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

MAGNET DESIGN AND CONTROL OF FIELD QUALITY FOR TPS BOOSTER AND STORAGE RINGS

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On behalf of magnet group, NSRRC

IPAC15

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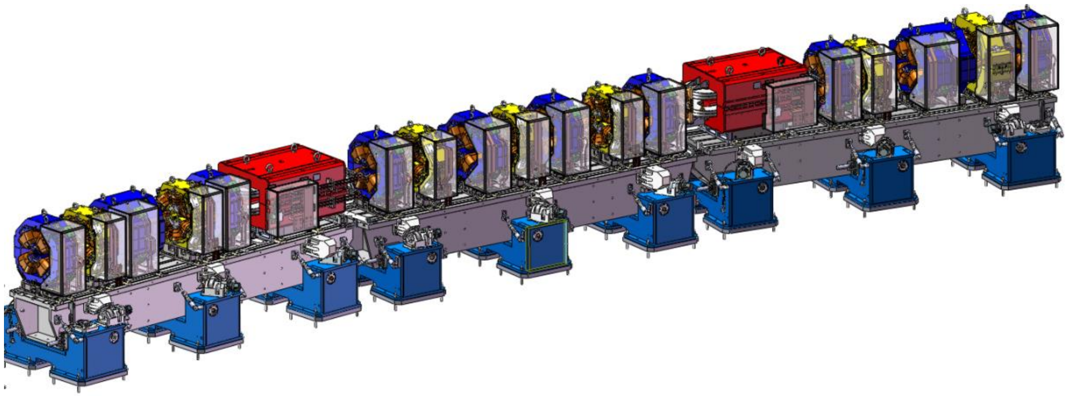
Outline

- Introduction
- Magnet manufacture and inspection
- Mechanical error of magnet
- Magnetic field performance of magnet
- Magnet center inspection
- Permeability inspect of BR vacuum chamber
- Field distortion from the permeability chamber
- Summary

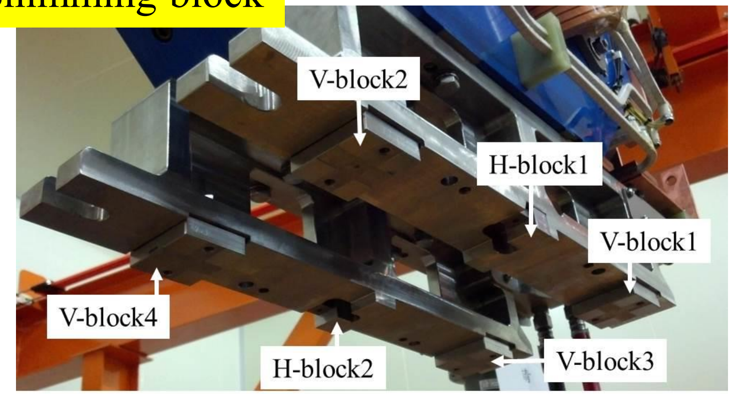
Milestone of magnet manufacture

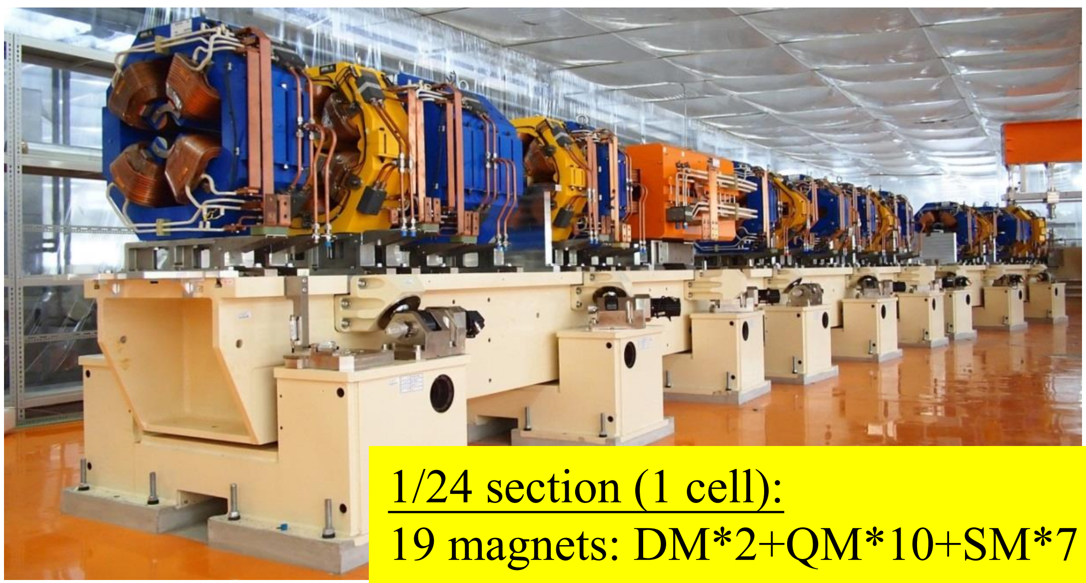
2005		Preliminary design of the magnet
2007		TPS project approved
2009		Magnet prototype constructed and examined in house
2011		One-section prototype (23 magnets) finished
2012		Mass production of magnet was begun
2013	Oct.	All magnets completed
2014	Aug.	Accelerator install completed
2014	mid-Dec.	Hardware testing and improvement completed
2014	Dec. 31	First synchrotron light at 3 GeV was observed (no corrector applied)

Overview-1/24 section (1 cell)

