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

Overview of magnetic field measurement in NSRRC

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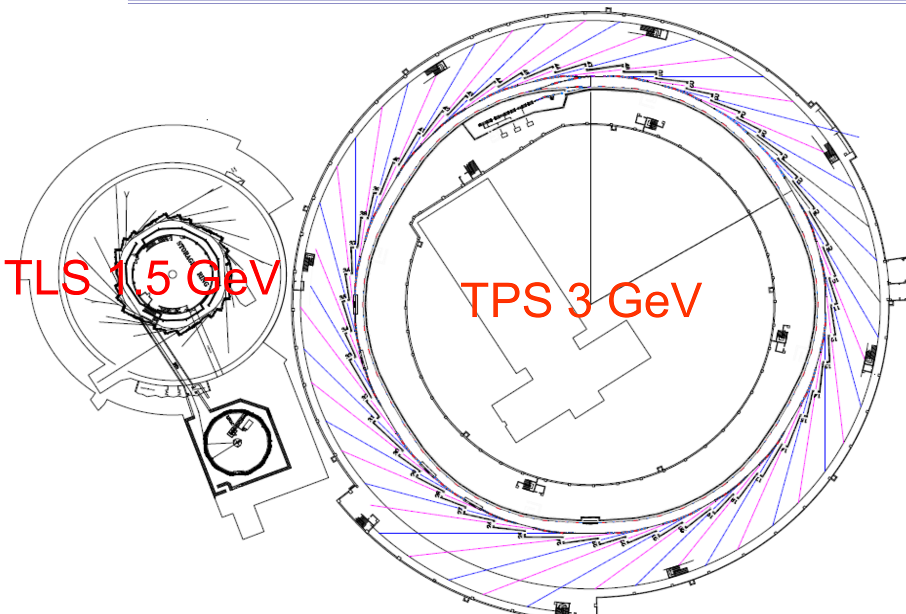
Outline

- Introduction
- Field measurement concept for various magnets
  - Superconducting undulator & wiggler, In-vacuum & Cryogenic undulator, Out-of vacuum ID, Accelerator magnet, Pulse magnet
- Various field measurement system & its precision
  - Hall probe, stretch wire, long coil, Helmholtz coil, in-situ field measurement in UHV & cryogenic system, search coil, et al
- Field analysis and measurement results
- Relative issue discussion
- Summary

Aerial view of NSRRC campus

Operating two Light Sources in NSRRC



		TLS	TPS
Energy	GeV	1.5	3.0
Circumference	m	120	518.4
Top-off Beam current (target)	mA	360	300 (500)
Lattice		TBA	DBA
Cell number		6	24
Nat. emittance	nm rad	25.6	1.6
Open to users		1994	2016

◆Currently, the beam current have been operated at 400 mA with minimum gap of ID

- **Field measurement concept for various magnets**

2-D analytic Methods of Hall probe & stretch wire

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

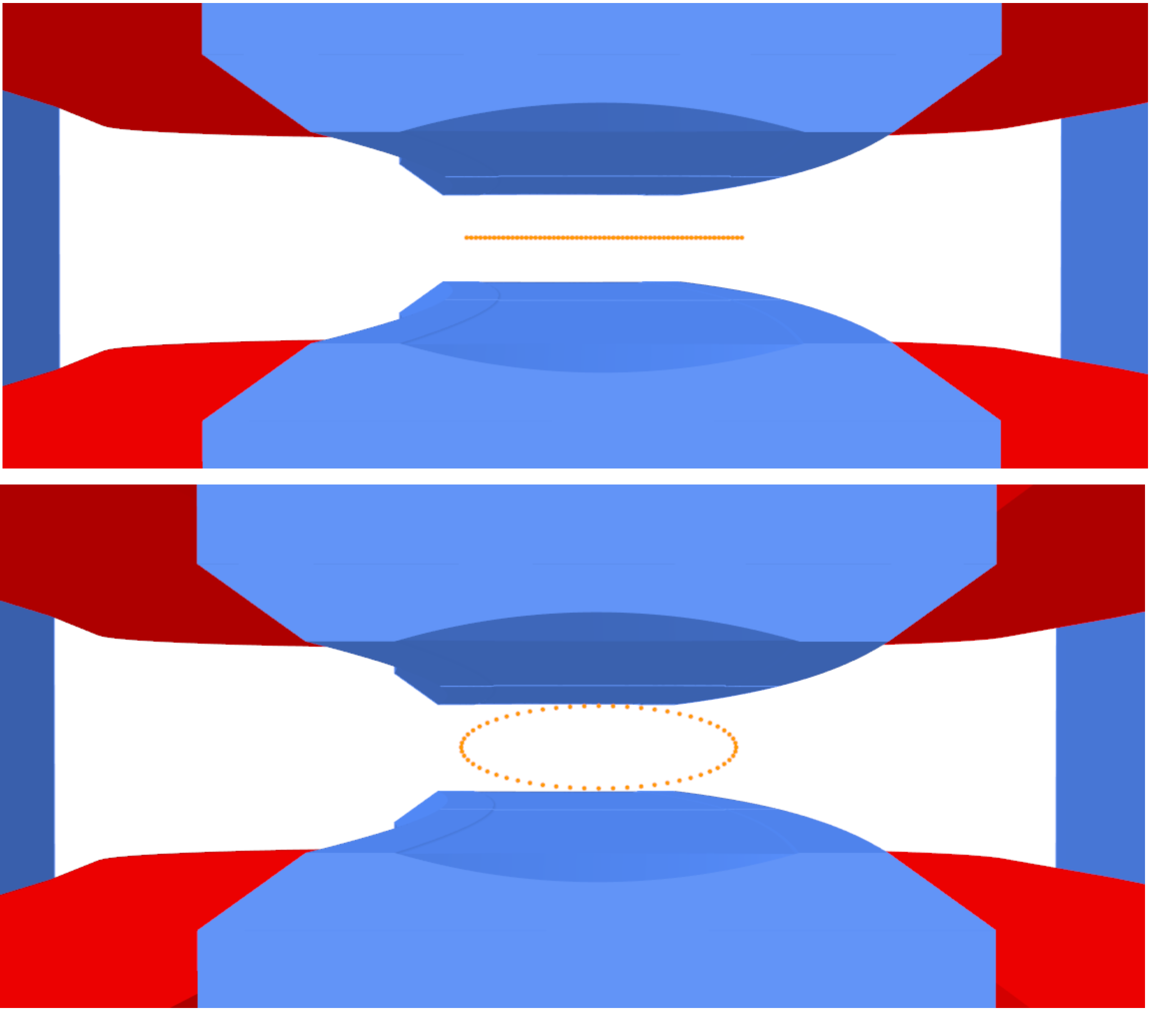
a_0:skew dipole term
a_1:skew quadrupole term

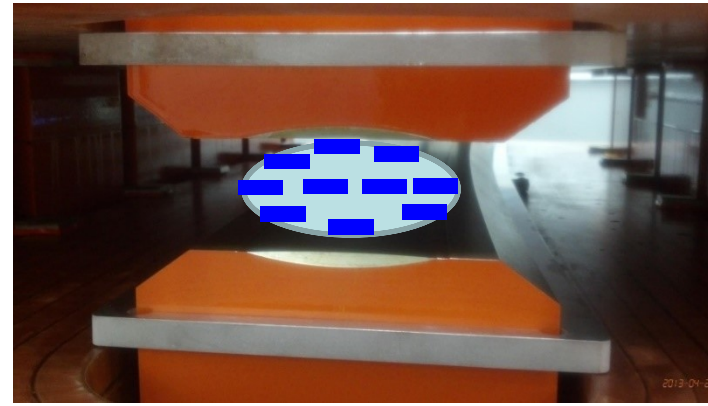
For 1D mapping, the $B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+\ldots\ldots$ (4)

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) for least square fitting
- You can measure the $B_x(x,y)$ distribution and put into the Eq(3) for least square fitting
- 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
- Fast Fourier Transform(FFT)

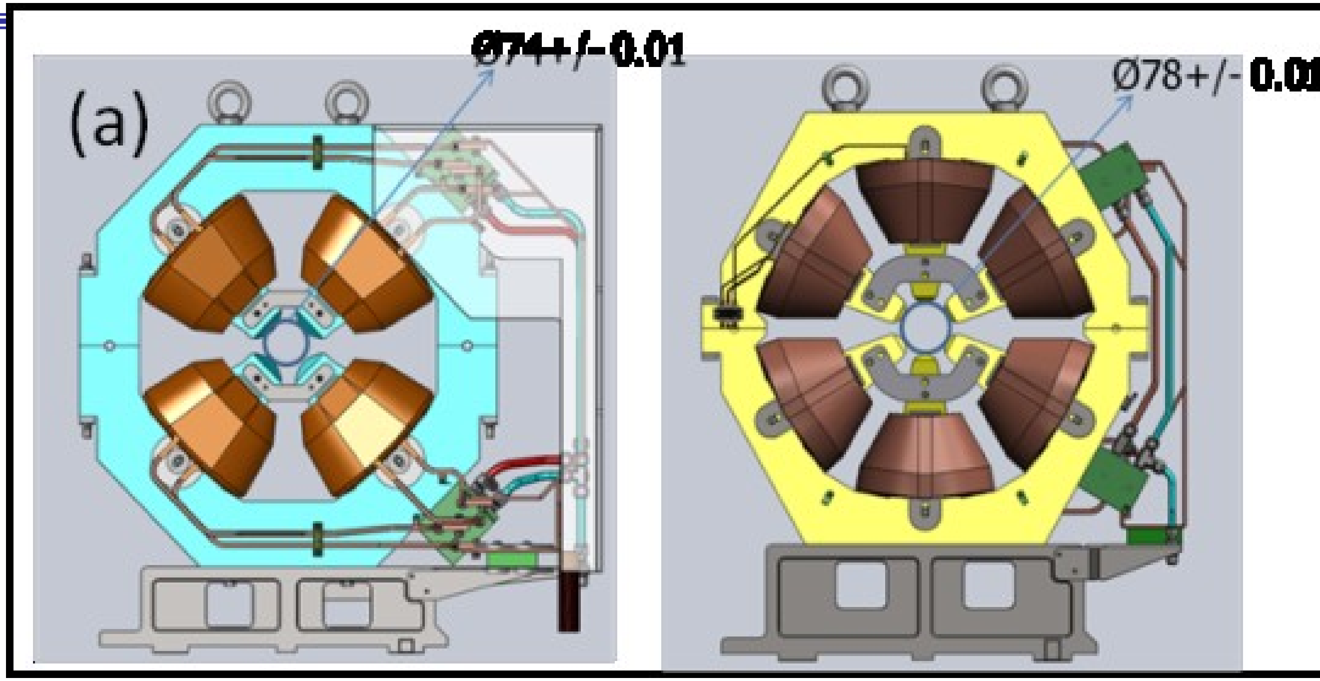
$$B_y(x,y)=b_0+a_1y+b_1x+2a_2xy+b_2(x^2-y^2)+\ldots$$

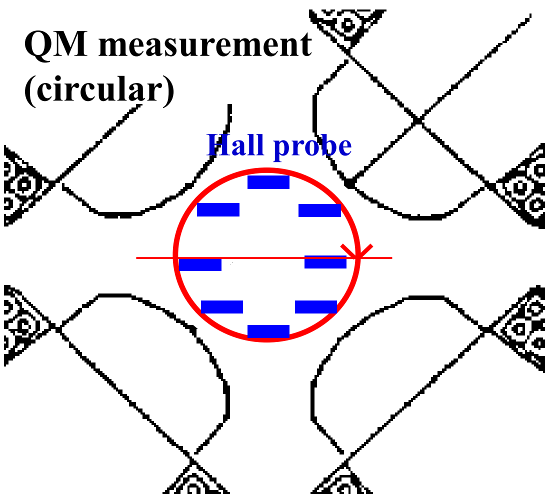
$B_r(\theta)=B_y\sin\theta+B_x\cos\theta$ for FFT analysis

Advantage:

- More accurate
- Get skew term

Hall probe measurement for multipole magnet





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

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

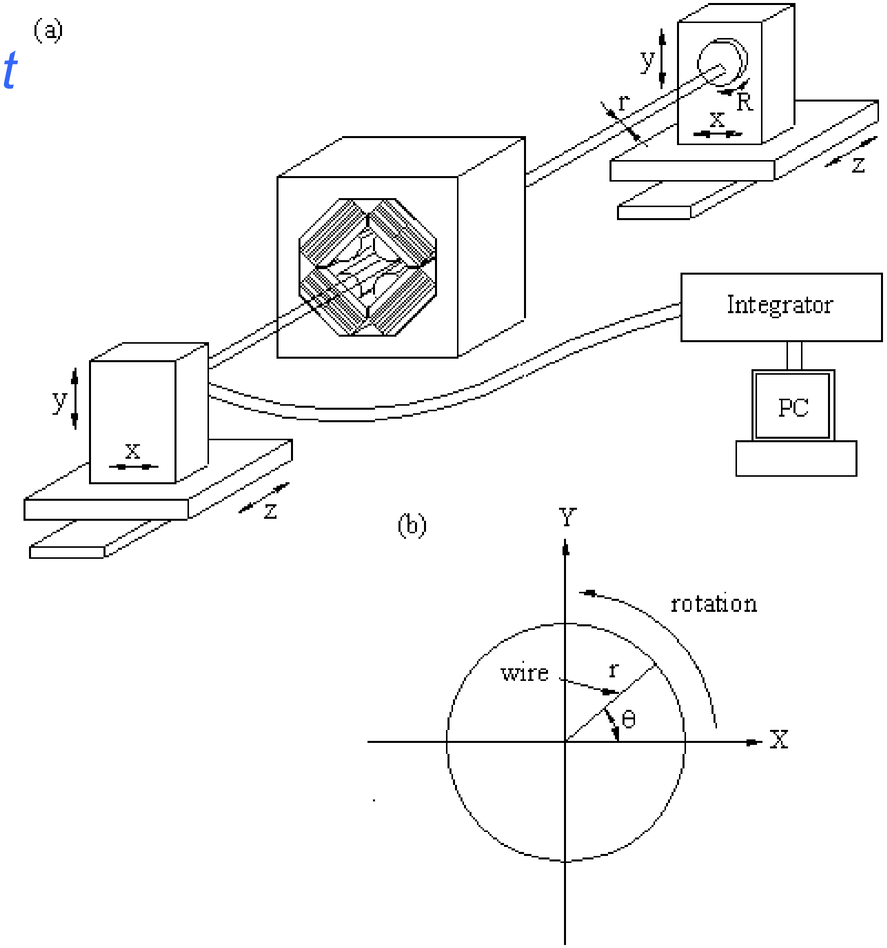
- Fixed angle with 2D Hall probe mapping on circle trajectory to measure the $B_y(x,y)$ & $B_x(x,y)$ for FFT analysis

$$B_r(\theta)=B_y\mathrm{Sin}\theta+B_x\mathrm{Cos}\theta$$

long loop coil system for lattice magnet

Harmonic field components measurement

$$\int_{t(\theta_i)}^{t(\theta_{i+1})} V dt = N \int_{-\frac{L}{2}}^{\frac{L}{2}} dz \int_{\theta_i}^{\theta_{i+1}} B_r R d\theta$$



$$A_{n,j}^{skew} = \frac{r_{ref}^{n-j} A_n}{B_{ref,j}}$$

$$B_{n,j}^{nor} = \frac{r_{ref}^{n-j} B_n}{B_{ref,j}}$$

$$\sum_{n=1}^{\infty} a_n cos(n\theta) + b_n sin(n\theta) = \sum_{n=1}^{\infty} \frac{2R^n N}{n} [A_n cos(n\theta) + B_n sin(n\theta)] sin\left(\frac{n\Delta\theta}{2}\right)$$

- The analysis method is the same as the rotating coil

Stretch wire measurement for multipole magnet

- Stretch wire mapping on circle trajectory to measure the vertical field $B_y(x,y)$

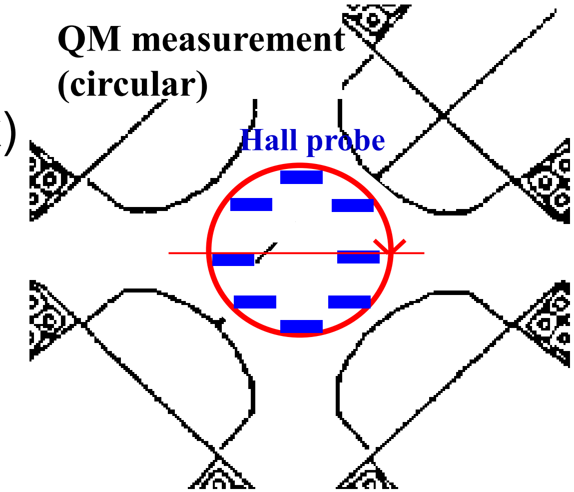
$$B_y(x,y) = b_0 + a_1 y + b_1 x + 2a_2 xy + b_2(x^2 - y^2) + \dots$$

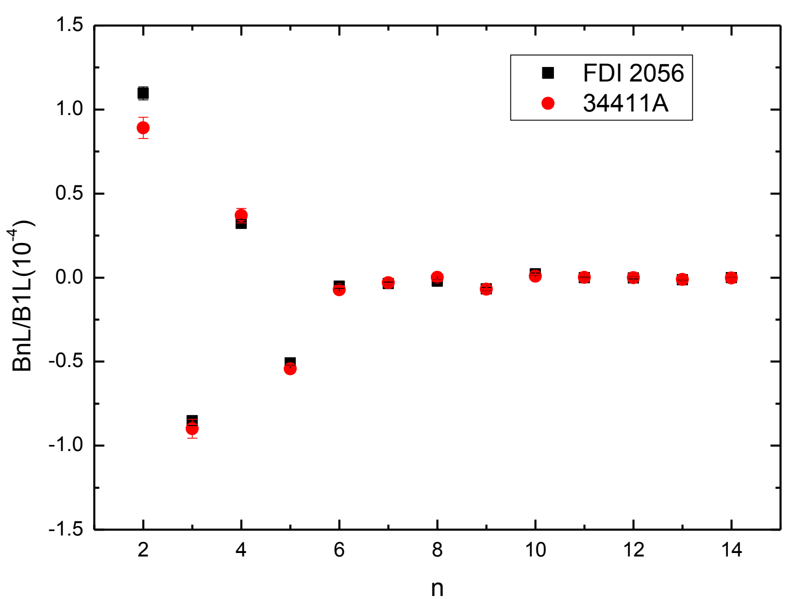
- Stretch wire mapping on tranverse axis to measure $B_y(x)$

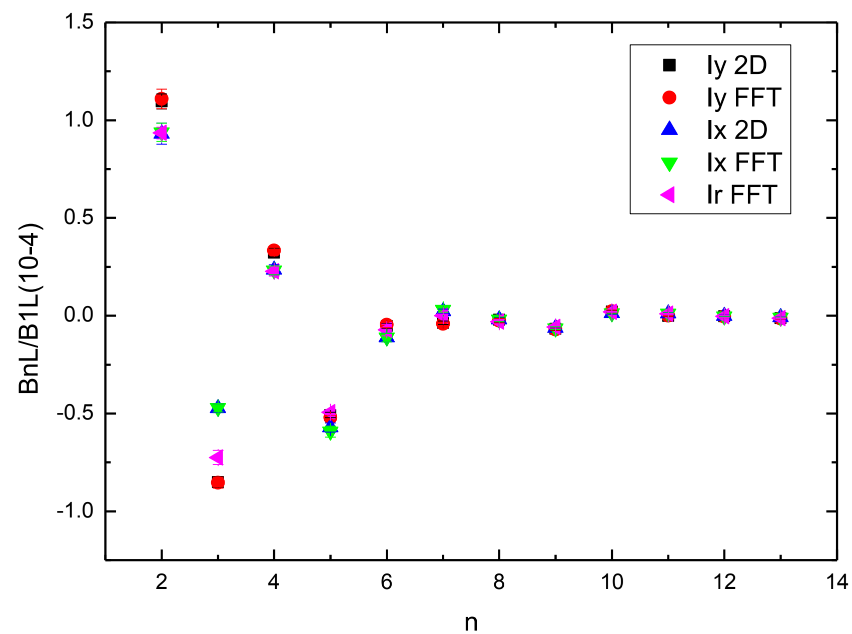
$$B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+\dots\dots$$

- Stretch wire mapping on circle trajectory to measure the $B_y(x,y)$ & $B_x(x,y)$ simultaneously

$$B_r(\theta)=B_y\sin\theta+B_x\cos\theta \text{ for FFT analysis}$$







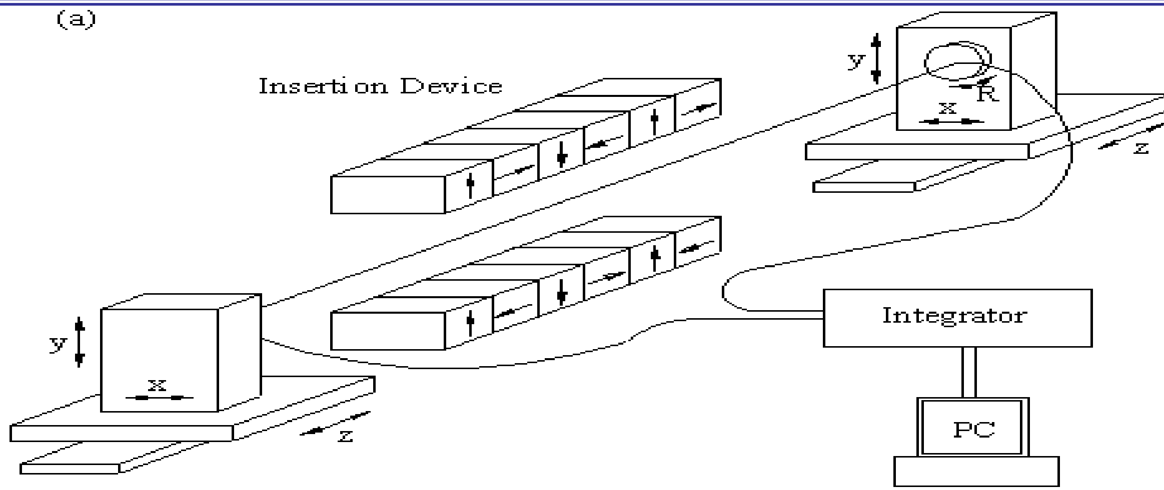
Stretch wire - QM Center Offset 0.25mm
OPERA Br FFT vs $B_r(\theta)=B_y\sin\theta+B_x\cos\theta$ FFT

QM with Br FFT R33mm Normalize@25mm Sag 0.25mm				
n	Normal	Skew	Normalize (Bn/B1)	Normalize (An/B1)
	(T/m^n)	(T/m^n)	(E-4)	(E-4)
0	-1.88E-09	-4.41E-03	0.000	-100.079
1	1.76E+01	4.72E-06	10000.0	0.003
2	-1.68E-04	-3.21E-04	-0.002	-0.005
3	-1.18E-03	-3.97E-04	0.000	0.000
4	4.51E-01	-8.97E-01	0.004	-0.008
5	5.46E+02	6.17E+00	0.121	0.001
6	-9.85E+01	-6.75E+01	-0.001	0.000
7	3.20E+02	-1.07E+03	0.000	0.000
8	-4.92E+05	1.01E+06	-0.002	0.004
9	-4.36E+08	-4.94E+06	-0.038	0.000

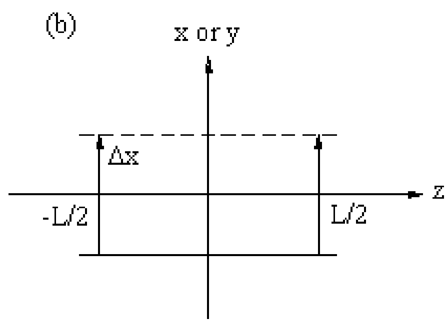
QM with BySin+BxCos FFT R33mm Normalize@25mm Sag 0.25mm				
n	Normal	Skew	Normalize (Bn/B1)	Normalize (An/B1)
	(T/m^n)	(T/m^n)	(E-4)	(E-4)
0	2.00E-07	-4.40E-03	0.005	-100.003
1	1.76E+01	5.55E-06	10000.0	0.003
2	-1.16E-04	-3.33E-04	-0.002	-0.005
3	4.03E-04	-1.13E-03	0.000	0.000
4	1.04E-01	-7.96E-01	0.001	-0.007
5	5.53E+02	3.55E+00	0.123	0.001
6	-7.15E+01	2.07E+01	0.000	0.000
7	-1.85E+03	-8.97E+02	0.000	0.000
8	4.53E+04	9.30E+05	0.000	0.003
9	-4.50E+08	-2.99E+05	-0.039	0.000

- The two analysis methods have almost the same results for the multipole components
- The dipole field strength is created that the dipole strength is equal to the sag amount
- We have proved $B_r(\theta)=B_y\sin\theta+B_x\cos\theta$ FFT method can be used

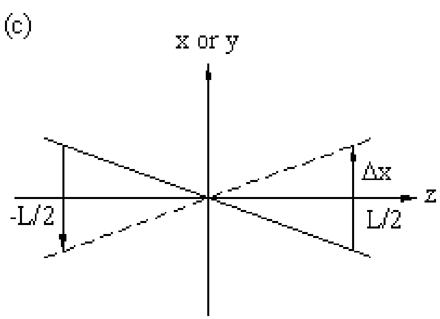
Stretch-wire system for Insertion device measurements

