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

Overview of magnetic field measurement in NSRRC

C. K. Yang, C. Y. Kuo, J. C. Huang, F. Y. Lin, T. Y. Chung, C. Hs. Chang, C.W. Chen, , J. C. Jan, C.H. Chang, **C. S. Hwang**

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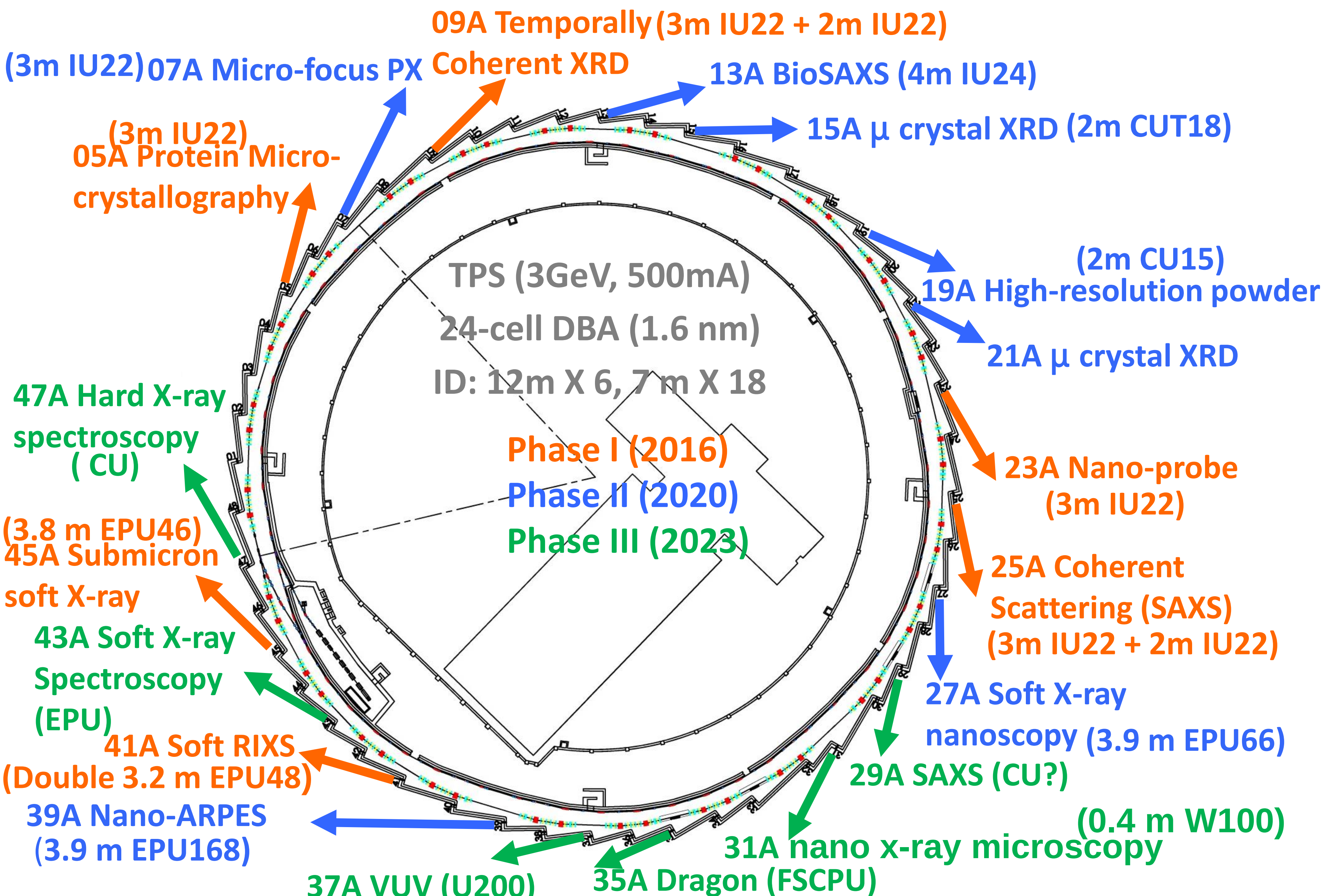
Outline

- Status of NSRRC insertion devices
- Introduction to magnet measurement system
  - Lattice Magnet
  - Out-of vacuum Insertion Devices
  - In-vacuum & cryogenic Insertion Devices
- Summary

Introduction of TPS Insertion Devices



Parameters of IDs in phase-I

Phase I		EPU48 x 2	IU22x2	IU22x4	IUT22	EPU46
photon energy /keV	HP	0.23-1.5	1.25-20	1.25-20	1.25-20	0.27-1.5
	VP	0.46-1.5				0.5-1.5
λ/mm		48	22	22	22	46
N_{period}		68	95	140	140	82
By(Bx) /T		0.83/0.55	1.13	1.13	1.13	0.81/0.54
Ky/Kx		3.72/2.47	1.56	1.56	1.56	3.48/2.32
L /m		3.436 x 2	2.58	3.57 x 2	3.57	3.89
gap /mm		13	5.4	5.4	5.4	13.5
Pole material		---	Permendur	Permendur	Permendur	---
Magnet material		NdFeB	NdFeB	NdFeB	NdFeB	NdFeB
Operation temp./K		295	295	295	295	295
Remanence (T)		1.24	1.19	1.19	1.19	1.24
Coercivity (kOe)		25	32	32	32	25

- Final operation parameter. EPU46: Bx=By=0.454T, . EPU48: Bx=By=0.46T.
- Phase I ID has been operated routinely.

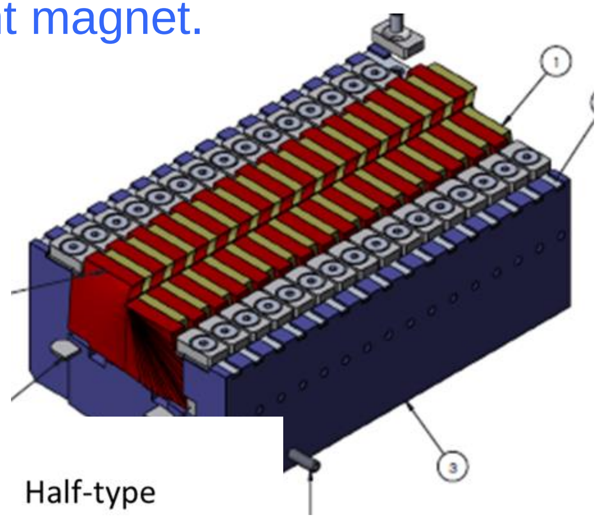
Parameters of IDs in phase-II & III

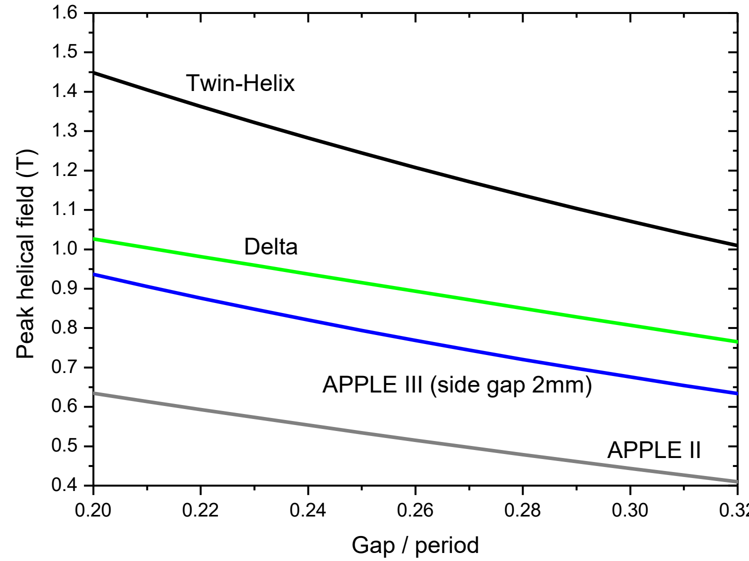
Phase II & III		EPU66	EPU168	IU22	CU15	CUT18	IU24	U266(?)	W100	FSCPU*
photon energy /keV	HP	0.085-2.5	>0.015	1.25-20	8-35	8-35	4-23	<0.005	5-50	2.5<CP<0.09
	VP	0.15-2.5	>0.07							
λ/mm		66	168	22	15	18	24	266	100	120
N_{period}		62	24	140	133	111	168	15	4	3
By(Bx) /T		0.87/0.64	0.52/0.23	1.13	1.01	1.08	0.905	0.452	1.81	0.34/0.34
Ky/Kx		5.36/3.94	8.1/3.5	2.32	1.42	1.81	2.03	11.23	16.91	3.7/3.7
L /m		4.36	4.36	3.57	2.49	2.49	4.52	4.5	0.6	0.6
Gap/mm		16.8	28	5.4	5.4	5.4	6.8	25	14	15
Magnet material		NdFeB	NdFeB	NdFeB	PrFeB (NMX-68CU)	NdFeB (NMX-U52SH)	NdFeB	NdFeB	NdFeB	NdFeB
Pole material		---	---	Permendur	Permendur	Permendur	Permendur	Permendur	Permendur	35CS210
Operation temp./K		295	295	295	<80	140	295	295	295	295
Remanence (T)		1.24	1.24	1.19	1.67	1.61	1.19	1.19	1.24	1.24
Coercivity (kOe)		25	25	28	78	44	28	28	25	25

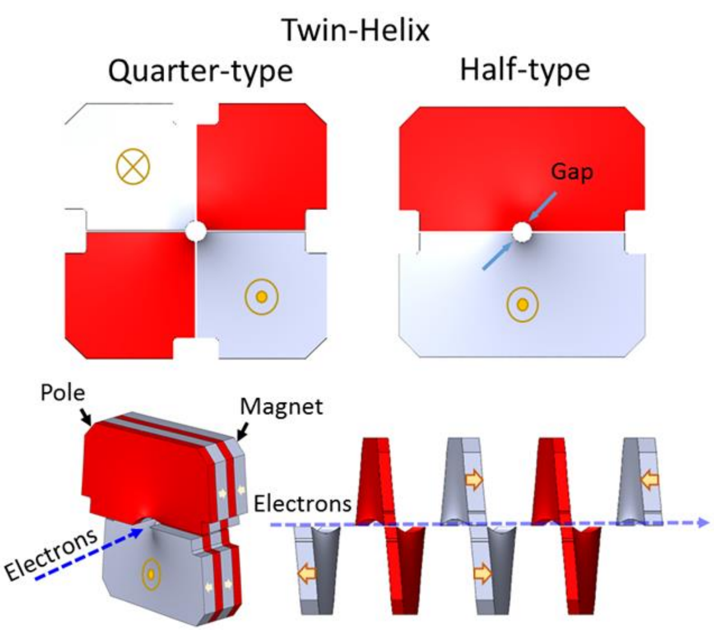
* Permanent magnet for horizontal field & electro-magnet with 450 A for vertical field.

Magnet Structure of Twin Helix Undulator

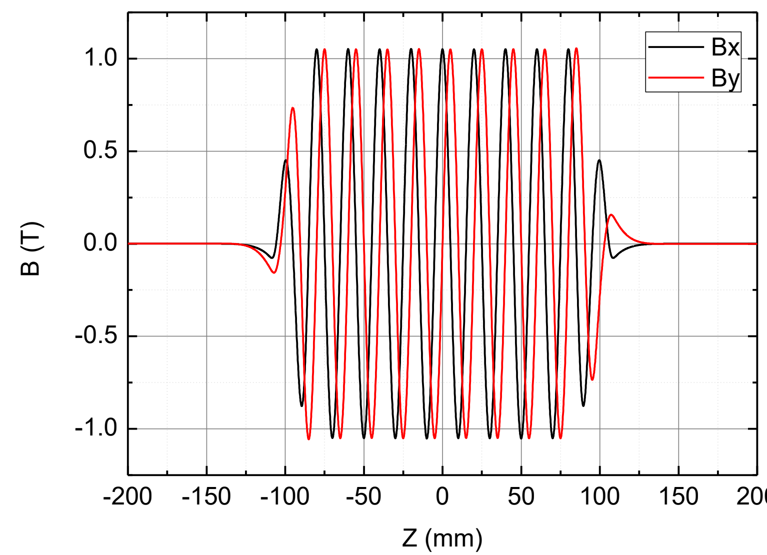
- This hybrid structure is the same as helical superconducting undulator. But the superconducting wire was replaced by the permanent magnet.



