Status of the magnetic measurement for the Heavy-Ion Medical Machine(HIMM)

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Overview

- Brief introduction of HIMM
- Magnetic measurement system
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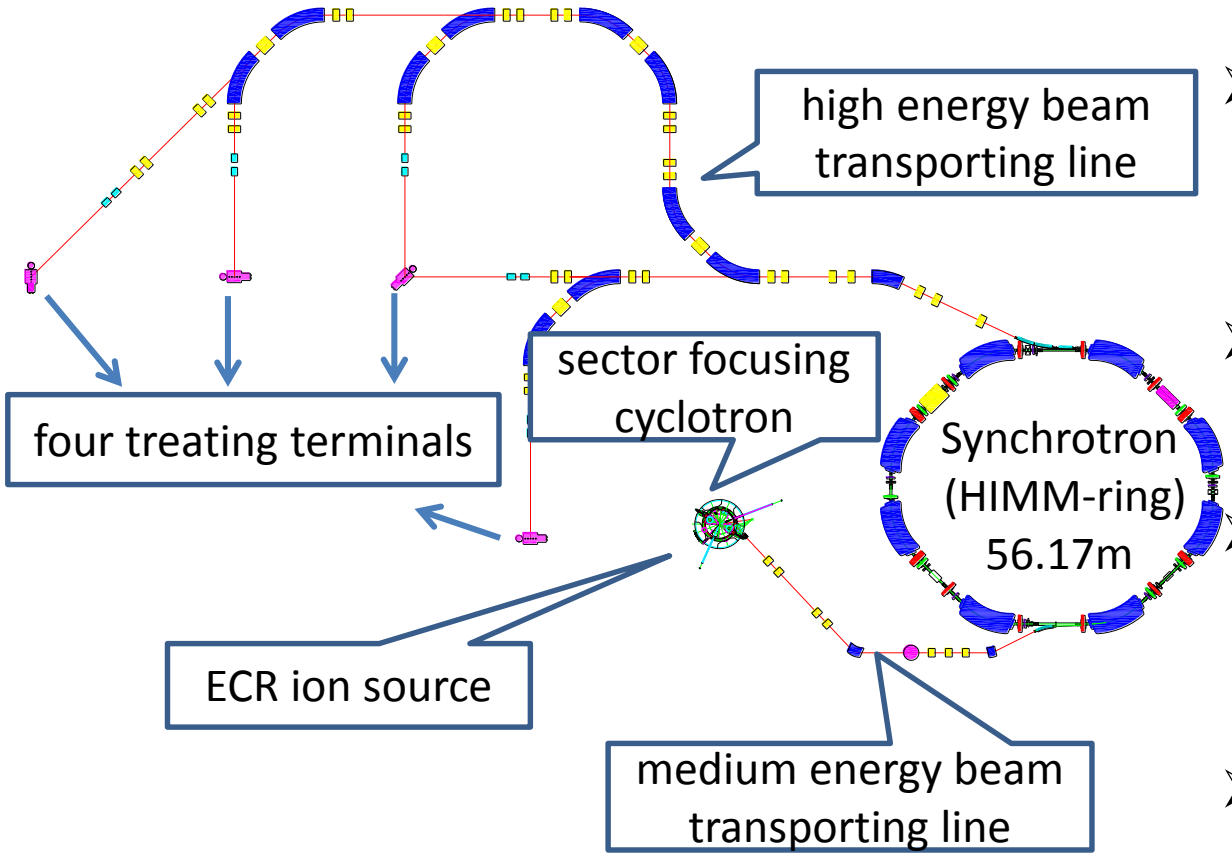
  - ✓ Hall mapping system
  - ✓ Long coil integral system
  - ✓ Rotating coil system
  - ✓ Infrastructure
- Measurement status of magnets
  - ✓ Cyclotron Magnet
  - ✓ Main dipole
  - ✓ HEBT dipole
  - ✓ Multi-polar magnet
- Summary and future works

Brief introduction of HIMM-1



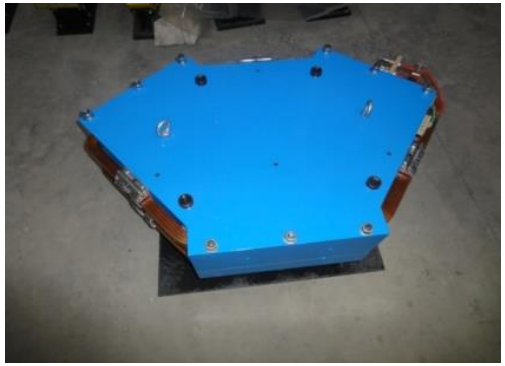
- HIMM （Heavy Ion Medical Machine） developed by IMP for commercial cancer therapy
- The facility were constructed in Wuwei City of Gansu Province China
- Tripartite cooperation projects (IMP, local government, Ronghua Group)
- The project was launched in 2010

Carbon ions from the ECR source are pre-accelerated to 7 MeV/u by the cyclotron, transferred and injected into synchrotron for higher energy, then slowly-extracted to terminal for cancer therapy . The energy of the beam delivered to the treatment room varies from 80 MeV/u to 400 MeV/u in a step length of 1.5 MeV/u.