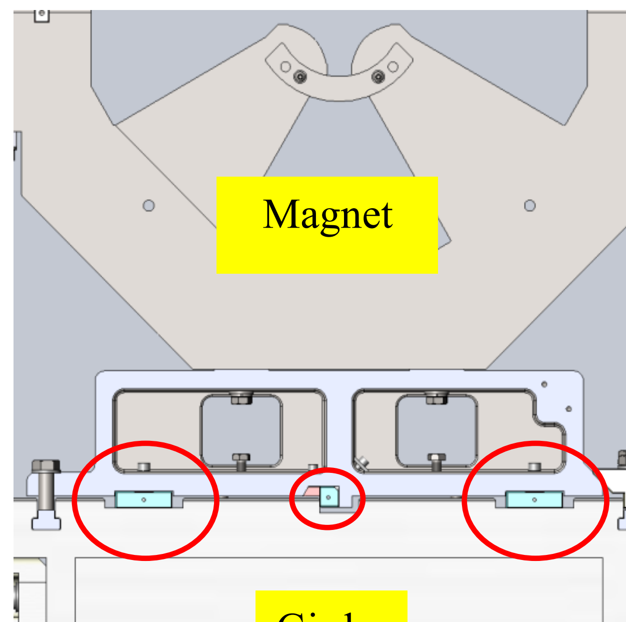


Shimming block





1/24 section (1 cell):
19 magnets: DM*2+QM*10+SM*7
3 girders: 4m-long/girder
1 vacuum chamber: 14m-long



Magnet parameter

SR magnet	Dipole	Quadrupole short/long	Sextupole A/B/C
Quantity	48	192 / 48	96 / 48 / 24
Magnetic length (m)	1.1	0.3 / 0.6	0.25
Field strength (T,T/m,T/m²)	1.191	17/15.63	478
Magnetic gap height/diameter (mm)	46	74	78
Number of turns / pole	36	54 / 48	26
Conductor dimension (mm²)	16 × 16	8×8 / 9×9	8 × 8
Coolant hole diameter (mm)	7	4 / 4.5	4

BR magnet	Dipole BD/BH	Quadrupole QF/Q1/Q2/QM	Sextupole S1/S2
Magnet quantity	42 / 12	48 / 12 / 12 / 12	24
Magnet length (m)	1.6 / 0.8	0.3	0.2
Bore diameter or gap (mm)	21.4~23.8	36	36
Number of turns / pole	24	18 / 18 / 12 / 6	18
Normal field (T, T/m,T/m²)	0.819,-1.72,-12.3	11.26,25.8/14.3/-9.1/-4.2	200
Conductor dimension(mm²)	13×13	5×5	3×2
Coolant hole diameter(mm)	6.5	2	---

Pole profile is machined by the Computer Numerical Control Machine (CNC) [red box: SR dipole 1.1, SR quadrupole 0.6, BR dipole 1.6 / 0.8]

Pole profile is machined by the Wire Electrical Discharge Machine (WEDM) [blue box: SR quadrupole 0.3, SR sextupole 0.25, BR quadrupole 0.3, BR sextupole 0.2]

Ref: C. S. Hwang et. al., "Status of accelerator lattice magnets design of TPS project", Proceedings of PAC 09, Canada (2009).

Magnetic field specification-SR/BR

Storage ring							
SR-dipole (SR-DM)		SR-quadrupole (SR-QM)			SR-sextupole (SR-SM)		
n	B_nL/B_1L [$\times10^{-4}$]	n	B_nL/B_1L [$\times10^{-4}$]	A_nL/B_1L [$\times10^{-4}$]	n	B_nL/B_2L [$\times10^{-4}$]	A_nL/B_2L [$\times10^{-4}$]
0	10000	1	10000	-	0	±15	±10
1	±3	2	±2	±2	2	10000	-
2	±3	3	±2	±1	3	±2	±2
3	±2	4	±0.5	±0.3	4	±3	±1
4	±3	5	±0.8	±0.3	5-7	±0.5	±0.5
		6-8	±0.3	±0.3	8	±0.5	±0.3
		9	±0.3	±0.3	9	±0.3	±0.3
		10-26	±0.3	±0.3	10-13	±0.3	±0.3
$\Delta b_0/b_0$	1×10^{-4}				14	±0.3	±0.3
$\Delta b_0L/b_0L$	1×10^{-3}				15-26	±0.3	±0.3

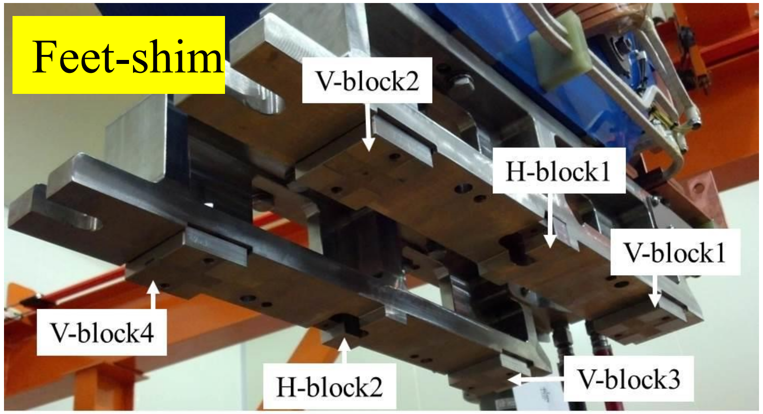
Booster ring											
BR-dipole (BR-BD/BH)		BR-Pure quadrupole (BR-QP)			BR-combined quadrupole (BR-QF)			BR-sextupole (BR-SM)			
n	B_nL/B_1L [$\times10^{-4}$]	n	B_nL/B_1L [$\times10^{-4}$]	A_nL/B_1L [$\times10^{-4}$]	n	B_nL/B_1L [$\times10^{-4}$]	A_nL/B_1L [$\times10^{-4}$]	n	B_nL/B_2L [$\times10^{-4}$]	A_nL/B_2L [$\times10^{-4}$]
0	10000	1	10000	-	1	10000	-	0	±45	-
1	-	2	±4	±10	2	-	-	2	10000	-
2	-	3	±4	±2	3	±4	±2	3	±15	±6
3	±3	4	±1	±1.5	4	±4	±1	4	±9	±6
		5	±3	±0.5	5	±2	±0.3	5-7	±3	±1.5
b_1L/b_0L	-2.1043	6-7	±1	±0.5	6-7	±1	±0.3	8	±10	±1.5
b_2L/b_0L	-7.5331	8	±0.5	±0.5	8	±5	±0.3	9-13	±3	±1.5
		9	±4	±0.5	9	±2	±0.3	14	±6	±1.5
		10-12	±0.5	±0.3	10	±4	±0.3	15-20	±3	±0.6
		13	±1.5	±0.5	11	±0.3	±0.3			
		14-16	±0.5	±0.3	12-13	±2	±0.3			
		17	±1.7	±0.5	14	±0.5	±0.3			
		18-20	±0.3	±0.3	15-16	±0.3	±0.3			
					17	±0.5	±0.3			
					18-20	±0.3	±0.3			

