Measurement Devices for Magnetic Fields of Superconducting Undulator Coils

Andreas Grau

for

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R&D of superconducting undulators

Develop, manufacture, and test superconducting undulators (SCUs) to generate:

- Harder X-ray spectrum
- Higher brilliance X-ray beams

with respect to permanent magnet undulators.

Why?

Larger magnetic field strength for the same gap and period length.

To realize:

- SCUs for high brilliance ID beamlines at ANKA
- Next generation SCUs for low emittance synchrotrons and FELs

A given photon energy can be reached by the SCU with lower order harmonic:

20 keV reached with the 5th harm. of SCU, with 7th harm. of CPMU and with the 9th harm. of IVU
Motivation

Task within our R&D program:

Improvement and quality assessment of magnetic field properties.

Magnetic errors can cause:

Perturbation of the closed orbit and the dynamics of the electron beam

- Measure field integrals

Reduction of the quality of the emitted radiation

- local field measurements to obtain phase error
Field errors are mainly caused by:

- mechanical deviations of the pole position e.g. the pole height
- bending of the yoke
- the position of the superconducting wire bundles
- pole and wire bundle size
CASPER - Characterization Setup for Field Error Reduction

**CASPER I** - Measurement facility for short undulator mock-up coils

**CASPER II** - A measurement system for undulator coils up to 2m length
Training and quench tests can be performed

New winding schemes,

New superconducting materials and wires

and new field correction techniques can be tested

- Operating vertical
- Test of mock-up coils in LHe
- Maximum dimensions 35cm in length and 35 cm in diameter.
- The magnetic field along the beam axis is measured by Hall probes mounted on a sledge moved by a linear stage with the precision for $\Delta B < 1\text{mT}$ and $\Delta z < 3 \mu\text{m}$. 

E. Mashkina et al., EPAC08
Measurement equipment

- Magnetic field distribution measured locally
- Field sensors: 3 calibrated Hall probes mounted on a sledge
- Hall current provided by a Keithley a precision current source
- Hall voltage measured with a Keithley multichannel voltmeter
- Sledge moved from outside by a low expansion coefficient non magnetic tube via a linear stage, a stepper motor and a gear box (resolution 3µm)
- Position measured with a linear encoder outside
- Operating currents provided by a 1500A/±5V and/or 500A/±5V power supply connected to a quench detectors
Which main errors effect the local field measurements?

1. Errors caused by Hall sample calibration
2. Field errors mainly due to mechanical misalignment of the guiding rails or the field sensors

Liquid helium bath cryostat, field $-3T < B < 3T$, homogeneity better than $10^{-4}$. 
Mechanical accuracy limits

Relative alignment precision of guiding rails 20µm.
For the Hall probe in the middle the distance to coils changes by 10µm.

In x-direction the field is fairly uniform error is negligible

In y-direction the 10µm yields according to [1] with \( \lambda_u = 0.015 \) to:

\[
\cosh\left(\frac{2\pi \Delta y}{\lambda_u}\right) = 1 + \frac{\Delta B}{B} \quad \Delta B/B = 9 \times 10^{-6}
\]

In longitudinal direction \( \Delta z < 5 \mu m \)

The angle errors cause a \( \Delta B/B < 5 \times 10^{-8} \)

⇒ Limiting factor on B is the Hall probe accuracy

Some results

To qualify the production process, the magnetic field quality for the new superconducting undulator for ANKA had to be checked.

Short model coils were produced, the field was measured and possible local shimming methods were checked.

Active shimming using racetrack coils

- measured field
- Radia simulations:
  - ideal field
  - real geometry

Bending appeared during impregnation process due to different materials and expansion coefficients.
**Final Device**

**Light source** Under development in collaboration with BNG for the beamline NANO at ANKA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length</td>
<td>15 mm</td>
</tr>
<tr>
<td>Number of full periods</td>
<td>100.5</td>
</tr>
<tr>
<td>Max field on axis</td>
<td>1.43 T</td>
</tr>
<tr>
<td>with 5.4 mm magnetic gap</td>
<td></td>
</tr>
<tr>
<td>Max field on axis</td>
<td>0.77T</td>
</tr>
<tr>
<td>with 8 mm magnetic gap</td>
<td></td>
</tr>
<tr>
<td>Max field in the coils</td>
<td>2.4 T</td>
</tr>
<tr>
<td>Minimum magnetic gap</td>
<td>5.4 mm</td>
</tr>
<tr>
<td>Operating magnetic gap</td>
<td>8 mm</td>
</tr>
<tr>
<td>Operating beam gap</td>
<td>7 mm</td>
</tr>
<tr>
<td>Gap at beam injection</td>
<td>16 mm</td>
</tr>
<tr>
<td>K value at 5.4 mm magnetic gap</td>
<td>2</td>
</tr>
<tr>
<td>Design beam heat load</td>
<td>4W</td>
</tr>
</tbody>
</table>