Brief introduction of HIMM-2

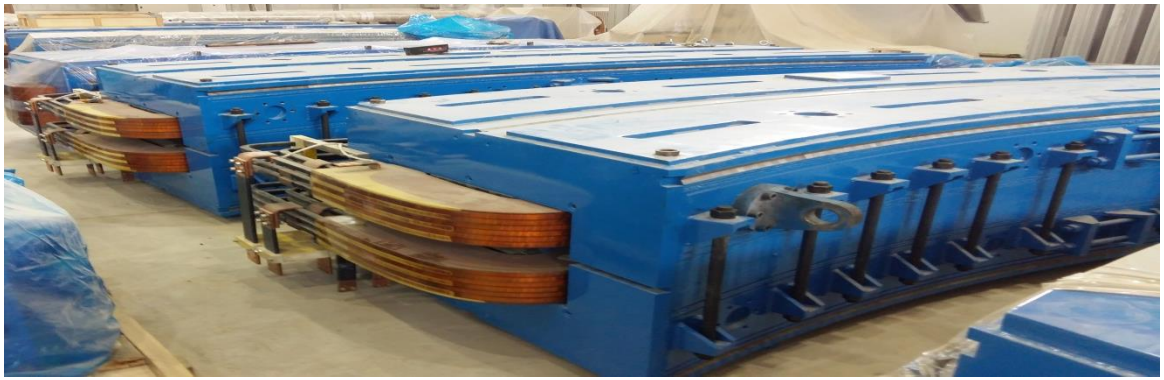






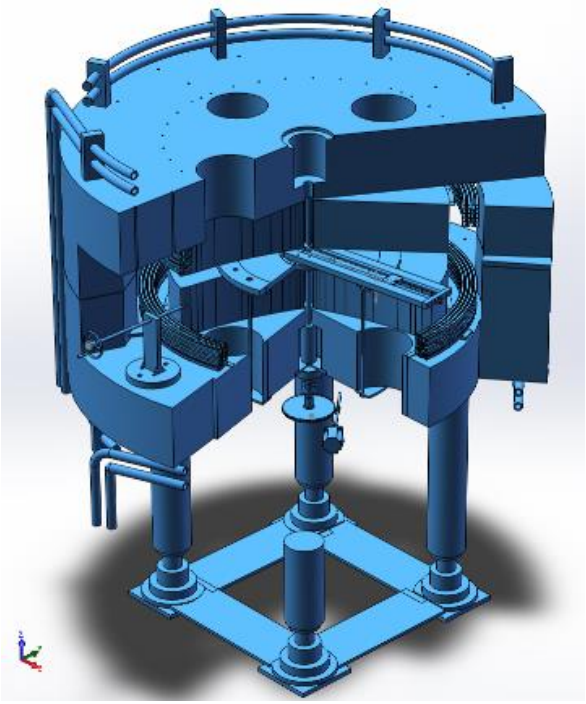
- There are more than 150 room temperature magnets including dipoles, quadrupoles ,sixtupoles and correctors.
- The types of the magnets are more than 35.
- All the magnets were designed, manufactured and tested by IMP.





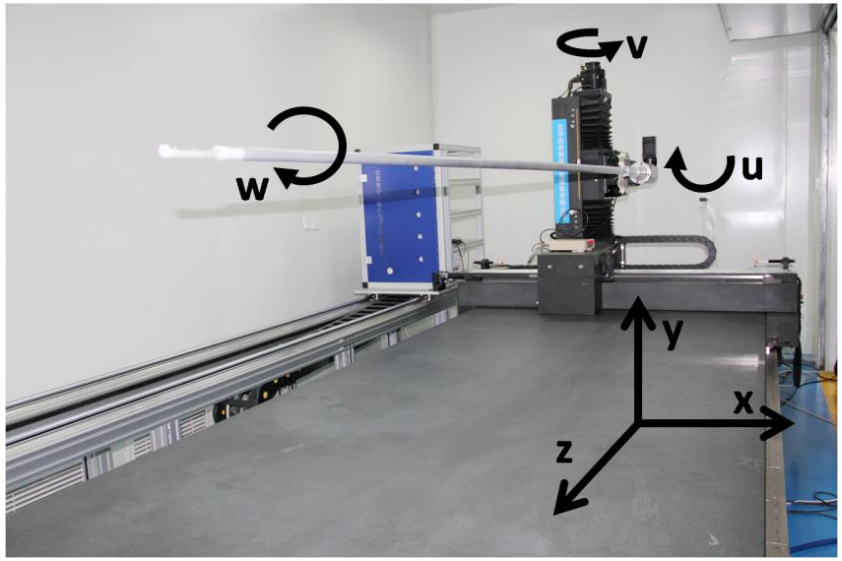
Cyclotron magnet measurement system

Parameters of measurement system					
Current	1387/A	Maximum magnetic field value	17000Gs	Magnetic field error	5/Gs
Radial step	20/mm	Radial measurement range	-20~820/mm	Radial positional error	0.01/mm
Angle step	1/°	Angle measurement range	0~360/°	Angle positional error	0.05/°



- ✓ *Adopts turbine worm drive*
- ✓ *Realizing the cyclotron magnet ring surface (polar field)measurement.*
- ✓ *One hall probe(MPT-141) is located on a thin bar*
- ✓ *Temperature monitoring*
- ✓ *Laser tracker monitoring*
- ✓ *Encoder measure the azimuthal movements*
- ✓ *Total measuring time is about 40 hours*

