PRECISION FIELD MAPPING SYSTEM FOR CYCLOTRON MAGNET*

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Abstract

This paper presents a Hall-probe mapping system for measuring the cyclotron magnet, which has been fabricated for the 13 MeV cyclotron at the Korea Institute of Radiological and Medical Sciences(KIRAMS). The Hall probe are mounted on the precision x-y stage, and maps the magnetic field in the Cartesian coordinates. To reduce the data-acquisition time, the system uses the “flying” mode field mapping method. The data acquisition time for mapping the whole gap-area of the cyclotron magnet is ~ 60 minutes. The relative random fluctuation error during the entire mapping process is under 0.01 %. The field measurement results after correction have indicated that the total phase excursion is less than ±15°.

INTRODUCTION

The cyclotron KIRAMS-13 has been operating since 2002 at the Korea Institute of Radiological and Medical Sciences to produce radio-isotopes such as ^{18}F and ^{15}O for positron emission tomography application. The magnetic field measurement system requires the specifications listed in Table 1 for the cyclotron magnet. The required relative accuracy of magnetic field measurement is 0.01 %. The field profile of a prototype magnet has been measured at first using the flip-coil method [1]. However, we found that accuracy with the flip-coil method is ~ 0.1 % at best being affected by the temperature fluctuation.

Table 1: Specifications of the mapping system.

System specifications	Unit	Value
X scan capability	mm	1100
Y scan capability	mm	480×2
Mechanical resolution	μm	5
Range of magnetic field	T	2.0
Accuracy of measurement system	G	±1

The accuracy of a gauss-meter has been improved significantly. So the Hall probes are being used for measuring the magnetic field of the insertion devices, such as an undulator and wiggler, which require a high accuracy for field measurement [2]. In order to measure cyclotron magnetic field, many laboratories had been designed field mapping system using the polar coordinate system [3]. However, it is very difficult to build a big wheel for mapping stage at a moderate cost; a thin wheel deforms in time and a thick wheel tends to be too heavy to handle it.

In this paper, a Hall probe mapping system and the results of field measurements for the KIRAMS-13 cyclotron magnet are described.

MECHANICAL SYSTEM

Cross sectional view of the Hall probe mapping stage and cyclotron magnet ⑩ are given in Fig. 1.

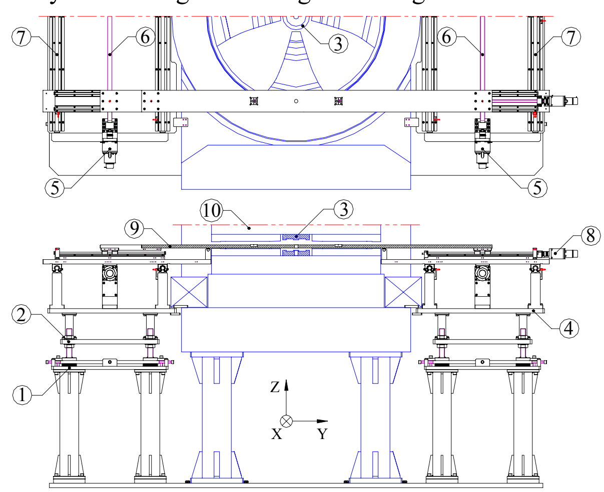

Figure 1: Cyclotron magnet and Hall probe mapping system: alignment stages ① and ②, center plug ③, mapping stage ④, x-axis motors ⑤, x-axis ball screws ⑥, x-axis guide rails ⑦, y-axis motor ⑧, Carrier ⑨, and magnet ⑩.

The Hall probe mapping stage was divided into two stages, an alignment stage and a mapping stage. Both x-y planes and height of the mapping stage were aligned using the slide bearings and screws of the alignment stages ① and ②. Two stepping motors ⑤ for x-axis and a motor ⑧ for y-axis are installed on the mapping stage ④. This stage was fabricated and aligned by the Coordinate Measuring Machine (CMM) in advance to have been putting together all the measurement system. Because the Hall probe carrier(Carrier) ⑨ is driven to the x-direction by two separate motors with tightly jointed at both ends of the Carrier, any misalignments of these components can jam the mapping stage. Thus the allowed alignment error for the ball-screws ⑥ and guide rails ⑦ has to be less than 30 μm. The magnet and measurement systems

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are laid on a steel plate and a rubber pad to absorb vibrations and to compensate uneven floor surface.

The Carrier is made of epoxy-fiber-glass, and its length, width, and thickness are 2000, 100, 20 mm, respectively. To prevent sag of the Carrier, it is supported by two non-magnetic oilless cylindrical type bearings located near the magnetic pole. With all these schemes, we can make the mechanical part to have flexibility and precision in three-dimensional space.

