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

# Overall of magnet measurement systems at NSRRC

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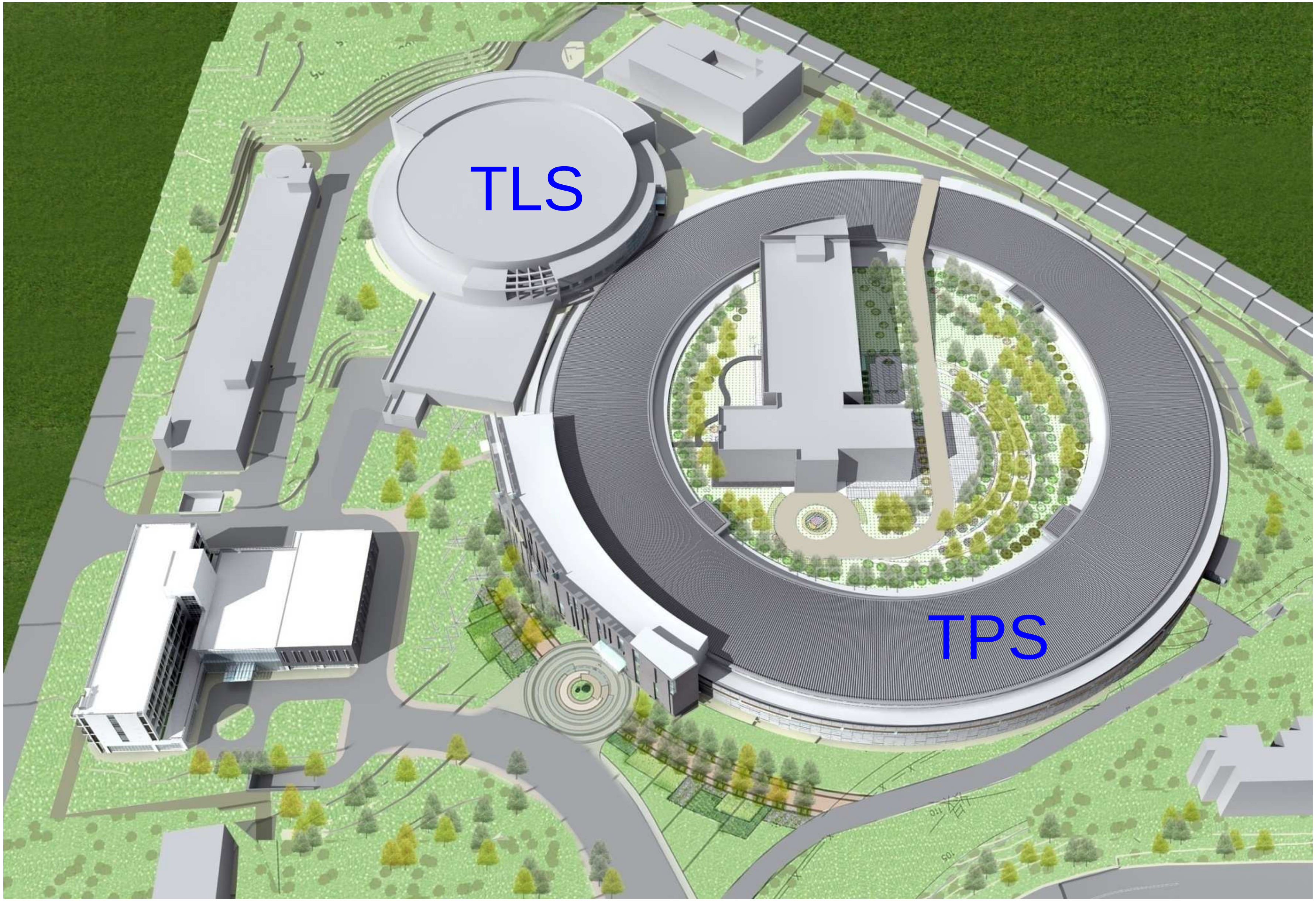
# Outline

- Status of 3 GeV TPS project
- Overview of magnet Lab.
- Measurement systems
- Hall probe measurement systems
- Magnetic field calibration system
- Rotating-coil measurement system
- Search-coil measurement system
- Pulse wire system
- Vacuum in-situ field measurement
- 3-D Helmholtz coil system
- 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 |
| June 2012 | Civil construction completed |
| Dec. 2013 | Installation completed & commissioning |
| 2014 | Open to users |

# TPS and TLS at NSRRC site



# TPS lattice parameters

| | |
|---|---|
| DBA lattice Circumference C (m) | 518.4 |
| Energy E (GeV) | 3.0 |
| Natural emittance $\varepsilon_{x0}$ (nm-rad) | 1.6 |
| Straight sections (m) | 12 (x6) + 7 (x18) |
| Revolution period (ns) | 1729.2 |
| Revolution frequency (kHz) | 578.30 |
| Radiofrequency (MHz) | 499.654 |
| Harmonic number h | 864 |
| Energy loss per turn (dipole) (MeV) | 0.85269 |
| Betatron tune $\nu_x/\nu_y$ | 26.18 /13.28 |
| Momentum compaction ($\alpha_1$, $\alpha_2$) | $2.4\times10^{-4}$, $2.1\times10^{-3}$ |
| Natural energy spread $\sigma_E$ | $8.86\times10^{-4}$ |
| Damping partition $J_x/J_y/J_s$ | 0.9977 / 1.0 / 2.0023 |
| Damping time $\tau_x/\tau_y/\tau_s$ (ms) | 12.20 / 12.17 / 6.08 |
| Natural chromaticity $\xi_x/\xi_y$ | -75 / -26 |
| Dipole bending radius $\rho$(m) | 8.40338 |

# Progressive status of TPS construction

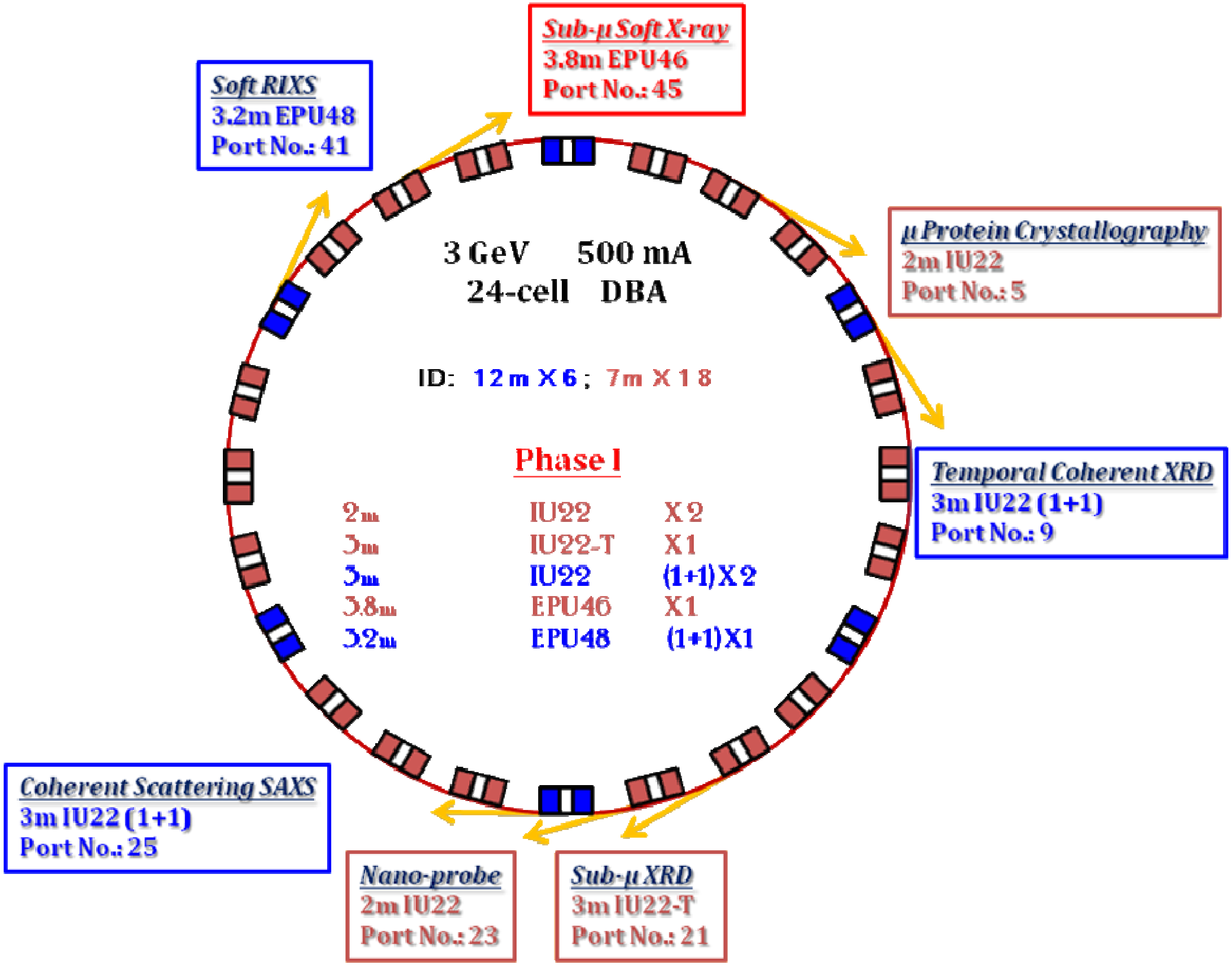
# Civil construction of TPS site

# Civil construction schedule

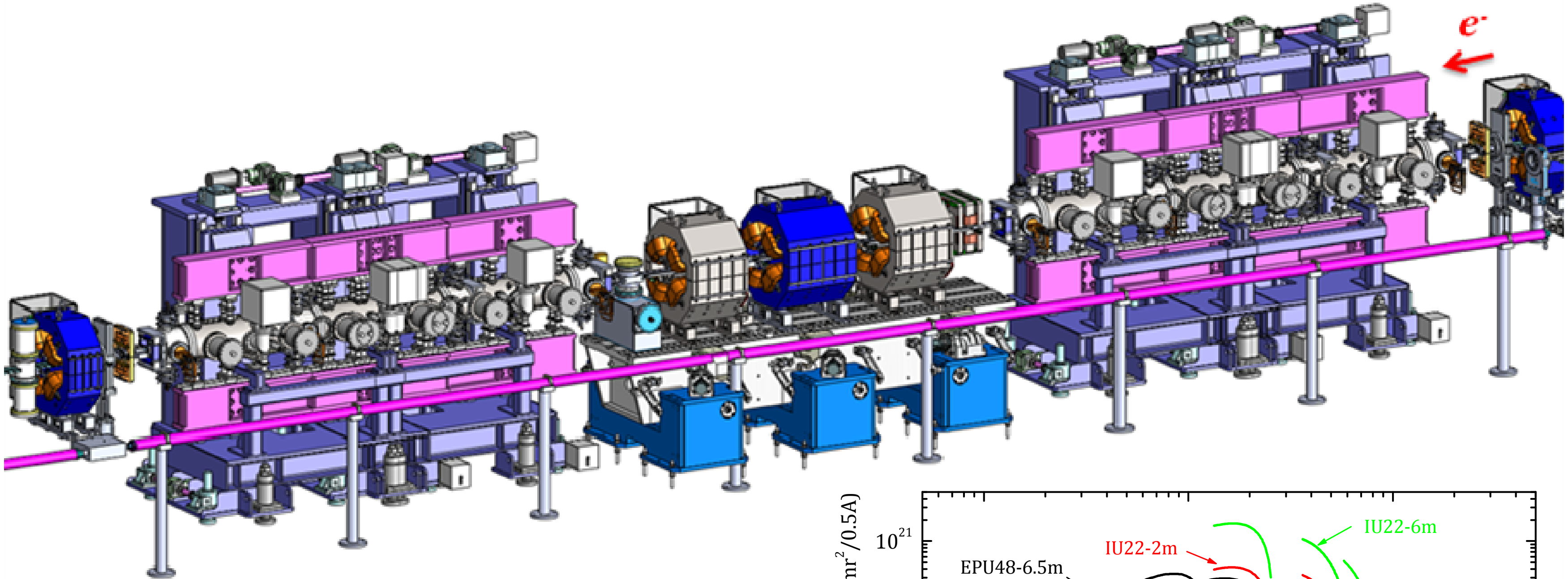


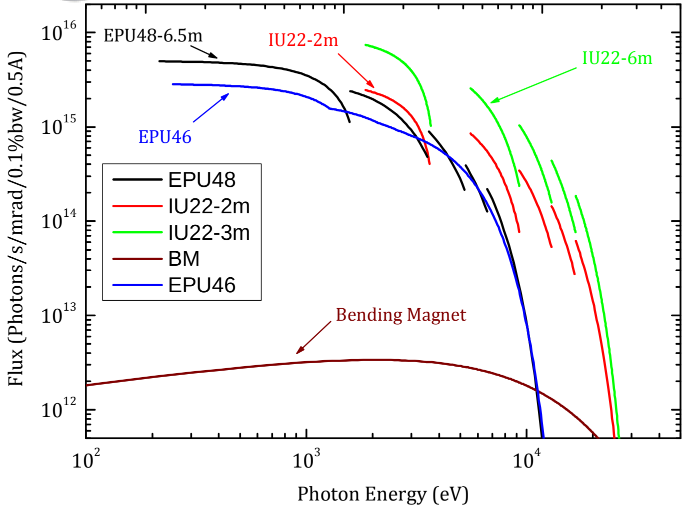

- The civil construction has been delayed half year due to the ground issue.

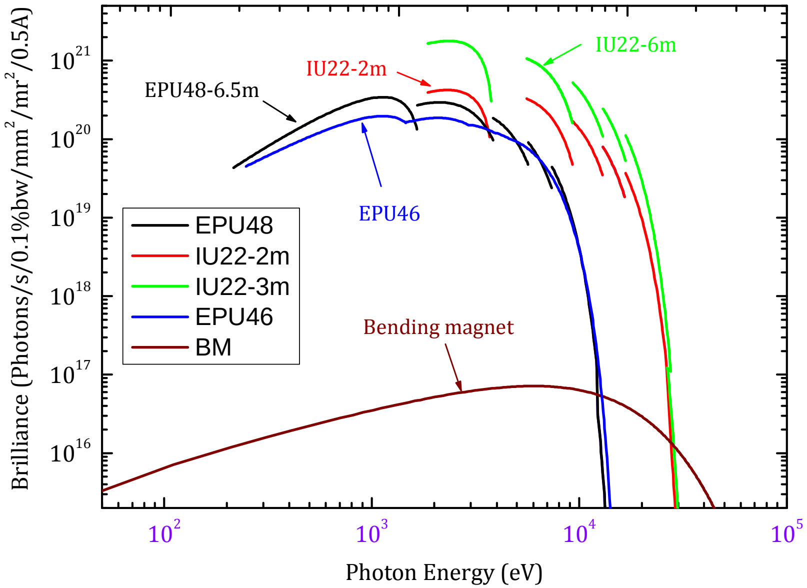
# Insertion devices in Phase I



# Three sections double minimum $\beta y$ for ID

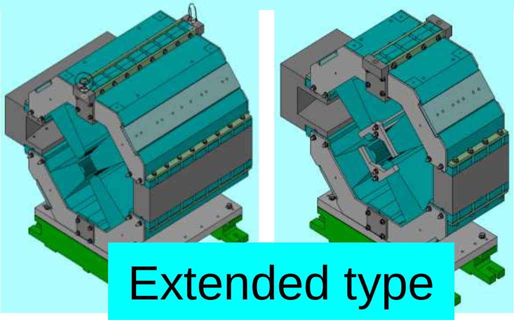


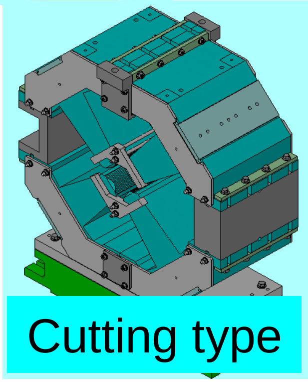



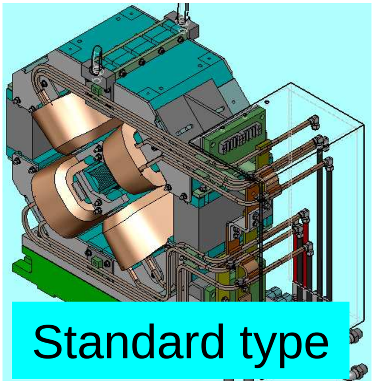



# Design of Dipole, Quadrupole and Sextupole in SR

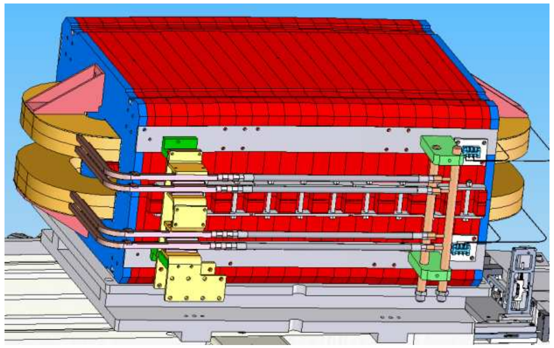

Four types of QP lamination shape

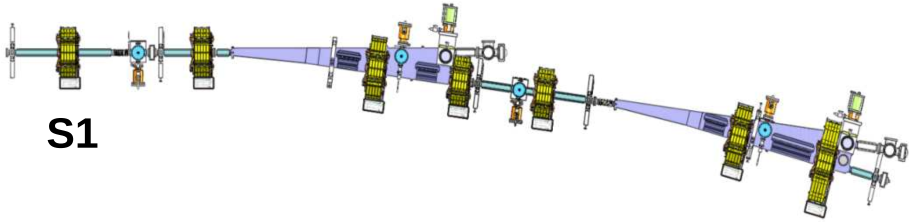


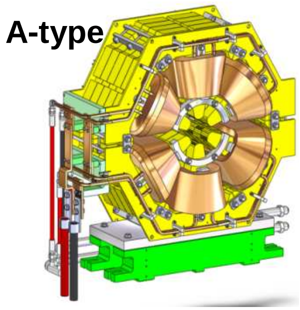



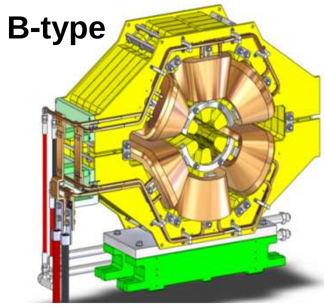

H-type DP lamination shape

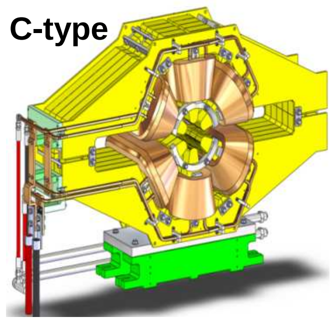




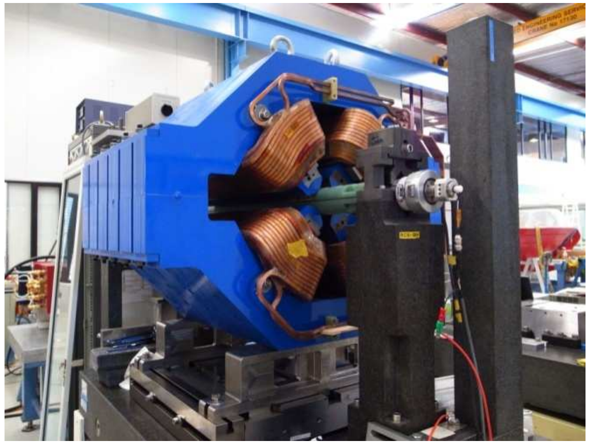

Three types of SP lamination shape



# Magnet construction

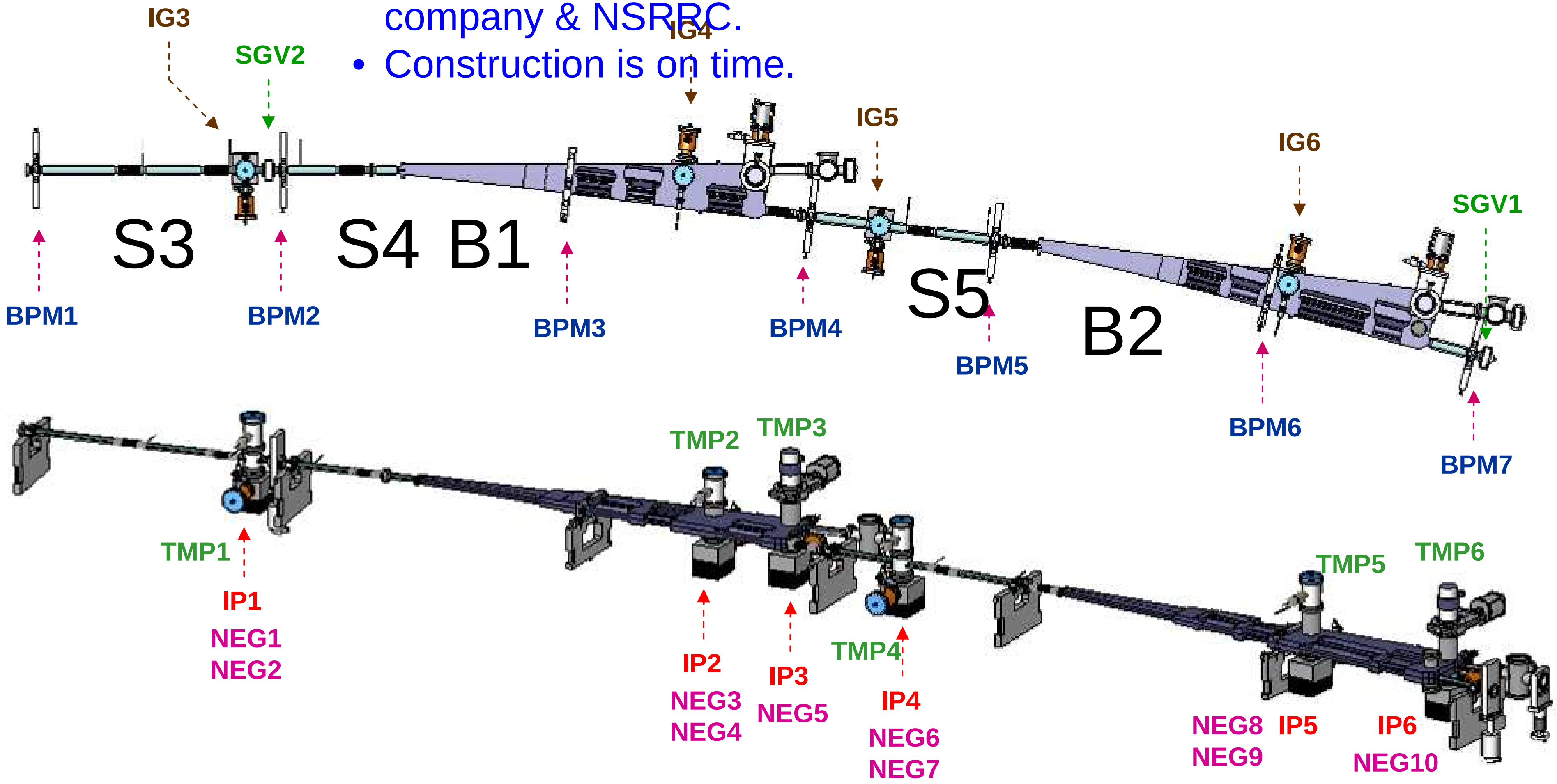




- BSL fabricates storage ring & booster ring magnets.
- Half part of prototype of Dipole, Quadrupole, and Sextupole are completed.
- Multipole error of SR magnet can be within specification but BR magnet is out of spec.
- Magnet field center will be adjusted by shim block and control within 10 μm.
- Most of mechanical precision is within 20 μm.
- Construction schedule has been delayed half year.

