Superconducting undulators: experience from ANKA

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Outline

- Motivation R&D of SCIDs
- SCU14 demonstrator
- Ongoing collaboration with BNG:
  - SCU15DEMO
  - SCU20
  - SCUW18-54
- HTS SCUs
- Tools and instruments for R&D
- Summary
Motivation R&D of scILDs

Develop SCUs for ANKA and low emittance light sources

With respect to permanent magnet undulators SCUs can generate:
- Harder X-ray spectrum
- Higher brilliance X-ray beams

Why? Larger magnetic field strength for the same gap and period length

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**Same magnetic length = 2 m and vacuum gap = 5 mm**

<table>
<thead>
<tr>
<th></th>
<th>IVU* (SLS)</th>
<th>CPMU† (DLS)</th>
<th>CPMU PrFeB#</th>
<th>SCU NbTi wire**</th>
<th>SCU NbTi APC††</th>
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<tbody>
<tr>
<td>$\lambda_u$ [mm]</td>
<td>19</td>
<td>17.7</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td># of periods</td>
<td>105</td>
<td>112</td>
<td>133</td>
<td>133</td>
<td>133</td>
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<tr>
<td>magn. gap [mm]</td>
<td>5</td>
<td>5.2</td>
<td>5.2</td>
<td>6</td>
<td>6</td>
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<tr>
<td>B [T]</td>
<td>0.86</td>
<td>1.04</td>
<td>1.00</td>
<td>1.18</td>
<td>1.46</td>
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<tr>
<td>K</td>
<td>1.53</td>
<td>1.72</td>
<td>1.4</td>
<td>1.65</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Simulations performed with SPECTRA§


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With respect to permanent magnet undulators SCUs can generate:
- Harder X-ray spectrum
- Higher brilliance X-ray beams

Why? Larger magnetic field strength for the same gap and period length

E=3 GeV
I=300 mA
$\epsilon_x$=3 nm rad

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Simulations performed with SPECTRA§


Motivation R&D of scIDs

At ANKA large vacuum gap 7 mm instead of 5 mm
longer period lengths

SCU20 has larger brilliancy and flux than SCU15

Simulations performed with SPECTRA§

C.W. Ostenfeld & M. Pedersen, IPAC10
D. Saez de Jauregui et al., IPAC11
SCU14 demonstrator

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

• Period length: 14 mm
• Periods: 100
• Conduction cooling
• NbTi - coils

Main issues:

• Reduction of peak field on axis B of ~30% from LHe 0.55 T to conduction cooling 0.4 T
• Performance in ANKA limited by too high beam heat load: in user operation B = 0.3 T

Outcome used:

• to measure beam heat load to a cold vacuum chamber at ANKA
• to improve the design of next generation sc undulators

SCU14 demonstrator

Beam heat load studies

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 to be studied
Ongoing collaboration of ANKA and BNG to develop SCUs for ANKA and low emittance light sources

- NbTi wire
- Conduction cooling
- Movable vacuum chamber

Common design ANKA and BNG
Manufacturing: BNG
Testing: ANKA

Mockup1                      Mockup2                       Long coils

SCU15DEMO

SCU20

SCUW18-54

Babcock Noell GmbH
SCU15DEMO: magnetic field measurements

Coils have been pre-bent at room temperature to try to compensate the bending measured at 4 K

\[ \lambda_u = 15 \text{ mm} \]

100.5 full periods

B = 0.69 T

v. gap = 7 mm

Stainless steel support structure, which fixes the magnetic gap at room temperature to 8.00 ± 0.01 mm

Mechanical shimming applicable to fixed gap undulators

Measurements performed at CERN in a LHe bath


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

![Graph showing magnetic field measurements with ideal, simulated, measured shimmed, and measured not shimmed plots.](image)
SCU15DEMO: spectral performance

\[ B = 0.69 \, \text{T} \]

**SCU15DEMO**
- ideal
- Radia sim. with mech. tol.
- meas. shimmed
- meas. not shimmed

**CPMU17.7**
- ideal

**Calculated with B2E\(^*\)**

S.C. et al., IPAC12

Slit of 4 mm x 0.9 mm @ 10 m distance

Slit dimensions: ± 2\(\sigma\) of 1\(^{\text{st}}\) harmonic

\[ *P. \, \text{Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)} \]
SCU15DEMO: spectral performance

"ideal" = flux produced by the field from ideal device

"Radia" = flux produced by the field simulated with Radia assuming mechanical tolerances measured at 300 K

