Alignment of a Solenoid System by Means of a Translating-Coil Magnetometer

M. Pentella, V. Kjellqvist, C. Petrone, S. Russenschuck, and L. von Freeden

***Abstract*—The electron cooler operating at the Antiproton Decelerator (AD) at CERN is at the end of its life cycle. The electron cooler, operated for over 40 years, has been used to decelerate anti-proton beams having an energy of about 5.3 MeV. A new electron cooler is being designed and expected to be commissioned during the Long Shutdown 3 (LS3) in 2026. The initial magnet system design consists of an array of pancake solenoid coils as well as an expansion solenoid. The mechanical alignment of the pancake coils must comply with challenging requirements, where the coils need to have 0.1 mrad angle positioning accuracy and $B_z/B_r < 5 \times 10^{-4}$ in terms of field quality. In this article, a new measurement method for the determination of a solenoid coil angle is presented, which allows for faster identification of the pancake-coil angles. The method was experimentally validated on an existing transducer, and the results were used for the design of a new measurement system capable of meeting the requirements.**

***Index Terms*—AD, electron cooler, solenoids, translating fluxmeter, translating-coil magnetometer.**

I. Introduction

The Antiproton Decelerator (AD) at CERN is used to decelerate antiproton beams to energies of about 5.3 MeV and deliver them to the experiments. The accelerator relies on electron cooling to decelerate the beam efficiently. The existing electron cooler has been in operation for over 40 years [1] but is at the end of its life cycle. With the addition of the ELENA ring, a new cooler will be built to continue operations for another 20 years [2].

The new electron cooler has been designed to work with antiproton beams at a higher energy level of 500 MeV. It will also be equipped with an expansion system to obtain an electron beam with reduced transverse energy for faster cooling. The magnetic system of the electron cooler, shown in Fig. 1, consists of an array of short pancake-coil solenoids in the drift, the gun, and the collector sections [2]. The new system has the advantage that local field errors can be corrected by adjusting the coil angle [3]. However, the pancake coils present challenging requirements in terms of mechanical alignment to ensure $B_z/B_r < 5 \times 10^{-4}$ in terms of field quality, where B_z is the axial field component and B_r the radial field component. This specification on the field quality led to a requirement for the angular positioning accuracy of 0.1 mrad.

Manuscript received 25 September 2023; revised 21 December 2023; accepted 23 January 2024. Date of publication 2 February 2024; date of current version 28 February 2024. *(Corresponding author: M. Pentella.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2024.3361430.

Digital Object Identifier 10.1109/TASC.2024.3361430

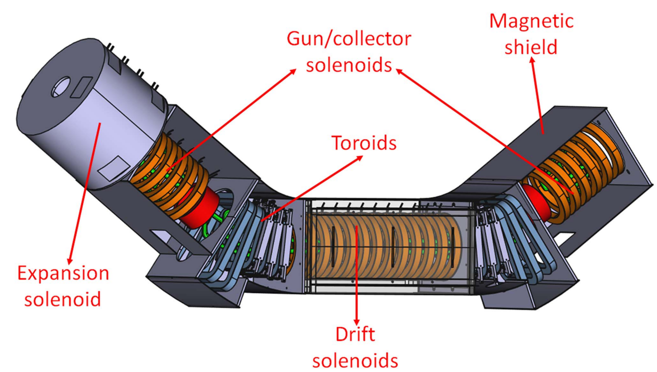

Fig. 1. AD electron cooler layout.

In this article, a new measurement method for the determination of the pancake-coil tilt angle through magnetic measurements is presented. The method relies on mapping the field profile of the pancake coils using a translating-coil magnetometer. Experimental validation was carried out on an already existing transducer [4] in view of the design of a new measurement head for the final application.

