Measurement facility and test results for FRIB superconducting magnets at IMP

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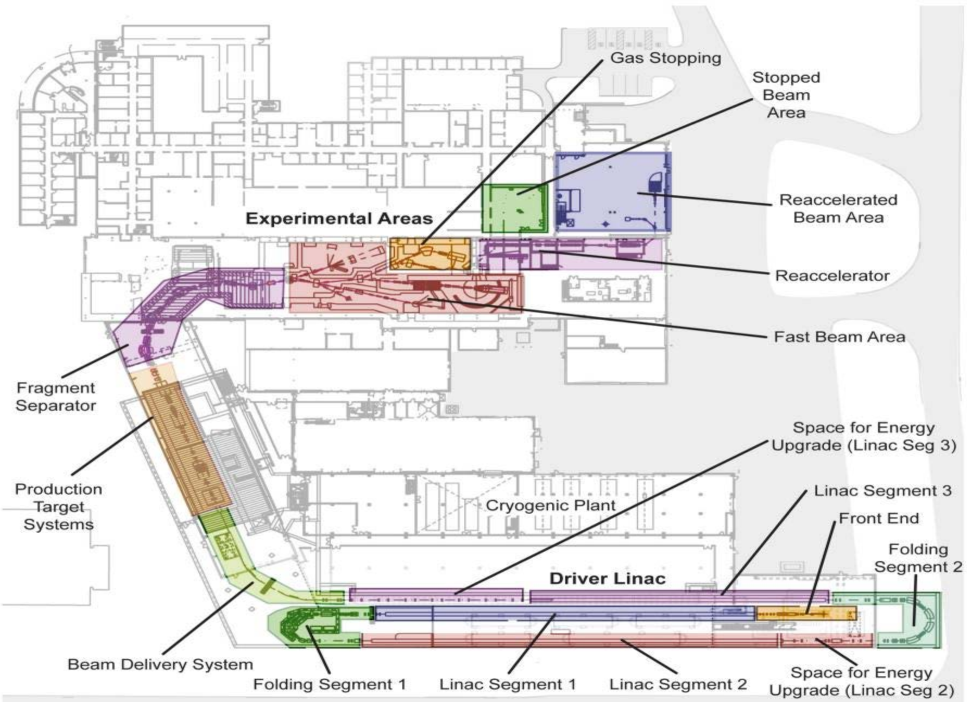
IMP,CAS

Overview

- Overview of the FRIB project
- Brief introduction of the SC magnet
- Measurement facility at IMP
- Measurement results
- Summary

Overview of the FRIB project



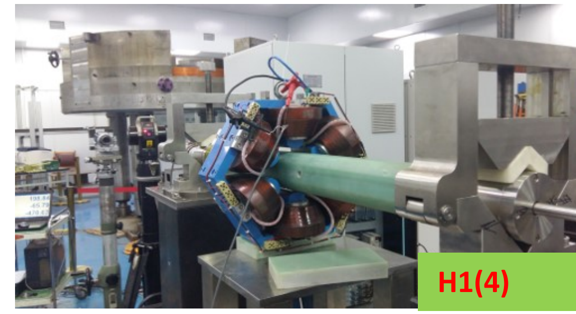
Layout of the FRIB driver accelerator

- The Facility for Rare Isotope Beams
- FRIB will be a new national user facility for nuclear science.
- FRIB is funded by the DOE-SC, MSU and the State of Michigan.
- The FRIB driver linac can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW.
- The project will be completed by 2022.

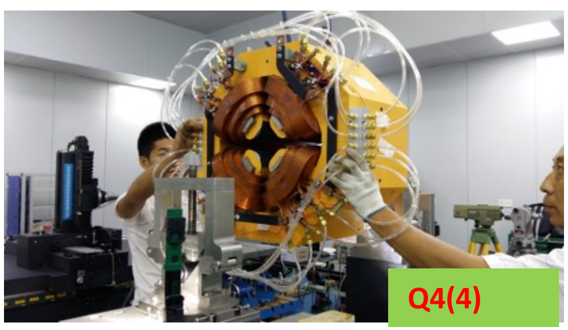
THE FRIB PROJECT – ACCELERATOR CHALLENGES AND PROGRESS J. Wei et al, HIAT'12, Chicago, 8 (2012).

Overview of the FRIB project (RT mgnet)

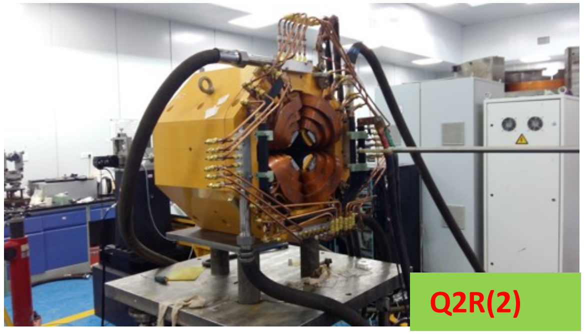
- ✓ FRIB have purchased 151 RT magnets from TaiJi Co. Ltd , China, it include 16 dipoles, 116 quadrupoles, 8 sextupoles and 11 correctors.
- ✓ IMP undertake the design and test of all the RT magnets.

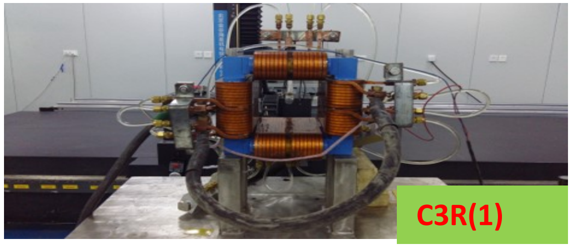


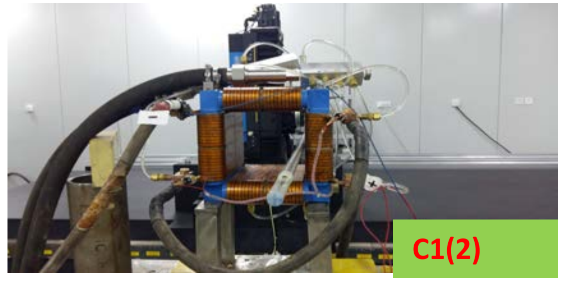
1. *Full-power tests*
2. *Field mapping*
3. *Field central axis defining*

