METHODS OF INCREASING ACCURACY IN PRECISION MAGNETIC FIELD MEASUREMENTS OF CYCLOTRON MAGNETS

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Abstract

A new magnetic field mapper was designed and built to provide increased accuracy of cyclotron magnetic field measurements. This mapper was designed for mapping the magnetic fields of TR-19, TR-24, and TR-30 cyclotron magnets manufactured by Advanced Cyclotron Systems Inc. A Group3 MPT-141 Hall Probe (HP) with measurement range from 2 G to 21 kG was used in the mapper's design. The analogue monitor output was used to allow fast reading of the Hall voltage. Use of a fast ADC NI9239 module and error reduction algorithms, based on a polynomial regression method, allowed the reduction of noise to 0.2 G. The HP arm was made as a carbon fibre foam sandwich. This rigid structure kept the HP arm in a flat plane within 0.1 mm. In order to measure the high gradient field, the design of this mapper provided high resolution of HP arm angle within 0.0005° and of radial position within 25 µm. A set of National Instrument interfaces connected through a network to a desktop computer were used as a base of control and data acquisition systems. The mapper was successfully used to map TR-19 and TR-24 cyclotron magnets.

MAPPING SYSTEM OVERVIEW

The mapping system consists of a mechanical motion device (MMD), acquisition and control electronics and software for operation and data processing.

Mechanical and Measurement Specifications

- Magnetic field accuracy: $5*10^{-5}$ T (in hills)
- Azimuthal, radial resolutions: 0.0005°, 25 µm
- Magnetic field range: 0.4 – 2.2 T
- Scanning speed: 75 – 500 mm/s
- Duration of 360° measurement: 70 min (at 150mm/s)
- Number of samples per scan: 52000

Mechanical Motion Device (MMD)

MMD moves the Hall Probe (HP) to any point in the mid-plane of the cyclotron's magnet through radial and azimuthal components of motion. Those components of motion are achieved by stepper motors mounted onto two shafts inserted through the center of a cyclotron's magnet.

The HP is located on the HP cart that slides along the rails of the HP arm (see Figure 1) which in turn is attached to the main (larger) shaft. This shaft allows azimuthal rotation of the HP arm through a Harmonic Drive (HD), which is a stepper motor that is operating in servo mode. According to the specifications of this motor, the accuracy of positioning is 30arc-s (2.8×10^{-4} degrees) [1]. An Inductosyn encoder [2] with resolution of 0.0001° is used for reading the angle of HP arm's position. Each angle position is read by an Inductosyn before and after scanning to guarantee the HP arm did not move. Compressed air brakes are applied to hold the angle. If the difference between readings is more than 0.0005°, the HP arm is reset and the process is repeated. Rigid bellows are used to join the HD to the main shaft without applying extra force to the HD bearings. Furthermore, the shaft is supported by two spherical bearings that allow for alignment adjustment.

Figure 1: The magnetic field mapper.

A second (smaller) shaft is located inside the main shaft and its stepper motor rotates a timing pulley. The timing pulley pulls a timing belt that is attached to the HP cart. This produces radial motion. The suspension system for the HP cart is made from sliders moving along the rails. For vibration reduction an adjustable mechanical system with shock absorbers is used.

A linear optical encoder with 2 mm period stripes is used for reading radial coordinates. The signal obtained by the HP arm's optical sensor (collected at 5 kHz for 150 mm/s) from this encoder is presented in Figure 2.

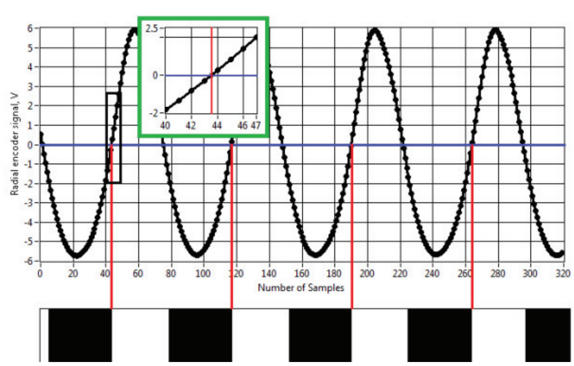

Figure 2: Determination of radial position.

The precise strip edge positions are defined where the optical sensor signal crosses zero voltage (i.e. where

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the encoder switches transparency). Interpolation between discrete readings is used in order to determine this precise position. Total error in the whole process (due to variability of encoder strips, dirt, scratches and interpolation) was determined to be less than 25 µm.

