Overview of magnetic field measurement in NSRRC


IMMW21, ESRF, Grenoble, France, 25th June 2019
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

TPS (3GeV, 500mA)
24-cell DBA (1.6 nm)
ID: 12m X 6, 7 m X 18

Phase I (2016)
Phase II (2020)
Phase III (2023)

09A Temporally (3m IU22 + 2m IU22)
13A BioSAXS (4m IU24)
15A μ crystal XRD (2m CUT18)
19A High-resolution powder
21A μ crystal XRD
23A Nano-probe (3m IU22)
25A Coherent Scattering (SAXS) (3m IU22 + 2m IU22)
27A Soft X-ray nanoscopy (3.9 m EPU66)
29A SAXS (CU?)
(0.4 m W100)

(3m IU22) 07A Micro-focus PX
(3m IU22) 05A Protein Micro-crystallography

47A Hard X-ray spectroscopy (CU)
(3.8 m EPU46) 45A Submicron soft X-ray
43A Soft X-ray Spectroscopy (EPU)
41A Soft RIXS (Double 3.2 m EPU48)
39A Nano-ARPES (3.9 m EPU168)
37A VUV (U200)
35A Dragon (FSCPU)
## Parameters of IDs in phase-I

<table>
<thead>
<tr>
<th>Phase I</th>
<th>EPU48 x 2</th>
<th>IU22x2</th>
<th>IU22x4</th>
<th>IUT22</th>
<th>EPU46</th>
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<tr>
<td>photon energy /keV</td>
<td>HP</td>
<td>0.23-1.5</td>
<td>1.25-20</td>
<td>1.25-20</td>
<td>1.25-20</td>
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<tr>
<td></td>
<td>VP</td>
<td>0.46-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>λ/mm</td>
<td>48</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>46</td>
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<tr>
<td>N_{period}</td>
<td>68</td>
<td>95</td>
<td>140</td>
<td>140</td>
<td>82</td>
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<tr>
<td>By(Bx) /T</td>
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<td>0.81/0.54</td>
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<td>Ky/Kx</td>
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<td>1.56</td>
<td>1.56</td>
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<td>3.48/2.32</td>
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<td>L /m</td>
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<td>2.58</td>
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<td>3.89</td>
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<td>gap /mm</td>
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<td>Permandur</td>
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<td>NdFeB</td>
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<td>NdFeB</td>
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<td>295</td>
<td>295</td>
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<tr>
<td>Remanence (T)</td>
<td>1.24</td>
<td>1.19</td>
<td>1.19</td>
<td>1.19</td>
<td>1.24</td>
</tr>
<tr>
<td>Coercivity (kOe)</td>
<td>25</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>25</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Phase II &amp; III</th>
<th>EPU66</th>
<th>EPU168</th>
<th>IU22</th>
<th>CU15</th>
<th>CUT18</th>
<th>IU24</th>
<th>U266(?)</th>
<th>W100</th>
<th>FSCPU*</th>
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<tbody>
<tr>
<td>photon energy /keV</td>
<td>HP 0.085-2.5</td>
<td>&gt;0.015</td>
<td>1.25-20</td>
<td>8-35</td>
<td>8-35</td>
<td>4-23</td>
<td>&lt;0.005</td>
<td>5-50</td>
<td>2.5&lt;CP&lt;0.09</td>
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<tr>
<td>VP 0.15-2.5</td>
<td>&gt;0.07</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>λ/mm</td>
<td>66</td>
<td>168</td>
<td>22</td>
<td>15</td>
<td>18</td>
<td>24</td>
<td>266</td>
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<td>120</td>
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<td>140</td>
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<td>111</td>
<td>168</td>
<td>15</td>
<td>4</td>
<td>3</td>
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<tr>
<td>By(Bx) /T</td>
<td>0.87/0.64</td>
<td>0.52/0.23</td>
<td>1.13</td>
<td>1.01</td>
<td>1.08</td>
<td>0.905</td>
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<td>1.81</td>
<td>0.34/0.34</td>
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<tr>
<td>Ky/Kx</td>
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<td>8.1/3.5</td>
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<tr>
<td>Gap/mm</td>
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<td>28</td>
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<td>5.4</td>
<td>5.4</td>
<td>6.8</td>
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<tr>
<td>Magnet material</td>
<td>NdFeB</td>
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<td>PrFeB (NMX-68CU)</td>
<td>NdFeB (NMX-U52SH)</td>
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<td>Pole material</td>
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<td>Permen dur</td>
<td>Permen dur</td>
<td>Permen dur</td>
<td>Permen dur</td>
<td>Permen dur</td>
<td>35CS210</td>
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<td>&lt;80</td>
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<tr>
<td>Coercivity (kOe)</td>
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<td>78</td>
<td>44</td>
<td>28</td>
<td>28</td>
<td>25</td>
<td>25</td>
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</tbody>
</table>

* Permanent magnet for horizontal field & electro-magnet with 450 A for vertical field.
This hybrid structure is the same as helical superconducting undulator. But the superconducting wire was replaced by the permanent magnet.
Field measurement of Twin Helix Undulator

