國家同步輻射研究中心
National Synchrotron Radiation Research Center

Magnet Mass Production and Field Measurements Results for TPS

C. S. Hwang, NSRRC, Hsinchu, Taiwan

IMMW 18, NSLSII (Long Island), 3 June 2013

Outline

- **Field measurement system**

  - Hall Probe, Rotating coil, search coil
- **Magnet alignment method**
- **Inspection of Storage ring magnets**
- **Inspection of Booster ring magnets**
- **Injection Magnets**
- **Summary**

Major Milestones of TPS project

- June 2005 TPS Proposal to Government
- Oct. 2007 Lattice (circ. 518.4m) approved by BOT
- Dec. 2007 TPS final approval by Legislative Yuan
- May 2008 EPA approval; site plan completed
- June 2008 Accelerator Design Book (DRAFT) issued
- Dec. 2008 TPS budget (Civil + Accelerator + BL) lock in
- Dec. 2009 Contract out of the civil construction
- Feb. 2010 Ground Break
- Dec. 2013 Civil construction completed
- Sep. 2014 Installation completed & start to commission
- Sep. 2015 Open to users

Status of the sub-components

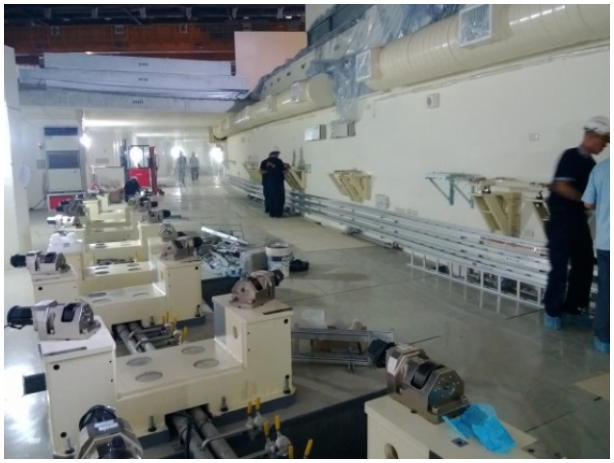
- Civil and utility construction will be completed before end of 2013.
- The storage ring installation has been started and will be finished in the third quarter of 2014 and then start the commissioning.
- 150 MeV linac system has been completed and prepare to move into TPS location.
- 3 sets of superconducting RF system has been finished and the high power test is processing in house.
- 700 kW Cryogenic system is already and prepare to move to TLS location.
- All magnets has been finished 80% by BSL company and will be done at the end of September.
- All the vacuum chambers of the 24 sections will be finished before September.
- All the power supply will be delivery to NSRRC before this year.
- Control system were developed and will be installed and tested next year.

Activity center &TPS outside view

TPS building

Academic & Activity center

The inside view of TPS






Overview of magnet Lab.

Measurement system	Measurement dimension	Purpose	Note
Hall probe (bench)	6 m	ID and EPU	Pulley driven by DC motor
	5.4 m	Wiggle, Undulator & EPU	Linear motor with air bearing
	1.5 m	Superconducting undulator	In vertical dewar
	2 m	For Lattice magnet	Mechanical precision 20μm
Rotating coil	840 cm	QM and SM-storage ring	
	570 cm	QM and SM-boost ring	
NMR ESR	0.043-13.7T	Hall sensor calibration	
	0.55-3.2 mT		
Search coil	Wire OD=0.12mm, 30turns Wire OD=0.05mm 30turns	Kicker and septum	
Stretch wire	-	Insertion Devices	Measure 1st & 2nd field integral
Long loop coil	5-axes	Insertion Devices	Measure 1st field integral
Helmholtz Coil	3-axis rotation	Magnet block	

Field measurement system for TPS magnets

Two Hall probe system (HPS):

- Main field strength of HPS was calibrated by NMR & ESR (Nuclear magnetic resonance & electron spin resonance system) using dipole magnet.
- This system used for all dipole magnet measurement and the inspection all of the prototype magnets.

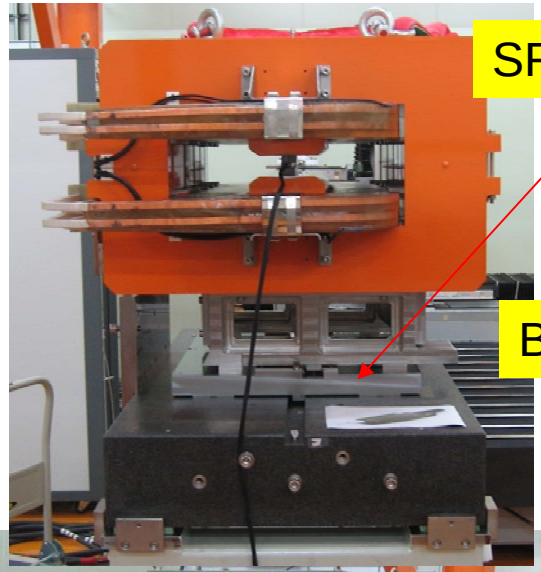
Two Rotating coil system (RCS):

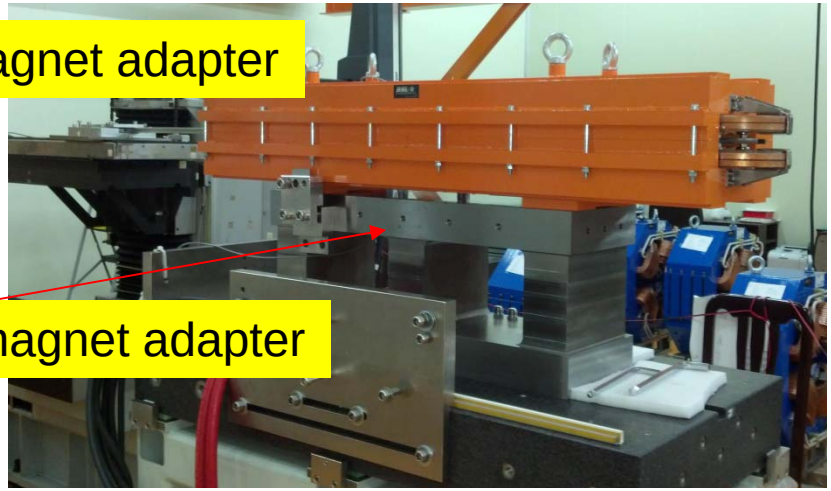
- Main field strength of RCS was calibrated by HPS using quadrupole and sextupole magnets.
- Field center of magnet was calibrated by CMM (3-D mechanical measurement system) using quadrupole and sextupole magnets.

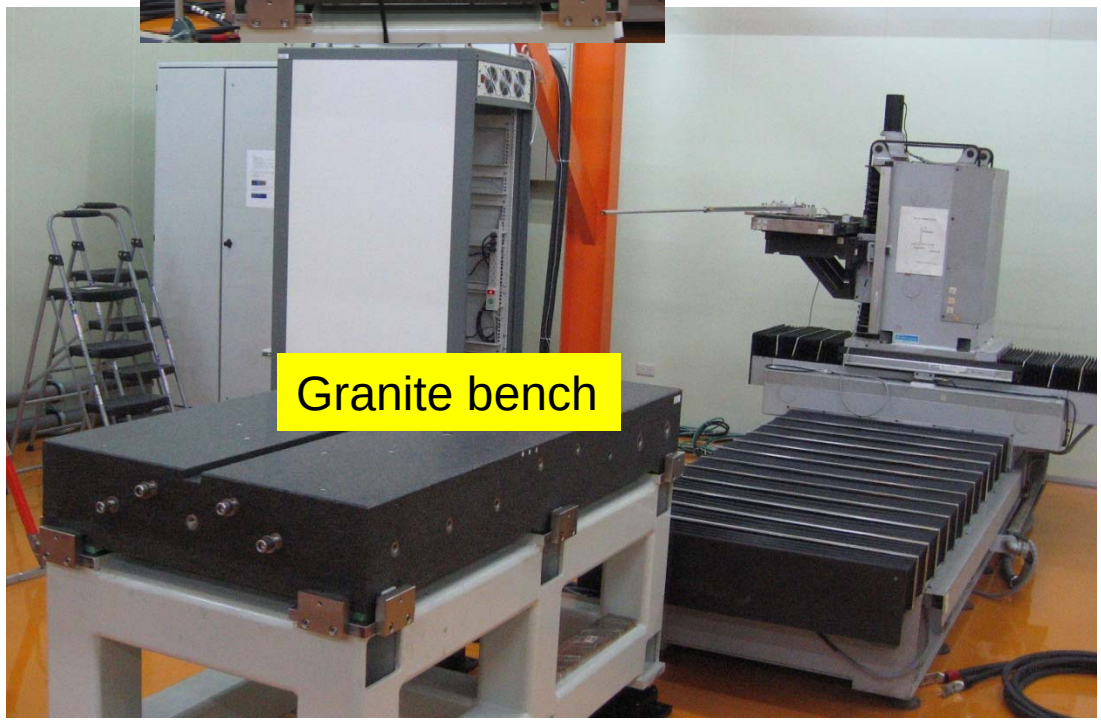
Long coil & Search coil system

- This system was used to measure Kicker and Septum. The pulse field and pulse current were recoded to be compared.

HPS and measurement bench



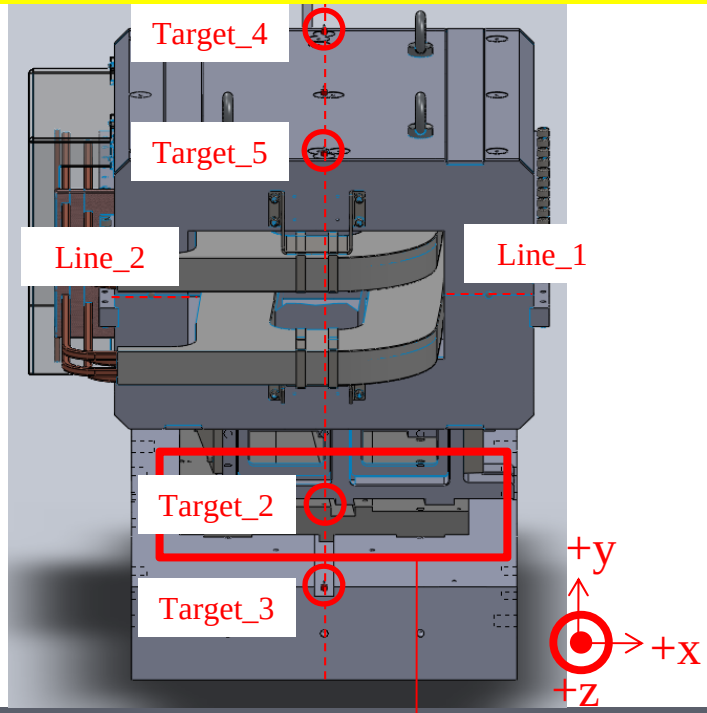


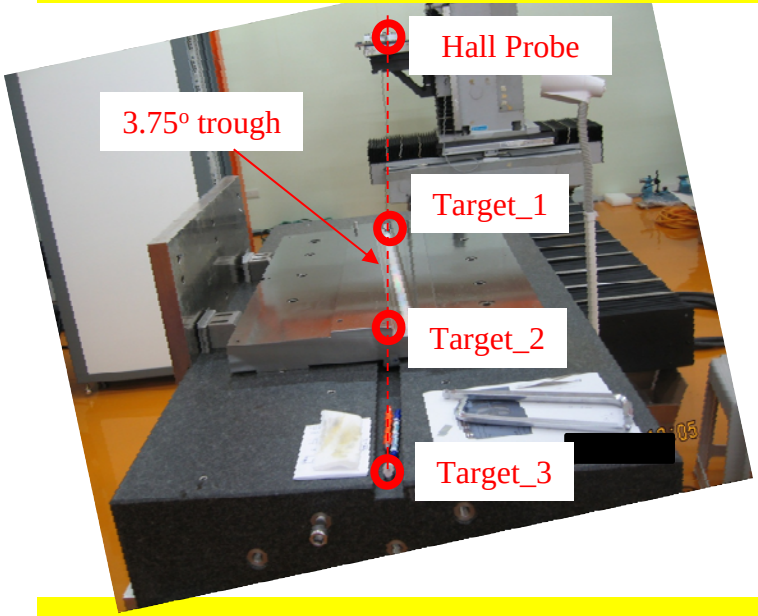


SR-Dipole alignment on the HPS bench

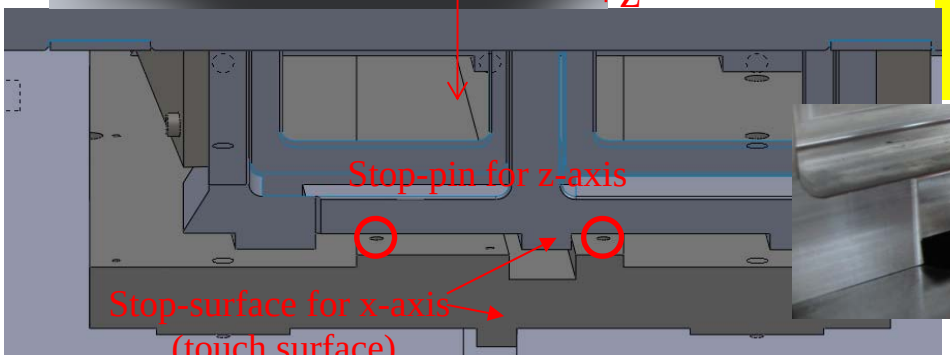
- SR-dipole position check: Hall probe, Tarage_2, Target_3, Target_4 and Targer_5 in alignment.
- Vertical height check: Hall probe, Line_1 (yoke seam) and Line_2 in alignment.

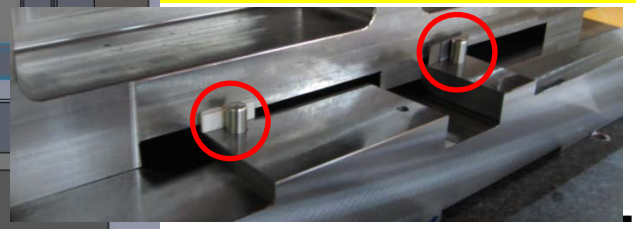
Adapter position check before SR-dipole installation. Hall probe, Tarage_1, Target_2 and Targer_3 in alignment.





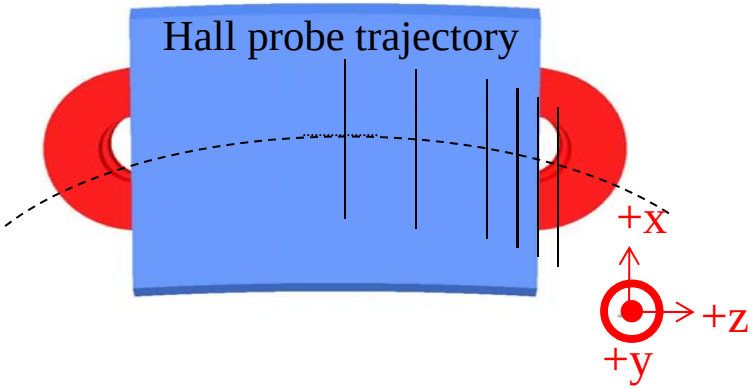
1. SR-dipole adapter (3.75º): Rotate the SR-dipole magnet to parallel the Hall probe.
2. The magnet and adapter are located by the stop-pin and stop-surface.
3. The horizontal alignment is checked by the l theodolite.
4. The vertical height of magnet is checked by the eveling.



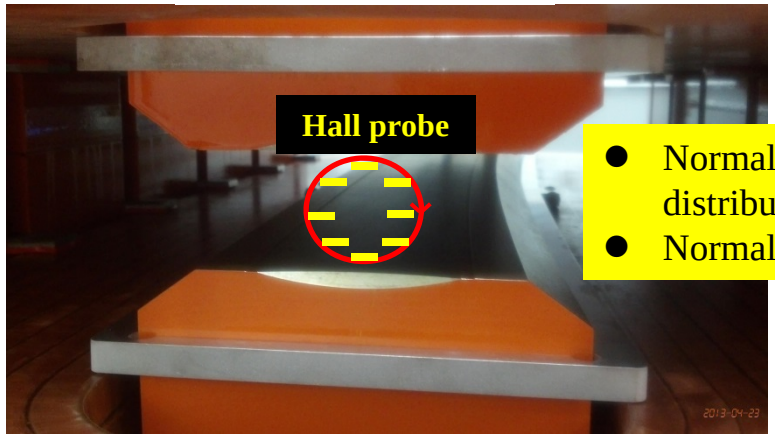


HPS measurement and analysis

- Hall probe mapping trajectory: Curve and lamina

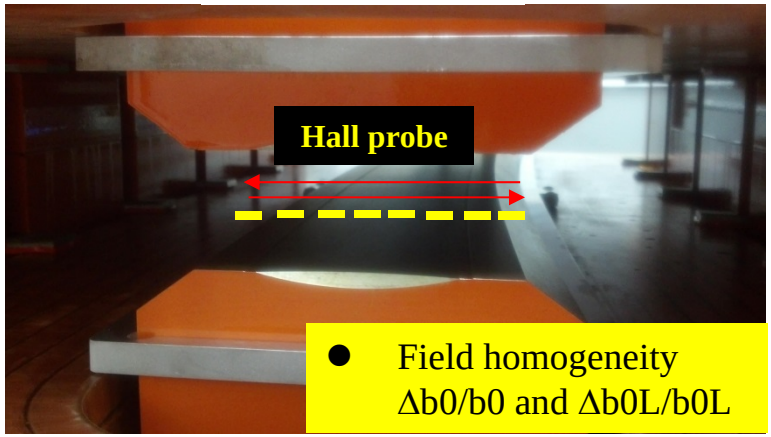


3D mapping: XY-Z
(circular & elliptical)



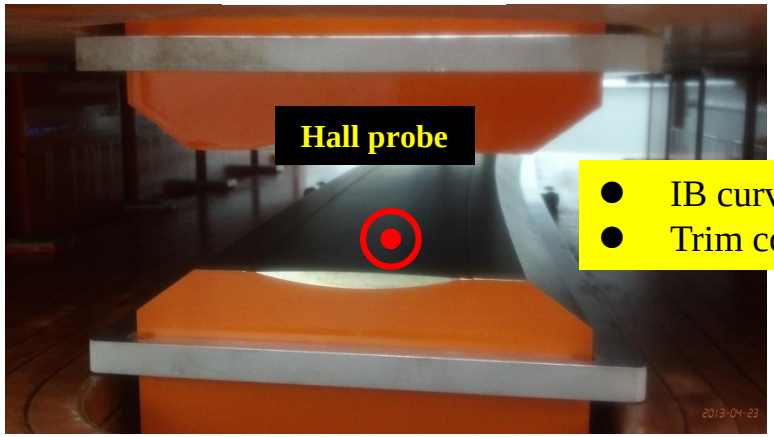
- Normal (Skew) multipoles distribution along Z-axis.
- Normalized multipoles.

