Superconducting Undulator Development
At Fermilab

C. Boffo, M. Turenne, F. McConologue
SLAC Accelerator Seminar 2022.07.28
Outline

Introduction to SCUs

Previous experience in industry

R&D and work for EuPRAXIA@SPARCLab

HTSU a superconducting staggered array undulator for PSI
Introduction

Design Evolution

Permanent Magnet Undulator
- Traditional design
- Controlled env.
- Cheaper design
- Low performance

In Vacuum Undulator
- In UHV chamber
- Reduced distance of magnets
- Good performance

Cryogenic Undulator
- Improved B field
- Increased complexity
- Better performance

Superconducting Undulator
- Highest B field
- 4 K design
- Electromagnet
- Best performance
Higher peak field on axis for the same gap and period length in operation with electron beam.

Demonstrated higher radiation resistance compared to permanent magnet undulators.

Full potential of superconductivity not yet exploited, margins on NbTi and increased potential of Nb$_3$Sn and HTS.

Performance of SCUs

A Proven Advantage

$K_{\text{eff}} = (eB \lambda_u)/(2\pi m_e c)$

<table>
<thead>
<tr>
<th>Facility</th>
<th>Start-finish of operations</th>
<th>$\lambda_0$ (mm)</th>
<th># of periods</th>
<th>Vacuum aperture (mm)</th>
<th>Gap loss (mm)</th>
<th>$B$ (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS 2 SCUs</td>
<td>2015–current</td>
<td>18</td>
<td>59.5</td>
<td>7.2</td>
<td>2.3</td>
<td>0.97</td>
</tr>
<tr>
<td>APS</td>
<td>2013–2016</td>
<td>16</td>
<td>20.5</td>
<td>7.2</td>
<td>2.3</td>
<td>0.8</td>
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<tr>
<td>APS Helical</td>
<td>2017–current</td>
<td>31.5</td>
<td>38.5</td>
<td>26</td>
<td>5</td>
<td>0.45</td>
</tr>
<tr>
<td>APS Upgrade</td>
<td>Planned – one example</td>
<td>16.5</td>
<td>216</td>
<td>6</td>
<td>2</td>
<td>1.07</td>
</tr>
<tr>
<td>KIT/accel</td>
<td>2005–2012</td>
<td>14</td>
<td>100</td>
<td>8,12,16,25 (open)</td>
<td>0.6 (? design)</td>
<td>0.3</td>
</tr>
<tr>
<td>KIT/Noell SCU16.5</td>
<td>2014–2015</td>
<td>15</td>
<td>100.5</td>
<td>7,16 (open)</td>
<td>1</td>
<td>0.73</td>
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<tr>
<td>KIT/Noell SCU18</td>
<td>2017–current</td>
<td>20</td>
<td>74.5</td>
<td>7,15 (open)</td>
<td>1</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Bahrdt–Gluskin NIMA 2018
A Challenging Superconducting Magnet

Specific requirements of superconducting undulators

<table>
<thead>
<tr>
<th>Conduction Cooled</th>
<th>High Precision</th>
<th>Beam Transparent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible system that can be adapted to cryomodule style cooling.</td>
<td>Winding groove: +/- 10 μm</td>
<td>Integrate corrector coils to minimize the first and second field integrals.</td>
</tr>
<tr>
<td>Modularity</td>
<td>Flatness coils: 50 μm</td>
<td></td>
</tr>
<tr>
<td>Ability to include more than one coil pair in a vessel to reduce inactive length.</td>
<td>Winding package: 50 μm</td>
<td></td>
</tr>
<tr>
<td>Beam Heat load</td>
<td>Coil alignment: &lt; 100 μm</td>
<td></td>
</tr>
<tr>
<td>Separate cooling of the cold beam pipe. Distance between coils and beam pipe 0.15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Density</td>
<td>Maximize current density to increase system performance.</td>
<td></td>
</tr>
</tbody>
</table>
Previous experience in industry
# SCU15 and SCU20 Specifications