II. The Translating-Coil Magnetometer

A. Measurement Principle

Translating-coil magnetometers have been extensively used to obtain solenoid field maps [4], [5], [6], [7] with resolutions on the order of 10^{-5} T. The measurement principle is based on Faraday's law of induction, where flux variations over time are detected by measuring the induced voltage at the terminals of an induction coil. More specifically, an induction coil moving inside a magnetic field $\mathbf{B}$, at a velocity $\mathbf{v}$, displays an induced voltage u at its terminals,

$$u = \int_{\partial A} (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{r}, \quad (1)$$

where ∂A is the boundary enclosing the coil surface A and $d\mathbf{r}$ the spatial increment.

The alignment characterization presented in this article uses the translating-coil magnetometer presented in [4]. It consists of a circular Printed Circuit Board (PCB) array of induction coils mounted on a measurement head, which is displaced in

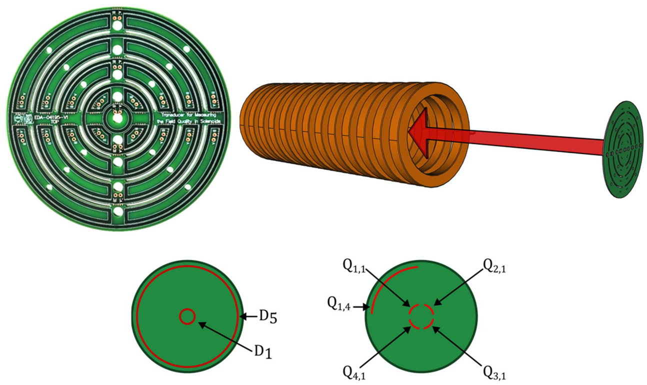

Fig. 2. PCB transducers for solenoid mapping.

the solenoid aperture along the longitudinal axis. Fig. 2 shows a photograph of the PCB and sketches of the numbering scheme and mode of operation. In particular, the coil array includes two induction coil types: 1) Disks, marked in Fig. 2 as D_i, and; 2) 90°-sector quadrants, marked as $Q_{q,j}$. i and j counted from inside out, with $i \in [1\ 5]$ and $j \in [1\ 4]$. $q \in [1\ 4]$, counted in the counter-clockwise direction as shown in Fig. 2. Due to the presence of air gaps among the sectors to allow for fixation screw holes, each sector quadrant has an arc length of 88.85°.

From the measured flux $\Phi_{z,j}(z_k)$, the axial field component measured by the disk j, $\bar{B}_{z,j}$ at the longitudinal position z_k can be calculated as

$$\bar{B}_{z,j}(z_k) = \frac{\Phi_{z,j}(z_k)}{S_j}, \tag{2}$$

where S_j is the surface of the j-th disk. The average radial field component can be computed as the flux linked with the cylindrical surface traced by the disk.

$$\bar{B}_{r,j}(z_k) = \frac{\Phi_{z,j}(z_k) - \Phi_{z,j}(z_{k-1})}{2\pi r_j (z_k - z_{k-1}) N}, \tag{3}$$

where r_j is the radius of the j-th disk, and N is the number of coil turns. The formulae similarly apply to the sector quadrants. The PCB parameters are reported in [4], with an area of the quadrants $Q_{q,4}$ of 0.0168 m^2.

B. Identification of the Solenoid Coil Angle

As reported in [4], the field maps measured by the sector quadrants can be used to obtain geometrical properties of the field, such as the magnetic axis position and the tilt angle of the fluxmeter with respect to the solenoid axis. This is possible by exploiting the field description using spherical harmonics, or *Legendre's polynomials*, for which the field can be expanded in Taylor's series

$$B_z(z_k) = p_0(z_c) + p_2(z_c)r^2 + p_4(z_c)r^4 + \cdots \tag{4}$$

$$B_r(z_k) = q_1(z_c)r + q_3(z_c)r^3 + q_5(z_c)r^5 + \cdots \tag{5}$$

where p_k and q_k are the polynomial coefficients, and r the radial coordinate. By performing multiple measurements at different radii, the coefficients can be determined through a polynomial fit, and it was demonstrated that the magnetic axis can be identified with a precision of 0.05 mm. In addition, the tilt angle can be identified with a precision of 0.1 mrad. On the downside, the method can be time-demanding for aligning the AD cooler entirely, as an iterative measurements procedure for each pancake would be required.