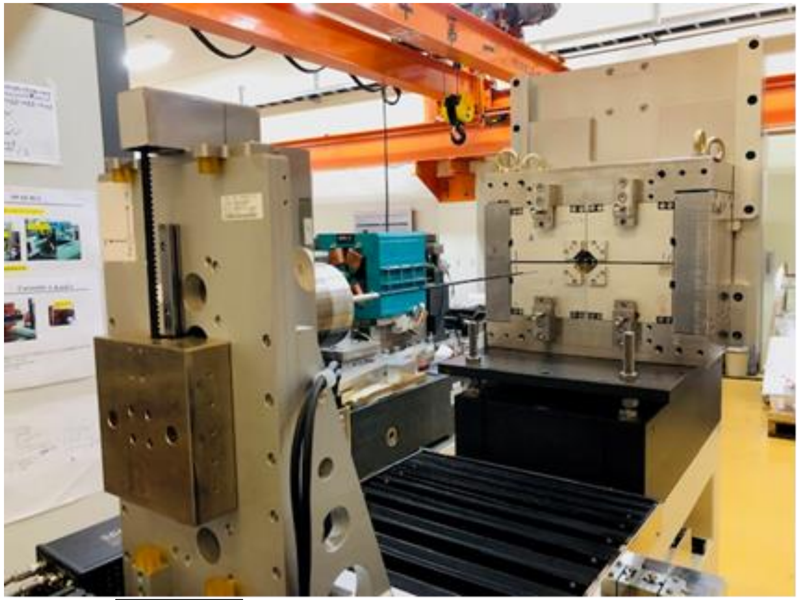


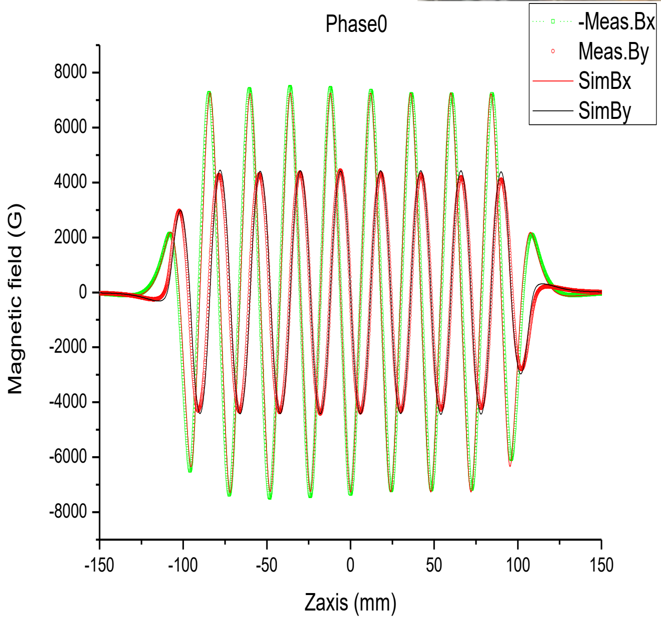


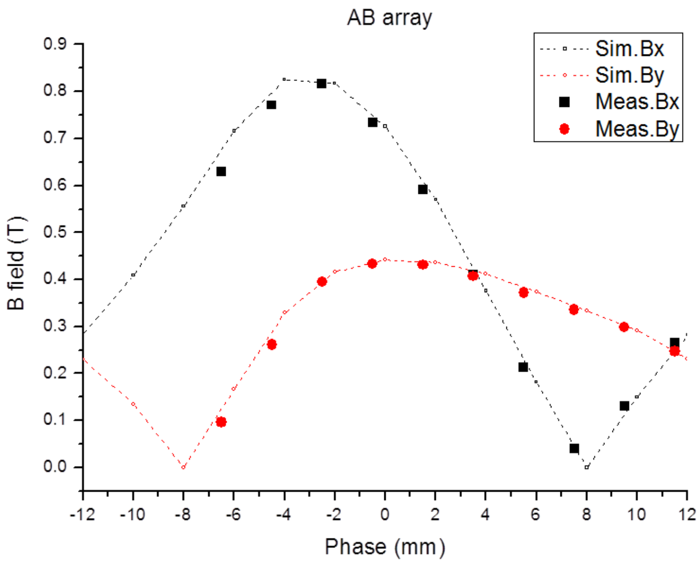
Round gap=5.6 mm,λ=20mm



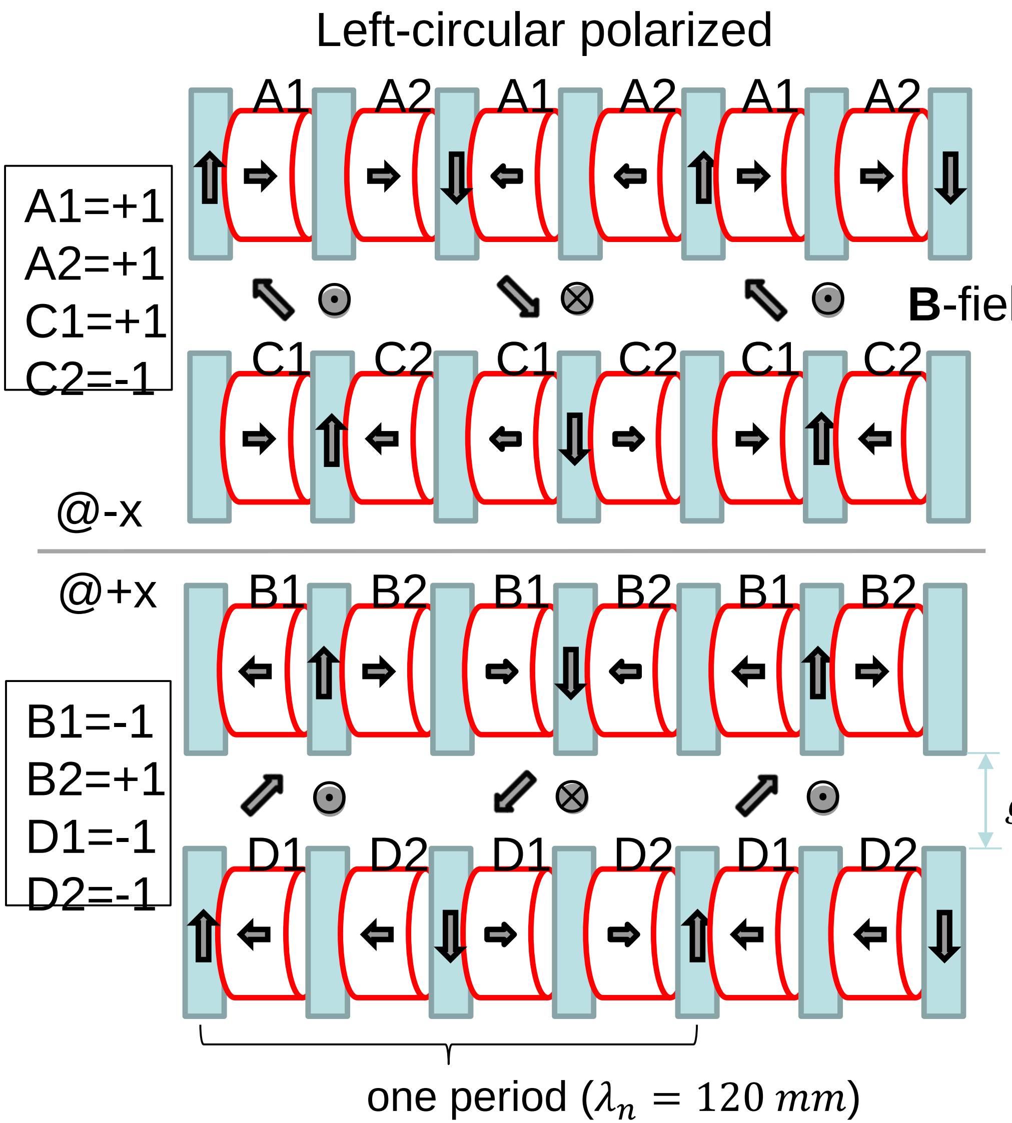
Field measurement of Twin Helix Undulator

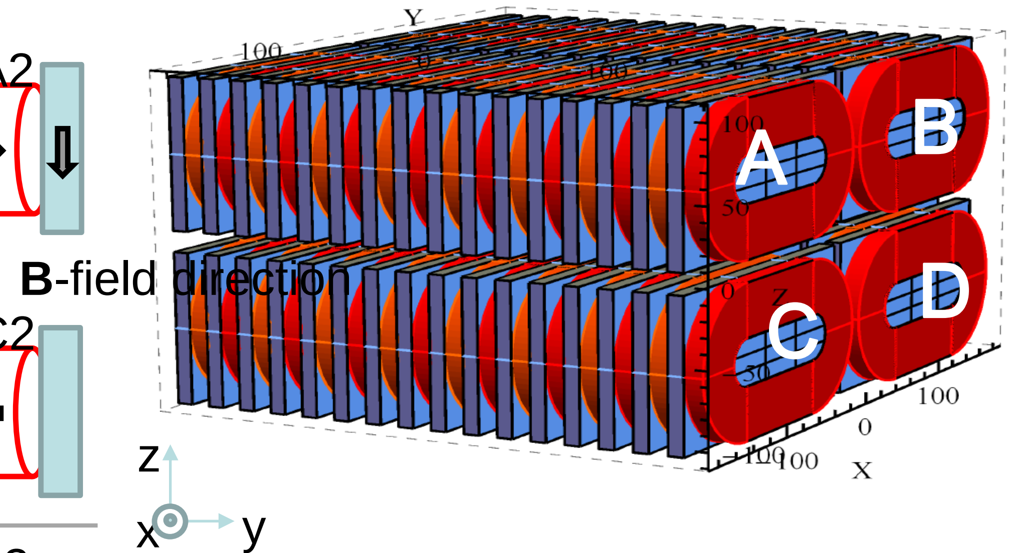






Bi-Planar electromagnetic elliptically polarized undulator



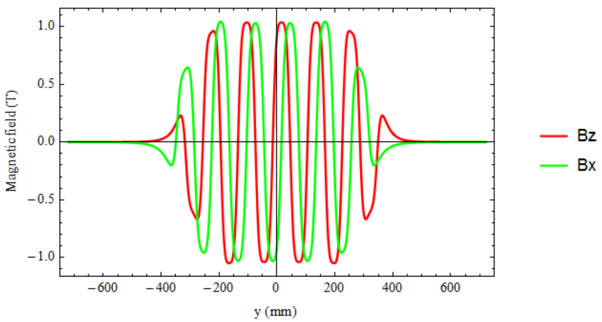


- For fast switching polarization
- Provide all the polarization modes
- Changing current polarity to switch polarization mode / No complicate moving mechanical
- Using superconducting wire to provide high magnetic field