<table>
<thead>
<tr>
<th></th>
<th>SCU15</th>
<th>SCU20</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length</td>
<td>15</td>
<td>20</td>
<td>mm</td>
</tr>
<tr>
<td>Full periods</td>
<td>100.5</td>
<td>74.5</td>
<td>#</td>
</tr>
<tr>
<td>Max field on axis 7 mm gap</td>
<td>0.73</td>
<td>1.19</td>
<td>T</td>
</tr>
<tr>
<td>Nominal current</td>
<td>150</td>
<td>395</td>
<td>A</td>
</tr>
<tr>
<td>Ramp to nominal current</td>
<td>450</td>
<td>300</td>
<td>s</td>
</tr>
<tr>
<td>Operating vacuum gap</td>
<td>7</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>Injection vacuum gap</td>
<td>15</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Beam heat load</td>
<td>4</td>
<td>4</td>
<td>W</td>
</tr>
<tr>
<td>Design temperature</td>
<td>4.2</td>
<td>4.2</td>
<td>K</td>
</tr>
</tbody>
</table>

![Diagram of SCU15 and SCU20](image-url)
SCU20 Performance

Cooldown and powering

Time (hours)

Temperature (K)

Magnet
Shield
Beam pipe

Time (minutes)

M TOP MID
M BOT MID
Main Coils
HH UP
AUX 1 UP/DW
SCU20 Performance
Extended ops and quench behavior

![Graphs showing temperature and current over time for SCU20 performance.](image-url)
SCU20 Performance

- No impact on beam lifetime
- No quench while in operation with beam
- Higher peak field compared to competing technologies
- 7th harmonic of emitted radiation in the expected range
SCU20 Performance

Heat load tolerance

Collimator was positioned outside nominal range

Heat load of 8 W on the beam pipe (beam pipe temperature 35 K)

Coils did not quench (temperature remained below 4.6 K)
Successful collaboration between **laboratory and industry**

**Fully conduction cooled** designs operating well for both SCU15 and SCU20

Demonstrated performance and **reliability** of SCUs

**Potential** for NbTi devices to reach higher performance

**Potential** for cost reduction and design modularity
FNAL R&D and SCU16 for EuPRAXIA@SPACLab
User facility: It’s a «beam driven» PWFA FEL lasing from a PWFA is an important achievement by itself

- Scientific case: soft-X rays and VUV (3-5 nm and 50-200 nm) Experiments require flexibility: wavelength tuning – energy tuning – multicolor – multiple pulses – pulse duration control

Two FEL lines:

1) AQUA: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

SASE FEL: 10 UM Modules, 2 m each – Two technologies under study: Apple-X PMU and planar SCU. Prototyping in progress

2) ARIA: VUV seeded HGHG FEL beamline for gas phase

SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm (see former presentation to the committee and Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.) – Undulator based on consolidated technology.
AQUA: use SCUs to extend the tuning range

PMU 16 mm period
Magnetic gap 6 mm; beam stay clear 5 mm

SCU Nb Ti operation parameters, beam stay clear aperture 5 mm

<table>
<thead>
<tr>
<th>Target Wavelength (nm)</th>
<th>Undulator Period (mm)</th>
<th>Resonant Wavelength (nm)</th>
<th>Saturation length (m)</th>
<th>Saturation length limit</th>
<th>Undulator strength limit</th>
<th>SCU added tuning range</th>
<th>New U. strength limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Courtesy L. Giannessi
Design based on NbTi technology with reduced temperature margin with respect to previous designs

Maintain 1 mm difference between magnetic and vacuum gap

Use rectangular wire to increase engineering current density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>&lt; 16</td>
<td>Mm</td>
</tr>
<tr>
<td>Beam stay clear</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>FEL wavelength</td>
<td>~3</td>
<td>Nm</td>
</tr>
<tr>
<td>K-value</td>
<td>&gt;1.2</td>
<td></td>
</tr>
<tr>
<td>Beam heat load</td>
<td>TBD</td>
<td>W</td>
</tr>
<tr>
<td>Ramp to operating field</td>
<td>&lt;600</td>
<td>s</td>
</tr>
<tr>
<td>Cooling</td>
<td>Cryocoolers</td>
<td>-</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.2</td>
<td>K</td>
</tr>
<tr>
<td>Magnet length</td>
<td>1.5-1.6</td>
<td>m</td>
</tr>
<tr>
<td>Flange to flange length</td>
<td>2.0-2.5</td>
<td>m</td>
</tr>
<tr>
<td>Beam height</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>Vacuum vessel diameter</td>
<td>&lt;1</td>
<td>m</td>
</tr>
<tr>
<td>Insulation vacuum</td>
<td>1*10^-5</td>
<td>mbar</td>
</tr>
<tr>
<td>Cooldown time</td>
<td>&lt;7</td>
<td>days</td>
</tr>
</tbody>
</table>
Prototyping
Coil manufacturing technology