The method proposed in this article measures the magnet's coil tilt angle more time efficiently, exploiting different field properties. When a solenoid coil is tilted, the field loses its axisymmetry, and two new field component appear, superimposed with the solenoidal component, which can be decomposed in a Fourier series:

$$B_r(r_0, \varphi) = \sum_{n=1}^{\infty} (B_n \sin(n\varphi) + A_n \cos(n\varphi)) \tag{6}$$

$$B_\varphi(r_0, \varphi) = \sum_{n=1}^{\infty} (B_n \cos(n\varphi) - A_n \sin(n\varphi)), \tag{7}$$

where the coefficient B_n and A_n are know as the *field harmonics* or *multipoles*, with n the harmonic order.

Focusing only on the radial field component that the magnetometer can intercept, (6) simplifies to

$$B_r(\varphi) \approx B_1 \sin(\varphi) + A_1 \cos(\varphi) = C_1 \sin(\varphi - \varphi_0) \tag{8}$$

where $C_1 = \sqrt{B_1^2 + A_1^2}$ and $\varphi_0 = \arctan(B_1/A_1)$.

The C_1 coefficient cannot be extracted from the field measurements by using the disk coils as it averages to zero along the circumference of disk coil. Nevertheless, the sector quadrant coils can be used to detect the dipole components since they cover only a portion of the arc length.

In two opposite sector coils (for example, $Q_{1,4}$ and $Q_{3,4}$), the dipole component sums up with the radial solenoidal component, while the other is subtracted. The axial field components result in a pair of mirrored signals along the magnet's longitudinal axis, with their peaks in correspondence with the solenoid coil conductor. Fig. 3 shows a simulation of this effect using the field level of the AD cooler pancake coils and a coil pitch angle of 22.5°, for illustration purposes.

The solenoid coil tilt angle (pitch or yaw) can be estimated by locating the position of these peaks. If $2r_c$ is the solenoid excitation coil diameter, the peak shift Δz between the two field distributions measured by two opposite sector quadrants can be calculated as:

$$\Delta z = 2r_c(k_\theta \sin\theta + k_\psi \sin\psi) \tag{9}$$

where θ and ψ are the magnet's coil pitch and yaw angles. k_θ and k_ψ are two constants depending on the roll angle of the PCB transducer with respect to gravity, and they have the following expressions:

$$k_\theta = \frac{\int_{\varphi_c - \frac{\varphi_d}{2}}^{\varphi_c + \frac{\varphi_d}{2}} \sin(\varphi - \varphi_0) \mathrm{d}\varphi}{\int_{-\frac{\varphi_d}{2}}^{\frac{\varphi_d}{2}} \sin(\varphi - \varphi_0) \mathrm{d}\varphi} = \frac{\sin(\varphi_c - \varphi_0)}{\sin(\varphi_0)} \tag{10}$$

$$k_\psi = \frac{\int_{\varphi_c - \frac{\varphi_d}{2}}^{\varphi_c} \cos(\varphi - \varphi_0) \mathrm{d}\varphi}{\int_{-\frac{\varphi_d}{2}}^{\frac{\varphi_d}{2}} \cos(\varphi - \varphi_0) \mathrm{d}\varphi} = \frac{\cos(\varphi_c - \varphi_0)}{\cos(\varphi_0)}, \tag{11}$$