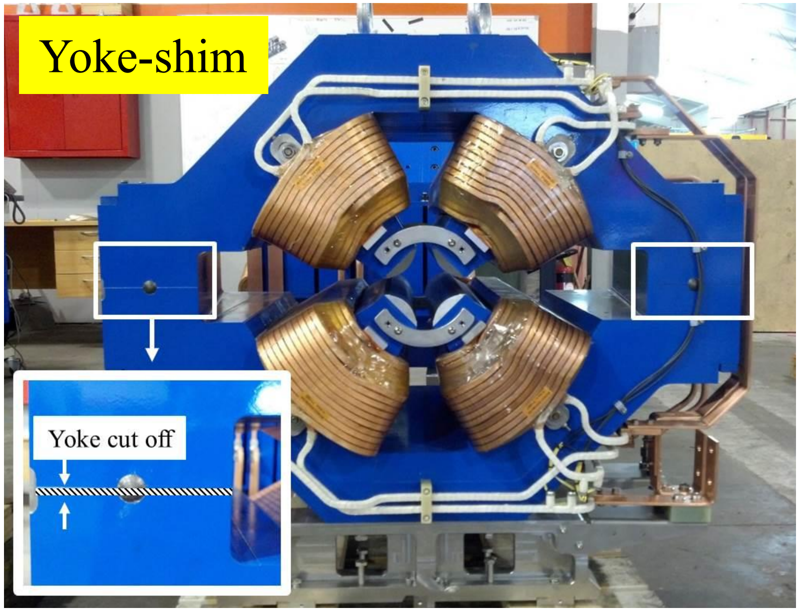
Magnet quantity and production

Magnet type	Symbol	installation (+spare)	
SR-dipole	SR-DM	48 (+2)	
SR-short quadrupole	SR-short-QM	192 (+3)	
SR-long quadrupole	SR-long-QM	48 (+2)	
SR-sextupole	SR-SM	168 (+6)	
BR-BD dipole	BR-BD	42 (+1)	Buckley System Ltd. (New Zealand)
BR-BH dipole	BR-BH	12 (+1)	
BR-pure quadrupole	BR-QP	36 (+5)	
BR-combined quadrupole	BR-QF	48 (+1)	
BR-sextupole	BR-SM	24 (+2)	
Double mini quadrupole-Q465	SR-Q465	6 (+1)	
Double mini quadrupole-Q565	SR-Q565	3 (+1)	Gongin Co., Ltd. (Taiwan)
Transfer line magnet	BTS-QM	7 (1)	
(LTB/BTS)	BTS-DM	2 (1)	
	LTB-DM/QM	1 (1)/11 (2)	Danfysik A/S (Denmark)
Corrector	CV/CH and FFC	134 and 100	

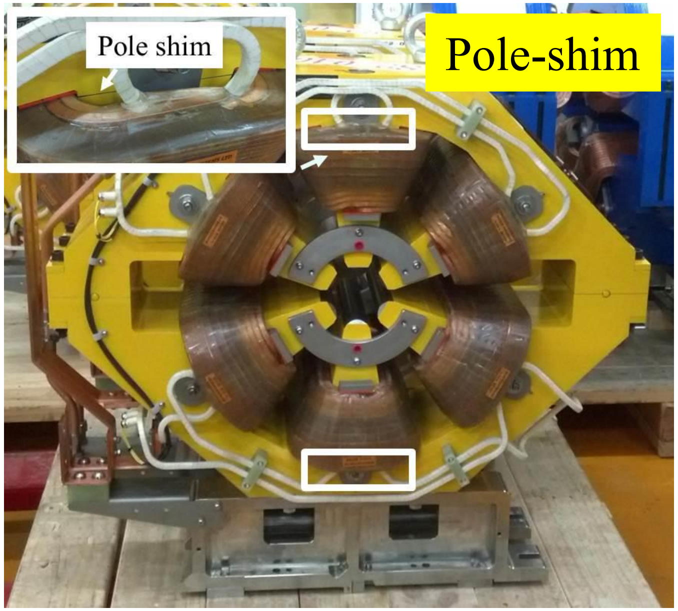
- ✓ **96.2% of fabricated magnets are installed. Only 3.8% of fabricated magnets for the spare (include prototype magnet).**
  → No more choice for the magnet installation

Field correction method





- ✓ **A feet-shim method was used to shim the mechanical and magnetic centers of quadrupole and sextupole magnet close to the ideal center.**
- ✓ **A yoke-shim method was used to reduce the octupole error (*B_3L/B_1L*) of initial several long-quadrupole magnets because the pole profile inaccurately.**
- ✓ **The pole-shim method was used to correct the multipole error of sextupole magnet.**



Ref: J. C. Jan, et. al., "Multipole errors and methods of correction for TPS lattice magnets", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, V24, NO. 3, 4100905 (2014).

