Progress on the superconducting undulator for ANKA and on the instrumentation for R&D

Sara Casalbuoni

for

S. Casalbuoni\textsuperscript{1}, T. Baumbach\textsuperscript{1}, S. Gerstl\textsuperscript{1}, A. Grau\textsuperscript{1}, M. Hagelstein\textsuperscript{1}, D. Saez de Jauregui\textsuperscript{1}, C. Boffo\textsuperscript{2}, J. Steinmann\textsuperscript{2}, G. Sikler\textsuperscript{2}, W. Walter\textsuperscript{2}

\textsuperscript{1}Karlsruhe Institute of Technology, Karlsruhe, Germany
\textsuperscript{2}Babcock Noell GmbH, Würzburg, Germany
Outline

1. Introduction
   ANKA
   Sources of synchrotron radiation
   Motivation R&D of SCIDs
   Experience at ANKA

2. Superconducting undulator

3. Experimental demonstration of feasibility of period length switching

4. Tools and instruments for R&D
   CASPERI
   CASPERII
   COLDDIAG

5. Summary
Energy: 2.5 GeV
Current: 200 mA
Circumference: 110.4 m
Three basic sources of synchrotron radiation

Bending magnet or dipole

Multiplicity Wiggler

Undulator

\[ \lambda = \frac{\lambda_u}{2n\gamma^2} \left( 1 + \frac{K^2}{2} + \theta^2 \gamma^2 \right) \]

\[ K = \frac{B_0 e \lambda_u}{m_0 c \frac{2\pi}{\theta}} = 93.36 \frac{B_0 \lambda_u}{\text{in m}} \]

(B_0 in T, \lambda_u in m)

Typical spectrum

Courtesy of J.Clarke
Undulator radiation

The tuning curves represent what the undulator is capable of as the K parameter is varied – but not all of this radiation is available at the same time!

\[ \phi_i(z_i) = -\frac{\pi z_i}{2\gamma^2\lambda} \left[ K^2 - K_i(z_i)^2 \right] \]

\[ \sigma_\phi = \sqrt{\frac{\sum_{i=1}^{N} \phi_i(z_i)}{N}} \text{ rms phase error} \]

\[ I = I_0 \exp(-n^2\sigma_\phi^2) \]

Peak intensity of the odd harmonics on axis for zero emittance and zero energy spread.

R.P. Walker, NIMA, 335 (1993) 328-337

ESRF – parameters, 14 mm period

![Graph showing undulator radiation tuning curves and ESRF parameters](image)
R&D of sclDs: objective

Develop, manufacture, and test superconducting undulators 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.

Same magnetic length=2 m and vacuum gap=6mm

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>SCU</th>
<th>CPMU</th>
<th>IVU</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>10^{19}</td>
<td>10^{18}</td>
<td>10^{17}</td>
</tr>
<tr>
<td>10</td>
<td>10^{18}</td>
<td>10^{17}</td>
<td>10^{16}</td>
</tr>
<tr>
<td>20</td>
<td>10^{17}</td>
<td>10^{16}</td>
<td>10^{15}</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IVU</th>
<th>CPMU</th>
<th>SCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_u (mm)</td>
<td>21</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>N</td>
<td>95</td>
<td>111</td>
<td>133</td>
</tr>
<tr>
<td>m. gap (mm)</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>B (T)</td>
<td>.75</td>
<td>.88</td>
<td>.98</td>
</tr>
<tr>
<td>K</td>
<td>1.47</td>
<td>1.48</td>
<td>1.37</td>
</tr>
</tbody>
</table>
R&D of scIDs

Comparison SCU CPMU for SCU magnetic gap=vacuum gap+1mm

D. Saez de Jauregui (KIT), OPERA3D, C10E steel and 70% of Ic =1700A/mm² wire φ=1mm, filling factor=0.82

SCU period length (mm)

- 20
- 17
- 15
- 12
- 10

meas

15 1.5m BNG-KIT S. Casalbuoni et al., ASC10
15 0.3m BNG-KIT S. Casalbuoni et al., SR110
15 1m Taiwan Jan et al., IPAC10
16 0.3m Argonne, Y. Ivanyushenkov et al., ANKA seminar

CPMU B_r=1.5T period length (mm)

T. Schmidt, S. Reiche, FEL09

- 16
- 15
- 14
- 13
- 12

meas

18 ESRF Chavanne et al., EPAC08
17.7 Diamond C.W. Ostenfeld & M. Pedersen, IPAC10
Experience at ANKA: SCU14 demonstrator

Proof of principle of scu technology first time worldwide demonstrated at ANKA (2005) developed in collaboration with ACCEL

- Period length: 14 mm
- Length: 100 periods
- NbTi - coils

Outcome used:

- to measure beam heat load to a cold vacuum chamber at ANKA
- to improve the design of next generation sc undulators
Experience at ANKA: SCU14 demonstrator

Beam heat load studies

Performance limited by too high beam heat load: beam heat load observed cannot be explained by synchrotron radiation from upstream bending and resistive wall heating. S. C. et al., PRSTAB2007

Pressure rise can be explained by including in eq. of gas dynamic balance electron multipacting.
S. C. et al., PRSTAB2010

Possible beam heat load source: electron bombardment of the wall, beam dynamics under study.
New superconducting undulator for the NANO beamline: SCU15

Light source for the beamline NANO at ANKA
- High-resolution X-ray diffraction
- Surface and interface X-ray scattering
- In-situ investigations of thin films, multilayers and nano-structured materials

- Cryogen free magnet
- NbTi superconductor
- Local shimming
- Integral field compensation
- Passive quench protection

Under development in collaboration with BNG

<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 with 5.4 mm magnetic gap</td>
<td>1.43 T</td>
</tr>
<tr>
<td>Max field on axis with 8 mm magnetic gap</td>
<td>0.77 T</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 magn. gap</td>
<td>2</td>
</tr>
<tr>
<td>r.m.s. phase error</td>
<td>3.5°</td>
</tr>
<tr>
<td>Design beam heat load</td>
<td>4W</td>
</tr>
</tbody>
</table>

Brilliance \( \times 10^{-7} \text{ ph}/\text{s}/\text{mm}^2/0.1\%/\text{mm}^2 \) vs. Energy (keV)
Design – Cryogenic circuit

Main concepts:

- Two separate circuits for magnet and beam liner.
- Two base temperatures: 4K for the magnet and 10K for the beam liner.
- Minimization of gradients between cold head and most distant point in the magnet.

<table>
<thead>
<tr>
<th>Heta Loads</th>
<th>Shield</th>
<th>Circuit B</th>
<th>Circuit A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>7.93</td>
<td>0.05</td>
<td>0.28</td>
</tr>
<tr>
<td>Conduction</td>
<td>21.98</td>
<td>0.53</td>
<td>0.20</td>
</tr>
<tr>
<td>Current leads</td>
<td>18.80</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Eddy currents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coupling SC</td>
<td>16</td>
<td>4.00</td>
<td>1.71</td>
</tr>
<tr>
<td>Beam Heat</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL (W)</strong></td>
<td>64.71</td>
<td>4.58</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Magnet Heating during Ramp - hot spot - Input power 2.5 W for 100s Init. 0.5W Cu RRR 40/20
SCU15 demonstrator

Cross section NbTi wire:
0.54mm x 0.34mm (including insulation)

End fields:
first winding packages 21 turns (3 layers)
second winding packages 63 turns (9 layers)

206 plates of high magnetic field saturation cobalt-iron alloy

Magnetization curve of cobalt-iron alloy from constructor @300K
Active shimming using racetrackcoils

- SCU15 prototype

- Meas. field
  - Radia simulations:
  - Ideal field
  - Real geometry

- Field, Tesla
- Position, mm

- SCU15 prototype prototype

- Pole 11
- Pole 17

- S. C. et al., SRI09
SCU15 demonstrator: magnet loadline

C. Boffo et al., ASC10

Measured @KIT

Measured @CERN

T=4.2K

3 periods mockup

Prototype

1.5m coils

Design Current

Current [A]

Magnetic Field [T]
SCU15 demonstrator: training

Next devices thicker wire and for the yoke C10E steel.

S. C. et al., ASC10

Measured @CERN
Experimental setup

Installation 31.03.10
Deinstallation 03.05.10
First magnet arrival 12.01.10
Test sledge 8.12.10

Hall probes
2 cm
30 cm
Hall probes calibrated at the Institute of Technical Physics (KIT) in a liquid helium bath in a field \(-3T < B < 3T\) with homogeneity better than \(10^{-4}\).

Local phase error induced by calibration of the Hall probes \(\Delta B < 1\,\text{mT} \):

\[
\Delta \Phi = \frac{K^2 \Delta B}{1 + K^2} \frac{360^\circ}{B} < 0.35^\circ
\]

\[ K = 93.37 \lambda_u B = 1.08 \]

\[ \lambda_u = 0.015 \text{m} \quad B = 0.77 \text{T} \]

S. C. et al., ASC10
SCU15 demostrator

Comparison with competing technologies and with SCU14 demonstrator

SCU14 Accel $\lambda=14\text{ mm}$
- $B$ (field meas.)
- $B$ (fundamental)