Manufactured two 300 mm yokes with technology that allows extension to 2 m.

Optimized 3D printed/G11 parts to guide/insulate coils.

Local cooling through Cu flags for each separate winding package.
Modular Design

Rail system based on PIP-II proven SRF cryomodule design -> modularity and assembly process improvement.

Cooling system compatible with both conduction cooled (cryocoolers) and LHe operations (SRF CM Style).

Focus on production cost reduction by employing standard commercially available components.

System independent from superconductor technology and coil configuration.

Reduction of cold mass dimensions to improve cooldown time.

Maximization of active length: 1.5 m over 1.8 m.
Cryogenic design

Cooling: 2 (+ 2) 1.8 W GM coolers.

Reduced vessel diameter to minimize: costs, space and radiation input at 50K.

Current leads optimized for higher current/heat load. Hybrid HTS/phosphor bronze system.

Integrated G11 support posts allow for mechanical stability and low heat load.

<table>
<thead>
<tr>
<th>Heat load</th>
<th>Shield 50k</th>
<th>Magnet 4.2k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>4.6</td>
<td>0.20</td>
</tr>
<tr>
<td>Conduction</td>
<td>9.6</td>
<td>0.28</td>
</tr>
<tr>
<td>Current Leads</td>
<td>50</td>
<td>0.21</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Dynamic losses</td>
<td></td>
<td>0.47</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>65.2 W</strong></td>
<td><strong>1.17 W</strong></td>
</tr>
</tbody>
</table>
Take away

- Ongoing R&D to expand FNAL experience
- Leveraging experience on NbTi devices to push performance and reduce cost
- Adapt SRF cryomodule design to SCU to include more than one unit in a vessel
- Deliver to EuPRAXIA@SPARCLab a prototype stand-alone system in 2023
HTSU – A Superconducting Staggered Array Undulator
Superconducting Staggered Array Undulator Concept

Example of field cooling magnetisation


Courtesy M. Calvi
Superconducting Staggered Array Undulator

@6k10mm period & gap = 4mm

GdBCO Bulks


Figure 1. Schematic diagram of a BHSAU.

Figure 3 shows the measurement increment in the solenoid field scale changed with $B_z$ of active area, calibration residual, and from the Gaussmeter.

Figure 4 shows the variation of peak field, a barometer of the undulator field. The result was consistent with the expected calculations.

The prototype features include six periods, 10 mm 2 T superconducting solenoid aligned so that the central axis is parallel to the direction of the magnetic field along the $z$-axis (other parameters are given in Ref. 23). For the six-period prototype, twelve bulk HTSs were located in a staggered array configuration, supported by copper supports. The HTS material is QMG-GdBCO, which is developed by Nippon Steel Corporation, 24) in which nanoparticles Gd and CuO, and Cu$_x$ at 20 K and 10 kA/mm by supercurrent $J_c$ and $J_{c0}$ is equal to the critical current density ($J_c$, $J_{c0}$). From Bean's critical state model, the current-flowing layer is small. Therefore, the bulks of active area, calibration residual, and from the Gaussmeter.

The undulator field was stronger than those for other types even at 20 K; the undulator amplitude near the bulk and the average amplitude is suppressed in any critical current density, is important. The experiment result was consistent with the numerical calculation. This phenomenon that the appearance of flux creep is one of the main concerns of the HTS superconducting transition can generate an undulator field correlated with the measured data; thus we introduce related numerical calculation. This has potential in resolving the largest problem of the HTS application.