MEASUREMENT SYSTEM

A block diagram of the mapping system is shown in Fig. 2. It consists of two Teslameters, digital volt meters (DVMs), three stepping motors and drivers, an encoder clock monitor, a trigger pulse counter, step pulse processor and computer, etc.

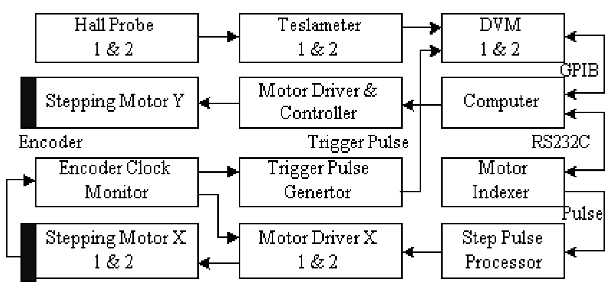

Figure 2: Block diagram of the mapping system.

Two DTM-141 Teslameters and the MPT-141 Hall probes from the GMW which have active areas of 1.0 mm × 0.5 mm are used. The output voltage of the DTM-141 Teslameter is digitized by the DVM HP3458A whenever trigger clocks are generated by the trigger pulse counter circuits. Those clocks translate the exact Hall-probe positions along the x-axis. As the encoder generates 2000 pulses/revolution and the pitch of the ball screw of the x-axis is 5 mm, the trigger clock for 1 mm resolution is continuously generated by trigger pulse counter circuits every 400 encoder pulses for "flying" mode field measurement while the Carrier is moving. An OEM010 indexer from Paker is used for generating the step pulses for x-direction. These pulses are duplicated for two x-axis drivers so that two x-axis motors are always rotating synchronously. If one of the two motors skips the step for some reason, the other one is disabled by the encoder clock monitor circuits, which generate fault signal when one is rotating but the other isn't for given short time. These situations occur many times during the system alignment. A S57-83 stepping motor and SX6 driver from Paker are installed to drive the y-axis.

FIELD MEASUREMENT

The Hall probe mapping should be fast enough to reduce the measurement time and signal drifts due to the temperature variation. Two Teslameters are used for field mapping for the purpose of reducing mapping time to one half. A Hall probe has a nonlinear response to the magnetic field and to the temperature variation. The MPT series Hall probes have a calibration table in its PROM for the compensation of those non-linearities. However, the data conversion rate of the DTM-141 Teslameter is so slow (~10 Hz) that the calibration table in the Teslameter can not be used for the mapping which requires about 15 reading/sec. Besides this Teslameter can not accept the external hardware trigger signal for sampling the field at the given exact time. Because of those reasons, the off-line calibration table were constructed for the two Hall probes using a uniform magnetic field. The digitizing process continues until a predefined number data acquisition is finished. And then off-line calibration table is applied to convert the sampled voltage into the magnetic field with the cubic spline interpolation.

The system noise level was measured for a scan along the x-axis at the same conditions with real field mapping except that the Hall sensors were put into a zero gauss chamber not to be affected by the terrestrial magnetism. For 10 ms of aperture time of the DVM, the noise in terms of field is about ±1.0 G as shown Fig. 3, which is under the specified measurement accuracy in Table 1.

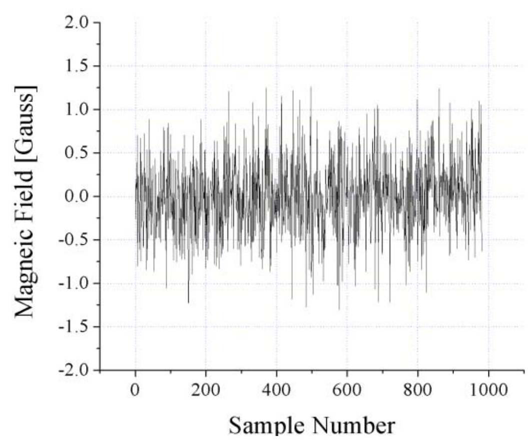

Figure 3: Measured system noise converted to magnetic field.

Two Hall probes are mounted at a distance 480 mm apart to the y-direction on the Carrier. Thus two Hall probes cover the magnetic pole diameter of 960 mm. Full mapping time over the magnet pole area (980 mm × 960 mm) was taken just 61 minutes with 1 mm by 10 mm resolution for x- and y-axis, respectively. The measured field shape was shown in Fig. 4 when the magnet was excited to 147 A. The field shape varies with the hills and valleys about from 1.9 T to 0.8 T.

These measured field data in Cartesian coordinate system were converted into polar coordinate using the two dimensional interpolator provided by the Magic Software [4] to meet the input data format of the beam dynamics simulator. The successive field mapping and shimming works were carried out until requirements of beam dynamics were satisfied.