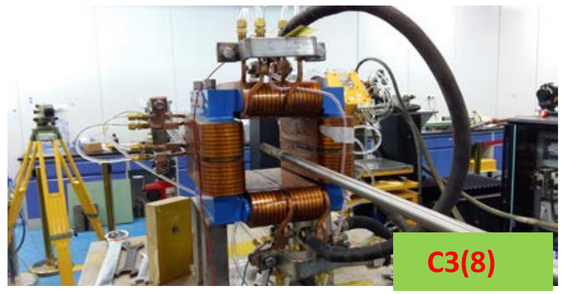


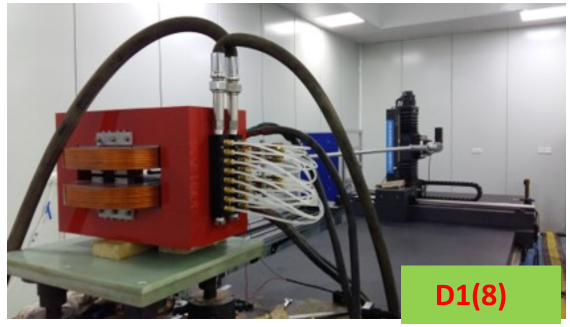
Overview of the FRIB project (RT magnet)

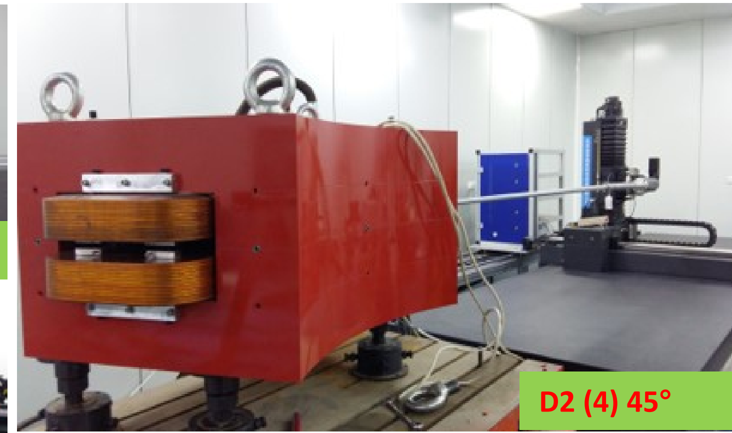












- ✓ All these magnets have been manufactured and measured in the end of 2016.
- ✓ Some of them have been installed in the tunnel of FRIB.

Overview of the FRIB project (SC magnet)

- ✓ FRIB has purchased 80 magnets from XSMT Co. Ltd, China. It Include 9 short and 71 long magnets.
- ✓ FRIB SC magnets are used to focus and steer the heavy ion beams of the driver linac.
- ✓ IMP undertaken the magnets design , 27 of the them have been tested at IMP.
- ✓ The fabrication and test of all magnets have been finish at the end of 2016.

50cm SC-magnet

25cm SC-magnet

Brief introduction of the SC magnet

Each magnet package consists of:

① A main focusing SC solenoid

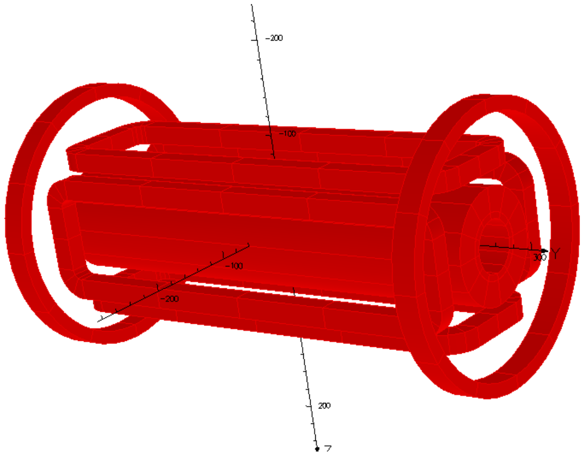
② SC dipole correctors (both horizontal and vertical)

③ A helium vessel

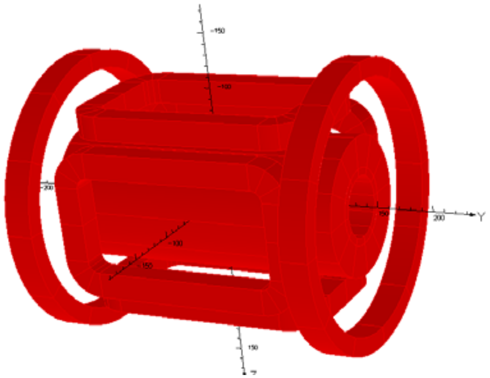
④ A stray field suppressor (bucking coils)

⑤ A quench protection system (self protection by diodes)

⑥ Fiducials for showing the magnetic axis of the solenoid coil.



Design model of 50cm SC



Design model of 25cm SC

Brief introduction of the SC magnet

- ✓ The SC magnet are operated in a helium bath at 4.5 K. It designed to operate at full field up to 5.0 K.
- ✓ The peak field on the beam axis is approximately 8 T.
- ✓ The generate integrated square fields for the solenoid

  $\int Bz^2dz$ = 28.2 T^2m (50cm)

  $\int Bz\,^2dz$ = 13.6 T^2m (25cm)

  uniformity ≤2% @ 80% r
- ✓ For the dipole , the integrated fields

  $\int Bx$dz =0.06 Tm (50cm)

  $\int By$dz =0.03 Tm (25cm)

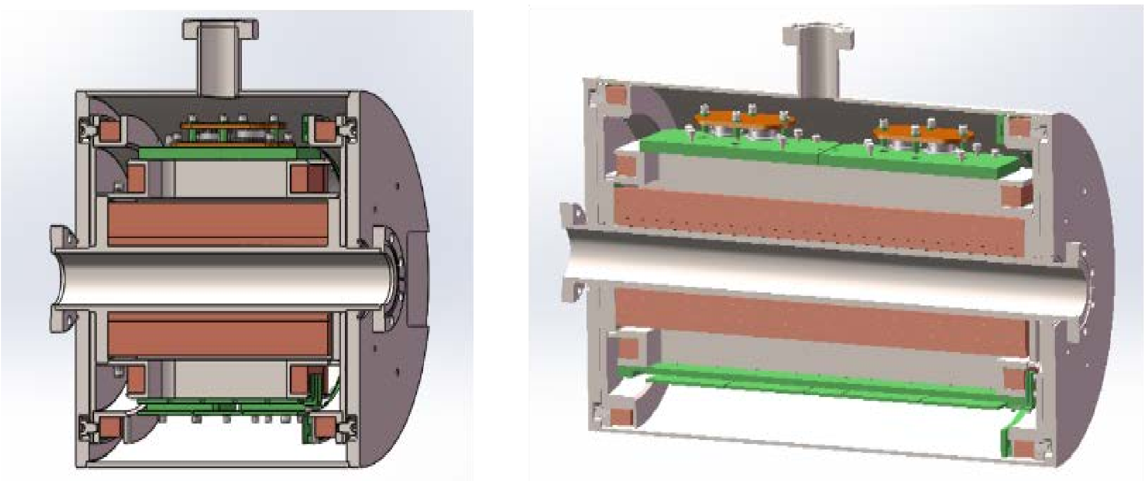
  uniformity< 5%
- ✓ The maximum tolerated magnetic stray field is:

  270 Gauss (z ≥ 390 mm) (50cm@ I_{nom})

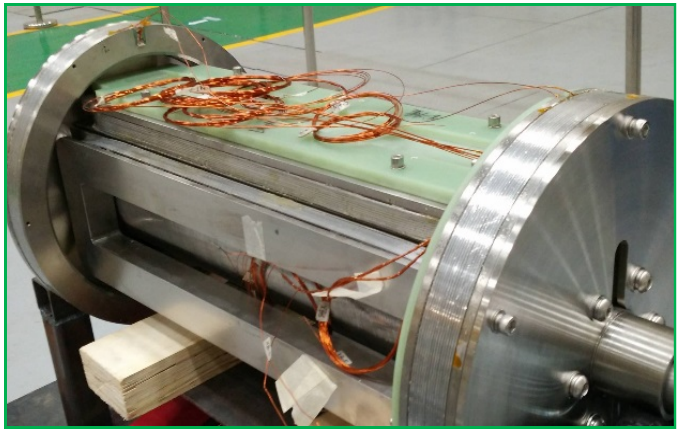
  240 Gauss (z ≥ 260 mm) (25cm@ I_{nom})

Brief introduction of the SC magnet

- ✓ Due to the stringent space restriction inside the cryo-modules, the solenoids is designed as compact as possible.
- ✓ The helium vessel made of 316L stainless steel to minimize remanent field
- ✓ Welding done in a way to minimize remanent field.
- ✓ Cold bore inner diameter is 40mm and the Helium vessel shell diameter is 304.8mm. The length is 589.53mm and 349.76mm respectively.