Magnetic field distribution in the six polarization mode

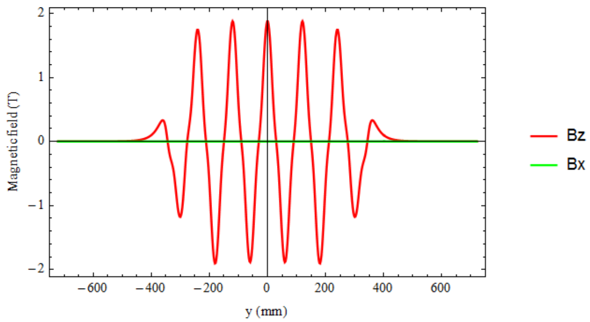
Left circular polarization

A1	B1	C1	D1	A2	B2	C2	D2
1	-1	1	-1	1	1	-1	-1



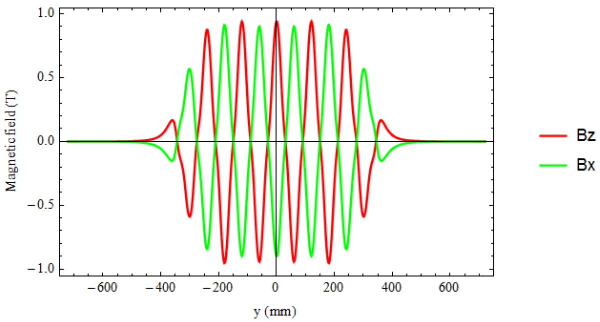
Horizontal linear polarization

A1	B1	C1	D1	A2	B2	C2	D2
1	1	-1	-1	1	1	-1	-1



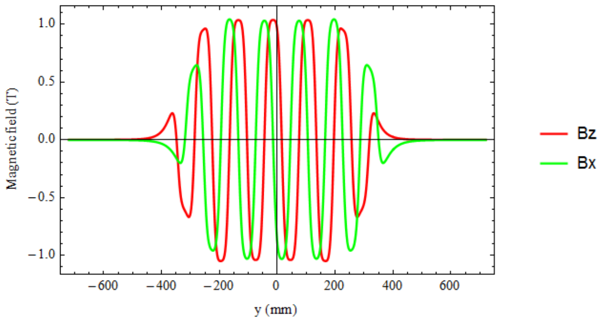
Incline at 45º polarization

A1	B1	C1	D1	A2	B2	C2	D2
1	0	0	-1	1	0	0	-1



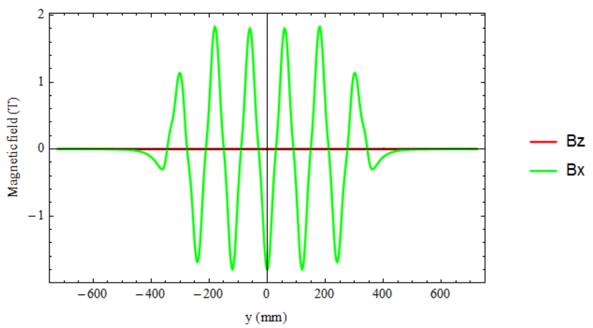
Right circular polarization

A1	B1	C1	D1	A2	B2	C2	D2
1	1	-1	-1	1	-1	1	-1



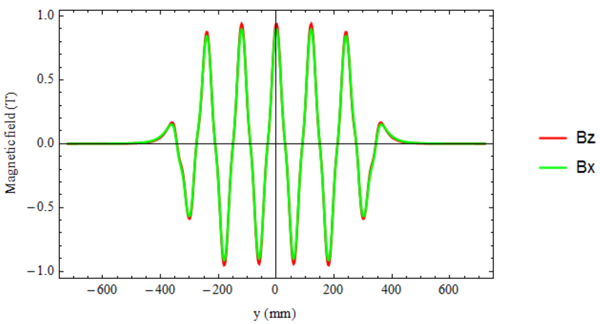
Vertical linear polarization

A1	B1	C1	D1	A2	B2	C2	D2
1	-1	1	-1	1	-1	1	-1



Incline at 135º polarization

A1	B1	C1	D1	A2	B2	C2	D2
0	1	-1	0	0	1	-1	0



Introduction to magnet measurement system

◆ **for Lattice Magnet**

Hall probe & stretch wire used for lattice magnets

The magnetic field B_x+iB_y is expressed in orthogonal polynomial expansions as

$$B_x + iB_y = \sum (a_n + ib_n)(x+iy)^n \quad (1)$$

The equation is divided into real part B_x and imaginary part B_y

$$B_y(x,y) = b_0 + a_1 y + b_1 x + 2a_2 xy + b_2(x^2 - y^2) + \ldots \quad (2)$$

$$B_x(x,y) = a_0 + a_1 x - b_1 y - 2b_2 xy + a_2(x^2 - y^2) + \ldots \quad (3)$$

b_0:normal dipole term
b_1:normal quadrupole term

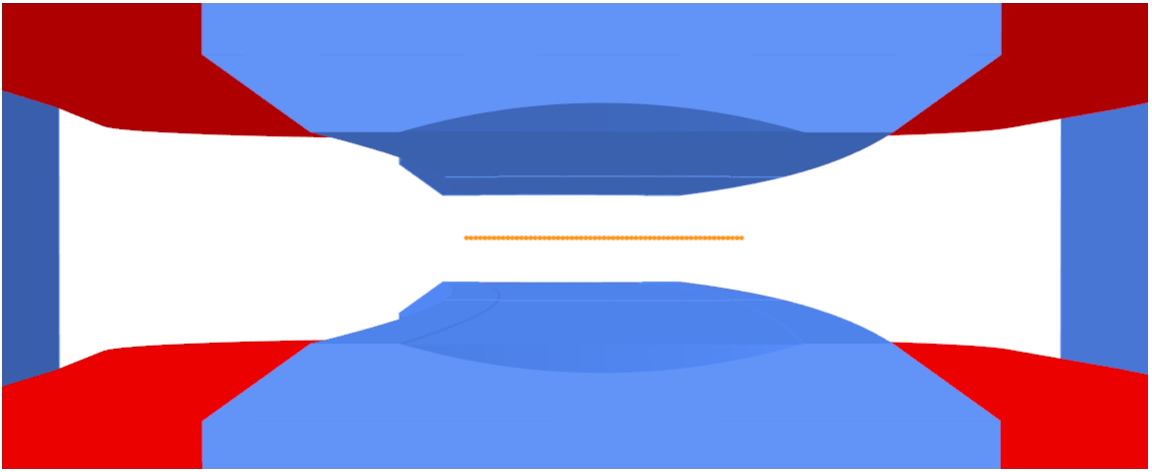
a_0:skew dipole term
a_1:skew quadrupole term

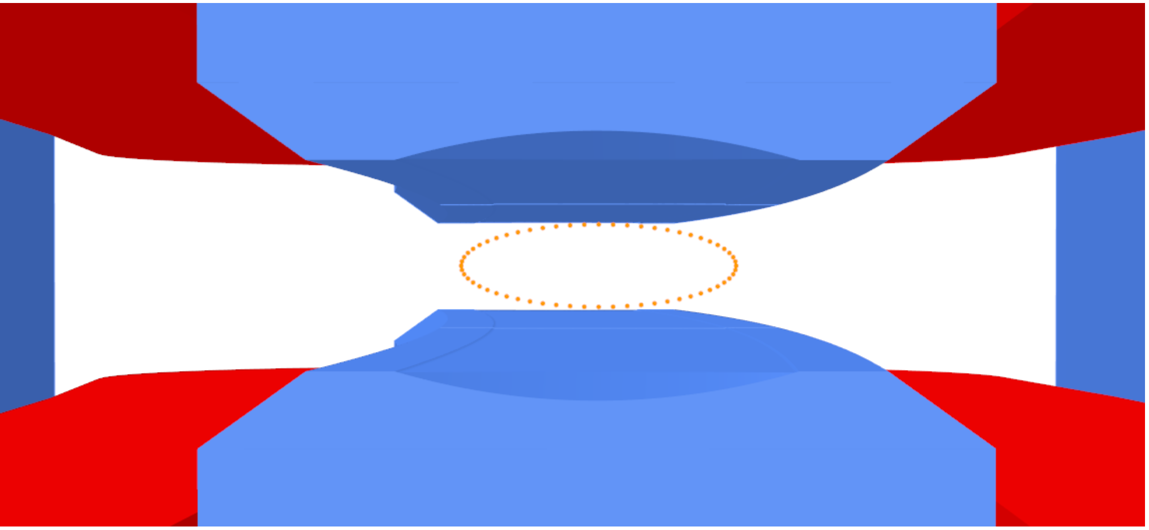
For 1D mapping, the $B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+$........ (4)

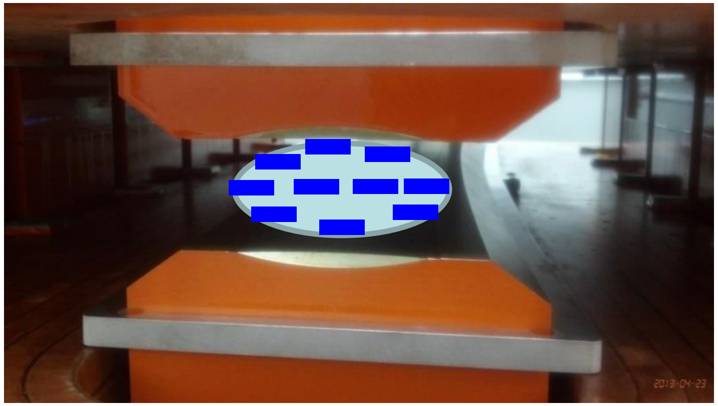
For 2D mapping $B_r(\theta)=B_y\mathrm{Sin}\theta+B_x\mathrm{Cos}\theta$ (5)

- You can measure the $B_y(x,y)$ distribution and put into the Eq(2)
- You can measure the $B_x(x,y)$ distribution and put into the Eq(3)
- You can measure the $B_y(x)$ distribution and put into the Eq(4) for least square fitting
- You can measure the $B_y(x,y)$ & $B_x(x,y)$ distribution simultaneously and combined into the Eq(5) for FFT analysis

Hall probe & stretch wire measurement in Dipole magnet







1D Measurement

- 1D least-square fitting

$B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+\ldots\ldots$

Advantage:

- Limited space measure
- Easy to get good field region

2D Measurement

(Circular or Elliptical Measurement)

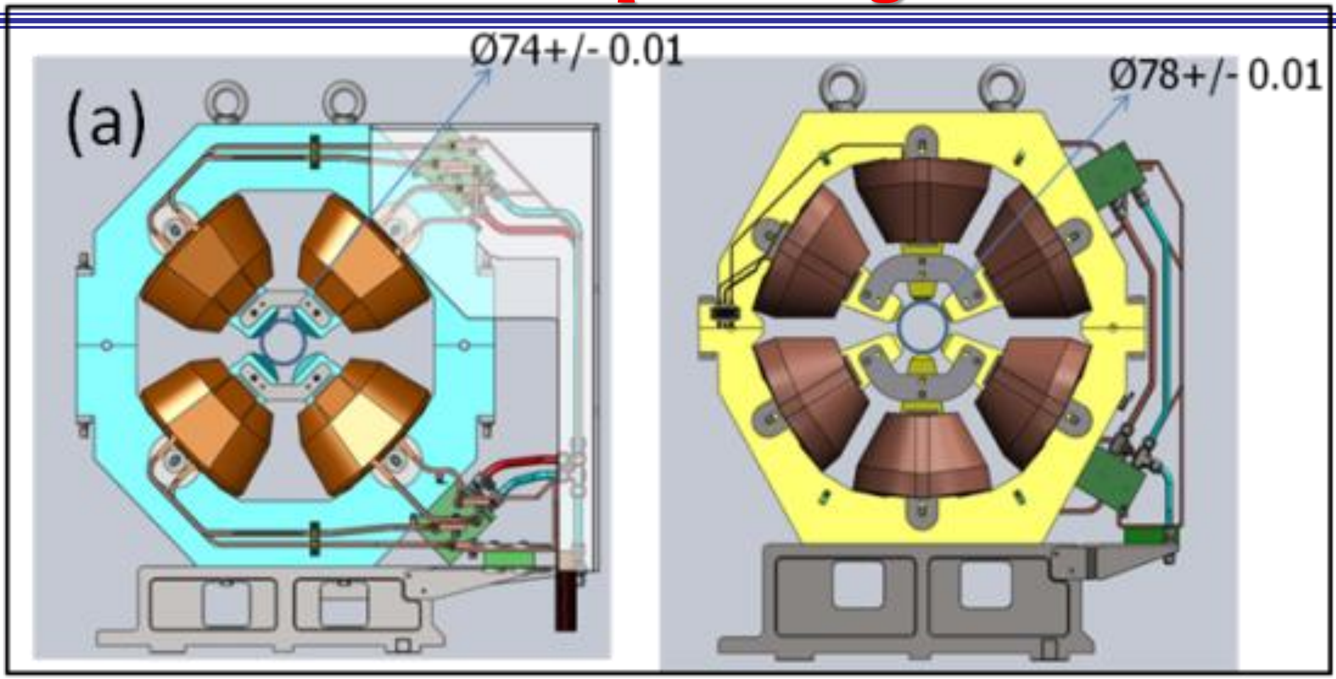
- 2D orthogonal fitting

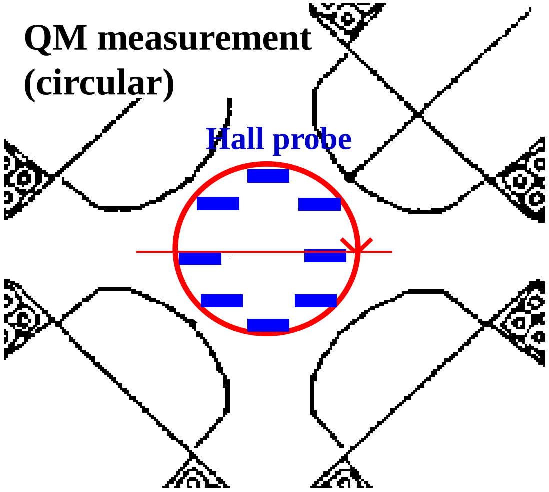
$$B_y(x,y)=b_0+a_1y+b_1x+2a_2xy+b_2(x^2-y^2)+\ldots$$

Advantage:

- More accurate
- Get skew term

Field measurement using Hall probe & stretch wire for multipole magnet





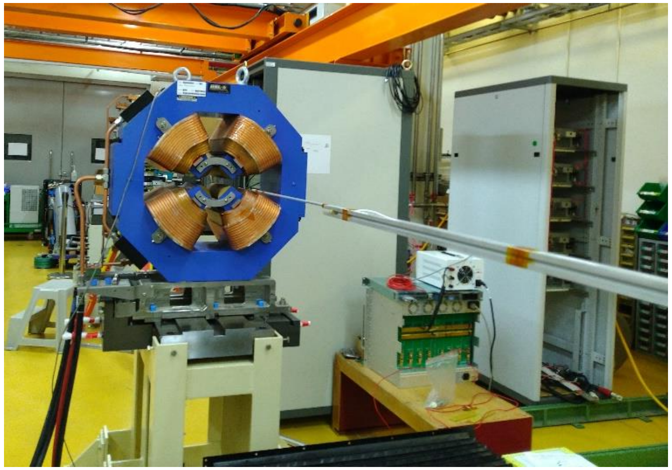
- Fixed angle with 1D hall probe and mapping on the transverse midplane $B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+\dots\dots$
- Fixed angle with 1D Hall probe mapping & stretch wire on circle trajectory to measure the vertical field $B_y(x,y)$

