The instrument for investigating magnetic fields of isochronous cyclotrons

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Abstract. A new instrument was designed and implemented in order to increase the measurement accuracy of magnetic field maps for isochronous Cyclotrons manufactured by Advanced Cyclotron Systems Inc. This instrument uses the Hall Probe (HP) from New Zealand manufacturer Group3. The specific probe used is MPT-141 HP and can measure magnetic field in the range from 2G to 21kG. Use of a fast ADC NI9239 module and error reduction algorithms, based on a polynomial regression method, allowed to reduce the noise to 0.2G. The design of this instrument allows to measure high gradient magnetic fields, as the resolution of the HP arm angle is within 0.0005° and the radial position resolution is within 25μm. A set of National Instrument interfaces connected to a desktop computer through a network are used as base control and data acquisition systems.

1. Instrument Overview
The instrument consists of the Hall Probe positioning mechanism, the electronics module based on compact National Instruments NI cDAQ-9188 chassis and a desktop computer equipped with custom-made LabVIEW 2011 software [1]. This software performs control, data acquisition and post processing tasks.

Table 1. Technical characteristics of the instrument

| Parameter                        | Value                        |
|----------------------------------|------------------------------|
| Magnetic field accuracy          | 5 * 10^-5 T (in hills)       |
| Azimuthal, radial resolution     | 0.0005°, 25μm                |
| Magnetic field range             | 0.4 – 2.2 T                  |
| Speed of radial motion           | 75 – 500 mm/s                |
| Measurement time                 | 70 min                       |
| Number of samples per one radial scan | 52000                          |

1.1. HP Positioning Mechanism (HPM)
HPM is designed to move the HP in the radial direction and to change the scan angle. HPM allows to move the HP to any coordinate of the middle plane, the plane mid-way between the cyclotron magnet’s poles. To provide this two-dimensional motion, two stepper motors with coaxial shafts are used. For azimuthal rotation, the Harmonic Drive LLC (FHA-25C-100-US250-A) is used [2]. The advantage of this motor is that it uses a harmonic gear, has a hollow shaft, and has turning accuracy of 2.8 * 10^-4°. Its transmission consists of specially designed disc brakes that allow to overcome inertia and allow to stop the shaft at the required angle with high precision. An inductosyn encoder Farrand Controls, Inc. [3] with a resolution of 0.0001° is used for angle measurements.
Figure 1. The design of the instrument’s transmission

The transmission includes: 1 - Stepper motor for the radial direction, 2 - Stepper motor with the harmonic gear for azimuthal rotation, 3 - The inductosyn, 4 - The bellows made of stainless steel, 5 - The clutch, 6 - The big spherical bearing sitting on an aluminum sphere, 7 - The small ball bearing, 8 - The pneumatic disk brakes, 9 - Flange for the attachment of the transmission to a cyclotron magnet.

The instrument’s transmission is inserted in the central hole of the cyclotron magnet and rotates the HP cart’s plastic panel in the plane between the magnet’s poles. The plastic panel was manufactured as a lamination of two carbon fiber layers (Illstreet Composites) with one layer of polyurethane foam (LAST-A-FOAM FR-7106, manufactured by Fiberlay, Inc.) placed in-between. This allows for the panel to be lightweight and rigid. To ensure precise mechanical tuning, lamination was done in a vacuum press and on a granite table. The panel also contains rails that provide radial motion of the HP cart along its length. The rails are made of Delrin (polyoxymethylene) and were machined in-place after the lamination process.
An experimental study showed that the mechanical vibration, recalculated in magnetic field, was 4G if the HP cart was moving on wheels and 0.5G if it was sliding on rails. Thus, the later design was chosen. The friction sliders were made of the self-lubricated material SP-21 manufactured by DuPont VESPEL.