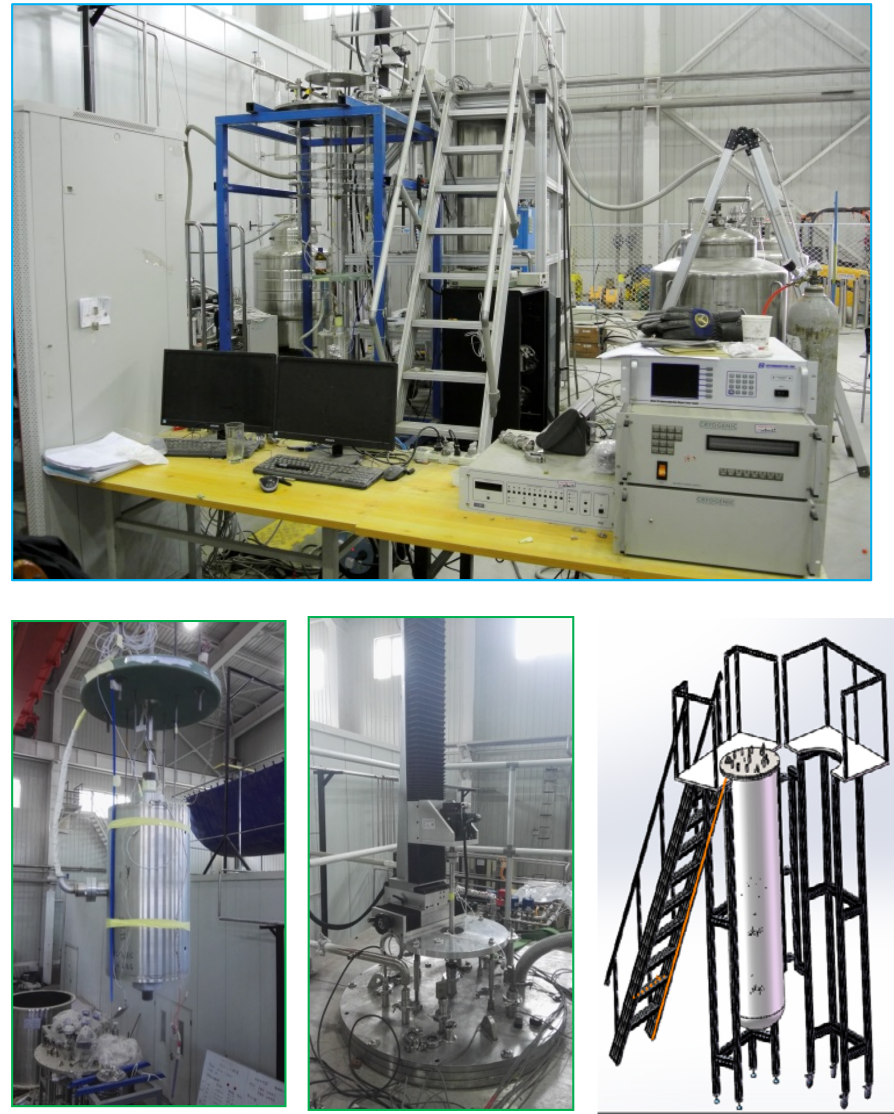
Mechanical model



Manufacture at XSMT Co. Ltd

Measurement facility

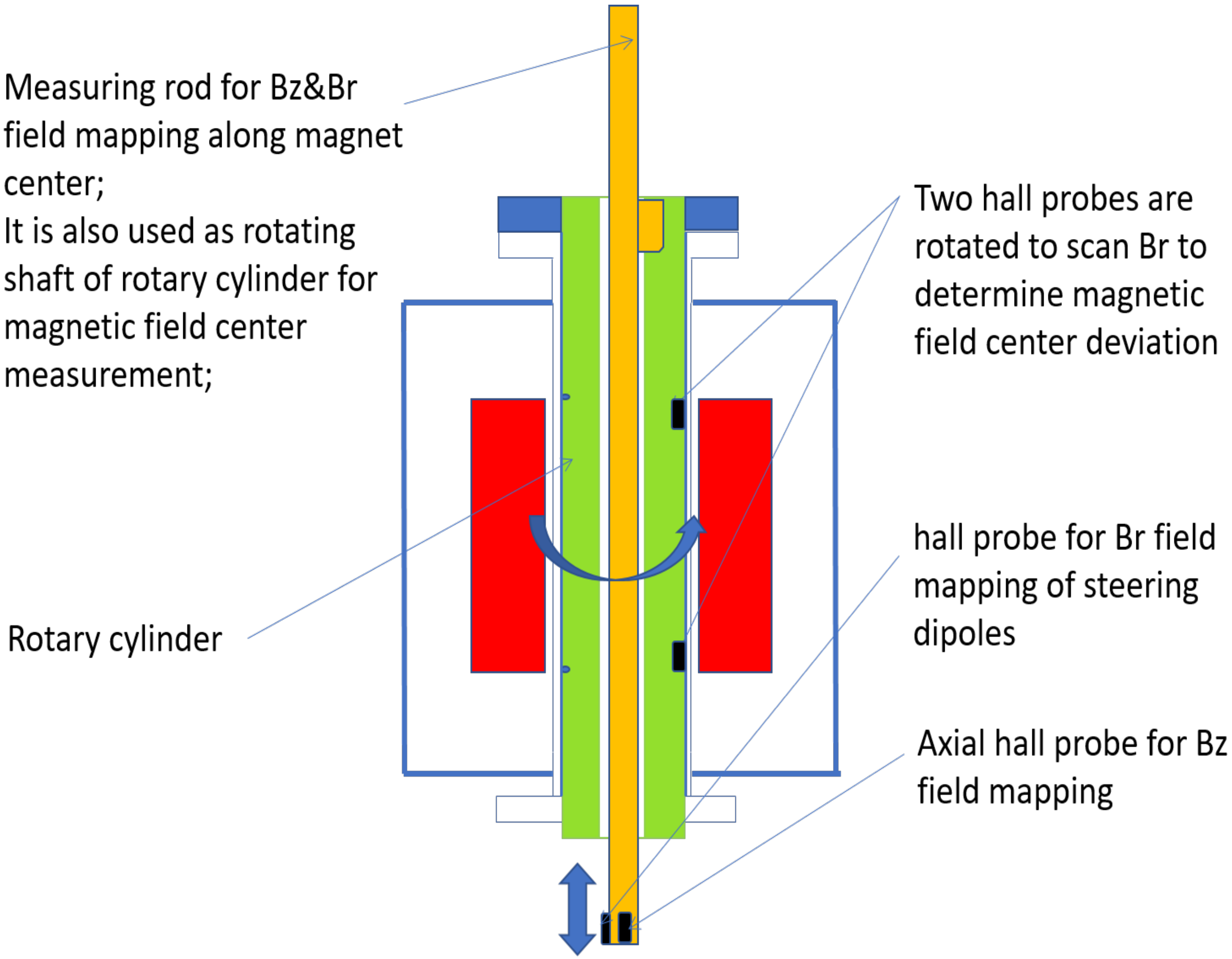
TCF10 cryogenic plant (35L/h)



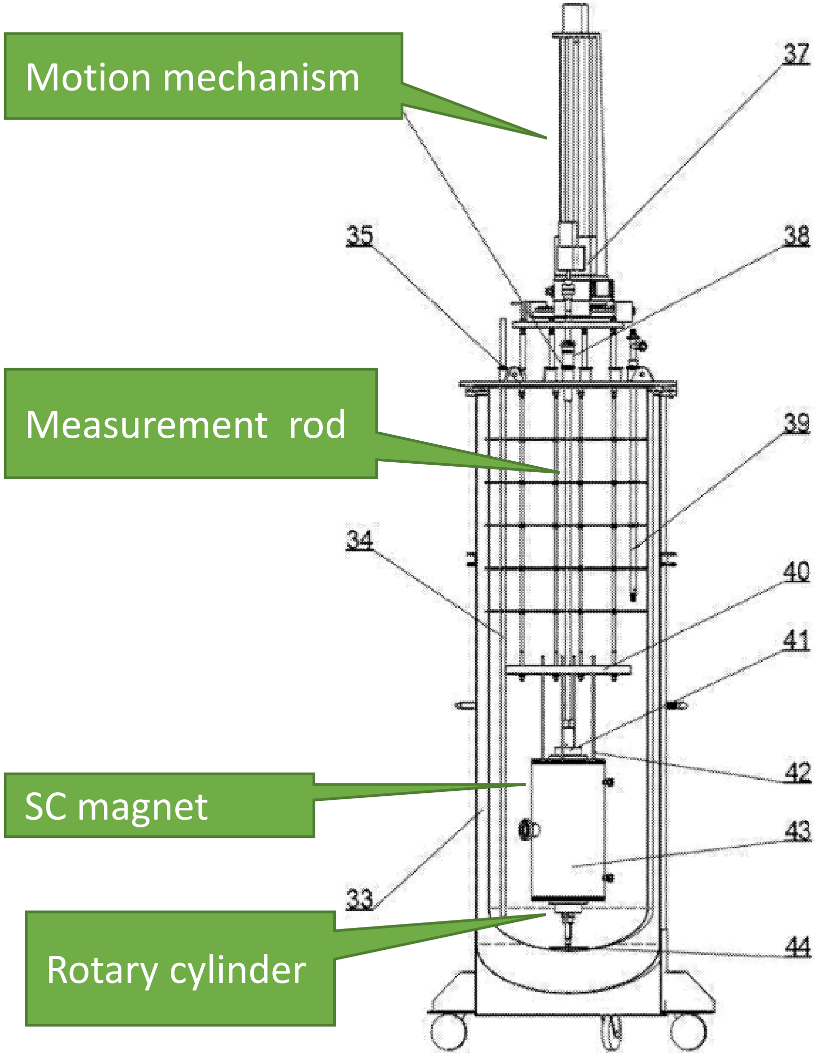
Vertical test facility

Measurement facility

- Due to the small bore size (40 mm), it is hard to develop and insert a anti-cryostat into the magnet for measurements at RT.
- So the measurement system are operated at cryogenic temperature.