The HP arm also contains an optical sensor for absolute measurements of angle relative to a reference point (i.e. home position). Consistency of home positioning was experimentally checked through comparison of home position's angles after a few 360° mapping cycles and was within 0.002°.

Acquisition and Control Electronics

Group3 MPT-141 Hall probe [3] is used in this mapper. A NI cDAQ-9188 CompactDAQ Ethernet chassis with five modules was used as the main interface between the CPU, the sensors and actuators. The main part of the code was written in LabVIEW 2011. This allowed control of all actuators and sensors as well as to carry out live data processing.

MAPPING CYCLE OVERVIEW

Prior to any data collection, the main shaft of the mapper as well as the HP probe's height are aligned so that the HP travelled within 100 µm of the mid-plane at all angles and radii.

Then HP calibration is performed through comparing the readings of the HP and of Drusch Gaussmeter NMR 20 at seven magnetic field levels. Two steel plugs are inserted into two service holes in the magnet in order to form relatively uniform and strong magnetic field in-between the plugs. In each case the magnetic field is stabilized prior to any data collection.

At the beginning of each data collection cycle, the HP arm is moved into the home position, which is determined by an optical switch.

MAPPING OPERATION MODE

Data Collection

Typically 360° mapping starts in the middle of the first hill and consists of 181 radial scans of 2° each (last scan overlaps the first scan to verify consistency). However, if necessary, starting position and scanning steps are adjustable. During radial scans, measurements of the magnetic field, two optical encoder signals and temperature are taken at a rate of 5 kHz (for the speed of 150mm/s).

In order to reduce transfer time between chassis and computer, data of every radial scan is only transferred to the computer's hard drive while the arm is turning to the next angle.

Data Processing: Hall Probe Noise Cancellation

In-between scans, computer not only transfers the data, but could also (optionally) reduce noise in the measured data. The method of least squares is used to fit a 3rd order polynomial over a rolling window of 100 points (3 mm). The polynomial is then used to provide the central point of this range for the reduced noise data array. The window size and polynomial order could be selected according to required accuracy and magnetic field's gradient [4, 5].

An experimental investigation showed that in the region of maximum gradient change, a cubic curve could be fitted to the reduced noise data array within a maximum deviation of 0.2 G for the interval of 3 mm length (Figure 3).

As mentioned earlier, the optical encoder only determines the precise radial position every 2 mm (i.e. at strip edges where there is a chance in transparency). Hence positions of all 100 points are not precisely known. However, for this method of data processing, it is only important that those points are evenly spaced. An experimental study was done that determined maximum deviation from perfectly even spacing was 0.2 µm. Then a simulation determined that this deviation corresponds to 20 mG error.

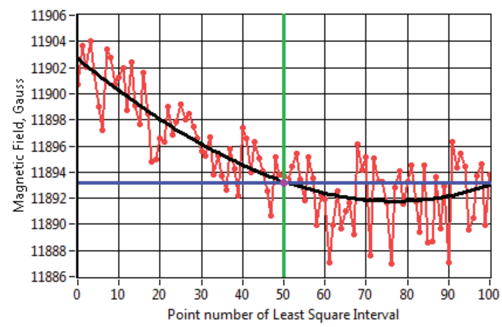

Figure 3: The Selection of Reduced Noise Point.

Hall Probe Calibration Analysis

The maximum magnetic field in the gap between plugs is used for calibration. Drusch Gaussmeter would be manually guided into the spacing between the plugs along guide lines drawn on the plugs. The visual error in this process was estimated to be ±2 mm. Based on azimuthal distribution of the magnetic field near the line of symmetry in-between calibration plugs (i.e. at the maximum), the associated error in the magnetic field reading is ±0.5 G. Radial position of Drusch Gaussmeter probe is determined by searching for the maximum reading.

HP maximum reading is found from a radial scan along with the HP arm. Fifty seconds were required to exchange probes over which field deviation was less than 20 mG.

Group3 MPT-141 Hall Probe has a temperature sensor that allows making temperature drift error compensation. A hot air blower is used to create different temperature environments. Temperature compensation is calculated by the following formula:

$$\Delta V_{corr}\left(B, V_{temp}\right) = \frac{dV_{hp}}{dV_{temp}}(B)\left(V_{temp_{initial}} - V_{temp}\right) \quad (1)$$

Where $\frac{dV_{hp}}{dV_{temp}}$ is the temperature sensor calibration coefficient which is determined from this experiment as seen in Figure 4.