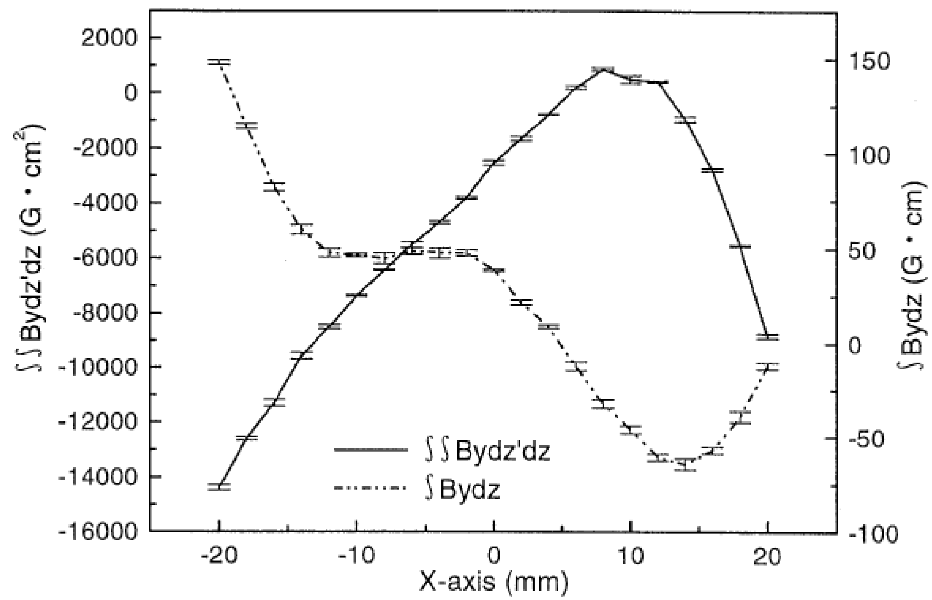


First field integral measurement

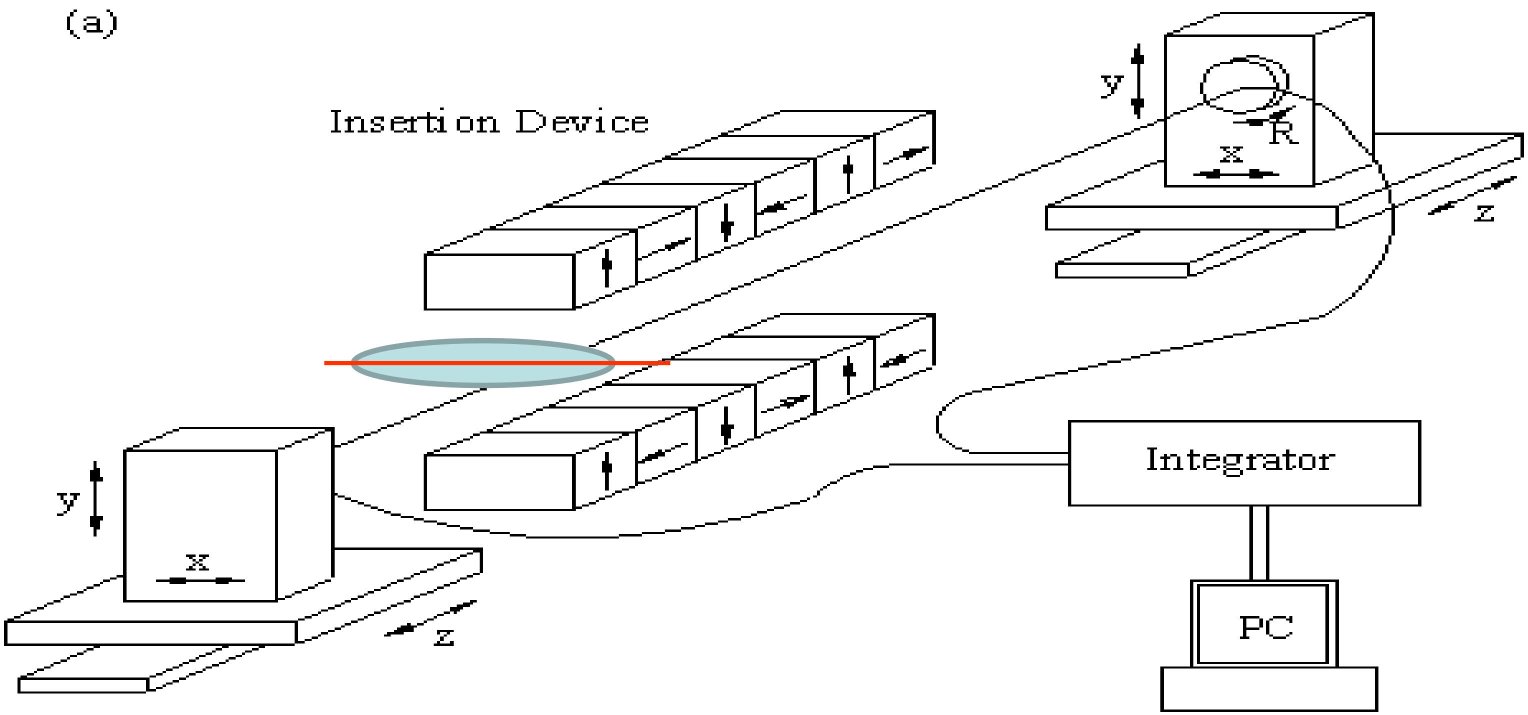


Second field integral measurement





Stretch wire for multipole error measurement of ID



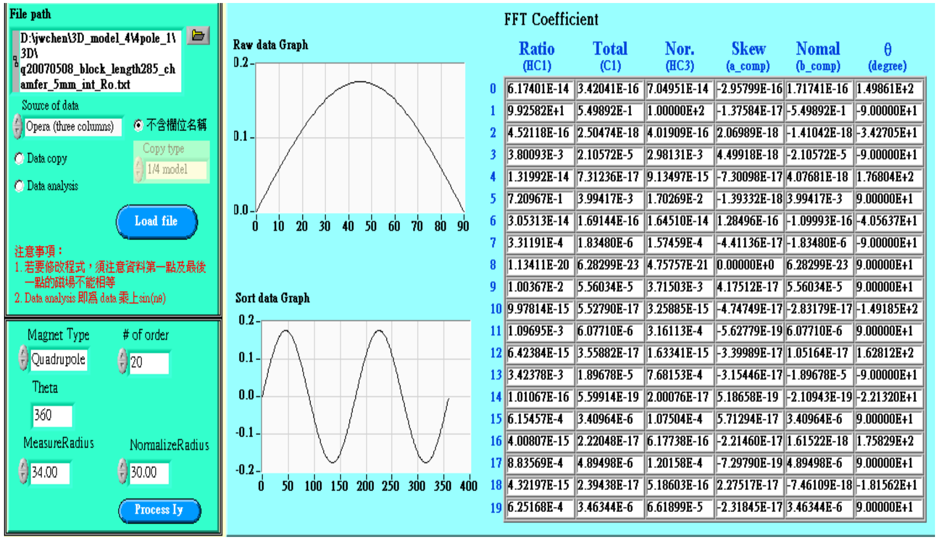
- 1D mapping on transverse trajectory to measure the $B_y(x)$ and least square fitting

$B_y(x)=b_0+b_1x+b_2x^2+b_3x^3+\ldots\ldots$ For measuring good field region

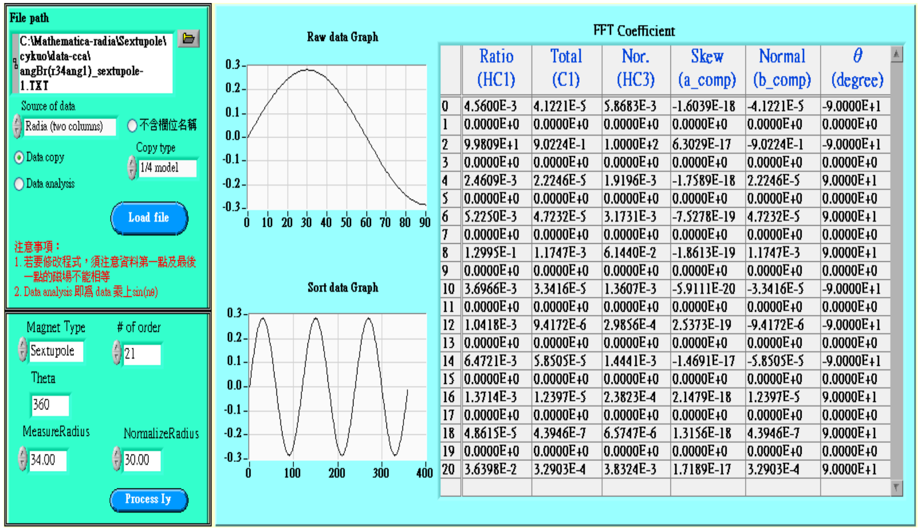
- Stretch wire mapping on elliptical trajectory to measure the $B_y(x,y)$ & $B_x(x,y)$ simultaneously

$B_r(\theta)=B_y\mathrm{Sin}\theta+B_x\mathrm{Cos}\theta$ for FFT analysis for measuringmultipole components

Rotating coil measurement and analysis by FFT method



Quadrupole magnet

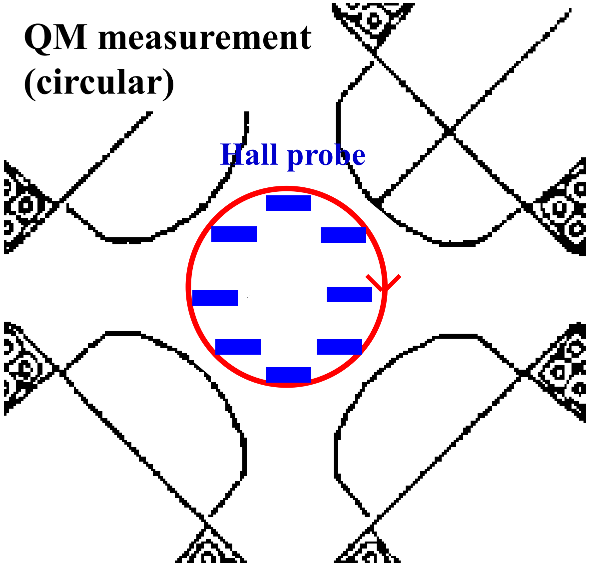


Sextupole magnet

- Quadrupole magnet: $B_r \times \mathrm{Sin}(2\alpha-\theta_2)$ Fast Fourier Transform
- Sextupole magnet: $B_r \times \mathrm{Sin}(3\ \alpha-\theta_3)$ Fast Fourier Transform
- Higher order multipole magnet: $B_r \times \mathrm{Sin}(n\alpha-\theta_n)$ Fast Fourier Transform

- **Various field measurement system and precision for magnet measurement**

Static-Hall probe system for lattice magnets

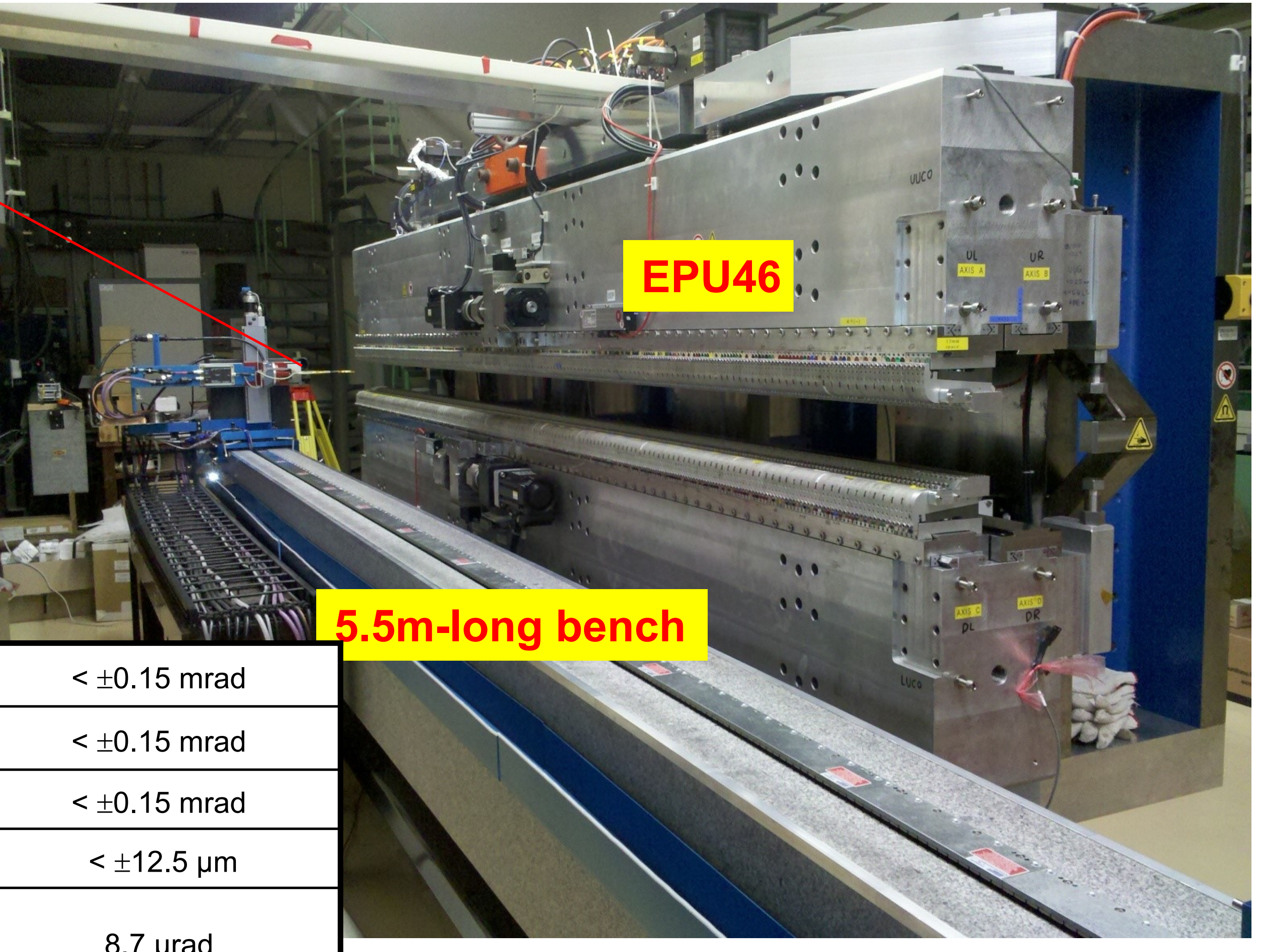


Specification	3-Axis Moving rang : 200 * 60 * 30 cm Stepping motor
Purpose	Dipole : Linear, Curve(1) Quadruple : Linear, Circular(2) Sextuple : Linear, Circular Corrector : Linear SWLS : On-fly
Accuracy & precision	Straightness : 15 μm Angle error: 8 arcsec Field strength: 0.1 G

- This system can be used for Dipole, Quadrupole, Sextupole, and the other higher order Multipole accelerator magnets

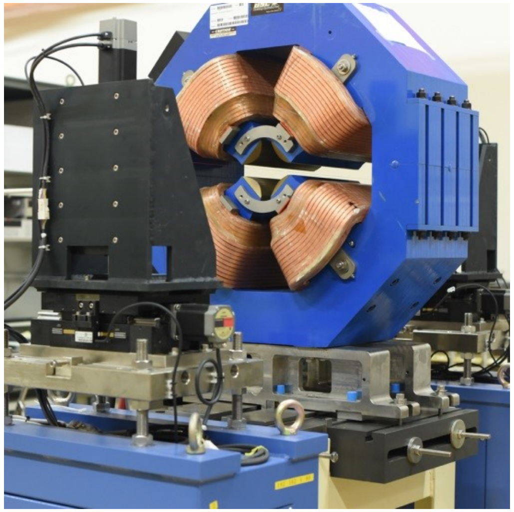
C. S. Hwang, et. al., "High-Precision Harmonic Magnetic-Field Measurement and Analysis Using a Fixed Angle Hall Probe", Rev. Sci. Instrum., 65(8), (1994) 2548-2555.