2D mapping: X-Z
(plane)



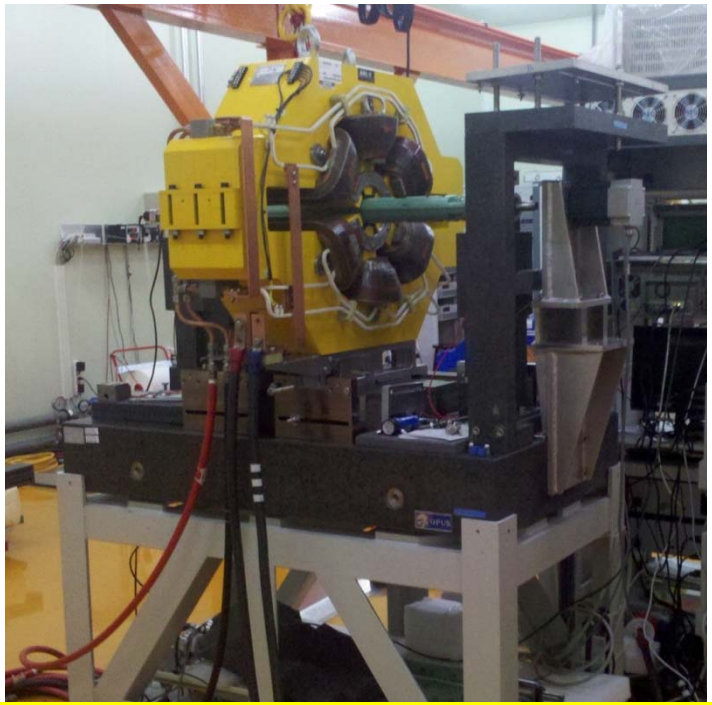
- Field homogeneity Δb0/b0 and Δb0L/b0L

1D mapping: Z
(on axis)

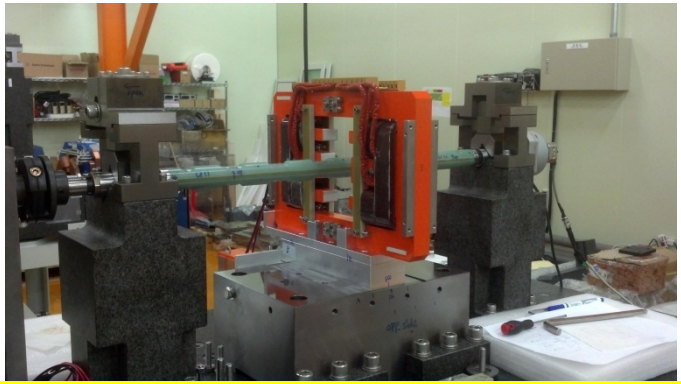


- IB curve
- Trim coil

Rotating coil system (RCS)



SR-QM/SM magnet measured by SR-RCS



SR-FFC magnet measured by BR-RCS

Corrector magnet measured by BR-RCS

Magnet measured by BR-RCS

Rotating coil - vertical offset calibration

Magnet	Q1	Q1	Q9	Q1	Q5	Q6	R4Q8	S1	S2	S3
SN	P01	P02	P01	P03	P01	P01	P01	P01	P01	P01
CMM V-offset	0.003	0.002	-0.002	-0.006	-0.002	0.003	-0.001	-0.005	0.002	0.004
RCS V-offset	0.106	0.098	0.084	0.085	0.087	0.100	0.085	0.089	0.099	0.106
Different	0.103	0.096	0.086	0.091	0.089	0.097	0.086	0.094	0.097	0.102

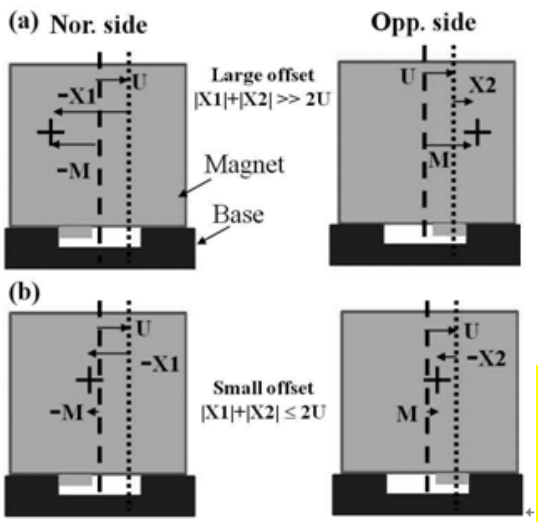
Average offset = 94 μm

STD = 5 μm

- The calibration value of RCS unit is -0.094 mm in the vertical offset.
- The precision of magnet center measurement of this system in vertical axis is 5 μm.

Rotating coil - horizontal offset

	Q1	Q10	Q1	Q9	Q5	Q6	R4Q8	S1	S2	S3
Note	P01	P01	P02	P01	P01	P01	P01	P01	P01	P01
H nor. side	0.005 (A)	0.060	0.021	0.060	0.048	0.070	0.066	0.012	0.002	0.030
H opp. side	0.018 (B)	0.038	0.000	0.038	0.014	0.029	0.036	0.002	0.009	0.015
Decision	X1+X2 >> 2U	X1+X2 >> 2U	X1+X2 >> 2U	X1+X2 >> 2U	X1+X2 >> 2U	X1+X2 >> 2U	X1+X2 >> 2U	X1-X2 <<2U	X1-X2 << 2U	X1+X2 >> 2U
H offset	0.012 (A+B)/2	0.049 (A+B)/2	0.011 (A+B)/2	0.049 (A+B)/2	0.031 (A+B)/2	0.050 (A+B)/2	0.051 (A+B)/2	0.005 (A-B)/2	0.004 (A-B)/2	0.023 (A+B)/2
Bench offset	0.007 (A-B)/2	0.011 (A-B)/2	0.011 (A-B)/2	0.011 (A-B)/2	0.017 (A-B)/2	0.021 (A-B)/2	0.015 (A-B)/2	0.007 (A+B)/2	0.006 (A+B)/2	0.008 (A-B)/2



$$-M = -X1 + U \quad (1)$$
$$M = U + X2 \quad (2)$$
$$M = (X1 + X2)/2 \quad (3)$$

In the small-offset case, equations (4) and (5) are obtained from the normal- and opposite-side measurements. The subtraction of equations (4) and (5) produces (6), which means the magnet-center offset.

$$-M = -X1 + U \quad (4)$$
$$M = U - X2 \quad (5)$$
$$M = (X1 - X2)/2 \quad (6)$$

The precision of magnet center measurement of this system in horizontal axis is 10 μm.

Test

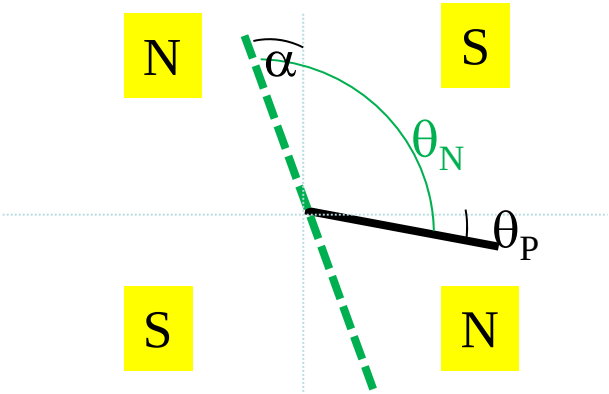
差異<0.01mm

Average offset= 11 μm

STD= 5 μm

The calibration value of RCS unit is 11 μm in the horizontal offset.

Roll Angle Measurement-QM



All symbol is ABS

Normal side: θ_N

Opposite side: θ_O

PCB effective angle: θ_P

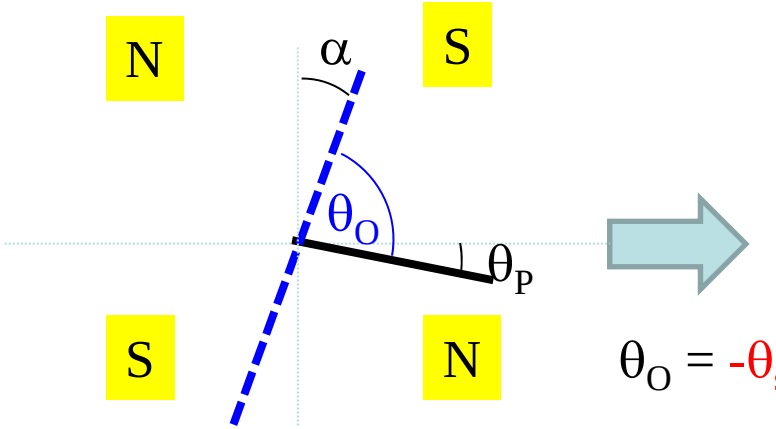
Real angle: θ_s

$$\theta_N = \theta_s + \theta_p \quad \text{------(1)}$$

Normal side of magnet

(1)-(2)

$$\theta_s = (\theta_O+\theta_N)/2$$

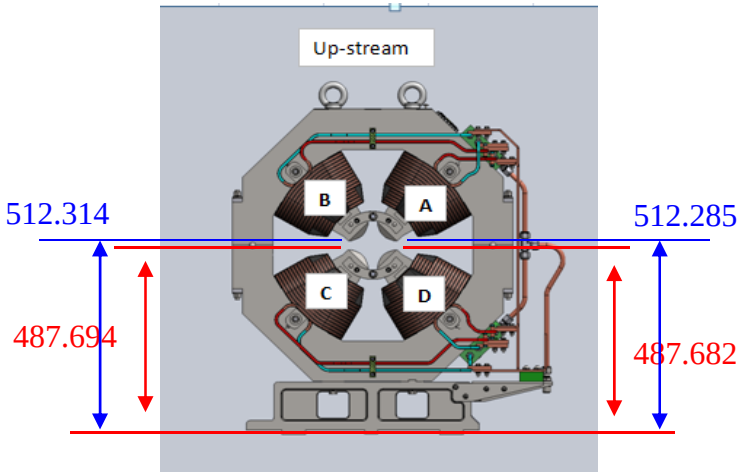


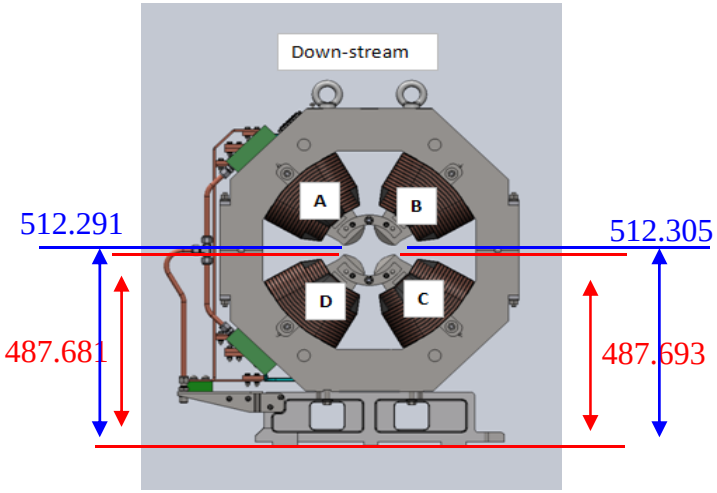
$$\theta_O = -\theta_s + \theta_p \quad \text{------(2)}$$

Opposite side of magnet

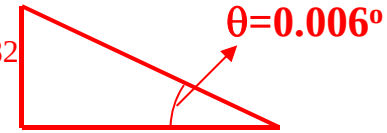
1. The resolution of rotary encoder is 9000.
2. The precision of the roll angle measurement is 0.01°.

Roll Angle measurement by CMM



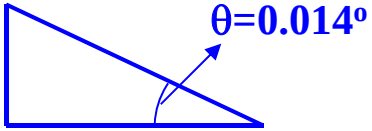


487.694 - 487.682
= 0.012 mm

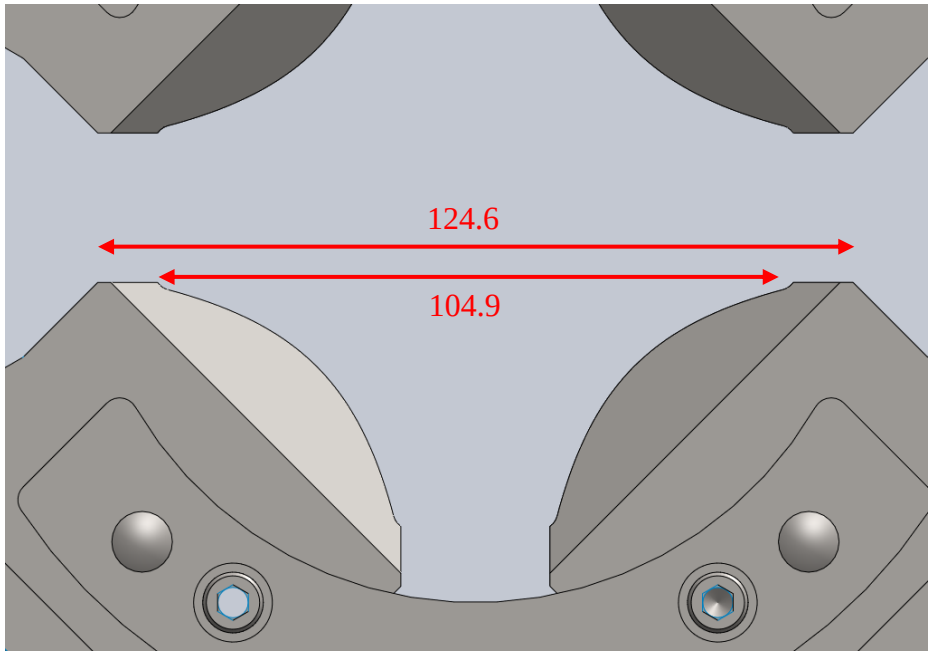


(124.6+104.9)/2
= 114.75mm

512.314 - 512.285
= 0.029 mm



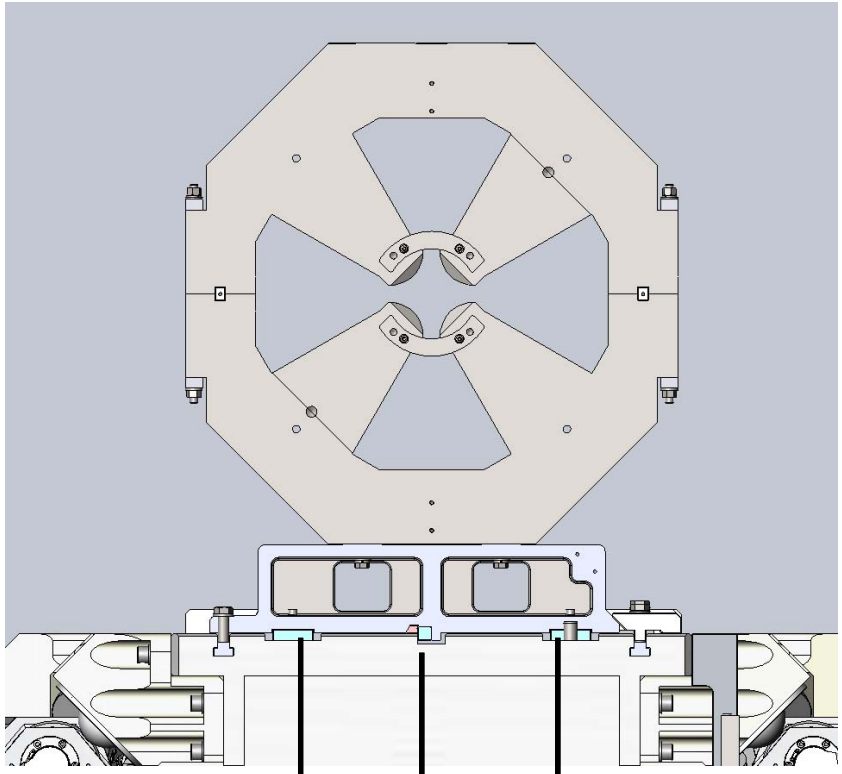
(124.6+104.9)/2
= 114.75mm

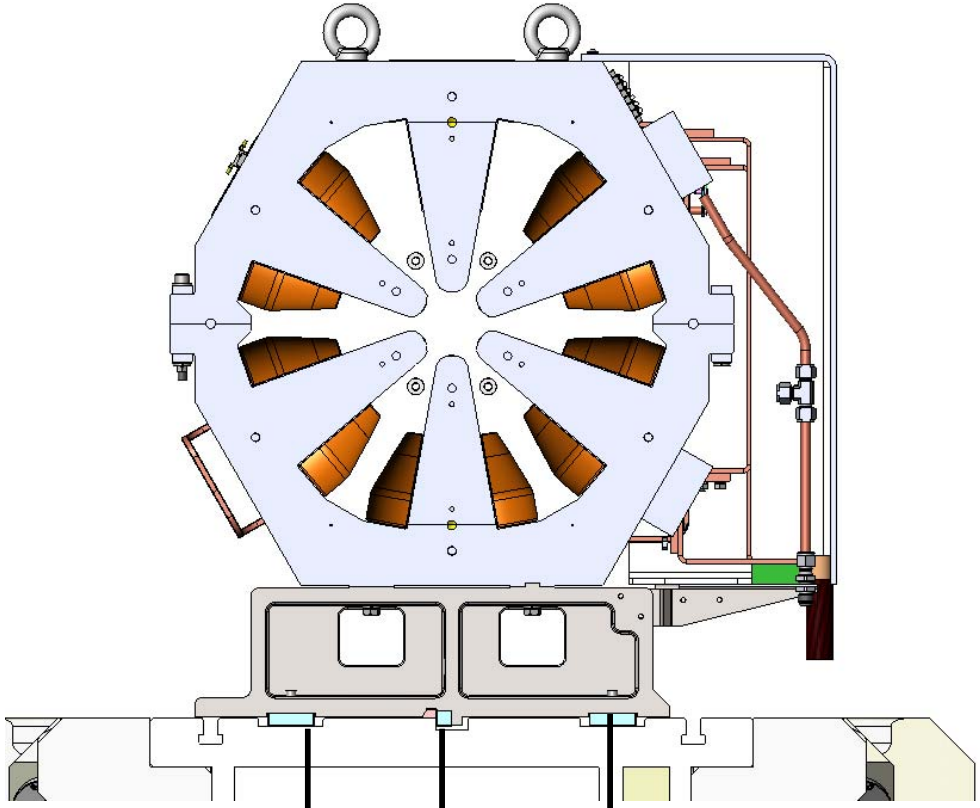


The roll angle of this magnet is 0.01º

Magnet alignment & position check

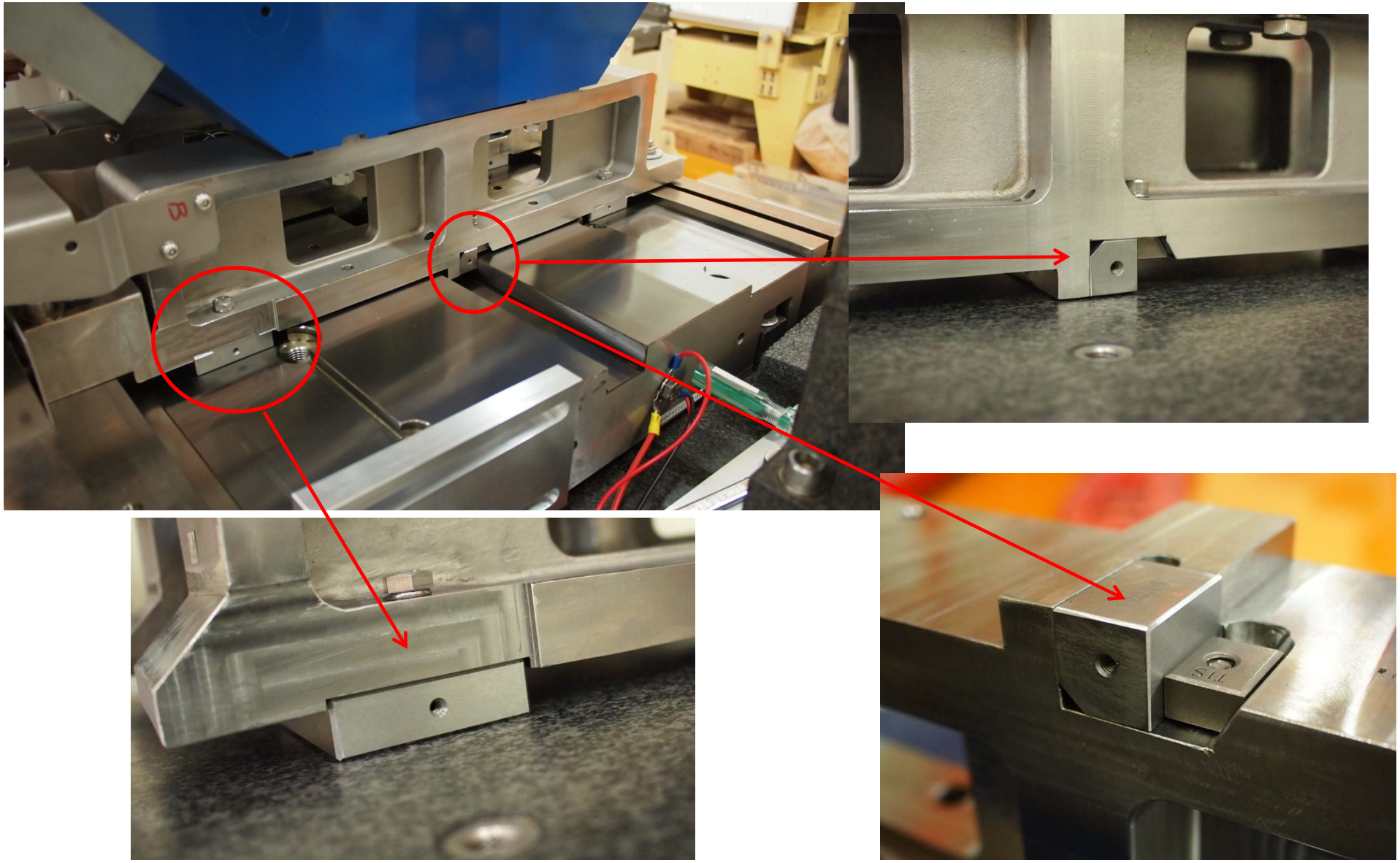
Positioning method of Quadrupole & Sextupole