# Layout of Vacuum system

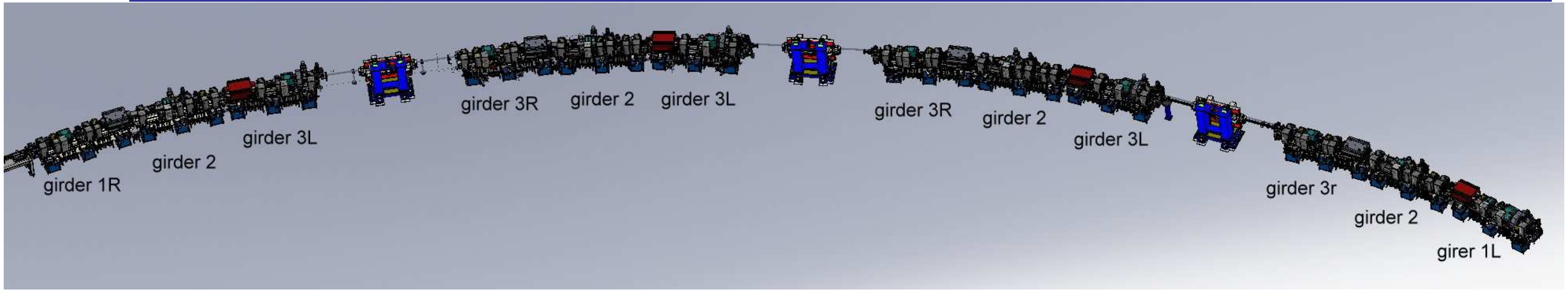
- Two 14 m long vacuum chamber of the whole 24 sectors has been completed.
- The aluminum chamber was fabricated and welding in local company & NSRRC.
- Construction is on time.



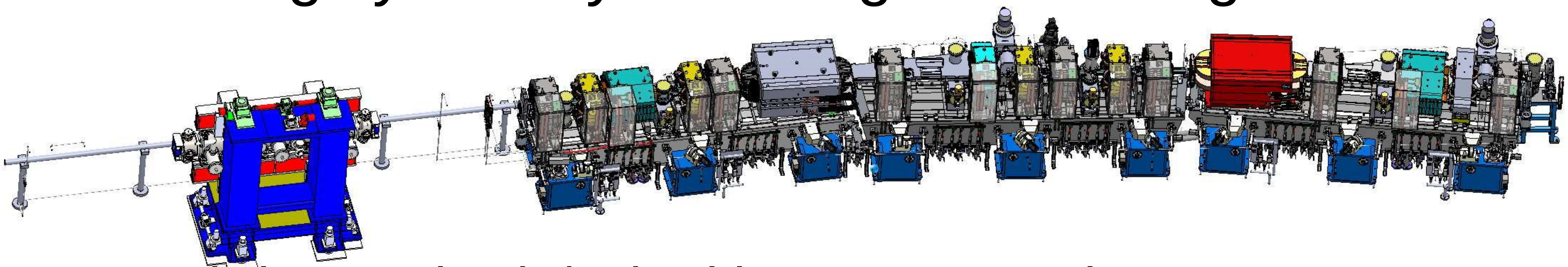
# Vacuum chamber



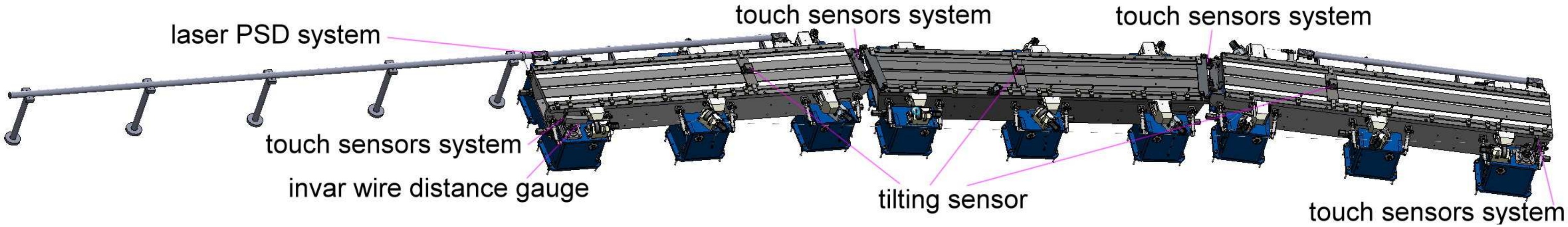

# Storage Ring Girder System Design




1/6 ring symmetry section girders configuration



One girder section(1/24) with magnets and vacuum system

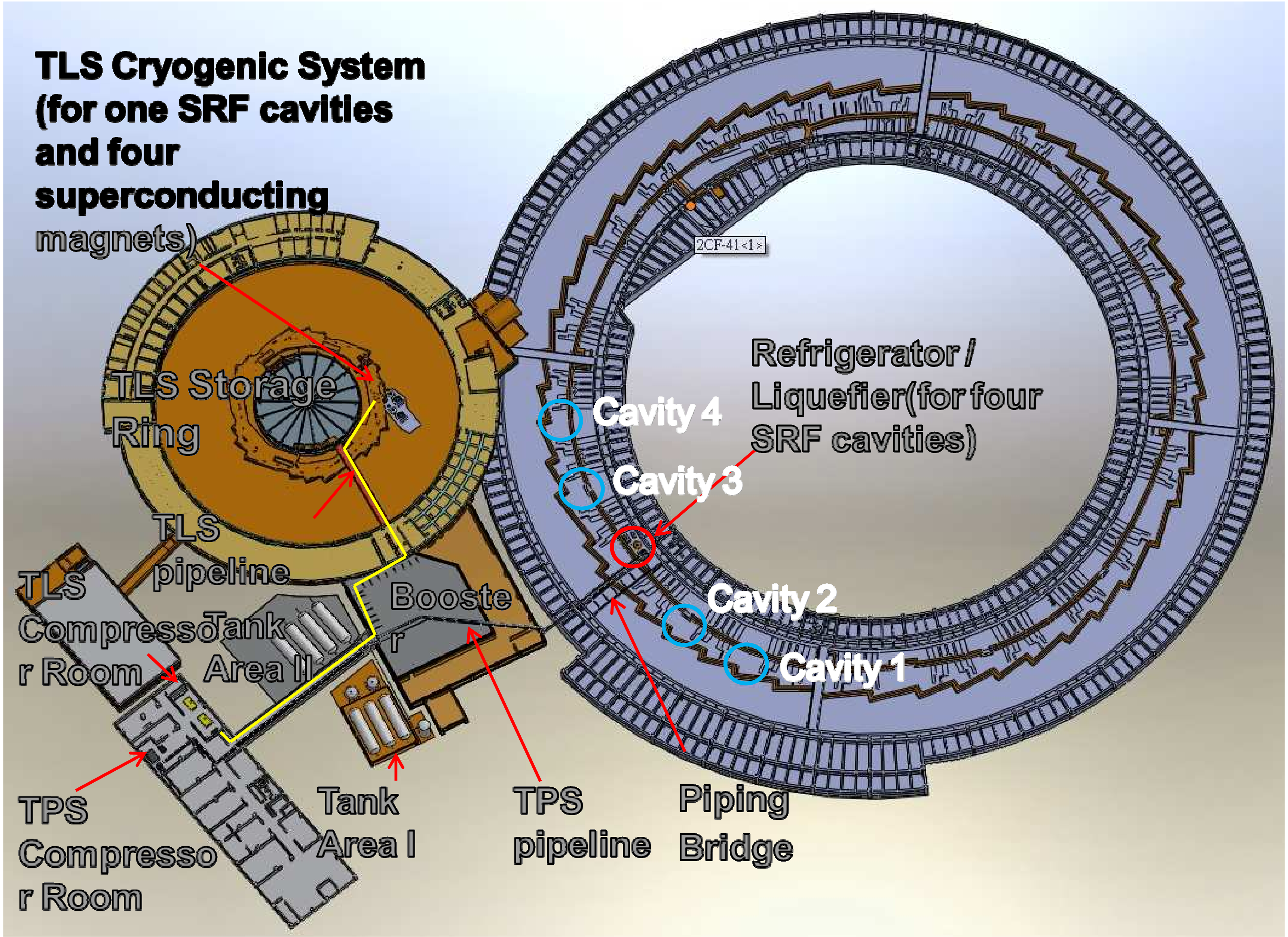



One girder section

# Girder construction and alignment

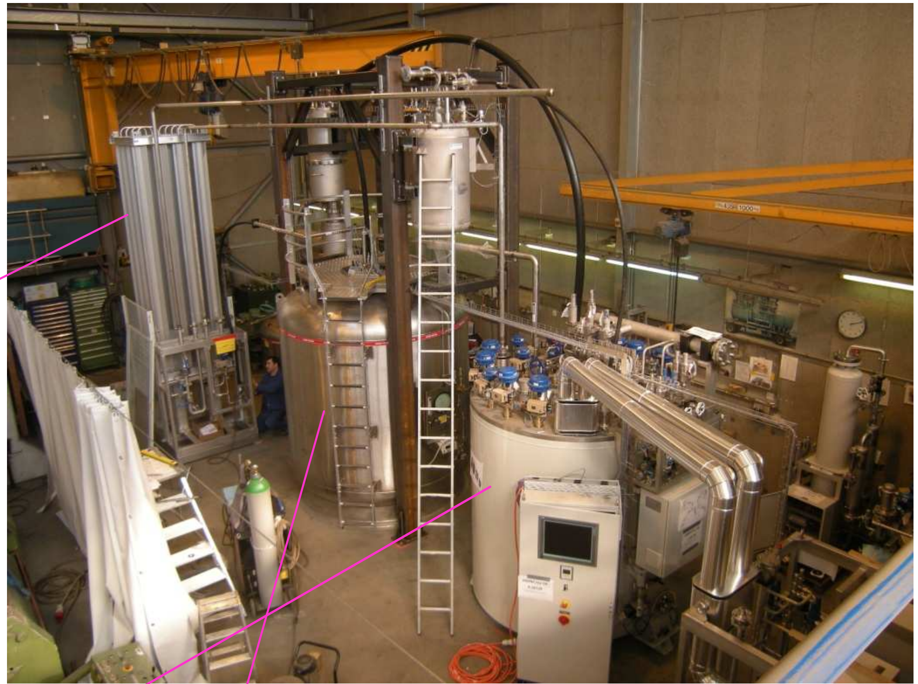
- Girder is constructed in an automatic alignment system.
- Alignment depend on the PSD with laser system.
- Girder has been mass production in Taiwan and on time delivery.

# Distribution of cryogenic system

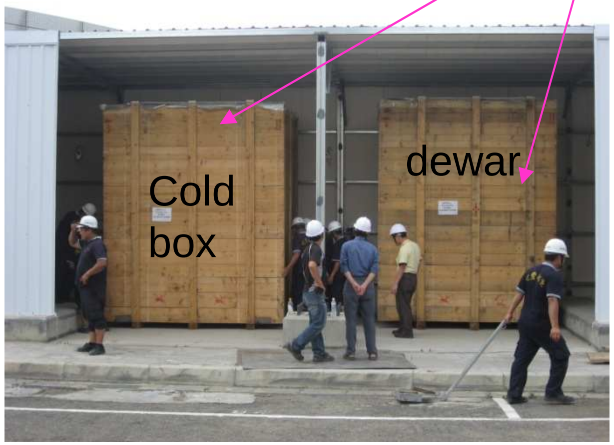


# Cryogenic system fabrication

warmer



turbine




Flexible transfer line

# Cryogenic system arrived at NSRRC

Mail oil removal module

Mail compressor

Recovery oil removal module

Recovery compressor

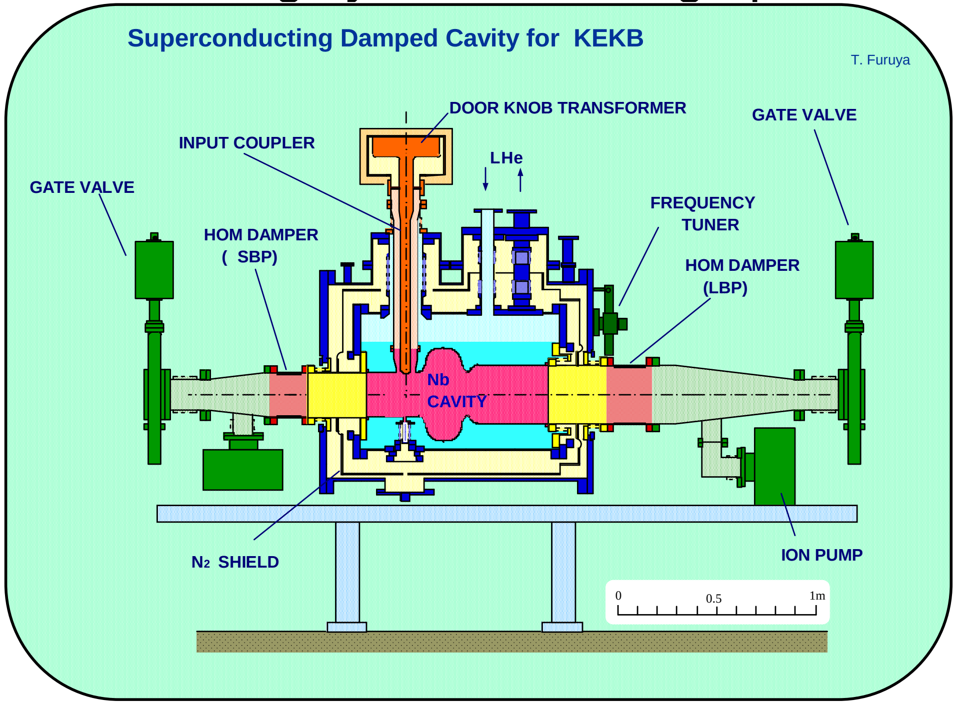


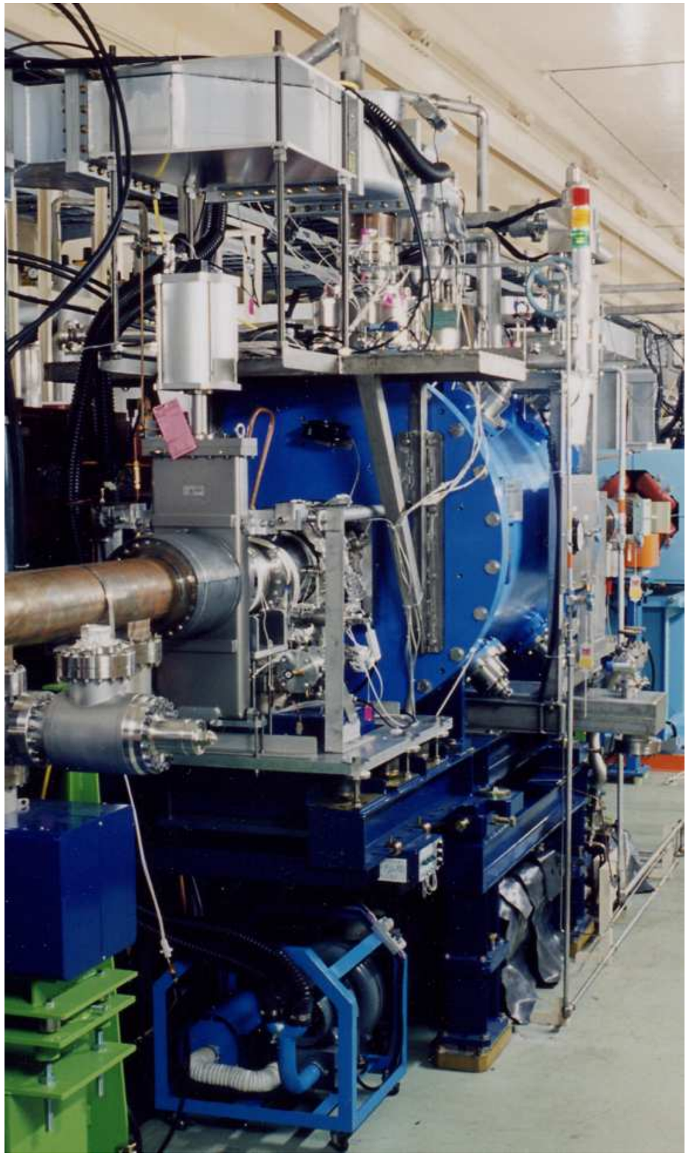
Dryer

Components are delivered too early. It is waiting for commissioning

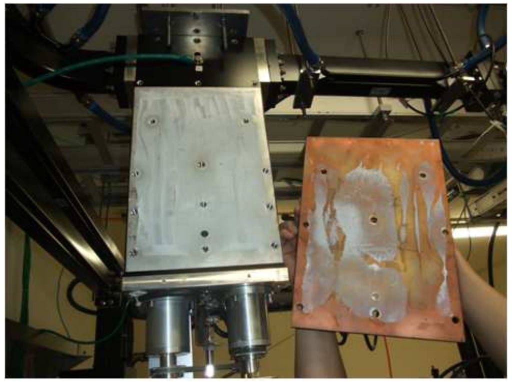
# Selection of RF Cavity - KEKB SRF Module

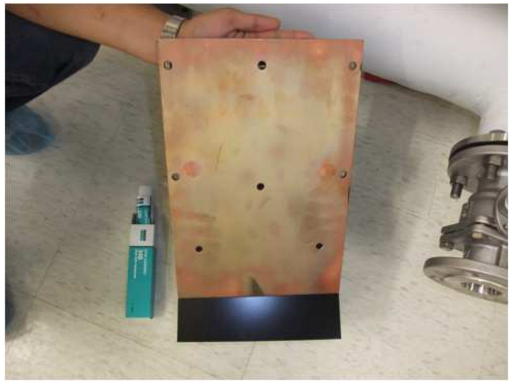
- installed at
  - KEKB (508 MHz) and
  - BECP-II/IHEP (500 MHz)
- Performance
  - Power handling > 300 kW
  - $Q_{ext}$ tunable
  - Highly reliable at high power



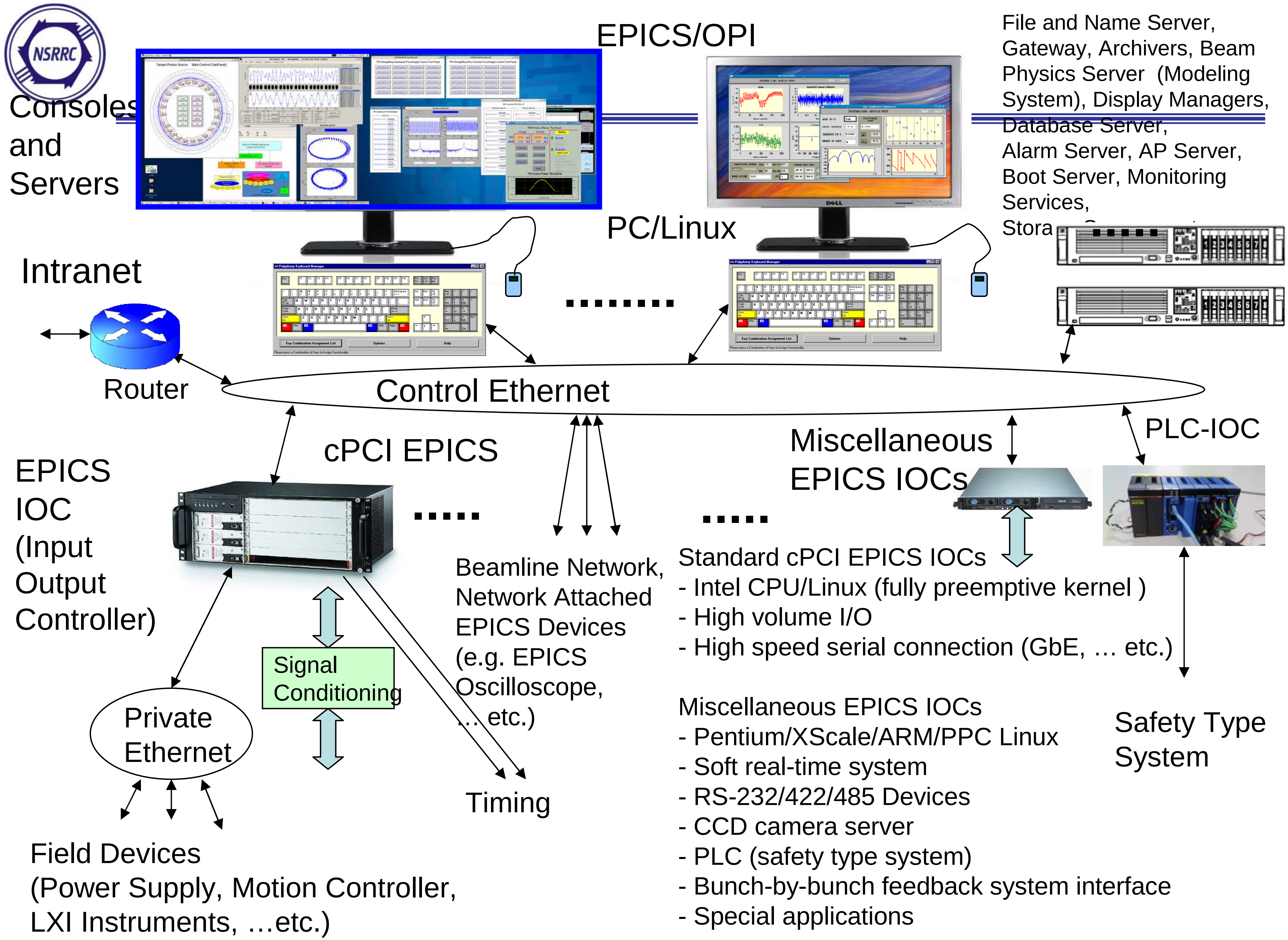
# Successful commissioning of the linac injection system





Cooling plate of RWG phase shifter

- First completed components of the TPS project.