Measurements were performed under zero-field cooling (ZFC) and field cooling (FC) conditions. These are implemented using a sine wave at various solenoid fields $B_z$. The sinusoidal current $I_s$ is 12.5 mm; the dimensions in $u$ (mm) 11 9 15 10 10, and 4 mm gap ($u$), and 4 mm gap ($u$) prototype. The prototype was installed in a vacuum chamber, in which the prototype is thermally independent of its critical current density. From Bean's critical state model, the current-flowing layer is small. Therefore, the bulks of active area, calibration residual, and from the Gaussmeter.

internal of the undulator was realized in a 10 keV high-energy electron beam. The prototype was installed in a vacuum chamber, in which the prototype is thermally independent of its critical current density. From Bean's critical state model, the current-flowing layer is small. Therefore, the bulks of active area, calibration residual, and from the Gaussmeter.

The reason why the variation of peak field were different in a precise sense.

$B_z$ component of the magnetic field along the $z$-axis was 0.508 mm. The experiment result was consistent with the numerical calculation. This phenomenon that the appearance of flux creep is one of the main concerns of the HTS superconducting transition can generate an undulator field correlated with the measured data; thus we introduce related numerical calculation. This has potential in resolving the largest problem of the HTS application.

The prototype was installed in a vacuum chamber, in which the prototype is thermally independent of its critical current density. From Bean's critical state model, the current-flowing layer is small. Therefore, the bulks of active area, calibration residual, and from the Gaussmeter.

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R&D Summary

1st Bulk Sample
6mm gap

2nd Bulk Sample

2G HTS Tape
4mm gap

Bulk Industrial Sample
4mm gap

Bulk Industrial Simplified Sample

2019

2022
**HTS Insert development**

\[ \lambda u = 10\text{mm} \]
\[ \text{gap} = 4\text{mm} \]
Without CoFe poles

\[ B_0 \text{ is the undulator field} \]
\[ \Delta B_s \text{ are the (-) changes in the background solenoidal field} \]

**Figure 1.**

Field cooling @ 8T

**solenoidal field**

1.54T

Cambridge GdBCO / FC 8T
HTS Insert development

\[
\lambda u = 10\text{mm} \\
gap = 4\text{mm} \\
\text{With CoFe poles}
\]

Field cooling @ 8T
solenoidal field

\[
B_0 \text{ is the undulator field} \\
\Delta B_s \text{ are the (−) changes in the background solenoidal field}
\]

- Cambridge GdBCO / FC 8T
- ATZ YBCO + CoFe / FC 8T

\[
\begin{align*}
\lambda u & = 10\text{mm} \\
gap & = 4\text{mm} \\
\text{With CoFe poles}
\end{align*}
\]
HTS Insert development

\[ \lambda u = 10\text{mm} \]
\[ \text{gap} = 4\text{mm} \]
With CoFe poles

\[ B_0 \text{ is the undulator field} \]
\[ \Delta B_s \text{ are the (-) changes in the background solenoidal field} \]

\[ \Delta B = 0.34\text{T increase expected also by the presence of CoFe poles} \]

\( \bullet \text{ Cambridge GdBCO / FC 8T} \)
\( \triangle \text{ ATZ YBCO + CoFe / FC 8T} \)
HTS Insert development

$\lambda_u = 10\text{mm}
\text{gap} = 4\text{mm}
\text{With CoFe poles}

$B_0$ is the undulator field
$\Delta B_s$ are the (-) changes in the background solenoidal field

Field cooling @ 8T
solenoidal field

- Cambridge GdBCO / FC 8T
- ATZ YBCO + CoFe / FC 8T

$\lambda_u = 10\text{mm}
\text{gap} = 4\text{mm}
\text{With CoFe poles}$
HTS Insert development

\[ \lambda u = 10 \text{mm} \]
\[ \text{gap} = 4 \text{mm} \]
With CoFe poles

\[ B_0(\text{T}) \]
\[ \Delta B_s(\text{T}) \]

\( B_0 \) is the undulator field
\( \Delta B_s \) are the (-) changes in the background solenoidal field