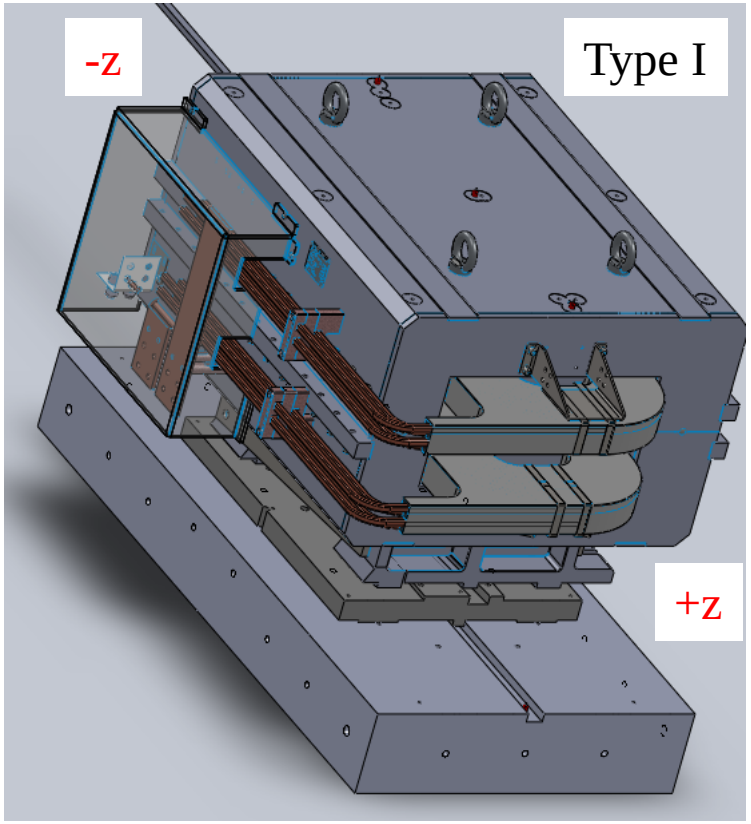


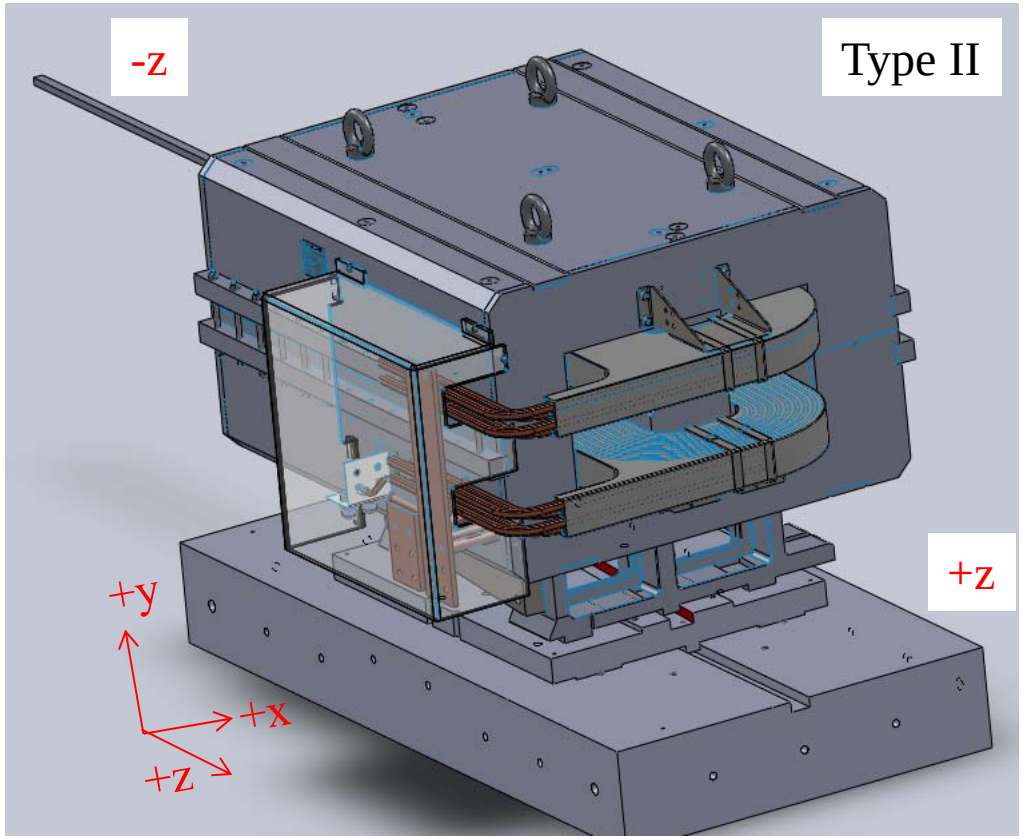
- The positioning precision of this method is within few μm.
- A PSD with laser is used to double check the system position.

Position shimming method of Quadrupole & Sextupole



Positioning method of SR-DM

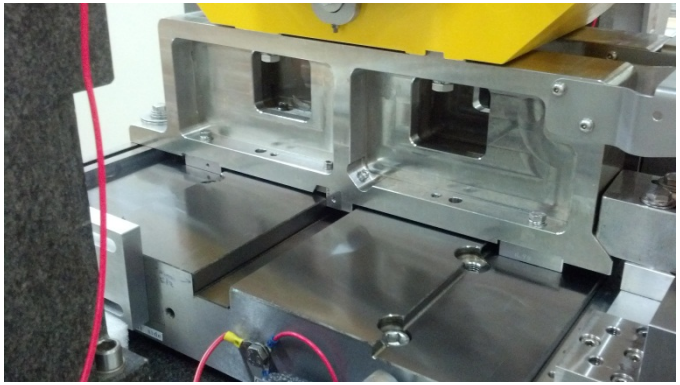


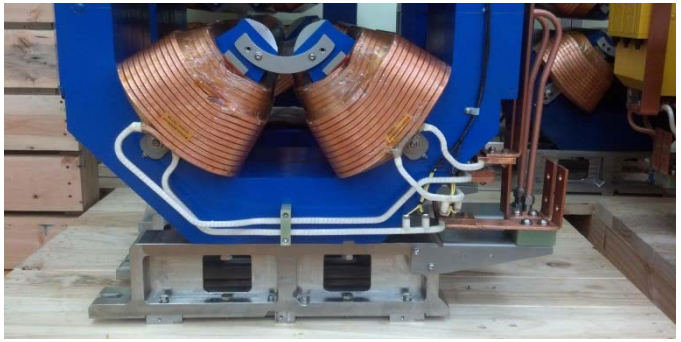


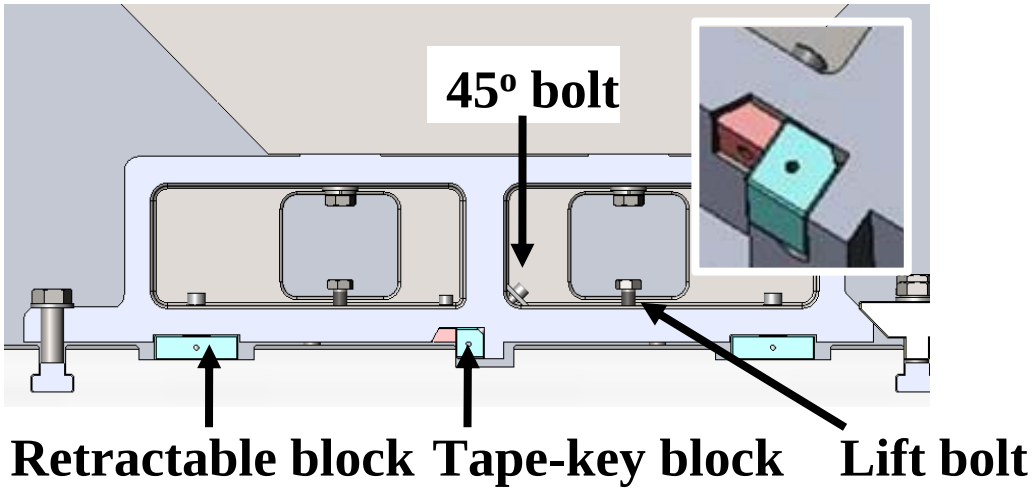
- Two reference plates are for defining the horizontal position and four reference plates are for defining vertical position.
- 45 degree clamper was used to push magnet to touch reference plane and fixed by the torque range tool.
- The positioning precision of this method is also within few μm.

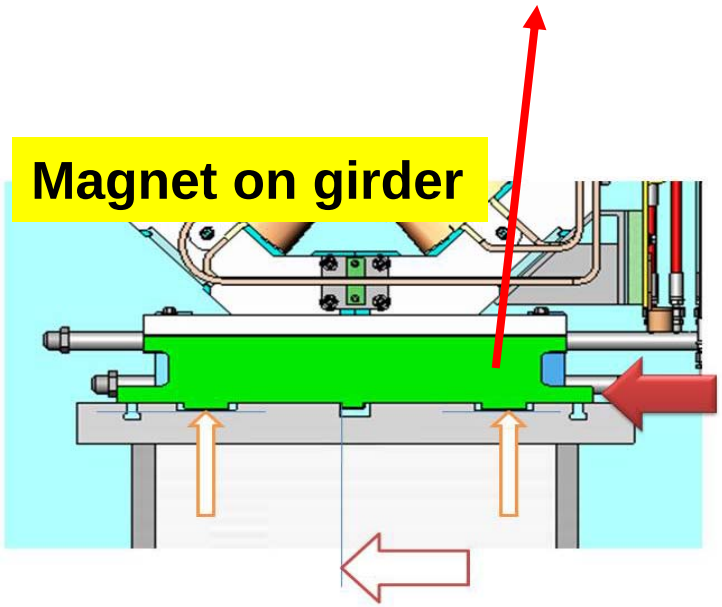
Magnet alignment method

- RCS bench (similar as girder)
- Both side measurement of RCS to indicate the field center of magnet.

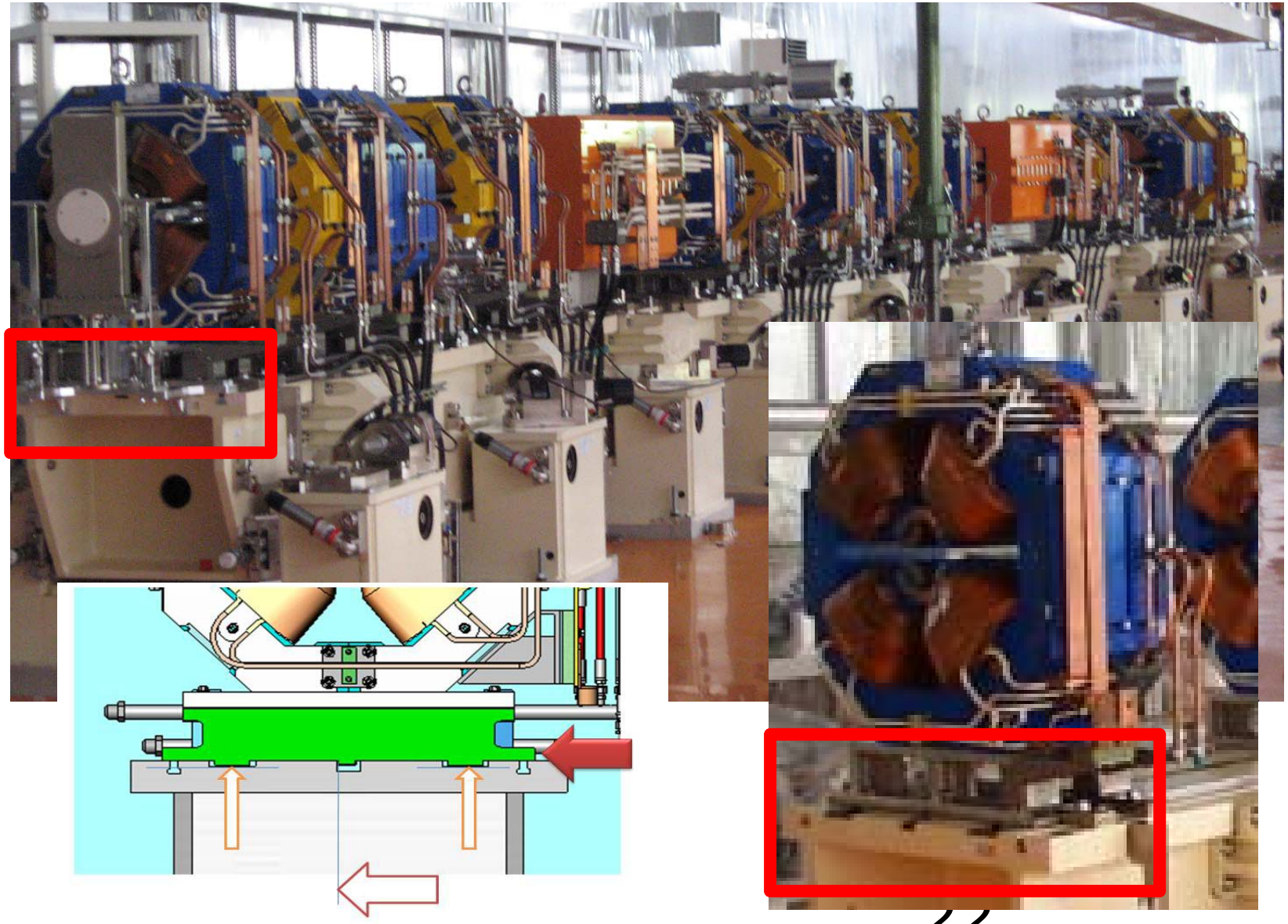






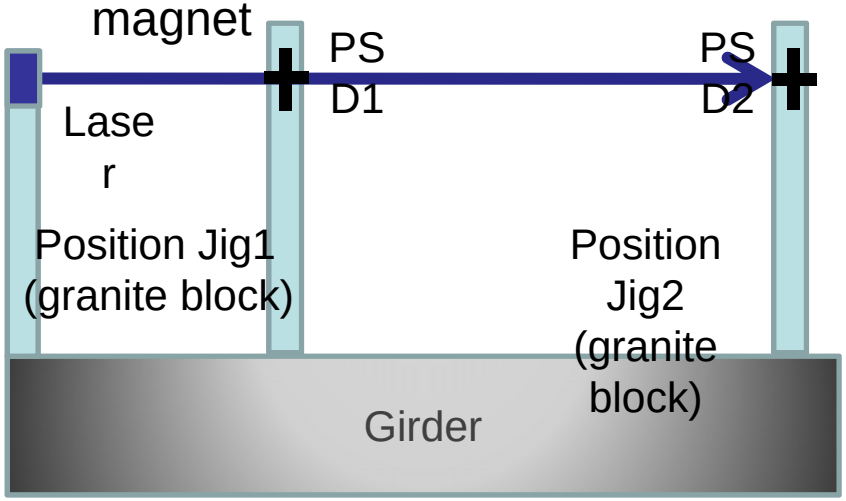


1/24 section magnets

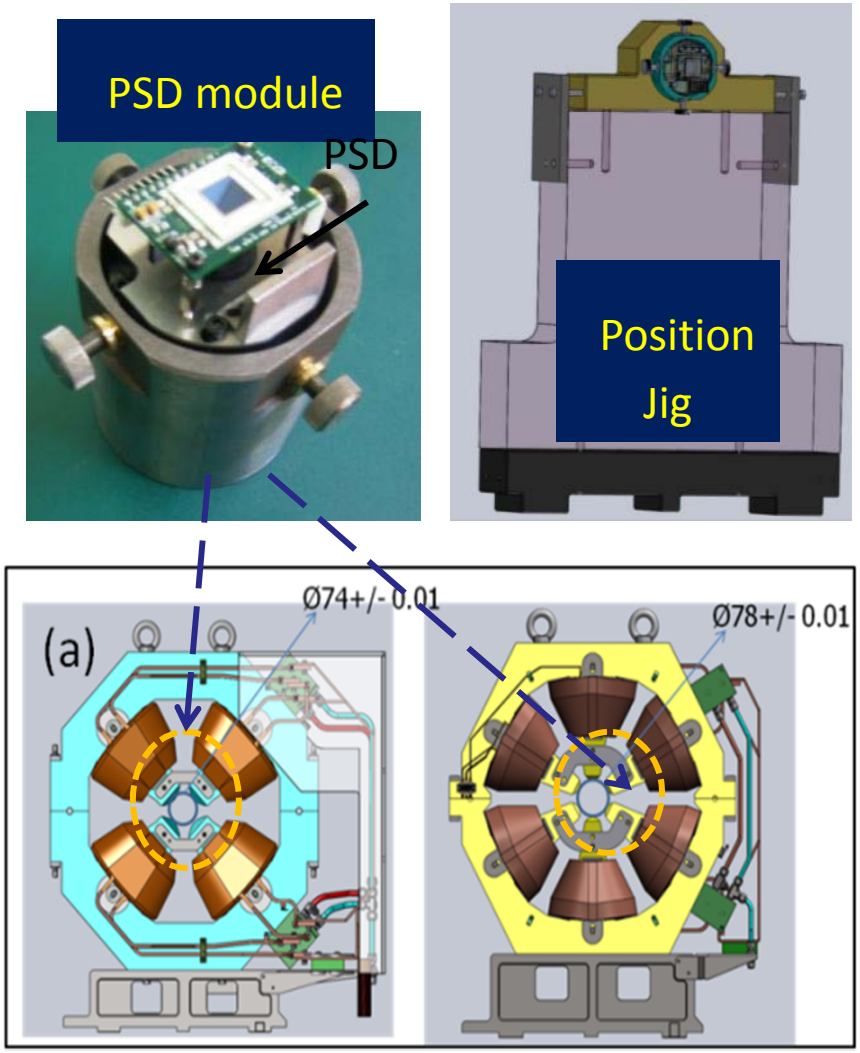


TPS Magnets Alignment Inspection

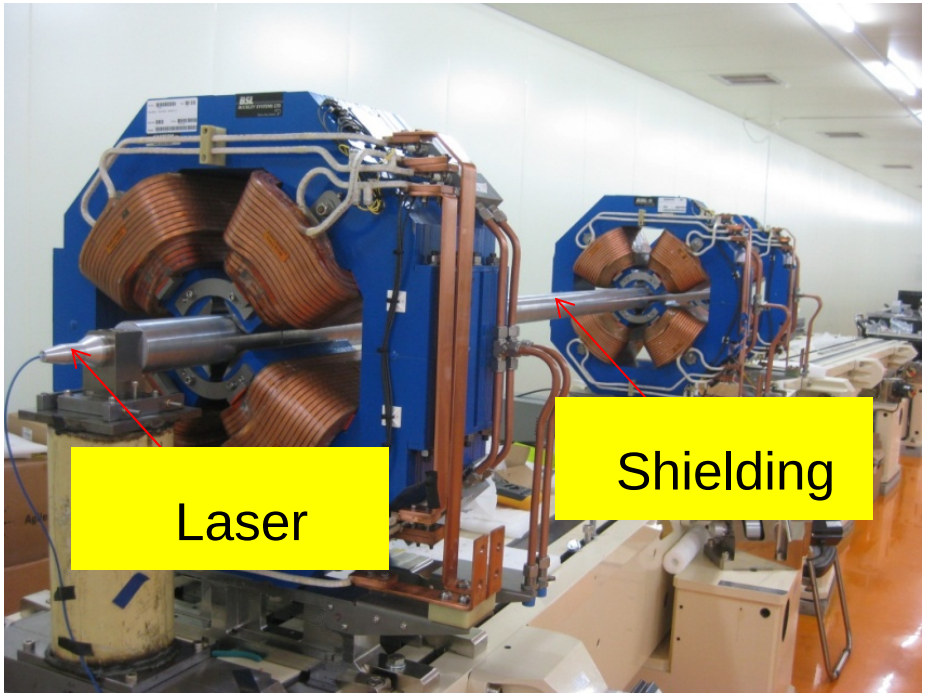
- **A laser positioning system** for TPS magnet alignment inspection is developed.
  - System is composed of a Laser and 2 PSD with 2 granite blocks.
  - PSD module is designed to install in quadrupole and sextupole magnet
  - Position jig is designed to symbolize magnet

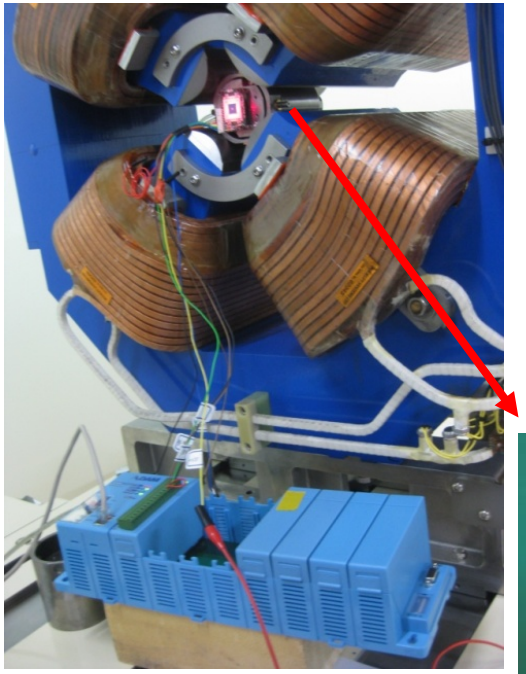


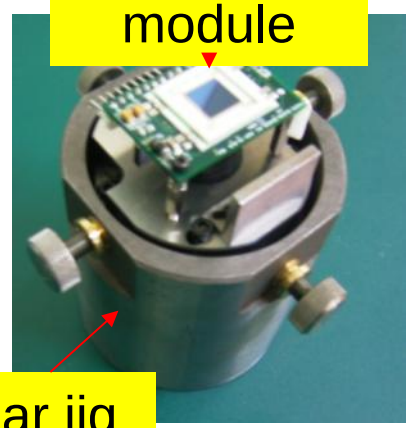
The optical axis of Laser is adjusted to parallel to girder through reference to position jig



Magnets alignment on the girder







- **A PSD module with circular jig was developed to check the magnet center of all magnet in the same girder.**
- **The measurement result was confirmed that all the magnet center is within 30 μm.**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Measurement of Storage ring magnets