Hall mapping system

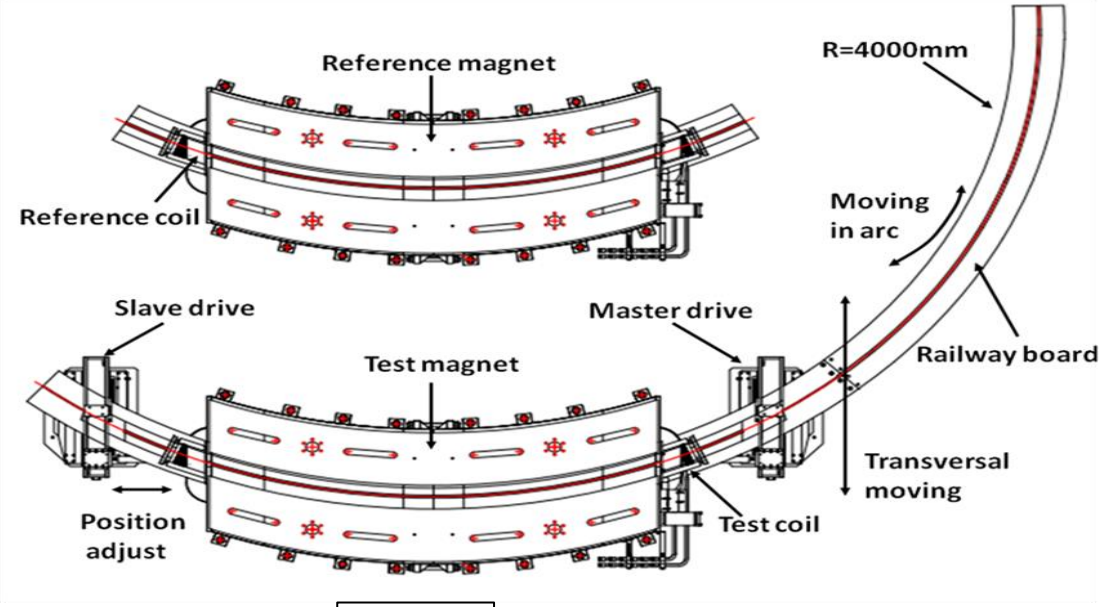


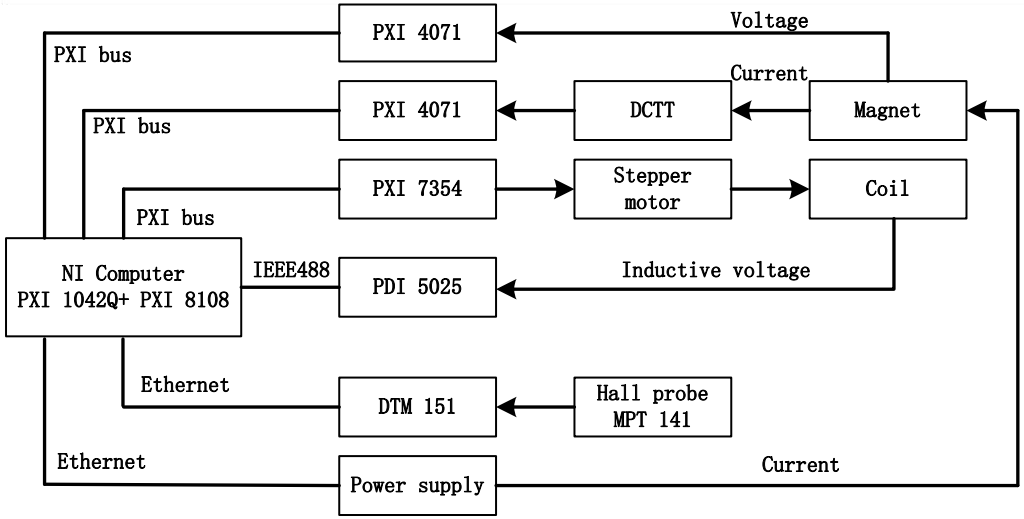
	Range (mm)	Accuracy (mm)	Repeatability (mm)
X	1200	±0.0014	±0.0004
Y	400	±0.0007	±0.0005
Z	4000	±0.0035	±0.0022

- ✓ *6 freedom bench (Air-cushions)*
- ✓ *Granite table (Extreme reliability)*
- ✓ *Coreless linear motor*
- ✓ *Precision controller Reduce oscillations*
- ✓ *Tesla-meter:DTM151 (Group3)*
- ✓ *Hall probe:MPT-141 Max range: 3T Resolution :1μT*
- ✓ *Carbon fiber arm*

Long coil integral system

Driving devices and measurement scene of long coil integral system



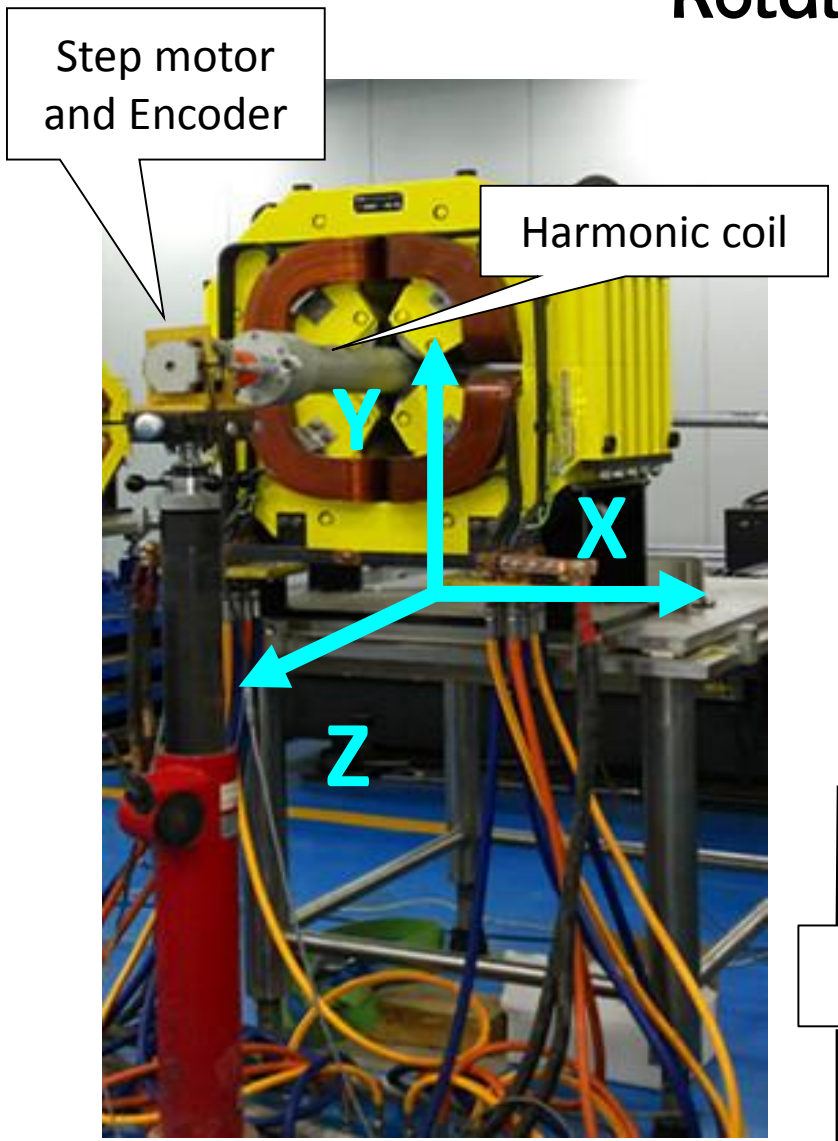


Measurement items :
(Design for curver dipoles)
Integral transfer function
Integral Field homogeneity
Magnet reproducibility

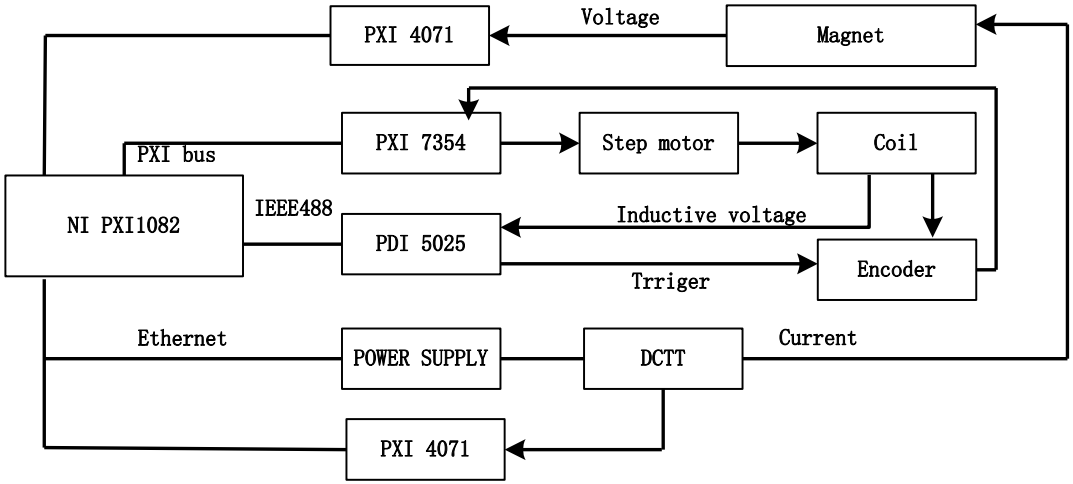
Driving devices:
Two parallel supporters
Two frames (outside)
Synchronous belt
3 step motor:
In -out direction(along arc)
radial direction