Measurement facility



The SC magnet install in the Dewar

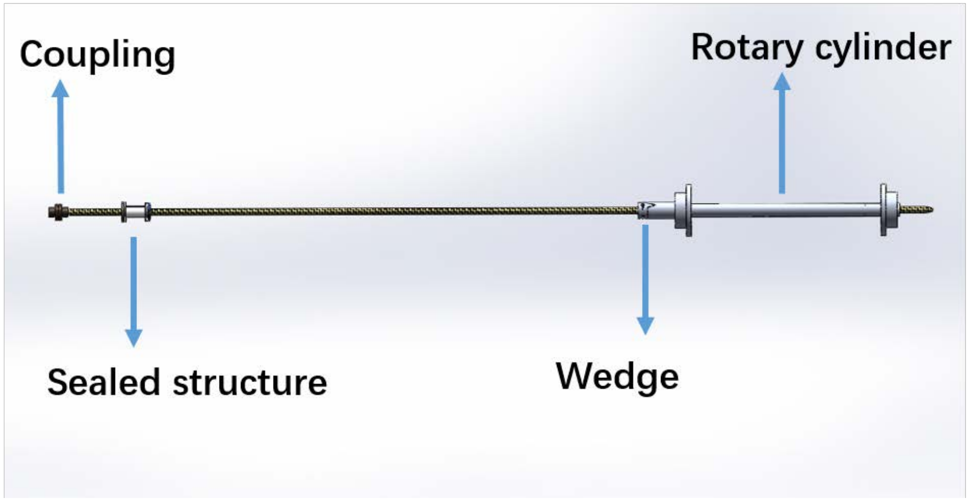
Measurement facility

Measuring rod

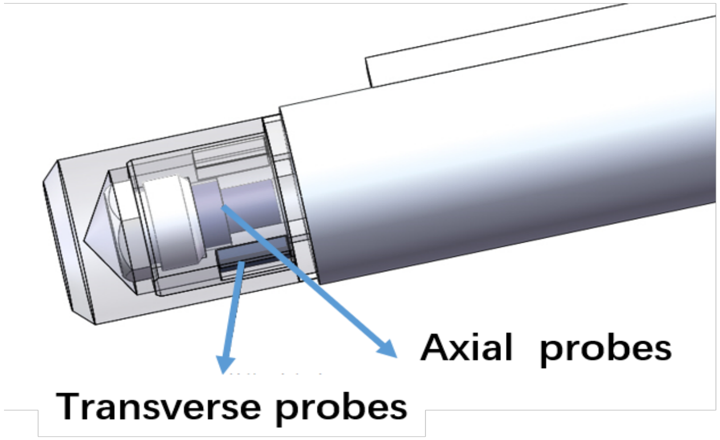
- Using a long non-magnetic stainless steel tube (diameter: 20mm leangth: 2.8m)
- The upper end is connected to the motor drive by a coupling
- The bottom end is installed two Hall probe to measure the integrated field

  Transverse probes(Br): dipole   Axial probes(Bz): main solenoid
- The top and the Dewar cover are sealed by a stainless steel flange sleeve

General mechanism of measurement



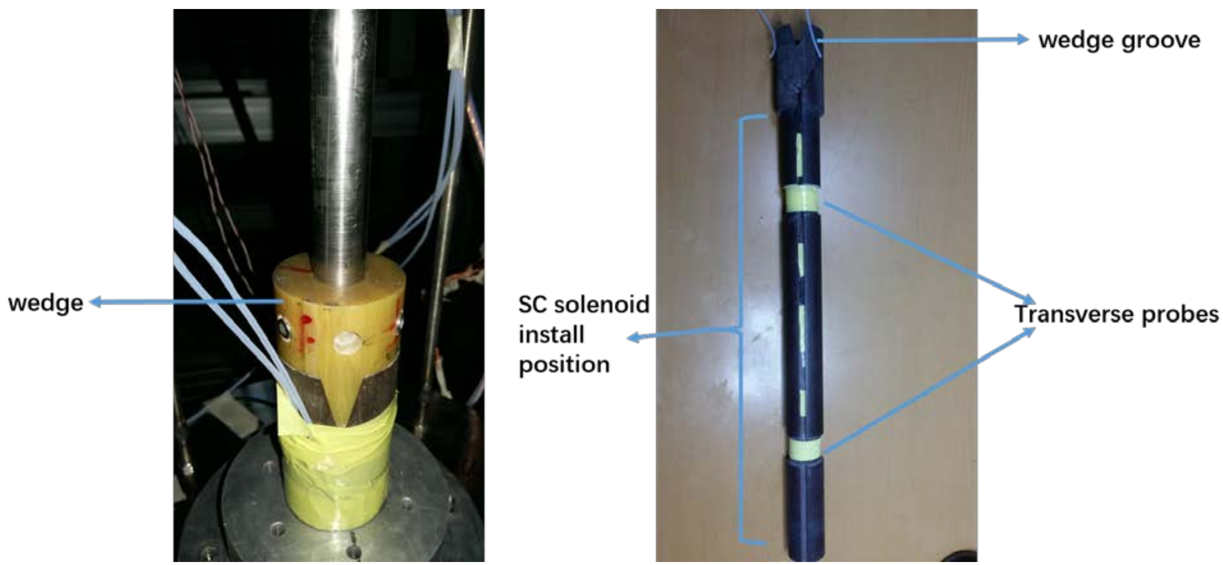
bottom end of the long arm



Measurement facility

Rotary cylinder

- Fabricated by bakelite
- Two transverse Hall probes are installed in the symmetrical position of the cylinder for determining magnetic center axis.
- There is a small gap between the G10 wedge and cylinder's groove.
- Coaxial with the magnet
- Uniform gap between inner surface of the magnet
- The bottom has a locking ring to keep the magnet stable.



Measurement facility

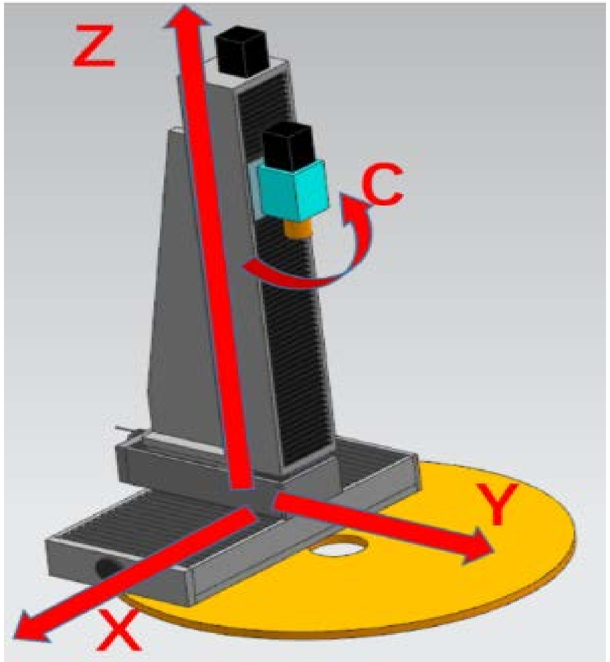
Motion mechanism

- 4 motion axes, X, Y are manual axes, Z, and C are motor drive axes.