Magnet manufacture and inspection

BSL (Vender site)

BR/SR-Magnets manufacture

- Iron laminate
- Iron cutting
- Coil winding
- Assembly
- CMM*1 - mechanical precise check (Mechanical center shimming within ±0.03mm)

QM/SM: field fail
SM: pole shim

Field quality pre-check

- RCS*2 - magnetic field pre-check (NSRRC staff and equipment)
- HPS*1 - magnetic field pre-check (vender's staff and equipment)

Shipping

NSRRC (vendee site)

Storage

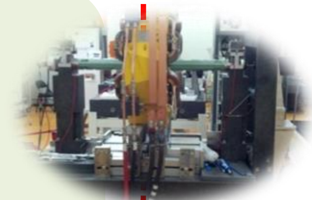
Field measurement

- HPS*2 - For dipole magnet
- RCS*2 - Full field quality check (Field center offset < 0.02mm)
- I-B curve measurement

SR-QM/SM
Field center offset
> 0.02 mm

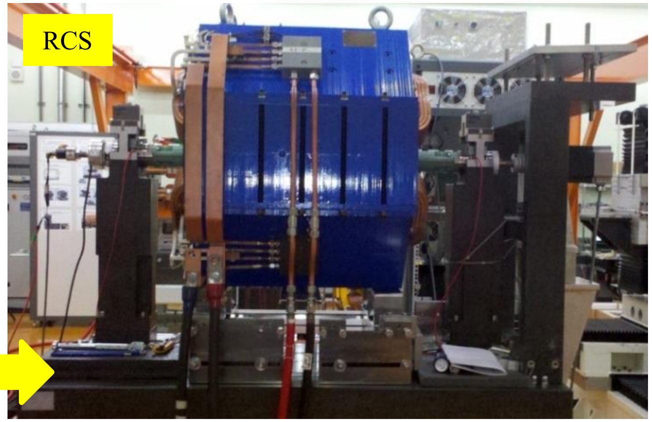
Mechanical shimming

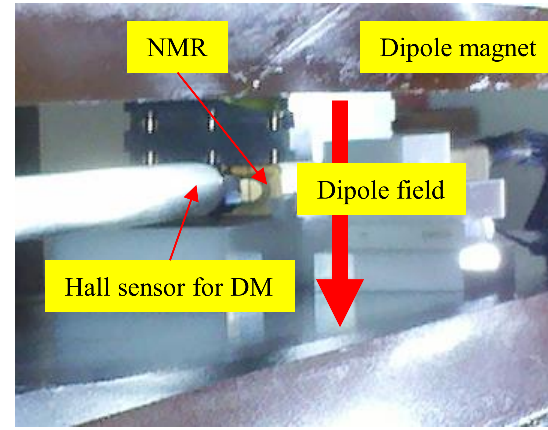
- CMM*1 - Mechanical center shimming within ±0.01mm



CMM: 3D coordinate measuring machine
RCS: Rotating coil measurement system
HPS: Hall probe measurement system

Magnetic measurement precision





HPS:

- ✓ The absolute field strength of Hall sensor has been calibrated by the Nuclear magnetic resonance & electron spin resonance system (NMR)
  → $\Delta B < 0.3$ G
- ✓ The repeatable of field strength is better than 0.01%.

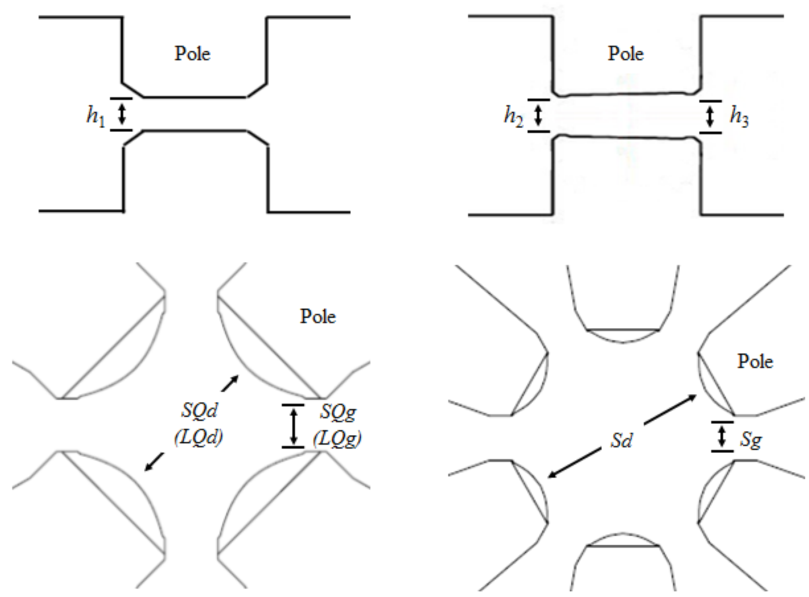
RCS:

- ✓ The absolute field strength of RCS has been corrected by the HPS.
- ✓ The repeatable of main field strength of RCS is better than 0.01%.
- ✓ The repeatable of normalized multipoles of RCS is better than 0.3×10^{-4}. (n>2 is better than 0.1×10^{-4})
- ✓ The repeatable and resolution of magnetic center offset measurement is better than 0.01 mm.