SR-magnet specification

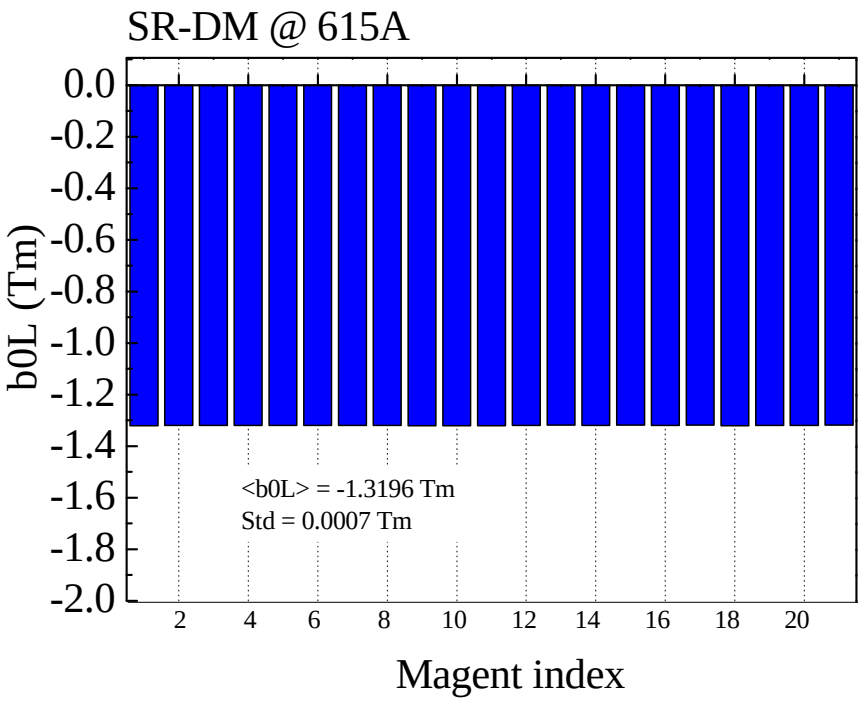
($x10^{-4}$)	SR-DM
n	BnL/B0L
0	10000
1	±3
2	±3
3	±2
4	±3
Normalized at 25mm ● Δb0/b0<1E-4 ● Δb0L/b0L<0.5E-3	

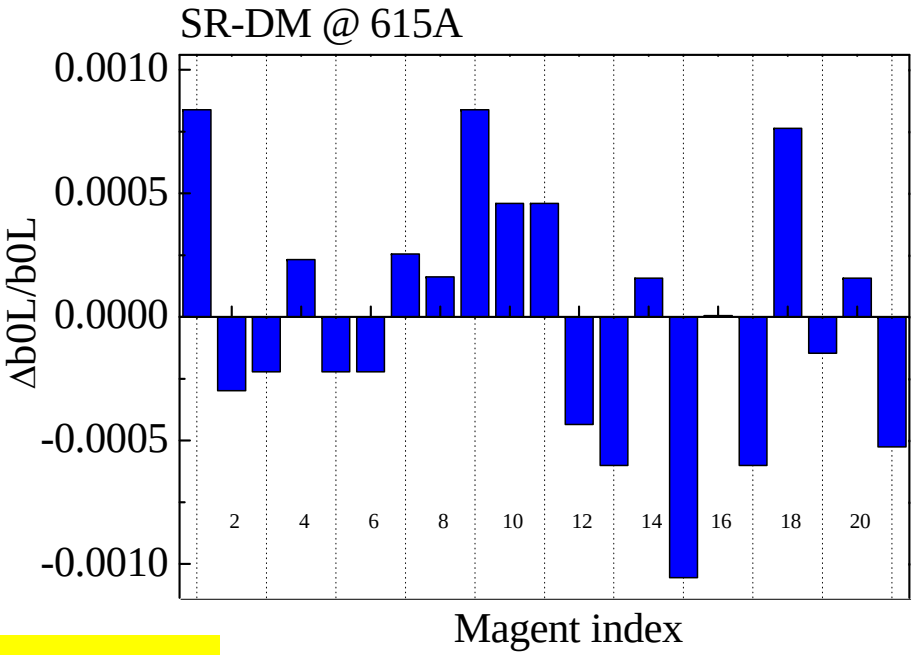
($x10^{-4}$)	SR-QM	
n	BnL/B1L	AnL/B1L
1	10000	-
2	±2	±2.0
3	±2.0	±1.0
4	±0.5	±0.3
5	±0.8	±0.3
6 - 8	±0.3	±0.3
9	±0.3	±0.3
10 - 29	±0.3	±0.3
Normalized at 25mm		

($x10^{-4}$)	SR-SM	
n	BnL/B2L ($x10^{-4}$)	AnL/B2L ($x10^{-4}$)
0	±15	±10
2	10000	-
3	±2	±2
4	±3	±1
5 - 7	±0.5	±0.5
8	±0.5	±0.3
9	±0.3	±0.3
10 - 13	±0.3	±0.3
14	±0.3	±0.3
15 - 29	±0.3	±0.3
Normalized at 25mm		

SR-DM-I and SR-DM-II

Field strength

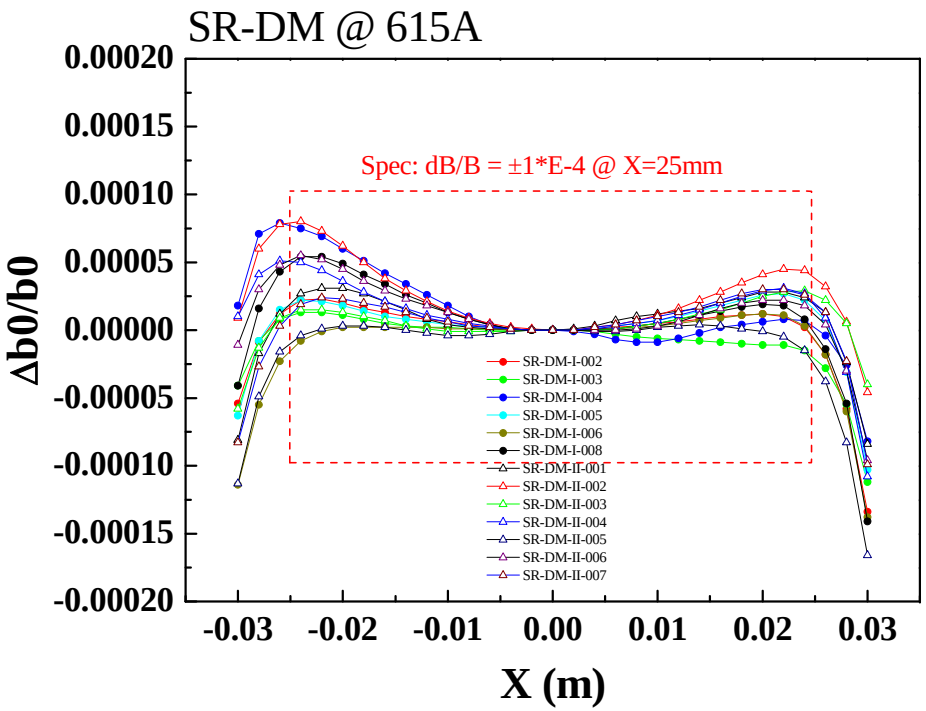


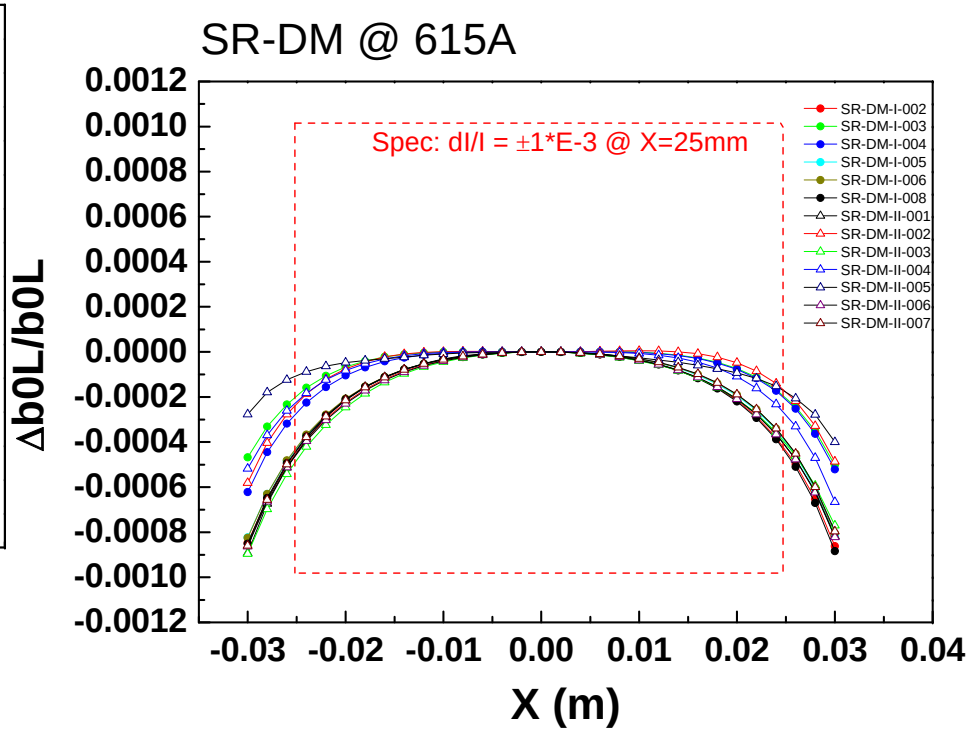


- 21 SR dipole magnets were examined at NSRRC. (50 magnets required)
- The dispersion of b0L is better than 0.11%.

SR-DM-I and SR-DM-II

Homogeneity Δb0/b0 and Δb0L/b0L



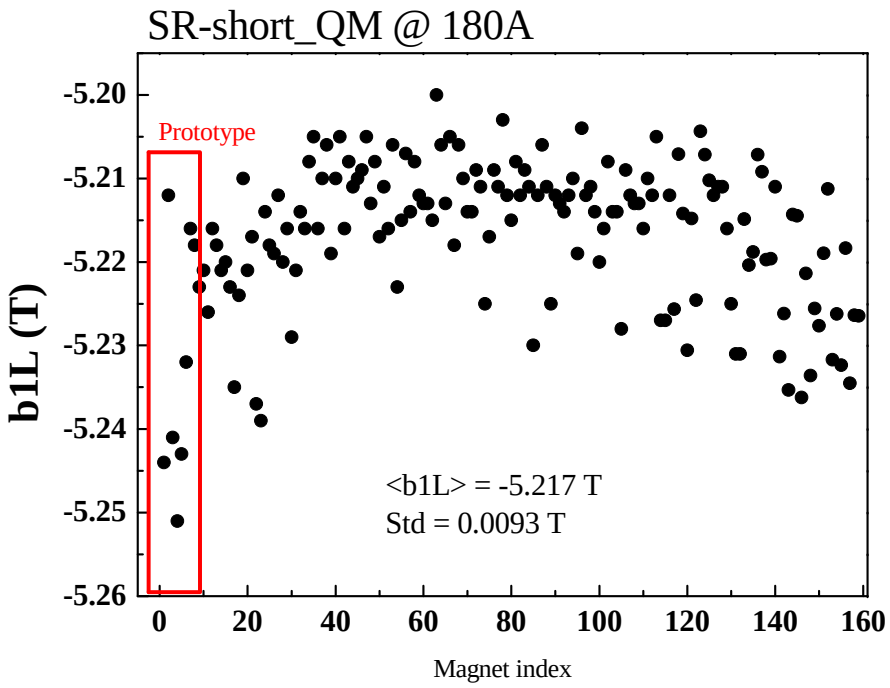


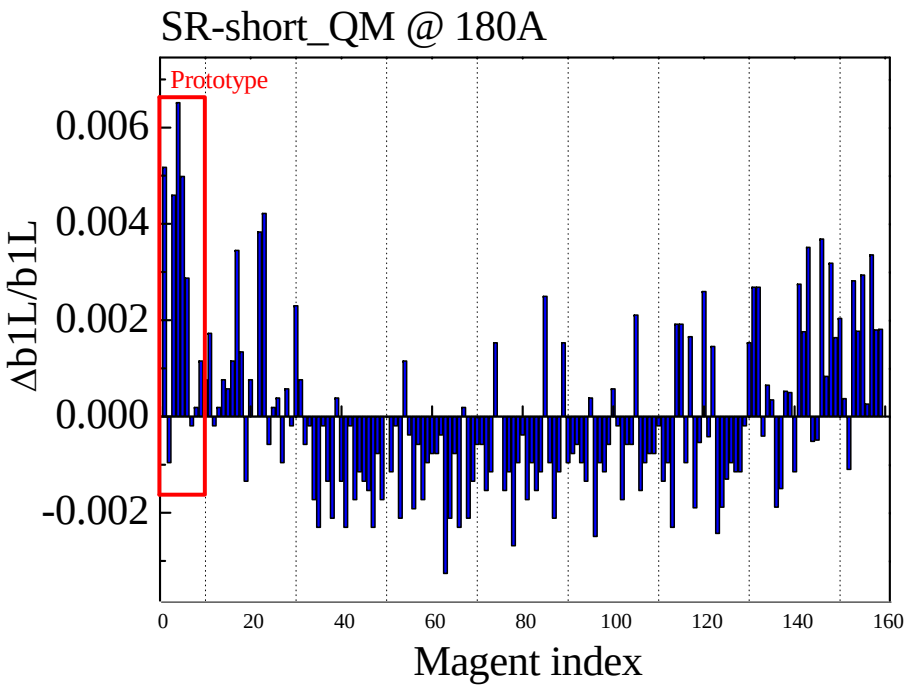
The Δb0/b0 and Δb0L/b0L are meet spec within good field region (GFR).

SR-short QM

Field strength

- 159 SR short-QM magnets were examined at NSRRC until 2013/05/30. (195 magnets required)
- The dediation of b1L will be compensated by independent power supply.



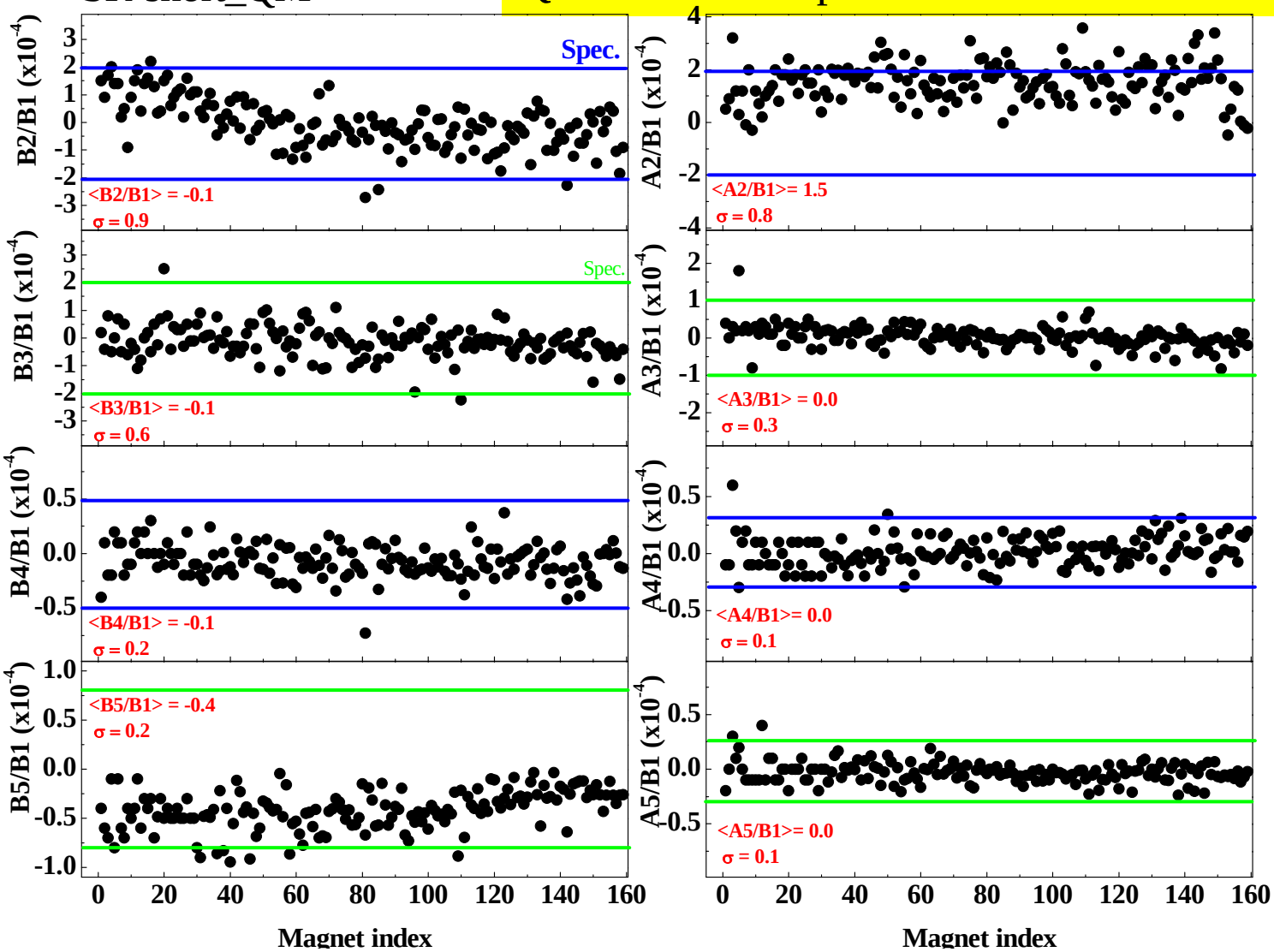


SR-short QM

Normalized multipoles

The mostly normalized multipoles of SR-short QM are within spec.

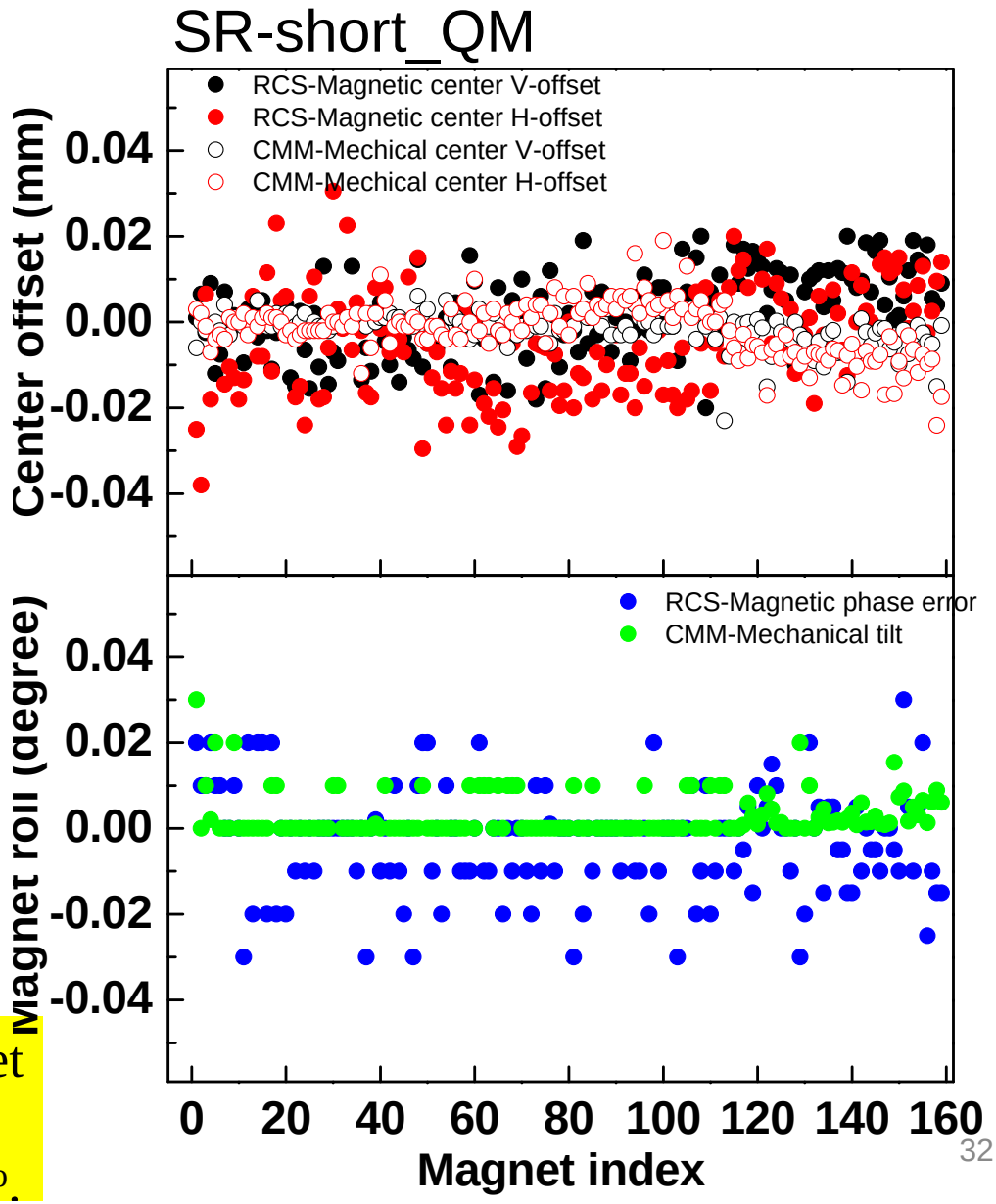
SR-short_QM



SR-short QM

Center offset and roll angle

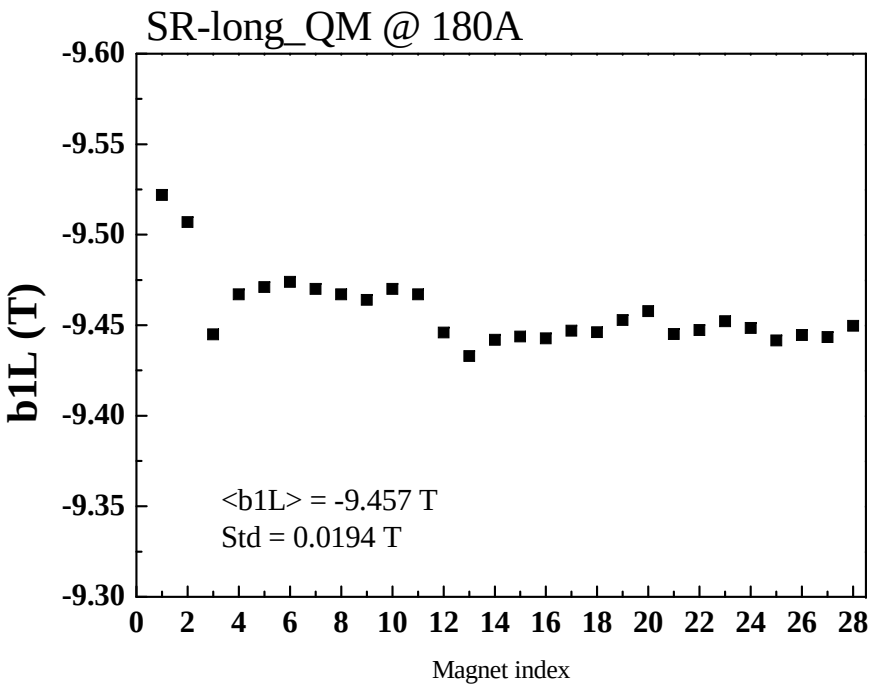
	159 short_QM magnets	
	Mean	**Std. Dev.**
Magnetic center, Vertical-offset (mm)	**0.002**	**0.009**
Magnetic center, Horizontal-offset (mm)	**0.005**	**0.012**
Magnetic Roll angle (degree)	**-0.0063**	**0.012**
Mechanical center V-offset (mm)	**-0.002**	**0.004**
Mechanical center H-offset (mm)	**-0.002**	**0.006**
Mechanical Roll angle (degree)	**0.003**	**0.005**