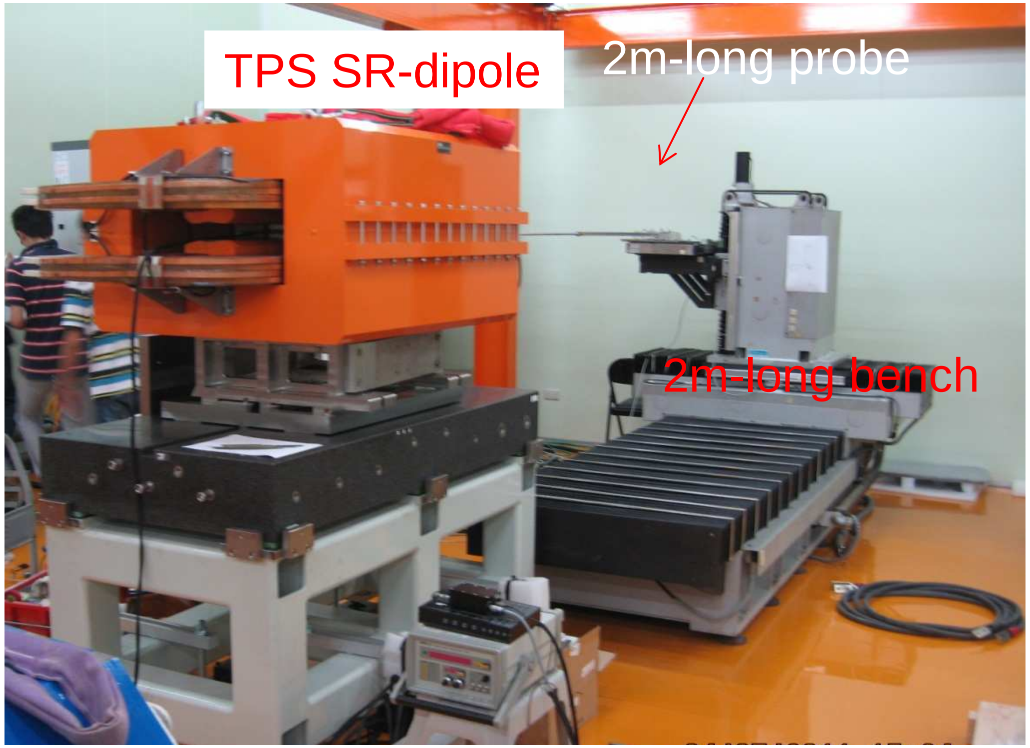


Consoles and Servers
EPICS/OPI
PC/Linux
File and Name Server, Gateway, Archivers, Beam Physics Server (Modeling System), Display Managers, Database Server, Alarm Server, AP Server, Boot Server, Monitoring Services,
Intranet
Router
Control Ethernet
cPCI EPICS
Miscellaneous EPICS IOCs
PLC-IOC
EPICS IOC (Input Output Controller)
Beamline Network, Network Attached EPICS Devices (e.g. EPICS Oscilloscope, … etc.)
Standard cPCI EPICS IOCs
- Intel CPU/Linux (fully preemptive kernel )
- High volume I/O
- High speed serial connection (GbE, … etc.)
Signal Conditioning
Private Ethernet
Timing
Miscellaneous EPICS IOCs
- Pentium/XScale/ARM/PPC Linux
- Soft real-time system
- RS-232/422/485 Devices
- CCD camera server
- PLC (safety type system)
- Bunch-by-bunch feedback system interface
- Special applications
Safety Type System
Field Devices (Power Supply, Motion Controller, LXI Instruments, …etc.)

# 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 | For Lattice magnet | Soak in LHe |
| | 0.6 m | Wiggle, Undulator & EPU | For ID and lattice magnet |
| | 2 m | For Lattice magnet | Mechanical precision 20µm |
| Rotating coil | 840 | QM and SM-storage ring | |
| | 570 | QM and SM-boost ring | |
| NMR<br>ESR | 0.043-13.7T | Hall sensor calibration | |
| | 0.55-3.2 mT | | |
| Search coil | WireOD=0.12mm, 30turns<br>Wire OD=0.05mm 30turns | Kicker and septum | |
| Stretch wire | - | Insertion Devices | |
| Long loop coil | 5-axes | Insertion Devices | |

# 2m-long Hall probe bench



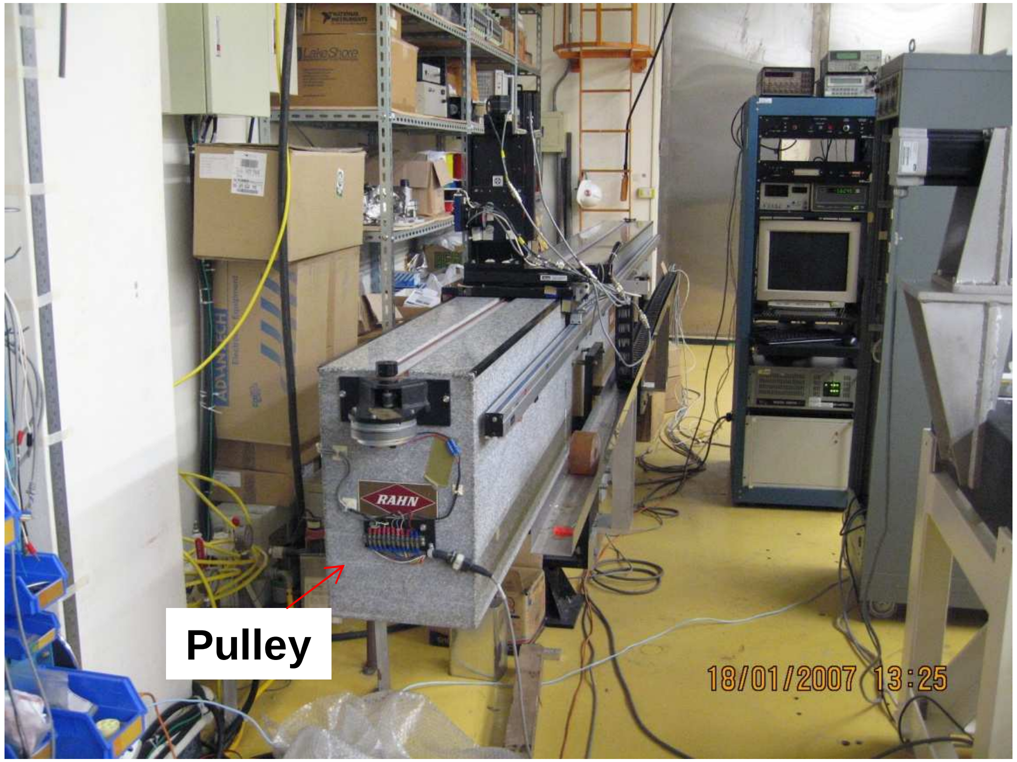

| | |
|---|---|
| **Specificat-ion** | **3-Axis & three angle adjustment**<br>**Moving rang : 200 * 60* 30 cm**<br>**Stepping motor** |
| **Precision** | **Pitch, Yaw, Raw: 0.1 mrad**<br>**Z-axis Position: 15 μm**<br>**X & Y-axis position:: 10 μm** |
| **Purpose** | **Dipole : Linear, Curve(1)**<br>**Quadruple : Linear, Circular(2)**<br>**Sextuple : Linear, Circular**<br>**Corrector : Linear**<br>**ID : On-fly** |
| **Sensor** | **Hall probe with High precision 0.005%** |

- Optical scalar is used for distance measurement and was calibrated by laser encoder.
- 2m-long Hall probe aligned with Hall Probe=1.19993T
- NMR=1.19996T

**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.

**C.S. Hwang**, F.Y. Lin, P.K. Tseng, "*A PC based real-time Hall probe automatic measurement system for magnetic fields*", *IEEE Trans. on Instrum. and Meas, Vol. 48, NO. 4, (1999)*.

# 6m-long Hall probe bench for ID

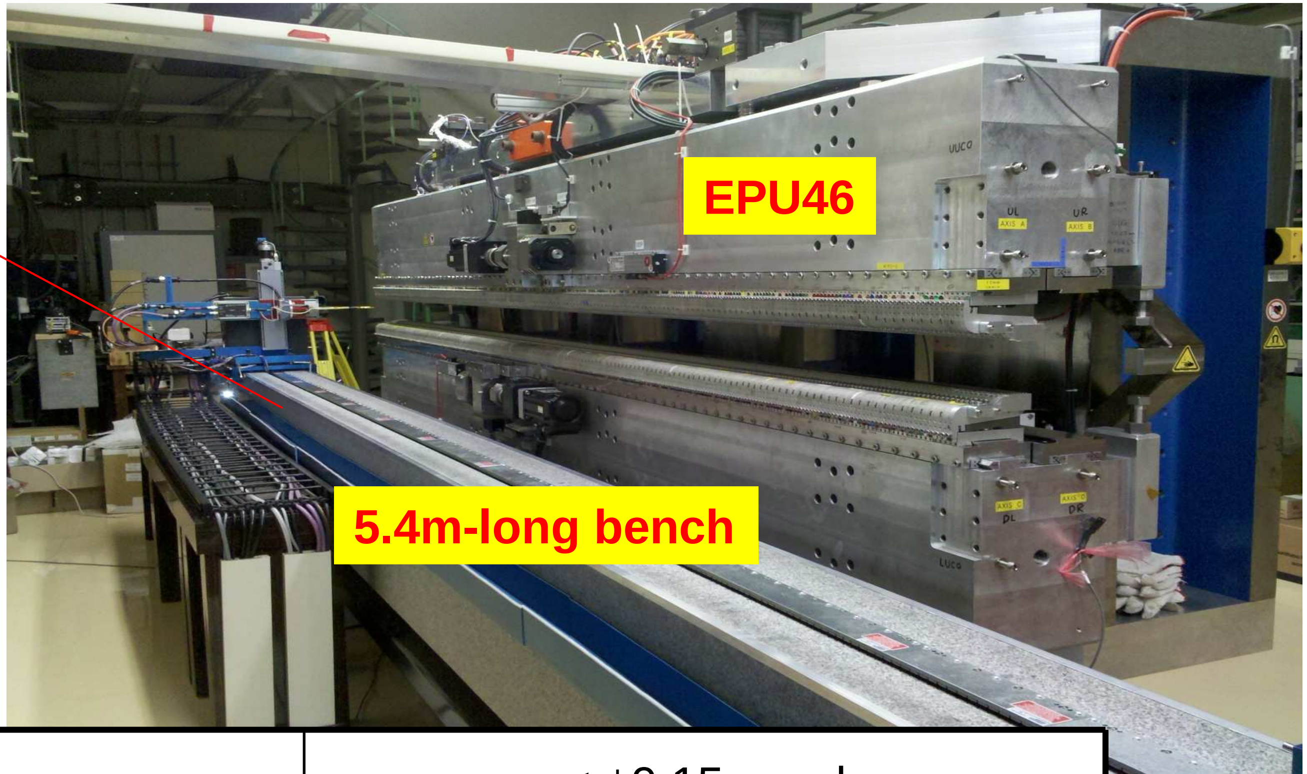



- Optical sensor for reference point & for limit switch.
- Optical scalar is used for distance measurement that has been calibrated by laser encoder

| | |
|---|---|
| Specificati-ons | 6m granite-bench<br>3-Axis 7 two angle adjustment<br>Moving range : 590*20 * 20 cm<br>Optical Linear encoder<br>Pulley driven by DC motor (only for on-fly) |
| precision | Pitch, Yaw, Raw: 0.1 mrad<br>Z-axis Position: 25 μm<br>X & Y-axis position:: 10 μm |
| Purpose | Wiggle<br>U10 prototype<br>EPU prototype<br>EPU56 |
| Sensor | One or two Hall probe with high precision 0.01% |

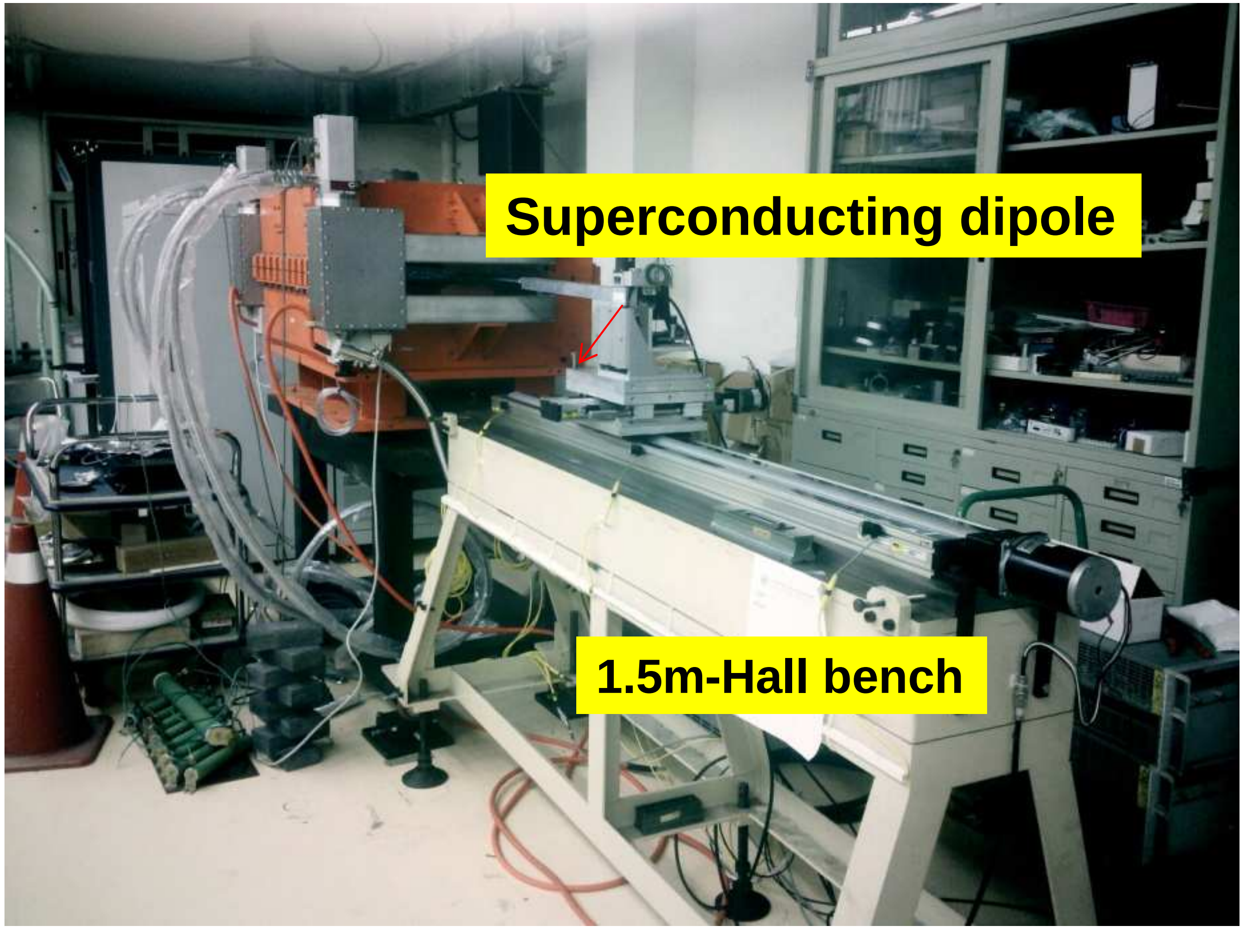

**C. S. Hwang**, et al.,, September," *Advance field measuremen method with three orthogonal Hall probe for an Elliptically Polarizing Undulator* ", *J. Synchrotron Rad.* **5**, (1998) 471-474.

# 5.4m-long Hall probe bench for ID

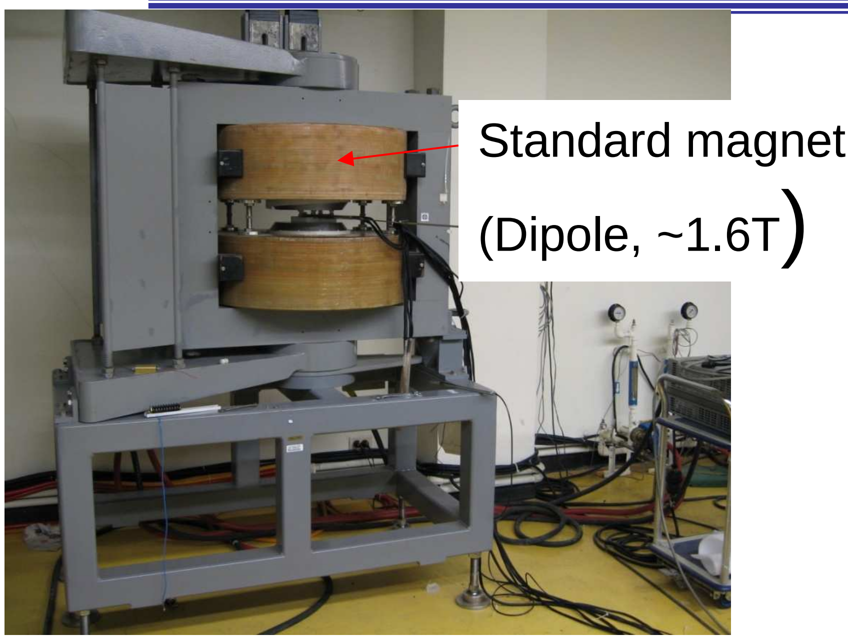

| | |
|---|---|
| Pitch | < ±0.15 mrad |
| Yaw | < ±0.15 mrad |
| Roll | < ±0.15 mrad |
| Horizontal and vertical straightness | < ±12.5 μm |
| Perpendicularity between each axis | 0.087 mrad |
| Peak field standard deviation | 0.23G for Bx, 0.21G for By |

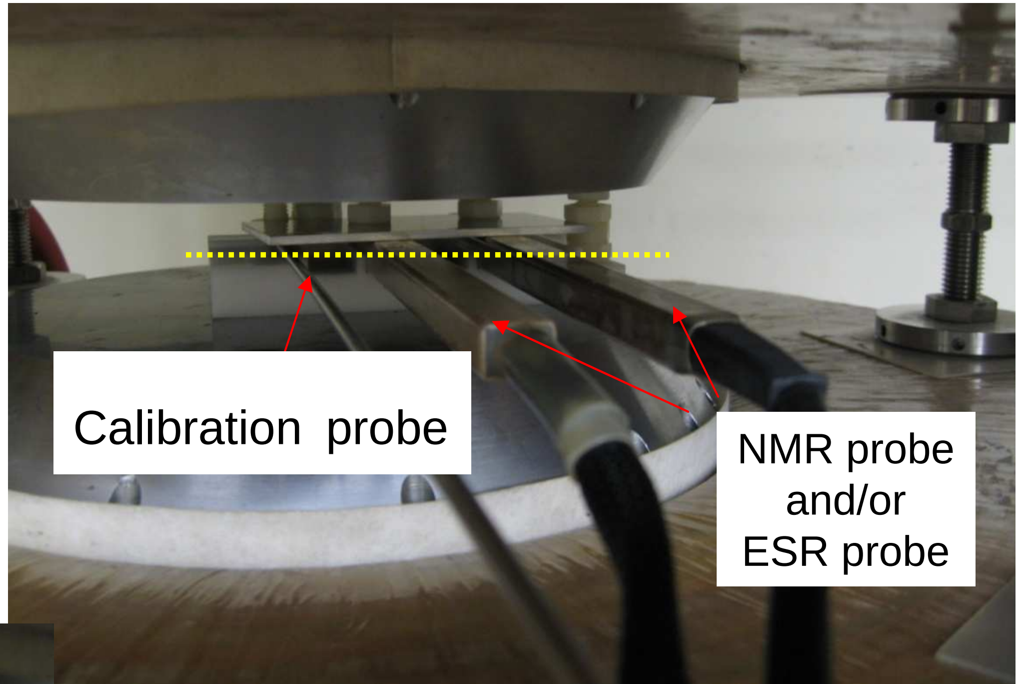
# 1.5m-long Hall probe bench

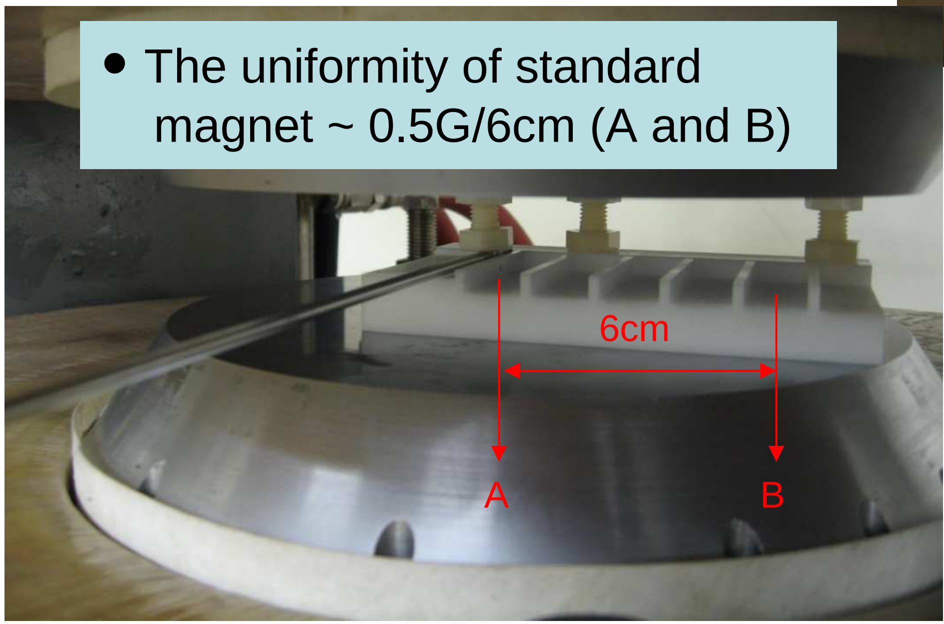



- Five degree of freedom- three translation and two rotation.
- A HTS superconducting dipole was measured by this system.