Mechanical error of magnet

	Design (mm)	Measure (mean±sd, mm)	Different (mm)
SR-dipole			
h_1	45.48	45.484±0.070	0.004
DL_1^+	1026	1026.228±0.460	0.228
Short SR-quadrupole			
SQd	74	74.011±0.018	0.011
SQg	24.6	24.611±0.018	0.011
SQL^+	265	264.909±0.389	-0.091
Long SR-quadrupole			
LQd	74	73.995±0.016	-0.005
LQg	24.6	24.601±0.020	0.001
LQL^+	565	564.783±0.689	-0.217
SR-sextupole			
Sd	78	**	-
Sg	18.3	18.298±0.020	-0.002
SL^+	227	226.997±0.315	-0.003
BR-dipole (BD)			
h_2	21.40	21.400±0.009	0
h_3	23.84	23.845±0.010	0.005
DL_2^+	1554	1553.885±0.207	-0.115
BR-dipole (BH)			
h_2	21.14	21.148±0.008	0.008
h_3	23.64	23.650±0.008	0.01
DL_2^+	754	754.159±0.320	0.159
BR-quadrupole (pure)			
BQd	36	35.997±0.017	-0.003
BQL^+	282	282.172±0.174	0.172

\+ Yoke length
** No CMM date measured after pole-shim



- ✓ The difference between the designed and machined values of the bore diameter (or pole high) is better than 0.011 mm.
- ✓ The difference between designed and machined value of the pole gap is better than 0.011 mm.
- ✓ The deviation of the laminate yoke length was controlled to be smaller than 0.1 % of the yoke length or one-piece thickness of lamina. Note: SR (BR) laminated by 1 mm (0.5mm) silicon steel.

Magnetic field performance of magnet

@3GeV	Spec.	Measure (mean±sd)
SR-dipole		
b_0L		-1.3201±0.0009
Short SR-quadrupole		
b_1L		-5.2160±0.0086
B_2L/B_1L	±2.0	0.1±1.1
B_3L/B_1L	±2.0	-0.2±0.7
B_5L/B_1L	±0.8	-0.4±0.2
Long SR-quadrupole		
b_1L		-9.4438±0.0087
B_2L/B_1L	±2.0	0.0±0.9
B_3L/B_1L	±2.0	-1.7±1.0
B_5L/B_1L	±0.8	-0.3±0.3
SR-sextupole		
b_2L		120.216±0.306
B_3L/B_2L	±2.0	0.0±1.1
B_4L/B_2L	±3.0	0.3±1.3
B_8L/B_2L	±0.5	0.4±0.1
BR-dipole (BD/ BH)		
b_0L		-1.3173±0.0019/ -0.6589±0.0007
b_1L		2.7719±0.0228/ 1.3922±0.0060
b_2L		9.9088±0.4514/ 4.3942±0.1146
BR-quadrupole (Q1)		
b_1L		Q1: 4.293±0.005
B_2L/B_1L	±4.0	-1.4±3.0
B_3L/B_1L	±4.0	-4.3±1.6
B_5L/B_1L	±3.0	1.9±1.0
Unit: b_0L (T·m), b_1L (T), b_2L (T/m), B_nL/B_mL ($\times10^{-4}$)		

- ✓ The index n=0 is dipole term, n=1 is quadrupole term.
- ✓ The dispersion of the field strength is generally dominated by the error of bore diameter and the yoke length. The multipole errors are dominated by the asymmetric or machining error of the pole profile.
- ✓ The magnetic field quality of magnet is much better than the specifications.
- ✓ The SR and BR magnets have a great quality of the field because of the strict mechanical machining.

Ref: J. C. Jan et. al., "SUMMARY OF FIELD QUALITY OF TPS LATTICE MAGNETS", Proceedings of International Particle Accelerator Conference , Dresden, Germany (2014).

