

# Cryogenic test of the FRIB superconducting magnets at IMP

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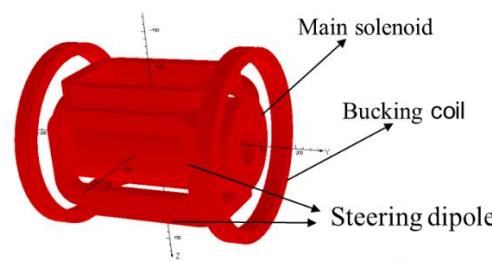
**Abstract.** The superconducting magnets of the Facility of Rare Isotope Beams (FRIB) are used to focus and steer the heavy ion beams of the driver linac. All the magnets are designed as a solenoid with bucking coils to suppress the stray field, and all the magnets have superconducting dipole correctors to steer both horizontal and vertical field. Two types of magnets have been manufactured in China, and some of them have been tested at Institute of Modern Physics (IMP). This paper describes the test system and magnetic axis measurement method. We also present a summary of the measurement process and test results of the magnetic performance for the magnets.

## 1. Introduction

The Facility for Rare Isotope Beams (FRIB) will be a new national user facility for nuclear science. It is funded by the DOE-SC, Michigan State University (MSU) and the State of Michigan. The driver linac of the FRIB facility can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW [1].

FRIB SC magnet packages are used to focus and steer the heavy ion beams of the driver linac. 80 magnets have purchased from XSMT Co. Ltd, China. It Include 9 short and 71 long magnets. IMP undertook the design tasks and then 30 of the magnets tested in cryogenic temperature at IMP.

Each FRIB SC magnet package consists of a main focusing solenoid, a pair of stray field bucking coil, a pair of SC dipole correctors both in the vertical and horizontal directions, a helium vessel, a passive quench protection device and the reference points for showing the magnetic axis of the solenoid coil. The solenoid coil length is 25cm and 50cm respectively [2]. The simulation model for 25cm solenoid coil is shown in Fig.1.



**Figure 1.** Simulation model of FRIB SC magnet package (25cm).



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The FRIB SC magnet is designed as a bath-cooled magnet. The operating temperature of the liquid helium bath is up to 5.0K. The peak field on the beam axis is approximately 8 T. Table 1 summarizes the main parameters of the magnet.

**Table 1.** Parameters for the FRIB SC magnet

Parameters	Unit	50cm	25cm
Main solenoid nominal current	A	90	90
Peak solenoid filed at $I_{\text{nom}}$	T	8	8
$\int B_z^2 dz$ at $I_{\text{nom}}$	$T^2 m$	28.2	13.6
$\int B_z^2 dz$ uniformity within $80\% \times R$	%	2	2
$\int B_x dz, \int B_y dz$ integrated field strength	Tm	0.06	0.03
$\int B_x dz, \int B_y dz$ uniformity within 15mm	%	5	5
Maximum current of dipole	A	19	19
Deviation of field centre	mm	$\leq 0.3$	$\leq 0.3$

Due to the stringent space restriction inside the cryo-modules, the solenoid was designed as compact as possible. The inner diameter of the cold bore is 40mm. The mechanical lengths of the SC magnets are 590mm and 350mm respectively. The solenoid and dipole correctors are mounted inside the helium vessel which has a diameter of 304.8mm. Fig.2 shows the two types of SC magnets after assembly.



**Figure 2.** Two types of FRIB SC magnets after assembly and preparing for vertical test in the helium dewar. 50-cm solenoid package(left),25-cm solenoid package(right).

The design of the solenoids minimized the stray field in order to ensure the adjacent SC RF cavities exposed to a field less than specified. The stray field are suppressed by the bucking coils. when the solenoid and dipoles are all powered at the nominal currents, the maximum acceptable magnetic stray field is 270 Gauss for all points where  $z \geq 390$  mm from the centre of the 50-cm solenoid and 240 Gauss for 25-cm type ( $z \geq 260$  mm) [3].

The helium vessel was made of 316L stainless steel to minimize residual field and welding also be done in a way to reduce the residual field [2]. The deviation of the field centre axis from the mechanical centre axis should be within 0.3mm.

## 2. Test system

### 2.1. Cryogenic test station

The cryogenic test station for the FRIB SC magnet is based on an old Linde TCF10 helium liquefier which has a liquefaction capacity up to 39L/h. Fig.3 shows main parts of the station. There are three vertical test cryostats in this test station. The inner diameters of the cryostats are 300mm, 700m and

800mm. The helium gas produced in the testing process is recovered by a 23Nm<sup>3</sup>/h piston compressor. Then the gas is purified by the purifier in the TCF10 liquefier and liquefied again.