The average magnetic field along the equilibrium orbit is shown in Fig. 5 where model field, measured field before correction and measured field after correction are shown.

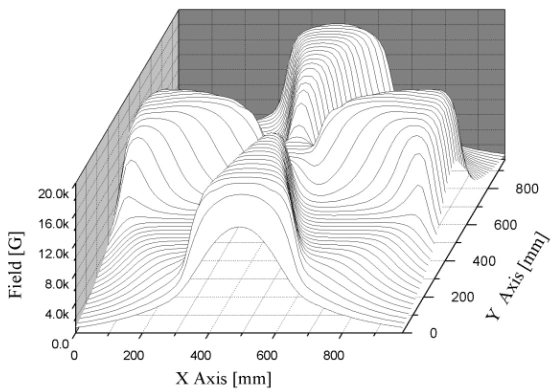

Figure 4: Measured magnetic field shape of the cyclotron magnet.

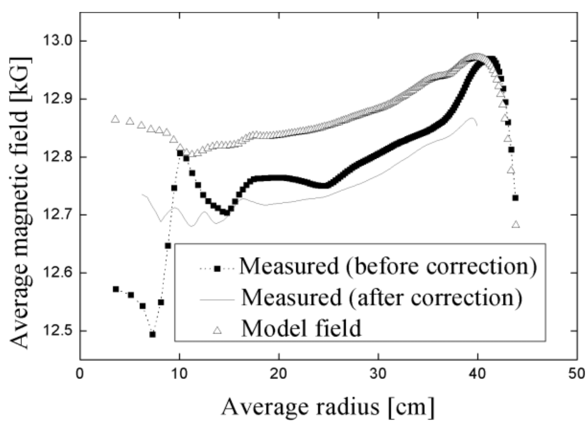

Figure 5: The average magnetic field along the equilibrium orbit as a function of the average radius.

It is seen from Fig. 5 that the measured field before correction is significantly different from the model field, due to various reasons such as difference in magnet material, fabrication error, etc. The figure also shows that the average magnetic field increases slightly along the radius to keep the isochronism in cyclotron. Deviation from isochronous field results in phase slip of the particle, which is usually expressed by (1)

$$\sin\phi(E) = \sin\phi_0 + 2\pi h \Big/ qV \int_{E_i}^{E} (\omega_{rf} / \omega(E) - 1)\, dE \quad (1)$$

where $\phi(E)$ is the phase excursion at energy E, ϕ_0 is the initial phase, h is the harmonic number, V is the dee voltage, ω_{rf} is the angular RF frequency and $\omega(E)$ is the angular revolution frequency of the particle at energy E. Fig. 6 shows that total phase excursion as a function of the radius for three cases as in Fig. 5. This figure indicates that total phase excursion after correcting the field is less than ±15º which is well within the usual tolerance of a cyclotron, ±20º.

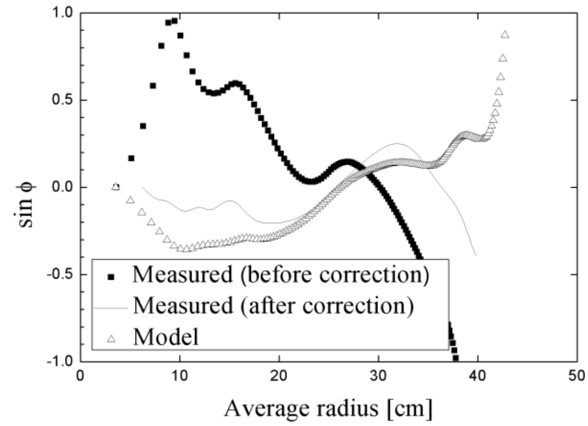

Figure 6: Phase excursion of a particle with respect to the average radius.

More details about the magnetic field measurement and the analysis are described elsewhere [5]. This cyclotron is now being successfully operated at the KIRAMS with nominal beam current of well over 50μA.

CONCLUSION

The field mapping system for the cyclotron magnet was constructed in the Cartesian coordinate system. This system has two x-axis motors for driving the Hall probe carrier at both ends in order to maintain consistency when moves. The Hall probe voltage was amplified by the DTM-141 Teslameter and digitized by the DVM with external trigger pulses from the encoder. The random error of the system was confirmed within ±1 G. The magnetic fields were digitized in "flying" mode within ~60 minutes at the resolution of 1 mm × 10 mm (x×y) of the area (980 mm × 960 mm). The magnetic field shape was successfully corrected with this mapping system. We confirmed that the total phase excursion after field correction was less than ±15º.

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