  C axis for rotation measurement

  Z axis for vertical direction mapping

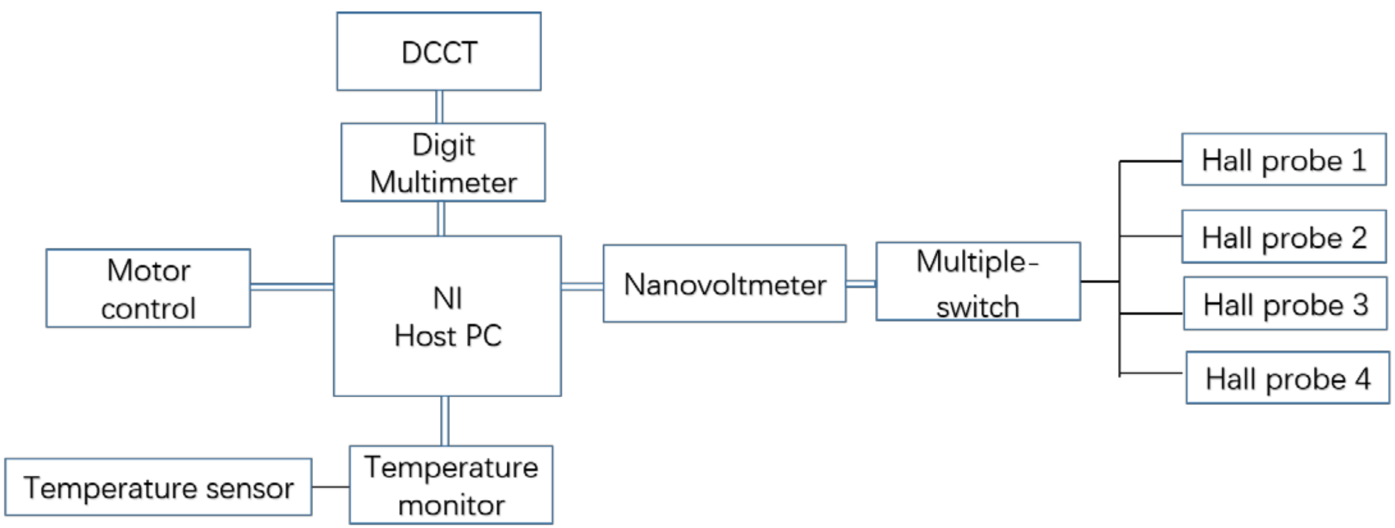
- Mounted on a aluminum disc
- By adjusting X and Y, the center of the C axis coincides with the center of the rod and coaxial with the magnet
- The position resolution of 1μm, C-axis resolution of 1 seconds



Measurement facility

Data acquisition

- Data acquisition core is a NI industrial PC.
- Monitor the temperature and voltage, control the power supply and motor drive.
- Low temperature axial and transverse Hall probes from Cryomagnetics company.
- Calibration at 4.2K (up to 9T) The linearity error of the probes is less than 0.2%, the sensitivity varies with the magnetic field less than 1%



Measurement results

Cooling down and training

- Pre-cooling by LN2 to reduce the consumption of LHe

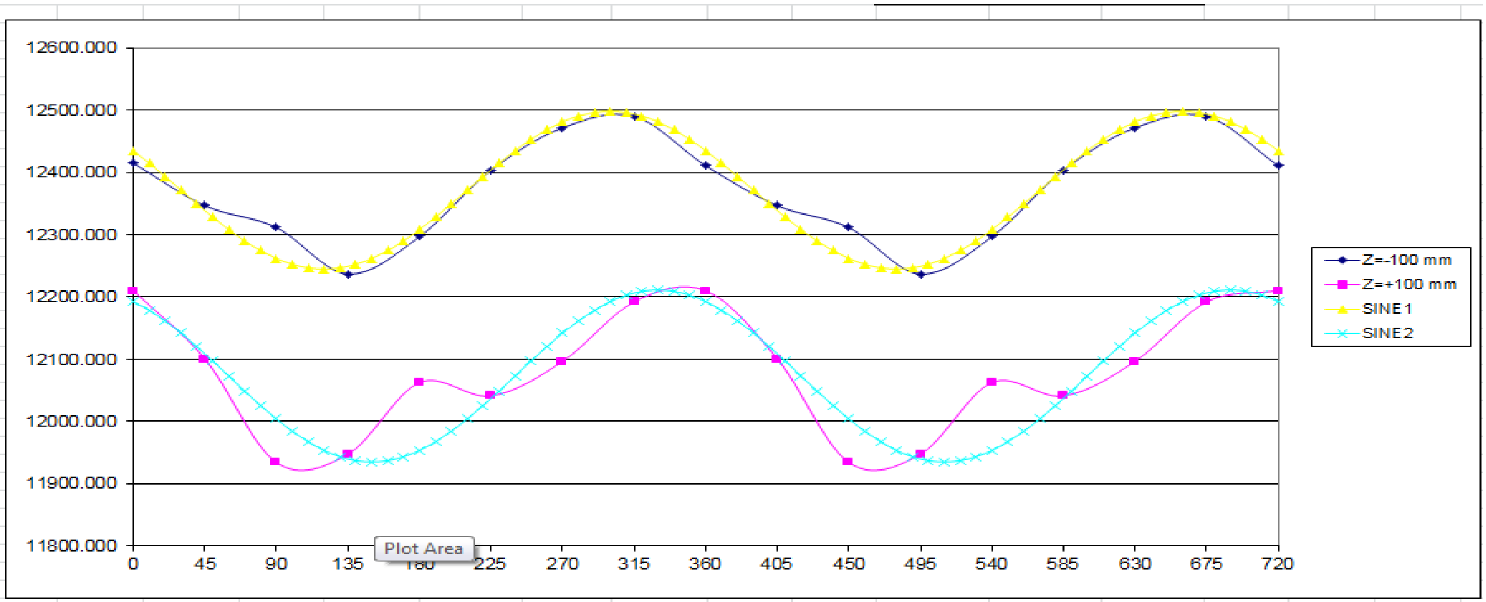
Type	liquid level cm	consumption of Time h	Testing time h	consumption of LHe L
25cm	40	4	2	350
50cm	70	6	2	450

- Minimum ramp rate of 0.5% of nominal current per second.
  - A. Solenoid magnet training
  - B. Dipole correctors training
  - C. Solenoid and correctors triple training simultaneously.
- Most of the SC magnet reach their nominal field without quenches. Some of the them needs two or three times training.