Delivery beginning 2012

Institute for Synchrotron Radiation (ISS) / ANKA

Andreas Grau - Measurement Devices for Magnetic Fields of Superconducting Undulator Coils
Training, Quench tests and field measurements of the SCU coils were performed in a vertical LHe bath cryostat at CERN (Thanks to L. Bottura, M. Bajko, C. Giloux)

Training and quench tests with CERN equipment

Field measurement equipment done by KIT

- Measurement like CASPER I
- Linear stage (45cm), encoder, moving tube
  - precise guided sledge with field sensors
- Array of Hall samples 5x3 (5 along the sledge to cover the whole coil length, 3 in a row)
Stainless steel support structure fixes the magnetic gap at room temperature to 8 ± 0.01 mm.

Phase error of 7.4 degrees over a length of 0.795 m, obtained by a simple mechanical shim, which is easily applicable to fixed gap devices.

Next devices round thicker wire and for the yoke C10E steel.

The goal...

Measure magnetic field distributions of superconducting coils with dimensions like in "real" IDs (e.g. up to ~2 m length, ~50 cm diameter)

Cryostat delivered July 2011

- Vertical configuration (in vacuum)
- Temperature shields to reduce thermal load
- Partially cryogen free:
  - To 4K via cryocooler
  - Precooling 4K plate and thermal shields (80K) with liquid N₂
- Dimensions 4K region 2m x 0.5m x 0.5m
- Current leads 8 x 500A, can be variable connected
- Local and integral field measurements possible, access through the flanges

For quality certification of new sc-insertion devices developed together with the industrial partner Babcock Noell GmbH.
Cryostat

**Component** | **Specified value** | **Reached value**
--- | --- | ---
Recipient pressure before starting turbo pump | $p \sim 0.5 \text{ mbar}$ | 1 mbar
Time to reach this pressure | $t < 1 \text{ h}$ | 35 min.
Base pressure before start cooling | $p \sim 10^{-4} \text{ mbar}$ | $5 \times 10^{-4} \text{ mbar}$
Time to reach base pressure | $t < 2 \text{ h}$ | 55 min.
Final pressure while operation | $p < 5 \times 10^{-6} \text{ mbar}$ | $< 10^{-6} \text{ mbar}$
Temperature 80K-plate | $T < 85 \text{ K}$ | $\varnothing 83 \text{ K}$
Temperature 80K-shield | $T < 100 \text{ K}$ | $\varnothing 85 \text{ K}$
Temperature 50K-shield | $T < 60 \text{ K}$ | $\varnothing 50 \text{ K}$
Temperature 4K-shield | $T < 10 \text{ K}$ | $\varnothing 6.2 \text{ K}$
Temperature 4K-plate | $T < 4.5 \text{ K}$ | $\varnothing 4.5 \text{ K}$
T1 targeted | $< 4 \text{ K}$ | 3.6 K
T2 | “ | 3.4 K
T3 | “ | 3.7 K

**Factory acceptance test**

Testsetup to simulate temperature in 4K region
Measurement setups

- Position measurements with a 3 beam laser interferometer (SIOS)
  - Precise z-position $\Delta z < 10^{-6}$
  - Values for angle deviation of the sledge during movement
- Field sensors: 3 calibrated Hall probes on a sledge
- Hall current provided by a Keithley precision current source
- Hall voltage measured with a Keithley multichannel voltmeter
- Field integral measurements with stretched wire technique (CuBe wire $\Omega 125\mu m$)
- Position adjustment for stretched wire in x-y-direction via linear stages with encoders (precision $\sim 1\mu m$)
Position measurement

Laser interferometer (3 beams)

- Z-positioning (1 beam)
- Angle deviation during moving (3 beams)

Problem: Beam distance 12mm, usable gap in the undulator max. 7mm

⇒ preliminary test and setup to reduce vertical beam distance

Final Device:

Commercial interferometer with attachment of two mirrors for beam distance rescaling
Local field measurements