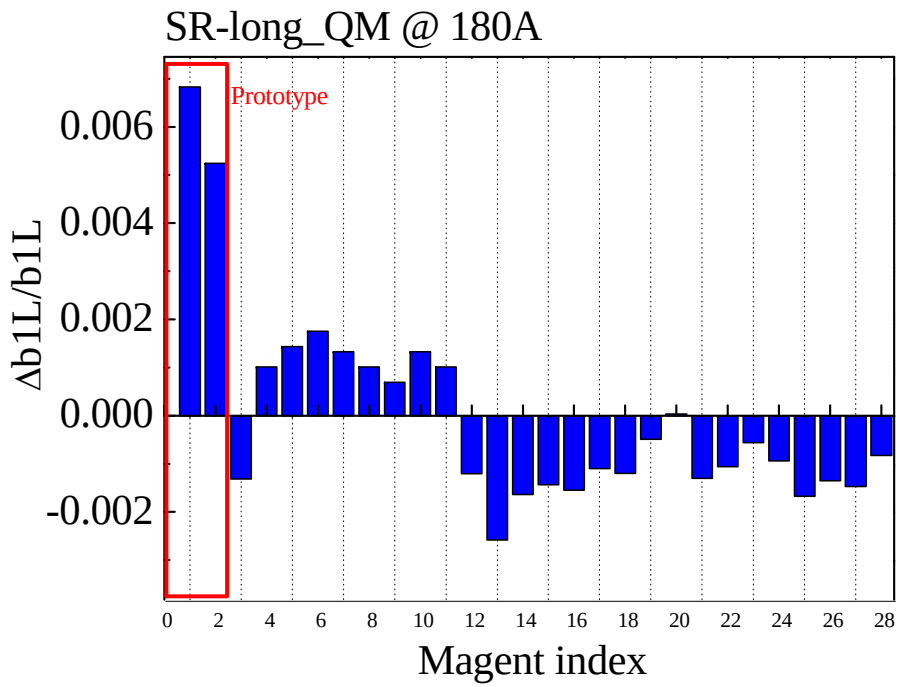
The mean value of magnetic center offset & magnet roll are within 0.01mm in the vertical (horizontal) direction and 0.012°.

SR-long QM

Field strength



- 28 SR long-QM magnets were examined at NSRRC until 2013/05/30. (50 magnets required)
- The prototype magnet have a large field dispersion.

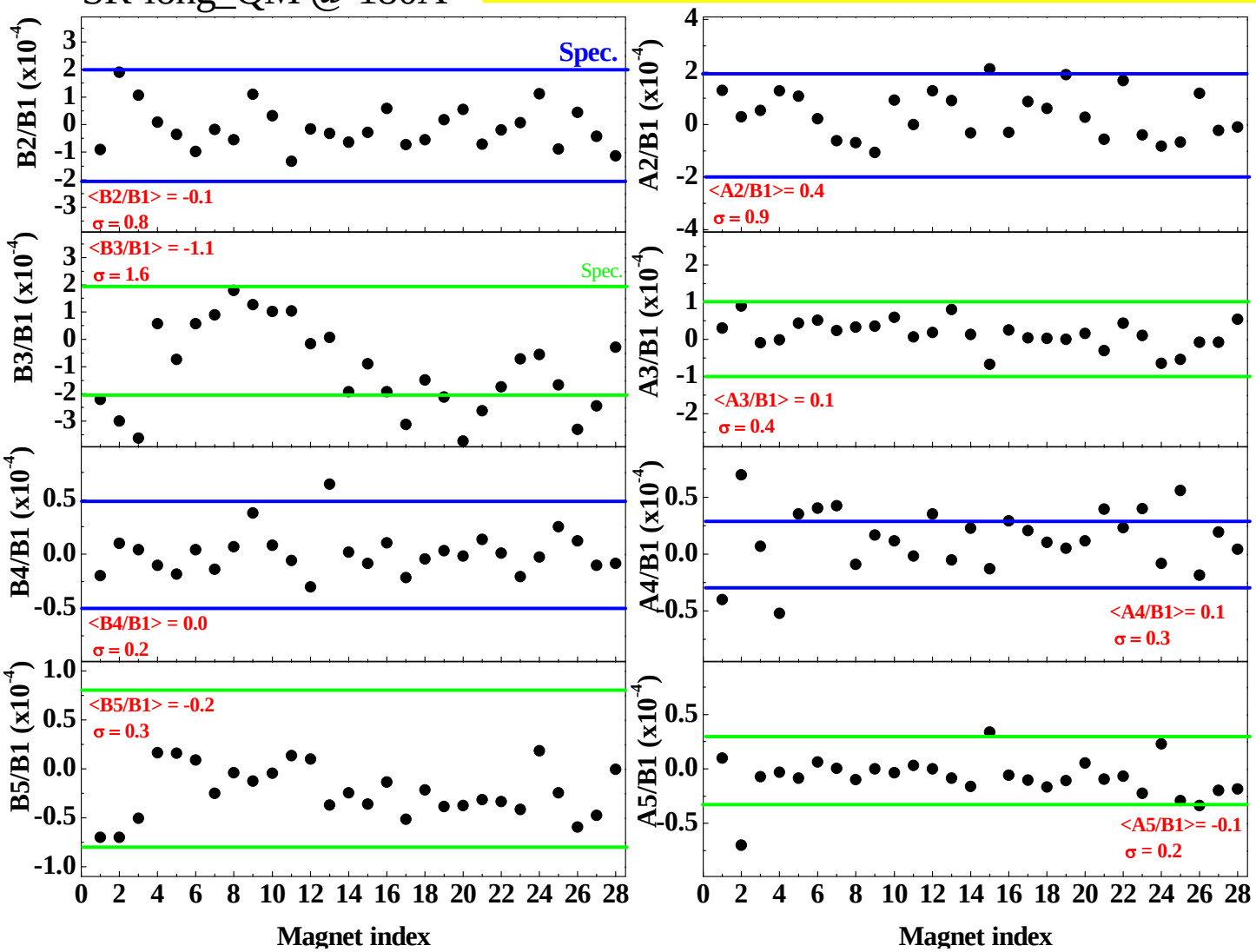


SR-long QM

Normalized multipoles

The mostly normalized multipoles of SR-long QM are within spec.

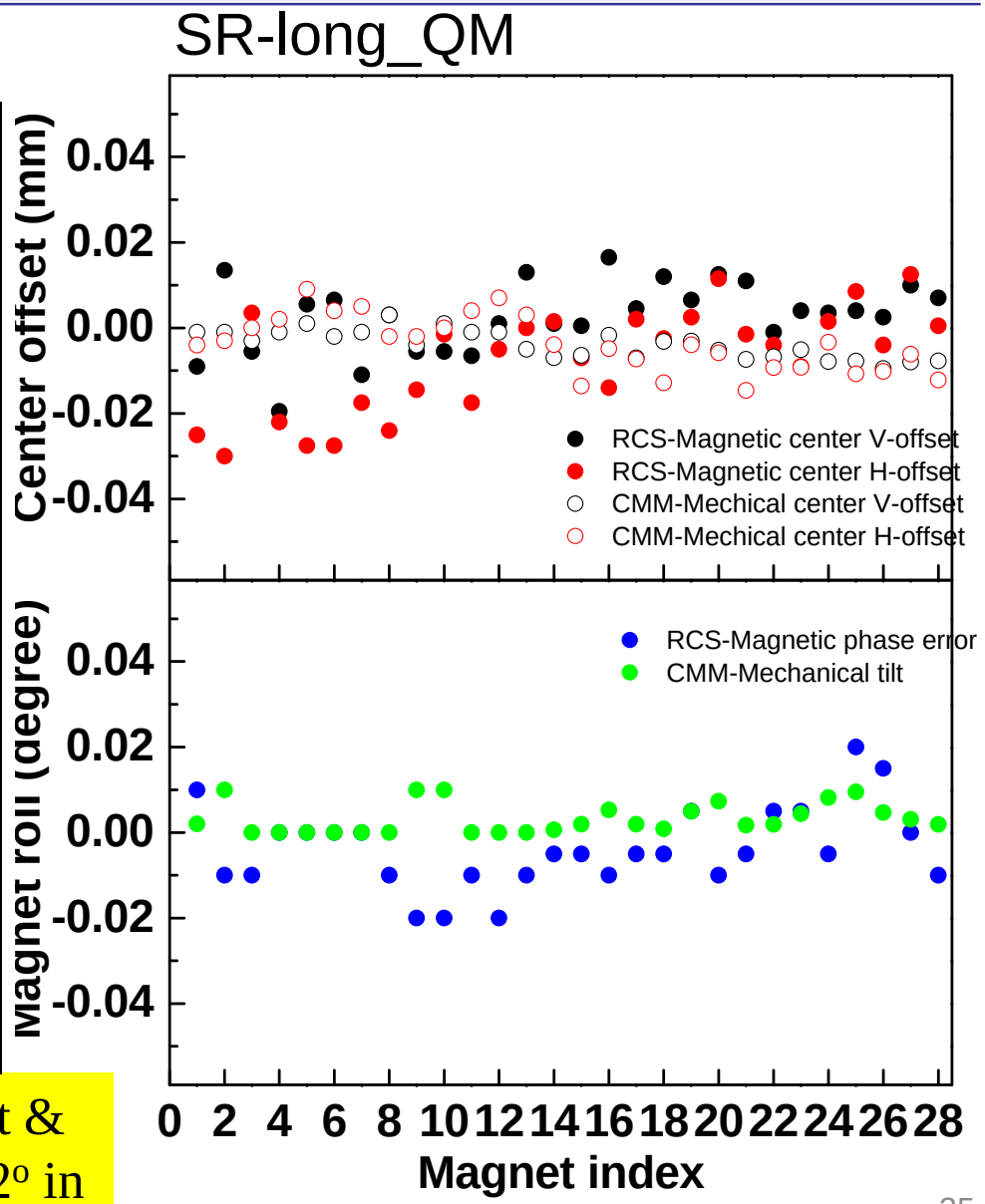
SR-long_QM @ 180A



SR-long QM

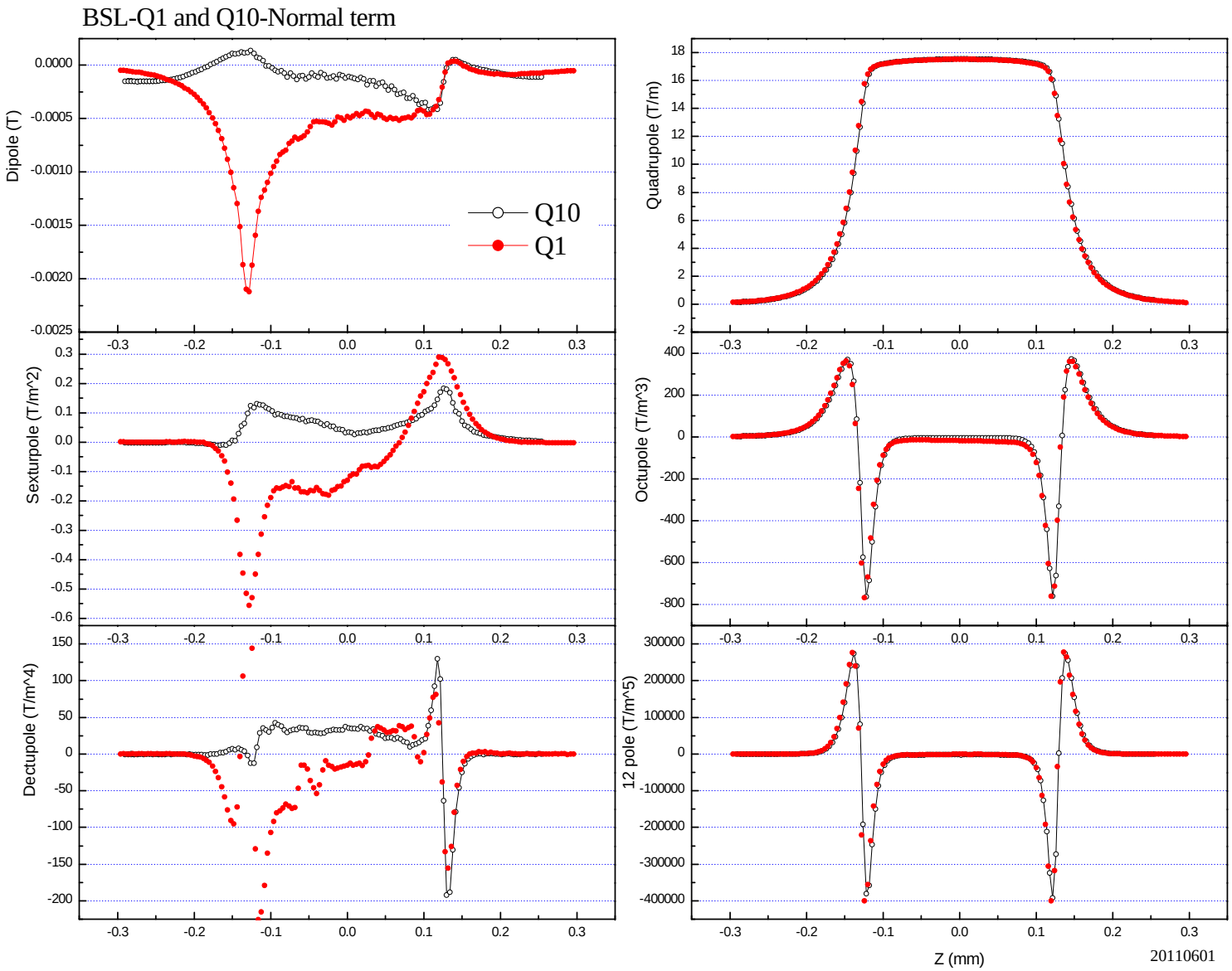
Center offset and roll angle

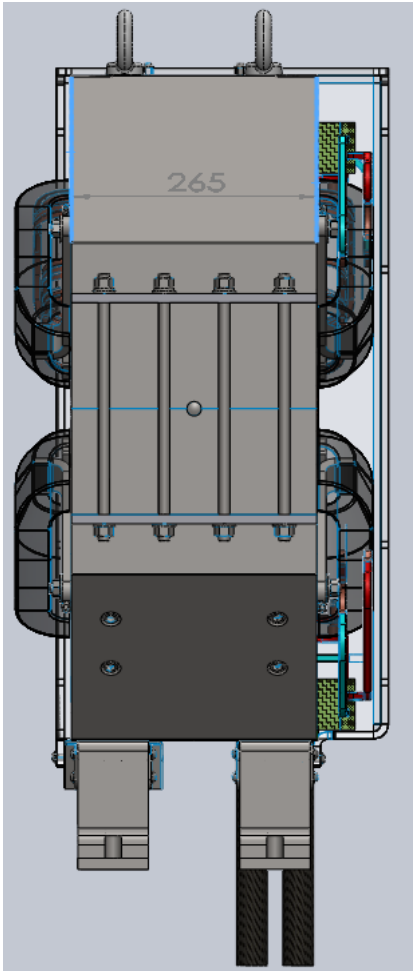
	28 long_QM magnets	
	Mean	Std. Dev.
Magnetic center, Vertical-offset (mm)	0.003	0.008
Magnetic center, Horizontal-offset (mm)	-0.008	0.012
Magnetic Roll angle (degree)	-0.004	0.009
Mechanical center V-offset (mm)	-0.004	0.003
Mechanical center H-offset (mm)	-0.004	0.006
Mechanical Roll angle (degree)	0.003	0.004



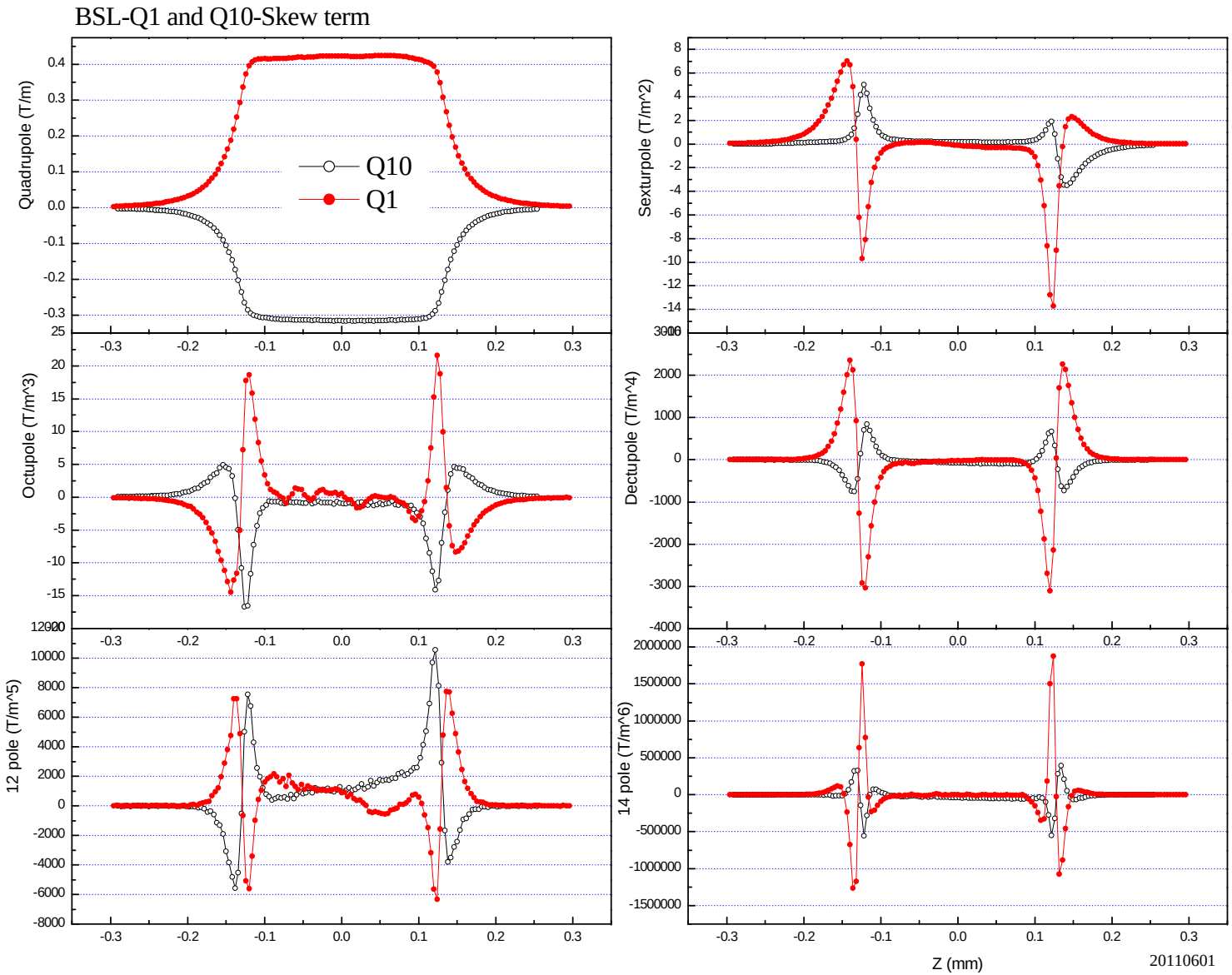
The mean value of magnetic center offset & magnet roll are within 0.01mm and 0.012° in the vertical and horizontal direction.