Mechanical tolerances reached at 300 K
- Half period length: 10 μm
- Pole heights deviation: 50 μm

C. Boffo et al.,

<table>
<thead>
<tr>
<th>Harmonic number</th>
<th>ANKA*</th>
<th>DLS †</th>
<th>MAXIV**</th>
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<tr>
<td>E (GeV)</td>
<td>2.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>I (A)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
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<tr>
<td>ΔE/E</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>εx (nm rad)</td>
<td>41</td>
<td>2.7</td>
<td>0.26</td>
</tr>
<tr>
<td>εy (nm rad)</td>
<td>0.3</td>
<td>0.27</td>
<td>0.008</td>
</tr>
<tr>
<td>βx (m)</td>
<td>14.7</td>
<td>4.8</td>
<td>9</td>
</tr>
<tr>
<td>βy (m)</td>
<td>1.93</td>
<td>1.43</td>
<td>4.8</td>
</tr>
<tr>
<td>ηx (m)</td>
<td>0.36</td>
<td>0.07</td>
<td>0</td>
</tr>
</tbody>
</table>

* A. S. Müller, priv. comm.
† I. P. S. Martin et al, PAC07

Ratio R = "Radia" / "ideal"

Ratio R > 75% for the existing and planned storage rings up to the 15th harmonic
SCU15DEMO: tests in conduction cooling

- FAT completed
- Cooling time 7 days
- Warming up 4 days
- Ramping time < 600 s
- Current stability of main coils at max. current 150 A and correction coils successfully tested for 6 days
- Movable vacuum chamber 7 mm – 15 mm: successful vacuum test < 3 x 10^{-10} mbar in cold conditions

Next steps:
- Installation in ANKA 12.2014-1.2015
- Tests with beam in 2015
Lessons learned from previous development of 1.5 m long undulator coils:
round wire, low carbon stainless steel, blocks ~0.15 m, racetrack,
ew winding scheme: from one groove to the next changing winding direction

Achievements of Mockup 2 (~ 30 cm long)

- Mechanical accuracies at 300 K
- Test in LHe and in conduction cooling 400 A reached without quench (nominal current 380 A)
- In conduction cooling at ~ 3.5 K 680 A reached at the end of training
SCU20: Achievements of Mockup 2

Calculated spectral performance with SPECTRA

SCU20: Considering an operating temperature of the magnet of 4.2 K, design temperature margin of about 2 K.

**SCUW18-54**

A device to switch between a 18 mm period length undulator and a 54 mm wiggler.

Foreseen for the planned IMAGE beamline at ANKA.

First experimental demonstration of period length switching for scIDs

Built by BNG


Conduction cooled superconducting switch

Aim:

- use only one power supply instead of several for the different circuits, reducing the thermal input to the device

Applications:

- period length switch (i.e., SCUW)
- active shimming

Minimum power dissipation of 200 mW per heater, demonstrated in an ad hoc conduction cooling setup in CASPER I

Minimum power dissipation can be further reduced: Ongoing additional tests in CASPERII

Applications:

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

**Brilliance (ph/s/mrad^2/mm^2/0.1%)**

- E = 2.5 GeV
- I = 200 mA
- ε = 40 nmrad

**Energy (keV)**

Application of other materials: HTS tape

HTS tape stacked undulator


KIT internal collaboration: ANKA with ITEP

Etching using Trumpf picosec YAG - IR laser, programmable beam control used for Roebel cables

Groove formation very reliable applying laser

No contamination of groove detected (SEM)

HTS tape planar undulator

C. Boffo, IDMAX10

BNG HTS tape planar undulator mockup: results of test at CASPERI (KIT)

Maximum current 555 A \( \Rightarrow I = 0.92 \text{ kA/mm}^2 \)

Tools and instruments for R&D: CASPERI

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
Tools and instruments for R&D: CASPERII

Successful factory acceptance test

Built by Cryovac

CuZn 33 kg (600 mm)

3.6 K

3.4 K

3.7 K

GRP

Cold head II

4K plate

Ongoing commissioning of:

• Local field measurements with Hall probes

• Field integral measurements with stretched wire

A. Grau et al., IEEE Trans. on Appl. Supercond. 2312-2315 Vol. 21-3 (2011)


A. Grau et al., IEEE Trans. on Appl. Supercond. 2312-2315 Vol. 21-3 (2011)
Tools and instruments for R&D: CASPERII

SCU20 Mockup 2

main coils 375 A
corr. coils 5.63 A

B(T)

z (mm)

Preliminary
Tools and instruments for R&D: COLDDIAG

Cold vacuum chamber for diagnostics to measure the beam heat load to a cold bore in different synchrotron light sources.

