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High-Temperature Superconducting Undulator Development at PSI/CHART

Joint Annual Meeting of ÖPG and SPS, 1st September 2021

WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN
Overview

• Introduction:
  - Synchrotron Radiation Source
  - The (HTS) Staggered Array Undulator
  - Tomography Microscopy beamline for SLS 2.0

• Status of the Project:
  - Simulations & Design
  - Experimental achievements (03.2021 campaign)
  - Industrial samples towards first meter-long prototype for SLS 2.0

• Conclusions and outlook
Synchrotron Radiation Source

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

\[ K = \frac{e}{2\pi m_e c} B_0 \lambda_u \]

Radiation wavelength

Undulator period length

Undulator deflection parameter

\( \gamma \): Lorentz factor of e\(^-\) ~ GeV

Effective magnetic field strength

Undulator
Permanent Magnet Undulator with iron poles

Iron poles

Permanent magnets

Electrons

\[ B_0 \]

gap

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

\[ K = \frac{e}{2\pi m_e c} B_0 \lambda_u \]
Staggered Array Undulator with iron poles

Iron poles

Electrons $\rightarrow$

Permanent magnets

$B_0$

gap

$\lambda_u$
Staggered Array Undulator

- Permanent magnets
- Electrons
- \( B_0 \)
- \( \lambda_u \)
- \( \text{gap} \)

- \( \text{Br(PM)} \sim 1.3 \text{ T} \) (1.7 T at 77 K)
- HTS material: “\( \text{Br} \)” \( \sim 17 \text{ T} \) in-situ magnetization
- Without iron poles: simplification for preliminary design
Superconducting Staggered Array Undulator

Example of \textit{field cooling (FC)} magnetisation

Undulator for I-TOMCAT beamline @ SLS 2.0

Dedicated to tomographic microscopy with photon energy up to 80 keV

CPMU, \( \lambda_u = 14 \text{ mm with } B_0 = 1.3 \text{ T} \)

HTSU, \( \lambda_u = 10 \text{ mm with } B_0 = 2.0 \text{ T} \)

@ 30m over 1.0x1.0mm²

100x more flux @50 keV
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10 period geometry for simulation and optimization:

- Starting point for optimization is close to the geometry of R. Kinjo
- ReBCO bulks
- $J_c(0 \text{ T, } 4.2 \text{ K}) = 1.5 \times 10^8 \text{ A/m}^2$
• Surface current density and trapped magnetic field after FC magnetization $10 \text{T} \rightarrow 0 \text{T}$:
Internal current density

Bulk HTS Staggered Array Undulator
Bulk HTS Staggered Array Undulator

Trapped currents

Trapped field

Resulting undulator field

Bulk HTS Staggered Array Undulator

Trapped currents

Trapped field

Resulting undulator field
Short Sample
Short Sample
Test Campaign – 03.2021

±12T

the solenoid
• The sample is cooled in a 8.0 T solenoid

• Temperature is stabilised at 10 K

• Solenoid is ramped down (1 T/h) in steps of 1 T

• Field profile (Bx,By1,By2,By3,Bz) was recorded during the plateau
Y positions of the Y-probes with respect to the undulator axis

-100μm
0
+100μm

Notice: It is requested to read and accept "IMPORTANT NOTICE"
Test Campaign – 03.2021

Cooling @ 8T / Solenoid @ 6T / 10.0K

-100μm
0
+100μm

Y positions of the Y-probes with resect to the undulator axis

printed Al₂O₃
x3yz-probe

InAs (HZ-116C)
Test Campaign – 03.2021

Y positions of the Y-probes with resect to the undulator axis

By (T)

z (mm)

-2
-1
0
1
2

-100μm
0
+100μm

-100μm
0
+100μm

printed Al₂O₃

x3yz-probe

InAs
(HZ-116C)

Cooling @ 8T / Solenoid @ 5T / 10.0K

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Test Campaign – 03.2021

Y positions of the Y-probes with respect to the undulator axis.

By (T) vs. z (mm) for Cooling @ 8T / Solenoid @ 4T / 10.0K.

-100μm
0
+100μm

Y positions of the Y-probes with respect to the undulator axis. 