The acquisition and motion control system

Rotating coil system



- ✓ Radial coil(main coil and bucking coil)
- ✓ Compensation mode can suppress the dipole (n=1) field component and the main (n=2) field component to get higher order multipole harmonics with high precision
- ✓ The uncompensated mode is used to get main field amplitude, phase and magnetic centre offsets
- ✓ Coil rotates at a constant angular velocity
- ✓ Analyzes integrated voltage using Metrolab PDI 5025 with 2 channels



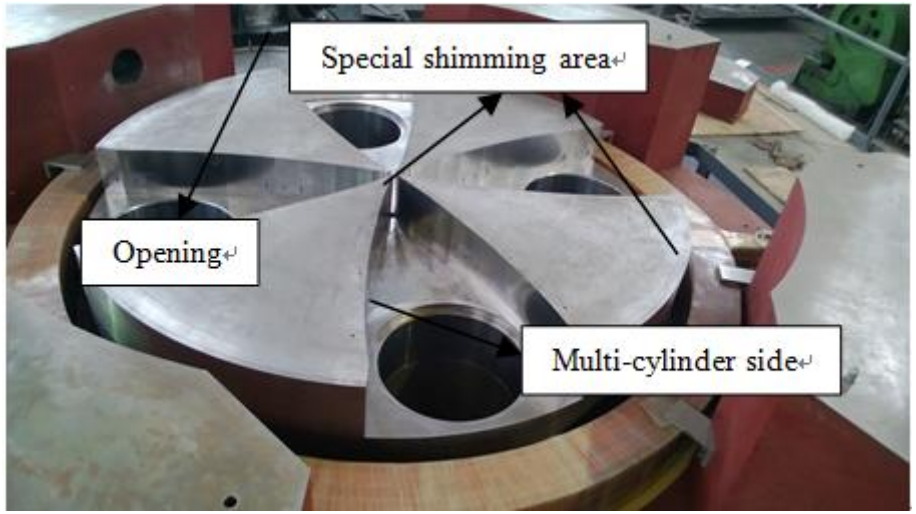
Infrastructure

- *200m² constant-temperature lab which can ensure that the variation of temperature could not affect the hall probe and magnet to improve measurement accuracy*
- *Temperature variation range : $\pm 1\ ^0C$*
- *25m² Movable ceiling*

- *2 Power supplies*
- *Module 854 from DANFYSIK*
- *Output power:2000A/150 Vdc*
  Output power:600A/50 Vdc
- *10ppm long term current stability*

Measurement status of magnets-Cyclotron Magnet-1

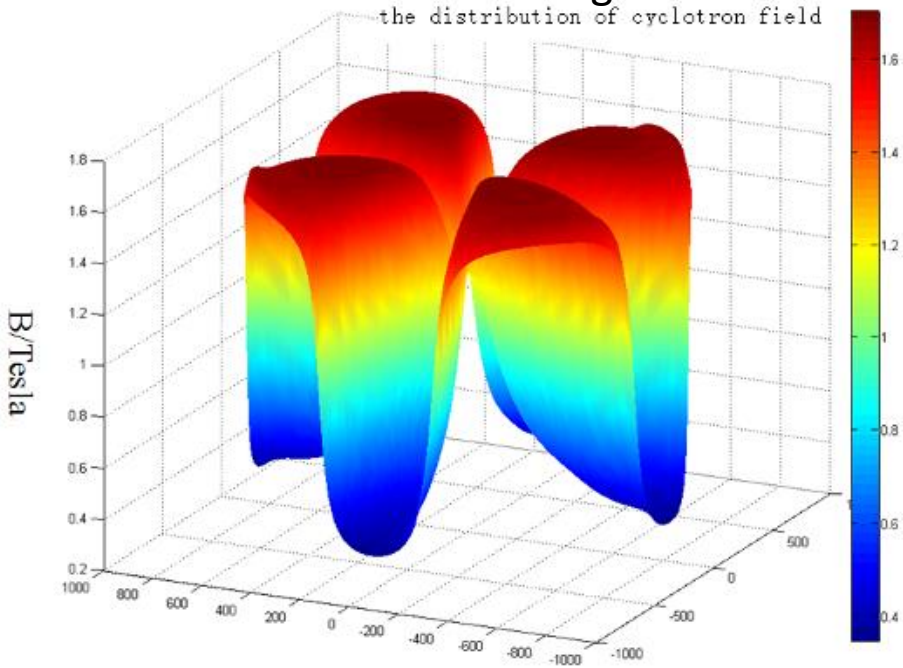
Parameter	Value
Hill angle, [degree]	56
Valley angle, [degree]	34
Average magnetic field[T]	1.2
Magnet aperture, [mm]	70-80
Injection radius, [mm]	27
Extraction radius, [mm]	750
Pole radius, [mm]	840
Diameter, [mm]	2920
Height, [mm]	1520
Weight, [tons]	About 70

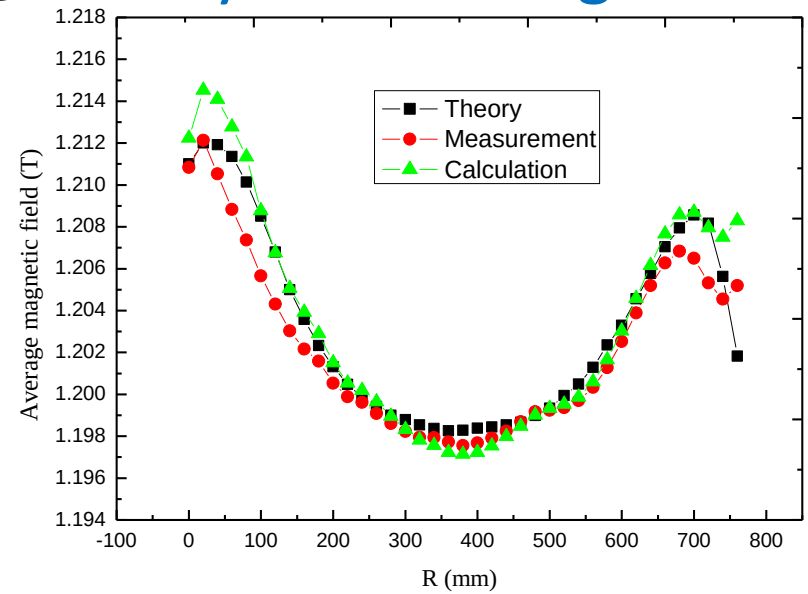


- ✓ Electrical pure iron DT4 is used for the pole
- ✓ No.10 steel is used for the yoke(the carbon content was as low as 0.003%.)
- ✓ water-cooled hollow copper conductor(18×18/Φ8 mm) for coil