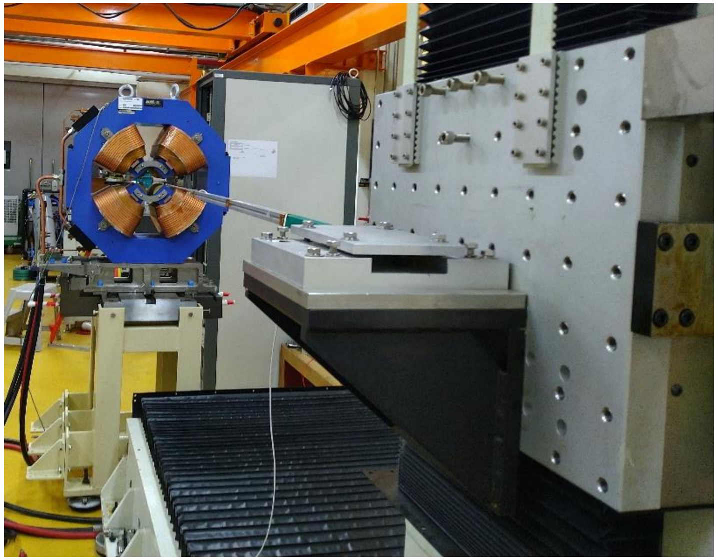
$$B_y(x,y)=b_0+a_1y+b_1x+2a_2xy+b_2(x^2-y^2)+\dots$$

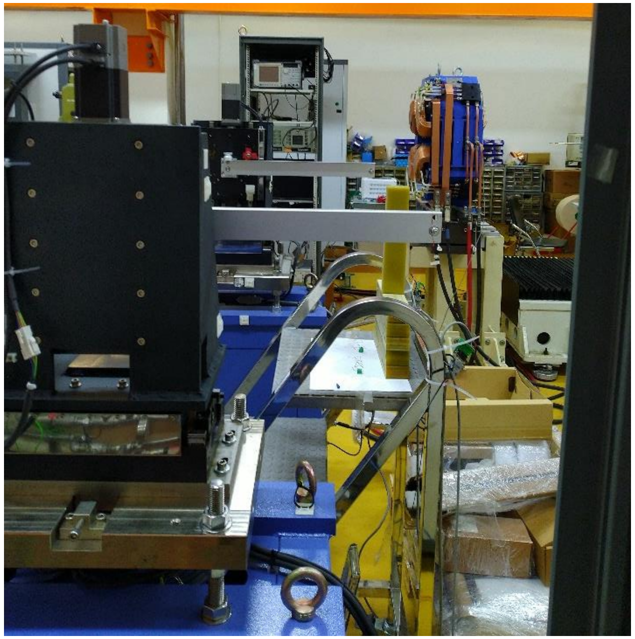
- Fixed angle with 2D Hall probe mapping & stretch wire on circle trajectory to measure the $B_y(x,y)$ & $B_x(x,y)$ for FFT analysis

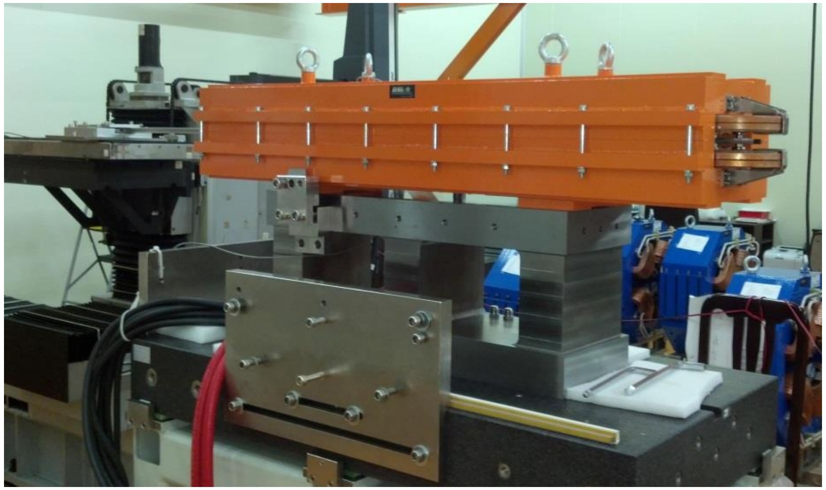
$$B_r(\theta)=B_y\sin\theta+B_x\cos\theta$$

Field measurement using Hall probe & stretch wire for lattice magnet









Introduction to magnet measurement system

- **For out-of vacuum Insertion Devices**

4.4 m long EPU field measurement

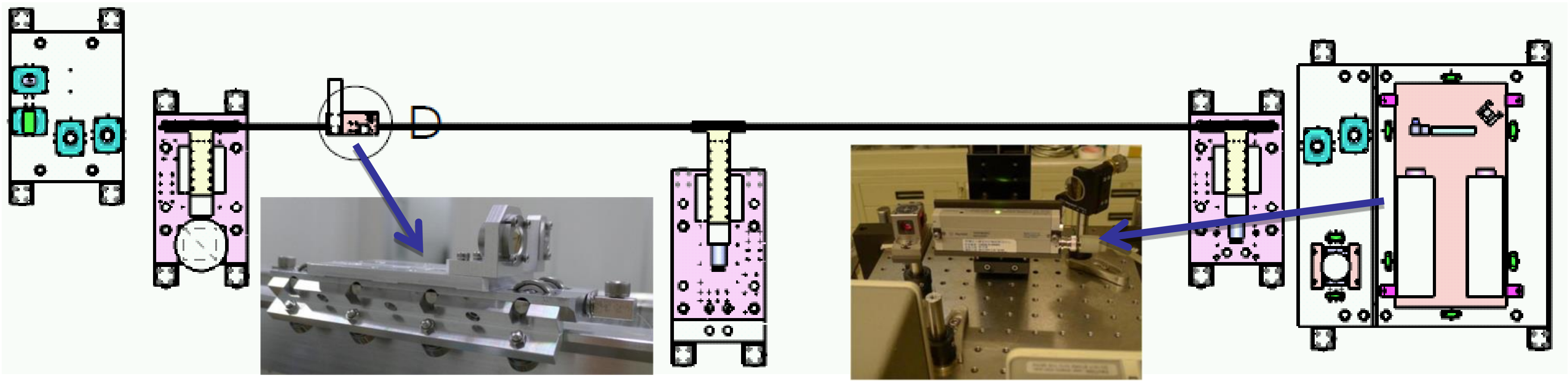
- Two EPU48 and one EPU46 in phase I had been finished.
- In phase II, one EPU66 and one EPU168 with the same mechanical structure of EPU48 are on going construction.
- The Senis 2-D Hall probe on 5.5 m long x-y-z table was use to correct the phase error of the EPU48 within 2.5 degree.
- A stretch wire system is used to measure the magnets on holder and sub-model for field sorting and also use to measure the integral multipole field in an elliptical trajectory.

Introduction to magnet measurement system

- **For In-vacuum & cryogenic Insertion Devices**

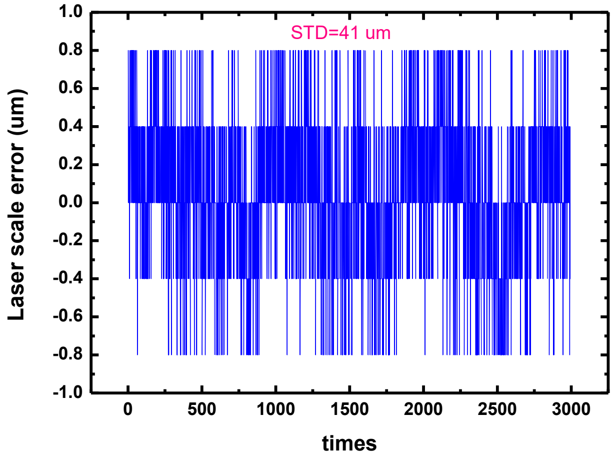
In-situ field measurement system requirements -- positions

Longitudinal axis -- Laser interferometer

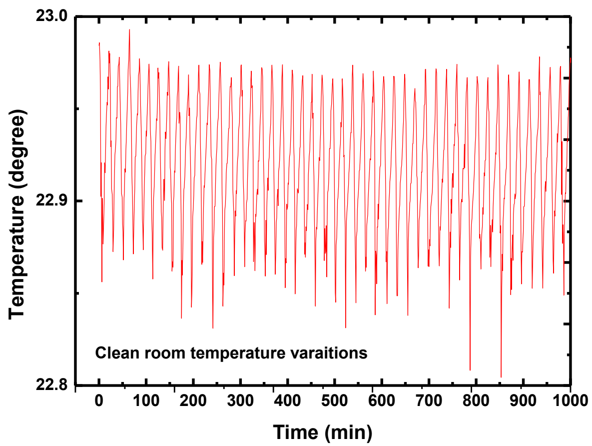


- Dual-Frequency Laser
- Minimize the temperature variations
- on the fly mode availabile

The accuracy of this system is better than 0.4 µm.

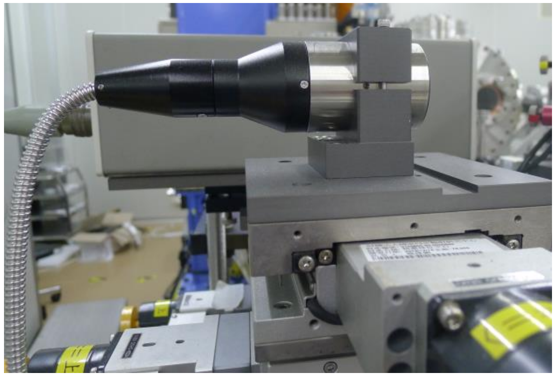
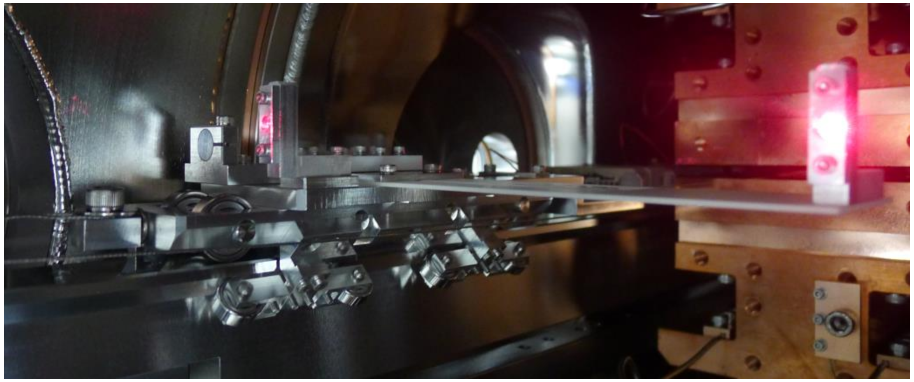
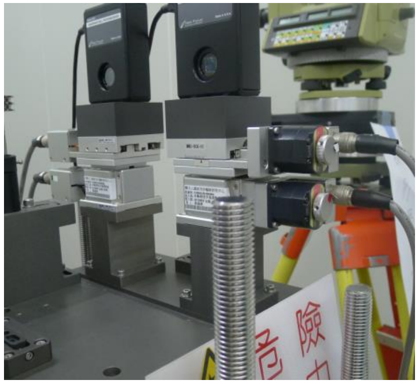


Temperature variations <0.2 ℃



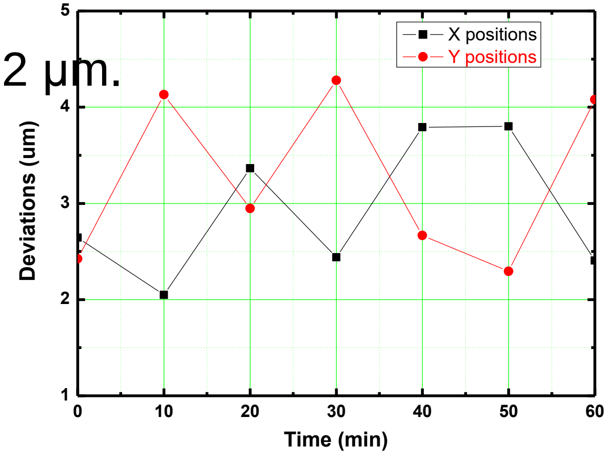
In-situ field measurement system requirements -- positions

Transverse and vertical axes – Laser diode and Quad cell PSD

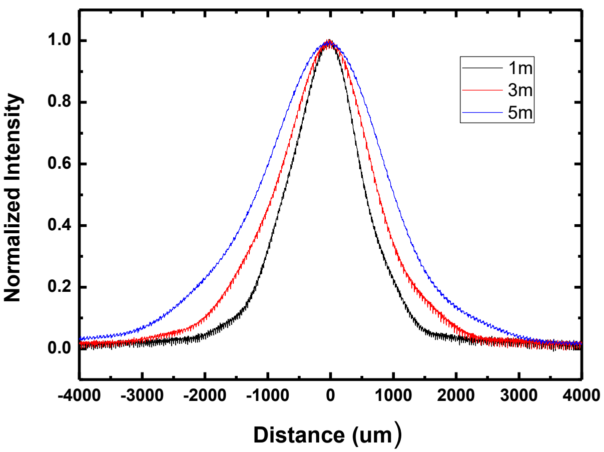




- Quad-cell instead of lateral PSD – high accuracy and resolution (1μm) , but depends on laser profile.
- Laser diode : high stability laser profile, small thermal drift < 5 μm, low pointing error < 1 μrad/C, low cost.
- Optimize beam size – diffraction, quad-cell characteristics.
- System precision better than 2 μm.