The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices.

The diagnostics includes measurements of the:

- heat load
- pressure
- gas composition
- electron flux of the electrons bombarding the wall

In collaboration with:
- CERN: V. Baglin
- LNF: R. Cimino, B. Spataro
- University of Rome "La sapienza": M. Migliorati
- DLS: R. Bartolini, M. Cox, E. Longhi, G. Rehm, J. Schouten, R. Walker
- MAXLAB: Erik Wallèn
- STFC/DL/ASTeC: J. Clarke
- STFC/RAL: T. Bradshaw

S. Gerstl et al., PRSTAB, 17, 103201 (2014)

Significant discrepancy compared to theoretical expectations …

S. C. et al., JINST 7 P11008 (2012)
Summary

- Advantages of SCIDs on permanent magnet IDs
- Experience with SCU14 demonstrator

SCU15DEMO achievements:
- Mechanical tolerances at RT < 50 µm
- 1.5 m long coils successful test in LHe and in conduction cooling
- Unique movable UHV vacuum chamber at 4 K: gap 7-15 mm
- Potential spectral performance advantages on CPMU and on APS-SCU0 to be demonstrated with test in the ring

SCU20 Mockup 2 achievements:
- Mechanical tolerances at RT < 60 µm
- Test in LHe and in conduction cooling 400 A reached without quench (nominal current 380 A)
- Spectral performance advantages on CPMU

SCUW18-54:
- Demonstrated feasibility of period length switching
- Successful studies on conduction cooled switch

Development of our own tools for R&D on SCIDs:
- CASPER II: cryostat succesful factory acceptance test, preliminary results of magnetic field measurements
- COLDDIAG measured beam heat load to a cold bore installed in the Diamond Light Source
Backup slides
Outlook
Motivation \textbf{R&D of scIDs}

Comparison SCU - CPMU

for SCU magnetic gap = vacuum gap + 1 mm

\begin{itemize}
\item SCU higher K CPMU, most pronounced for longer period lengths
\item Novel materials give further improvements, especially for SCUs
\end{itemize}
Experience at ANKA: SCU14 demonstrator

Proof of principle of scu technology first time worldwide demonstrated at ANKA (2005)

- 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
Accuracies measured @300K

Yoke 2 Planarity

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

SCU15DEMO: beam vacuum chamber

Challenges:
- Must withstand UHV radiation hard environment
- Resistive losses must be kept as low as possible
- Must move: it needs to open to 15 mm during electron beam injection and energy ramping in the ANKA storage ring

The chamber has been manufactured and successfully withstood the vacuum test reaching < 3 x 10^{-10} mbar in cold conditions
Lessons learned from previous development of 1.5 m long undulator coils:
- rectangular wire 0.54 mm x 0.34 mm
- round wire diameter 0.76 mm
- cobalt-iron yoke
- low carbon stainless steel
- plates made of one pole and blocks ≈ 0.15 m
- one groove

Optimization of coils performance by varying winding pack geometry to minimize:
- required wire current to achieve specified peak B on axis
- magnetic field on the conductor at maximum required wire current
Racetrack shape to reduce multipoles

New winding scheme: from one groove to the next changing winding direction. Staggering removed to avoid possible unwanted increase of field integrals and a reduction of on axis B quality

Correctors included in the coils

\[ \approx \frac{1}{4} \approx \frac{3}{4} \]
Superconducting switch

Aim:
use only one power supply instead of several for the different circuits, reducing the thermal input to the device

Applications:
• period length switch (i.e., SCUW)
• active shimming

Minimum power dissipation of 200 mW per heater, demonstrated in an ad hoc conduction cooling setup in CASPER I


Minimum power dissipation can be further reduced: Ongoing additional tests in CASPER II
Application of other materials: NbTi wire with artificial pinning centers

ANKA collaboration with ITeP (Th. Schneider and M. Kläser, KIT) and SupraMagnetics, Inc., USA

NbTi with artificial pinning centers wire developed by SupraMagnetics, Inc., USA:
- outer diameter = 0.31 mm
- Including insulation = 30 μm,
- Cu/SC = 2.125
- 37 filaments with diameter = 21 μm

Racetrack loadline and wire critical current density measured at JUMBO (ITeP, KIT)