Multipoles distribution of Q-magnet along Z-axis





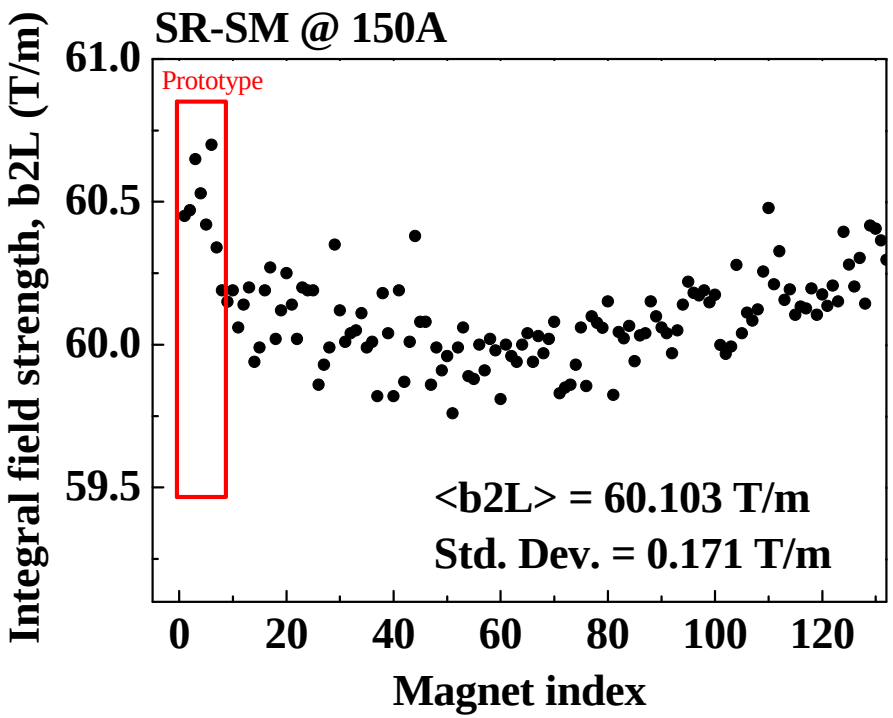
Multipoles distribution of Q-magnet along Z-axis



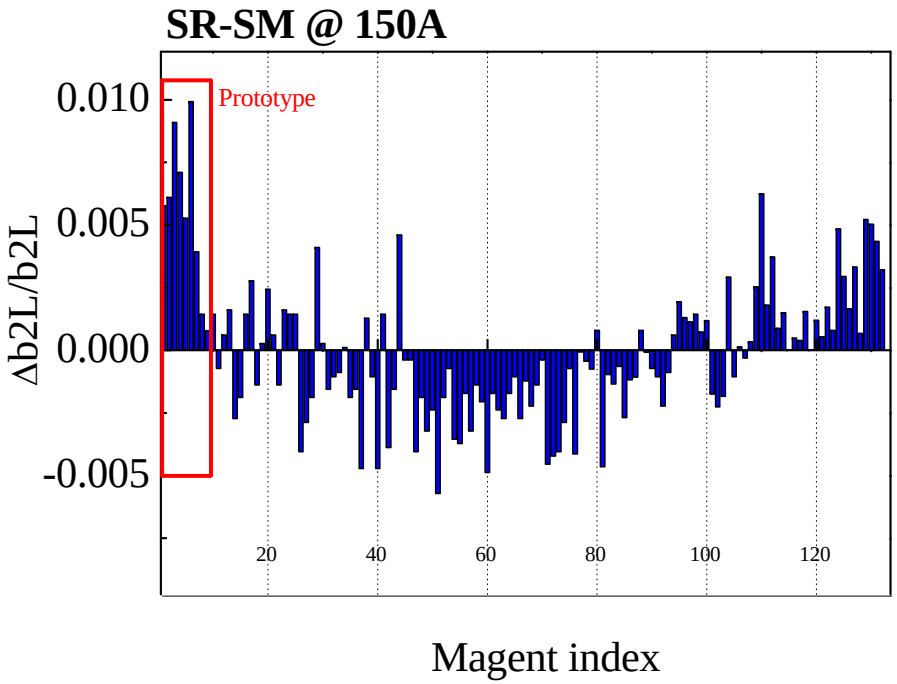
- Exact Skew quadrupole term can be obtained after the angle calibration of Hall probe.

SR-Sextupole Magnet (SM)

Field strength



- 132 SR-SM magnets were examined at NSRRC until 2013/05/30. (174 magnets required)
- The large dispersion is dominated by prototype magnet.

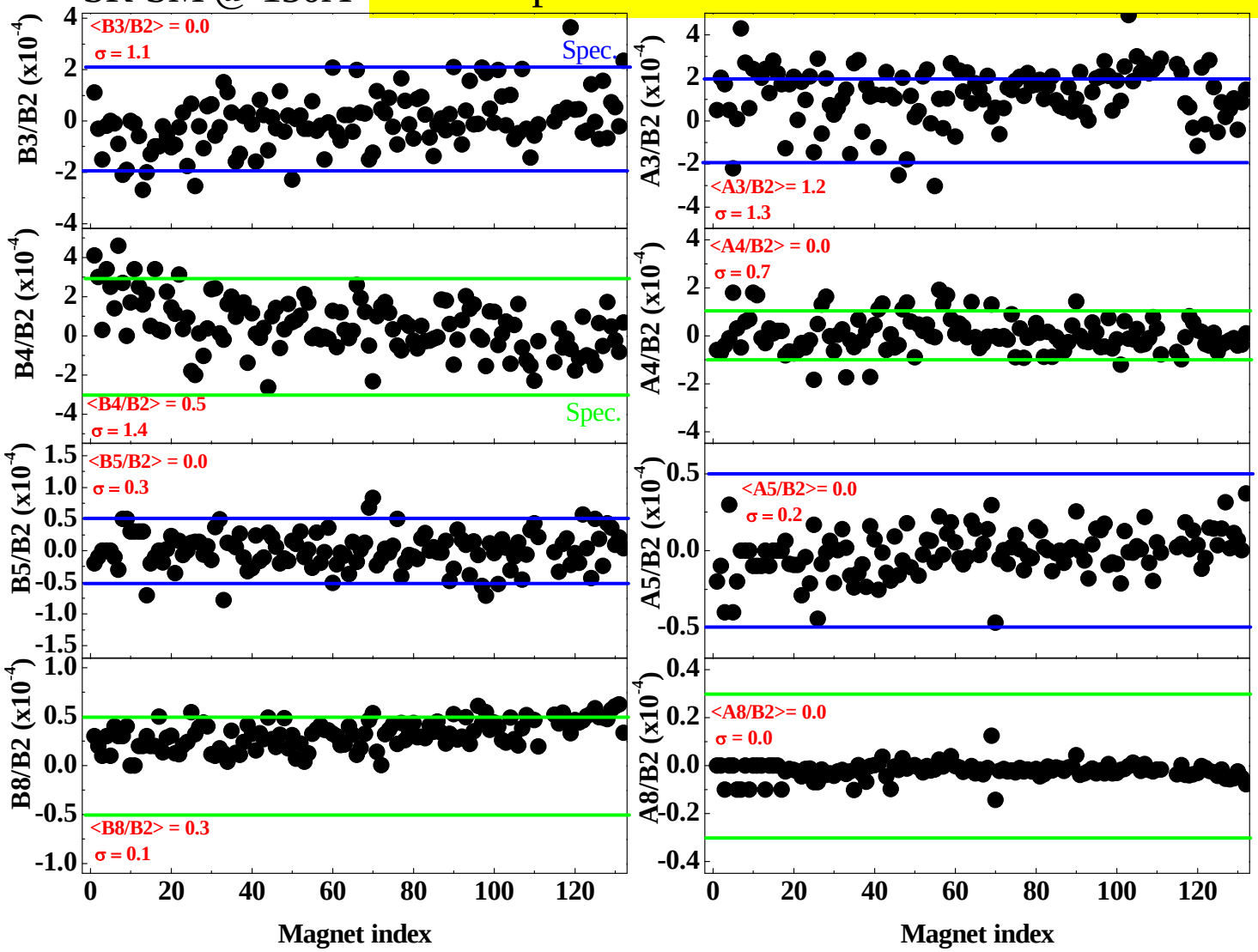


SR-SM

Normalized multipoles

The mostly normalized multipoles of SR-SM are within spec.

SR-SM @ 150A

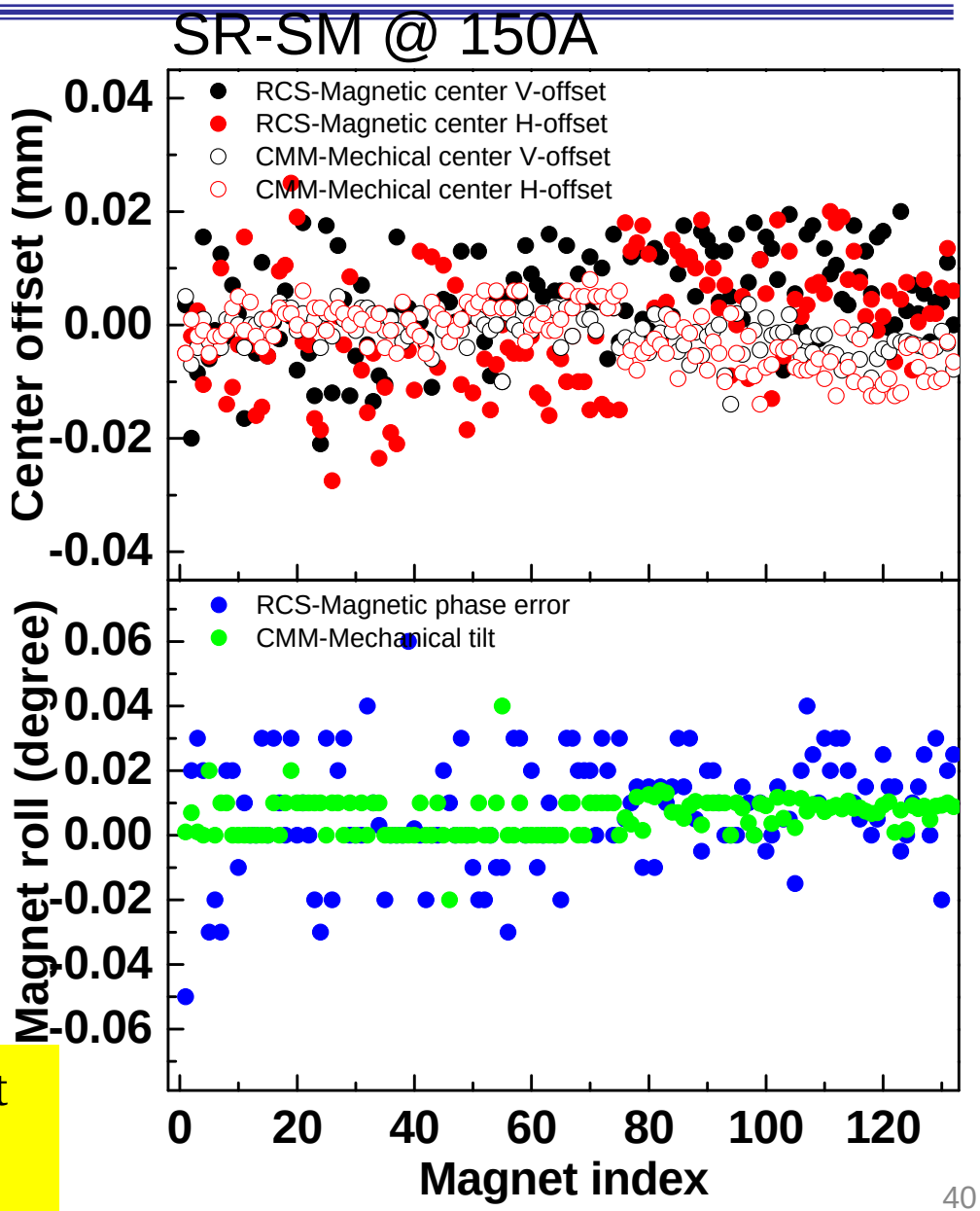


SR-SM

Center offset and roll angle

	132 SM magnets	
	Mean	Std. Dev.
Magnetic center, Vertical-offset (mm)	0.004	0.009
Magnetic center, Horizontal-offset (mm)	0.000	0.011
Magnetic Roll angle (degree)	0.008	0.017
Mechanical center V-offset (mm)	-0.001	0.003
Mechanical center H-offset (mm)	-0.002	0.005
Mechanical Roll angle (degree)	0.006	0.006

The mean value of magnetic center offset & roll are within 0.011mm in the vertical (horizontal) direction and 0.017°.



Measurement of Booster ring magnets

BR-magnet specification

x10^{-4}	BR-DM
n	BnL/B0L
0	10000
1	*
2	**
3	±3
4	±2

Normalized at 15mm
- Δb0/b0<5E-4
- Δb0L/b0L<0.5E-3

*b1L/b0L= -2.1043
**b2L/b0L= -7.5331

x10^{-4}	BR-Pure QM	
n	BnL/B1L	AnL/B1L
1	10000	-
2	±4	±10
3	±4	±2
4	±1	±1.5
5	±3	±0.5
6-7	±1	±0.5
8	±0.5	±0.5
9	±4	±0.5
10-12	±0.5	±0.3
13	±1.5	±0.5
14-16	±0.5	±0.3
17	±1.7	±0.5
18-20	±0.3	±0.3

Normalized at 15mm

x10^{-4}	BR-combined QM	
n	BnL/B1L	AnL/B1L
1	10000	-
2	-	-
3	±4	±2
4	±4	±1
5	±2	±0.5
6	±1	±1
7	±1	±0.5
8	±5	±0.5
9	±2	±0.5
10	±4	±0.5
11	±0.5	±0.5
12-13	±2	±0.3
14-17	±0.5	±0.3
18-19	±0.3	±0.3
20	±0.5	±0.3

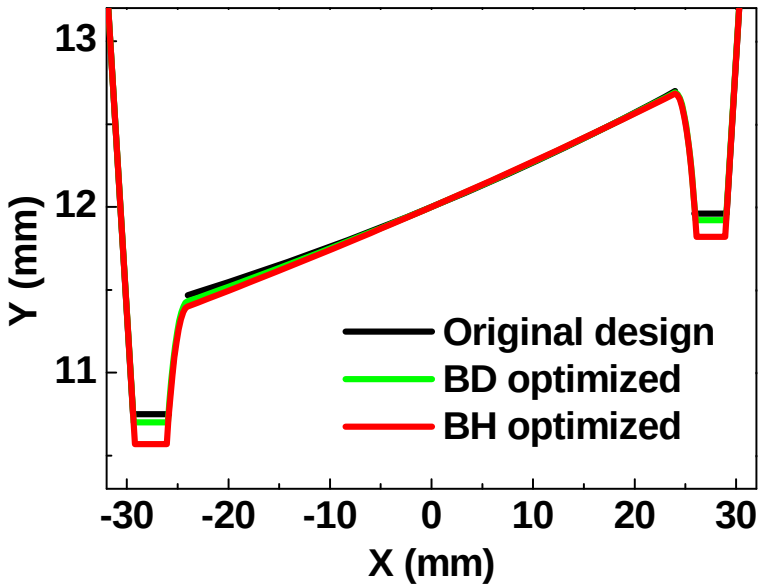
Normalized at 15mm
- b2L/b1L=1.145

x10^{-4}	BR-SM	
n	BnL/B2L	AnL/B2L
0	±45	±30
2	10000	-
3	±15	±6
4	±9	±6
5-7	±3	±1.5
8	±10	±1.5
9-13	±3	±1.5
14	±6	±1.5
15-20	±3	±0.6

Normalized at 15mm

BR-combined function dipole magnet

Homogeneity of BR-BH-001 and BR-BD-002 magnets

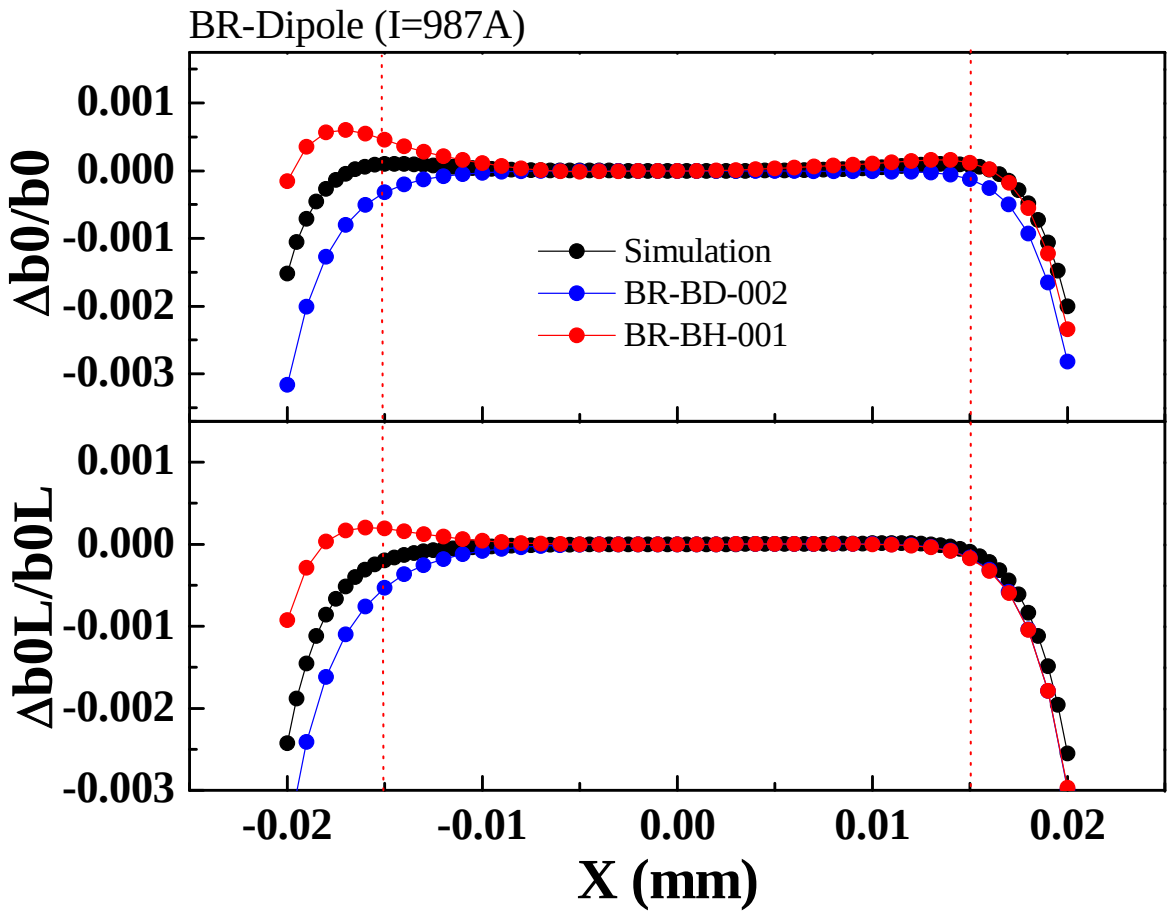


- Increase the slope of pole profile to increase the quadrupole component.
- Cancel the end-chamfer of pole.
- Yoke length of BH dipole magnet reduce 4 mm from 758 mm to 754 mm.