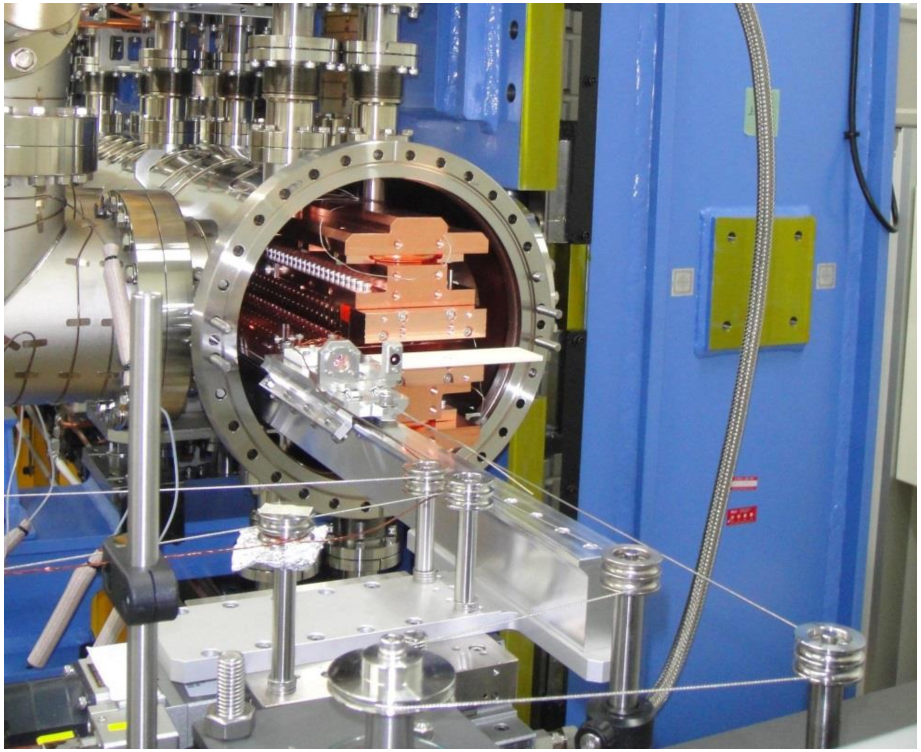
Laser beam drift



Laser beam profile



In-situ Hall probe for in-vacuum undulator (IU)

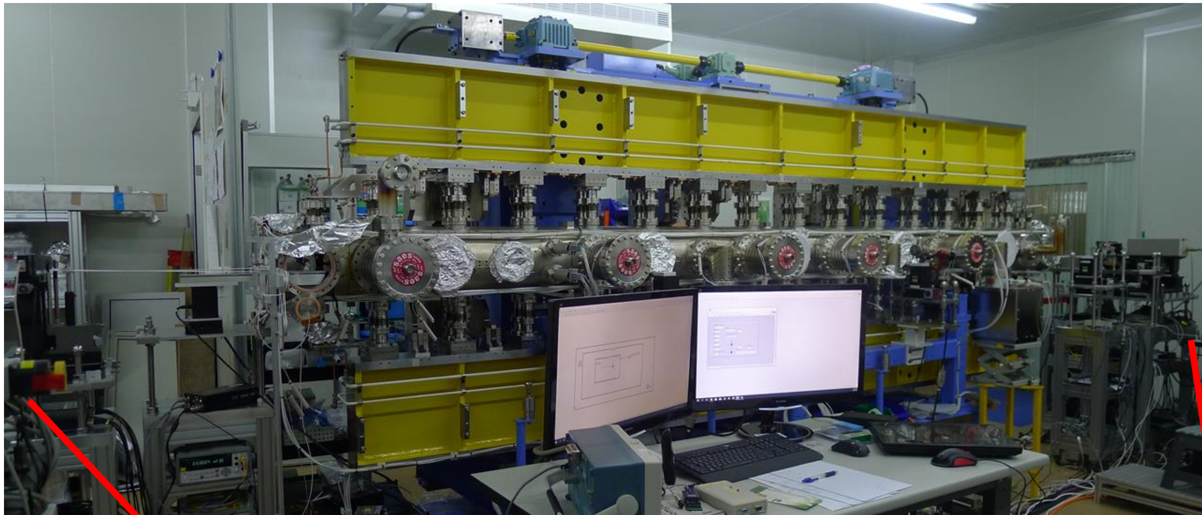


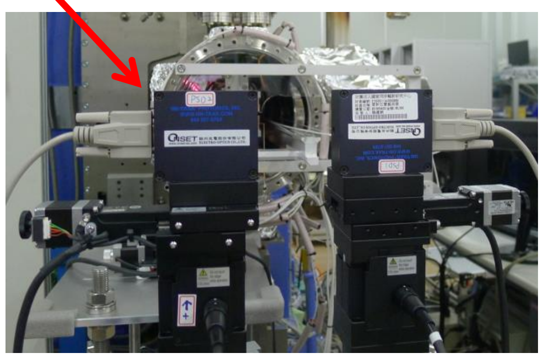
System Reproducibility

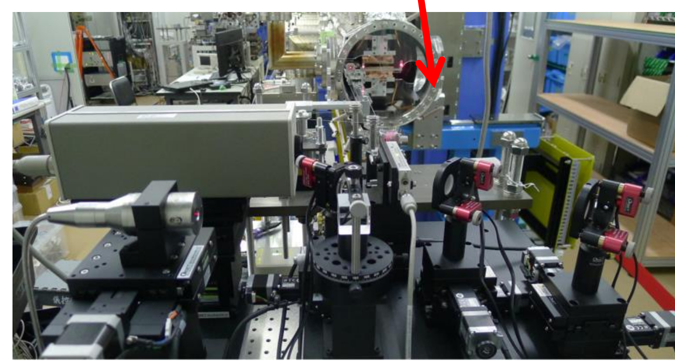
	Phase error (degree)	Half integral deviation (%)	Peak field deviation(%)
STD	<0.1	<0.1	<0.02

- Measuring magnetic field inside a vacuum chamber
- Small magnetic array gap allowable
- Dynamical monitoring and correcting Hall probe positions
- All the system components should be used in the UHV condition

In-situ measurement system for 4.5 m IU24



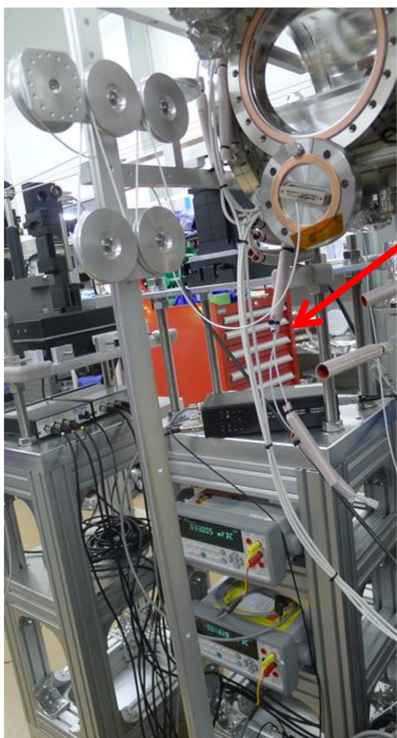




Optics design :

- One diode laser separated into two beams – cheap, more freedoms.
- Optics adjusted by stages and pico-motors –stable, fine and auto tuning available.
- Mounted on optical table – reduce vibration, fasten alignment.

In-situ measurement system for 4.5 m IU24



Signal wire collecting :

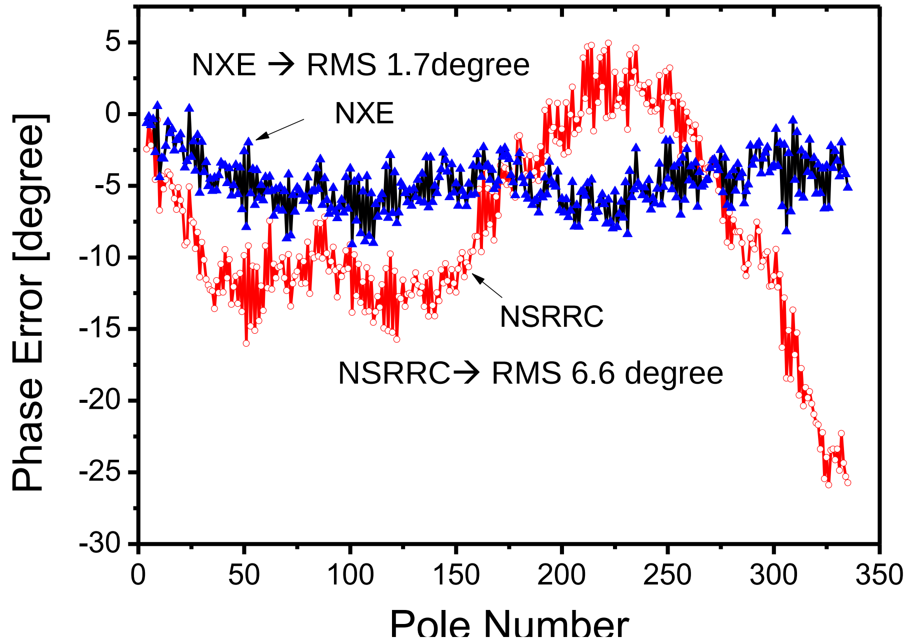
- UHV compatible
- Collecting by winding wires
- 4.5 meters available

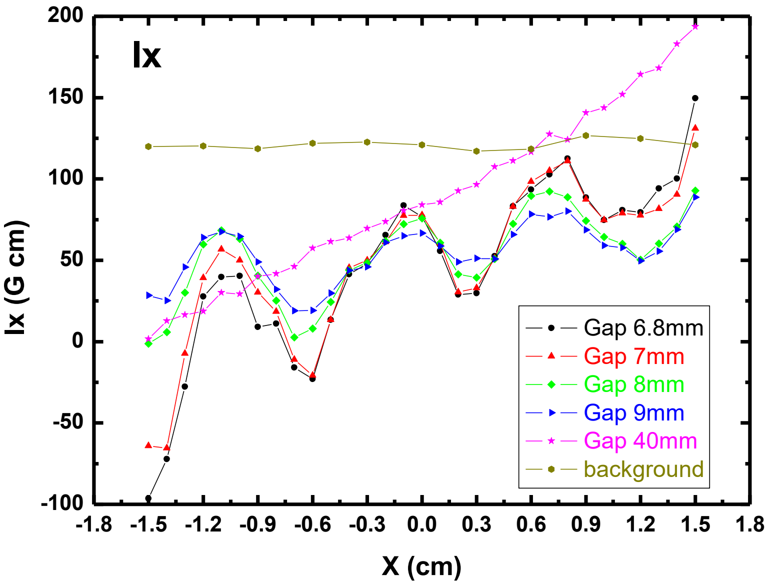
Correcting positions by stages during measurement not by calculating

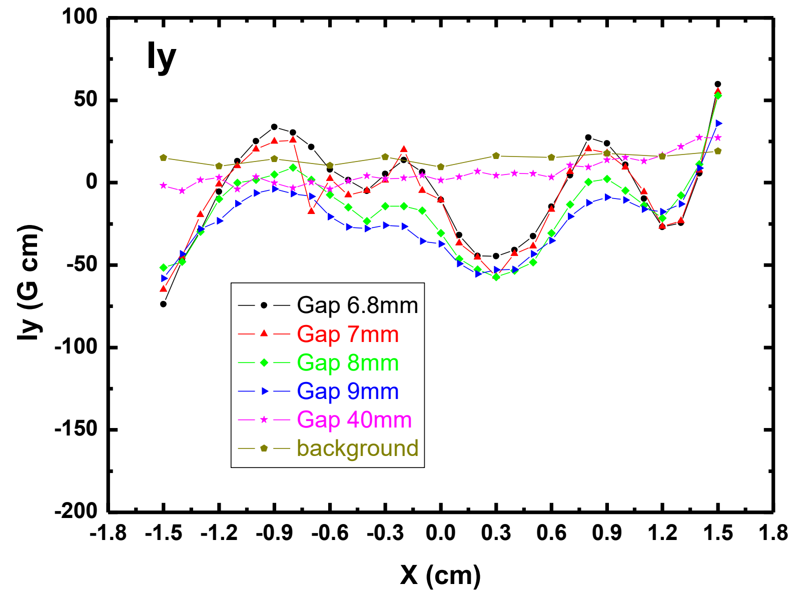
Stage movement resolution :
1 μm in x axis 0.5 μm in y axis

Field measurement of 4.5 m long IU24 by stretch wire & Hall probe

- Before transportation to NSRRC, the phase error and the multipole error is very small. However, it become worse when magnet transport to NSRRC.
- This may be come from: The field error due to the baking or the temperature variation & the large vibration in the transportation.