By (T) vs. z (mm) for Cooling @ 8T / Solenoid @ 4T / 10.0K.

-100μm
0
+100μm

Y positions of the Y-probes with respect to the undulator axis.
Cooling @ 8T / Solenoid @ 3T / 10.0K

BY positions of the Y-probes with resect to the undulator axis

-100μm
0
+100μm

Y positions of the Y-probes with resect to the undulator axis

printed Al₂O₃
x3yz-probe

Test Campaign – 03.2021
Cooling @ 8T / Solenoid @ 1T / 10.0K

Y positions of the Y-probes with resect to the undulator axis

By (T)

-2 -1 0 1 2

z (mm)

20 40 60 80 100

-100μm
0
+100μm

printed Al₂O₃

x3yz-probe
Test Campaign – 03.2021

The new 3.0mm diameter probe

x3yz-probe

x

y

z

printed

Al₂O₃

InAs

(HZ-116C)

InAs...

back of the front cover of this catalogue.

注意:弊社製品のご検討にあたっては本カタログの表紙裏の「重要注意事項」を良くお読みください。

冷却 @ 8T / 磁石 @ 0T / 10.0K

By (T)

z (mm)

-2

-1

0

1

2

-100μm

0

+100μm

Y positions of the Y-probes with respect to the undulator axis

printed Al₂O₃

x3yz-probe

InAs (HZ-116C)
Summary of the results

Subcooling from 10 K to 7 K to freeze the flux creeping

$B_S: 8 \text{T} \rightarrow 0 \text{T}, \Delta B = 8 - B_S$

$Nb_3Sn @ 4.2K$

$\tau = 3.263 \text{ years}$
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Ideas to enhance the field

At the time being the record undulator field demonstrated is:

\[ B_0 = 1.54 \text{ T} \]

Extrapolation with ferromagnetic poles:

- Fe \[ B_0 = 1.70 \text{ T} \]
- CoFe \[ B_0 = 1.75 \text{ T} \]
- Ho \[ B_0 = 1.85 \text{ T} \]
The HTS crystals are embedded (shrink-fit) into a copper matrix with micro-meter accuracy, to be mechanical and thermally stabilised. An additional Aluminium shrinking cylinder is used to precisely assemble the undulator array.
Next test campaign is expected in this month. Series of samples are on the way to test the performance of the iron poles and different HTS material.
2 meter-long full scale prototype for SLS 2.0
Conclusions and outlook

• The first experimental results are encouraging
• Higher fields (>1.54 T) should be possible with ferromagnetic poles
• Quality control (pre-sorting) at the production site is a key element
• Field quality, i.e. peak to peak variation < 5% shall be achieved to allow a fine magnetic field optimization below 0.1% (phase error <2°)
• Further possible applications:
  - Compact FELs, like 2nd hard X-ray beamline for SwissFEL
  - ILC positron source requiring short-period, high-field helical
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Thanks for your attention!
Short Sample

- Magnetic gap 4.0 mm
- Period length 10.0 mm
- Bulk diameter 30.0 mm
- Bulk thinness 4.0 mm
- End field shaping → to match the electron orbit
Summary of the results

- $B_0$ is the undulator field
- $B_s$ is the solenoidal field
- $\Delta B = 8 - B_s$ (T)

Profile measurement

- $\lambda_u = 10$ mm
- 15K & 4mm gap

Graphs showing:

- Nb$_3$Sn @ 4.2K
- NbTi @ 4.2K
- PrFeB @ 77K
- NdFeB @ 300K

- Time (h) vs. $B_s$ (T)
- $\Delta B$ (T) vs. $B_0$ (T)
Summary of the results

James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator
and Beams 17, 022401 (2014)]
• Measure the undulator field versus solenoid field
• Study the quench behavior
• Study the pre-stress: shrink fitting techniques (bulks)
• Test different bulks: YBCO, GdBCO, EuBCO
• Bulk versus tapes: high field versus homogeneity
• Different geometries: planar, hybrid (circular)
• Estimate the peak to peak field variation (phase error)
• Try different shimming approach: swapping/period/pole height
• Reproducibility of the magnetization process
• End optimization study
• Flux freezing