3 Hall probes in a row placed perpendicular to beam axis (20mm distance)

Sledge movement by a taut wire for each direction spooled on a bobbin at each side mounted in the extensions of the cryostat.
### Accuracy requirements

**Mechanical requirements to reach measurement accuracy for phase error**
\[ \Delta \phi = 1^{\circ} (\lambda_U=15\text{mm}, K=1.1, \text{ANKA SCU 15}): \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calculated value [1]</th>
<th>Set limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal deviation (( \Delta x ))</td>
<td>500 ( \mu )m</td>
<td>300 ( \mu )m</td>
</tr>
<tr>
<td>Vertical deviation (( \Delta y ))</td>
<td>200 ( \mu )m</td>
<td>50 ( \mu )m</td>
</tr>
<tr>
<td>Horizontal deviation (( \Delta z ))</td>
<td>13 ( \mu )m</td>
<td>3 ( \mu )m</td>
</tr>
<tr>
<td>Roll angle error (( \alpha ))</td>
<td>2.5 mrad</td>
<td>1 mrad</td>
</tr>
<tr>
<td>Pitch angle error (( \beta ))</td>
<td>83 mrad</td>
<td>30 mrad</td>
</tr>
<tr>
<td>Yaw angle error (( \chi ))</td>
<td>500 ( \mu )rad</td>
<td>300 ( \mu )rad</td>
</tr>
</tbody>
</table>


Setup accuracy limits

Relative alignment precision of guiding rails $\Delta y_{\text{guiding rail}}=40\mu m$. For the Hall probe in the middle the distance to coils changes by $\Delta y=20\mu m$.

- In x-direction the field is fairly uniform $\Rightarrow$ error is negligible
- $\Delta y=20\mu m$ in y-direction fulfills the requirements
- In longitudinal direction precision for $\Delta z = 1\mu m$

Roll

According to the drawing with $x_{\text{sledge}}=0.15m$ the maximum roll angle $\alpha=266\mu\text{rad}$

$\Rightarrow$ below the limit

Yaw

The yaw angle $\chi=270\mu\text{rad}$ results from taking into account a maximum misalignment of the guiding rails with respect to the coils of 0.2mm along the whole support structure length of 1.8m (z-axis)

$\Rightarrow$ set limit fulfilled

Pitch

Due to guiding rail precision the limit for pitch angle $\beta=30\mu\text{rad}$ (rotation around x-axis) is not a critical point

$\Rightarrow$ Limiting factor on measurement precision is the Hall probe accuracy

Stretched wire

- Copper Beryllium wire
- Diameter 125µm
- Length through the whole cryostat ~2.5m
- Movable along 2 axes (150mm x-axis, 20mm y-axis) synchronous or opposite directions

Error consideration

Accuracy limit is set by the sag \( \Delta y \) in the middle \((l/2)\) of the wire and depends on the tension and the self-weight [1]

\[
\Delta y \left( \frac{l}{2} \right) \approx - \frac{\omega_{CuBe} l^2}{8 T} = -100 \, \mu m
\]

Resulting Error in the field integral [2]

\[
\frac{\Delta I_y}{I_y} \approx \frac{1}{2} \left( \frac{2\pi}{\lambda_U} \right)^2 \cosh \left( \frac{2\pi}{\lambda_U} \Delta y \right) (\Delta y)^2 \approx 8.8 \times 10^{-4}.
\]

With \( \varnothing_{CuBe} = 125 \, \mu m, \omega_{CuBe} = 0.064g/m, \lambda_U = 0.015m \)


Supplementary

Field shielding chamber to adjust the zero-point of Hall samples when cold

Racetrack coils mounted in Helmholtz configuration to check calibration curve of the Hall samples

Field homogeneity over 40mm in the center \( \sim 0.2 \text{mT} \)

- Can be improved (in design stage)

Winding at ITeP at KIT
Quench diagnostics

**Quench detection**

- 6 quench detectors to protect superconducting wire during training an quench tests
- Sampling rate 100 kS/s
- Adjustable parameters: pre- and post-trigger time, quench limit voltage, quench time, voltage offset between compared coil parts, etc.
- Software controlled
- Suitable for individual connection to all coil parts
- Manufactured by IPE at KIT

**Quench diagnostics**

- Data acquisition system up to 64 channels
- 8 x 8 channel simultaneous sampling multifunction cards
- Sampling rate 250 kS/s
- Pre- and post-trigger time variable up to 5s
- Data processing for quench analysis via Labview (IPE)
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For sure we get nice results