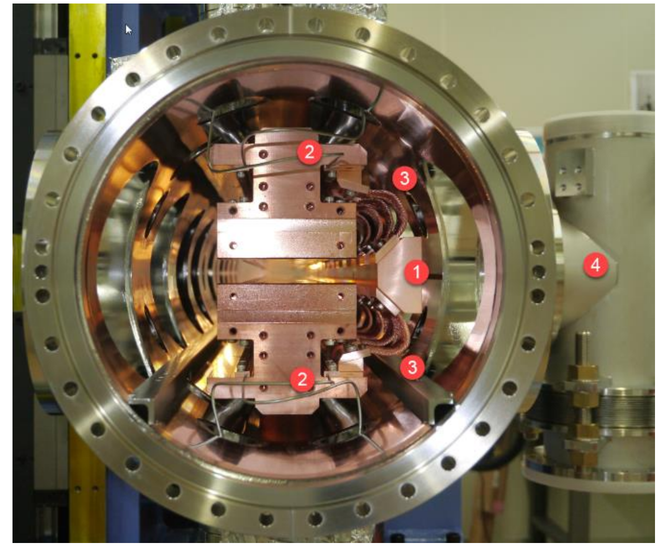






TPS CPMU, CU15

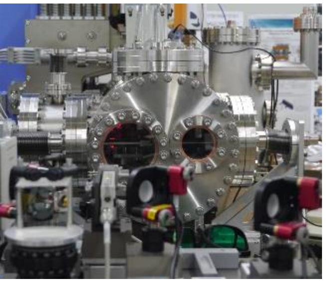
Inner structure



Overall structure

1. **Thermal conductor bar**
2. **Heaters**
3. **Flexible thermal straps**
4. **Insulated vacuum for cold-heads**

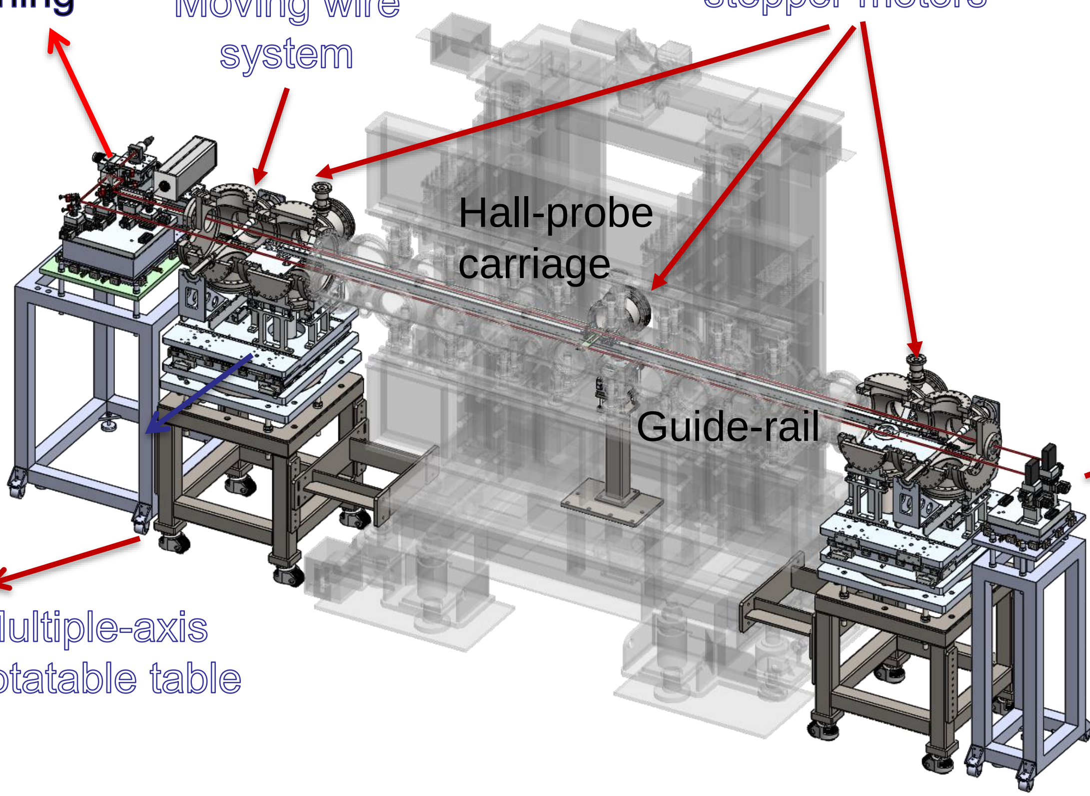
In-situ measurement system for CPMU CU15



- Measuring magnetic field distributions and integrals in vacuum and low temperature environments.
- Small magnet gap of 3mm is allowable.
- Dynamical monitoring and correcting Hall probe positions.
- On-the-fly measurement.

Reproducibility

	Phase error (degree)	First field integral (G.cm)	Peak field deviation (G)
STD	<0.2	0.9	0.2

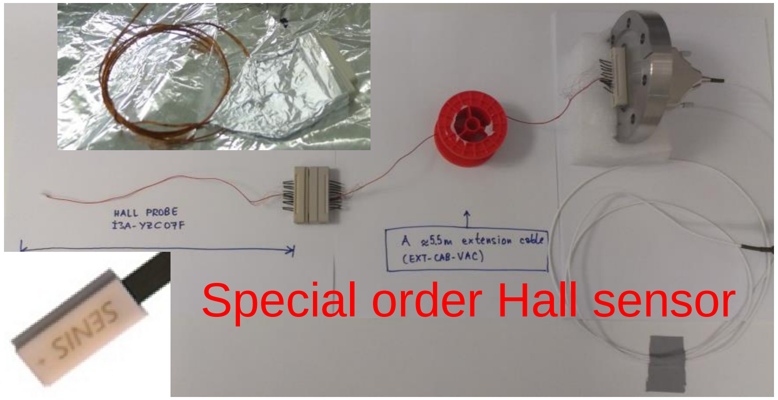


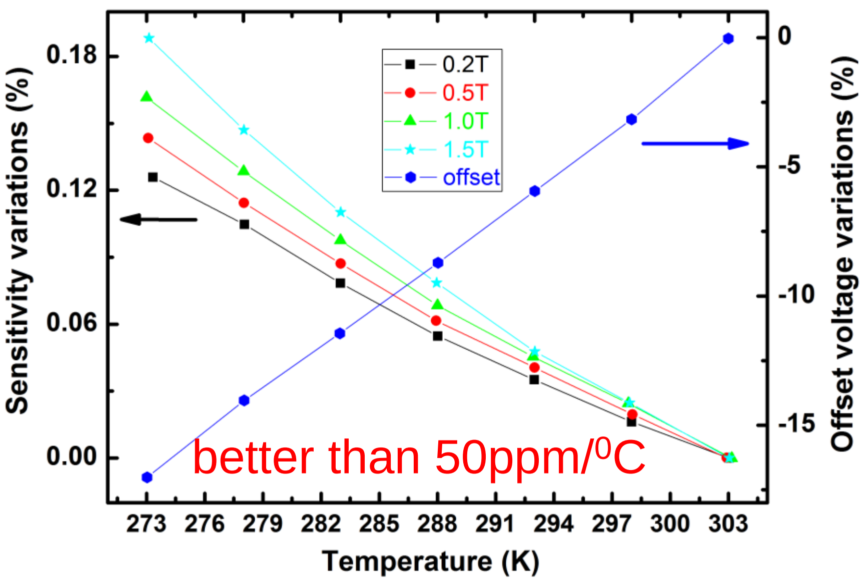
Senis Hall probe for CPMU CU15

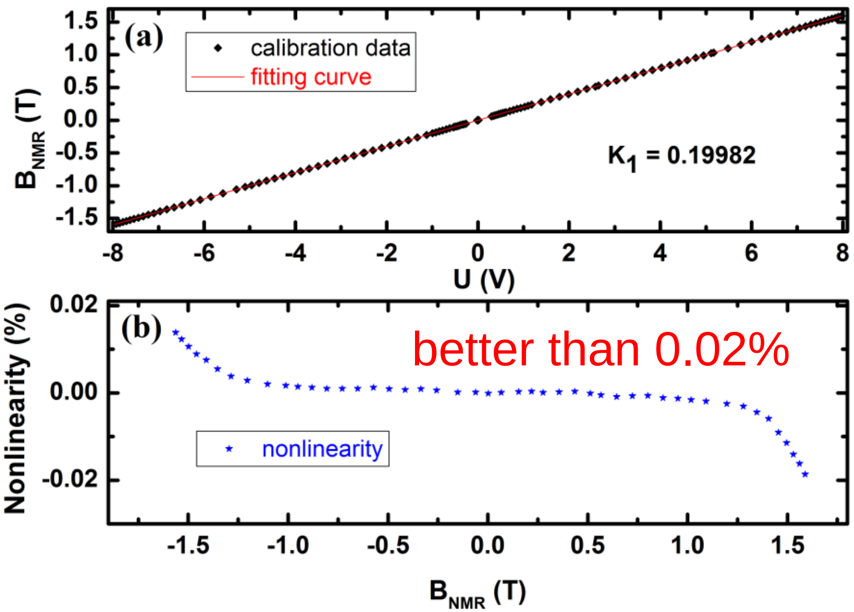
Senis probe :

- **Ceramic package and home made kapton insulated wire and peek D-sub connect.**
- **low non-linearity, angle error, and planar Hall coefficient**
- **high reproducibility**
- **Low temperature dependence**

	SENIS specifications	Measurement results	
Angular accuracy of axes with respect to the reference surface	< ±0.5⁰	~ 0.1 ⁰	error ~0.02G
Planar Hall coefficient	< 0.01 %	~ 0.007%	error ~0.01G

