manoeuvred into all the positions required for magnetic measurements. With the use of the CMM arm the probe can be positioned to within ±0.5mm of the required locations with a repeatability of ±0.1mm.

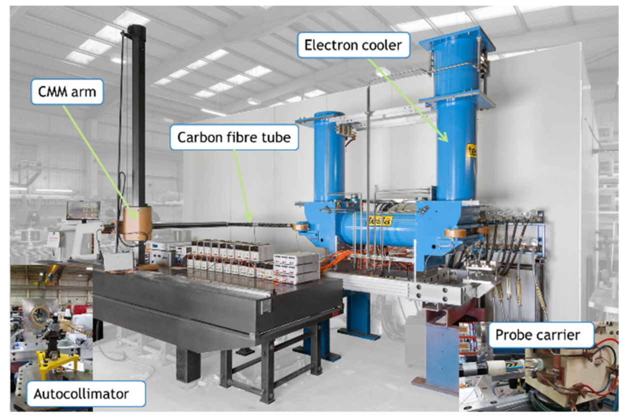

Figure 4: The measurement stand.

There are two main sources of systematic errors that affect the measurements, the first of these is the transverse Hall effect. This is a small signal in the Hall chip that is produced by magnetic fields in the plane of the chip. As it is proportional to the planar magnetic field B_ρ, the sign of this component does not change if the magnetic field direction is reversed. It can therefore be cancelled out by taking measurements with both field directions and retaining the absolute average value of the field component at the measurement point.

The second source of error is due to misalignment of the Hall plates which is caused by their mounting in the head and by the probe fixation to the carrier. Corrections for these misalignments are made by recording the actual orientation of the probe during the scan with the autocollimator and by determining the angular deviations α, β, and γ between the magnetic field and each Hall plate of the 3-axis probe. The field components corrected for probe misalignment to first order are then given by [4]:

$$B_i = s_1(B_1 - \beta_1 s_2 B_2), \qquad s_1 = sign(\alpha_1)$$

$$B_j = s_2(B_2 - \alpha_1 s_1 B_1), \qquad s_2 = sign(\beta_2)$$

$$B_k = s_3(B_3 - \alpha_3 s_1 B_1 - \beta_3 s_2 B_2), \qquad s_3 = sign(\gamma_1)$$

β_1 and β_3 can be determined by measuring the same field inside the solenoid with the probe in its normal position and with the probe rotated 180 degrees around the axis of the main field (j) and verifying the rotation with autocollimation to the mirror fixed to the front of the probe. Angle α_2 can be determined similarly but using a dipole field and rotating the magnet about the vertical axis (i) as shown in figure 5. Angle α_3 is harder to determine but can, however, be inferred from measurements of the same

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position with the probe at different angles or by rotating the probe by 180 degrees about the j axis in the dipole field.

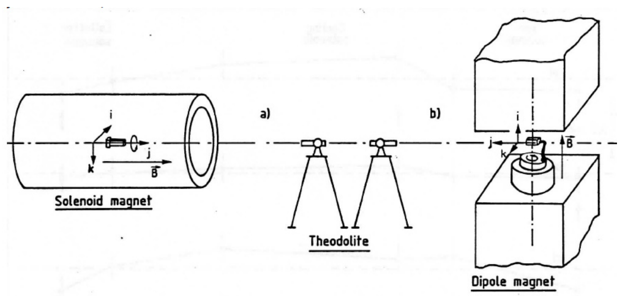

Figure 5: Misalignment correction scheme.

Each element of the magnetic system was measured individually, and the influence of the circular and saddle coils was checked to confirm the magnetic model. From the measurements of the standard solenoids, the unit having the best field characteristics was chosen as the central drift solenoid.