Measurement results

Determining solenoid field axis

- The alignment scans are performed at both ends of the solenoid （preferably where the Br component is a maximum）
- The increments of measurement is set 45° @I_{nom} （dipoles off）
- Fit data using sin wave to get the orientation of the misalignment.



- The requirement of deviation of the field center from the mechanical center are smaller than 0.3 mm.
- After the cold test, we mark the field center on the helium vessel for the solenoid alignment.

Measurement results

Field integral

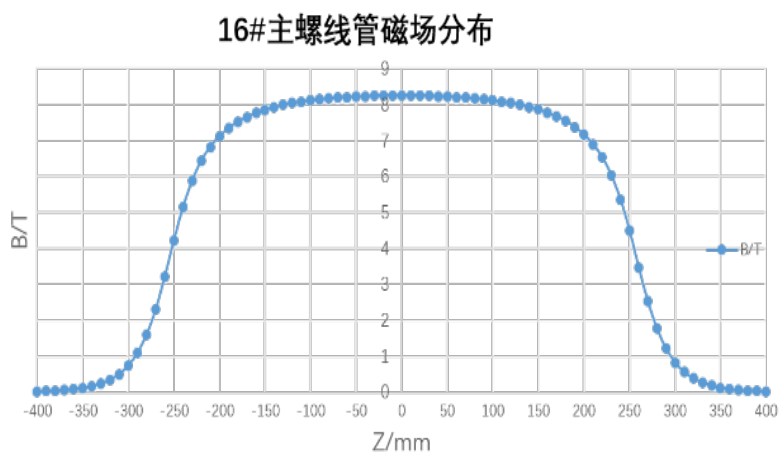
◆The solenoid field Bz measured at I_{nom} every 5 mm along the z-axis

– 400 mm ≤ z ≤ +400(50mm)

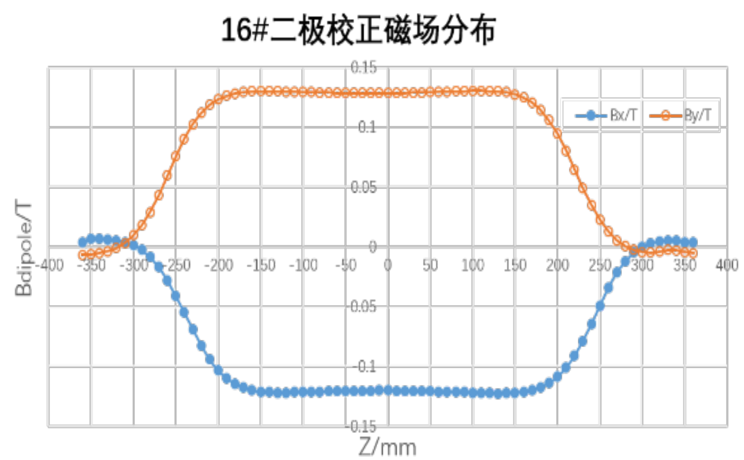
-200 mm ≤ z ≤ +200 (25mm)

In order to obtain integrated squared field. $\int Bz^2 dz$ [T^2m]

◆Rotating the measuring rod can get $\int Bx$dz and $\int By$dz respectively.