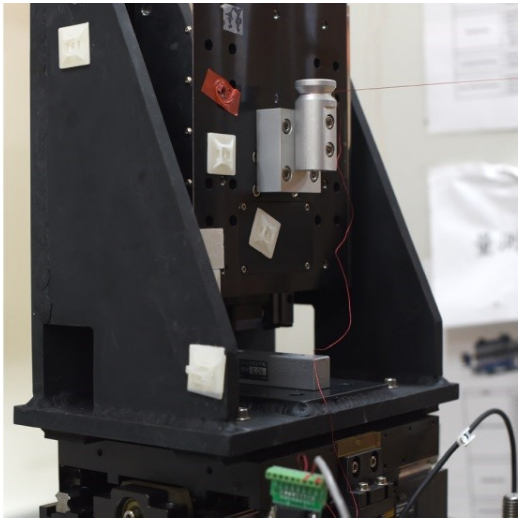
On-fly Hall probe measurement for insertion devices



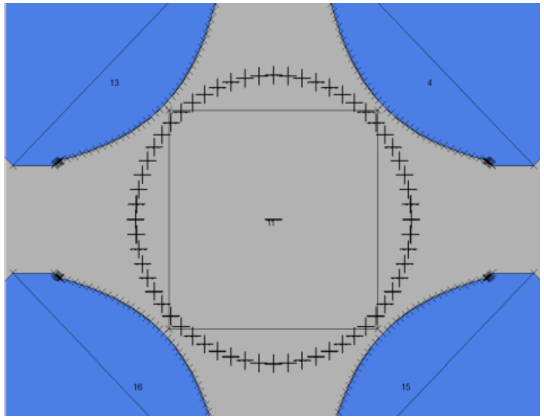
Pitch	< ±0.15 mrad
Yaw	< ±0.15 mrad
Roll	< ±0.15 mrad
Horizontal and vertical straightness	< ±12.5 μm
Perpendicularity between each axis	8.7 μrad
Peak field standard deviation	0.23G for Bx, 0.21G for By

Stretch wire system for accelerator multipole magnets





- FDI2056 integrator are used and results are almost the same as the multimeter (34411A).
- The movement of transverse and vertical direction are moving by stepping motors.
- The wires are stretched by moving the stage longitudinal manually.
- Mechanical centre can be found by level meter and theodolite.
- Litz wire with 8 turns copper wires and BeCu are tested.

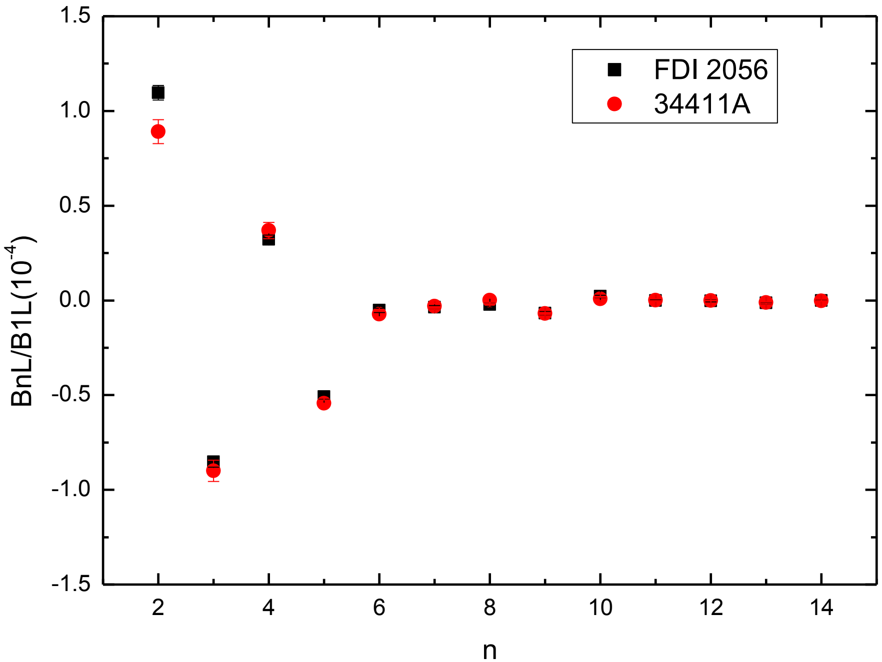


➢ A circle divided to 61points for the measurement and analysis

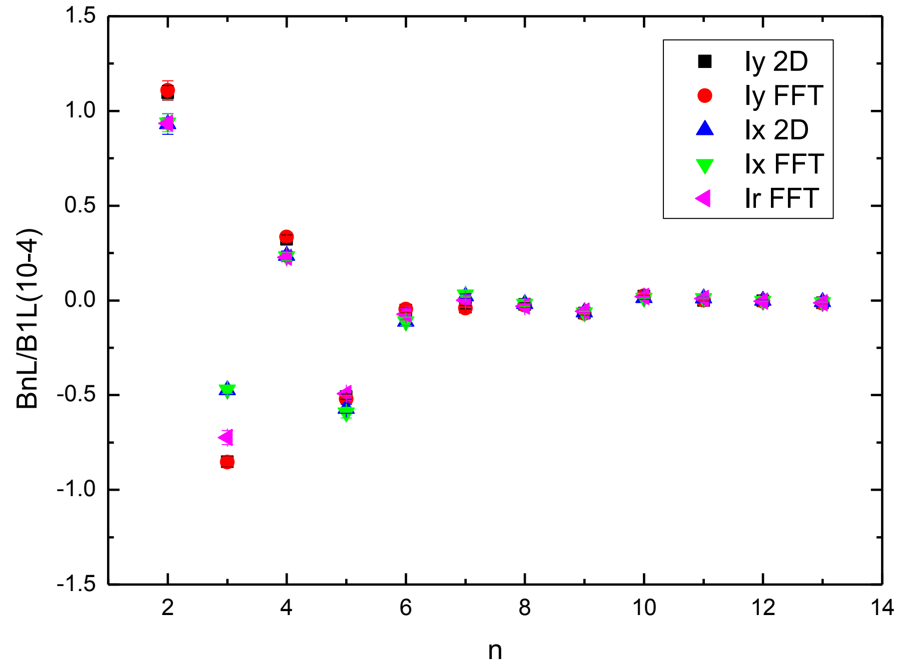
C. S. Hwang, C.H. Hong, F.Y. Lin and S.L. Yang, 2000, "Stretch-wire system for the integral magnetic field measurement", *Nucl. Instrum. Meth. A* **467** (2001) 194-197

Stretch wire precision testing for lattice magnets

precision

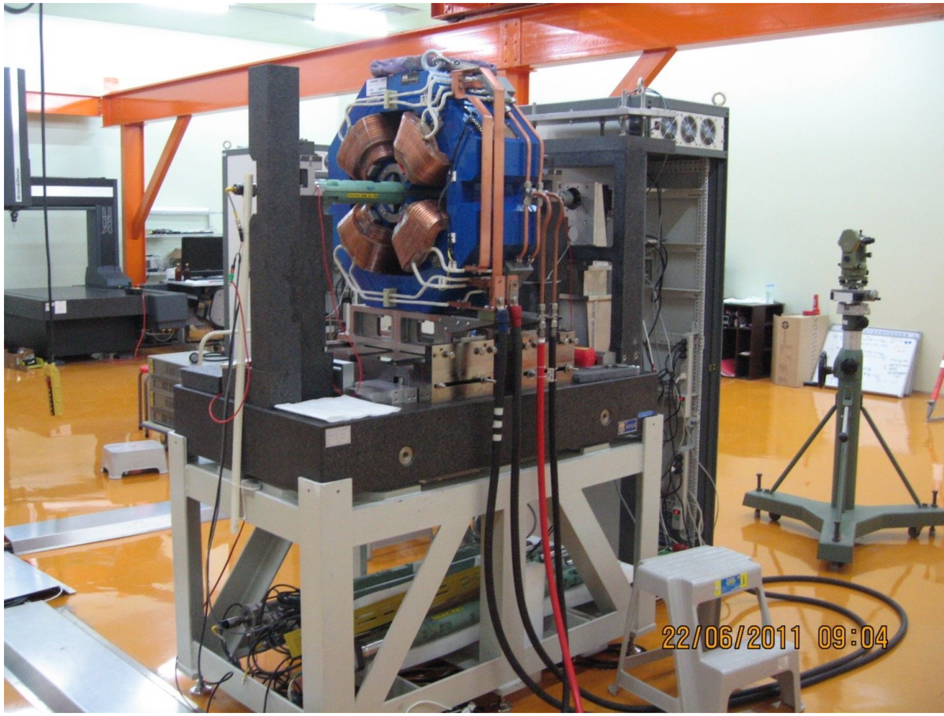


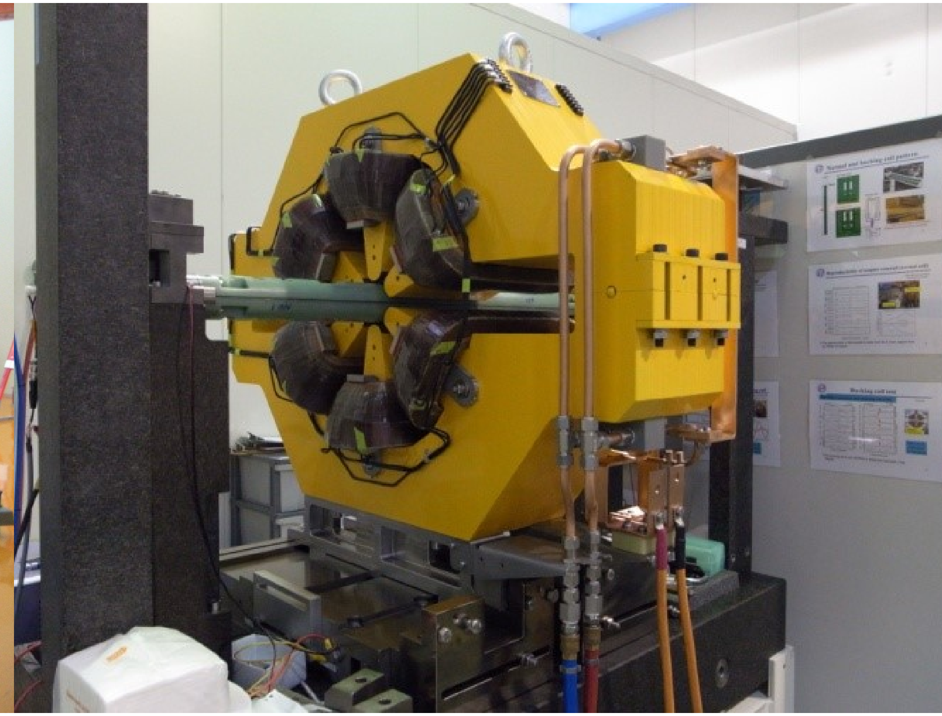
different analysis method



- The precision of the each multipole component using FDI 2056 is within $4\text{x}10^{-6}$. However, the precision of 34411A is $1.5\text{x}10^{-5}$.
- For different analysis method, the largest difference of the field components is sextupole term that is within $1\text{x}10^{-5}$. However, the other multipole components are all within $5\text{x}10^{-6}$.
- However, some items still need to be developed and improved of the stretch wire system

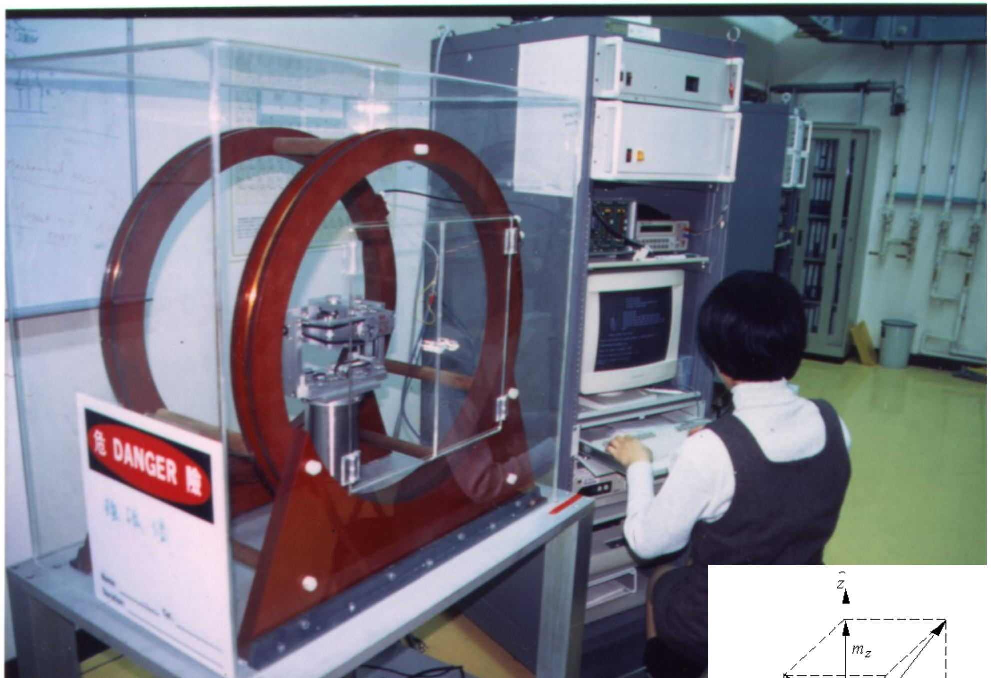
Rotating coil for accelerator multipole magnets