# Magnetic field calibration system



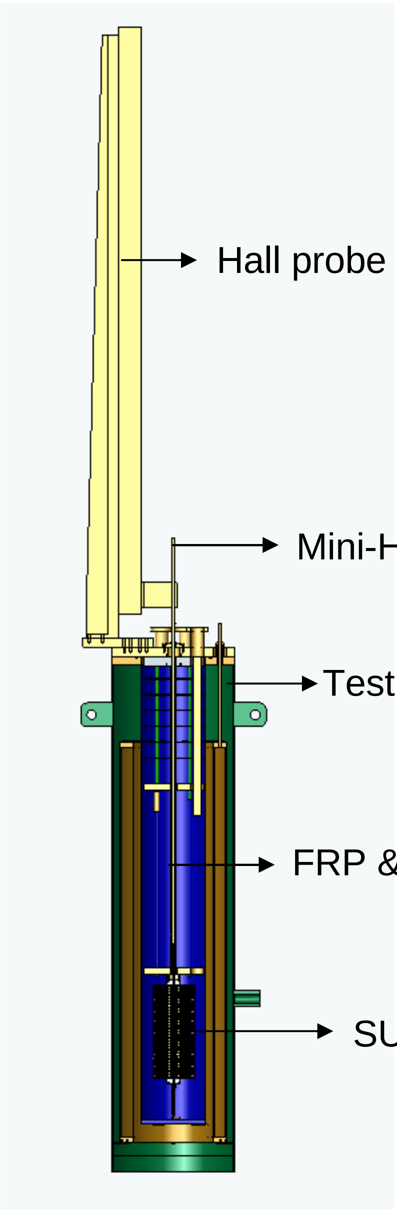



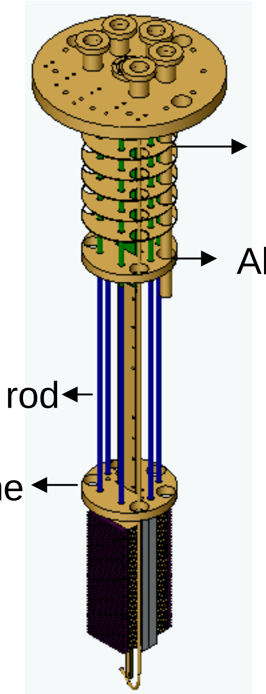



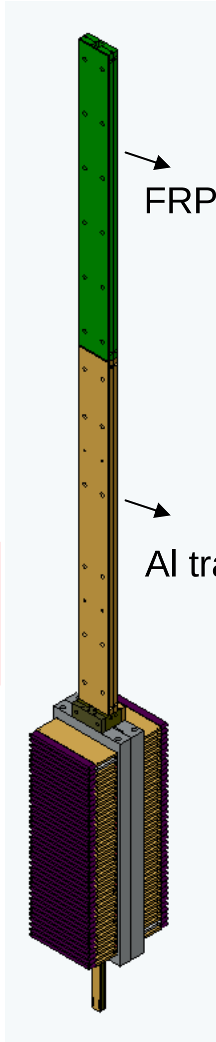

- The uniformity of standard magnet ~ 0.5G/6cm (A and B)

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

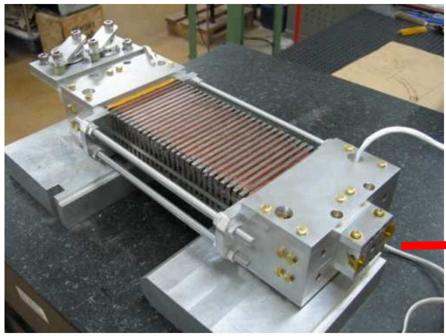
# Cryogenic field measurement system

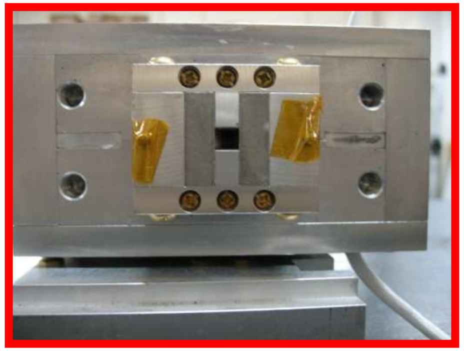



Magnet gap = 5.6mm
→ Mini-Hall probe



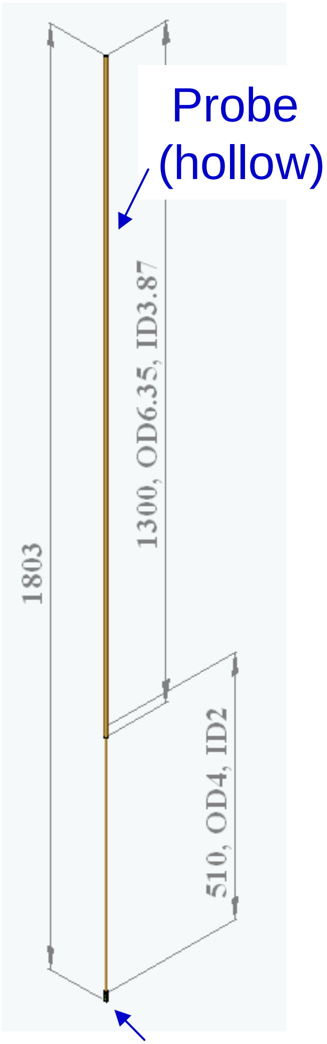


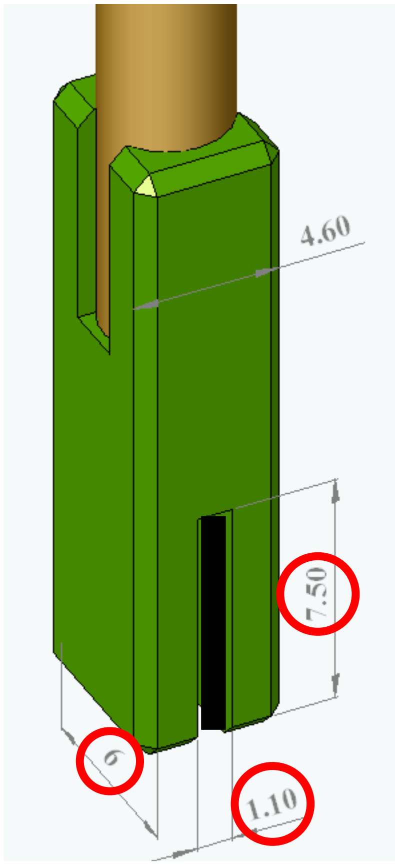
# Cryogenic Hall probe design

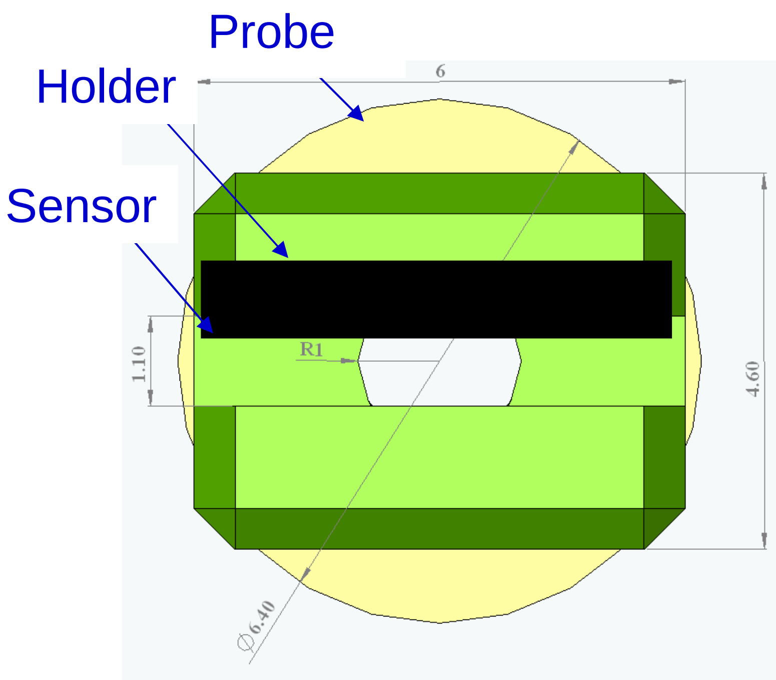
| | Dimension/ Action area (mm) | Control current lead (mm) | Magnetic field range (T) | Temperature range (K) | Sensitivity (mV/T) | Linearity error at 4.2K, B=0-5T (%) |
|---|---|---|---|---|---|---|
| HHP | 5*7*1/0.1*0.1 | OD=0.1 | 0-5 | 1.5-350 | >20 | <1.5 |

- **Glue expansion rate 2.5-6.5E-5 $K^{-1}$**
- **Package hall probe material 0.5-1.5E-5 $K^{-1}$ (ex: Ceramic, Steel, glass)**

Mini-Hall probe



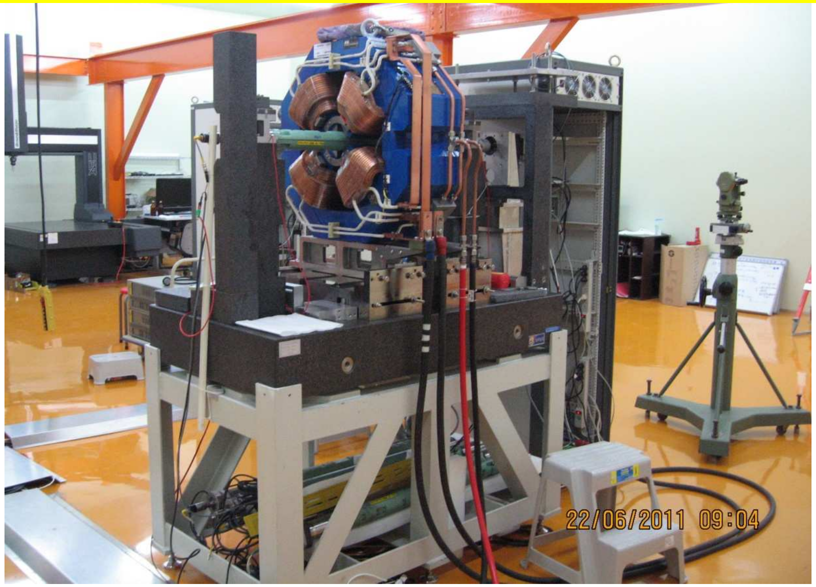



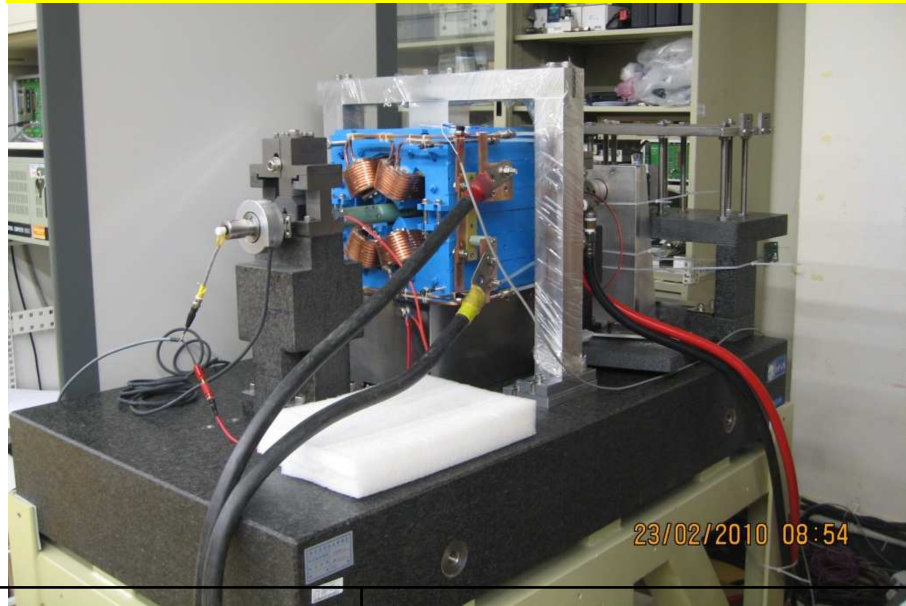

- Material of Hall probe and holder ~ Stainless Steel (SS316)

# Rotating coil measurement system

**Storage-ring magnet measurement system**

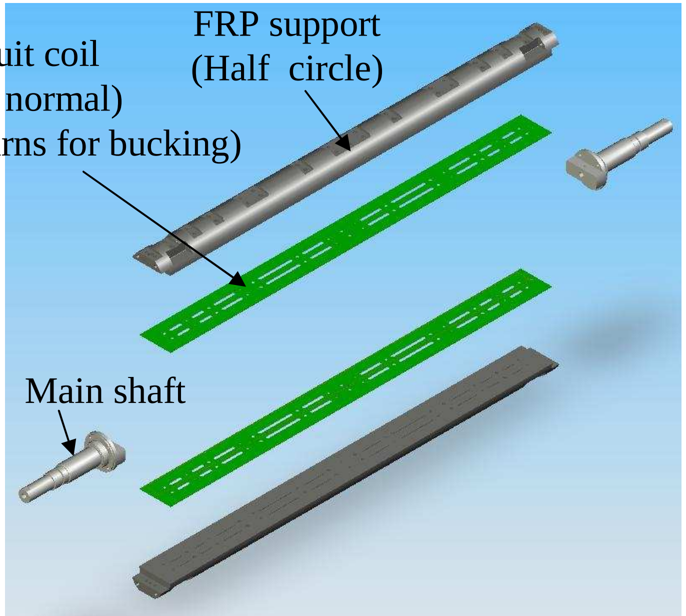



**Booster-ring magnet measurement system**




| | Vertical offset (mm) | Horizontal offset (mm) | Normalized multipoles (*E-4) |
|---|---|---|---|
| reproducibility | < 0.001 | < 0.001 | < 0.1 |
| reinstall reproducibility | < 0.005 | < 0.005 | n=2, Δ< 0.3 |
| | | | n>2, Δ< 0.1 |
| n=2 is quadrupole term, n=3 is sextupole term | | | |

# Rotating coil measurement units

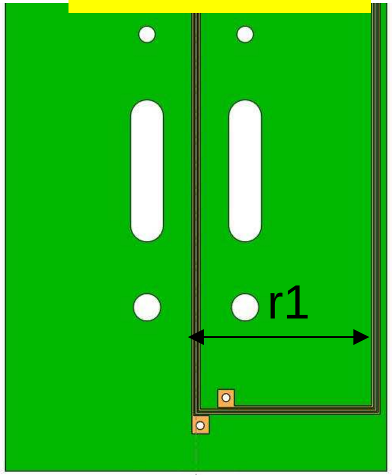


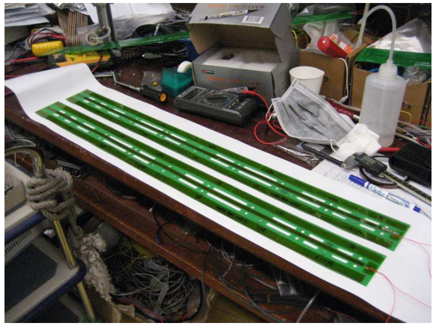

J. C. Jan, C. S. Hwang, J. W. Chen, C. H. Chang, T. C. Fan and F. Y. Lin, "**DESIGN OF A PRECISE UNIT FOR THE ROTATING COIL MEASUREMENT SYSTEM",** Proceedings of PAC07, Albuquerque, New Mexico, USA.

| Parameter | Nm (turns) | Nb (turns) | r1 (mm) | r2 (mm) | r3 (mm) | r4 (mm) | Measurement length (mm) |
|---|---|---|---|---|---|---|---|
| SR-Normal-QM/SM | 3 | - | 33 | - | - | - | 840 |
| QM-Bucking | 150 | 300 | 33 | 17.6 | 28.6 | 13.2 | |
| SM-Bucking | 150 | 300 | 33 | 25.6 | 22.98 | 19.36 | |
| BR-Normal-QM/SM | 12 | - | 16 | - | - | - | 570 |

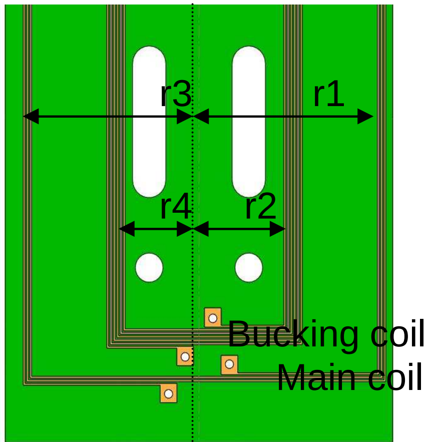
# Rotating coil design & fabrication

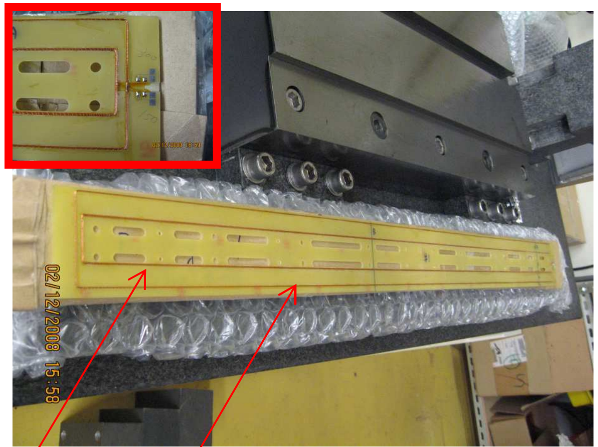
## Normal coil



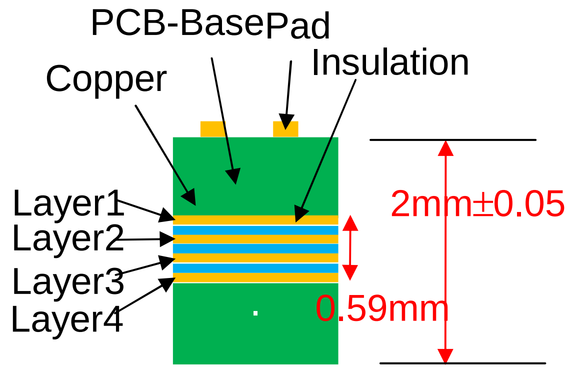
## Bucking coil

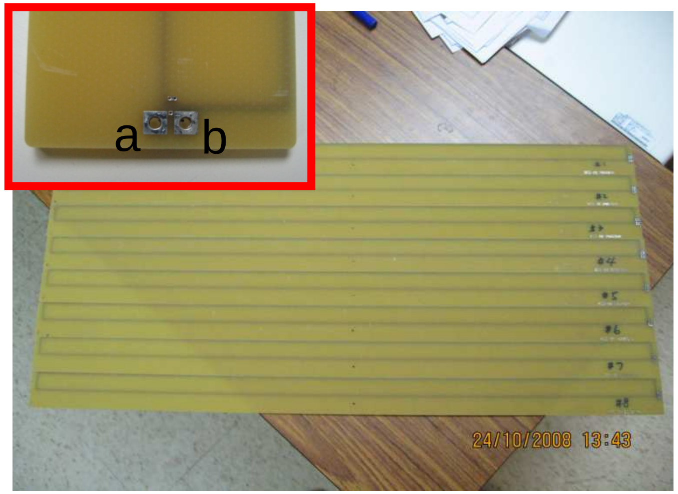


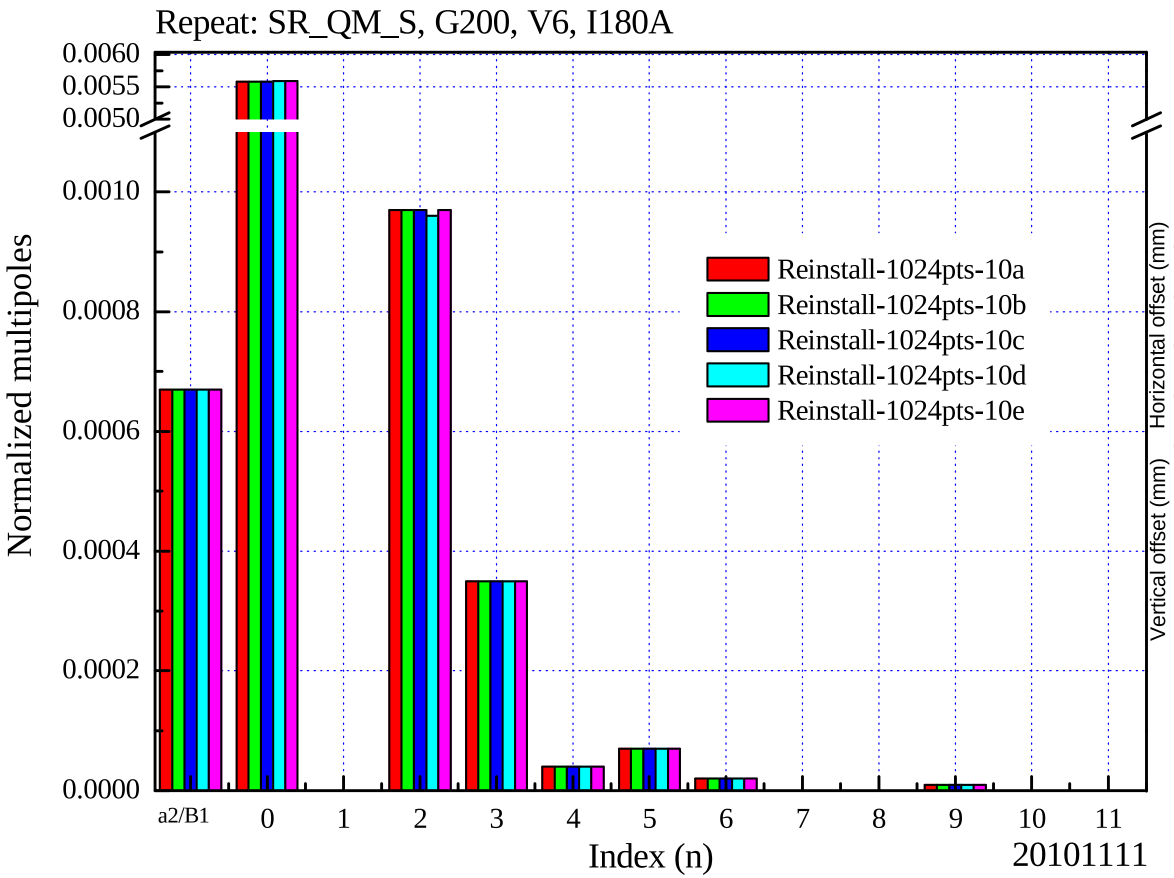

Main coil (150 turns in 1mm groove)
Bucking coil (300 turns in 1.4 mm groove)

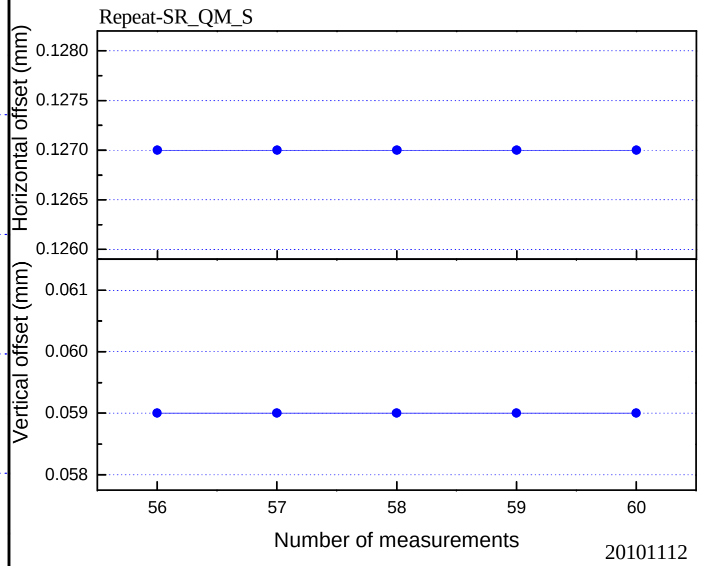
## Normal coil



# RCS repeatability testing

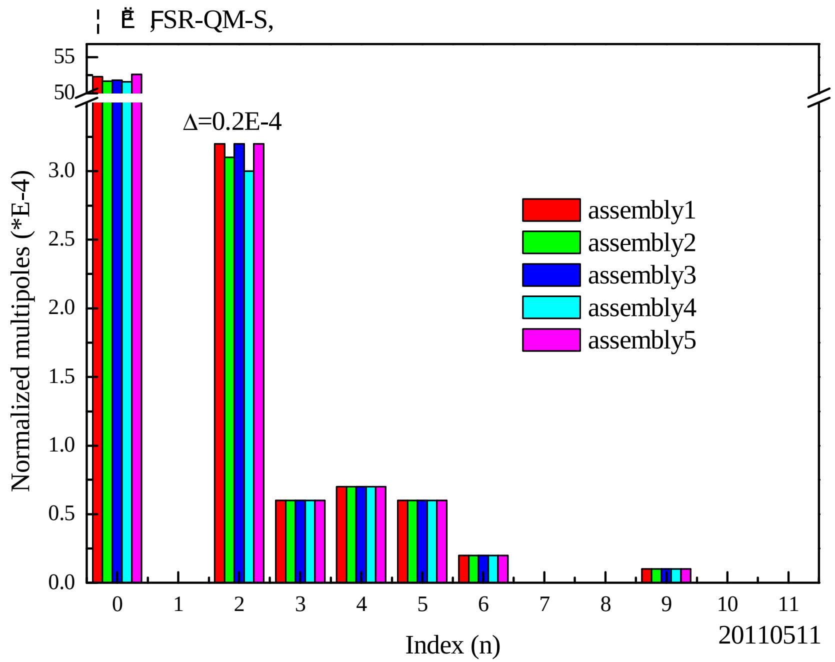


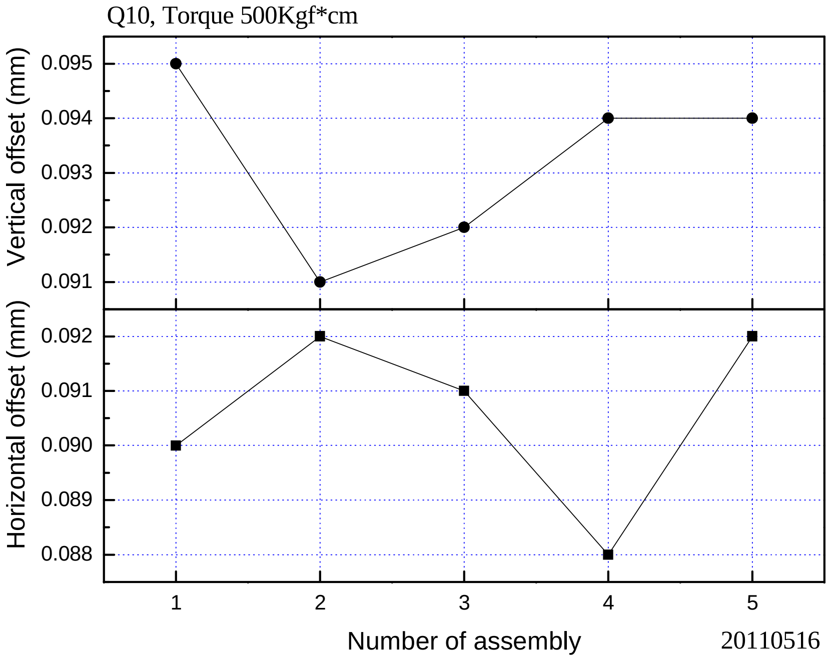




Three factors should be considered if 10 μm precision of field center is required:

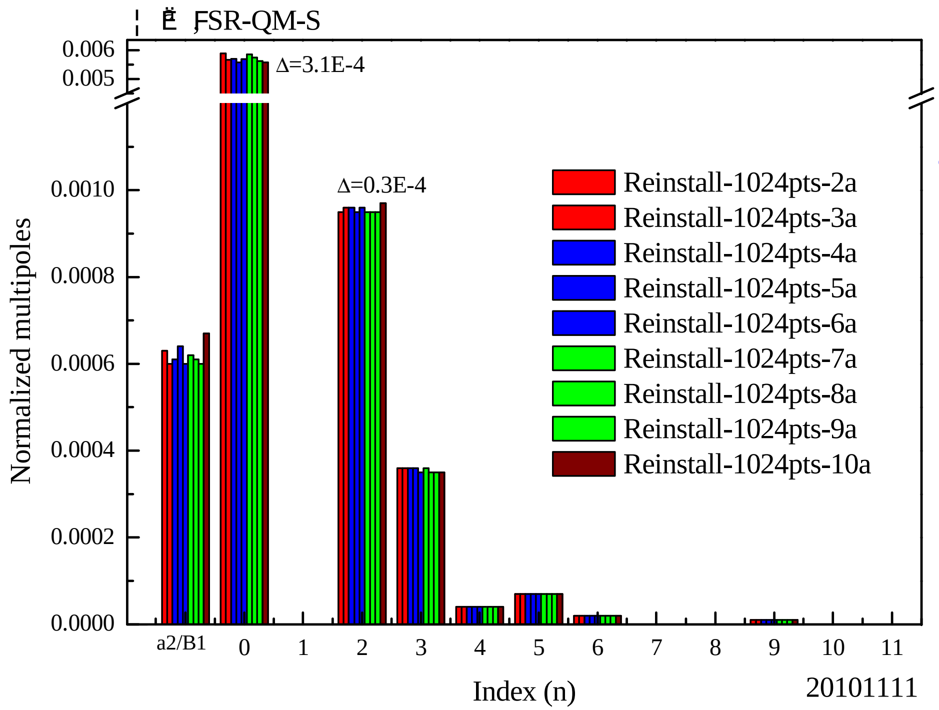
- The temperature of measurement laboratory should be controlled within ±0.5°C.
- The coil temperature variation also keep within ± 2.5°C.
- The high resolution of rotary encoder and the digital leveling meter to decide exact skew quadrupole (in Q-magnet) & sextupole (in S-magnet) components.