The magnets were pre-cooled by liquid nitrogen. Then the nitrogen was pressured out by helium gas. Before filling in the liquid helium the cryostat should be vacuumed and filled with pure helium. After the test and magnetic measurement, the liquid helium remaining in the test cryostat was pressured back into the helium storage dewar. This step can save the liquid and reduce the time for warm up.



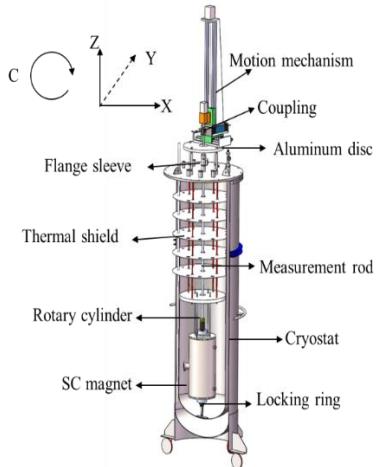
**Figure 3.** Cryogenic test station High pressure helium storage tank(1),Air bag(2), Compressor(3),TCF10(4), Liquid helium dewar(5).

## 2.2. Vertical measurement setup

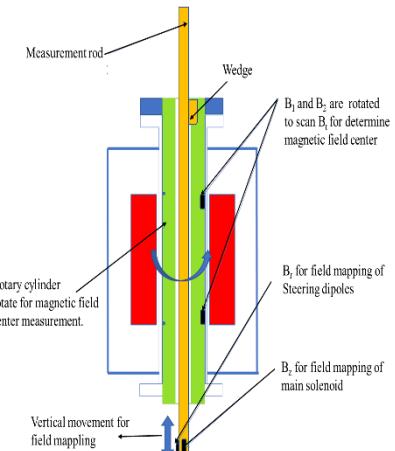
Due to the small-bore size (40 mm), it is hard to develop and insert an anti-cryostat into the magnet for keeping the measurement device at room temperature, so the measurement system is operated at cryogenic temperature. According to the performance requirements of the SC magnet, the key content of cryogenic test is to measure the integral fields of the main solenoid and steering dipoles. The deviation of the solenoid field centre axis from the mechanical centre are also determined by the field measurements.

The vertical measurement set up and measuring coordinate system are shown in Fig.4. The SC magnet was tested in the 700mm cryostat. There is a motion mechanism on the top of the cryostat which contains 4 motion axes. X&Y are manual axes and Z&C are motor drive axes. The C axis is used for rotation measurement and the Z axis is used for vertical direction mapping. The position resolution is 1μm and 1 seconds for Z and C axis respectively.

The motion mechanism is mounted on an aluminium disc and connected to the measurement rod by a flexible coupling. By adjusting X and Y axis the centre of the C axis can coincide with the centre of the measurement rod and can be coaxial with the magnet. We reserve a uniform gap between inner surface of the magnet and the rotary cylinder by precision machining. The bottom of SC magnet has a locking ring to keep the magnet stable during the test.



**Figure 4.** The vertical measurement setup for cryogenic test.



**Figure 5.** The measurement rod and rotary cylinder.

### 2.3. Measurement rod and Rotary cylinder

We used a long non-magnetic stainless-steel tube as the measurement rod (diameter: 20mm, length: 2.8m). The upper end is connected to the motor drive by a flexible coupling and the bottom end has two Hall probes to measure the integrated field. The transverse Hall probes ( $B_r$ ) can map the field of the steering dipoles and the axial probes ( $B_z$ ) can measure the field of the main solenoid along the magnet centre. There is a small gap between the G10 wedge and cylinder's groove, which is shown in Fig.5. Based on this configuration, the measuring rod can be used as rotating shaft of the rotary cylinder simultaneously.

Additional two transverse Hall probes ( $B_1$  and  $B_2$ ) are installed in the symmetrical position of the cylinder for determining magnetic centre axis. These two probes are rotated to scan  $B_r$  at both ends of the main solenoid where the radial field component is a maximum. At this position the  $B_r$  components are most sensitive for the deviation of magnetic field centre.

All the used Hall probes are from Cryo-magnetics company. They were calibrated at 4.2K up to 9T. The linearity error of the probes is less than 0.2%, the sensitivity varies with the magnetic field are less than 1%. The core of the data acquisition system is a NI industrial PC, which is used to monitor the temperature and voltage, control the power supply and motor drive. A stable, low noise nanovoltmeter model 2182A from Keithley is used to measure the Hall voltage. The multi-channel acquisition can be reached via a multi-channel acquisition switch instrument, Keithley model 2700.

## 3. Test result

### 3.1. Training

We carried out the cryogenic performance tests for all the SC magnet. During the initial cold tests, the number of the quenches to reach the nominal operating field at 4.5 K are recorded.