During the measurements a problem was discovered concerning the reproducibility of the data. A variation of up to 0.5 G on the transverse field components could be seen on successive measurements of the same magnetic element. Several sources of error were investigated; equipment misalignment, probe calibration, and background field variation. The maximum individual error recorded for any of these effects was less than 30 mG. After further investigations the problem was traced to a probe holder/mirror instability. It was seen that the mirror to probe angle changed slightly after each rotation. By replacing the nylon studding with aluminium ones, the measurement reproducibility was reduced to 50 mG.

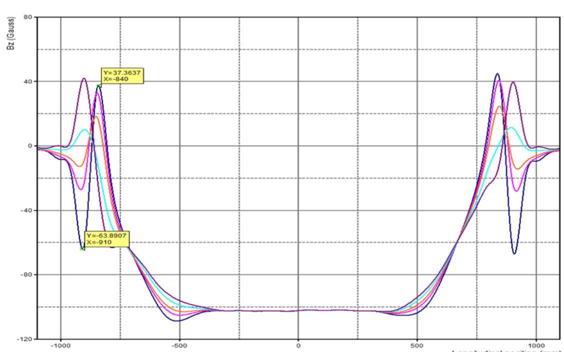

Figure 6: B_z as a function of vertical position along the cooling axis.

The full assembly was then mounted and the field at the nine radial positions was measured every 50 mm along the circulating beam axis. Figure 6 shows the plot of the measured longitudinal field component as a function of the vertical position (0, ±10 mm, ±25 mm) which is in good agreement with our model.

After completion of the coarse measurements, the central section of the drift solenoid was re-measured more precisely and the 24 fine-tune coils were used to further reduce the transverse field components. Using the magnetic measurements of each fine-tune coil, the current required to produce the smallest perpendicular field in the plane of interest was calculated. These currents were applied to the coils and the field re-measured to confirm the correction. Figure 7 shows the result of the transverse field correction on the beam axis (r=0, θ=0°) where the variation in B_x and B_y is reduced from 0.1 G to 0.053 G and 0.04 G to 0.019 G respectively.

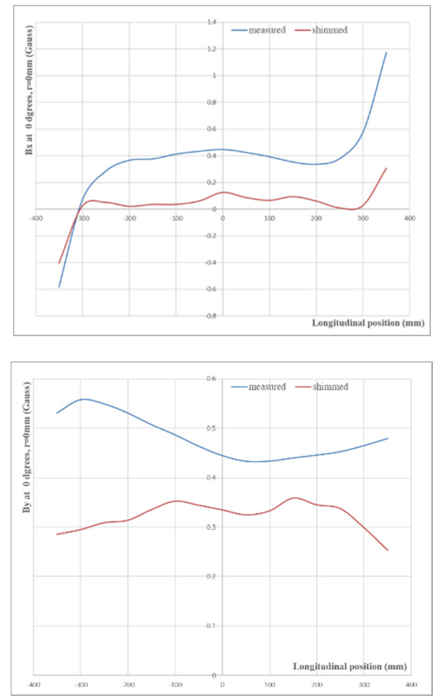

Figure 7: Reduction of B_x and B_y along the beam axis using the fine-tune (shim) coils.

The above compensation scheme unfortunately uses all the available coils in the drift solenoid to improve the transverse field. On the ELENA ring only 15 of the 24 fine-tune coils will be connected to power supplies, therefore a more optimised scheme must be used. Recent simulations have found that a transverse field variation below 30 mG in both planes can be obtained using only 13 coils. The remaining residual field offset can easily be compensated using the steering coils which produce a constant field along the beam axis.

STATUS

The ELENA electron cooler magnet system was delivered to CERN in August 2017 and has been certified by the CERN magnets group. The precise measurement and correction of the transverse field was a challenge, but we are confident that the solutions that have been implemented will result in a homogeneous magnetic field for optimum cooling of the antiproton beam. The full assembly (vacuum and magnets) was installed on the ELENA ring at the end of 2017. The bake-out of the vacuum system has been successful and commissioning of the device is now underway with first cooling results at the lowest energies expected soon.

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