# Precision of magnet re-installed

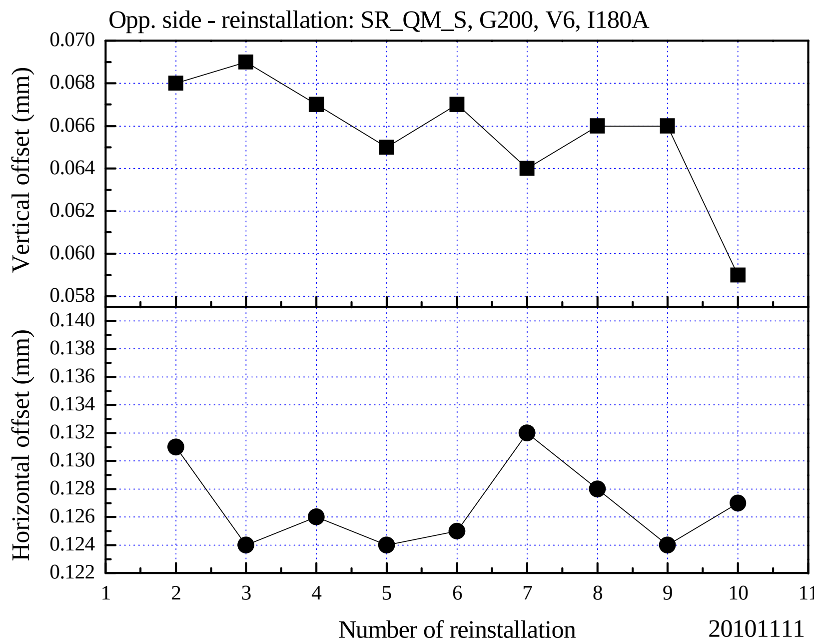


# RCS repeatability testing after re-assembly



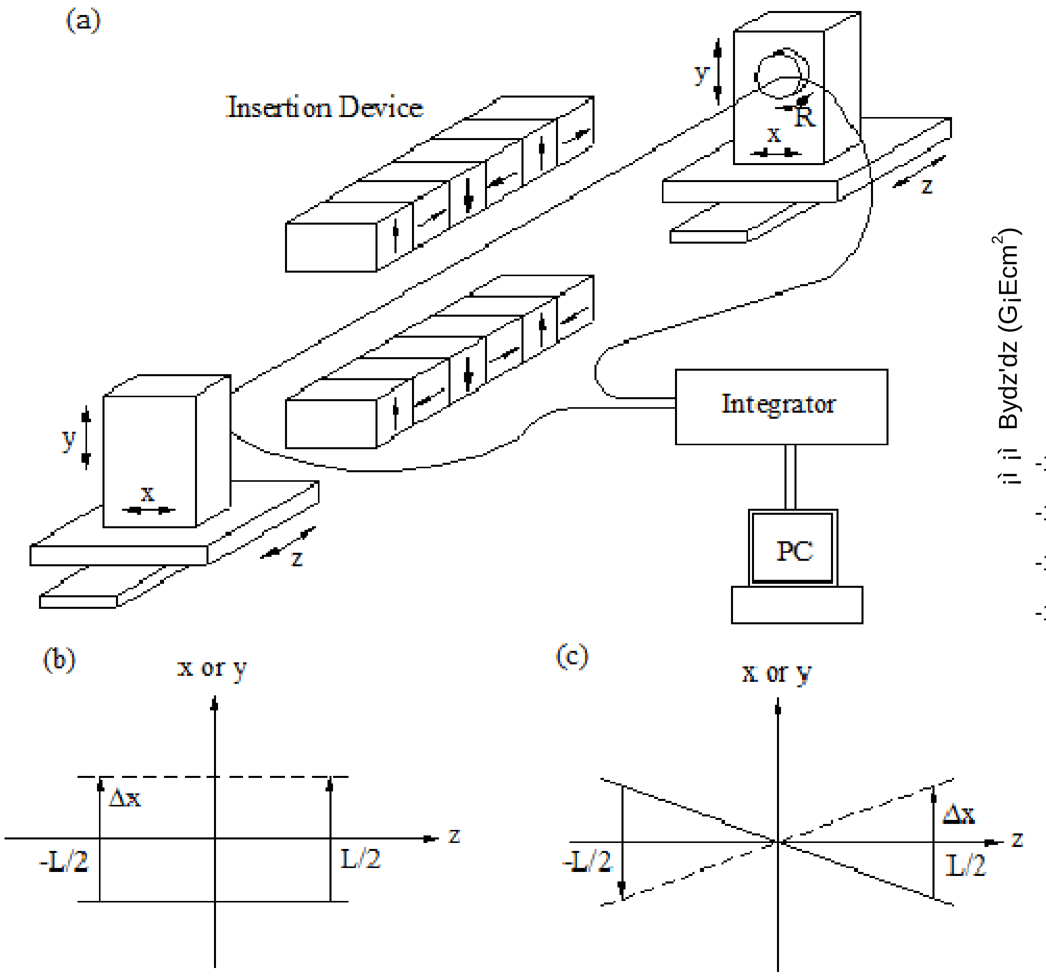

- This precision include the re-assembly of RCS system and magnet.

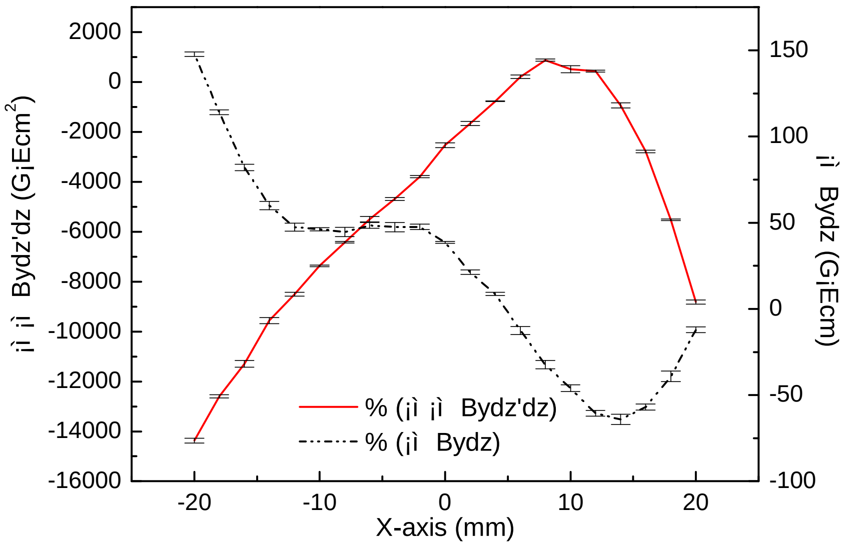



- Systematic error check & test:

1. The magnet was moved everywhere on the longitudinal axis on the bench.
2. The magnet was inversed 180º.
3. Rotatory encoder with 18000 pulses & a high precision digital angle meter on coil is necessary to have a resolution better than 0.1 mrad.

# Stretch wire for ID measurement



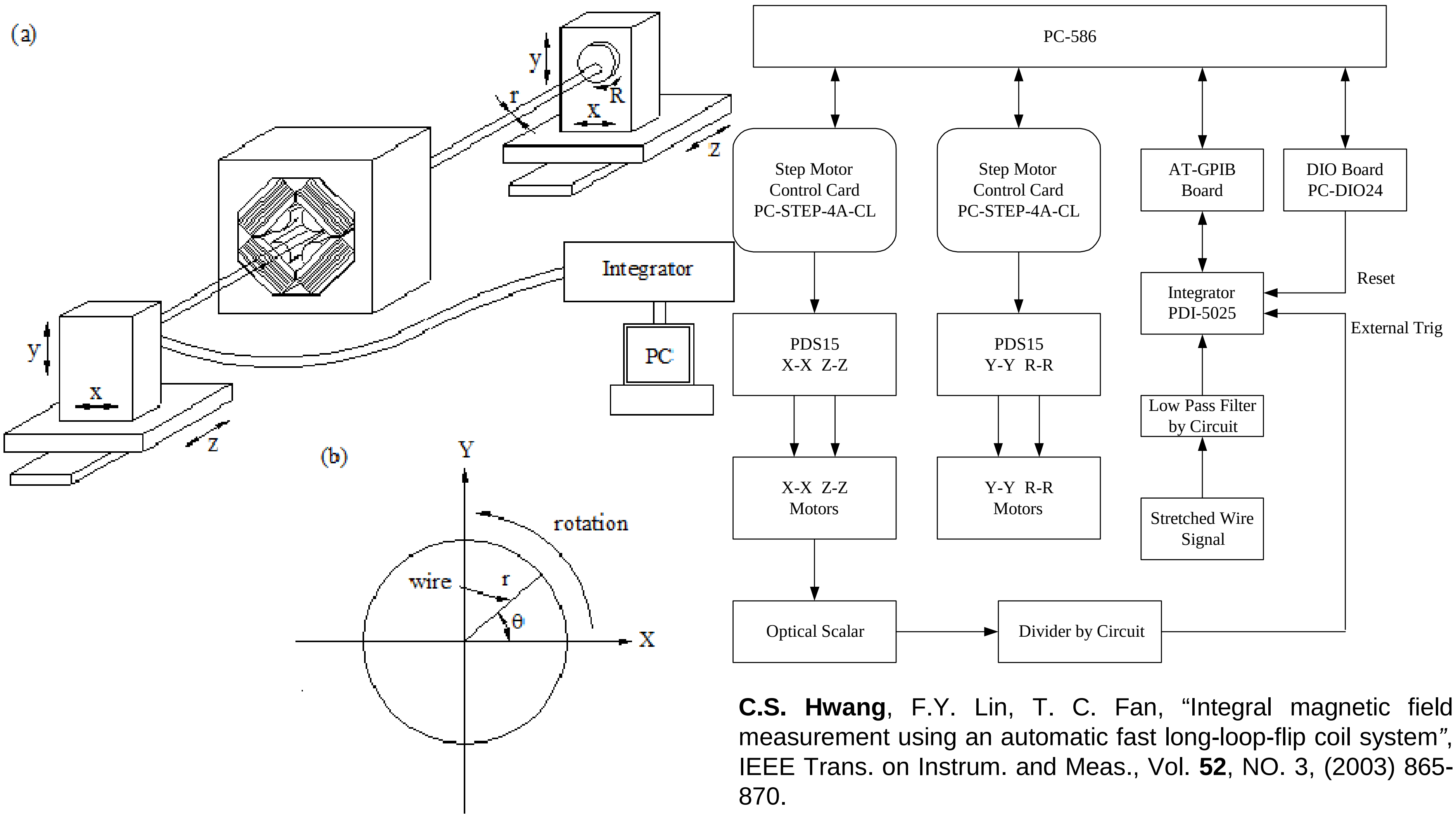




First integral

Second integral

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

# Long loop coil for accelerator magnet measurement

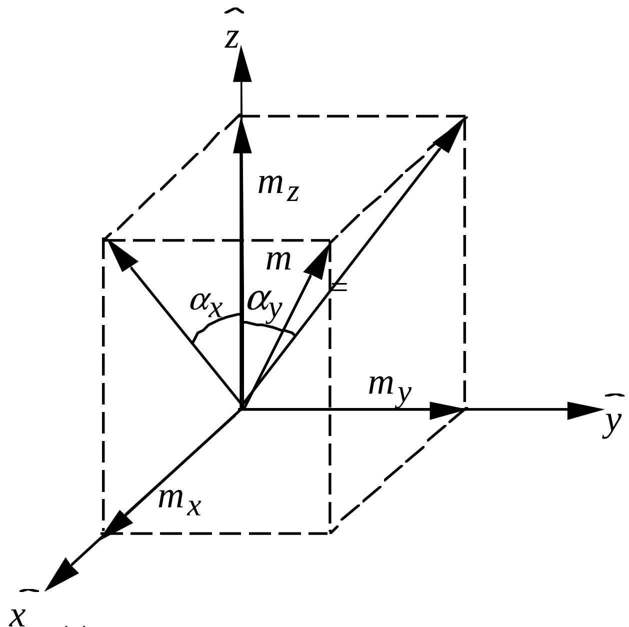




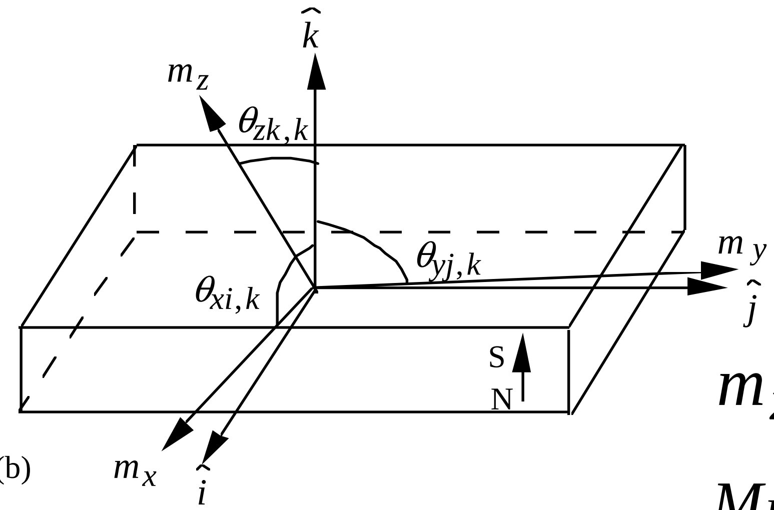
**C.S. Hwang**, F.Y. Lin, T. C. Fan, "Integral magnetic field measurement using an automatic fast long-loop-flip coil system", IEEE Trans. on Instrum. and Meas., Vol. **52**, NO. 3, (2003) 865-870.

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

# Helmholtz coil system




(a)




(b)

- Automatic measurement for the three magnet dipole moment of permanent magnet.

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

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

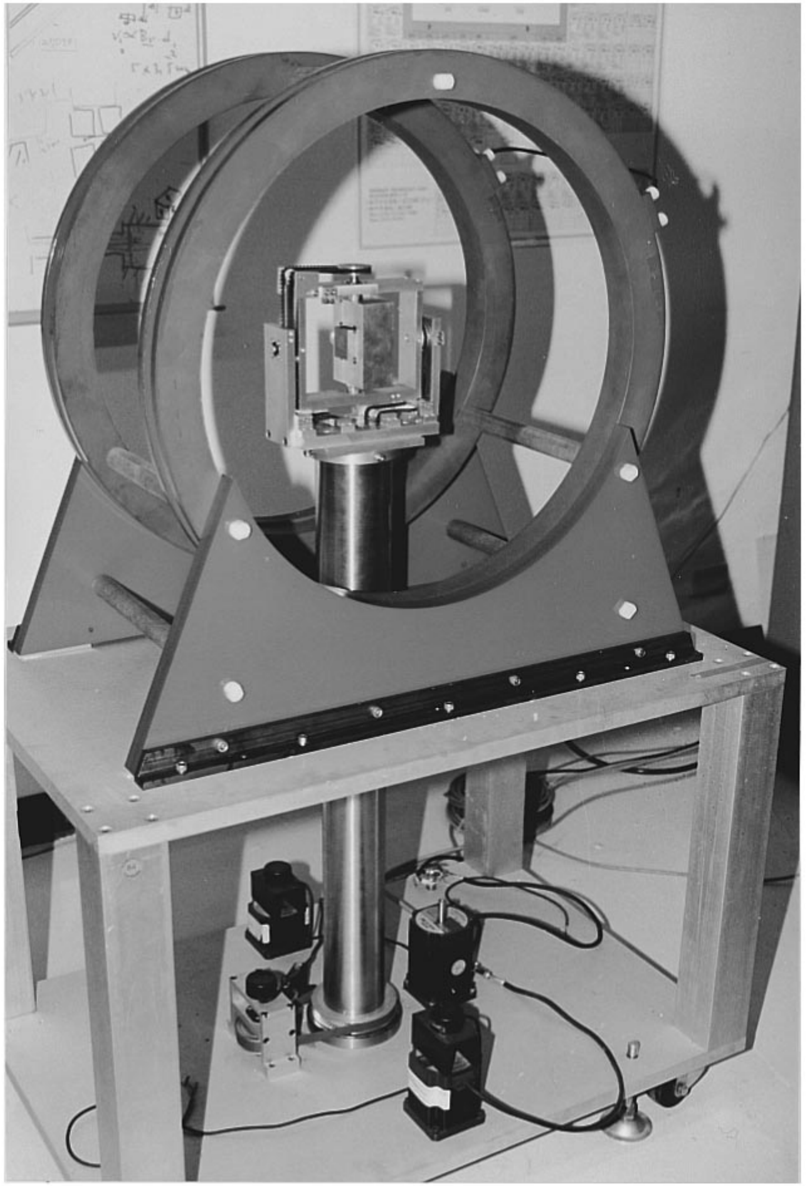
$$m = \sqrt{m_x^2 + m_y^2 + m_z^2}$$

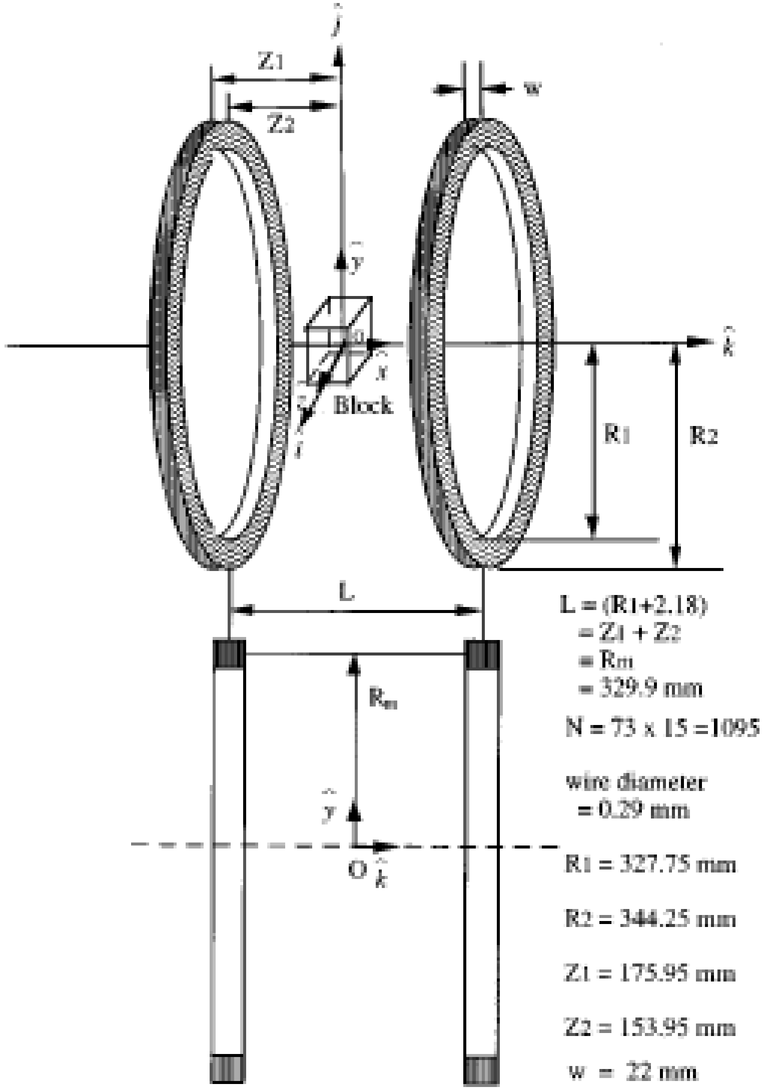
$$\alpha_y = tan^{-1}\left(\frac{m_y}{m_z}\right)$$

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

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

# Helmholtz coil system





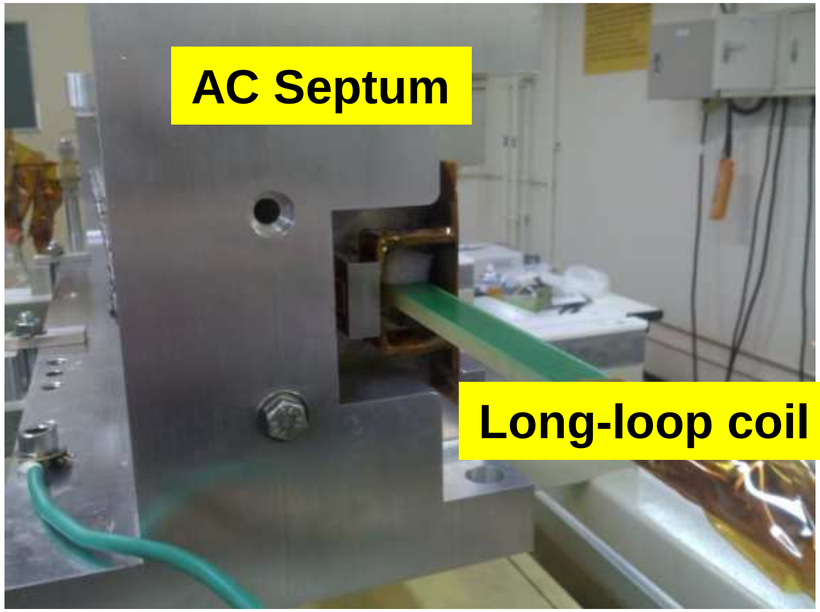

**C. S. Hwang**, et al."*A Highly Automatic Measurement System for Three-Orthogonal Magnetic Moment of the Permanent Magnet block",* Rev. Sci. Instrum. **67(4)**, (1996) 1741-1747.

