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CH Type 2 Solenoid Steering Coil Polarity Measurement

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This note describes the magnetic field polarity measurement of steering dipoles of Type 2 CH section solenoids, which are in the final stage of production. The main goal of this work was to develop a simple method that would allow measurement of the magnetic field direction in the horizontal and the vertical steering dipoles before the solenoid is cooled down to the cryogenic temperature as part of the QA input control.

Because the measurements are made at room temperature, the excitation current can not be set as high as it can be set when the steering coils are superconducting. The current density in the strand used to make the steering dipoles can not exceed ~2 A/mm^2. Giving the content of copper in the NbTi strand, this results in the maximum current of ~0.5 A. Another limitation comes from the use of a Hall probe-based AlphaLab, Inc. DC Milligauss Magnetometer (Fig. 1) that has the measured magnetic field range from 0 up to 2 Gs. This limits the current in the strand to ~0.25 A.

Fig. 1. AlphaLab, Inc. DC Milligauss Magnetometer and Hall probe sensors

As a result, the maximum magnetic field during the measurement is quite comparable with the magnetic field of the Earth (~0.5 Gs). Inside the flux return, where the steering coils are placed, the magnetic field of Earth is significantly distorted. First, the Earth field is mainly shunted by the flux return. Second, the residual magnetization of the flux return after cold tests at Cryomagnetics, where the solenoids were fabricated, results in the presence of some background magnetic field inside the bore, which is directed mainly along the axis if the device. Nevertheless, near the flux plugs on both sides of each solenoid, this field has significant radial component. This results in some uncertainty in the measurement results if the Hall probe is not centered exactly in the center of the solenoid. For example, during one of the measurement cycles, the background transverse field measured in the center and near the two ends of the CH-T2-02 solenoid was 900 mG

at -100º at the lead end, 1000 mG at +85º at the return end, and 172 mG at +62.5º in the center of the device.

The next algorithm of the measurements was accepted:

1. The field is measured in the center of the solenoid, where only the longitudinal component of the residual magnetization field exists.
2. The vector of the background transverse magnetic field inside the solenoid is measured when the steering coils are not energized – vector B1 in Fig. 2. The "zero" angle is assigned to the vector directed up vertically or horizontally depending on which steering coil is used.
3. The vector of the magnetic field is measured after the vertical or horizontal steering coil is energized – vector B2 in Fig. 2. This magnetic field is a vector sum of the background field at this point and the field of the corresponding steering coil.
4. The field of the steering coil (B_coil) is a difference between the field measured at step 2 (vector B2 with the Angle2 in Fig. 1) and the background transverse field (vector B1 with the Angle1 in Fig. 2).

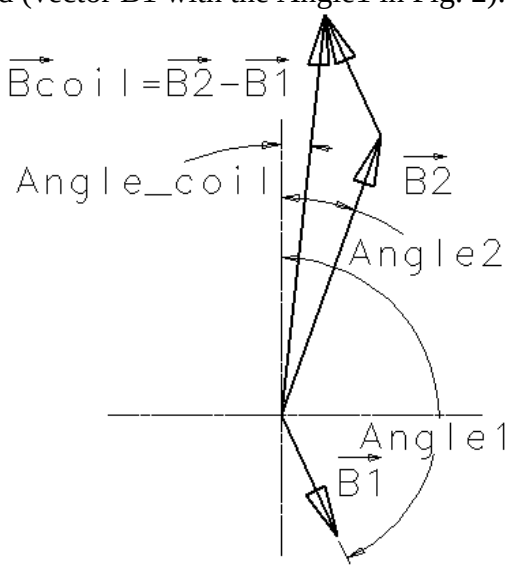

Fig. 2. Vector diagram of the steering coil field direction measurement procedure

5. Knowing the position of the vertical plane, it is easy to find the field direction Angle_coil after the amplitudes B1 and B2 and the directions Angle1 (or A1) of the background field and Angle2 (or A2) of the total field are measured.

$$Angle_coil = \arctan\left[\frac{B2\cdot\sin(A2) - B1\cdot\sin(A1)}{B2\cdot\cos(A2) - B1\cdot\cos(A1)}\right] \qquad /1/$$

This procedure applies to both the horizontal and the vertical steering dipoles. To avoid possible problems due to specific properties of the *arctan* function, it is recommended to use the vertical plane as a reference for the horizontal dipole and the horizontal plane as a reference for the vertical dipole.

