

Field Mapping System Design for the Superconducting Cyclotron CYCIAE-230

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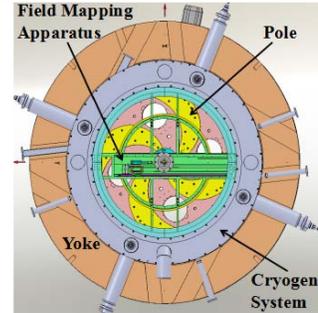


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Introduction

Proton therapy has proven to be an effective cancer treatment with minimal side effects. In order to promote the development of proton therapy in China, CIAE has designed a superconducting cyclotron to extract a 230 MeV, 300 nA proton beam. The cryogenic system has been manufactured. The excitation and quench test of the coil has been completed to verify the reliability. Meanwhile, the rough machining of the magnet is finished and the precision machining is ongoing. When the magnet arrives in the factory, field maps must be generated to validate the performance and provide data for field shimming. The field mapping system aims to measure the magnetic field distribution in the median plane with grids in polar coordinates.



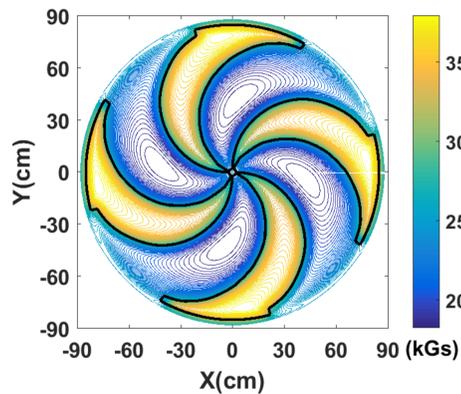
Parameter	Value
Number of Sectors	4, spiral
Radius of Sectors	85 cm
Radius of Magnet	160 cm
Hill Gap	5.0 cm
Radius of Central Hole	2.5 cm
Average Magnetic Field	23 kGs-30 kGs
Min/Max Magnetic Field	18 kGs/38 kGs

Conclusion

Field mapping and shimming of the superconducting cyclotron CYCIAE-230 is planned for the near future. The physics design requires the relative field measurement accuracy to be better than 5.0×10^{-5} . A field mapping system based on a search coil sensor and NMR probe is designed to satisfy the field mapping requirements. A Hall probe is also integrated in the system to check the field data. The three search coils have been designed, manufactured and calibrated. The mechanical and control system were designed with emphasis on the position precision, reliability and convenience. Presently, the machining of the mechanical system is almost finished and the hardware part of the control system is integrated in a cabinet. Supporting equipment is under construction to hold the mechanical apparatus, to allow us to start debugging the whole system.

Requirements

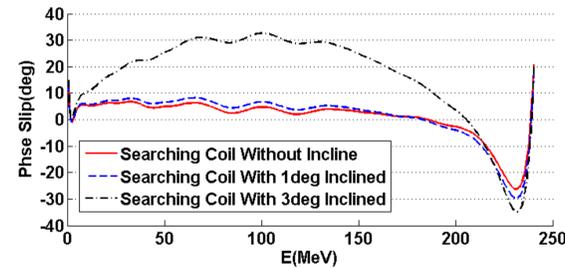
Field Distribution on the Median Plane



There are many factors leading to measured field inaccuracy, including random errors and system errors. The position of probes is obtained through the encoder or grating ruler, which results in random errors in the data. Horizontal and vertical alignment of the mechanical system, also with the position error of the probe fixed on the slider, lead to system errors in the position.

TOLERANCE OF THE MEASUREMENT ERROR FOR FIELD MAPPING

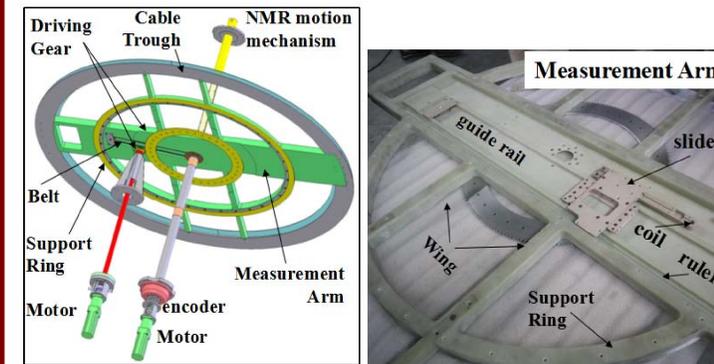
Error Term	Value
Measure magnetic field/Gs	2
Measured radial position/mm	0.05
Measured azimuthal position/s	6
Horizontal off-axis of apparatus/mm	0.05
Vertical off-plane of apparatus /mm	0.2
Horizontal position of probe on the slider /mm	0.5
Searching coil Incline/deg	1



The searching coil inclined with the cyclotron axis has a cosine dependence accuracy. The different of the phase slip could reach 30 deg with 3 deg inclined.

Mechanical System

The mechanical apparatus for field mapping, including the motion mechanism for the NMR probe, central shaft, off-center shaft, measurement arm, support ring and cable trough, aims to support the measurement devices and other hardware.