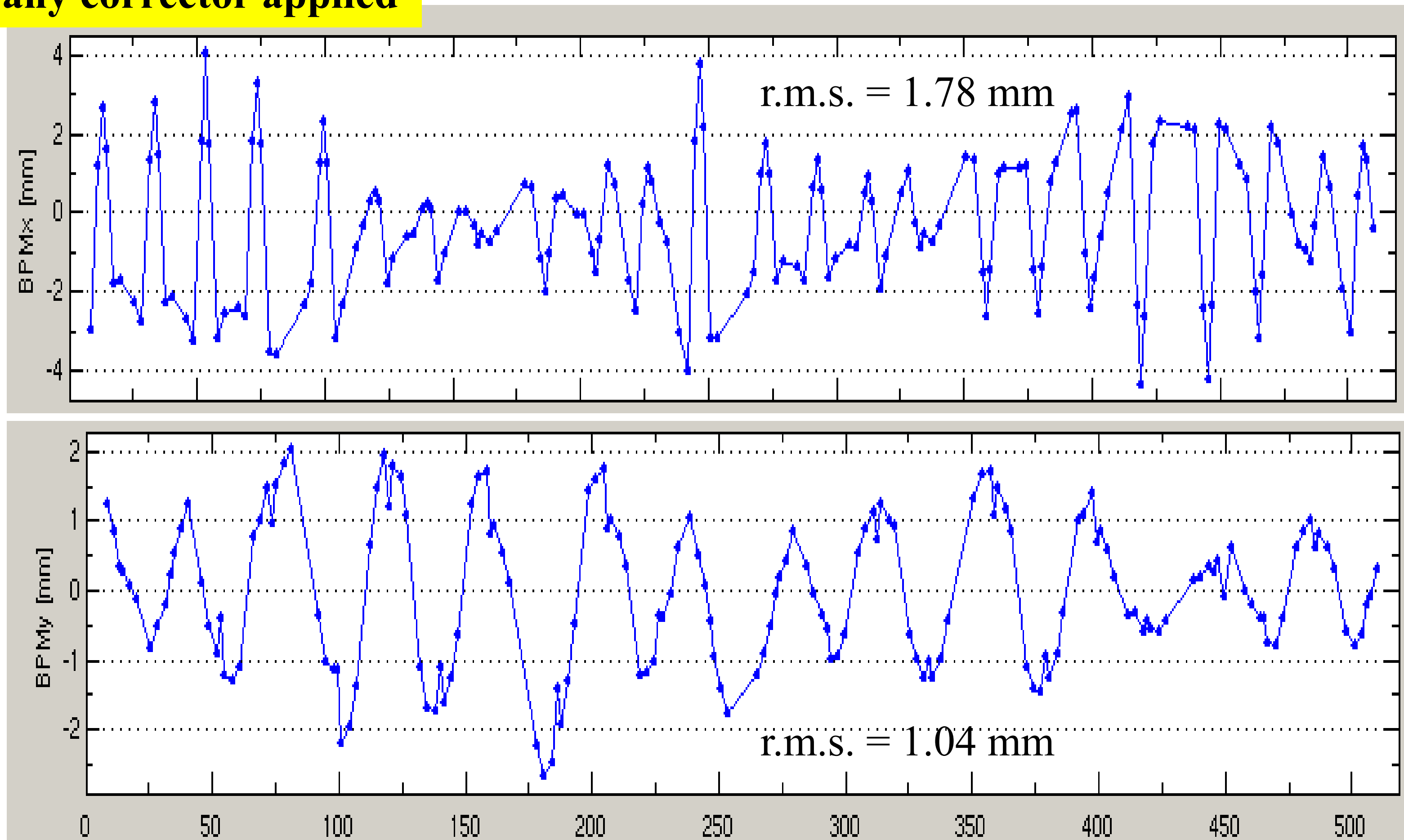
Magnet center inspection

	Measurement (mean value±sd)		
	short SR-quad.	long SR-quad.	SR-sext.
Mechanical center offset-vertical (mm)	-0.002±0.004	-0.005±0.004	-0.002±0.004
Mechanical center offset-horizontal (mm)	-0.005±0.006	-0.008±0.004	-0.005±0.005
Magnetic center offset-vertical (mm)	0.003±0.009	0.002±0.007	0.005±0.008
Magnetic center offset-horizontal (mm)	0.006±0.011	0.007±0.009	0.005±0.009
Mechanical tilt (deg.)	0.00±0.00	0.00±0.00	0.01±0.01
Magnetic tilt (deg.)	0.00±0.01	0.00±0.01	0.01±0.01

- ✓ The mechanical center offset was shimmed better than ±0.01 mm in both vertical and horizontal directions.
- ✓ The magnetic center offset was measured better than ±0.02 mm in both vertical and horizontal directions after feet-shim.
- ✓ The mechanical and magnetic tilt of magnet is better than 0.01^{o} after feet-shim.

