Short Period Superconducting Undulators

Sara Casalbuoni
European XFEL

EAAC23 Workshop 21 September 2023

Outline

- Why superconducting undulators?
- Storage rings: State of the art
- Plans at X-ray FELs
- Plans at compact light sources
- R&D: new materials and geometries
- Summary

Why short period undulators?

- To increase the photon beam energy with the same electron beam energy it is necessary to reduce the period length λ_U ⇨ short period undulators

$$\lambda = \frac{\lambda_U}{2\,n\,\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{e}{2\pi mc} B_0\,\lambda_U = 0.9336\;B_0[T]\;\lambda_U[cm]$$

- To increase the tunability range of the photon energy

⇩

Develop technology to increase B_{max}

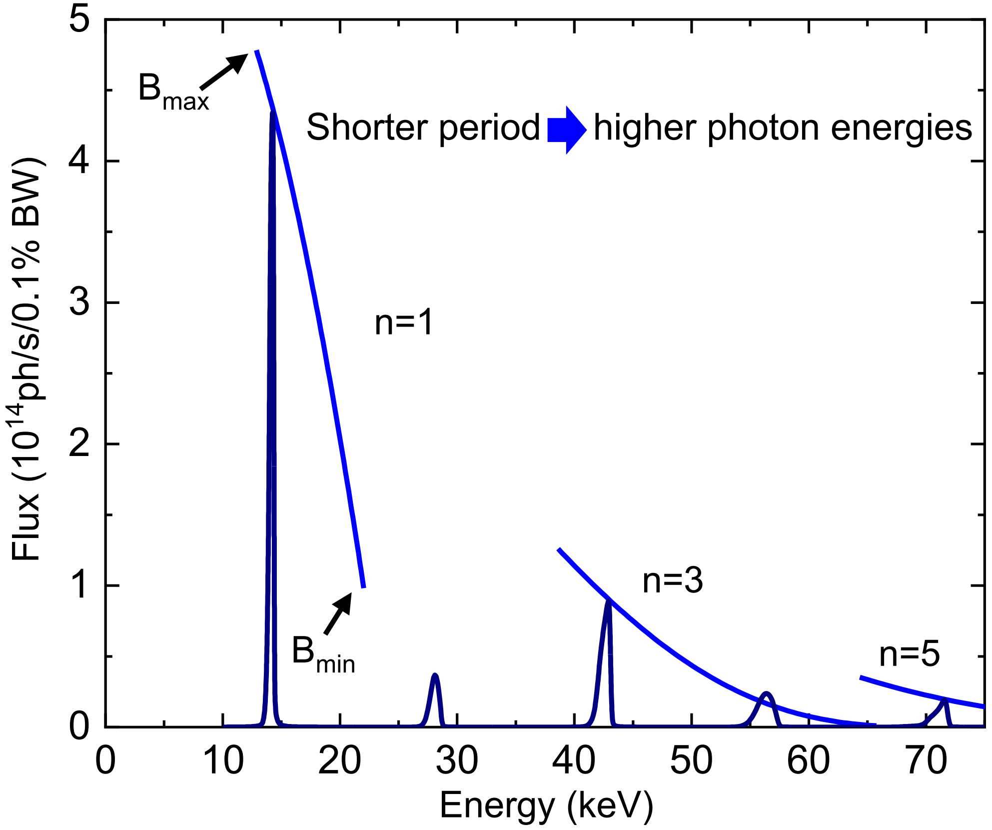
- FEL undulators: shorter period with higher B_{max}