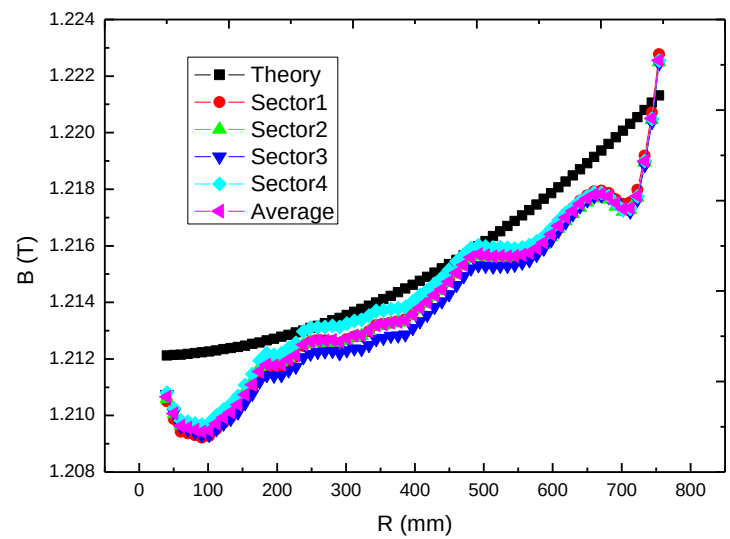
Measurement status of magnets-Cyclotron Magnet-2

The distribution of maximum magnetic field





Comparison between measurement and theory value.



- ✓ After three shimming processes. the magnetic result satisfies the physical requirement.
- ✓ For the different radii. The maximum error is about 150 Gauss, which is located in the border of hill and valley where field gradient is very high.
- ✓ Successful commissioning ! Carbon extracted 7MeV /u, beam intensity up to 12 mA (2014/9)

Measurement status of magnets-Synchrotron dipole -1

MAIN PARAMETERS OF SYNCHROTRON DIPOLES

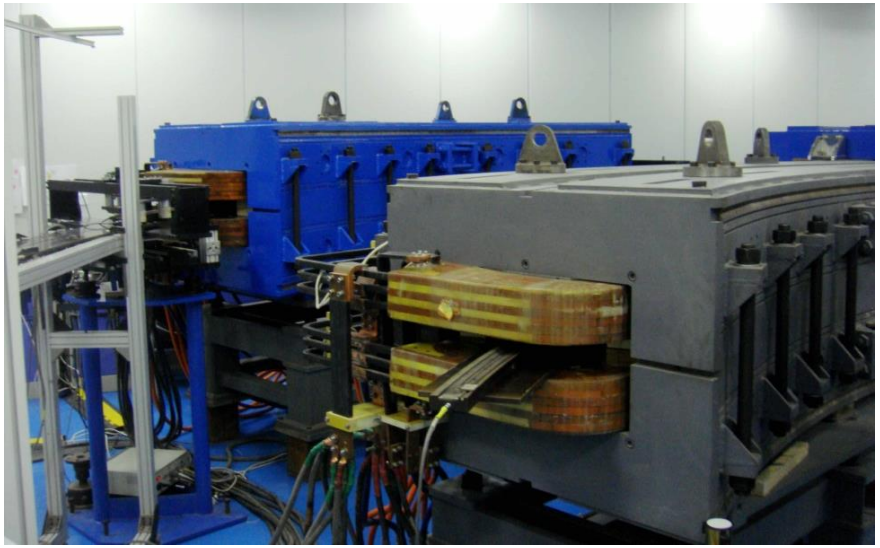
Items	Unit	Value
Number		8
Field range	T	0.18~1.66
Ramping rate	T/s	1
Reference field	T	0.2
Bending radius	mm	4000
Bending angle	degree	45
Effective Length	mm	3141.6(0.2T)
Effective aperture	mm^2	120×60(0.2T)
Gap	mm	74
Field uniformity		$\pm 1.5\times 10^{-4}$
Integral uniformity		$\pm 1.5\times 10^{-4}$
Magnet reproducibility		$\pm 1.5\times 10^{-4}$
Current	A	1750
Resistance	mΩ	31.5
Coil conductor size	mm^2/mm	20×20/Φ10
Coil turns/pole		36

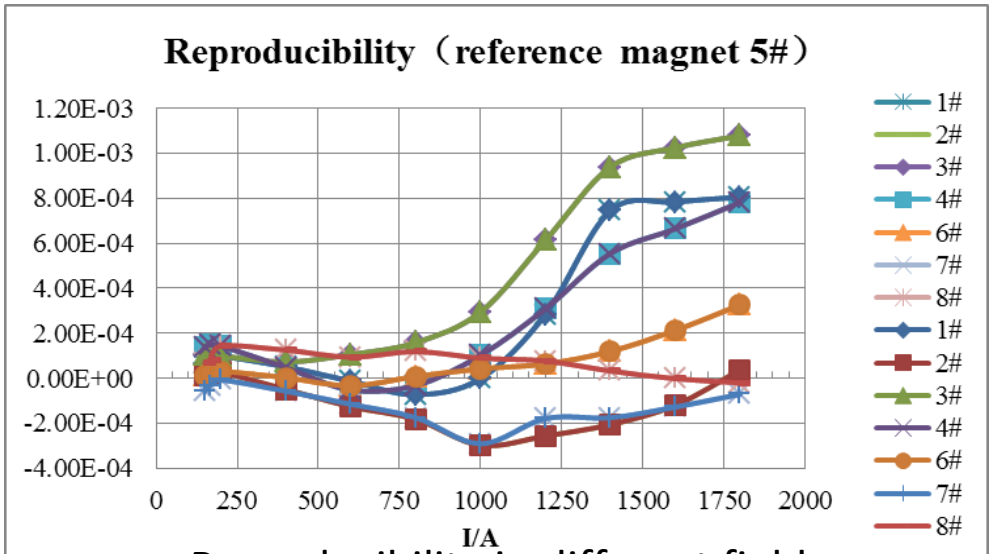
- G11, 2 pairs
- Has the same shape as the beam orbit
- R: 4000mm L:4400mm
- 9 piecewise stitching
- N: 260 turns W:0.01mm