Closed Orbit of TPS Storage Ring

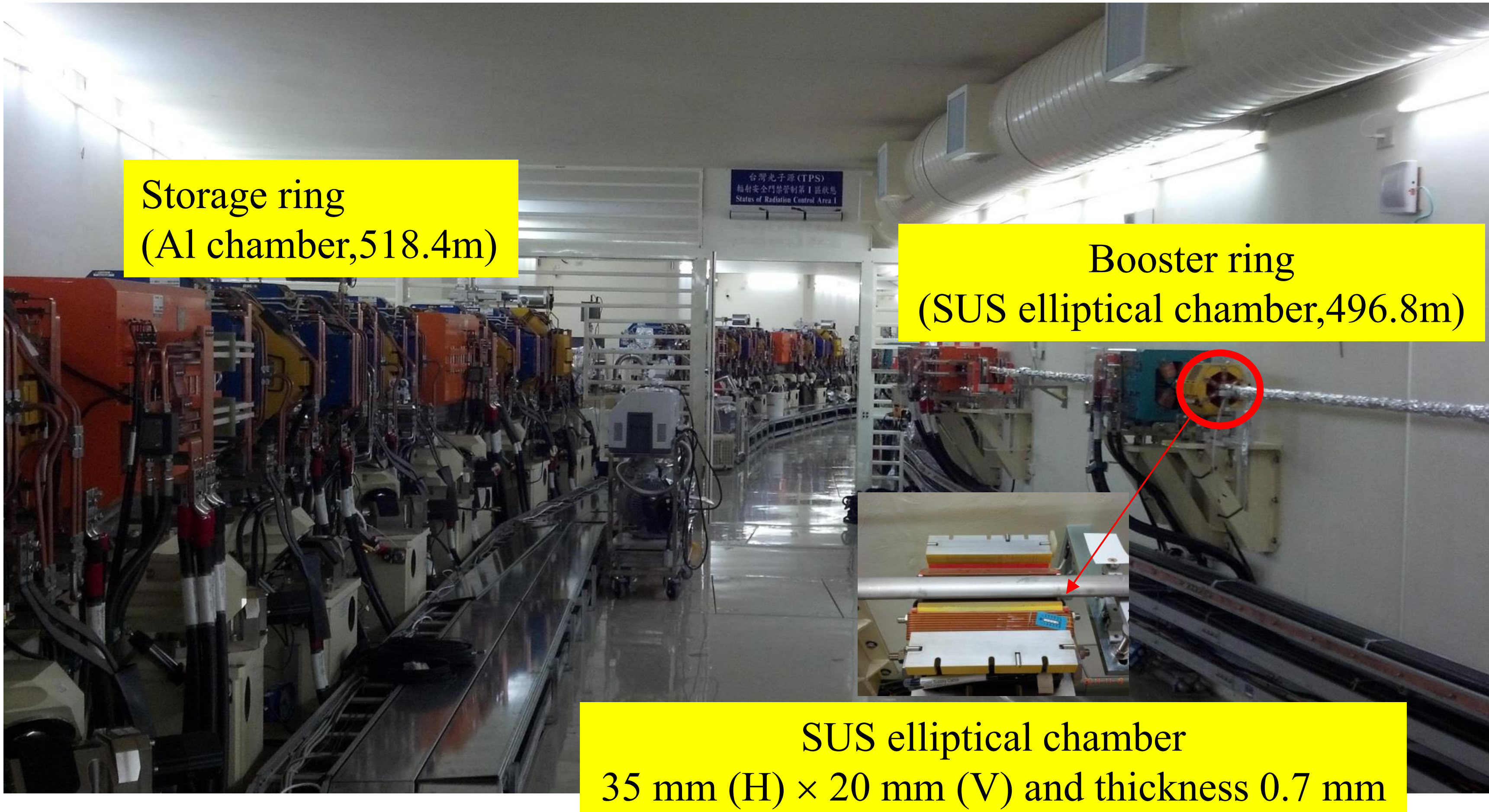
Without any corrector applied



- ✓ The closed orbit distortion (COD) measurement without any corrector: 1.78 mm (rms) horizontal and 1.04 mm (rms) vertical after the LOCO and BBA.
- ✓ The COD results demonstrate very high quality of magnets and the girder alignments.

Ref: C. C. Kuo et. al., "Commissioning of the Taiwan Photon Source", TUXC3, this proceeding.
T. C. Tseng et. al., "The Auto-Alignment Girder System of TPS Storage Ring", THYB2, this proceeding.

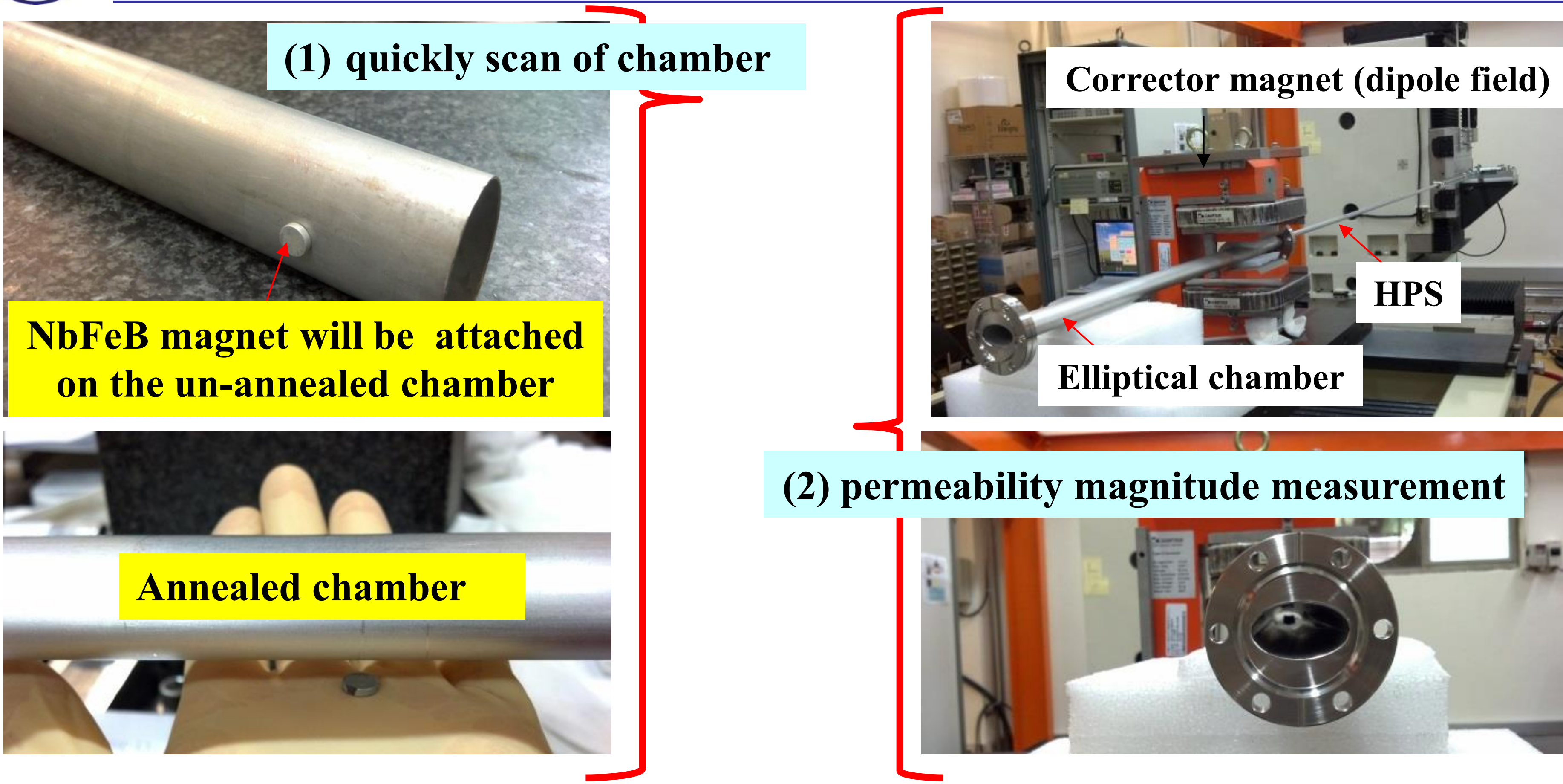
Chamber permeability studies of Booster ring



- ✓ Elliptical chambers are cold-drawn from circular tube of stainless steel (SUS304). The relative permeability (μ_r) of the vacuum chamber appeared after the drawing process.
- ✓ An annealing process was used to eliminate the permeability of the BR chamber.