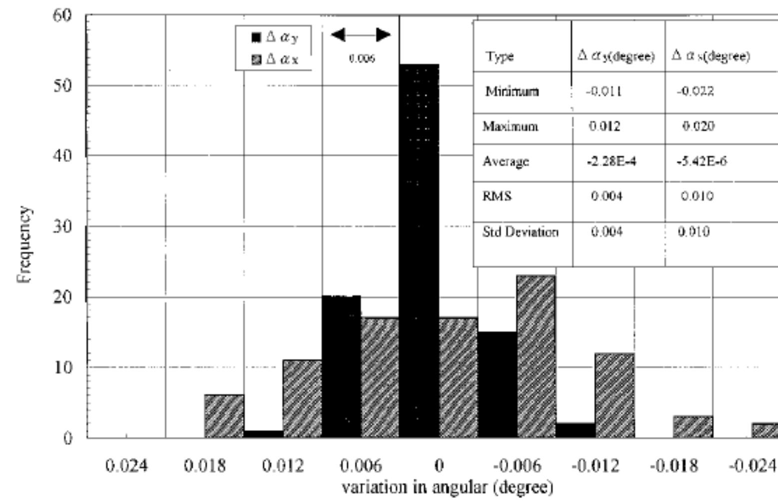


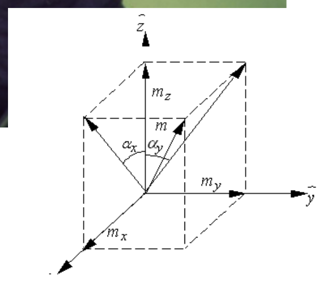


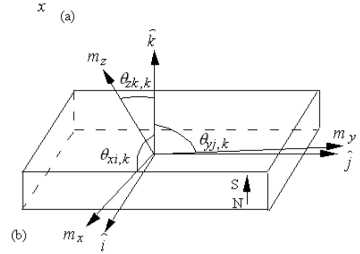
	Vertical offset (mm)	Horizontal offset (mm)	Normalized multipoles (*E-4)
System reproducibility	< 0.001	< 0.001	< 0.1
Measurement-unit and magnet reinstall reproducibility	< 0.01	< 0.01	n=2, Δ< 0.3
			n>2, Δ< 0.1
n=2 is quadrupole term, n=3 is sextupole term			

3D Helmholtz coil system for magnet block measurement









$$\vec{m} = m_x \hat{x} + m_y \hat{y} + m_z \hat{z} ,$$

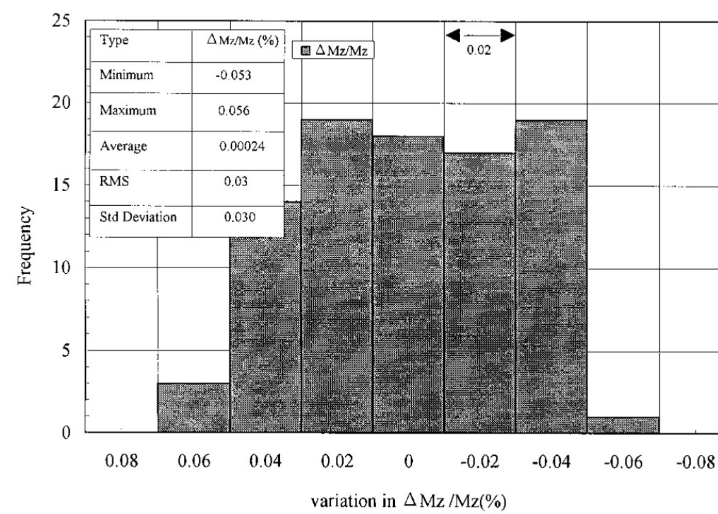
$$m = \sqrt{m_x^2 + m_y^2 + m_z^2} ,$$

$$\alpha_x = \tan^{-1}\left(\frac{m_x}{m_z}\right),$$

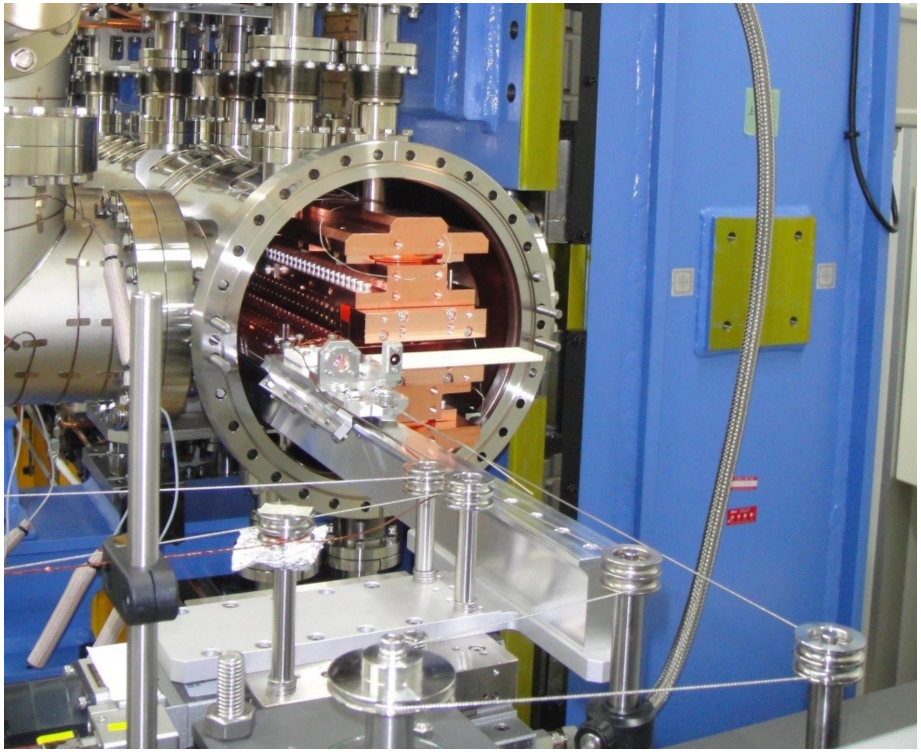
$$\alpha_y = \tan^{-1}\left(\frac{m_y}{m_z}\right) .$$

$$M_k = \vec{m} \cdot \hat{k} = m_x \hat{x} \cdot \hat{k} + m_y \hat{y} \cdot \hat{k} + m_z \hat{z} \cdot \hat{k}$$

$$= m_x \cos \theta_{xi,k} + m_y \cos \theta_{yj,k} + m_z \cos \theta_{zk,k} ,$$



In-situ Hall probe for in-vacuum undulator

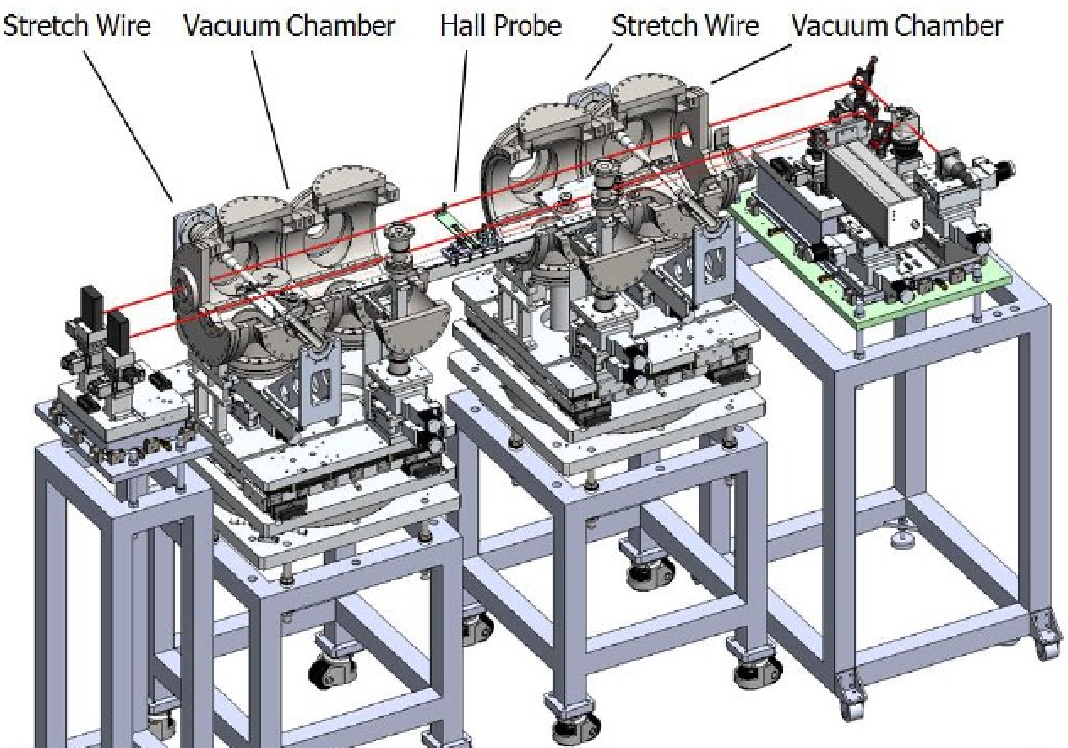


System Reproducibility

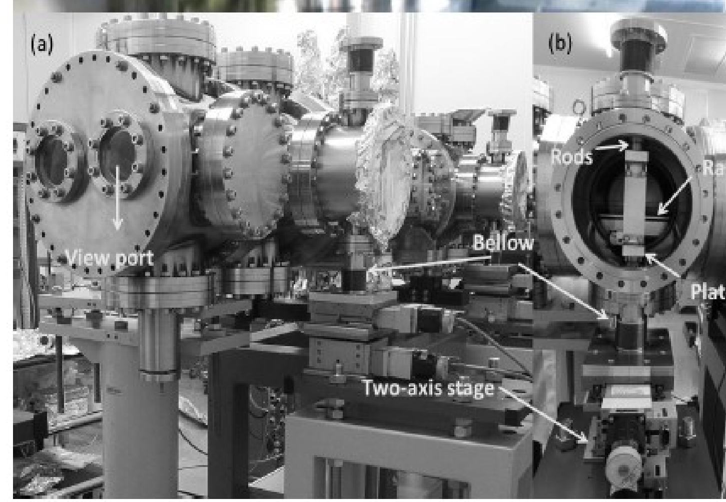
	Phase error (degree)	Half integral deviation (%)	Peak field deviation(%)
STD	<0.1	<0.1	<0.02

- 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 field measurement for cryogenic undulator



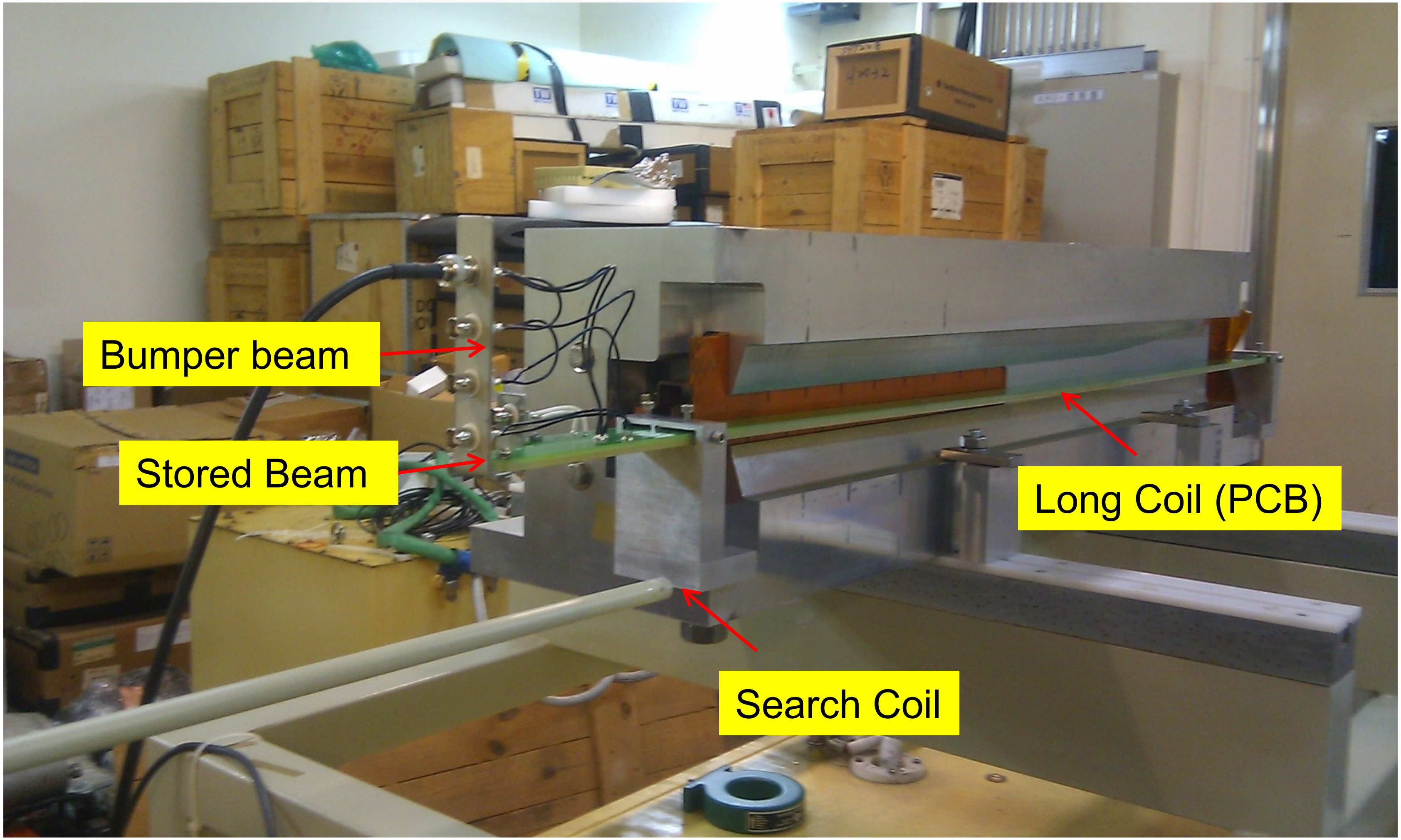
- System is operating at vacuum pressure ~10^{-4} Pa.
- A magnet arrays (length 0.2 m) with period 22 mm and a fixed gap of 7 mm is dedicated to testing.
- The reproducibility of phase error is around 0.2 degree.