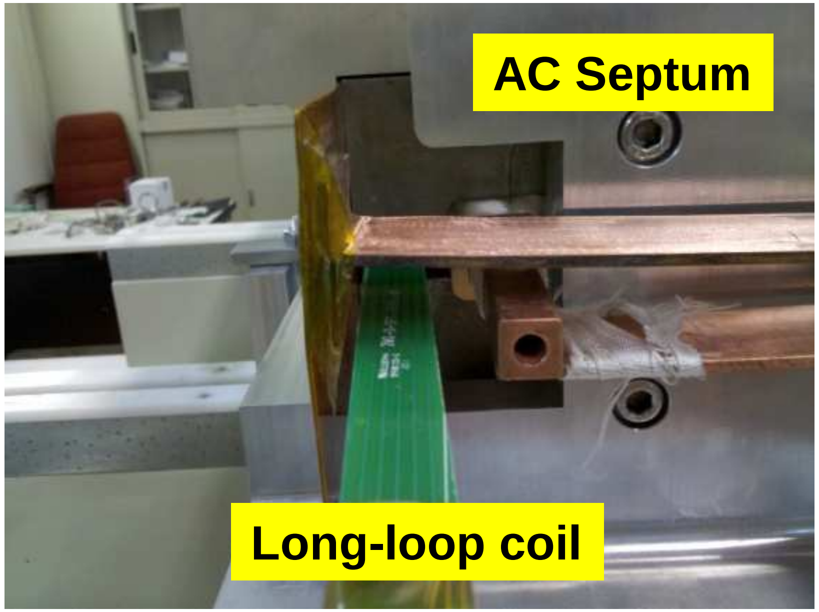
# Accuracy of Helmholtz coil

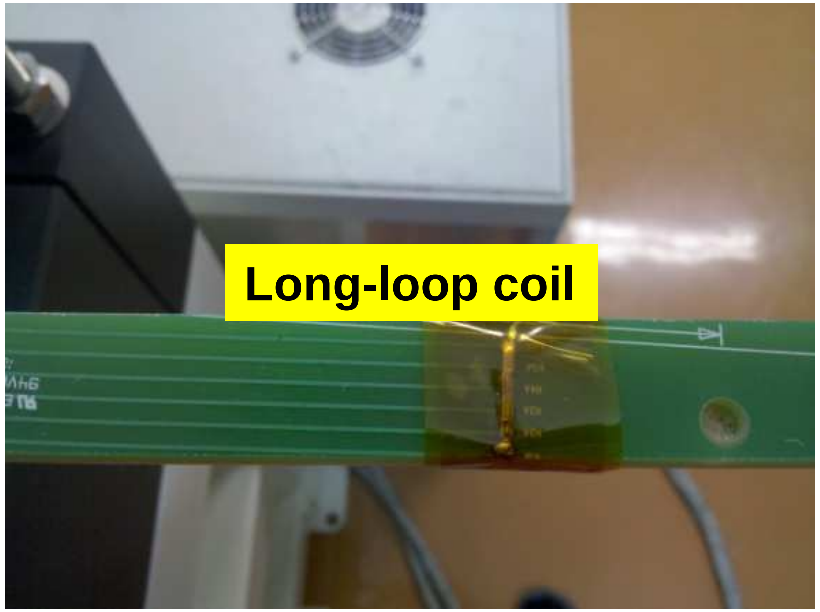
| Component (Unit) | Block direction | | | |
|---|---|---|---|---|
| | $(\hat{x},\hat{y},\hat{z})$ | $(-\hat{x},-\hat{y},\hat{z})$ | $(\hat{x},-\hat{y},-\hat{z})$ | $(-\hat{x},\hat{y},-\hat{z})$ |
| $m_z$ ( T ) | 1.2273 | 1.2272 | -1.2276 | -1.2277 |
| $m_y$ ( T ) | 0.0086 | -0.0090 | -0.0090 | 0.0087 |
| $m_x$ ( T ) | 0.0139 | -0.0135 | 0.0137 | -0.0140 |

- Replacing the different direction of the magnet on the holder to survey the absolute angle error and the main component deviation of the block magnetic moment of the measurement system.

# Long-loop coil measurement system for pulse magnet



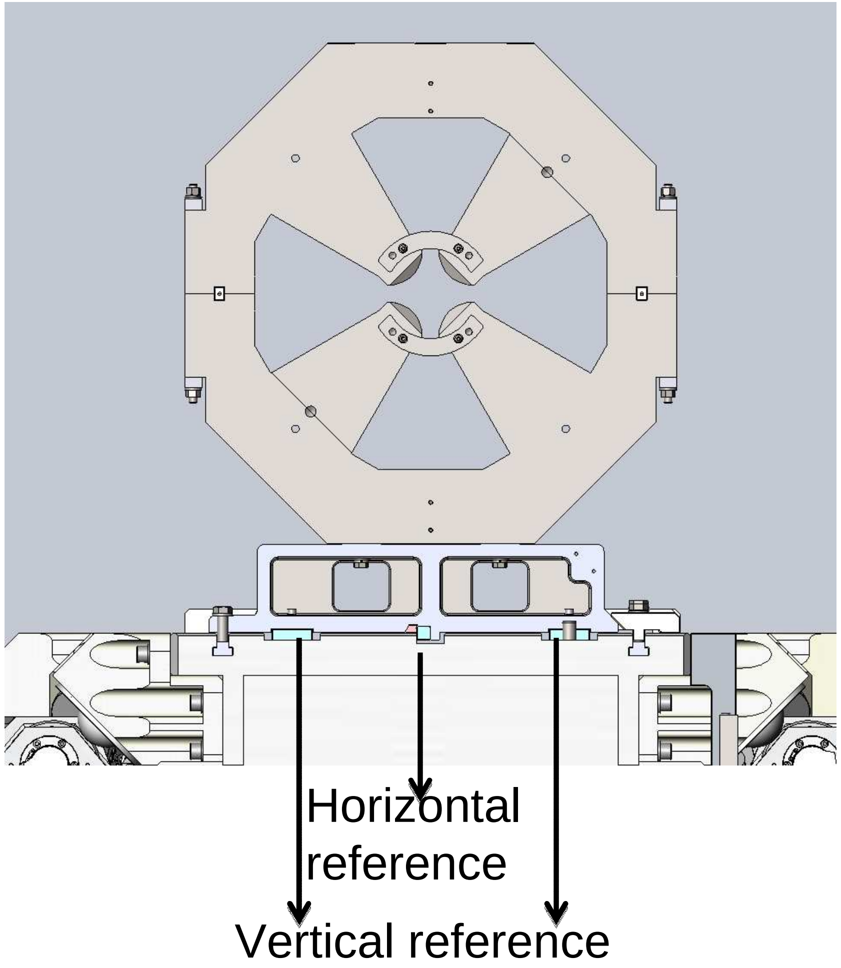



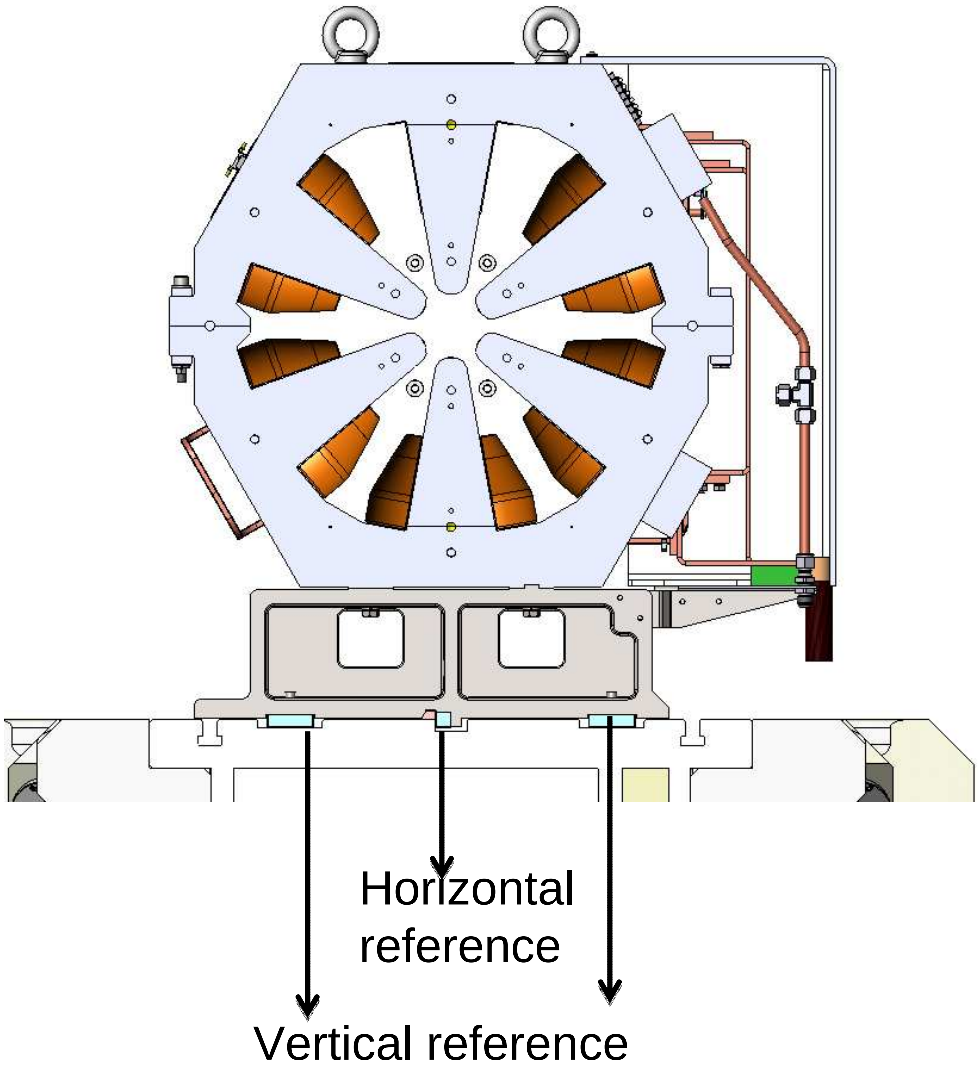




- Print-circuit board for the wire with various shape to match magnet.

# Field measurement results

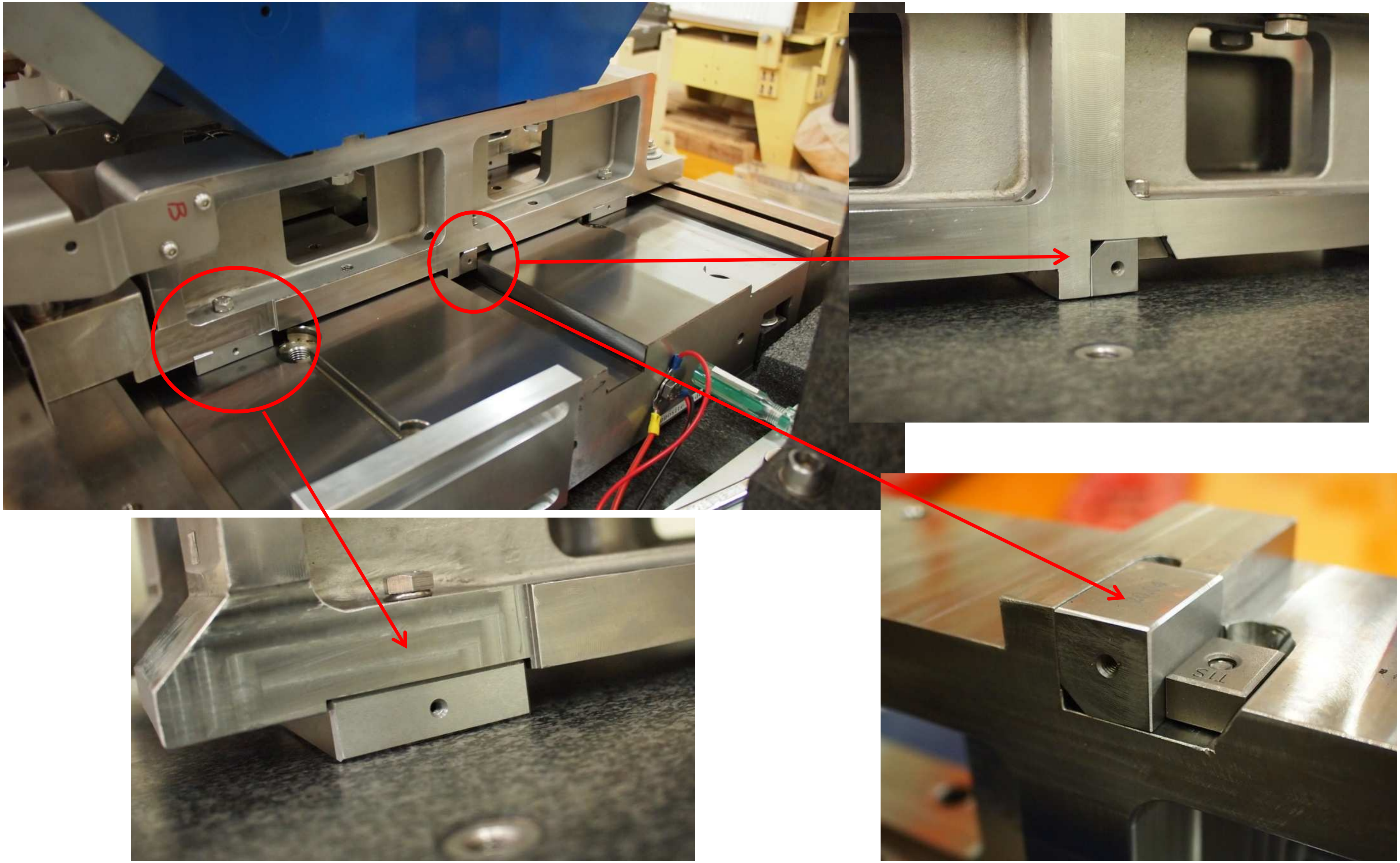
# Positioning method of Quadrupole & Sextupole



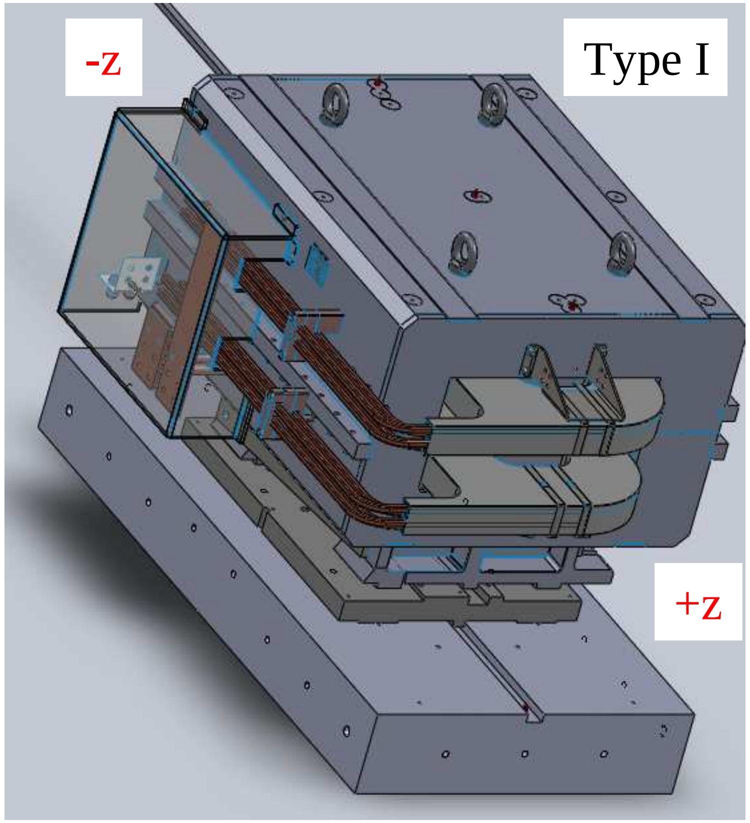



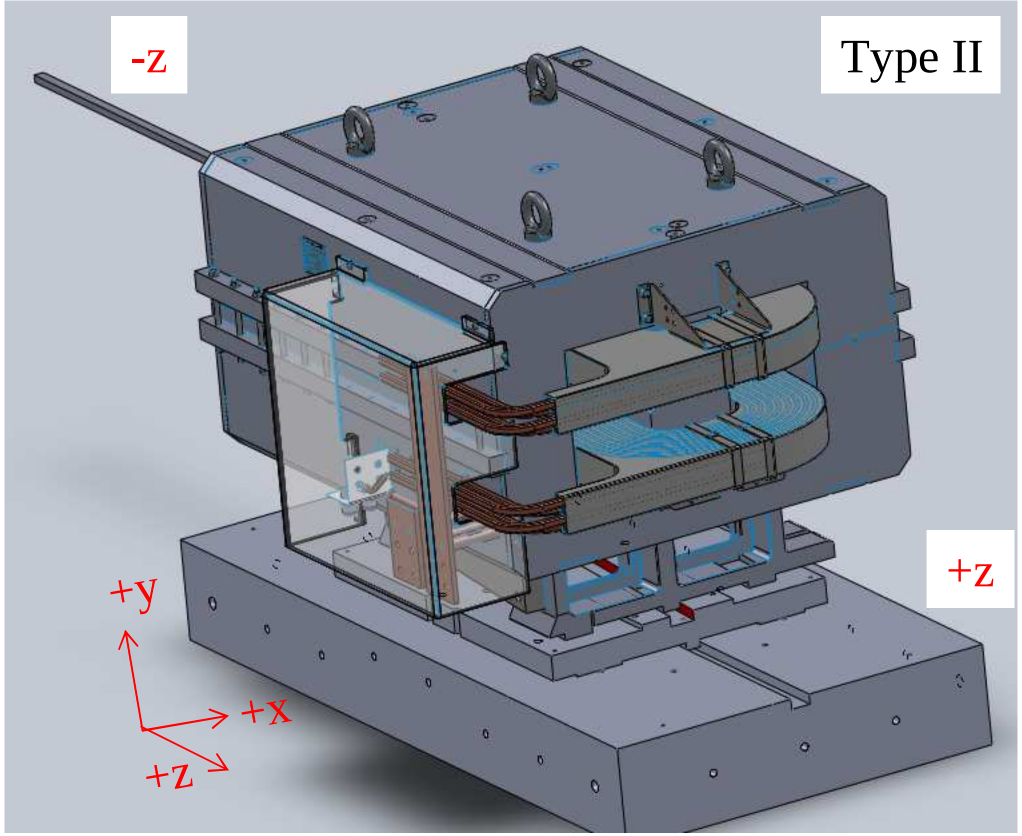

- The positioning precision of this method is within few μm.
- A PSD with laser is used to double check the system position.

# 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.

# SR prototype Quadrupole-9

| Mutipoles | Spec. | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| at 180 A Normalized at 25 mm | Bn/B1 (*E-4) | 1st Bn/B1 (*E-4) | 2nd Bn/B1 (*E-4) | 3rd Bn/B1 (*E-4) | 1st Normal T/m^(n-1) | 1st Skew T/m^(n-1) |
| a2/B1 | ±3 | -1.298 | -1.053 | -0.936 | - | - |
| 0 | ±4 | 10.3 | 9.6 | 9.9 | 2.996586E-4 | -1.644090E-4 |
| 1 | 10000 | 10000 | 10000 | 10000 | -9.459655E+0 | -3.823846E-2 |
| 2 | 2 | 1.9 | 1.6 | 1.7 | 5.137301E-2 | -4.911613E-2 |
| 3 | 3 | 2.5 | 2.6 | 2.6 | 3.122671E+0 | 2.184476E+0 |
| 4 | 1 | 0.4 | 0.5 | 0.5 | 1.627533E+1 | 2.140293E+1 |
| 5 | 1 | 0.7 | 0.7 | 0.7 | 1.590206E+3 | -2.410482E+2 |
| 6 | 0.1 | 0.1 | 0.1 | 0.1 | -8.719932E+3 | 1.015964E+4 |
| 7 | 0.1 | 0.0 | 0.1 | 0.1 | 1.260526E+5 | -1.315574E+5 |
| 8 | 0.1 | 0.0 | 0.0 | 0.0 | -3.570981E+6 | -5.576548E+5 |
| 9 | 1 | 0.0 | 0.1 | 0.0 | 2.740021E+8 | -5.932885E+7 |
| 10 | 0.1 | 0.0 | 0.0 | 0.0 | -1.198612E+9 | 7.470333E+9 |
| 11 | 0.1 | 0.0 | 0.0 | 0.0 | -4.699822E+11 | -9.200139E+10 |
| 12 | 0.1 | 0.0 | 0.0 | 0.0 | 4.674313E+11 | 6.325149E+12 |
| 13 | 1 | 0.0 | 0.0 | 0.0 | -2.947123E+13 | 8.355250E+13 |
| 14 | 0.1 | 0.0 | 0.0 | 0.0 | 4.906529E+14 | -1.218156E+15 |
| 15 | 0.1 | 0.0 | 0.0 | 0.0 | 2.658651E+17 | 8.639098E+16 |
| 16 | 0.1 | 0.0 | 0.0 | 0.0 | -2.870477E+17 | -4.874336E+18 |
| 17 | 1 | 0.0 | 0.0 | 0.0 | 3.998351E+17 | -6.829160E+19 |
| 18 | 0.1 | 0.0 | 0.0 | 0.0 | -1.401894E+21 | 8.486373E+20 |
| 19 | 0.1 | 0.0 | 0.0 | 0.0 | -1.234247E+23 | -1.880334E+22 |
| Vertical offset (mm) | 0.010 | 0.014 | 0.014 | 0.016 | - | - |
| Horizontal offset | 0.010 | 0.011 | 0.010 | 0.008 | - | - |