Measurement status of magnets-Synchrotron dipole -2

Reproducibility measurement:

- ✓ 2 coils locate in the center of the magnets respectively
- ✓ Remain stationary
- ✓ Two magnet connection in series
- ✓ Two coils connection in series reversely
- ✓ Exchange coils repeat measurement
- ✓ Counteract the difference of coil coefficient

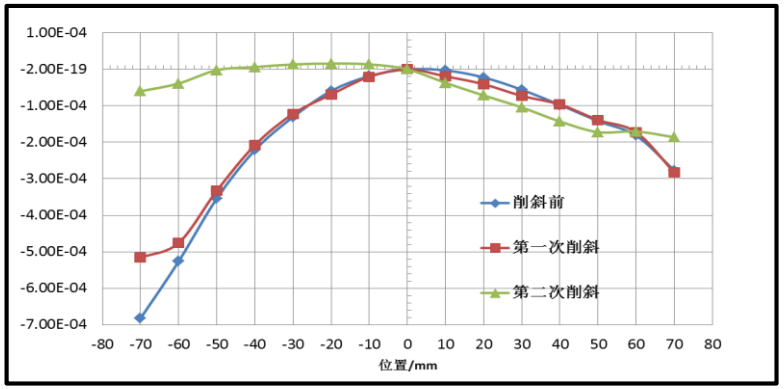




Reproducibility in different field

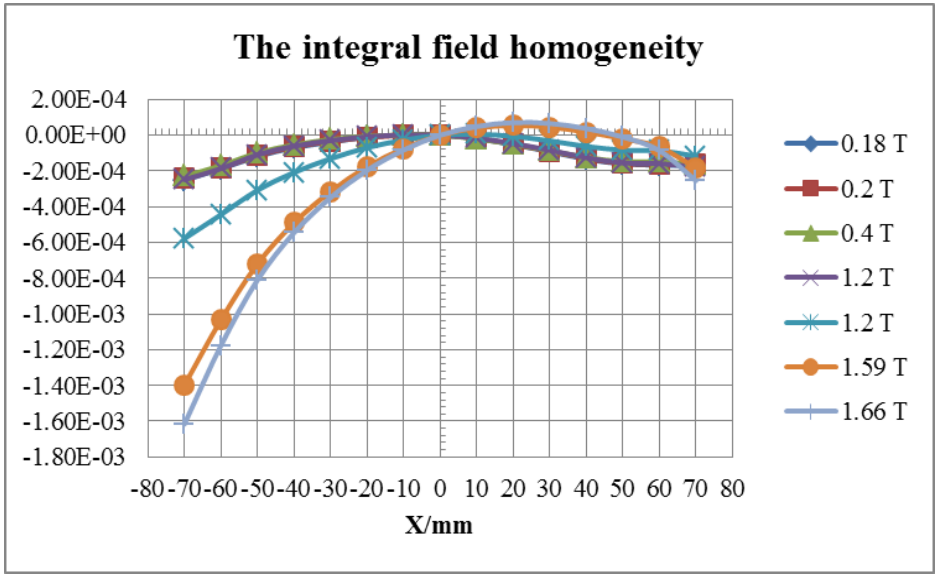
- ➢ The magnet which has the largest effective length is reference magnet.
- ➢ The stainless steel sheets are increased for the other magnets to reduce the reproducibility.
- ➢ At the reference field(2000Gs), the reproducibility of 7 dipole magnets is less than $\pm 1.5\times 10^{-4}$.

Measurement status of magnets-Synchrotron dipole -3



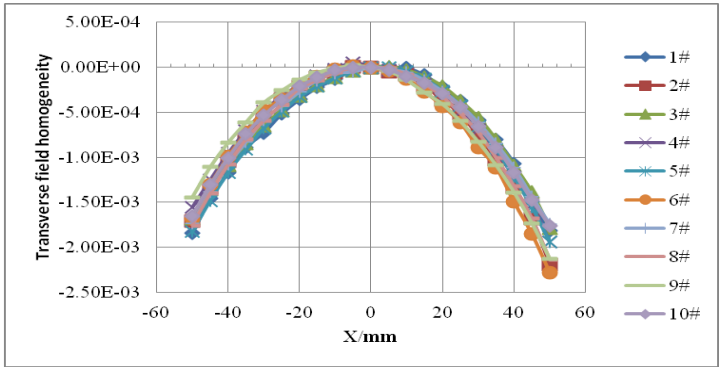
- The removable pole is designed that can be easily chamfered. The Rogoski curve is used to avoid the field saturation in the end of magnet.
- There is little difference between the design and the first test result because of material property and manufacture influence.
- Modify the removable poles, at the reference field level, the integral field homogeneity is less than ±2×10-4 and it is satisfy with the physical requirement.

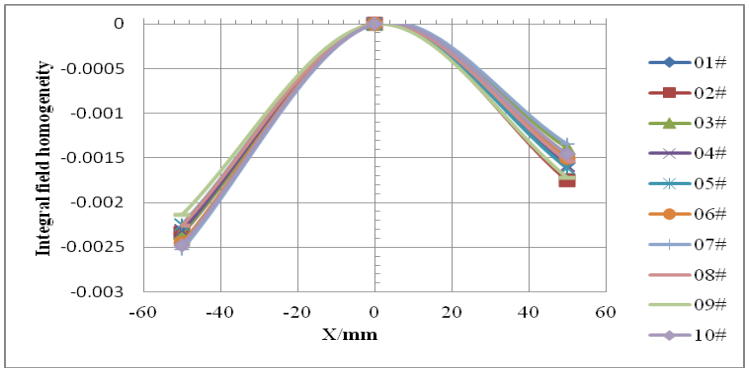
- At the different field level, From 0.2 T to 1.2 T, the difference of integral field homogeneity is small.
- For higher fields, the results become worse due to iron saturation.
- The greatest contribution of multiples distortion comes from quadruple component.



Measurement status of magnets-HEBT dipole

- ✓ The dipole magnet of high energy beam line is operated at DC State, the maximum magnetic field is 1.6 T.
- ✓ 10 dipole magnet is distributed at 4 cancer therapy terminal.
- ✓ The requirement of field homogeneity is lower than synchrotron dipole .
- ✓ The structure with small dimension is similar with the synchrotron dipole magnet .