$$\int B_Z^2\, dz = 30.01\, T^2 m$$



$$\int B_x\, dz = 0.057\, Tm,$$
$$\int B_y\, dz = 0.061 Tm。$$

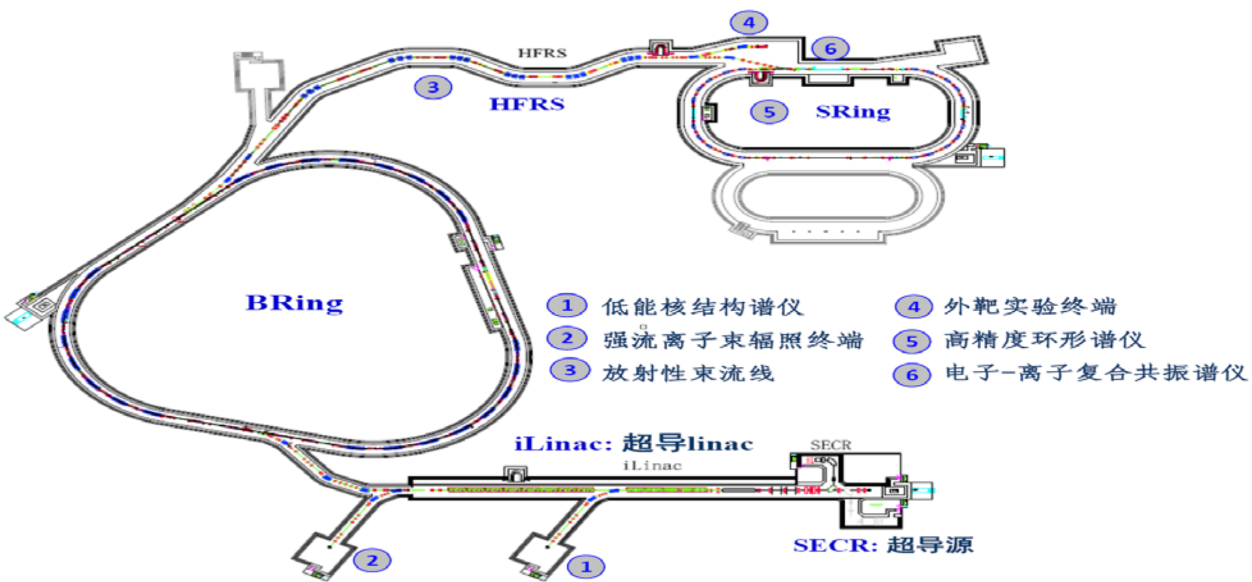
Measurement results

			Solenoid field	Dipole field	Solenoid Ramping rate	Dipole Ramping rate	Mechanical center error	Quench times	Quench current	Integrated field	Ramping to max current	Test Place
NO	XSMT batch number	Solenoid Serial Number	8T @ I < 90A	> 0.06Tm @ I < 20A			< 0.3 mm			≧ 28.2 T^2m		
1	50cm-06	S00005	8T @ I =89.8A	0.078Tm @ I =19A	0-90A at 0.3A/s	0.5	0.298	0	/	28.291	99A	IMP
2	50cm-01	S00006	8T @ I =89.86A	0.06Tm @ I =19A	0-90A at 0.3A/s	0.5	0.153	0	/	28.263	99A	IMP
3	50cm-07	S00007	8T @ I =88.36A	N/A	0-90A at 0.3A/s	0.5	0.307	0	/	28.324	99A	IMP
4	50cm-10	S00008	8T @ I =88.98A	N/A	0-90A at 0.3A/s	0.5	0.172	0	/	29.153	99A	IMP
5	50cm-11	S00009	8T @ I =86.4A	0.084Tm @ I =19A	0-90A at 0.3A/s	0.5	0.135	2	48.7A,80.9A	30.809	99A	IMP
6	50cm-08	S00010	8T @ I =87.4A	0.08Tm @ I =19A	0-90A at 0.3A/s	0.5	0.398	2	69.3A,70.6A	30.05	99A	IMP
7	50cm-09	S00011	8T @ I =89.95A	0.064Tm @ I =19A	0-60A at 0.45A/s, 60-80A at 0.35A/s, 80-90A at 0.1A/s	0.5	0.134	0	/	28.3	95A	XSMT
8	50cm-04	S00012	8T @ I =89.9A	0.066Tm @ I =19A	0-90A at 0.3A/s	0.5	0.267	0	/	28.3	99A	IMP
9	50cm-05	S00013	8T @ I =87.40A	0.066Tm @ I =19A	0-90A at 0.3A/s	0.5	0.347	0	/	28.1	99A	IMP
10	50cm-02	S00014	8.09T @ I =90A	0.062Tm @ I =19A	0-90A at 0.3A/s	0.5	0.186	0	/	28.77	99A	IMP
11	50cm-03	S00015	8.01T @ I =90A	0.064Tm @ I =19A	0-90A at 0.45A/s	0.5	-0.132	0	/	28.32	95A	XSMT
12	50cm-12	S00016	8.04T @ I =90A	0.063Tm @ I =19A	0-90A at 0.3A/s	0.5	-0.274	0	/	28.46	99A	IMP
13	50cm-13	S00017	8.01T @ I =90A	0.063Tm @ I =19A	0-90A at 0.45A/s	0.5	-0.218	0	/	28.22	95A	XSMT
14	50cm-14	S00018	8T @ I =89.94A	0.065Tm @ I =19A	0-60A at 0.45A/s, 60-80A at 0.3A/s, 80-90A at 0.1A/s	0.5	0.208	0	/	28.6	95A	XSMT
15	50cm-15	S00019	8T @ I =87.3A	0.063Tm @ I =19A	0-90A at 0.3A/s	0.5	0.173	1	89.2A	28.2	99A	IMP
16	50cm-16	S00020	8T @ I =90A	0.063Tm @ I =19A	0-80A at 0.3A/s, 80-90A at 0.1A/s	0.5	0.275	0	/	28.24	99A	IMP
17	50cm-17	S00021	8T @ I =89.9A	0.063Tm @ I =19A	0-90A at 0.3A/s	0.5	0.11	0	/	28.5	99A	IMP
18	50cm-18	S00022	8.02T @ I =90A	0.063Tm @ I =19A	0-90A at 0.3A/s	0.5	0.257	0	/	28.64	99A	IMP
19	50cm-19	S00023	8.02T @ I =90A	0.064Tm @ I =19A	0-90A at 0.45A/s	0.5	-0.21	0	/	28.58	95A	XSMT
20	50cm-20	S00024	8.04T @ I =90A	0.064Tm @ I =19A	0-90A at 0.3A/s	0.5	-0.102	1	81A	28.65	99A	IMP
21	50cm-21	S00025	8.04T @ I =90A	0.064Tm @ I =19A	0-90A at 0.3A/s	0.5	0.29	0	/	28.56	99A	IMP

			Solenoid field	Dipole field	Solenoid Ramping rate	Dipole Ramping rate	Mechanical center error	Quench times	Quench current	Integrated field	Ramping to max current	Test Place
NO	XSMT batch number	Solenoid Serial Number	8T @ I < 90A	> 0.06Tm @ I < 20A			< 0.3 mm			≧ 28.2 T^2m		
1	25cm-04	S00001	8T @ I =87.96A	N/A	0-90A at 0.3A/s	0.5	0.305	0	/	14.408	99A	IMP
2	25cm-03	S00002	8T @ I =87.3A	0.036Tm @ I =19A	0-90A at 0.3A/s	0.5	-0.285	1	64A	13.87	99A	IMP
3	25cm-02	S00003	8T @ I =88.44A	0.042Tm @ I =19A	0-90A at 0.3A/s	0.5	0.373	1	88A	13.85	99A	IMP
4	25cm-05	S00004	8T @ I =86.8A	0.03Tm @ I =19A	0-90A at 0.3A/s	0.5	-0.284	3	58.5A,69.6A,76.6A	13.8	99A	IMP
5	25cm-06	S00005	8T @ I =86.8A	0.031Tm @ I =19A	0-90A at 0.3A/s	0.5	0.2	0	/	13.76	99A	IMP
6	25cm-07	S00006	8T @ I =86.6A	0.03Tm @ I =19A	0-90A at 0.3A/s	0.5	0.145	0	/	13.73	99A	IMP
7	25cm-08	S00007	8T @ I =86.8A	0.032Tm @ I =19A	0-90A at 0.3A/s	0.5	0.282	0	/	13.77	99A	IMP
8	25cm-09	S00008	8T @ I =86.75A	0.031Tm @ I =19A	0-90A at 0.3A/s	0.5	0.042	0	/	13.78	99A	IMP
9	25cm-10	S00009	8T @ I =87.3A	N/A	0-90A at 0.3A/s	0.5	0.203	0	/	N/A	99A	IMP

Summary

- It is the first time for batch test of SC magnet at IMP and all of them are accepted by FRIB.
- The measurement facility works well during the test .
- Can’t get the stray field and the integral field uniformity
- The vertical test consume more time and LHe, and has a great risk of failure.(Data acquisition failure, movement not smooth etc.)
- HIAF(High Intensity Heavy-ion Accelerator Facility)



Thanks very much for your attentions !