- Meas.Bx
- Meas.By
- SimBx
- SimBy

Magnetic field (G)
Zaxis (mm)
Phase0

AB array
- Sim.Bx
- Sim.By
- Meas.Bx
- Meas.By

Magnetic field (G)
Zaxis (mm)

Phase (mm)
Bi-Planar electromagnetic elliptically polarized undulator

Left-circular polarized

A1=+1
A2=+1
C1=+1
C2=-1

@-x

@+x

B1=-1
B2=+1
D1=-1
D2=-1

gap = 14 mm

one period (λn = 120 mm)

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

<table>
<thead>
<tr>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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<tr>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
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Right circular polarization

<table>
<thead>
<tr>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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<td>-1</td>
<td>1</td>
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<td>-1</td>
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</table>

Horizontal linear polarization

<table>
<thead>
<tr>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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<tbody>
<tr>
<td>1</td>
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<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
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Incline at 45° polarization

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<thead>
<tr>
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<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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<tr>
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<td>0</td>
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Vertical linear polarization

<table>
<thead>
<tr>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
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<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
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Incline at 135° polarization

<table>
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<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
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<tbody>
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<td>0</td>
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<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
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</table>
Introduction to magnet measurement system

◆ for Lattice Magnet
The magnetic field $B_x+iB_y$ is expressed in orthogonal polynomial expansions as

$$B_x + iB_y = \sum (a_n + ib_n)(x + iy)^n$$  \hspace{1cm} (1)

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

$$B_y (x, y) = b_0 + a_1 y + b_1 x + 2a_2 xy + b_2 (x^2 - y^2) + ...$$  \hspace{1cm} (2)

$$B_x (x, y) = a_0 + a_1 x - b_1 y - 2b_2 xy + a_2 (x^2 - y^2) + ...$$  \hspace{1cm} (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

$$B_y(x) = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + ...$$  \hspace{1cm} (4)

For 2D mapping

$$B_r(\theta) = B_y \sin \theta + B_x \cos \theta$$  \hspace{1cm} (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
  \[ B_y(x) = b_0 + b_1x + b_2x^2 + b_3x^3 + \ldots \]
  Advantage:
  - Limited space measure
  - Easy to get good field region

2D Measurement
(Circular or Elliptical Measurement)
- 2D orthogonal fitting
  Advantage:
  - More accurate
  - Get skew term

\[ B_y(x, y) = b_0 + a_1y + b_1x + 2a_2xy + b_2(x^2 - y^2) + \ldots \]
Field measurement using Hall probe & stretch wire for multipole magnet

- Fixed angle with 1D hall probe and mapping on the transverse midplane
  \[ B_y(x) = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + \ldots \]

- Fixed angle with 1D Hall probe mapping & stretch wire on circle trajectory to measure the vertical field \( B_y(x,y) \)
  \[ B_y(x, y) = b_0 + a_1 y + b_1 x + 2a_2 xy + b_2 (x^2 - y^2) + \ldots \]

- 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
For out-of vacuum Insertion Devices
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 available

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)

- 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

System Reproducibility

<table>
<thead>
<tr>
<th>Phase error (degree)</th>
<th>Half integral deviation (%)</th>
<th>Peak field deviation(%)</th>
</tr>
</thead>
</table>
| STD                  | <0.1                        | <0.1                    | <0.02
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.

Before transportation to NSRRC:

- NXE \( \rightarrow \) RMS 1.7°
- NSRRC \( \rightarrow \) RMS 6.6°

During transportation:

- Pole Number
- Phase Error [degree]
- NXE \( \rightarrow \) RMS 1.7°
- NSRRC \( \rightarrow \) RMS 6.6°

The field error is due to the baking or the temperature variation & the large vibration in the transportation.
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

<table>
<thead>
<tr>
<th></th>
<th>Phase error (degree)</th>
<th>First field integral (G.cm)</th>
<th>Peak field deviation (G)</th>
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</thead>
<tbody>
<tr>
<td>STD</td>
<td>&lt;0.2</td>
<td>0.9</td>
<td>0.2</td>
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</tbody>
</table>

Optical positioning system

Moving wire system

Hall-probe carriage

Guide-rail

Two-axis stepper motors

Quad-cell position sensitive detector

Multiple-axis rotatable table
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

<table>
<thead>
<tr>
<th>SENIS specifications</th>
<th>Measurement results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular accuracy of axes with respect to the reference surface</td>
<td>&lt; ±0.5°</td>
</tr>
<tr>
<td>Planar Hall coefficient</td>
<td>&lt; 0.01%</td>
</tr>
</tbody>
</table>

- better than 50ppm/°C
- better than 0.02%
- error ~0.02G
- error ~0.01G
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).

Low temperature Hall probe calibration system

- 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

\[ \lambda u = 15 \text{ mm}, \; \text{Lu} = 2 \text{ m} \; (N = 133 \text{ periods}), \; G_{\text{min}} = 4 \text{ mm}, \; \text{Max. effective field / Force} : 1.13 \text{ T} / 23 \text{ kN} \; (300K), \; 1.30 \text{ T} / 32 \text{ kN} \; (77K) \]
Cooling performance of the CU15

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