Magnet	Items	b1L/b0L		b2L/b0L	
		Design	Measure	Design	Measure
	Spec.	-2.1043	-	-7.5331	-
BD (1.6m)	Original simulation	-2.0365	-2.049	-7.5524	-8.480
	Optimized simulation	-2.1041	-	-7.6129	-
BH (0.8m)	Original simulation	-1.9758	-	-7.1151	-
	Optimized simulation	-2.1050	-	-7.7164	-

BR-combined function dipole magnet

Homogeneity of BR-BH-001 and BR-BD-002 magnets

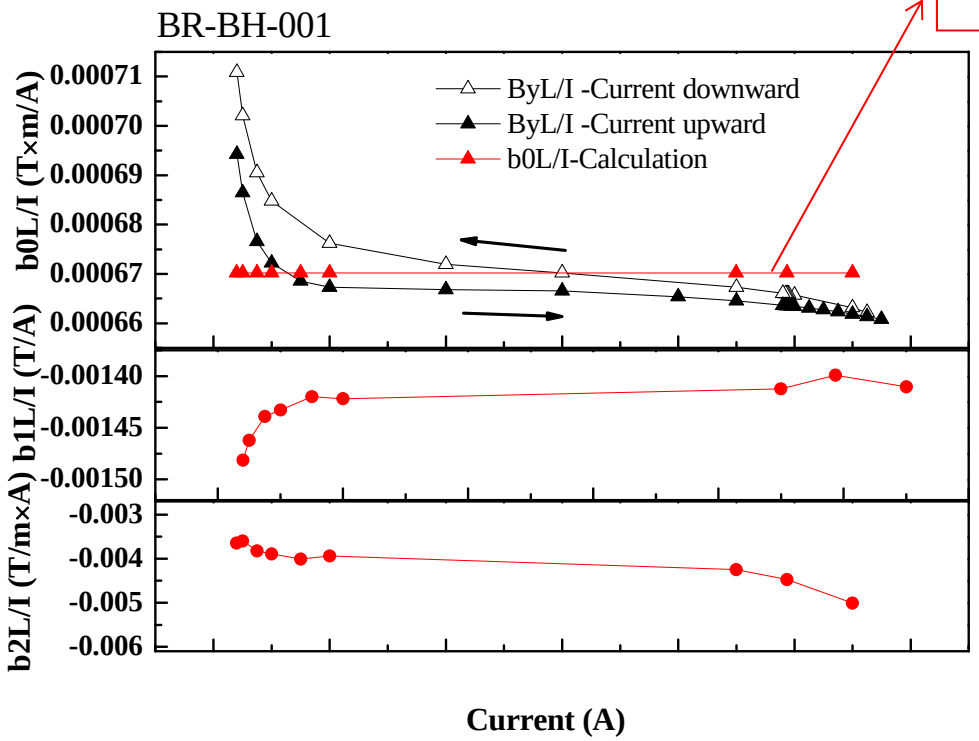


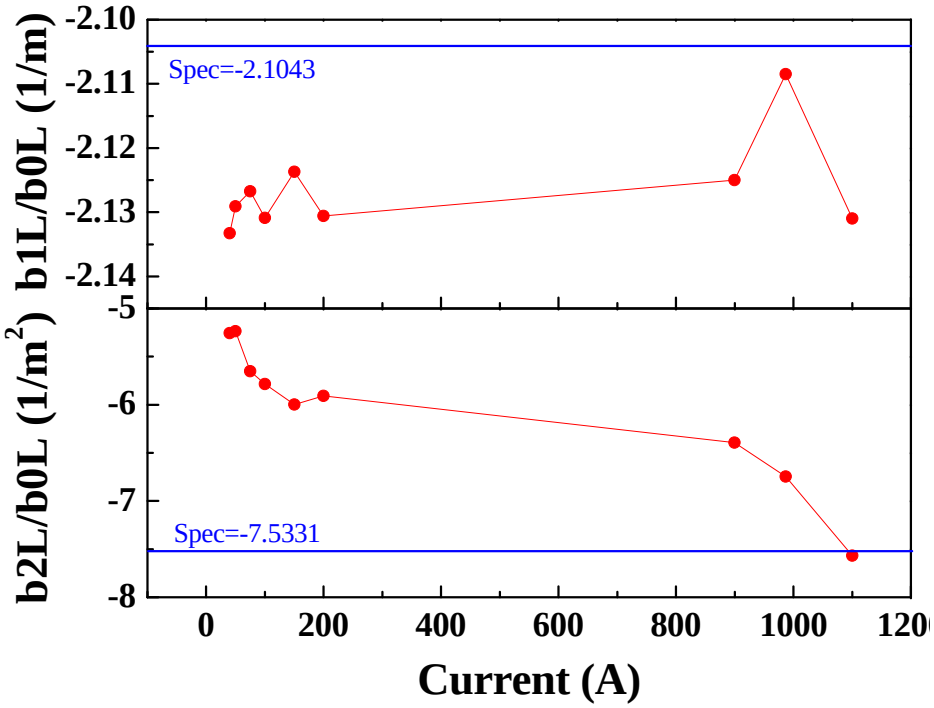
- The Δb0/b0 of BR-BH-001 and BR-BD-002 is better than 4.5×10^{-4} and -3.0×10^{-4}, respectively
- The Δb0L/b0L of BR-BH-001 and BR-BD-002 is better than 1.9×10^{-4} and -5.3×10^{-4}, respectively.

BR-combined function dipole magnet

Field strength

$$\frac{b0L}{I} = \left(\frac{\mu_0 N}{g + \frac{L}{\mu_r}} + B_r\right) \times L_{eff}$$

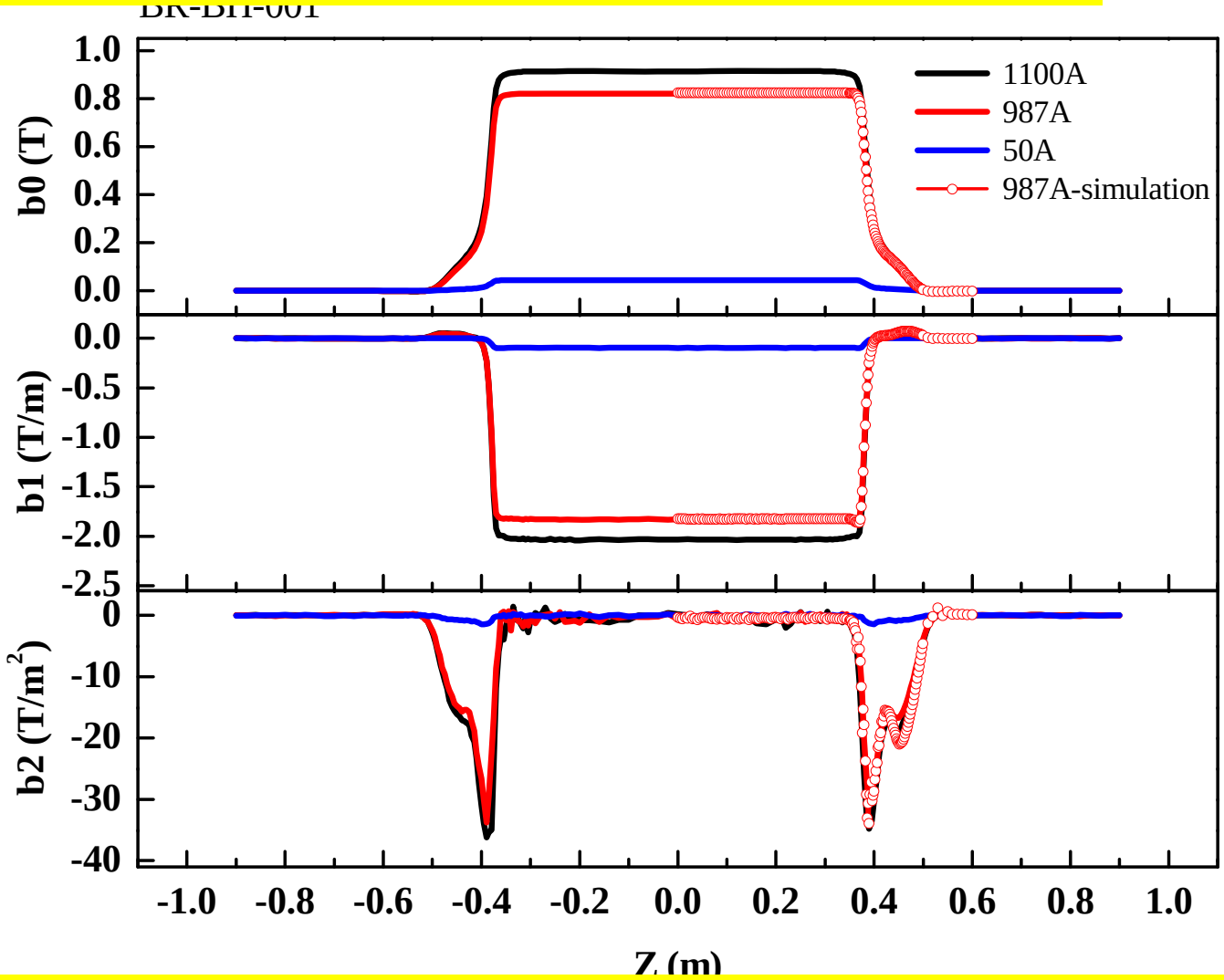




- The measurement of ByL/I is confirmed by the calculated value with ignore μ_r and B_r between 100 A to 900 A.
- The ByL/I of BR-BH-001 magnet has clearly increasing is due to the remnant field effect in the low current.
- The ByL/I of BR-BH-001 magnet has slowly decreasing is due to the yoke situation over 900A.

BR-combined function dipole magnet

Combined multipoles along electron-beam trajectoy (Z-axis)

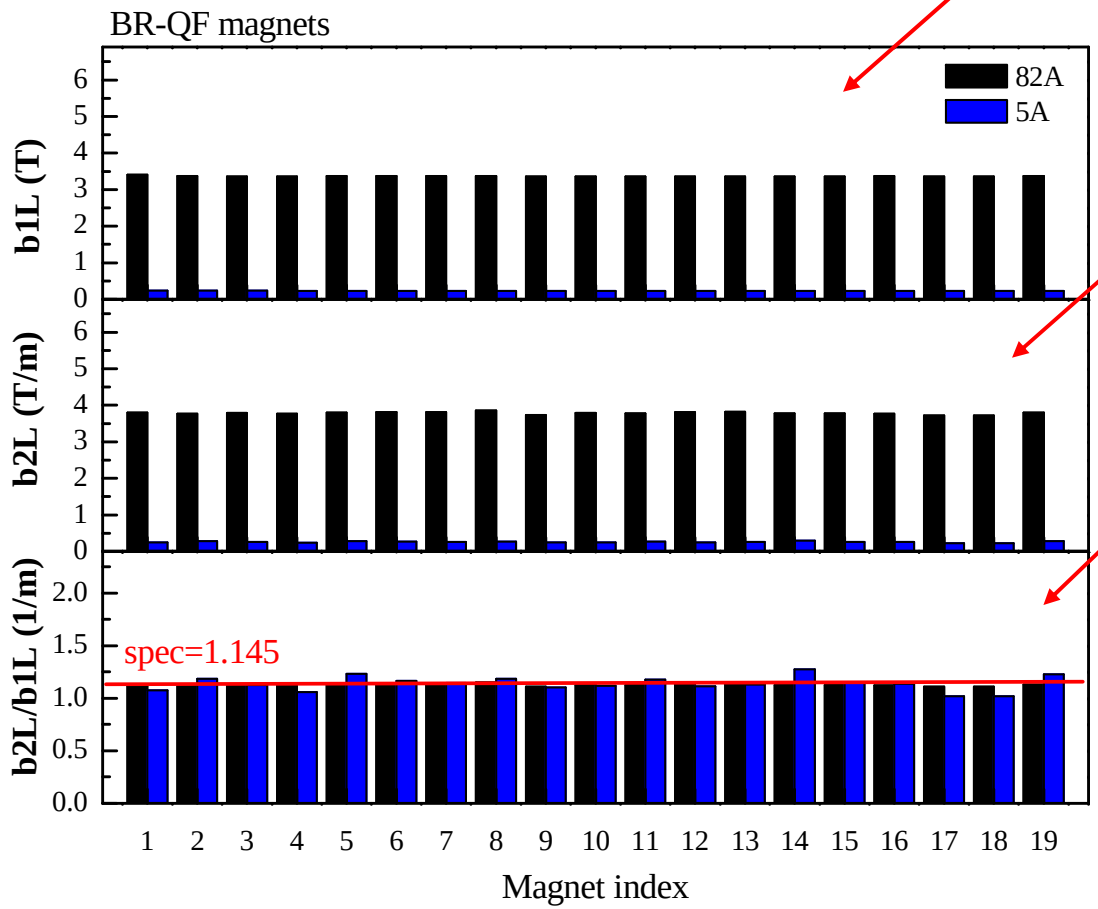


The multipole distributions of measurement are agreement with the simulation result.

Combined function quadrupole magnet

Field strength: Pre-measurement at vendor site

<b1L> @ 82A = 3.3647 T , Std @ 82A = 0.0032T
<b1L> @ 5A = 0.2280 T , Std @ 5A = 0.0004T



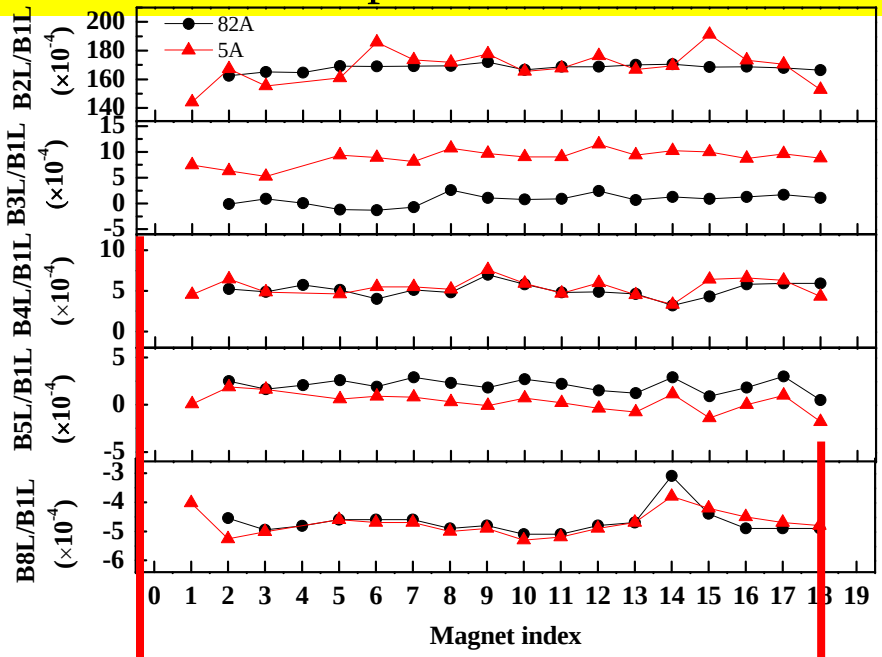
<b2L> @ 82A = 3.7871 T, Std @ 82A = 0.0356T
<b2L> @ 5A = 0.2602 T, Std @ 5A = 0.0161T

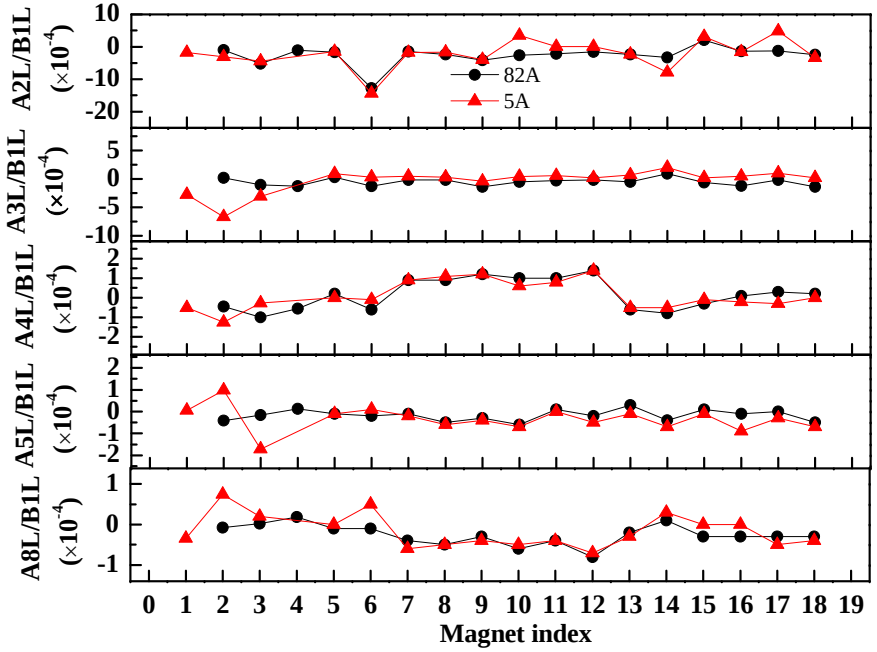
<b2L/b1L> @ 82A = 1.1256 T, Std @ 82A = 0.0101T
<b2L/b1L> @ 5A = 1.1409 T, Std @ 5A = 0.0695T

The b2L/b1L deviation of 5 A is larger than 82 A, because the remnant field obviously influence in the low current.

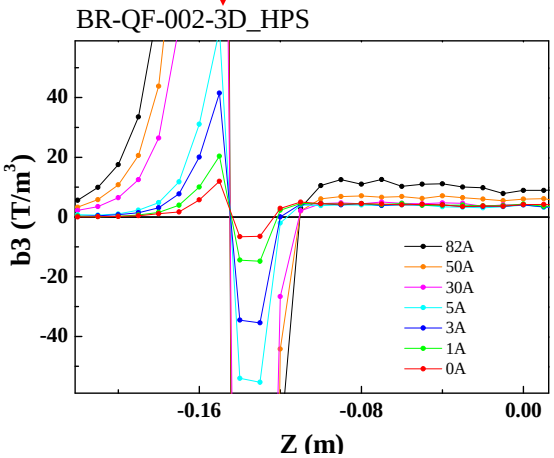
Combined function quadrupole magnet

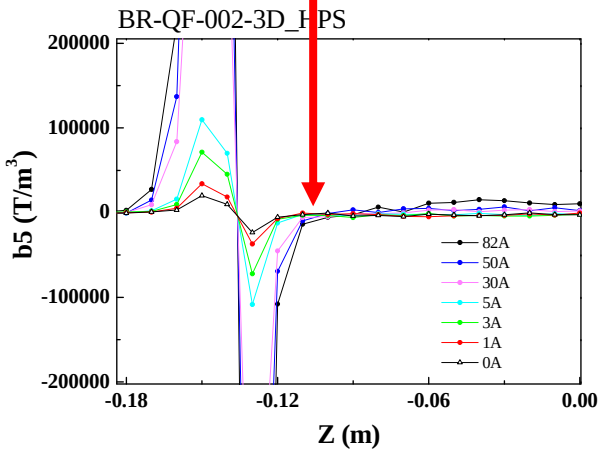
Normalized multipoles: Pre-measurement at vendor site





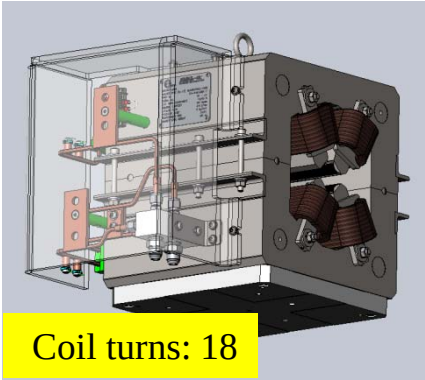
Dominated by remnant field in the low current.
The b3 component is same in the 0A ~ 5A

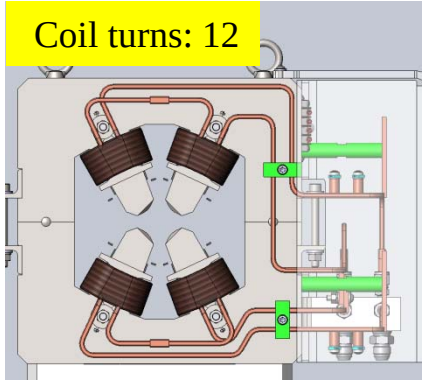


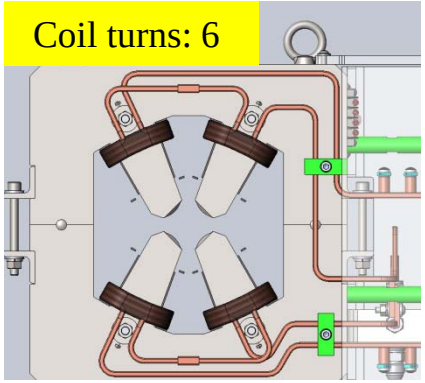


All of multipoles distribution, exclude B3L/B1L and B5L/B1L, are quite similar in the 82 A and 5 A.

Remnant field improvement of BR-QP magnet







			Original		Improved	
Magnet L=0.3 (m)		Spec. b1L (T)	Coil turns	Energy @ current	Coil turns	Energy @ current
QP	Q1	4.2985	18	3GeV @ 104A	18	3GeV @ 104A
		0.2149		150MeV @ 5.1A		150MeV @ 5.1A
	Q2	-2.7174	18	3GeV @ 66A	12	3GeV @ 99A
		-0.1359		150MeV @ 3.3A		150MeV @ 5.0A
	QM	-1.2623	18	3GeV @ 30A	6	3GeV @ 90A
		-0.0631		150MeV @ 1.5A		150MeV @ 4.5A

- The excitation current of BR-pure quadrupole magnet will be increased after coil no. reduced.
- The remnant field effect will be solved by reducing length for the low-current (150MeV) increase.