- Period length: 15 mm
- Length: 100 periods
- NbTi - coils

$\lambda=15\text{ mm}$ gap=7.2mm
- cryogenic in vacuum undulators

$\lambda=15\text{ mm}$ gap=8mm
- goal from specs
- meas.@ 2K
- working point@4.4K

vacuum gap=7 mm

S. C. et al., ASC10
Accuracies measured @300K by BNG

WINDING POSITIONING ACCURACY: 40 μm
POLE LONGITUDINAL POSITION: 30 μm
LENGTH DIFFERENCE BETWEEN COILS: 20 μm
COIL PLANARITY ALONG 1.5 M: 50 μm
GAP DIMENSION AT ENDS DEVIATION: 10 μm

C. Boffo et al., IPAC10

Yoke 2 Planarity

Period length deviation within a magnet

Period length shift within magnets

Deviation (μm)

Deviation (μm)

Deviation (μm)

Deviation (μm)

Deviation (μm)

Deviation (μm)

Deviation (μm)

Deviation (μm)

Plate Number

Plate Number

Plate Number

Plate Number

Plate Number

Plate Number

Plate Number

Plate Number
Stainless steel support structure, which fixes the magnetic gap at room temperature to $8 \pm 0.01$ 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.


S. C. et al., ASC10

Sara Casalbuoni, 14.10.10
CHESS – CLASSE Seminar, Cornell
Shimmed field:
Phase error of 7.4 degrees over a length of ~0.8 m
Radia* simulations with meas. pole heights and half period lengths at 300K (~50μm):
Phase error of 5.6 degrees over a length of ~1.4 m

The use of mechanical shims to reduce the bimetallic effect, applicable to fixed gap undulators, together with a planarity further reduced to 40 μm would make it possible to reach 3.5 degrees phase error without additional correction coils.

*P. Elleaume, O. Chubar, J. Chavanne, PAC97
SCU15 demonstrator: field integrals

For all currents it is possible to correct the first and second field integrals by means of two pair of Helmoltz coils.

S. C. et al., ASC10
A device which allows switching between a 15 mm period length undulator and a 45 mm wiggler.

B. Kostka et al., PAC05, 2005
A. Bernhard et al., EPAC06, 2006
A. Bernhard et al., EPAC08, 2008

Applications:
• High brilliance of the undulator from 6 to 15 keV for imaging,
• wiggler mode for higher photon energies to perform phase contrast tomography.

Foreseen for the planned IMAGE beamline at ANKA.
First experimental demonstration of period length switching for scIDs

Training

Test results SCUW prototype

<table>
<thead>
<tr>
<th>Current Density in conductor A/mm²</th>
<th>SCUW prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current</td>
<td>Z = 0</td>
</tr>
<tr>
<td>Undulator mode</td>
<td>Z = 3</td>
</tr>
<tr>
<td>Wiggler mode</td>
<td>Z = 6</td>
</tr>
</tbody>
</table>

Max field in conductor T

Training

<table>
<thead>
<tr>
<th>Mag. Gap</th>
<th>undulator</th>
<th>wiggler</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mm</td>
<td>0.77</td>
<td>1.08</td>
</tr>
<tr>
<td>5 mm</td>
<td>1.46</td>
<td>2.05</td>
</tr>
</tbody>
</table>

A. Grau et al., IPAC10

*P. Elleaume, O. Chubar, J. Chavanne, PAC97

Simulations performed with Radia*

Hall probes @ 3.75mm

Built by BNG
R&D strategy

Tasks

- Design and test winding schemes
- Develop and test field correction techniques
- Apply and test different superconducting materials and wires
- Quality assessment of magnetic field properties
- Understand beam heat load mechanisms
- Test performance of the device with beam

How to realize this program?

i) Close collaboration with our industrial partner Babcock Noell GmbH (BNG)

ii) Tools and instruments to improve the magnetic field properties and understand the beam heat load mechanisms

iii) Need of a dedicated straight section and front end for tests
To test:

- New winding schemes
- New superconducting materials and wires
- New field correction techniques

**Operating vertical test in LHe of mock-up coils** with maximum dimensions 35 cm in length and 30 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
For **quality certification** of new sc insertion devices

- Under construction horizontal cryogen free test of long coils with maximum dimensions 1.5 m in length and 50 cm in diameter.

- Local field measurements with Hall probes. Field integral measurements with stretched wire.

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 $\Delta z = 1 \mu m$.