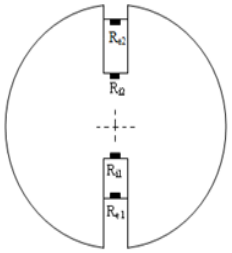
- The I-B curve and the transverse field homogeneity are measured with hall mapping system.
- The transverse field homogeneity in the range of ±50 mm is $\pm 1\times 10^{-3}$.
- The integral field homogeneity is no more than $\pm 1.5\times 10^{-3}$.

Measurement status of magnets-Multi-polar magnet-1

Multi-polar magnets parameters in HIMM

Magnet Type	Installation position	Number	Gap(mm)	Effective length (mm)	gradient
Quadrupole Magnet	Middle Energy Beam Line	3	Φ80	400	3T/m
	Synchrotron	8	Φ140	200	7.5T/m
	Synchrotron	9	Φ140	350	7.5T/m
Sextupole Magnet	Synchrotron	7	Φ150	150	40T/m^2
	Synchrotron	2	Φ194	140	40T/m^2
Quadrupole Magnet	High Energy Beam Line	5	Φ100	800	7.8T/m
	High Energy Beam Line	31	Φ100	400	13T/m

The structure diagram of harmonic coil



Radial structure of double coils

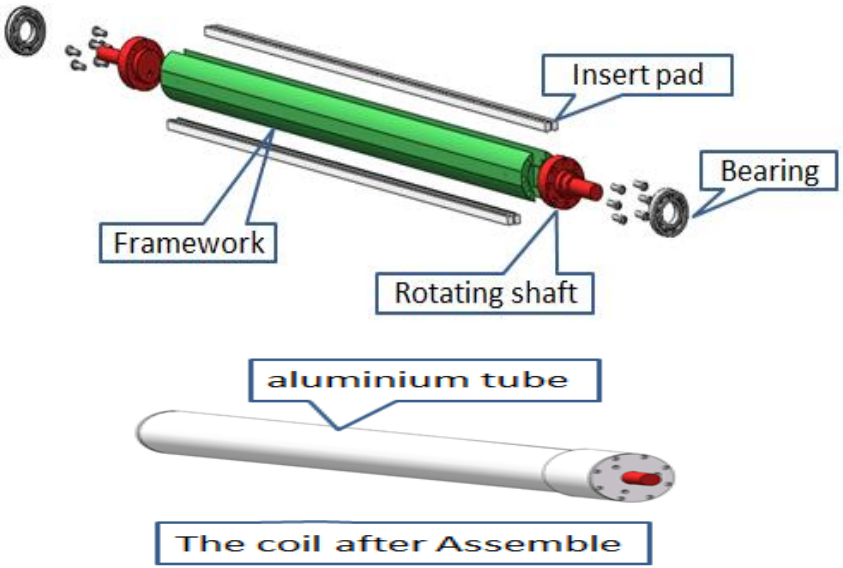
Re2 and Re1 are the outer coil radius

Ri2 and Ri1 are the inner coil radius

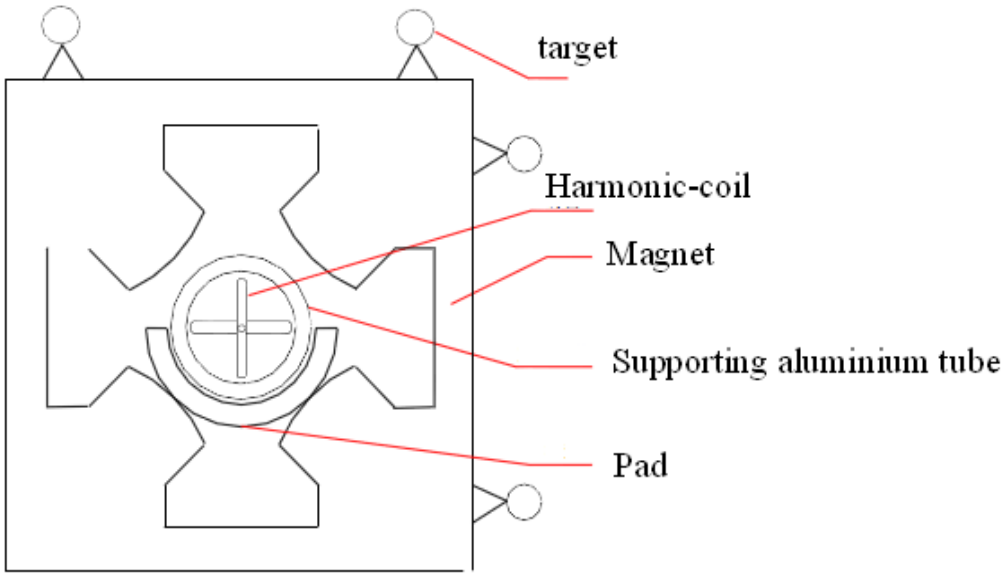
The two coils are coaxial and coplanar

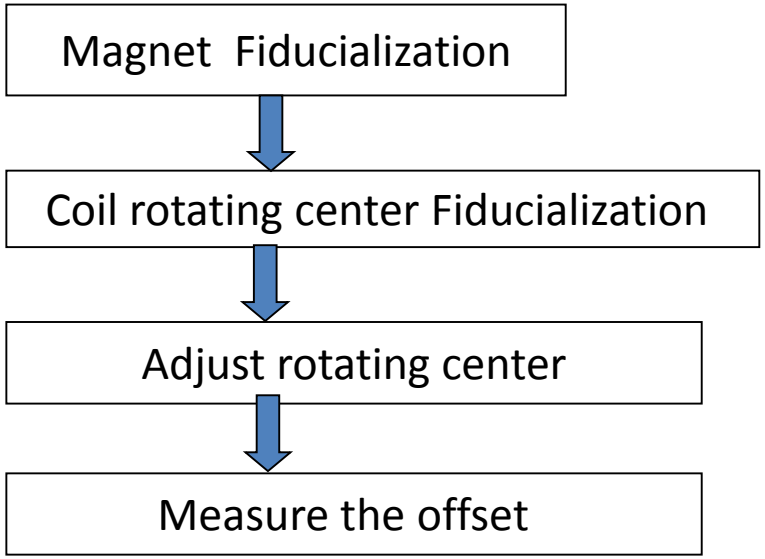
Parameters of Harmonic Coils

Harmonic Coil	QHA100	QHA80	QHA140	SHA150
R_{e2}(mm)	40.08	31.99	53.54	59.99
R_{e1}(mm)	35.99	19.98	29.57	36.49
R_{i2}(mm)	20.99	19.02	32.78	38.46
R_{i1}(mm)	16.98	7.01	8.86	28.31
L（mm）	900	1180	960	800
N_e	400	400	400	400
N_i	200	200	200	120