# SR prototype Quadrupole-1

| Mutipoles | Spec. | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| at 180 A Normalized at 25 mm | Bn/B1 (*E-4) | $1^{st}$ Bn/B1 (*E-4) | $2^{nd}$ Bn/B1 (*E-4) | $3^{rd}$ Bn/B1 (*E-4) | $1^{st}$ Normal T/m^(n-1) | $1^{st}$ Skew T/m^(n-1) |
| a2/B1 | ±3 | -1.816 | -1.802 | -1.814 | - | - |
| 0 | ±4 | 19.1 | 18.7 | 18.8 | 3.571710E-4 | -3.402627E-5 |
| 1 | 10000 | 10000 | 10000 | 10000 | -5.244257E+0 | -1.348971E-2 |
| 2 | 2 | 1.8 | 1.8 | 1.8 | -5.866955E-3 | -3.808722E-2 |
| 3 | 3 | 0.3 | 0.3 | 0.3 | 2.264807E-1 | 1.626916E-1 |
| 4 | 1 | 0.3 | 0.3 | 0.3 | 8.390936E+0 | 2.075744E+0 |
| 5 | 1 | 0.4 | 0.5 | 0.4 | 5.647749E+2 | 1.741828E+2 |
| 6 | 0.1 | 0.1 | 0.1 | 0.1 | -4.957759E+3 | -6.833708E+2 |
| 7 | 0.1 | 0.0 | 0.0 | 0.0 | -1.854480E+4 | -7.362824E+4 |
| 8 | 0.1 | 0.0 | 0.0 | 0.0 | 8.744259E+5 | -1.345069E+6 |
| 9 | 1 | 0.1 | 0.1 | 0.1 | 2.753422E+8 | 3.764507E+7 |
| 10 | 0.1 | 0.0 | 0.0 | 0.0 | -1.330702E+9 | 3.628597E+8 |
| 11 | 0.1 | 0.0 | 0.0 | 0.0 | -1.819496E+10 | -1.718076E+9 |
| 12 | 0.1 | 0.0 | 0.0 | 0.0 | 5.529156E+11 | -1.423449E+11 |
| 13 | 1 | 0.0 | 0.0 | 0.0 | 2.687614E+13 | -3.817813E+12 |
| 14 | 0.1 | 0.0 | 0.0 | 0.0 | 2.631261E+14 | 4.143867E+14 |
| 15 | 0.1 | 0.0 | 0.0 | 0.0 | -9.759332E+15 | -2.181725E+16 |
| 16 | 0.1 | 0.0 | 0.0 | 0.0 | -2.642545E+17 | 7.471516E+17 |
| 17 | 1 | 0.0 | 0.0 | 0.0 | 1.370692E+17 | -8.421653E+18 |
| 18 | 0.1 | 0.0 | 0.0 | 0.0 | -3.280692E+19 | 6.163954E+19 |
| 19 | 0.1 | 0.0 | 0.0 | 0.0 | -1.478186E+22 | -2.184053E+21 |
| Vertical offset (mm) | 0.010 | 0.007 | 0.008 | 0.008 | - | - |
| Horizontal offset (mm) | 0.010 | 0.046 | 0.046 | 0.046 | - | - |

# SR prototype Sextupole-2

| Mutipoles Normalized at 25 mm | Spec. Bn/B2 (*E-4) | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| | | 1st Bn/B2 (*E-4) | 2nd Bn/B2 (*E-4) | 3rd Bn/B2 (*E-4) | 1st Normal T/m^(n-1) | 1st Skew T/m^(n-1) |
| a1/B2 | | -23.25 | -23.32 | -23.13 | - | - |
| a3/B2 | | 1.9 | 1.9 | 1.9 | | |
| 0 | 5 | 9.5 | 9.5 | 9.8 | -3.136285E-5 | -7.786636E-6 |
| 1 | 8 | 63 | 62.7 | 63.7 | -4.147906E-3 | -3.493627E-3 |
| 2 | 10000 | 10000 | 10000 | 10000 | -6.009598E+1 | -5.415864E-1 |
| 3 | 2 | 2.0 | 2.0 | 2.0 | -1.407316E-1 | 4.503019E-1 |
| 4 | 3 | 2.9 | 2.9 | 3.0 | -1.728943E+1 | -2.157091E+1 |
| 5 | 0.5 | 0.2 | 0.2 | 0.2 | 2.648301E+0 | 8.968352E+1 |
| 6 | 0.5 | 0.4 | 0.4 | 0.3 | 2.148019E+3 | 5.144451E+3 |
| 7 | 0.1 | 0.5 | 0.4 | 0.4 | 1.417338E+4 | 2.827699E+5 |
| 8 | 1 | 0.2 | 0.2 | 0.2 | -4.290391E+6 | 2.585182E+5 |
| 9 | 0.1 | 0.1 | 0.1 | 0.1 | -6.433356E+6 | 9.227237E+7 |
| 10 | 0.1 | 0.1 | 0.1 | 0.1 | 2.305557E+9 | 3.838703E+9 |
| 11 | 0.1 | 0.0 | 0.0 | 0.0 | -9.488260E+8 | -7.090756E+9 |
| 12 | 0.1 | 0.0 | 0.0 | 0.0 | -1.184387E+12 | -1.909906E+12 |
| 13 | 0.1 | 0.0 | 0.0 | 0.0 | -7.790049E+12 | 1.894125E+13 |
| 14 | 1 | 0.1 | 0.1 | 0.1 | 6.599919E+15 | 1.305047E+15 |
| 15 | 0.1 | 0.0 | 0.0 | 0.0 | 4.700664E+15 | 1.213193E+16 |
| 16 | 0.1 | 0.0 | 0.0 | 0.0 | -5.175815E+16 | -7.482834E+17 |
| 17 | 0.1 | 0.0 | 0.0 | 0.0 | -2.054579E+18 | 7.672270E+18 |
| 18 | 0.1 | 0.0 | 0.0 | 0.0 | 2.000669E+20 | 6.171257E+20 |
| 19 | 0.1 | 0.0 | 0.0 | 0.0 | 7.112764E+21 | 8.019615E+21 |
| Vertical offset (mm) | 0.010 | 0.028 | 0.028 | 0.029 | - | - |
| Horizontal offset (mm) | 0.010 | 0.071 | 0.072 | 0.073 | - | - |

# SR prototype Sextupole-3 (profile error)

| Mutipoles at 150 A Normalized at 25 mm | Spec. Bn/B1 (*E-4) | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| | | 1st Bn/B1 (*E-4) | 2nd Bn/B1 (*E-4) | 3rd Bn/B1 (*E-4) | 1st Normal T/m^(n-1) | 1st Skew T/m^(n-1) |
| a1/B2 | | -16.9 | -17.6 | -17.6 | - | - |
| a3/B2 | | -4.3 | -4.4 | -4.5 | | |
| 0 | 5 | | | | -2.163753E-5 | -5.868658E-6 |
| 1 | 8 | | | | 2.978029E-3 | -2.590860E-3 |
| 2 | 10000 | 10000 | 10000 | 10000 | -6.116219E+1 | -5.983428E-1 |
| 3 | 2 | 4.6 | 4.6 | 4.7 | -2.795541E-1 | -1.052999E+0 |
| 4 | 3 | 4.7 | 4.6 | 4.6 | -4.578662E+1 | -5.008176E+0 |
| 5 | 0.5 | 1.0 | 0.9 | 0.9 | -1.179174E+2 | -3.642117E+2 |
| 6 | 0.5 | 0.7 | 0.7 | 0.8 | -1.040865E+4 | 3.893147E+3 |
| 7 | 0.1 | 0.7 | 0.7 | 0.7 | 3.476476E+5 | -2.902809E+5 |
| 8 | 1 | 0.4 | 0.4 | 0.4 | -1.028134E+7 | -1.354698E+6 |
| 9 | 0.1 | 0.2 | 0.2 | 0.2 | -1.519771E+8 | -1.748291E+8 |
| 10 | 0.1 | 0.1 | 0.1 | 0.1 | 2.922619E+9 | 2.768967E+8 |
| 11 | 0.1 | 0.0 | 0.0 | 0.0 | -6.597758E+9 | -2.560621E+10 |
| 12 | 0.1 | 0.0 | 0.0 | 0.0 | 1.485046E+11 | -8.208480E+11 |
| 13 | 0.1 | 0.0 | 0.0 | 0.0 | 1.737667E+13 | -1.835243E+13 |
| 14 | 1 | 0.1 | 0.1 | 0.1 | 6.207252E+15 | 2.098087E+14 |
| 15 | 0.1 | 0.0 | 0.0 | 0.0 | -1.699607E+16 | -1.760120E+15 |
| 16 | 0.1 | 0.0 | 0.0 | 0.0 | -7.587530E+17 | -1.394927E+17 |
| 17 | 0.1 | 0.0 | 0.0 | 0.0 | 2.516843E+19 | -5.071084E+18 |
| 18 | 0.1 | 0.0 | 0.0 | 0.0 | 5.837298E+20 | 4.616485E+20 |
| 19 | 0.1 | 0.0 | 0.0 | 0.0 | 1.147833E+22 | 1.116455E+21 |
| Vertical offset (mm) | 0.010 | 0.021 | 0.022 | 0.022 | - | - |
| Vertical offset (mm) | 0.010 | 0.023 | 0.023 | 0.023 | - | - |

# BR prototype pure Quadrupole magnet

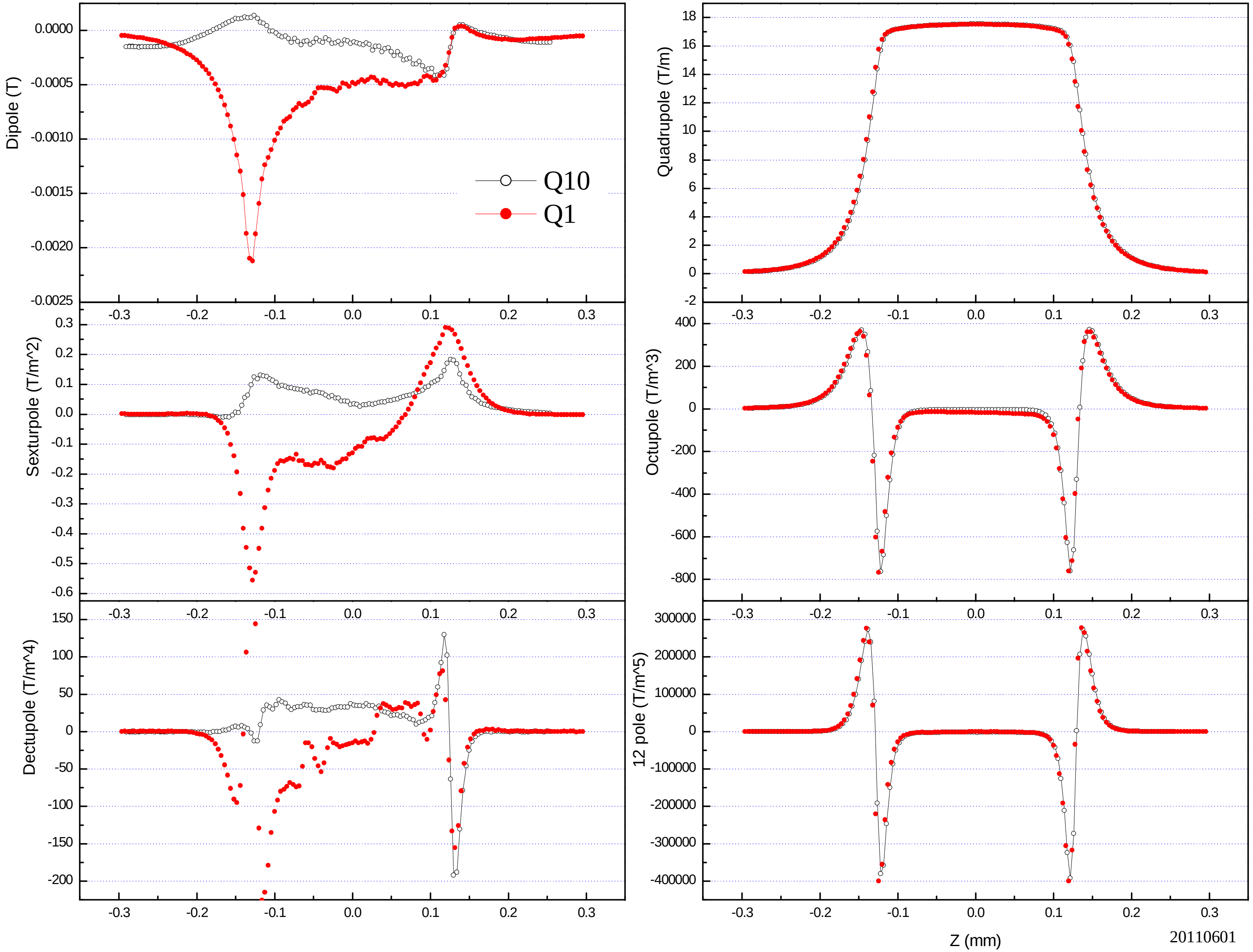
| Mutipoles | Spec. | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| at 104 A Normalized at 15 mm | Bn/B1 (*E-4) | 1st Bn/B1 (*E-4) | 2nd Bn/B1 (*E-4) | 3rd Bn/B1 (*E-4) | 1st Normal T/m^(n-1) | 1st Skew T/m^(n-1) |
| b2/b1 | | -0.575 | -0.525 | -0.530 | | |
| 0 | 10 | 15.2 | 15.2 | 15.261 | -8.282768E-5 | -5.209089E-5 |
| 1 | 10000 | 10000 | 10000 | 10000 | 4.291535E+0 | -8.604185E-3 |
| 2 | 2 | 4.3 | 4.2 | 4.1 | -3.948385E-2 | 1.164597E-1 |
| 3 | 2 | 2.1 | 2.1 | 2.1 | 1.317052E-1 | -4.072819E+0 |
| 4 | 1 | 1.1 | 1.1 | 1.2 | 8.494773E+1 | -1.161403E+2 |
| 5 | 1.5 | 4.5 | 4.4 | 4.5 | -3.823356E+4 | -1.869368E+3 |
| 6 | 0.1 | 1.0 | 1.0 | 1.0 | -5.528513E+5 | 2.190070E+4 |
| 7 | 0.1 | 0.8 | 0.8 | 0.7 | -2.860565E+7 | -4.592194E+6 |
| 8 | 0.1 | 0.4 | 0.3 | 0.3 | -4.889079E+8 | 7.430564E+8 |
| 9 | 4 | 1.1 | 1.1 | 1.1 | 1.834613E+11 | 3.597940E+10 |
| 10 | 0.1 | 0.1 | 0.1 | 0.0 | 3.725822E+11 | 5.424058E+11 |
| 11 | 0.1 | 0.1 | 0.0 | 0.1 | -5.437919E+13 | -2.031411E+13 |
| 12 | 0.1 | 0.1 | 0.1 | 0.1 | 2.156903E+15 | 2.013668E+15 |
| 13 | 1.5 | 1.7 | 1.7 | 1.6 | -5.469661E+18 | 2.557826E+17 |
| 14 | 0.1 | 0.0 | 0.0 | 0.1 | -4.115876E+18 | 5.745330E+18 |
| 15 | 0.1 | 0.1 | 0.0 | 0.0 | 6.708047E+20 | 7.681672E+20 |
| 16 | 0.1 | 0.1 | 0.0 | 0.0 | 4.724460E+22 | 1.704108E+22 |
| 17 | 1.7 | 0.7 | 0.7 | 0.7 | -4.841145E+25 | 9.877609E+22 |
| 18 | 0.1 | 0.0 | 0.0 | 0.0 | 4.752598E+25 | 1.590276E+26 |
| 19 | 0.1 | 0.1 | 0.1 | 0.0 | -1.281045E+28 | -9.083549E+27 |
| 20 | 0.1 | 0.0 | 0.0 | 0.0 | -1.824090E+29 | 7.933266E+29 |
| 21 | 0.3 | 0.2 | 0.1 | 0.2 | -1.951992E+32 | -1.178698E+32 |
| Vertical offset (mm) | 0.010 | 0.012 | 0.012 | 0.012 | - | - |
| Horizontaloffset (mm) | 0.010 | 0.019 | 0.019 | 0.019 | - | - |

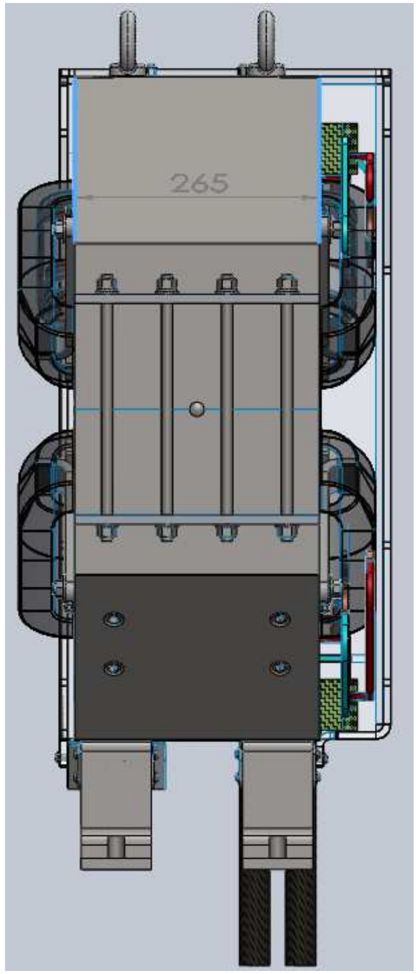
# BR prototype Sextupole magnet

| Mutipoles at 7.3 A Normalized at 15 mm | Spec. Bn/B1 (*E-4) | Measurement (*E-4), ±0.2E-4 | | | | |
|---|---|---|---|---|---|---|
| | | 1st Bn/B1 (*E-4) | 2nd Bn/B1 (*E-4) | 3rd Bn/B1 (*E-4) | 1st Normal T/m^(n-1) | 1st Skew T/m^(n-1) |
| 0 | 15 | 18.5 | 18.8 | | 3.836347E-6 | 7.407058E-6 |
| 1 | 20 | | | | -4.487201E-4 | 9.340750E-3 |
| 2 | 10000 | 10000 | 10000 | | 2.000387E+1 | 2.971728E-1 |
| 3 | 2 | 9.5 | 9.6 | | -1.209543E+0 | 3.848630E-1 |
| 4 | 1 | 7.1 | 6.9 | | 5.740646E+1 | -2.546079E+1 |
| 5 | 0.1 | 0.7 | 0.8 | | -2.185156E+2 | 3.746713E+2 |
| 6 | 0.1 | 0.8 | 1.0 | | 2.937958E+4 | 1.236416E+4 |
| 7 | 0.1 | 2.5 | 2.5 | | 4.632514E+6 | -4.743206E+6 |
| 8 | 5 | 12.4 | 12.3 | | -2.179059E+9 | -7.225766E+7 |
| 9 | 0.1 | 0.7 | 0.7 | | -7.496574E+9 | -2.191975E+9 |
| 10 | 0.1 | 1.3 | 1.2 | | -5.266996E+11 | 8.314161E+11 |
| 11 | 0.1 | 0.3 | 0.4 | | 9.695191E+12 | 1.004291E+13 |
| 12 | 0.1 | 0.6 | 0.5 | | 1.669382E+15 | -1.018460E+15 |
| 13 | 0.1 | 1.5 | 1.5 | | 4.201977E+16 | -3.442069E+17 |
| 14 | 6 | 5.8 | 5.8 | | -8.870901E+19 | -5.013780E+18 |
| 15 | 0.1 | 0.1 | 0.2 | | 1.502377E+19 | -7.083296E+19 |
| 16 | 0.1 | 0.2 | 0.1 | | 1.464512E+22 | -7.027373E+21 |
| 17 | 0.1 | 0.1 | 0.1 | | -6.007293E+23 | -2.735263E+23 |
| 18 | 0.1 | 0.1 | 0.1 | | -2.909266E+25 | 8.263152E+24 |
| 19 | 0.1 | 0.0 | 0.1 | | 6.278958E+26 | 2.891611E+26 |
| 20 | 1 | 0.1 | 0.2 | | -3.903250E+28 | -1.708578E+29 |
| 21 | 0.1 | 0.1 | 0.1 | | -8.758961E+30 | -5.154087E+30 |
| Vertical offset (mm) | 0.010 | 0.233 | 0.233 | | - | - |
| Horizontal offset (mm) | 0.010 | 0.011 | 0.010 | | - | - |

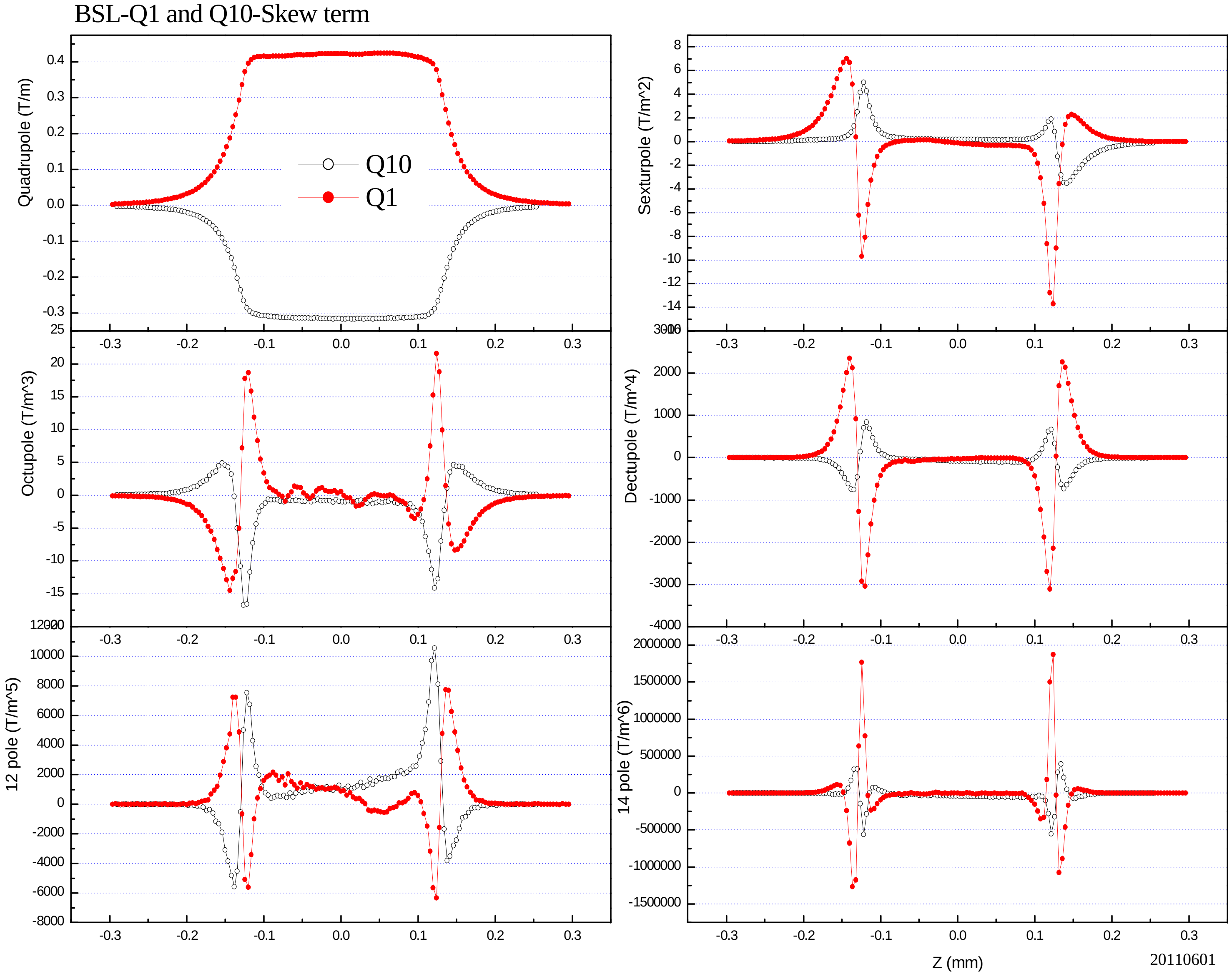
# Multipoles distribution of Q-magnet along Z-axis

BSL-Q1 and Q10-Normal term



# Multipoles distribution of Q-magnet along Z-axis




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

# In-situ magnetic field measurement system (IMMS)

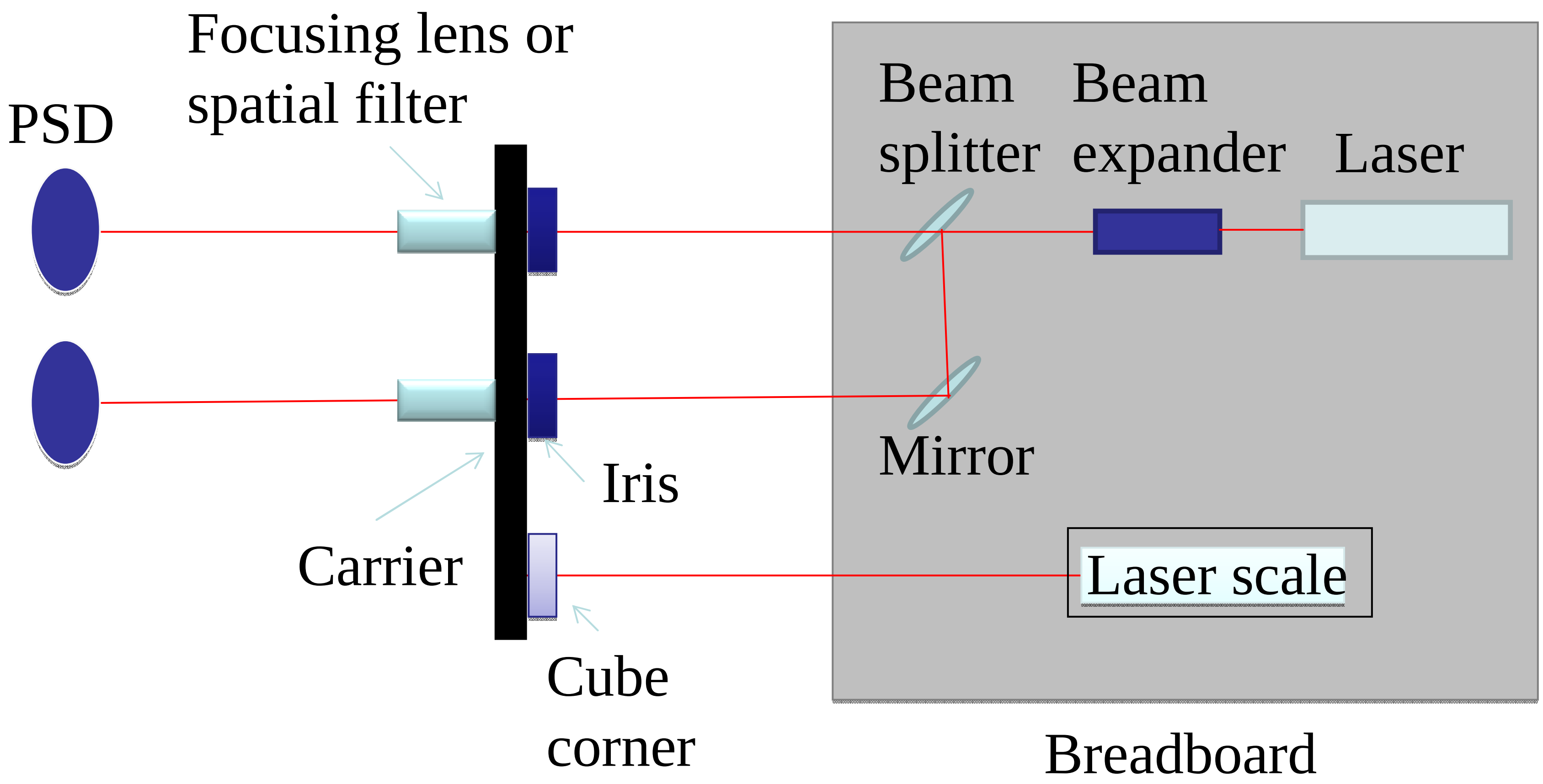
- Purpose : Check magnetic performance of in-vacuum undulators
- Design goals :

  - Measure the magnetic field inside the vacuum chamber without contaminating the chamber.