A device to make the measurements of the magnetic field vectors consists of a rotating stage (Newmark rotary positioner RT-5DR) with an extension rod that can be inserted in the solenoid bore. A Hall probe sensitive to the transverse magnetic field is

attached to the end of the rod. Angular position of the probe is measured with the use of a digital readout unit (that comes with the positioner) with the precision of ~0.1 degrees. Fig. 3 shows the measurement setup.

Fig. 3. Steering coils polarity measurement setup

The issue remains how well the position of the vertical plane is known. This is not so trivial questions taking into account the size of the Hall probe. The Hall probe used with the magnetometer, although sensitive, is quite small (Fig. 4), and this results in some difficulties in establishing its angular position.

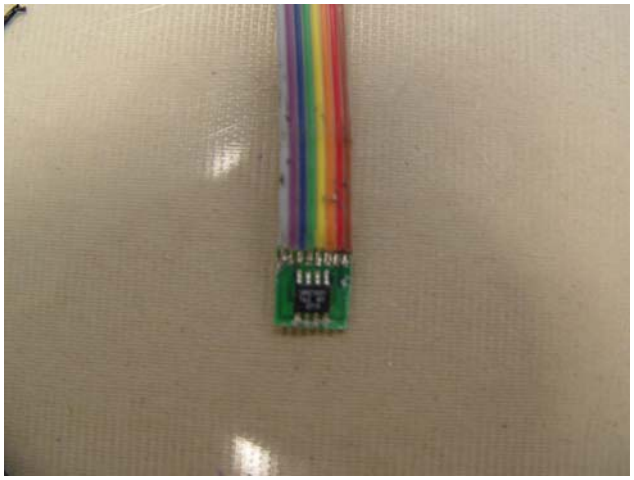

Fig. 4. Photo of the Hall probe of the Milligauss Magnetometer.

To resolve this issue, a simple method was developed to establish the vertical plane of the measuring device. A long, one-layer solenoid was used with turns laid perpendicular to its axis; the field inside the solenoid is directed along its axis if not measured too close to the turns. The vertical alignment of the solenoid axis can be quite accurately defined by pure mechanical means.

The extension rod of the vector magnetic field measurement device described above (with the Hall probe fixed at the end of the rod) was inserted inside the solenoid through a narrow opening (Fig. 5). The Hall probe is positioned close to the solenoid winding at the side of the cylinder opposite to the opening. Magnetic modeling shows that with the chosen solenoid configuration, the field at the distance of ~5 mm from the winding is parallel to the axis of the solenoid within 0.5º.

Fig. 5. The setup to establish well defined vertical plane for the steering coil polarity measurements

The process starts with establishing a preliminary vertical plane (geometrically). Then a set of measurements is made similar to what was described above to find the direction of the compound magnetic field in the solenoid (background field plus the field of the solenoid). Knowing that the field of the solenoid is vertical, a correction to the established (preliminary) direction of the vertical plane is made using the field recalculation defined by /1/, and the measurements are repeated with variation of the position of the measurement device and the current in the solenoid. Six cycles of the measurements were made to verify that the position of the "new" vertical plane is stable within +/-0.25º. This position is then taken as a reference vertical plane to measure the direction of the magnetic field of the horizontal steering dipoles. This reference vertical plane position must be found only once if the base plate of the measurement device is not altered or replaced. It will be checked periodically to improve the measurement statistics. The horizontal plane is perpendicular to the vertical plane and is known as soon as the vertical plane is established. The newly established vertical direction usually differs from the earlier (preliminary) established direction by several degrees.

After the vertical (or horizontal) reference plane is established, the field direction of each corrector can be measured as it was described above. The result of this measurement for the solenoids CH1201 and CH1203 are shown in the table below. "Reference Plane" column shows which plane was assigned the "zero" angle.

	Reference Plain	Angle	Data spread
CH1201 horizontal	vertical	-0.63º	
CH1201 vertical	horizontal	-0.57	
CH1203 horizontal	vertical	1.55º	+/- 0.25º
CH1203 vertical	horizontal	-0.12º	+/- 0.3º

Conclusion

A tool for polarity measurement of the steering dipoles in the solenoids equipped with dipole correctors and a procedure to measure the polarity were developed. The tool was calibrated by finding the magnetic field direction in a specially designed solenoid. This direction was found to be reproducible within +/-0.25º.

Accuracy of the steering magnetic field direction was also on the level of +/-0.25º. Nevertheless an uncertainty was found leading to a possible significant systematic error related to a residual magnetization of solenoids' flux returns. Having this uncertainty in mind, field polarization measurements must be made at high steering field level, while the solenoid magnetic axis positioning is studied, using the stretched wire technique.