Measurement status of magnets-Multi-polar magnet-2

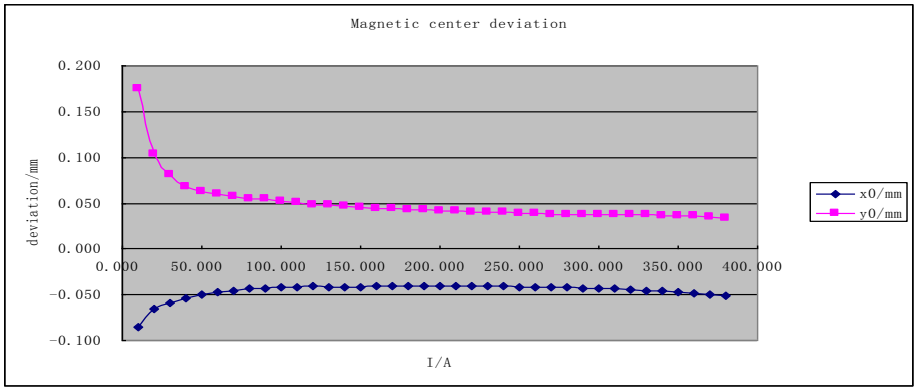


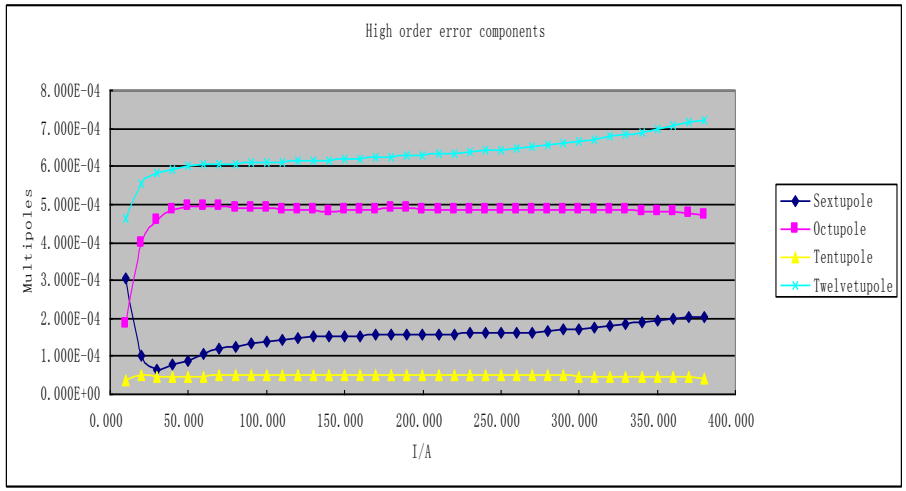


- The rotating coil is placed on the surface of the magnet poles through the aluminum tube and pad sleeve.
- Assure that the rotating center of the coil and the mechanical center of the magnet is in the same position.(Magnet alignment within: ±0.03 mm, ±0.2 mrad)
- The Δx and Δy are calculated using the ratio of dipole strength to the quadrupole strength of the field.

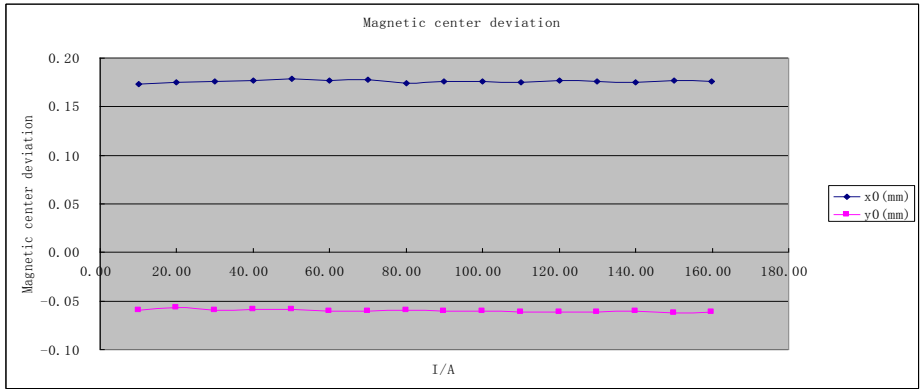
Measurement status of magnets-Multi-polar magnet-3

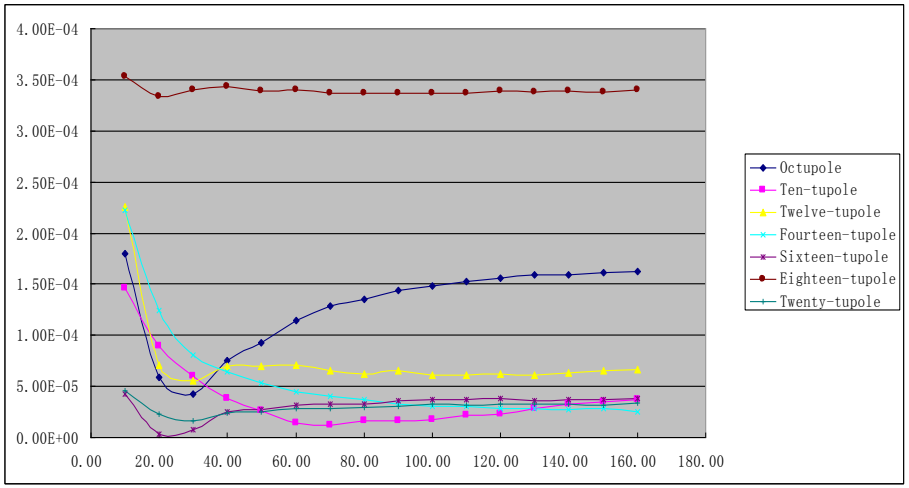
Φ140L200-Quadrupole





Φ150L150-Sixtupole





Summary and future works

- All the measurement system worked properly and achieved desired accuracy.
- After chamfering, the magnetic field homogeneity of dipole magnets for synchrotron satisfy with the physical requirements.
- The measurement work has been finished including the injector and extraction （2012.12~2014.11）. Data analyze is still underway. Measurement work for the second set of HIMM has started this year.
- The magnet installation is coming the end. The ECR source and cyclotron had successful commissioning.

Thanks for your attention