  - The accuracy of Hall probe positions in transverse and vertical axes are less than 30 μm.

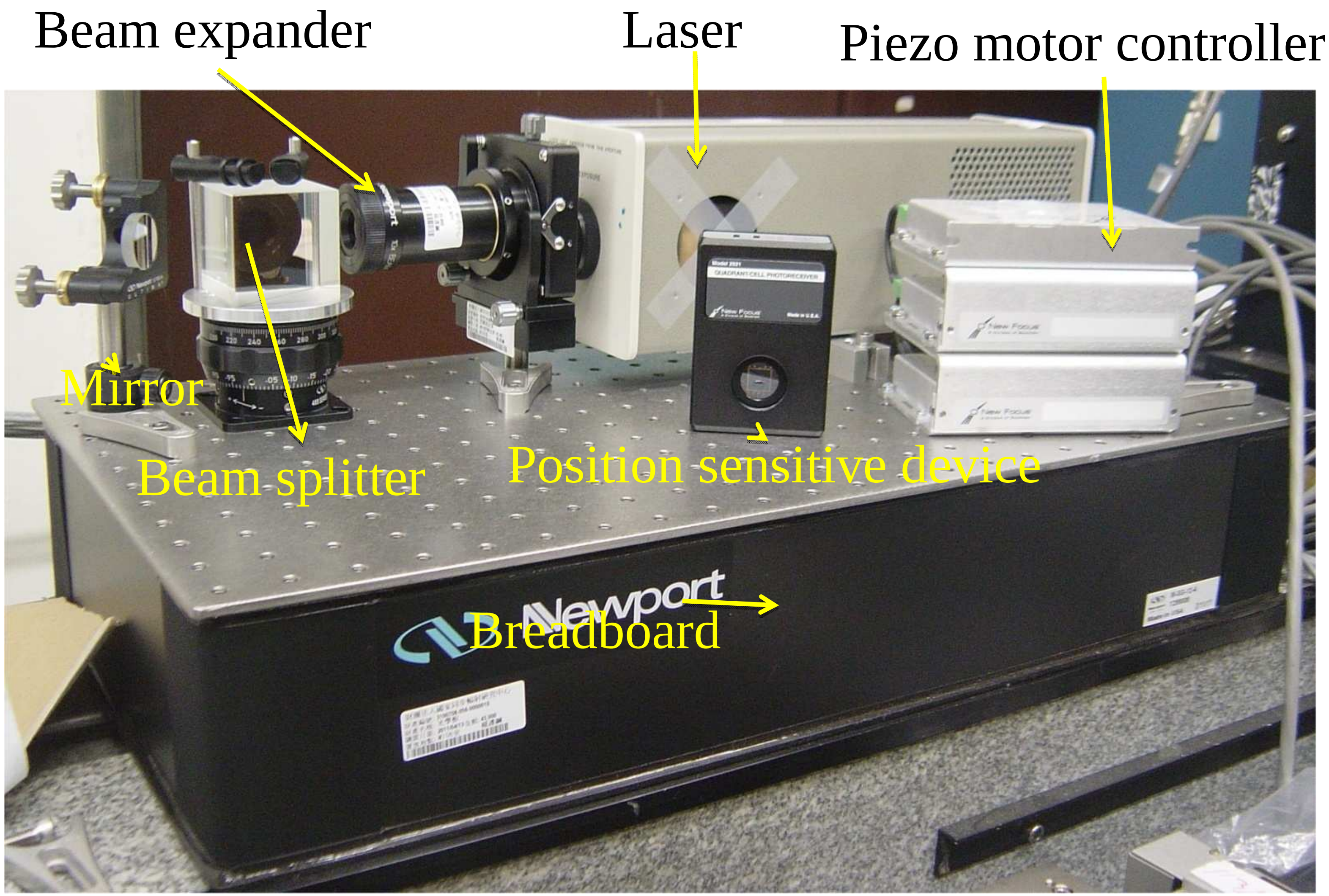
  - The measurement time of 3m undulator is less than 10 minutes.
- Two major parts : Optical positioning system, Hall probe transferring system.
- Status : All components are almost getting ready, and we are assembling them now.
- Future work : Control program development, measurement data analysis software development, undulator prototype magnetic field measurement.

# IMMS optical positioning system

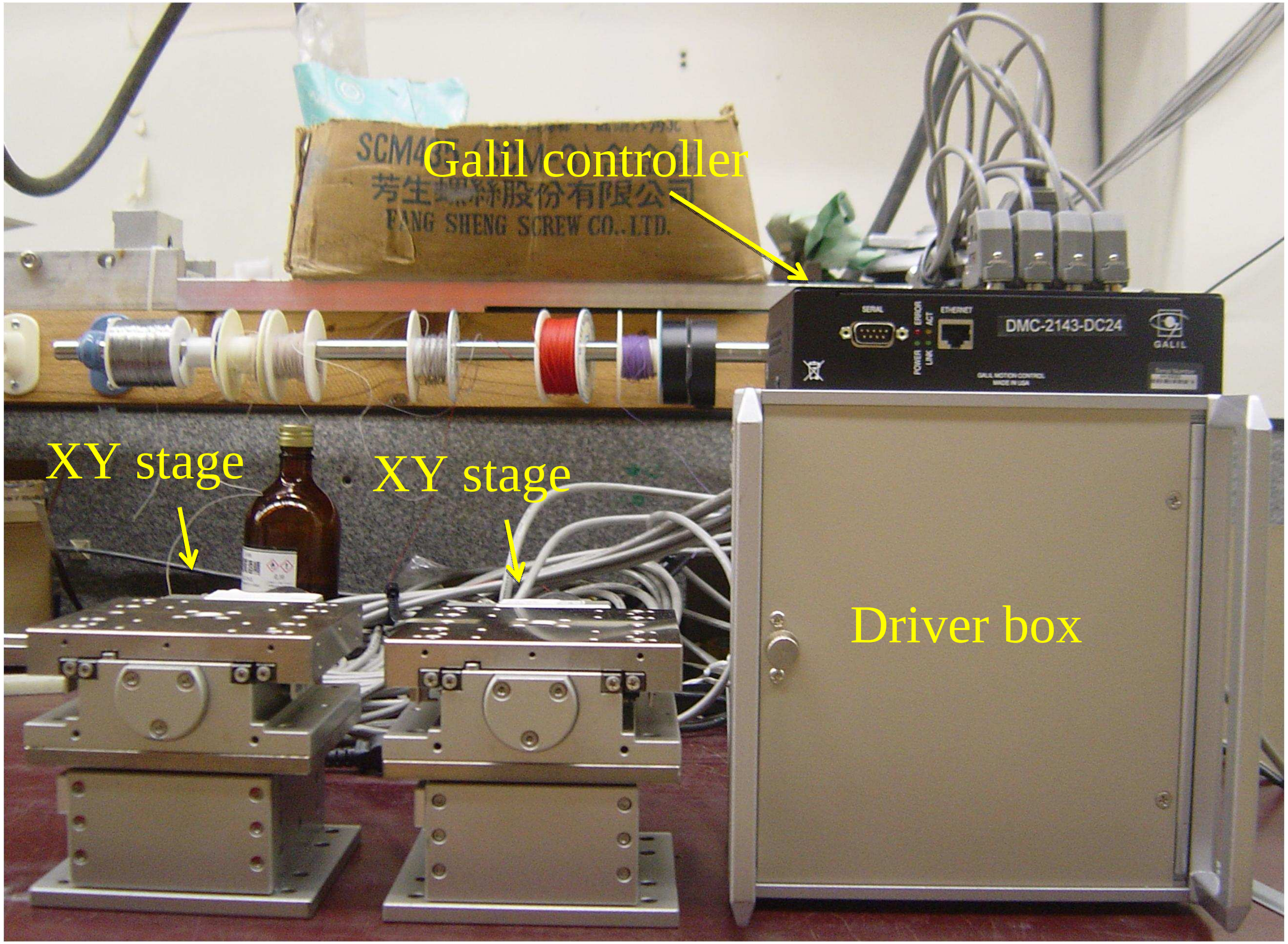



- Function : Detect the position of Hall probe and feed back to transferring system.

# IMMS optical component assembly

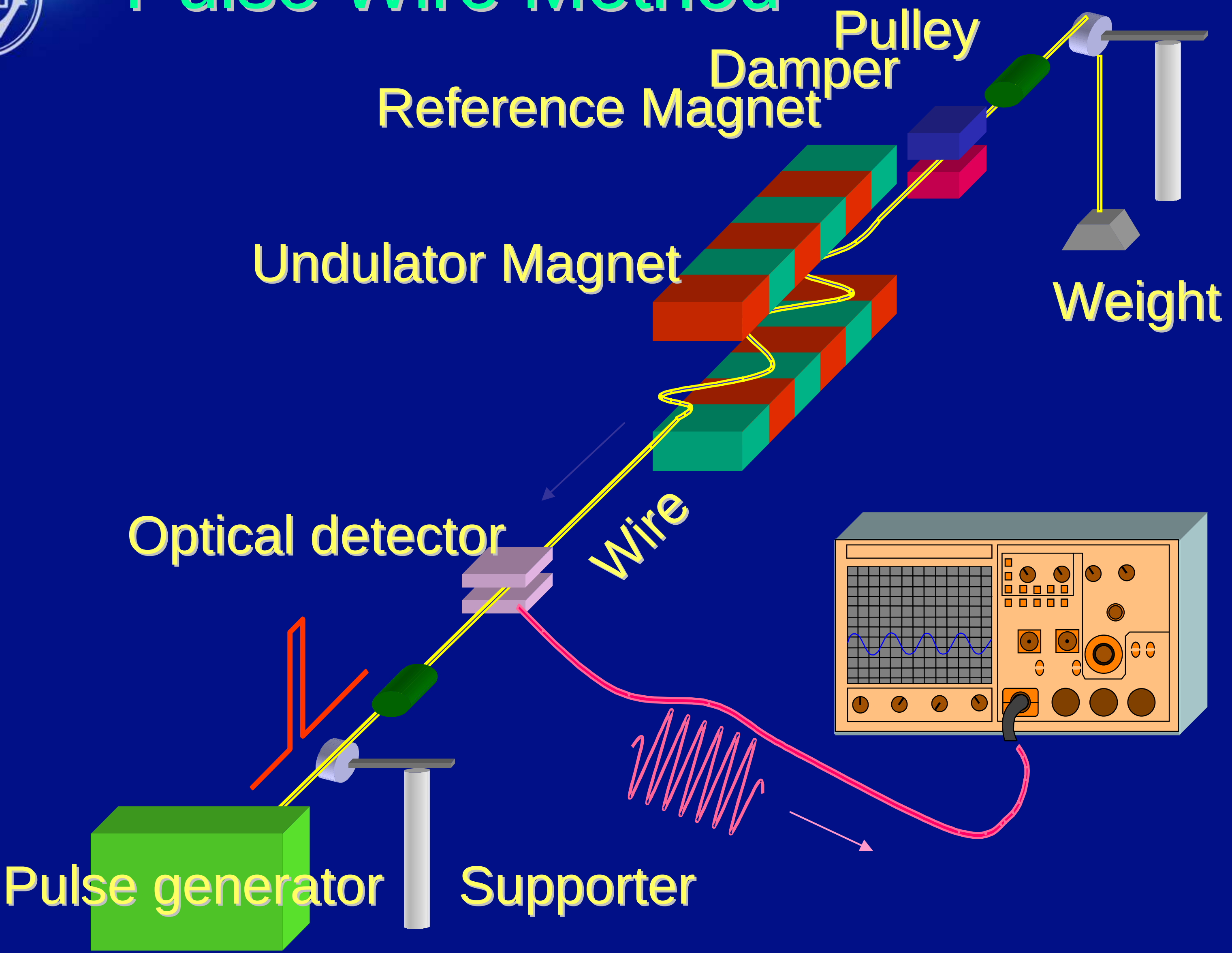


# IMMS Position & control system

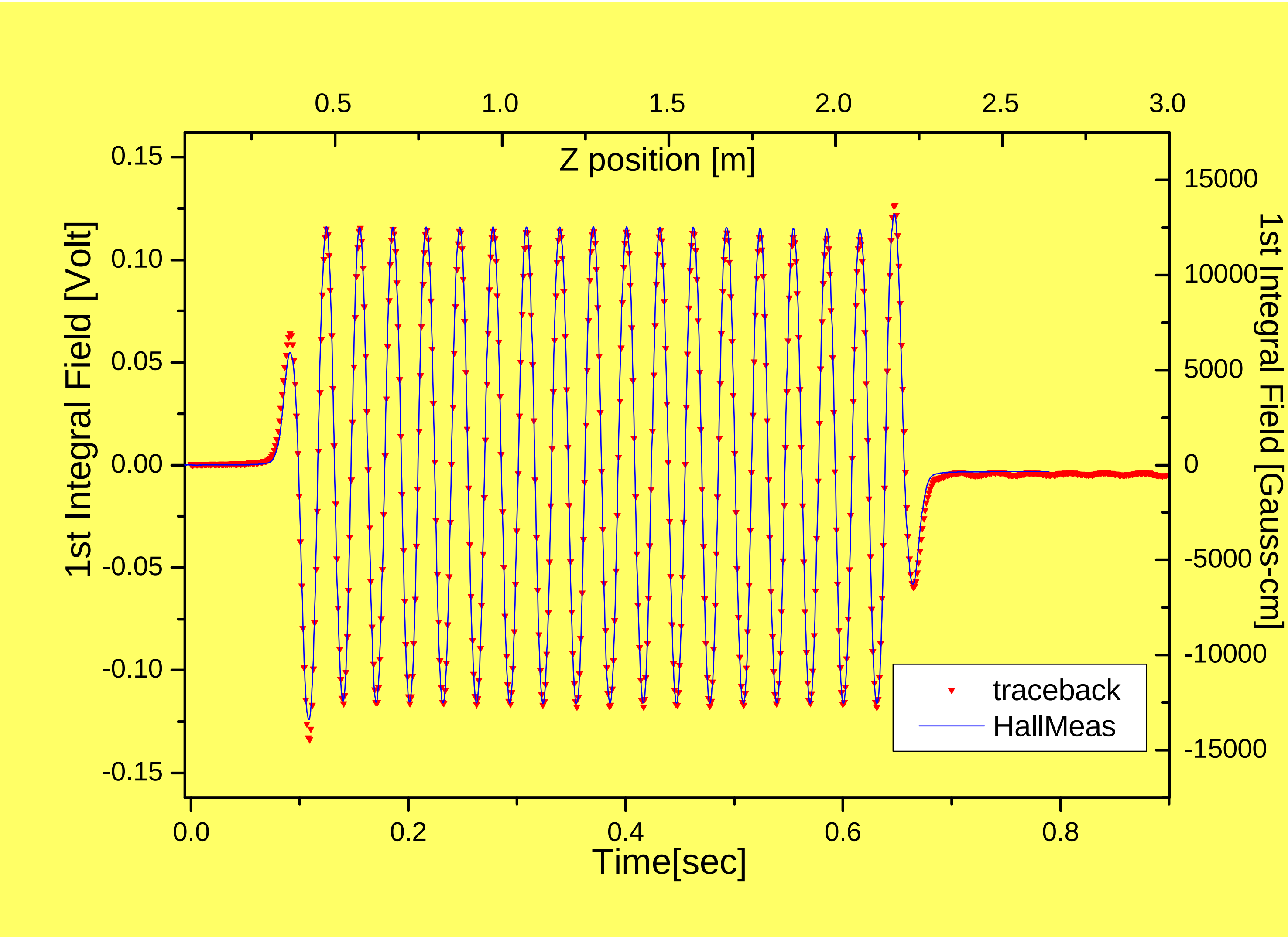



- This system is just under development. It will be finished before the end of this year and test in the in-vacuum undulator in next year..

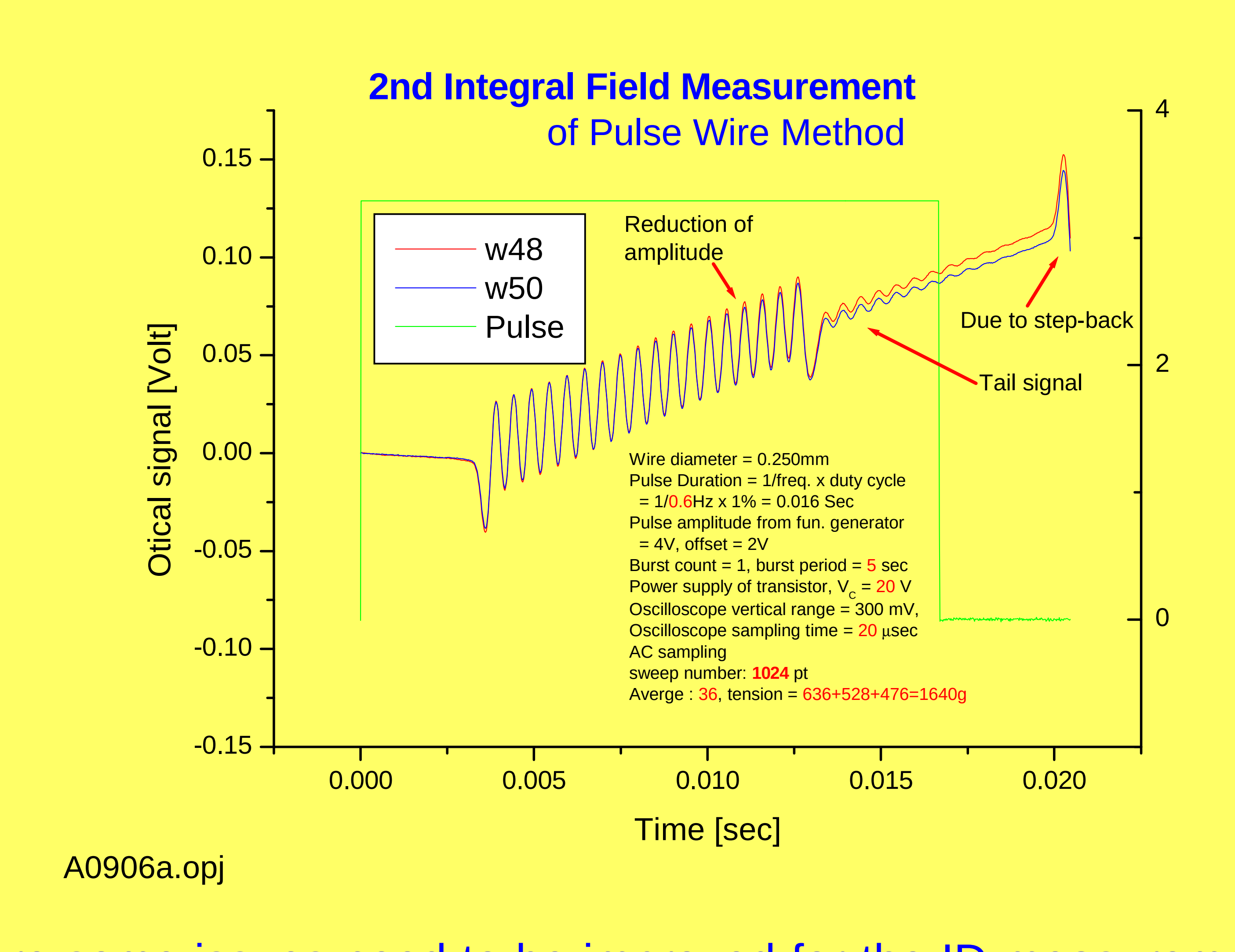
# Pulse Wire Method



# A comparison between Pulse wire and Hall probe measurement



# 2nd integral field by pulse wire




- There are some issues need to be improved for the ID measurement. So we just use the Hall probe to measure the ID. But it can be used to determine the field center of the quadrupole and sextupole magnet precisely.

# Summary

- Lattice magnet

  - Moving fixed angle Hall probe system => point-by-point for any type magnet
  - Rotating coil system => global measurement for multipole magnets
  - Stretch wire system => simple mechanism for quick double check

- Insertion device magnet

  - Three-orthogonal Hall probe system => helical field for phase shimming
  - Highly automatic Helmholtz system => magnet block sorting
  - Pulse-wire system (not yet mature) => mini-gap undulator
  - Stretch wire system => fast multipole shimming

- 3D-Hall probes issues

  - Position & angle calibration on a reference magnet should be done
  - The planar Hall effect and probe temperature should be compensated
  - Field calibration should consider the orthogonal between three Hall probe

- Wire measurement system

  - The wire length for the harmonic components measurement should be within 1 m long for Cu wire and 2 m long for Be-Cu wire to keep high precision of 0.01%
  - Use the Litz wire to enhance the resolution and accuracy
  - Print-circuit board as wire is good for rotating coil

***Thanks for your attention***