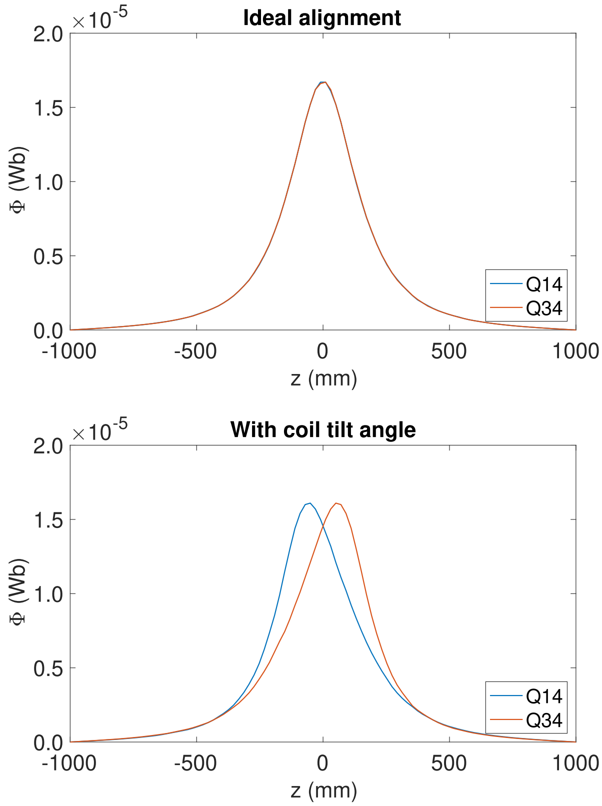

Fig. 3. Simulated peak shifts and mirroring effect measured by a sector quadrant pair in the presence of a pitch angle of 22.5°.

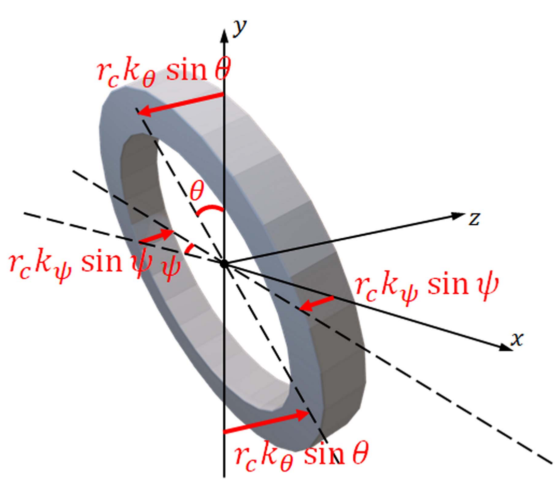

Fig. 4. Representation of the quantities of interest of (9).

where $\varphi_0 = f(\theta, \psi)$, φ_c is the angular position of the sector coil and φ_d the angular aperture of the sector coil. Fig. 4 shows a geometric representation of (9).

C. Experimental Validation

The experimental validation was carried out by measuring a normal-conducting solenoid magnet having a length of 360 mm and an aperture of 145 mm. The peak of the axial field component is 75 mT, comparable with the field of the pancake coils for the final application. The solenoid coil diameter is 230 mm. Fig. 5 shows a photograph of the measurement setup.

Fig. 5. Measurement setup used for the experimental validation. In green, the solenoid magnet.

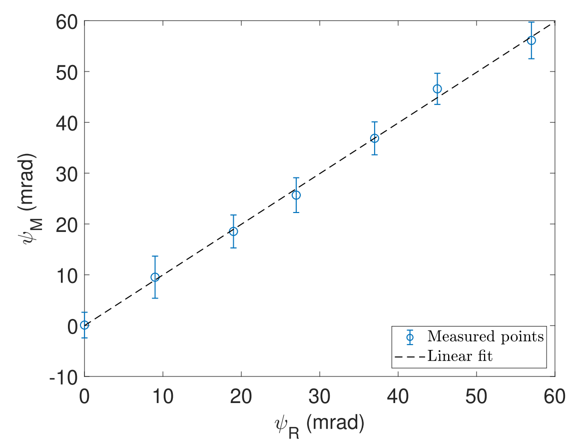

Fig. 6. Measured angles as a function of the reference angular positions. In round blue, the measured points, and in black line, the linear fit.

The position of the PCB array of coils was measured by a wire encoder [8], and the signals were acquired using a set of Fast Digital Integrators (FDI) [9]. The position of the magnetometer tube in the magnet frame was measured using a Leica AT960 laser tracker [10].