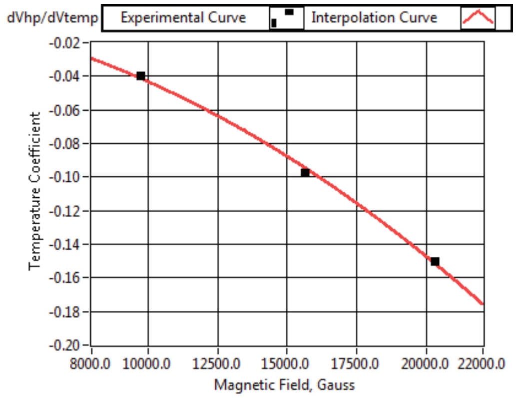

Figure 4: Temperature HP sensor calibration.

The field corrections are calculated as:

$$V_{hp\ corr} = \Delta V_{corr} + V_{hp} \quad (2)$$

(where V_{hp} is the HP Voltage).

ERROR ANALYSIS

Effect of Mechanical Errors

The effect of error in radial positioning was simulated in Labview with real experimental data as input. The results showed error contribution less than 20 mG.

Larger error contributions were from the azimuthal oscillations of the HP cart near transitions between hills and valleys. The maximum field gradient in those regions was $\frac{dB_z}{d\theta} = 1980\ G/\text{degrees}$. Azimuthal oscillation error was determined through repeated scans over such a region. Previously, the HP cart was equipped with a wheel suspension system that resulted in amplitudes of ≈8 G. Hence the switch to a slider system was made which reduced the error to ≈2 G.

Error Generated by Bending Moving Cable

Previously the mapping system used twisted pair cable to connect the HP. Twisted cable consists of tiny loops located in-between the twists, which induce voltage. If cable is straight, then voltages from nearby loops compensate each other. However, when cable starts to move and to bend (due to HP movement) then the dimensions of the loops will change and one loop's signal doesn't compensate next loop's signal. Furthermore variation of this kind is also present in regions of high field gradient.

As an experiment, one 90° mapping experiment used a flexible SENIS HP cable and the HP was replaced by equivalent to HP 1.1 Ω resistor. The results showed variation in the output signal of as much as 14 mV that was equivalent 45 G. In order to prevent this error, twisted quad cable was used, the design of which better compensates induced voltage. The maximum error with the quad cable was under 0.2 G.

Furthermore, while the probe is moving, the HP can cause many DC offset problems, such as eddy currents in the probe and induced emfs. Those were reduced by using the high frequency current in the HP and filtering out the voltage at this frequency. Hence only voltages correlated with the Hall current are observed and not the DC effects. It was shown that there is negligible difference between the fields taken at 75, 150 and 250 mm/s cart speeds.

Dynamic HP Reading Error from Low-pass Filter

As the HP moves in the static magnetic field with radial variation, the output signal changes according to the magnetic field and thus the HP output signal could be considered as non-periodic, time dependent signal. For the HP cart with a velocity 150 mm/s calculations were done to determine the dependency of the maximum error near zero and near the largest mapping radii on the low-pass cut-off frequency. Results show (Figure 5) that a low-pass filter should not have cut-off frequency lower than 103 Hz for 200 mG resolution. However Group3 DTM-133 amplifier has low-pass filters with cut-off frequencies of as high as 16 kHz and 1746 Hz.

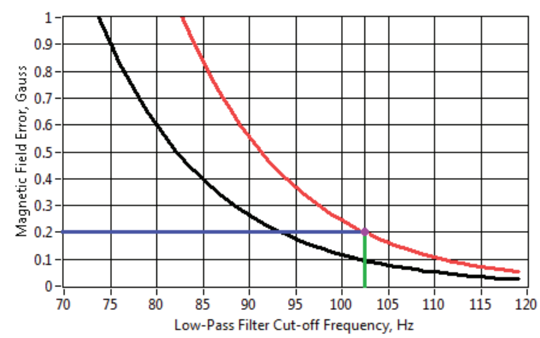

Figure 5: Low pass filter analysis.

CONCLUSION

Operation of the mapper was verified by comparison of mapping data with calculations and an older mapping system. At this moment the mapper is in the production line of ACSI, it has completed at least 9 cycles of mapping and magnetic field adjustments for TR-19, TR-24 cyclotrons. All data was stable and reproducible.

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