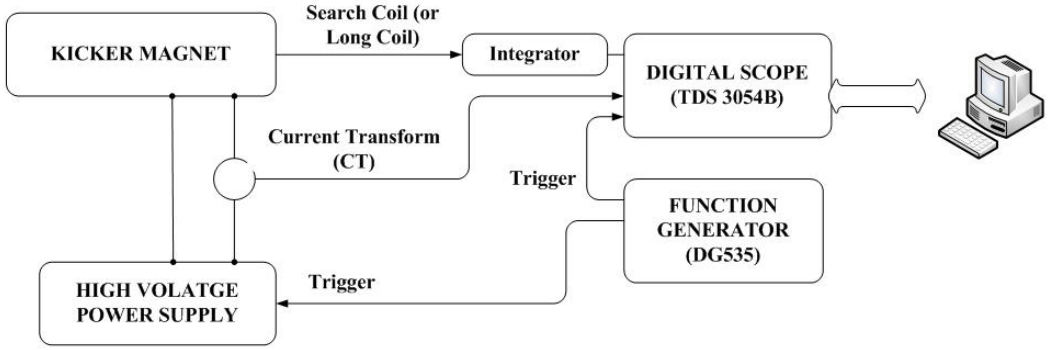
Pulse magnet measurement

Pulse Magnet Type

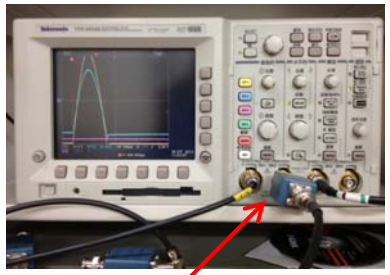
- Half-sine Kickers
  - SR injection kickers x 4
- Half-sine Septum magnet
  - Booster injection septum x 1
  - Booster extraction septum x 1
  - SR injection septum x 1
- PFN Kickers
  - Booster injection kicker x 1
  - Booster extraction kicker x 1

Long Coil and Search coil Measurement system for Storage Ring Kicker Magnet

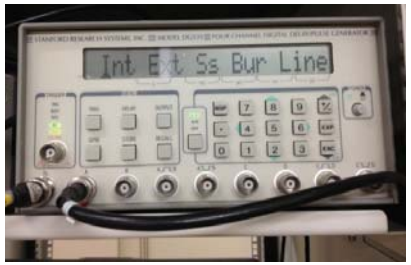
- Long coil : One turn loop of length 1000 mm and width 1.7 mm
- Search coil : The is 5 mm, from winding thirty turns of enamel wire (thickness 0.5 mm)



SCOPE

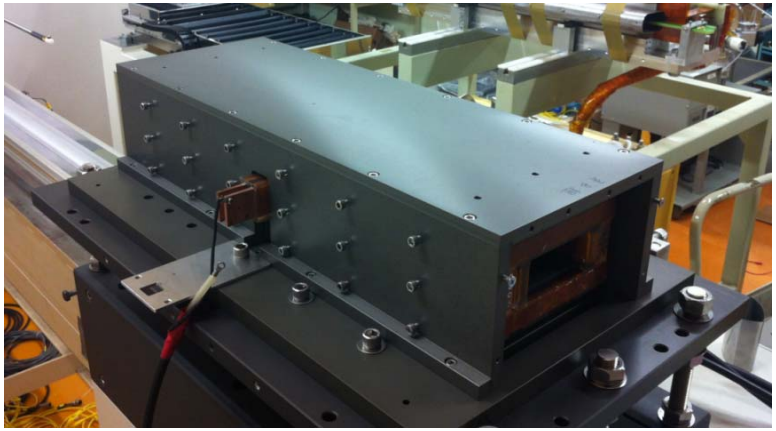


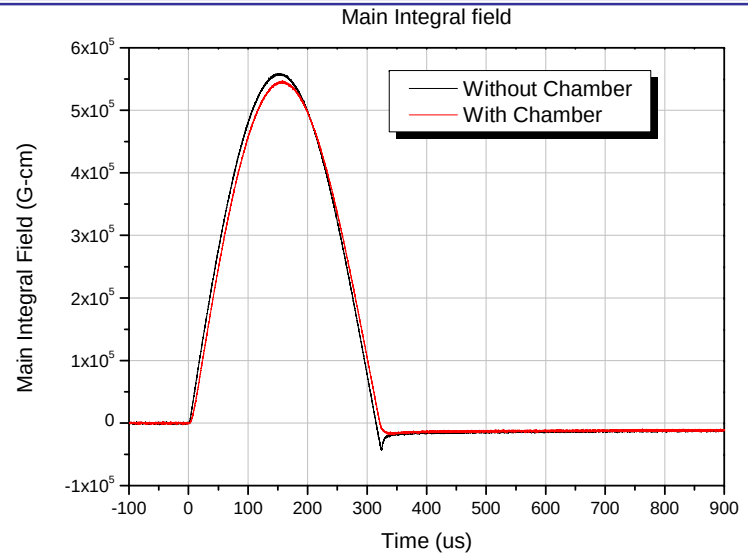
Function Generator



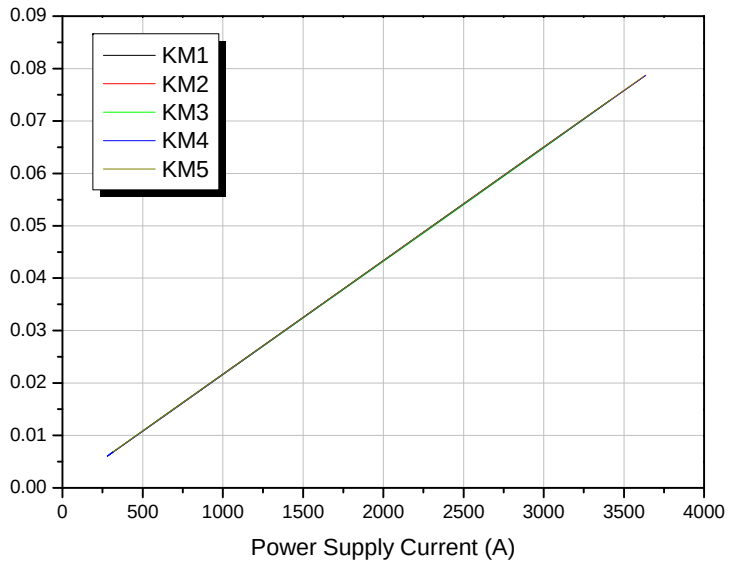
Integrator

Storage ring Kicker Magnet

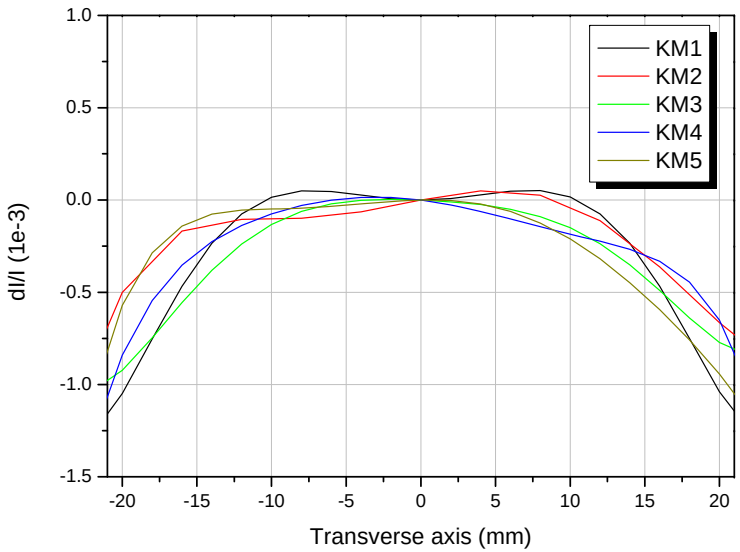




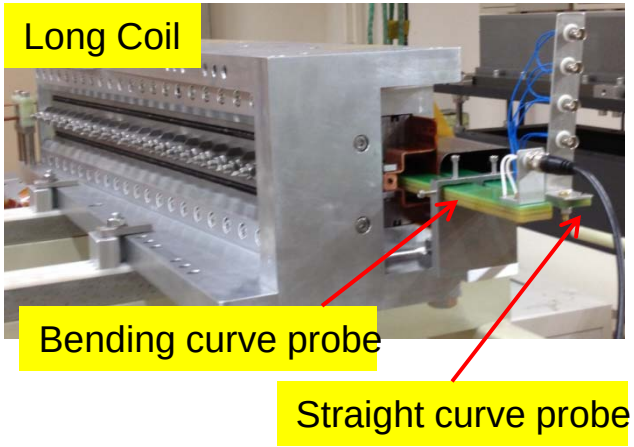
B-I Curve



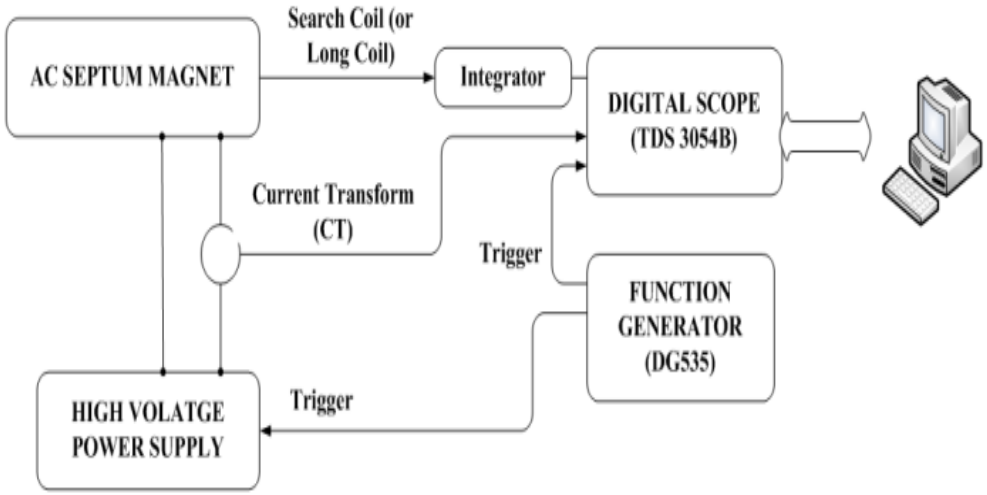
Integral Bfield Roll-Off



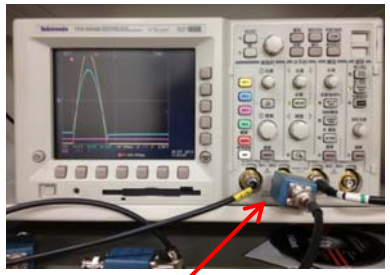
Long Coil and Search coil Measurement Systems for SR Injection and BR Extraction Septum



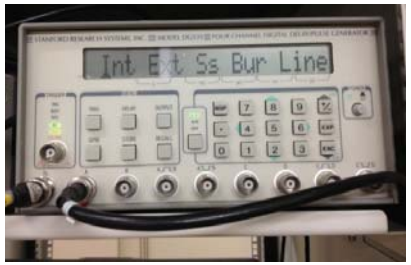
- Long coil :
  - Bending curve : Measures the on-axis magnetic field of the septum magnet
  - Straight curve : Measures the leakage magnetic field of the bumped orbit and stored orbit
  - One turn loop of length 1000 mm and width 1.7 mm.
- Search coil : The is 5 mm, from winding thirty turns of enamel wire (thickness 0.5 mm)



SCOPE

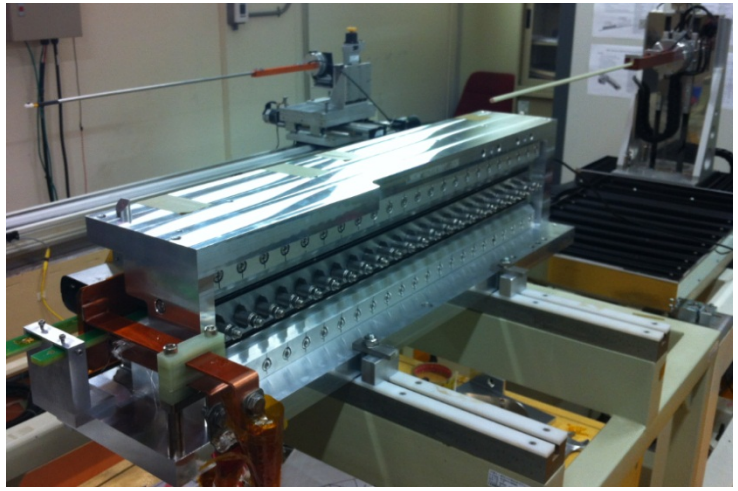


Function Generator

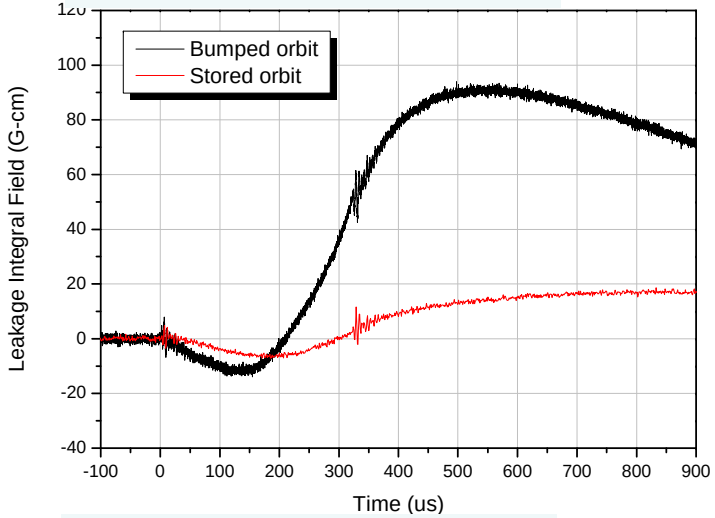


Integrator

Storage ring Injection Septum Magnet



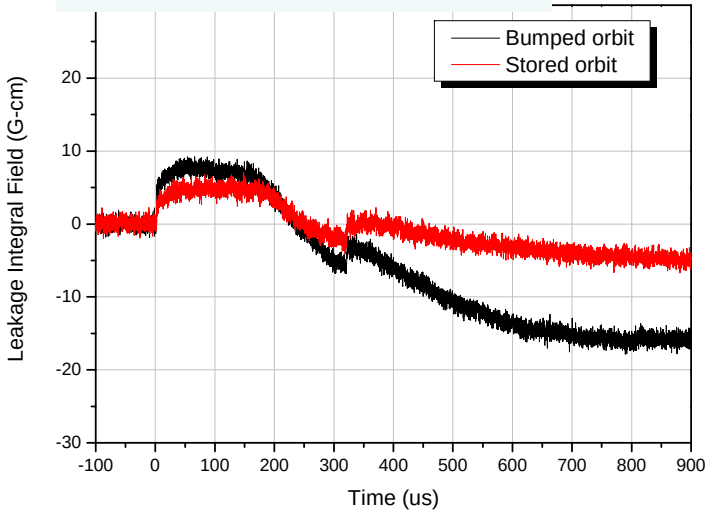
By leakage field



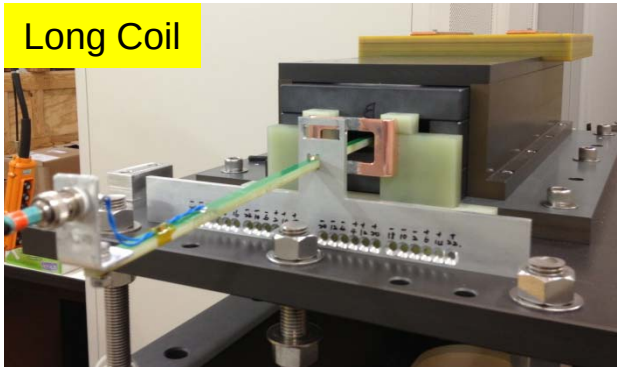
By Leakage field	
Bumped orbit (G-cm)	90 (0.15%)
Stored orbit (G-cm)	18 (0.03%)

Bx Leakage field	
Bumped orbit (G-cm)	15 (0.03%)
Stored orbit (G-cm)	4 (0.01%)

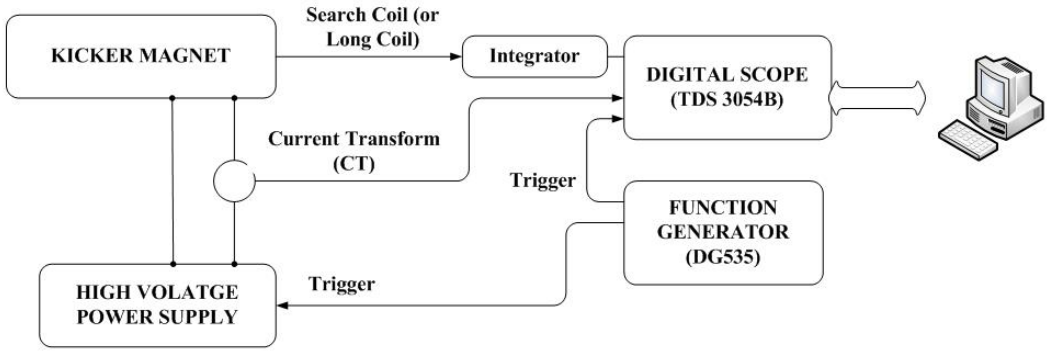
Bx leakage field



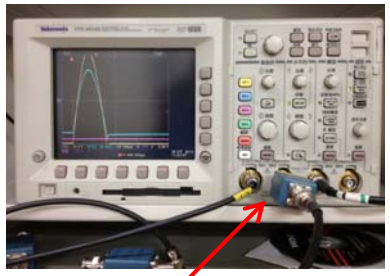
Field measurement of Booster Injection and Extraction Kicker Magnet



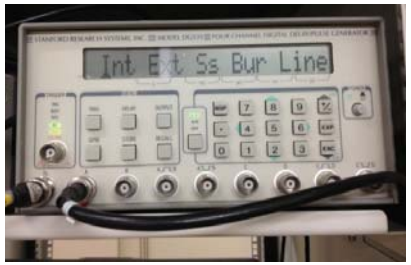
- Long coil : One turn loop of length 1000 mm and width 1.7 mm
- Search coil : The is 5 mm, from winding thirty turns of enamel wire (thickness 0.5 mm)



SCOPE



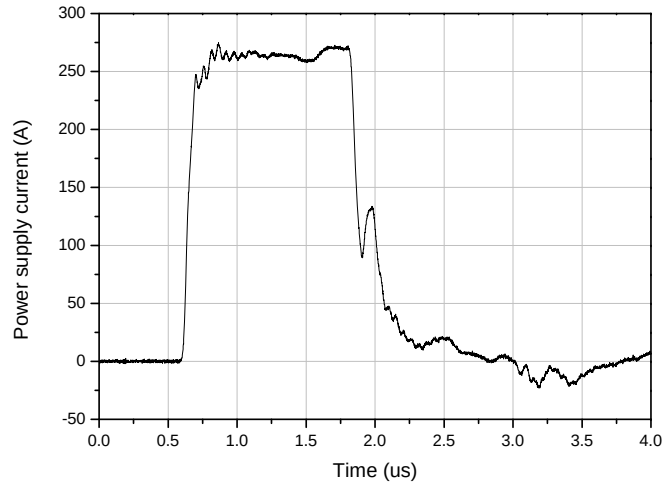
Function Generator



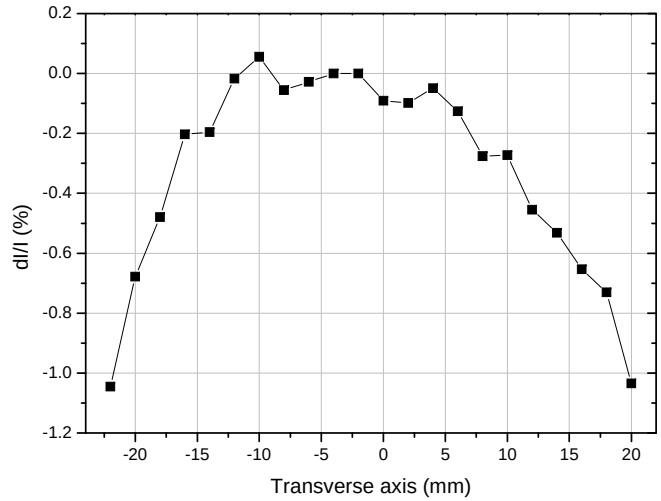
Integrator

Booster Injection Kicker Magnet

Current output



Integral Bfield Roll-Off



Parameters	Measurement
Pulse shape	Flat top
Fall time (ns)	400
Flat top (us)	1
Flatness (%)	± 1

Summary

- Most of the magnet can be meet the specification. However, much effort to solve the technique problem is necessary.
- The deviation of b0L of SR-dipole magnets is better than 0.1 %.
- Deviation of magnetic center & roll angle are within 0.02 mm and 0.02^{o}.
- A PSD module with circular jig can be used to check all the magnet center on the same girder.
- The ratio of quadrupole and sextupole of the combine dipole magnet is quite consistence between the TOSCA simulation and the construction results.
- The deviation of b2L/b1L of QF magnet with current below 5 A is much larger than 82 A, because the remnant field exist in the hysteresis behavior.
- The coil turns and length of booster magnets should be as small as possible to avoid the current ripple and the remnant field effect in the low energy injection region.

Thanks for your attention