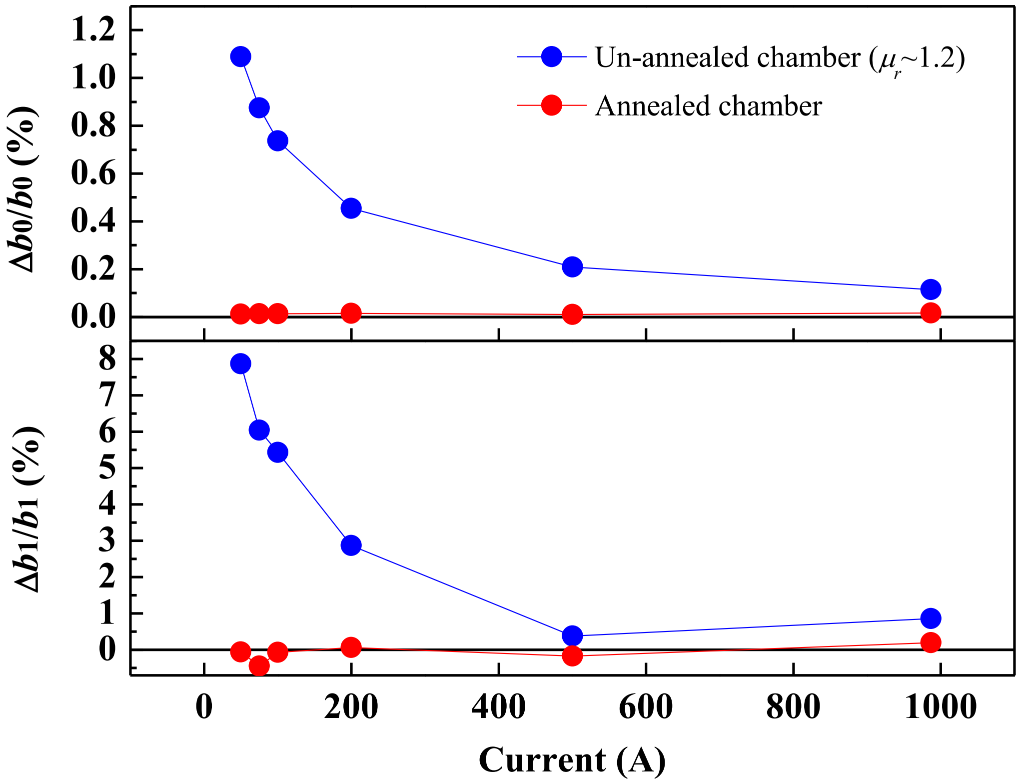
Ref: I. C. Sheng et. al., "Demagnetized Booster Chambers in TPS", WEPHA049, this proceeding.

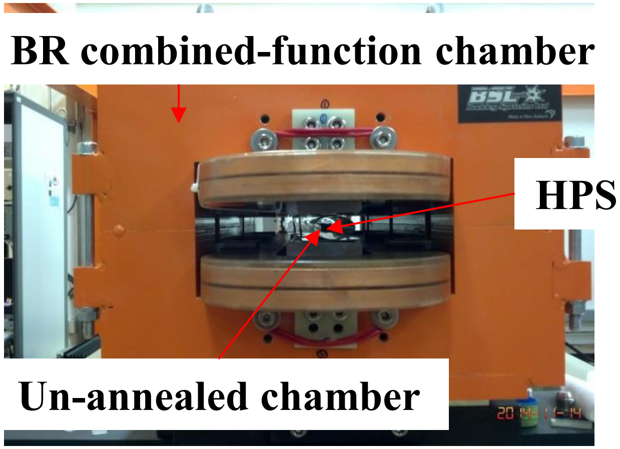
Chamber permeability inspection



- ✓ A two-step test of the chamber permeability: (1) a quickly scan of the chamber by the NbFeB permanent magnet and (2) the magnitude measurement by the HPS.
- ✓ NbFeB permanent magnet: 6 mm(D)×2 mm(t)×2 g(w) with 0.25 T field strength.
- ✓ The relative permeability of the BR chamber is less than 1.01 after annealing.

Field distortion from the un-annealed chamber





$$\frac{\Delta b_0}{b_0} = \frac{b_0(permeability\ chamber) - b_0(without\ chamber)}{b_0(without\ chamber)}$$

- ✓ An un-annealed chamber was measured to understand the field distortion in the BR dipole (combined-function) magnet.
- ✓ The field distortion increases with decreasing excitation current in the un-annealed chamber indicates that the electron beam at low energy will be perturbed seriously due to the effect of un-annealed chamber in the BR.

Summary

- ✓ **The machining error of the pole profile of a TPS magnet is better than 0.02 mm as manufactured with the CNC and WEDM techniques. The multipole errors of these magnets thereby conform to the strict requirements of the spec.**
- ✓ **A precise mechanical and magnetic center was shimmed and measured with the CMM and RCS. The mechanical center offset was shimmed better than ±0.01 mm in both vertical and horizontal directions.**
- ✓ **The magnetic center offset was better than ±0.02 mm in both vertical and horizontal directions after feet-shim.**
- ✓ **The mechanical and magnetic tilt of magnet is better than 0.01^{o} after feet-shim.**
- ✓ **The permeability of the BR chamber was less than 1.01 after heat treatment.**
- ✓ **A serious distortion of the field from the un-annealed chamber was observed, indicates that the electron beam at low energy will be perturbed seriously due to the effect of un-annealed chamber in the BR.**

Thanks for your attention