The experimental validation was performed by tilting the magnetometer tube by a known, measured quantity ψ_{R} in the horizontal plane to simulate an equivalent coil yaw angle ψ. The roll angle of the PCB was 15°. As only a yaw angle is present, φ_0 and θ can be assumed equal to zero because the dipole component is in the horizontal direction (x) and the angle ψ can be determined as

$$\psi = \arcsin\left(\frac{\Delta z}{2 r_c k_\psi}\right). \tag{12}$$

To validate the procedure, the assigned yaw angles were correlated with the measured one ψ_{M} by induction coils. The standard deviation was computed over ten consecutive measurement repetitions. Fig. 6 shows the measured angles as a function of the applied mechanical misalignment, while the corresponding numeric values are reported in Table I.

As expected, the measurement results validate the proposed measurement procedure, with an average mismatch between the measured values and the reference of 4 ‰. Nonetheless, the high value of standard deviations proves that the sensitivity of

TABLE I
MEASURED ANGLES AS A FUNCTION OF THE REFERENCE ANGULAR POSITIONS

Reference angle (mrad)	**Measured angle** (mrad)	**Std.** (mrad)
0	0.1	1.3
9	9.5	2.1
19	18.5	1.6
27	25.7	1.7
37	36.9	1.6
45	46.6	1.5
57	56.1	1.8

Fig. 7. Newly designed PCB transducer for the AD cooler.

the existing measurement transducer is incompatible with the required angle accuracy needed for the measurement of the AD cooler solenoids.

III. DESIGN OF THE NEW TRANSLATING-COIL MAGNETOMETER

The high standard deviation values reported in Table I can be explained by combining different factors. A first contribution is the low signal-to-noise ratio because the system was initially designed to qualify a 9 T solenoid for the WISArD experiment [11]. More in detail, given the low coil surface of 0.0168 m^2 of the coil $Q_{3,4}$, the peak voltage is of about 2.5 mV at an average speed of 0.12 m/s, with a peak-to-peak noise of about 0.1 mV. This leads to a repeatability in the peak shift determination in the order of 0.2 mm. Additionally, mechanical vibrations in the transverse direction, in the order of 60 μm, contribute to the measured angle by 0.1 mrad.

Considering the outcome of the experiment and metrological characterization results, a new translating coil magnetometer was designed. Fig. 7 shows the latest PCB design, where the PCB diameter was increased from 90 mm to 170 mm, and the number of turns on each PCB coil was raised by a factor 4, twice the number of turns and twice the number of layers, for a total of 20 layers and a maximum sector coil surface of 0.217 m^2. The increase in the sector coil surface will improve the signal-to-noise ratio by at least a factor of 10. This improvement, in combination with more refined mechanics and an improved peak identification algorithm, will allow the measurement system to meet the measurement requirements of 0.1 mrad. Moreover, smaller angular sectors, by about a factor of 10, were added and superimposed to the 90°-sector coils. In this way, higher-order harmonics can also be measured. As these higher-order harmonics scale with the measurement radius, the sensitivity in the peak shift can be further increased. Finally, the pancake coils of the AD cooler are much larger and shorter than the solenoid coil used for the experimental validation, which can help to improve the mechanical angle identification further.

IV. CONCLUSION

This article proposed a new method for measuring the tilt angle of solenoid magnets. The measurement method is based on translating-coil magnetometer measurements, exploiting the field symmetry of dipole field distributions, which appear when a solenoid coil is tilted. The method was experimentally validated, albeit it also expressed the limitation as the experimental results showed a precision of only 2 mrad, which is insufficient to meet the requirements. Nonetheless, the metrological characterization has been crucial for designing an enhanced magnetometer based on PCB technology. Hence, for the upcoming AD electron cooler, the solenoid field angle will be aligned mechanically (or electrically) to reach the field homogeneity required using the proposed method.

An extensive test campaign using the newly developed device is foreseen in the upcoming months before the actual measurement campaign.

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