Instrumentation for Local and Integral Magnetic Field Measurements of Superconducting Undulator Coils

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for

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1. Introduction
   - Motivation
   - Magnetic field errors

2. CASPER measurement setups
   - Cryostat Design
   - Local field measurement setup
   - Accuracy requirements and setup limits
   - Additional components
   - Setup for field integrals
   - Quench diagnostics

3. Next steps
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 setup for undulator coils up to 1.8m length
CASPER I

To test:
- New winding schemes
- New superconducting materials and wires
- New field correction techniques

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 fixed to a sledge moved by a linear stage with the following precision $\Delta B < 1\text{mT}$ and $\Delta z < 3 \ \mu\text{m}$.

E. Mashkina et al., EPAC08
The goal...

Test superconductor performance and measure magnetic field distributions and field integrals of superconducting coils with dimensions like in „real“ IDs (e.g. up to ~1,8 m length, ~50cm diameter)

Cryostat overview

- Horizontal 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 $N_2$
- 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
Local field measurements via Hall samples on a sledge
Position (z-direction) measurement with laser interferometer
Zero Gauss chamber for zero check of Hall sample calibration (possible after every thermal cycle)
possibly in addition 2 Helmholtz coils for linearity check of Hall sample calibration (not shown)
Integral field measurements with stretched wire technique (CuBe wire Ø125µm)
Position adjustment for stretched wire in x-y-direction via linear stages with encoders
Local field measurements

Measurements with 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
Field measurement equipment

- Field sensors: 3 calibrated Hall probes
- Hall current provided by a Keithley precision current source
- Hall voltage measured with a Keithley multichannel voltmeter

3 beam laser interferometer for position measurement (SIOS)
- Precise z-position
- Values for angle deviation during moving
Measurement accuracy

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

Hall sample calibration (ITeP at the KIT)
Accuracy requirements

Mechanical requirements to reach measurement accuracy for phase error

$\Delta \phi = 1^\circ$ ($\lambda_U=15\text{mm}$, $K=1.1$, 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>


(A.Grau et al., ASC 2010, Washington)
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 $\alpha=266\mu rad$
$\Rightarrow$ below the limit

**Yaw**
The yaw angle $\chi=270\mu rad$ 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 $\beta=30mrad$ (rotation around x-axis) is not a critical point

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

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

Company Sekels

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

Field homogeneity over 40mm in the center ~0.2mT

⇒ Can be improved (in design stage)

Winding at ITeP at KIT
- **Copper Beryllium wire**
- Diameter 125µm
- Length through the whole cryostat ~2.5m
- Position adjustment via linear stages with encoders
- movable along 2 axes (150mm x-axis, 20mm y-axis) synchronous or opposite directions

**Integral field measurements with stretched wire**
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]

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

Resulting Error in the field integral [2]

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


Quench diagnostics

Quench detection

- 6 quench detectors to protect superconducting wire during training and 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)
CASPER II status

Done:

- Final drawings and calculations
- Recipient is built, Temperature shields are fabricated and assembled
- Cooling components like cryocoolers, heat exchanger are present at the company, pumping units are bought and delivered
- Temperature sensors and controllers are delivered
- Other „hardware“ components are machined and ready for assembling (flanges, cryostat base structure, LN2 connections etc.)
- Vacuum parts for measurement setup are ordered

To do:

- Complete assembling, wiring, factory acceptance test and final acceptance at ISS
- ~50% construction of measurement setup parts (N. Glamann) and complete assembling
- Purchasing of parts for stretched wire measurement setup (linear stages and encoders)
- Special adapted interferometer will be procured soon
- Procurement of Keithley current sources, voltmeters and additional power supply
- Quench detection and diagnostic system is in the ordering stage (from IPE at KIT and NI)
Acceptance Test

Check specific values like:

- Functionality of all mechanical and electrical parts, pumps, pressure gauges and temperature sensors
- Pumping time to start Turbo pump (p = 0.5 mbar, time = 1h)
- Time to reach base pressure of 10⁻⁴ mbar for cooling start (time = 2h)
- Pumping to working pressure < 10⁻⁵ mbar (time = 12h)
- Check for leaks
- Nitrogen precooling of the „4k“ plate (T~80K)
- Nitrogen cooling of the „80k“ plate (T~85K)
- Temperature „80K“ shield (~120K, cooled by a one stage cryocooler)
- Temperature „50K“ shield (T~45K, cooled by the first stage of the cryocoolers)
- Cooling of „4K“ region (T=4K, at sensor in the middle of the 4K plate)
- Over all cooling time 60h
- Warm up time 30h
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ITEP
IPE

Fa. Cryo Vac
SIOS
National Instruments

... and to you for your attention!

For sure we get nice results