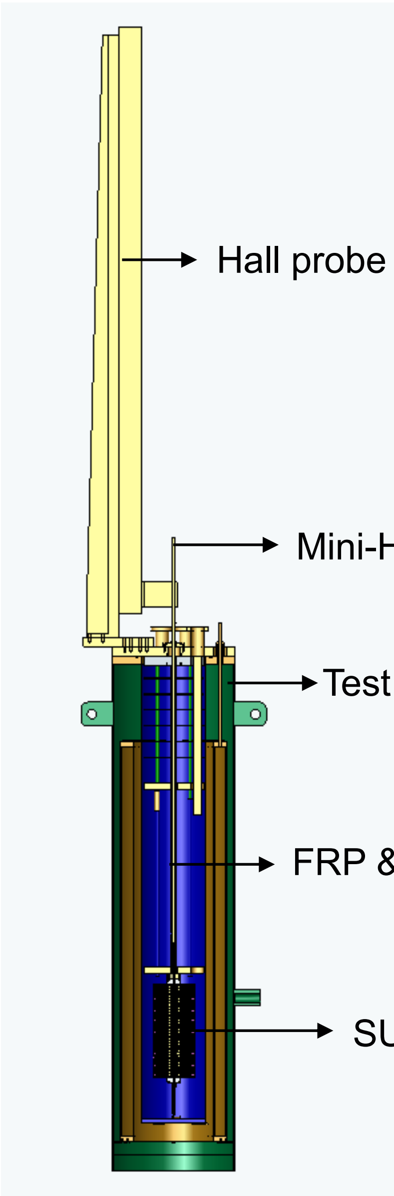
◆ We combine the Hall probe and stretch wire method in the same system

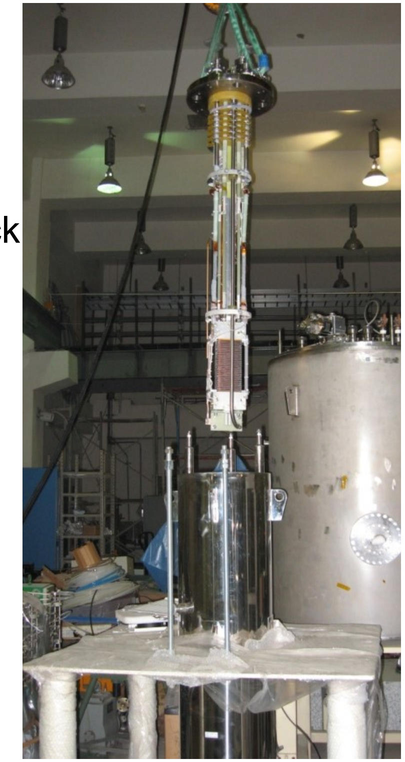
◆ Design had been completed and prototype will be constructed recently

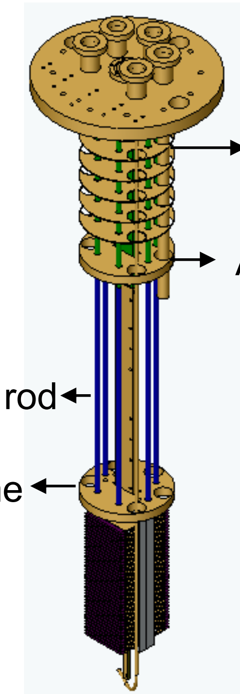
Long Coil and Search coil Measurement Systems for septum & kicker magnets

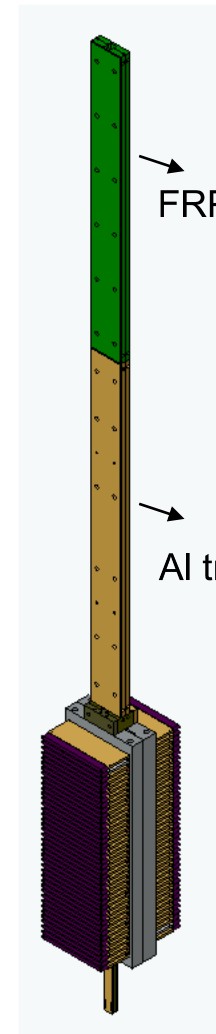


Cryogenic field measurement for superconducting magnet

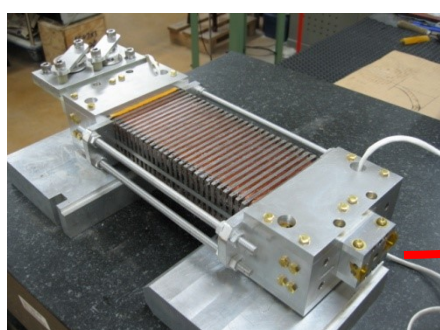


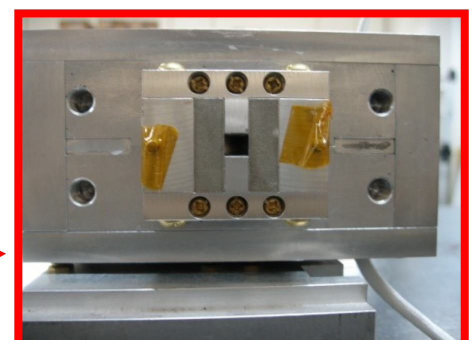




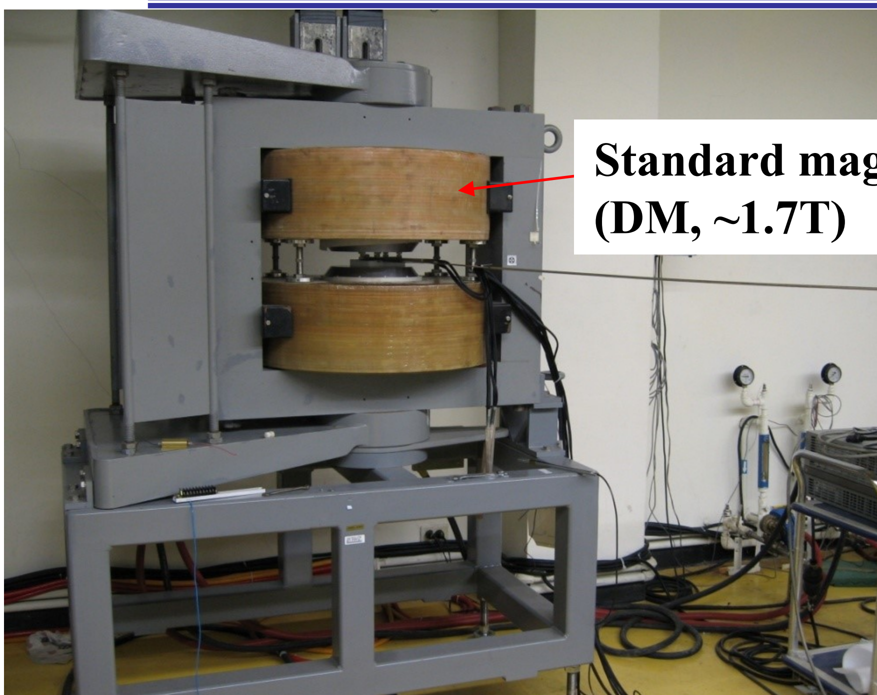


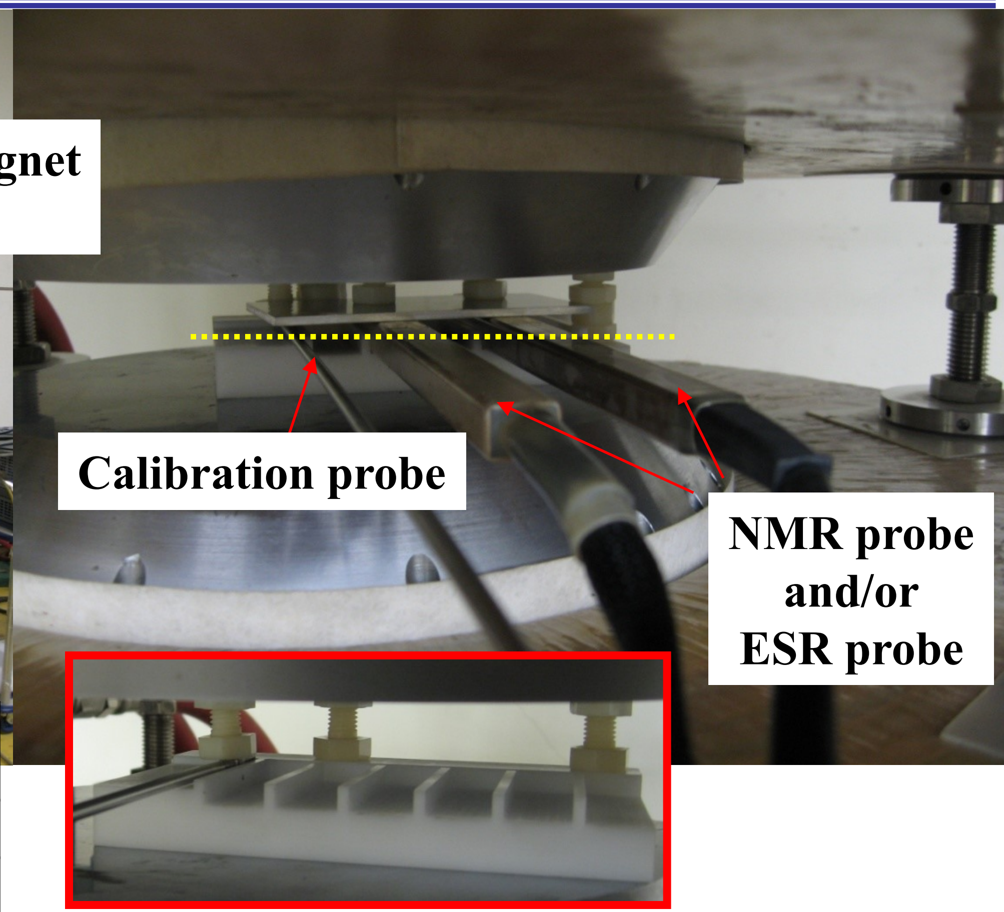
Magnet gap = 5.6mm
➔ Mini-Hall probe





Magnetic field calibration system



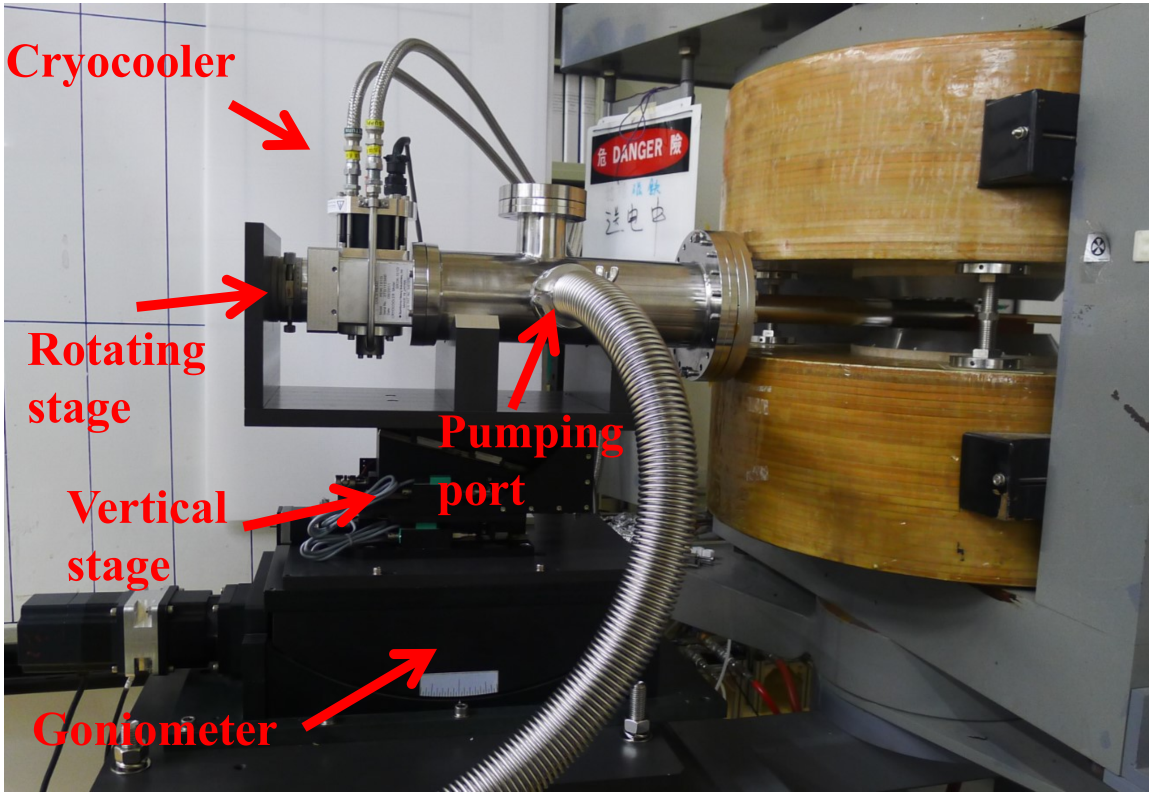


Hall sensor	Measure ment	Precision	Note
Group 3	1-axis	<0.01%	calibrated
SENSIS	1-axis	<0.01%	calibrated
	3-axis	<0.02%	calibrated
APEPOC	1-axis	---	cryognic
LakeShore	1-axis	<0.2% (below 1T)	calibrated cryognic
NMR	-	±5 ppm	
ESR	-	±50 ppm	