The Parker-Compumotor ES23B stepper motor pulls the HP cart via a timing belt and a timing pulley located at the end of motor’s shaft. The radial coordinate readings are made using optical transmissive sensors (HOA1872-012) and a transparent plastic film. The film contains 2mm black transverse strips, placed with a 4mm period. These strips interrupt the sensor’s light beam and generate voltage pulses as a result (Fig. 3). When the voltage reading is zero, the HP cart is located precisely at the black strip’s edge. Linear interpolation is used to determine those exact points and adjust magnetic field readings accordingly.

![Figure 2. The HP cart panel as installed inside the magnet of the TR-24 Cyclotron](image)

![Figure 3. Determination of HP’s radial coordinate](image)
The total error of coordinates depends on the tolerance of etching strips, dirtiness of film, scratches of the film and on deflections in the position of the film from the center of optical sensor’s gap. The experimental study of this error showed that the error is less than 25μm.

This instrument also contains an optical sensor to determine a reference point for the panel’s angles (i.e. a home position). Reproducibility of the home position was experimentally checked by comparing home position angles before and after 360° mapping cycles. The initial and final angles were within 0.002°.

1.2. Acquisition and control electronics
A NI cDAQ-9188 CompactDAQ Ethernet chassis with five modules is the main interface between the CPU, the sensors and the actuators. Most of the software is written in LabVIEW 2011. This allows to control all actuators and sensors and to carry out live data processing.

2. Alignment and Calibration
Prior to any data collection, the main shaft of the instrument as well as the HP height are aligned so that the HP travels within 100μm of the mid-plane at the all angles and radii. A spacer is used to position the HP panel in the middle plane. After installation, the HP panel’s position is verified by a Mitutoyo dial gauge (25μm resolution). Three tuning screws are used to adjust the angle of the rotational axis. Those screws move the transmission assembly with respect to the aluminum sphere which is attached to the magnet. The results of this alignment are checked by attaching an aluminum bar to the main hollow shaft and placing the same dial gauge at the outside end of the bar, with the tip pointing down to the magnet’s surface. Then the main shaft is manually rotated and dial gauge readings are checked to ensure that the angle of the rotational axis is within ±0.0025°.

The inductosyn is used to measure the panel’s angle. The inductosyn is a transformer with the primary winding installed on the rotor and two secondary windings installed on the stator. The required amplitude of the secondary winding’s signal is adjusted by changing the gap between the stator and the rotor. According to the datasheet for this inductosyn, this gap should be in the range from 0.1mm to 0.3mm. The error is caused by the shifts in the stator and rotor axis. To minimize the error, the rotor’s position is tuned relative to the hollow shaft’s axis. The shift between the stator and the rotor is measured in two steps. The dial gauge is attached to the stator in the first step and to the rotor in the second step. The hollow shaft is rotated during those measurements. The inductosyn signal is converted to the quadrature signal and is then processed by the NI 9411 module to obtain the digital value of HP panel’s angle.

The calibration of the HP is performed by comparing the HP readings with the readings of the Drusch Gaussmeter NMR 20. For calibration purposes, a relatively uniform magnetic field is formed in the small gap between two steel plugs inserted into the cyclotron’s magnet. The calibration is done at seven different levels of the magnetic field.

The calibration of the temperature sensor is performed through comparison of HP’s voltage and temperature sensor’s voltage. During the calibration, the HP is heated by a fan for ten minutes and is then cooled down by ambient air for 20 minutes. The calibration is done at three different levels of the magnetic field. The following formulas is used for voltage correction (1):

\[ \Delta V_{\text{corr}}(B, V_{\text{temp}}) = \frac{dV_{\text{HP}}}{dV_{\text{temp}}}(B)(V_{\text{temp initial}} - V_{\text{temp}}) \]  

(1)

Coefficients \( \frac{dV_{\text{HP}}}{dV_{\text{temp}}} \) are determined (Fig. 4) from the time dependences of HP’s voltage and of temperature sensor’s voltage.
3. Data Collection and Analysis