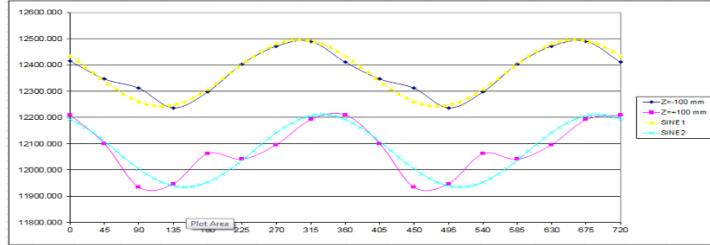
The solenoids and steering dipoles used a passive quench protection device. At 4.2 K, the solenoids are powered and ramped up to their nominal field with a minimum ramp rate of 0.5% of  $I_{\text{nom}}$  per second. After solenoid training, each steering dipole should be powered and ramped up to its nominal field separately. At last, all three coils (solenoid, horizontal steering dipole and vertical steering dipole) triple training at their nominal fields simultaneously.

Most of the SC magnet reached their nominal field without quenches. The others quench for two to three times.

### 3.2. Magnetic Centre

The alignment scans are performed at both ends of the solenoid. The increment of measurement is set  $45^\circ$  with a current of  $I_{\text{nom}}$  (dipoles off) at both ends of the solenoid. The solenoid field  $B_r$  data is fitted

using sine wave as shown in Fig.6. Limited by the length of Hall probes leads, each measurement process is within two circles to obtain data from  $0^\circ$  to  $720^\circ$ . We compare theoretical results with actual measurements, to determine the displacement and orientation of the axis from the magnetic axis [4].

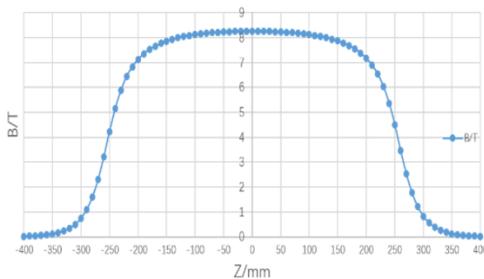


**Figure 6.** Fitted of the magnetic centre data.

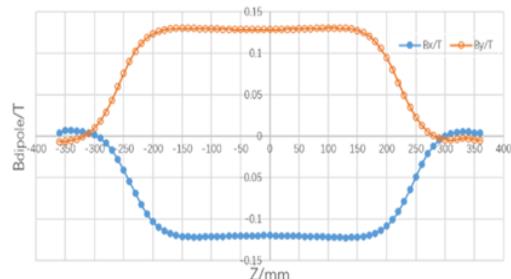
After the cold test, we mark the field centre on the helium vessel for the solenoid alignment. The flanges are chosen to the location of the fiducials.

### 3.3. Integral field

The solenoid field  $B_z$  shall be measured at  $I_{\text{nom}}$  every 5 mm along the Z-axis through  $-400 \text{ mm} \leq Z \leq +400$  for the 50 cm solenoid and  $-200 \text{ mm} \leq Z \leq +200$  for the 25 cm solenoid in order to obtain integrated squared field  $\int B_z^2 dz$ . The measurement result of a 50cm magnet are shown in Fig.7. The series measurement results show that the actual value is about 2% higher than the theoretical calculated value.



**Figure 7.** A 50cm magnet test results for the integral field of main solenoid.



**Figure 8** A 50cm magnet test results for the integral field of steering dipole.

The integral field of the steering dipole at  $I_{\text{nom}}$  be measured along the Z axis parallel to the centre of the magnet and at a distance  $R=15\text{mm}$  from the beam axis. Rotating the measuring rod can measure  $\int B_x dz$  and  $\int B_y dz$  respectively as Fig.9. The series measurement result can reach the requirement defined in table1.

## 4. Conclusion

It is the first time for serial cryogenic test of SC magnet at IMP and all the results are accepted by FRIB even some of the magnets have been already successfully commissioning.

The measurement system works well during the test. The major flaw is that the stray field map is limit by the maximum displacement of motion mechanism. The uniformity of solenoid cannot be measured, because of the axial probes ( $B_z$ ) is installed in the centre of the measurement rod. The uniformity can be ensured by precision machining and examine the roundness of the coil bobbins.

Through iterations tests for one magnet proved that the repeatability of test system is better than 0.1%. During the measurement of magnetic centre, the results in the same angle is consistent and the magnetic axis offset is less than 0.3mm from the data fitting. For the integral field, the dispersion between the 30 magnets are less than 1%.

The vertical test consumed much time and liquid helium, and has a great risk of failure (Data acquisition failure, move not smooth etc.). For example, a 50cm magnet cooling down and test takes 8 hours and consumes 450L liquid helium. Maybe a horizontal test programme would solve these problems.

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