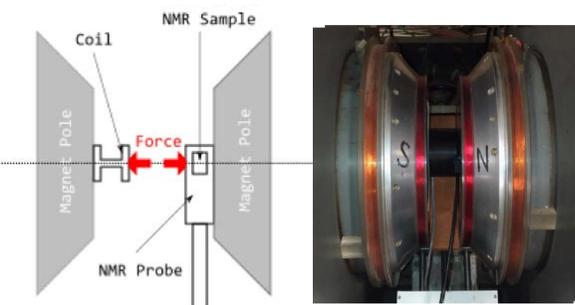
- The mechanical system is designed considering the following issues:
- (1) The NMR probe is attached to a shaft in the top central hole. Through a cylinder, the probe can move to the center of the cyclotron.
 - (2) Using a hole in a valley intended for the RF system, the off-center shaft is driven by a motor and then the arm is rotated through the transmission by a small and large gear.
 - (3) The center shaft is hollow and there is another shaft in the middle. The motor drives the shaft and moves the slider via a belt. The search coil and Hall probe are assembled in the slider and attached to the grating ruler, so the radial position can be measured precisely.
 - (4) The measurement arm. As the slider moves along the guide rail on the arm, the dimensional accuracy and shape tolerance of the measurement arm is very critical to determine the positioning error of probes, and thereby affects the quality of the final measured field map. The wings are added to the arm to increase the rigidity and also the touch area with the support ring.
 - (5) A cable trough is added in the outer ring, and then the cable can be put in the drag chain and drawn out through the extraction hole.

Search Coil

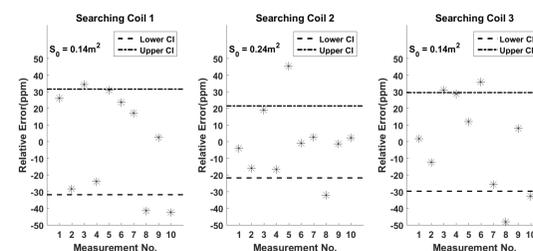
Search Coil Design

(1) As the coil is cylindrical but used to determine the field at a point, there is an error due to the field inhomogeneity. An optimal design of the search coil geometry can eliminate the undesired field error to the fourth order. The search coil design parameters were chosen through numerical analysis. The search coil is very compact, to reduce the errors due to field inhomogeneity, but uses a very thin wire to increase the number of turns and thus the generated voltage.

(2) The material of the form is another factor to be taken into account in the coil design. A low coefficient of thermal expansion is the most critical characteristic, but good mechanical properties, machinability, non-magnetic, non-conducting and even the cost should also be considered.



Calibration Results of three Coils



Search Coil Calibration

The effective area of the search coil is obtained with an industrial electromagnet and NMR probe. The coil being calibrated is placed in the center of the pole and aligned with an NMR probe on the magnetic axis. A force, applied by a polymer spring, pushes the coil and the NMR probe against the magnet poles to ensure they are perfectly aligned with the pole.

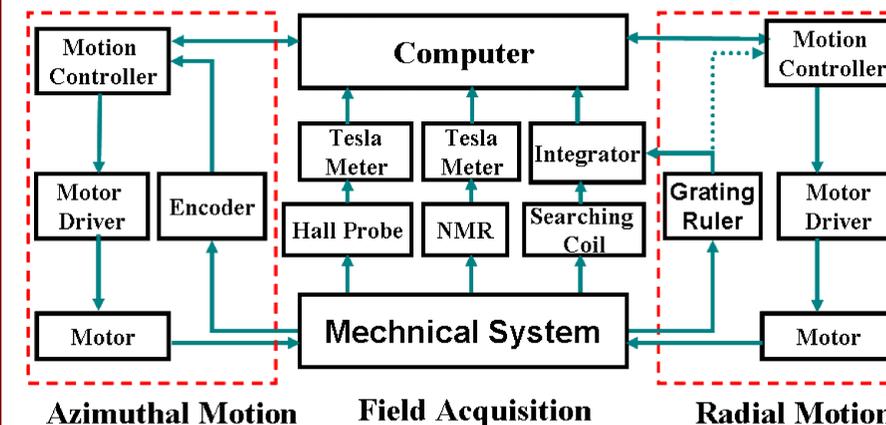
The calibration procedure has three steps:

- (1) We generate a magnetic field of 1.25 T in the dipole for about 1 minute. When the field is stable, the field, recorded as B1, is measured with NMR, and simultaneously the integration is started.
- (2) The power supply is switched to generate the same magnetic field but with an opposite sign. The integrator is still integrating the voltage.
- (3) When the field is stable, B2 is measured with NMR and simultaneously the integration is ended. Then we can compute the effective area as $S = \Phi / (B2 - B1)$, where Φ is the integrated magnetic flux value from the integrator.

In order to eliminate random calibration errors, every coil is measured ten times. The calibration results of the three coils confirmed that the calibration accuracy is 30 ppm with a confidence level of 99%.

Control System

The control system is designed to position the probe (NMR, Hall probe and Search coil) and get the field data automatically. The overall design of the control system is illustrated in the figure. Two driver systems are used to move the slider in the radial and azimuthal directions respectively. The azimuthal position is measured by a HEIDENHAIN encoder RON785 with 18000 lines; an IBV adapter converts the sine wave to a squarewave signal with x10 subdivision. The radial position is measured by a RSF grating ruler. As the integrator needs the signal from the grating ruler to trigger the integration, a splitter after the ruler divides the signal into two identical signals. Considering the large gear backlash and required high positioning accuracy, a clever algorithm is implemented to approach the desired position iteratively.



The field map can be measured with the Hall probe or the search coil. In the "Hall probe" mode, the probe moves along the radius and stops at every desired position. While in "search coil" mode, the coil starts at $r = -15$ cm, travels forward at 40 cm/s to the end, and then travels back to the start point to verify the reproducibility of the measured data. Before measuring the field along the radius, the NMR probe is inserted into the median plane to measure the center field. In this state, radial motion of the slider is not enabled in the software.

The software is developed with C# and provides a friendly human interface for the operator to test the system. Also, a one-key operation can start the system and complete the field mapping automatically.