A. Grau et al., IPAC10
Mechanical requirements to reach measurement accuracy for phase error
\[ \Delta \phi = 1° \quad (\lambda_U=15\text{mm}, \ K=2): \]
\[ \Delta x = 400 \ \mu m \]
\[ \Delta y = 50 \ \mu m \]
\[ \Delta z = 5 \ \mu m \]
roll = 1 mrad
yaw = 1 mrad
pitch = 30 mrad

Relative longitudinal position of Hall probes measured with laser interferometer with 1\(\mu\)m accuracy.  
A. Grau et al., IPAC10
CASPERII: Integral field measurements with stretched wire

\[ \frac{\Delta I_y}{I_y} \approx \frac{1}{2} \left( \frac{2\pi}{\lambda_U} \right)^2 \cosh \left( \frac{2\pi}{\lambda_U} \Delta y \right) \left( \Delta y \right)^2 \approx 5 \times 10^{-3}. \]

\[ \phi_{CuBe} = 100 \, \mu m \]
\[ \omega_{CuBe} = 0.064 g/m \]
\[ \lambda_U = 0.015 m \]

A. Grau et al., IPAC10
For quality certification of new sc insertion devices

Timeplan

• Factory acceptance test November 2010

• Hall probe sledge and streched wire December 2010

• Fast acquisition system for quench detection
  1) first tests with 5 channels at CASPERI November 2010
  2) multichannel data acquisition system at CASPERII February 2011

• Under construction horizontal cryogen free test of long coils with maximum dimensions 1.5 m in length and 50 cm in diameter.

• Local field measurements with Hall probes. Field integral measurements with stretched wire.

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 \( \Delta z = 1 \text{µm} \).
Under construction cold vacuum chamber for diagnostics to measure the beam heat load to a cold bore in a storage ring. The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices.

In collaboration with
CERN: V. Baglin
LNF: R. Cimino, M. Commissio, B. Spataro
University of Rome 'La sapienza': A. Mostacci
DIAMOND: M. Cox, J. Schouten
MAXLAB: Erik Wallèn
Max-Planck Institute for Metal Research: R. Weigel,
STFC/DL/ASTeC: J. Clarke, D. Scott
STFC/RAL: T. Bradshaw
University of Manchester: I. Shinton, R. Jones

A first installation at the synchrotron light source DIAMOND is foreseen in June 2011.

S. Gerstl et al., IPAC10
COLDDIAG: the vacuum chamber

• Cryogen free: cooling with Sumitomo RDK-415D cryocooler (1.5W@4.2K)

• Cold vacuum chamber located between two warm sections to compare beam heat load with and without cryosorbed gas layer

• 3 identically equipped diagnostic ports with room temperature connection to the beam vacuum

• Exchangeable liner to test different materials and geometries

• Copper bar copper plated (50µm)

S. Gerstl et al., IPAC10
The diagnostics will include measurements of the **heat load**, the **pressure**, the **gas composition**, and the **electron flux of the electrons bombarding the wall**.

S. Gerstl et al., IPAC10
**Under construction** cold vacuum chamber for diagnostics to measure the beam heat load to a cold bore in a storage ring. The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices.

A first installation at the synchrotron light source DIAMOND is foreseen in June 2011.

### Timeplan

- **Factory acceptance test November 2010**
- **Tests at ANKA out of the storage ring December 2010-February 2011**
- **Delivery to DIAMOND March 2011**
- **Installation in DIAMOND June 2011**

S. Gerstl et al., IPAC10
COLDDIAG

Planned Measurements

Monitoring the temperature, the electron flux, pressure and gas composition with different:

- **average beam current** to compare the beam heat load data with synchrotron radiation and resistive wall heating predictions
- **bunch length** to compare with resistive wall heating predictions
- **filling pattern** in particular the bunch spacing to test the relevance of the electron cloud as heating mechanism
- **beam position** to test the relevance of synchrotron radiation and the gap dependence of the beam heat load
- **injected gases** naturally present in the beam vacuum (H₂, CO, CO₂, CH₄) to understand the influence of the cryosorbed gas layer on the beam heat load
Summary

1. Training and magnetic field measurements of 1.5 m undulator coils
   • Reached peak field 0.7 T for an undulator with 15 mm period length and a magnetic gap of 8 mm. This value overperforms the competing technologies for the same geometry.

   • We have proved that coils wound with single length wire can be repaired without rewinding the whole coil.

   • Furthermore, we have demonstrated for the first time that it is possible to build superconducting undulator coils with a 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.

   • The thin rectangular wire used will be replaced in the next devices by a thicker wire and for the yoke C10E steel will be used.

2. First experimental demonstration of period length switching for sclIDs

3. Tools and instruments to improve the magnetic field properties (CASPERI, CASPERII) and understand the beam heat load mechanisms (COLDDDIAG)
Thanks

To:
• Jerome Feuvrier, Julienne Hurte, Michael Ky, Patrick Viret… from Block 4
• Marta Bajko, Luca Bottura, Christian Giloux

For the tests at CERN

And to you all for your attention!
COLDDIAG
Gas injection

Extracto gauge
Leak valve flange
All metal shutter