- The calibration sensor and NMR(ESR) sensor in the same plane. (yellow line)
- Temperature control ~ ±0.25^{o}C

Low temperature field calibration system

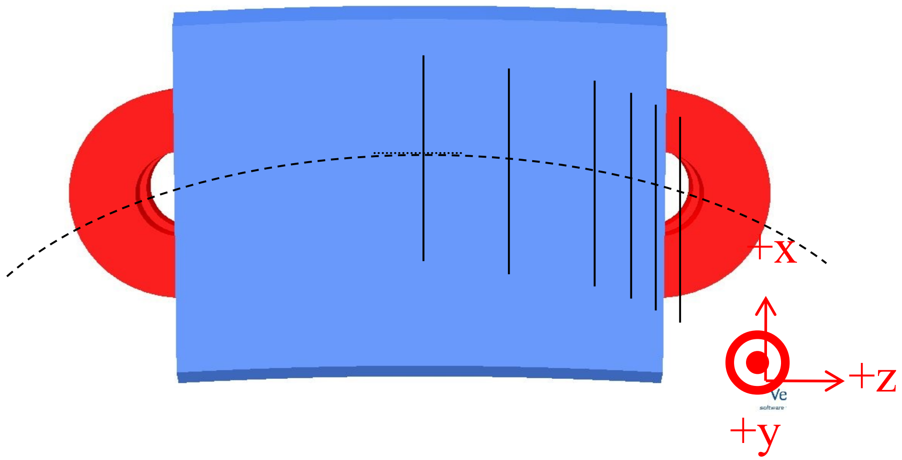
- Calibrate a Hall probe at different temperature and field strength
- Fine adjustment for height, rolling, and pitch of a Hall probe to Minimize the error of Hall sensor angle and position during calibrations.
- Temperature as low as possible (not only for CU but also Superconducting magnets)

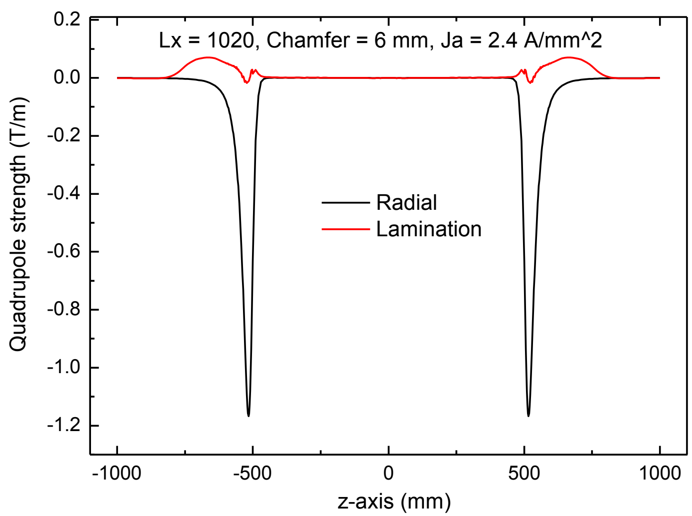


- **Field analysis & measurement results**

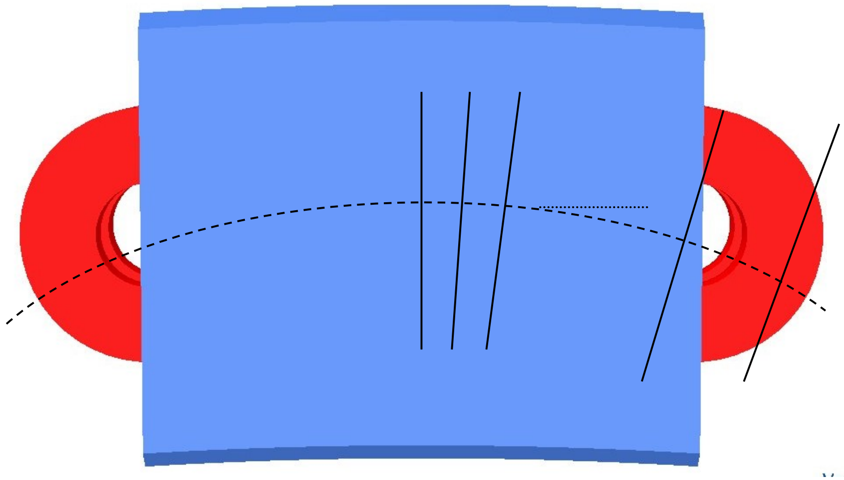
Field measurement of dipole magnet by static-Hall probe

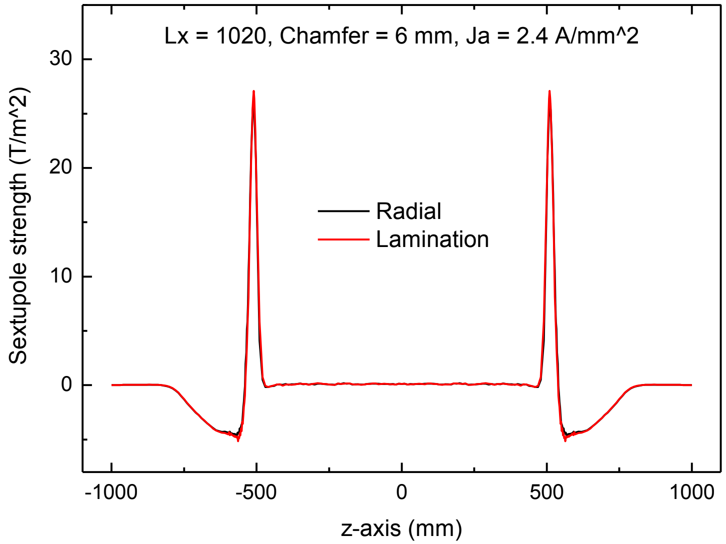
Lamination mapping





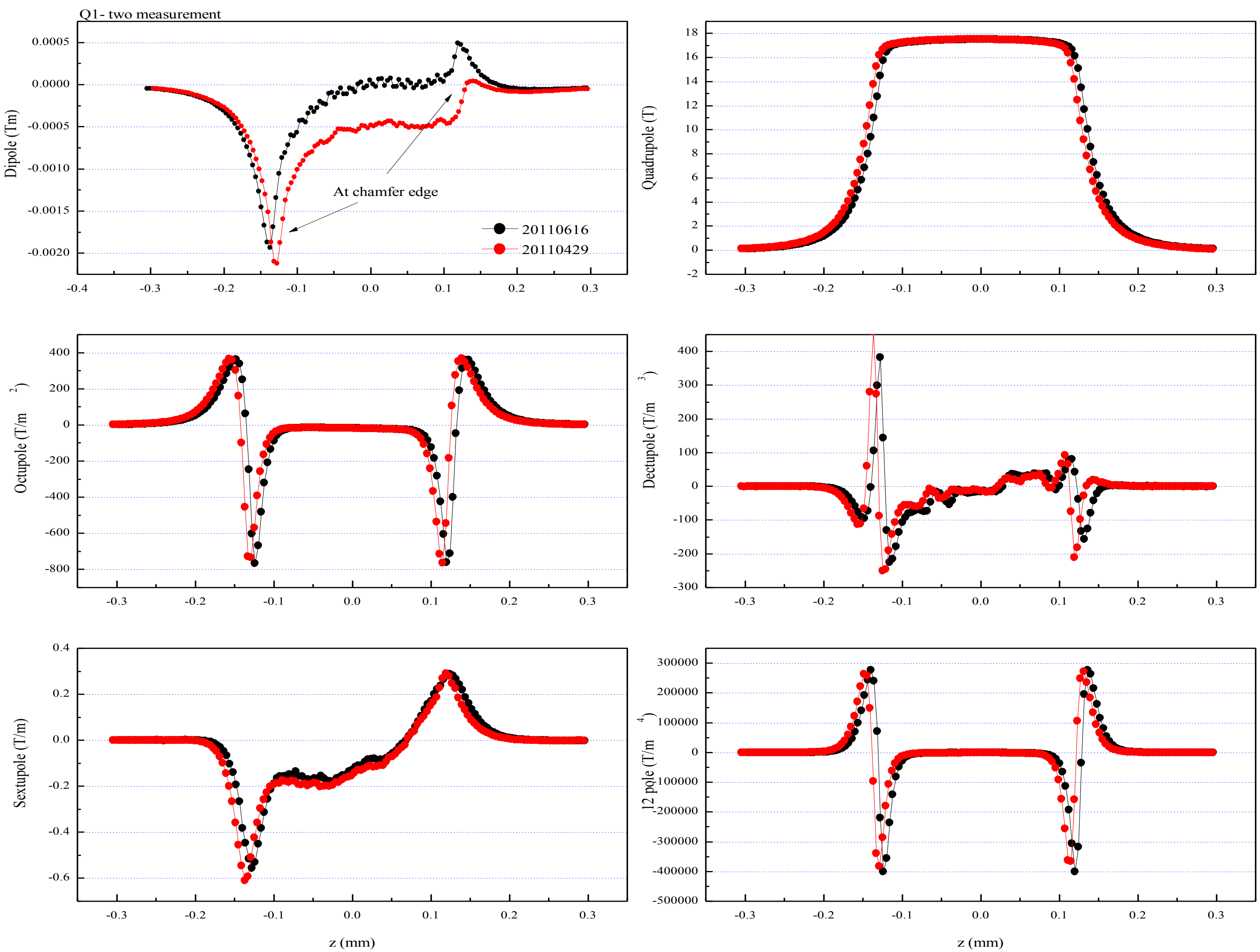
Radial mapping

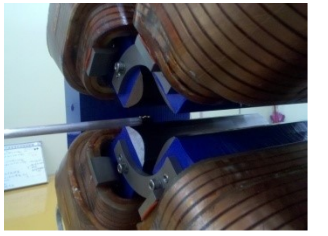




■ The weak edge focus strength is around 0.026 T (k=0.0026 m^{-1})

Quadrupole magnet measurement by static-Hall probe



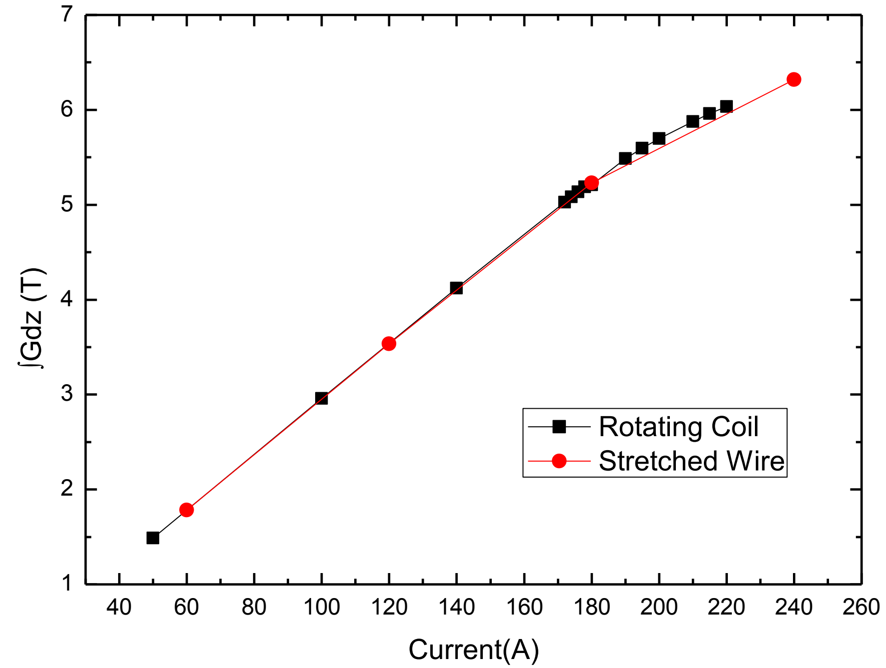


Stretch wire (SW) compare to rotating coil (RCS)