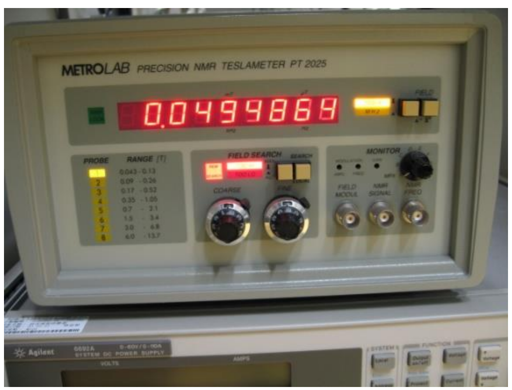






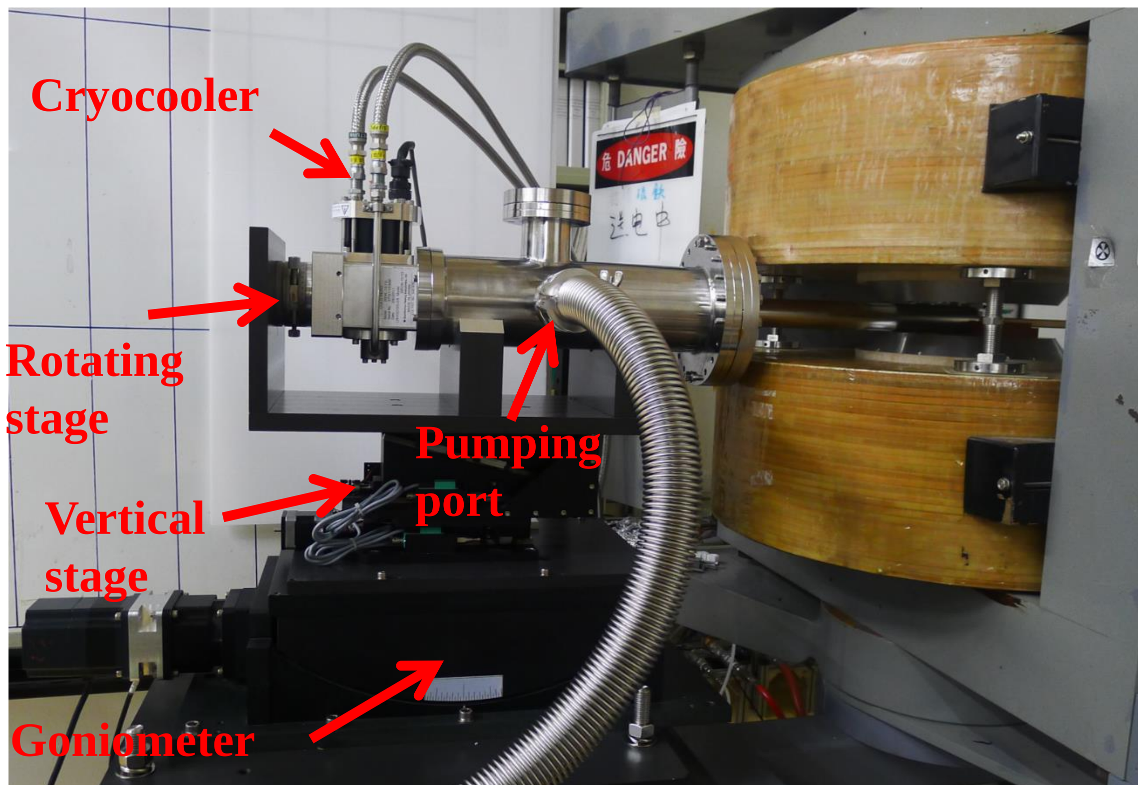
Low temperature Hall probe calibration system

- Calibrate a Hall probe at different temperature and field strength
- Fine adjustment for height, rolling, and pitch of a Hall probe to Minimize the error of Hall sensor angle and position during calibrations.
- Temperature as low as possible (not only for CU but also Superconducting magnets)

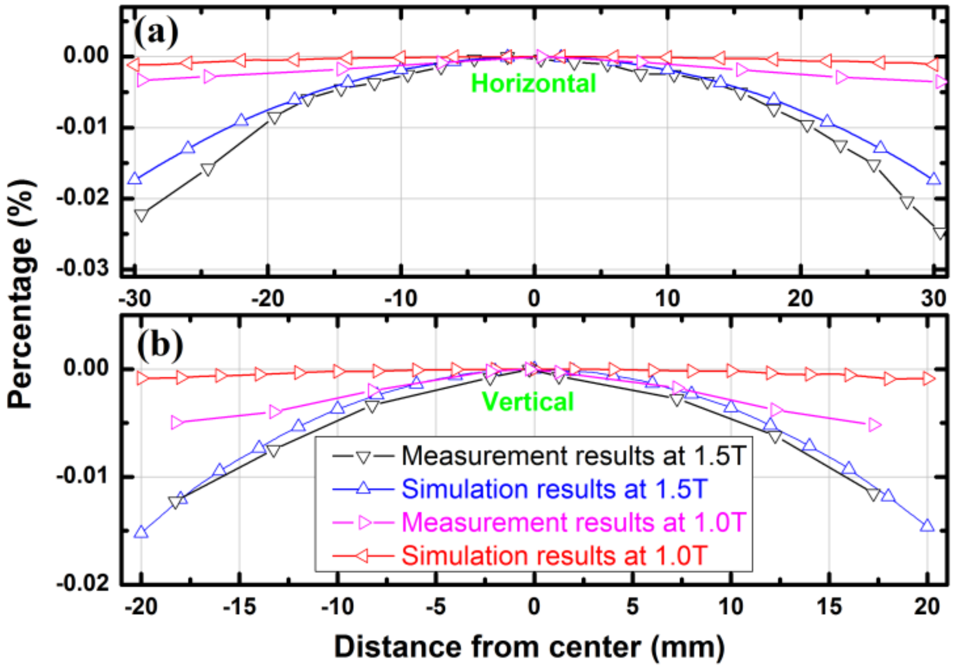


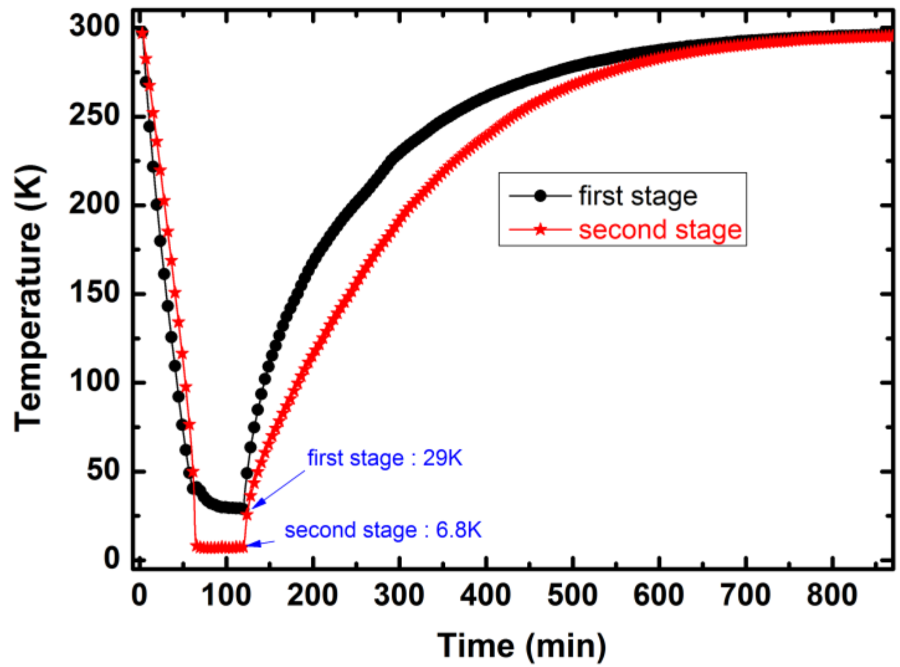
METRO-Lab Precision NMR Tesla-meter (PT2025)

Agilent Power supply



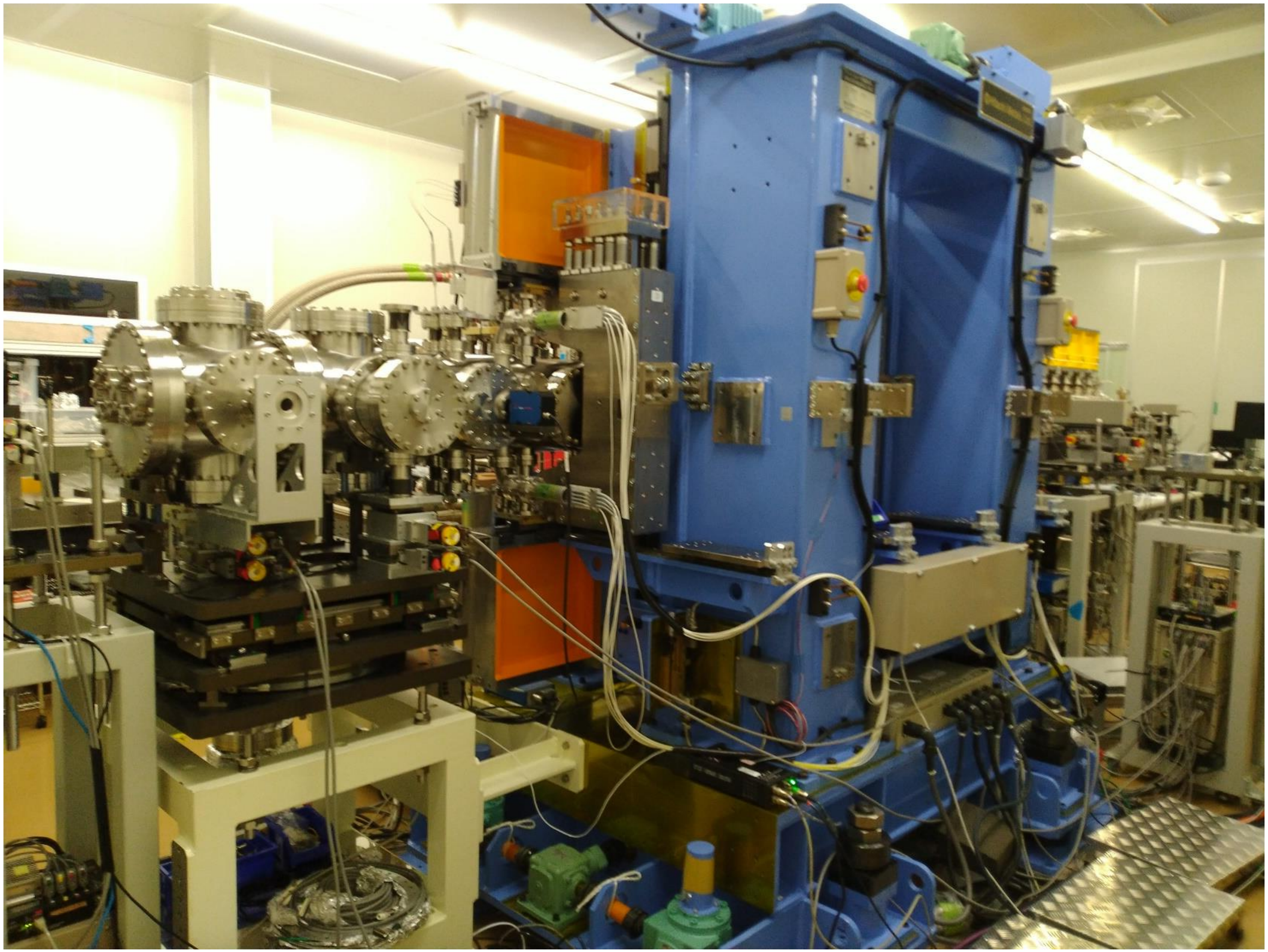
Calibration system performance



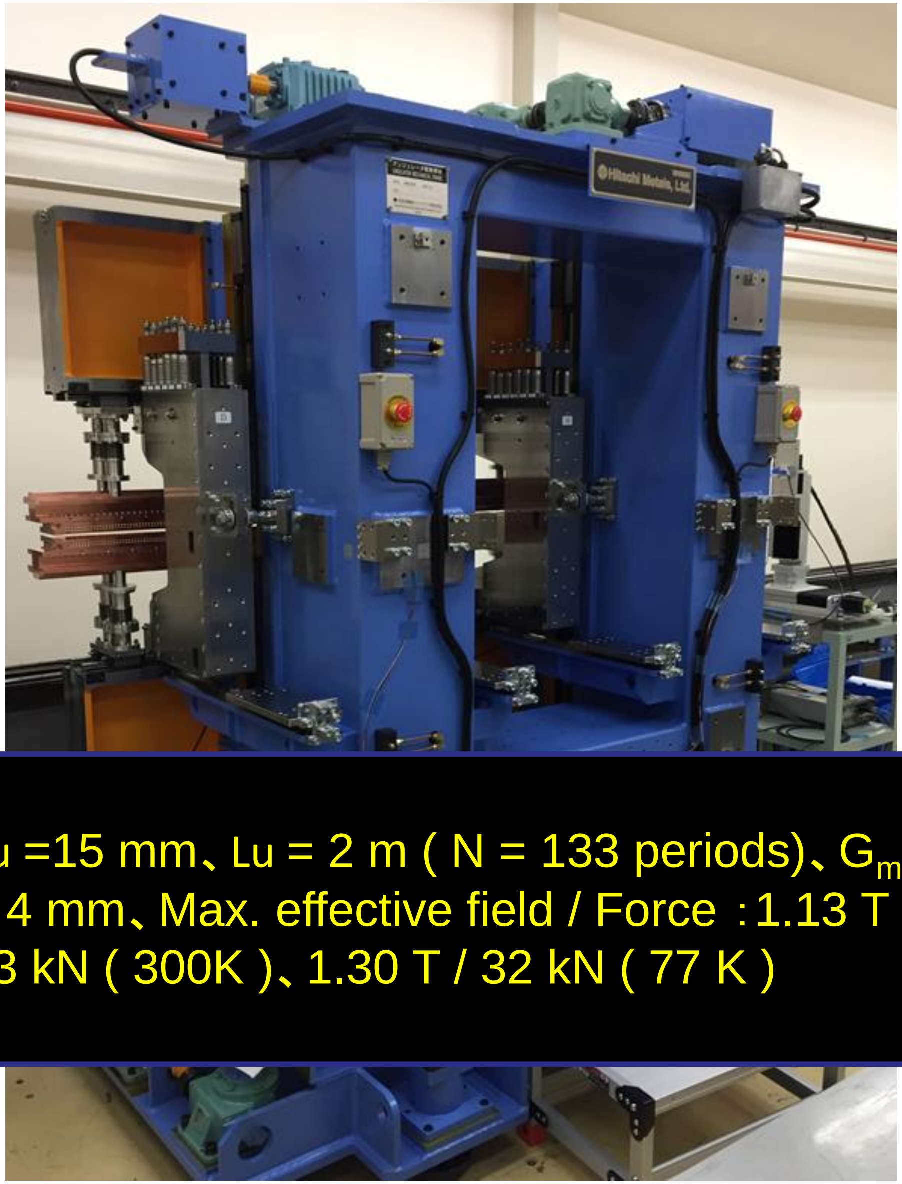


- Using cryocooler – the temperature can reach 10K, temperature variation ~ ±0.1K.
- Multi-axis probe available.
- Field difference between a Hall probe and NMR probe is smaller than 0.1G.
- Rotatable plate – resolution is 0.3 mrad. It can determine the Hall probe angle error and planar Hall coefficient.