3.1. Data acquisition
Usually, the 360° mapping process 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). If necessary, the starting position and the step size are adjustable. To determine the initial angle of the HP panel, an optical sensor is used. All trajectories of the HP motion pass through the centre of the magnet to obtain field samples from the opposite part of the magnet. These samples are used to correct for the magnetic field errors due to mapper alignment, air temperature drift and HP noise. These samples are also used to determine the radial direction’s midpoint and magnet’s centre position (where the magnetic field reaches its minimum). To reduce the data acquisition cycle, all data from HP, two optical coordinate encoders and the temperature sensor are recorded in the memory of ADC NI 9239. Then, when the HP cart moves backward, the memory contents are transferred to the computer.

3.2. Magnetic field measurements data treatment
The post-processing of data reduces the data’s noise level and is done as the HP cart moves backwards. This correction is performed using sliding 100-point data intervals. For each data interval, a 3rd order polynomial curve is fit using the method of least squares. For the interval’s mid-point, the interpolated value becomes the new true value of the magnetic field at that point (Fig. 5).

Figure 4. Coefficient of temperature calibration
An investigation of magnetic field measurement errors determined that errors of at most 0.2G are found in the areas of large magnetic field gradients (210G/mm). It was also experimentally determined that the vibration of HP cart increases the error by 20μG in the same areas of large magnetic field gradients. This increase was negligible in comparison to the 0.2G error measured otherwise.

3.3. Magnetic field measurement equipment
Group3’s Hall Effect Digital Teslameter DTM-133 with HP cable MPT-141 [4] were modified for use in this instrument. Specifically, the amplifier was modified to have higher gain and components were added to read temperature. This field measurement equipment has some advantages in comparison to similar equipment offered by other companies. Specifically, to reduce noise and instrument drift, this equipment uses amplitude-modulated signal from the HP instead of the DC signal used in other instruments. This modulation has frequency of 20 kHz. Another advantage is that Group3’s equipment uses double twisted pair cable for the HP signal and single twisted pair cable for the BIAS and the temperature sensor. The Group3 cables were compared to the cables from SENIS through a study of induced voltages, when the cables were loaded by a 1.1Ω resistor instead of the HP. The results show that the maximal error for the SENIS’s HP cable is 45G and for Group3’s HP cable is 0.2G.

3.4. Dynamic errors of measurement of magnetic fields
To suppress parasitic noise and the other parasitic signals, DTM-133 has two low-pass filters with cutoff frequencies of 16 kHz and 1746 Hz. To improve the signal-noise ratio, an additional low-pass filter with lower cutoff frequency could be installed, but in this case additional errors appeared to be caused by this filter. Specifically, as the HP moves in the static magnetic field that is variable in the radial direction, the signal at the amplifier’s input becomes the signal changing over time. This dynamic error depends on the filter’s cutoff frequency as illustrated in Fig.6.

![Figure 5. HP Noise Reduction](image-url)
Figure 6. Analysis of the error caused by the use of a low-pass filter

4. Conclusion
The new instrument was verified through comparison of the magnetic field maps it produced to the ones produced by an instrument which was successfully used by Advanced Cyclotron Systems Inc. for over 20 years. The verification was performed at HP speeds of 75 mm/s, 150 mm/s and 250 mm/s. At the present time, more than 12 cyclotrons were built and commissioned using this instrument. The instrument demonstrated reliability, accuracy, and high performance throughout.

References
[1] Avreline N V, Gyles W, Watt R L, Methods of increasing Accuracy in Precision Magnetic Field Measurements of Cyclotron Magnets, 20th International Conference on Cyclotrons and their Applications, Vancouver, Canada, 2013, p.283
[2] Harmonic Drive, http://www.harmonicdrive.net
[3] Ruhle Companies Inc., http://www.ruhle.com
[4] Group 3 Tech., http://www.group3technology.com