Measure at R=33mm, normalize at 25mm

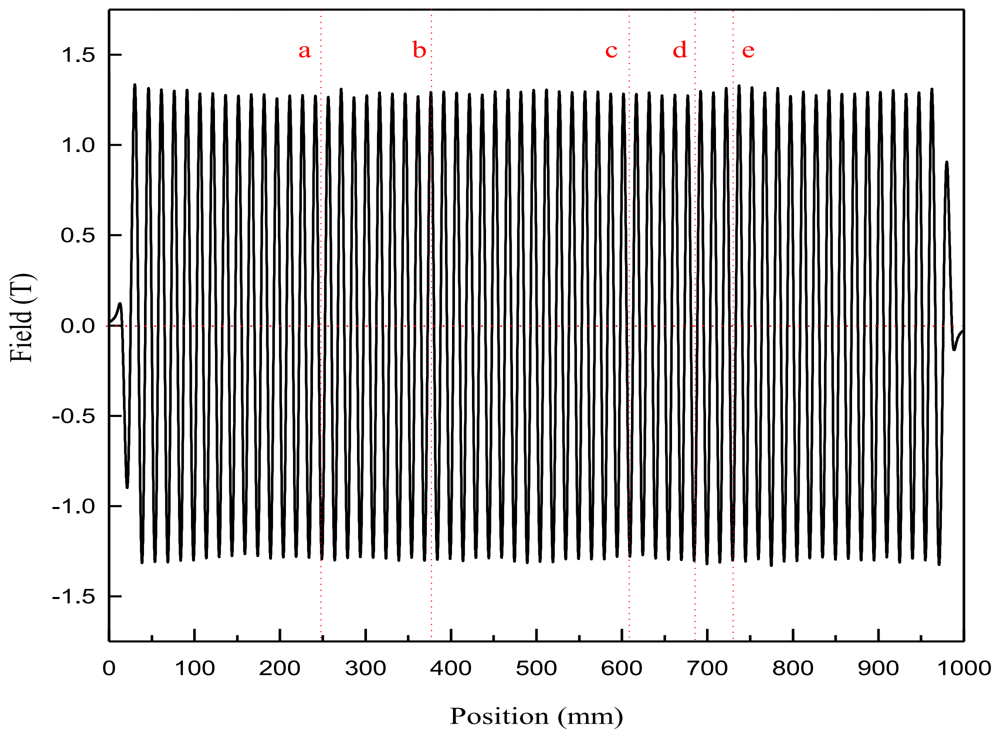
	180A-FDI2056-IrFFT		180A-RCS data		SW-RCS	
n	(Bn/B1)	(An/B1)	(Bn/B1)	(An/B1)	ΔBn	ΔAn
	(E-4)	(E-4)	(E-4)	(E-4)	(E-4)	(E-4)
1	10000.0	-0.246	10000.0	-0.342		
2	0.935	0.090	0.095	1.910	-0.840	1.820
3	-0.725	-0.072	-1.155	0.006	-0.430	0.078
4	0.227	-0.236	0.144	-0.140	-0.083	0.096
5	-0.493	-0.017	-0.549	-0.059	-0.056	-0.042
6	-0.072	-0.085	-0.053	-0.064	0.019	0.021
7	0.000	0.022	-0.013	0.016	-0.013	-0.006
8	-0.031	0.018	-0.005	0.022	0.026	0.004
9	-0.057	0.024	-0.048	0.010	0.009	-0.014

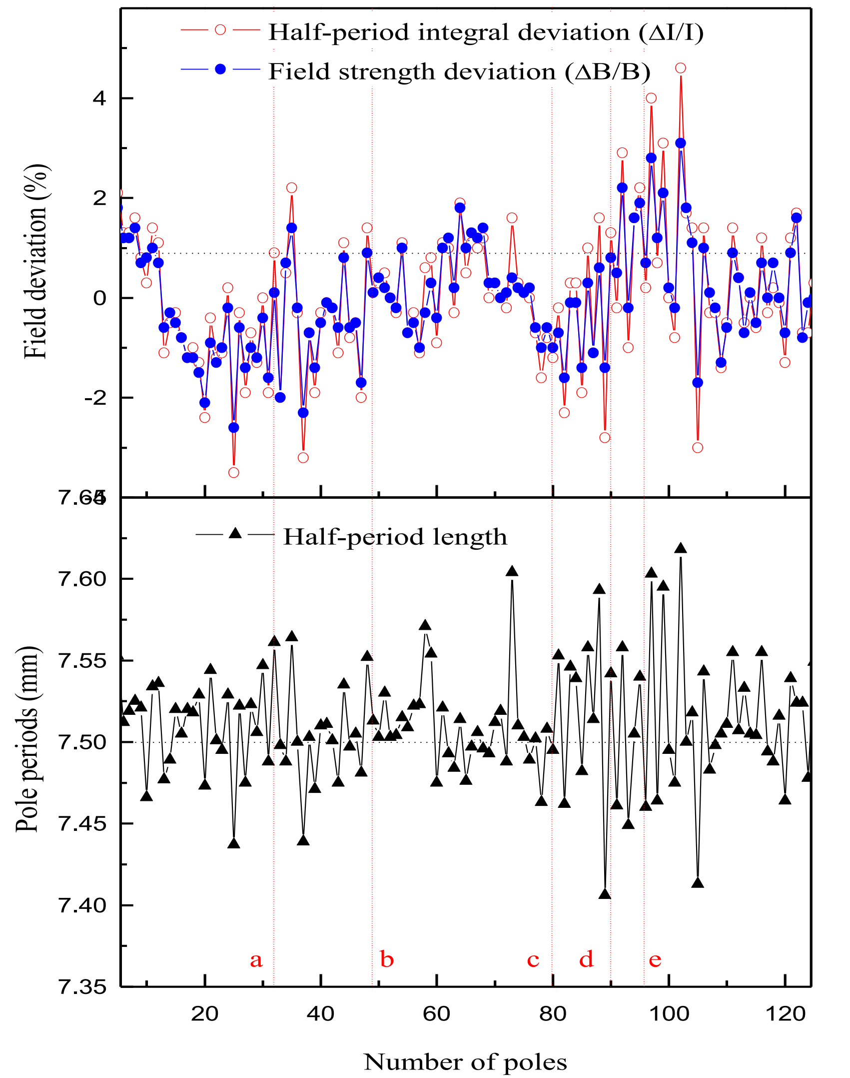
- The difference are within 1.8E-4 between rotating coil system and stretched wire system.



- Integral quadrupole strengths as function of current are measured by rotating coil system and stretched wire system.
- Field strength is consistence between two measurement systems.

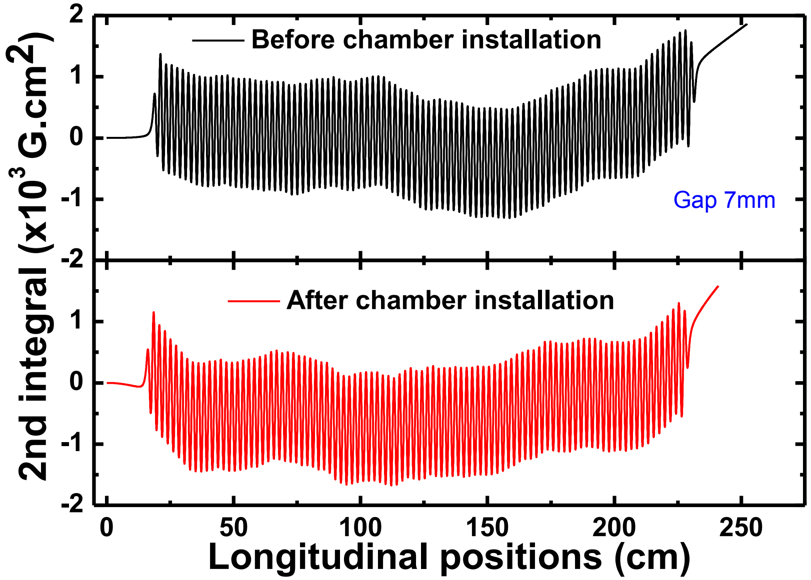
Field measurement of SU15 by cryogenic Hall probe



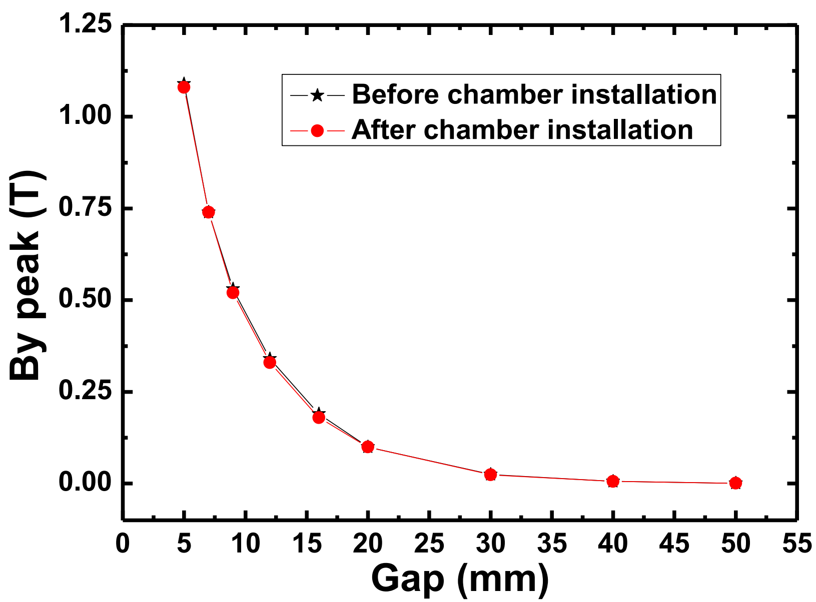


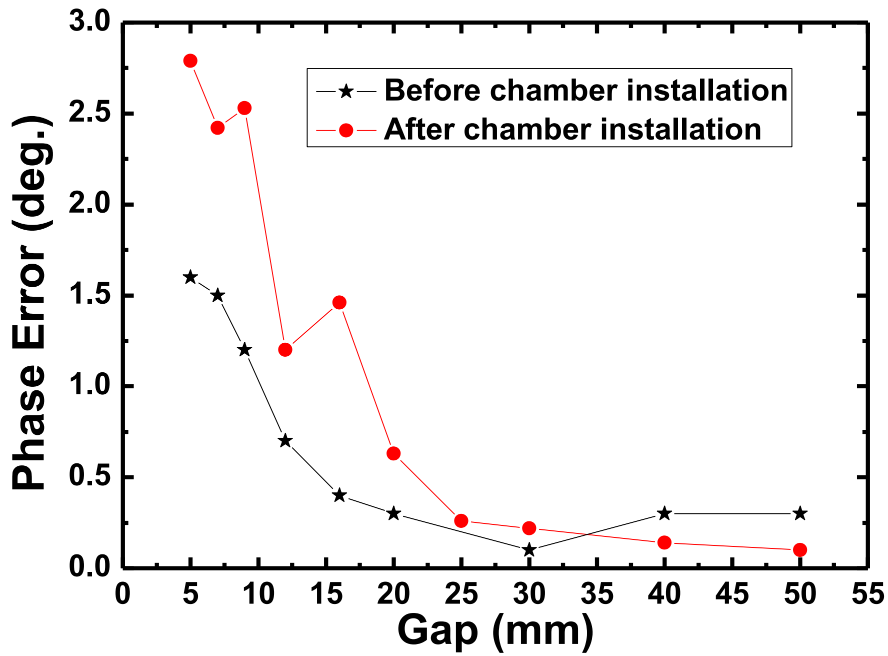
- These distortions should be improved after the iron pole shimming and addition a corrector outside the superconducting undulator.
- Before shimming, the phase error is 6 degree.

IU22 measurement results by using in-situ measurement system



- Trajectory wonders are almost the same.
- Peak field at different gaps doesn’t change.
- Phase errors increase about one degree at small gap, but still within specification (<3^0).





Issue discussion of the field measurement system

- Rotating coil system is a high precision measurement method for the multipole magnets and can determine the magnetic field center and the tilt angle in transverse axis precisely.
- However, the system is quite complex compare with the stretch wire method
- Stretch wire method with Cu wire have high precision measurement but has large sag. If BeCu wire is used, the measurement precision will a little worse but the sag will be smaller. So we try to use the Ti-Al-V to test the stretch wire method
- Stretch wire with elliptical trajectory moving in the insertion devices will obtain high precision measurement in the higher harmonic components
- The difference of higher order multipole strength of the field measurement at large & small aperture range that is due to the different field profile in magnet edge area
- The sag of the stretch wire will induce the field error that can be corrected. However, for very high accuracy measurement, the sag will be as small as possible, especially for the very short length of magnet

Summary

- The 3D coordinate mapping method by Hall probe can be used to measure & analysis all the accelerator magnets and the ID.
- Stretch wire measurement method is easy to installation, construction and operation. It also can be used for field measurement of accelerator multipole magnets (except the dipole magnet) & insertion devices
- Currently, the rotating coil method is higher precision compare with Hall probe and stretch wire. So we need to improve the system accuracy of the Hall probe and stretch wire in the future.
- Combined stretch wire and Hall probe in the same measurement system is necessary for the measurement of the multipole components and the phase error of cryogenic undulator
- The ultimate storage ring request a very small aperture of magnet. Therefore, the mini-Hall probe and stretch wire will become the best choice for the field measurement system
- How to use stretch wire measurement to find out the magnetic field center and tilt angle in transverse axis of magnet is our future work
- We also need to develop the vibration wire or pulse wire to align all the magnet in the same girder

SRI2018 host by NSRRC in Taipei city on 10-15 June 2018

Thank you for your attention