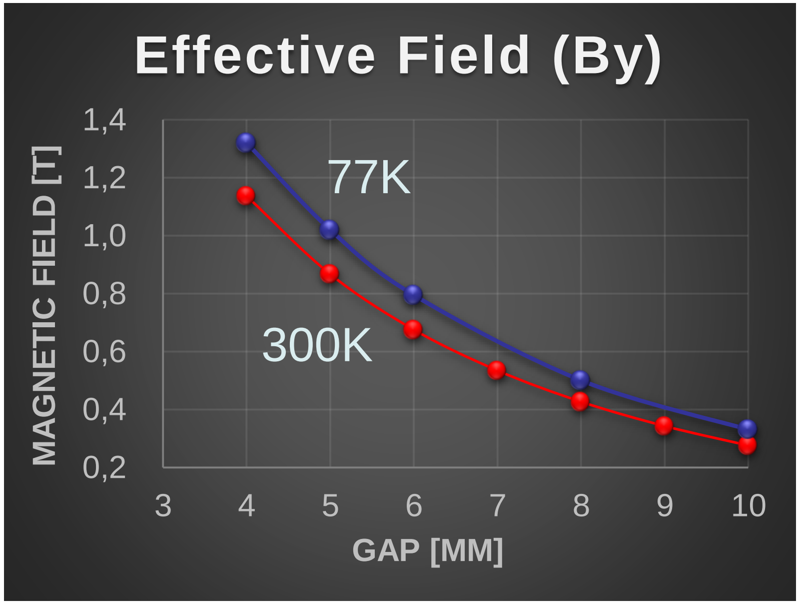
Stretch wire and Hall probe on the same In-situ measurement system for the CPMU CU15

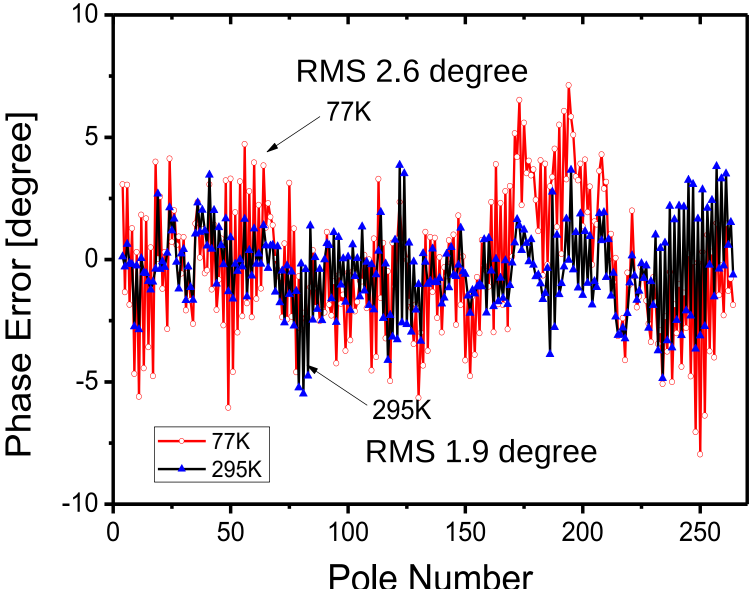


Magnetic performance of the CU15



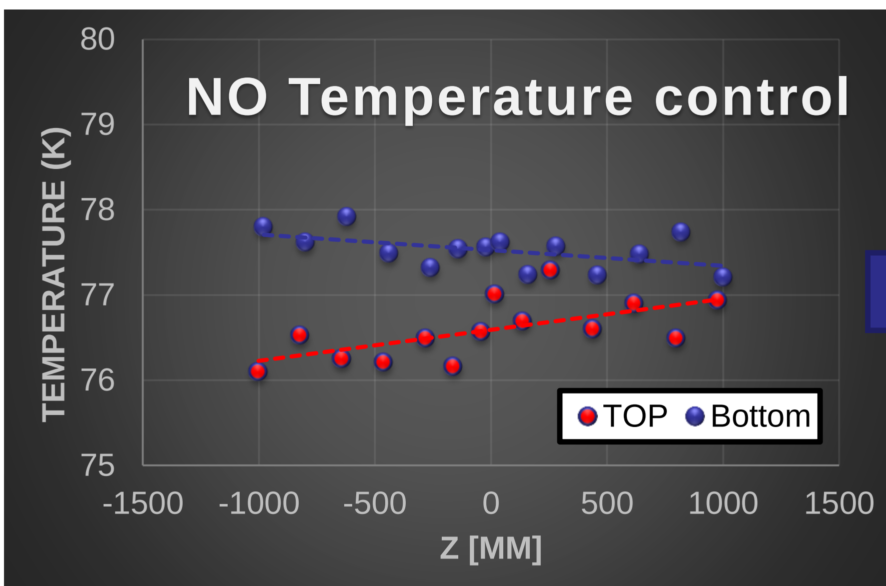
λu =15 mm、Lu = 2 m (N = 133 periods)、G_{min} = 4 mm、Max. effective field / Force ：1.13 T / 23 kN (300K)、1.30 T / 32 kN (77 K)

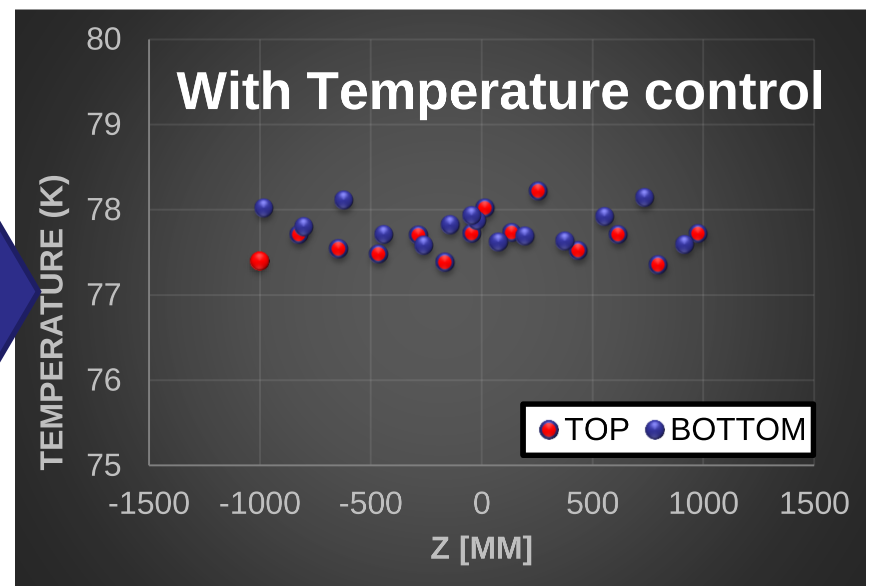




Cooling performance of the CU15

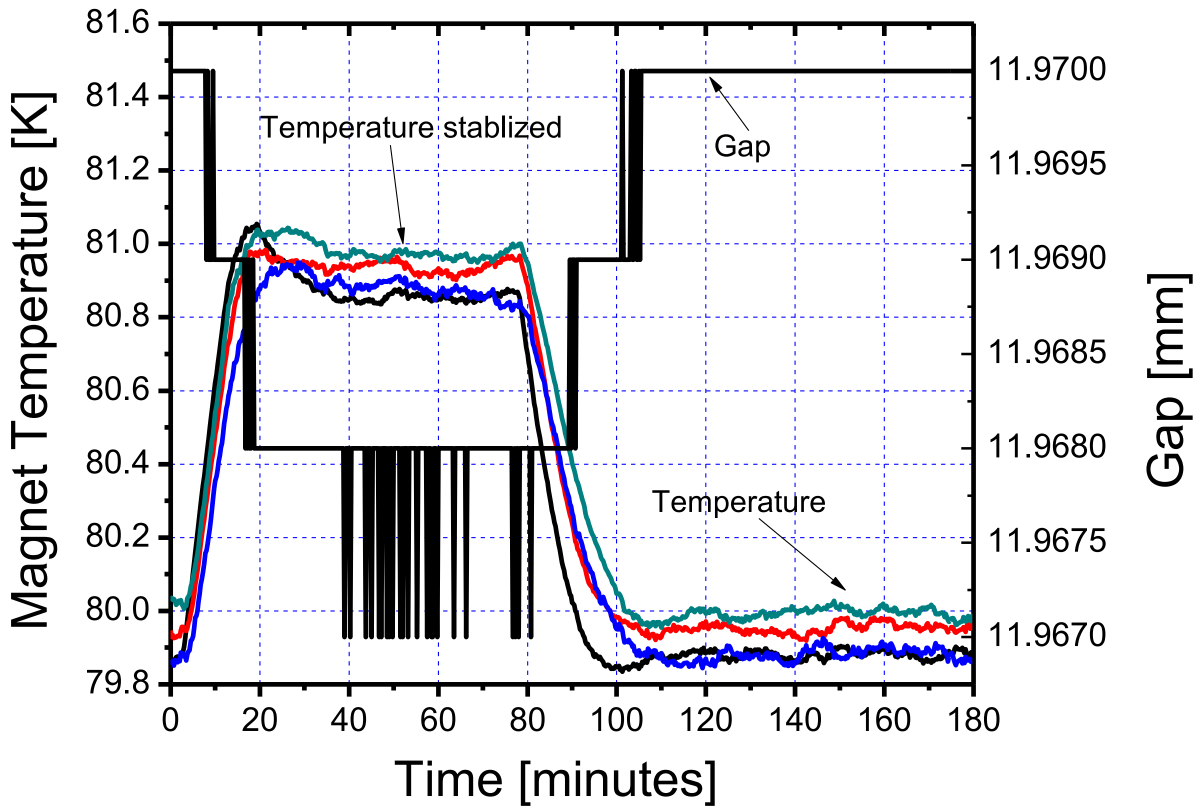
- The lowest achievable temperature of PMs is ~ 60 K in 48 hours. (cold-head : 45 K, thermal conductor bar: 57 K)
- If the temperature of PMs is controlled to ~ 80 K, the cold head is 48.5 K, thermal conductor bar is 70 K.
- In magnet arrays, the temperature variation within ± 0.4 K with temperature control system. (PT100 is calibrated , the tolerance is within ± 0.1 K).
- At ~ 80 K, the magnet gap is 0.99 mm wider.
- Total shrinkage of a 2m-copper-magnet-array is 5.65 mm.





Stability of the temperature of magnet arrays

A Gifford-McMahon cooler (with a cooling capacity of 200W per each at 80K) was adopted to minimize the undulator vibration amplitude. The temperature control system on the magnets is consist of eight sheath heaters (38Wx8) are installed along the magnet arrays with high precision PID temperature controllers (RKC HA900). During a non-stop test for 30 days, the current temperature control system has been shown to provide a stable temperature within ± 0.05 K and a constant gap within ± 0.125 um.



Summary

- The 3D coordinate mapping method by Hall probe and stretch wire can be used to measure & analyze all diffraction-limited storage ring accelerator magnets and the ID.
- The reproducibility of the in-situ field measurement system in room or cryogenic temperature is 0.2^{o}, 0.9 Gcm and 0.2 G for the STD phase error, integral field strength, the peak field, respectively.
- A 4.5 m IU24 and 2.4 m CPMU CU15 has been measured by using the same in-situ measurement system include Hall probe & stretch wire.
- The temperature control can reduce the residual temperature gradient and temperature variations along the 2m-magnet- array are below ± 0.4 K.
- A tuning of spring-settings of 2.4 m CU15 and 4.5 m IU24 will be performed to achieve low phase errors.

Thank you for your attention