Field cooling @ 8T solenoidal field

- Cambridge GdBCO / FC 8T
- ATZ YBCO + CoFe / FC 8T
- ATZ YBCO + CoFe / FC 10T

\( 55 \text{ mm} \)
HTS Insert development

\[ \lambda u = 10\text{mm} \]
\[ \text{gap} = 4\text{mm} \]
\[ \text{With CoFe poles} \]

\( B_0 \) is the undulator field
\( \Delta B_s \) are the (-) changes in the background solenoidal field

\[ \text{Field cooling @ 8T solenoidal field} \]

- Cambridge GdBCO / FC 8T
- ATZ YBCO + CoFe / FC 8T
- ATZ YBCO + CoFe / FC 10T
- CAN* GdBCO w/wo CoFe
- CAN* EuBCO w/wo CoFe
- NS** GdBCO w/wo CoFe

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©CAN-SUPERCONDUCTORS

**Nippon Steel Co.
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Upcoming samples

Courtesy M. Calvi
Main requirements

Active length : 1.0 m
Total length : < 2 m
Period length : 10 mm
Magnetic gap : 4.0 mm
K: 2
Cooling: Conduction
HTS temperature: 10 K
LTS temperature: 4.0 K
### Concept and solenoid requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Nb&lt;sub&gt;3&lt;/sub&gt;Sn &amp; NbTi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting coil conductor</td>
<td>Nb&lt;sub&gt;3&lt;/sub&gt;Sn &amp; NbTi</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>12T</td>
</tr>
<tr>
<td>Nominal magnetic field</td>
<td>10T</td>
</tr>
<tr>
<td>Nominal ramp rate (&lt;10T)</td>
<td>3mT/s</td>
</tr>
<tr>
<td>Ramp rate (&gt;10T)</td>
<td>1mT/s</td>
</tr>
<tr>
<td>Warm bore diameter</td>
<td>50mm</td>
</tr>
<tr>
<td>Length of the good field (1%) parallel to the beam axis, r&lt;15mm</td>
<td>1m</td>
</tr>
<tr>
<td>Stray field along the beam axis &gt; 1.5m from the center</td>
<td>&lt;0.1mT</td>
</tr>
<tr>
<td>Radial stray field from the center outside the cryostat</td>
<td>&lt;1mT</td>
</tr>
<tr>
<td>Current leads conductor</td>
<td>HTS</td>
</tr>
<tr>
<td>Maximum current</td>
<td>1.0 kA</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Solid conduction with cryocooler</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>&lt;4K</td>
</tr>
<tr>
<td>Persistent mode</td>
<td>NO</td>
</tr>
</tbody>
</table>
12T magnet design

Coil geometry optimized for field homogeneity requirement.

Simplest design for easier stress management.

Main coil Nb$_3$Sn and boosters NbTi.

Passive magnetic shielding -> vessel.

Main coil divided in 4 sections + 1 proto/spare.

Use standard and available AUP conductor.
Cryogenic design

Conduction cooled design using 1.8W GM cryocoolers

Thermal shield in Al with 30 layers MLI

Support of the magnet on the cold bore

RRR copper on outer layer of coils for heat transport.

<table>
<thead>
<tr>
<th></th>
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<th>Magnet 4.2k</th>
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</thead>
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<td>3.6</td>
<td>0.07</td>
</tr>
<tr>
<td>Conduction</td>
<td>7.2</td>
<td>0.12</td>
</tr>
<tr>
<td>Current Leads</td>
<td>25</td>
<td>0.25</td>
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<td>Instrumentation</td>
<td>1</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>36.8</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Take away

Best of two worlds

Leap in performance for very short period devices

HTS insert field quality being optimized

Solenoid and integrated system to be completed in Q3 2023
Final remarks

Superconducting undulators are mature for machine installation.

At Fermilab we are focusing on the overall system performance and use lessons learned from SRF and SC Magnet modules.

The prototype NbTi SCU16 for EuPRAXIA @SPARCLab and the HTSU for PSI will be completed in 2023.
Questions?

Acknowledgments

KIT: S. Casalbuoni (now XFEL), A. Grau, D. Saez De Jauregui

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