⇩

Shorter saturation length ⇨ shorter undulator line

⇩

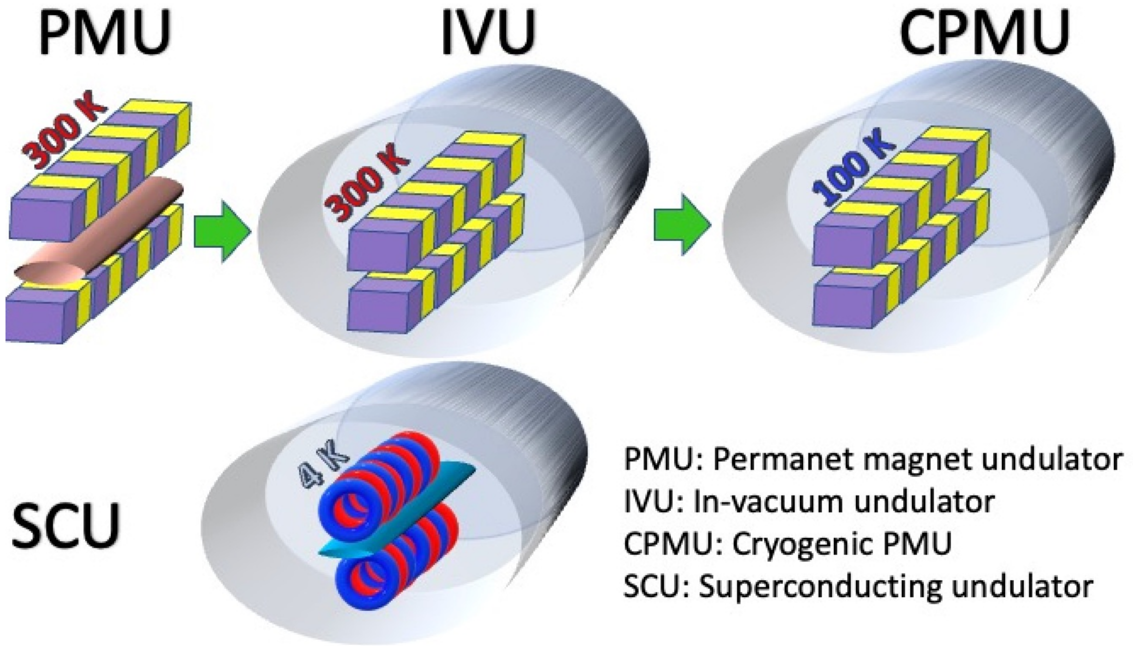
Savings in civil construction cost

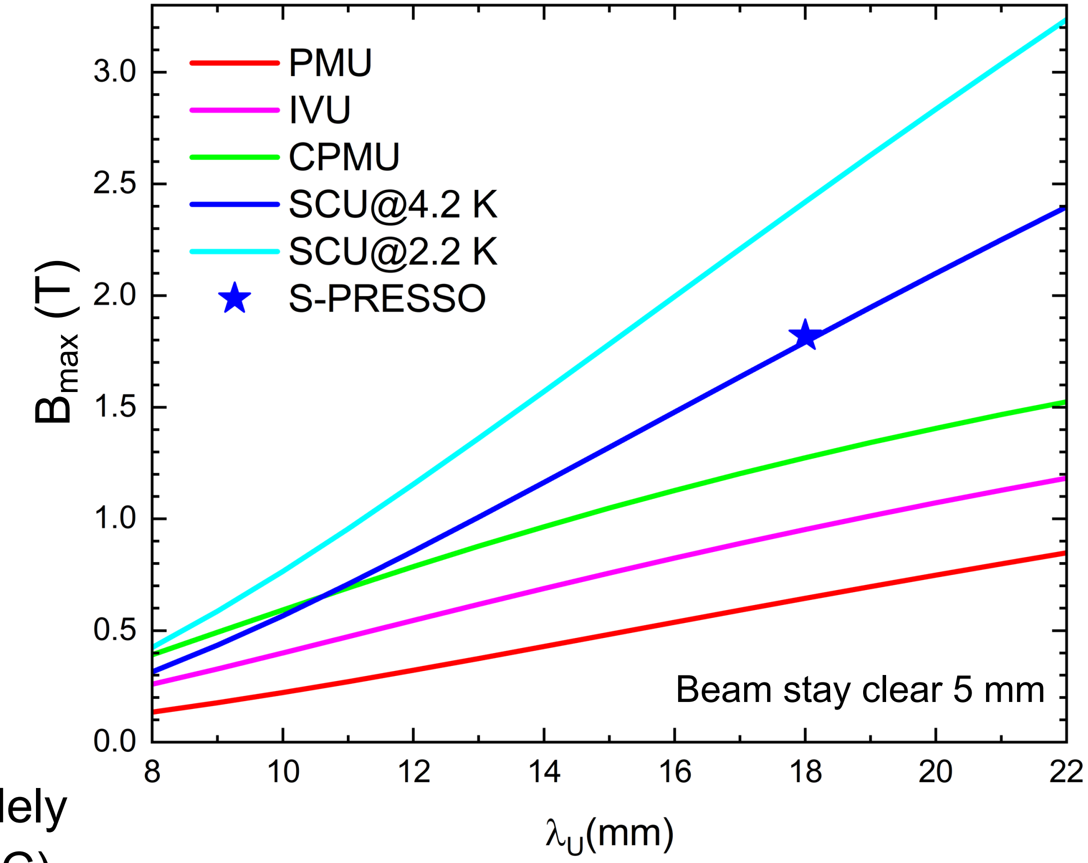


The position of the harmonics is shifted by changing the on axis peak magnetic field B_0

Why superconducting undulators?

- Technology development to increase B_{max}





temperature margin of 1 K

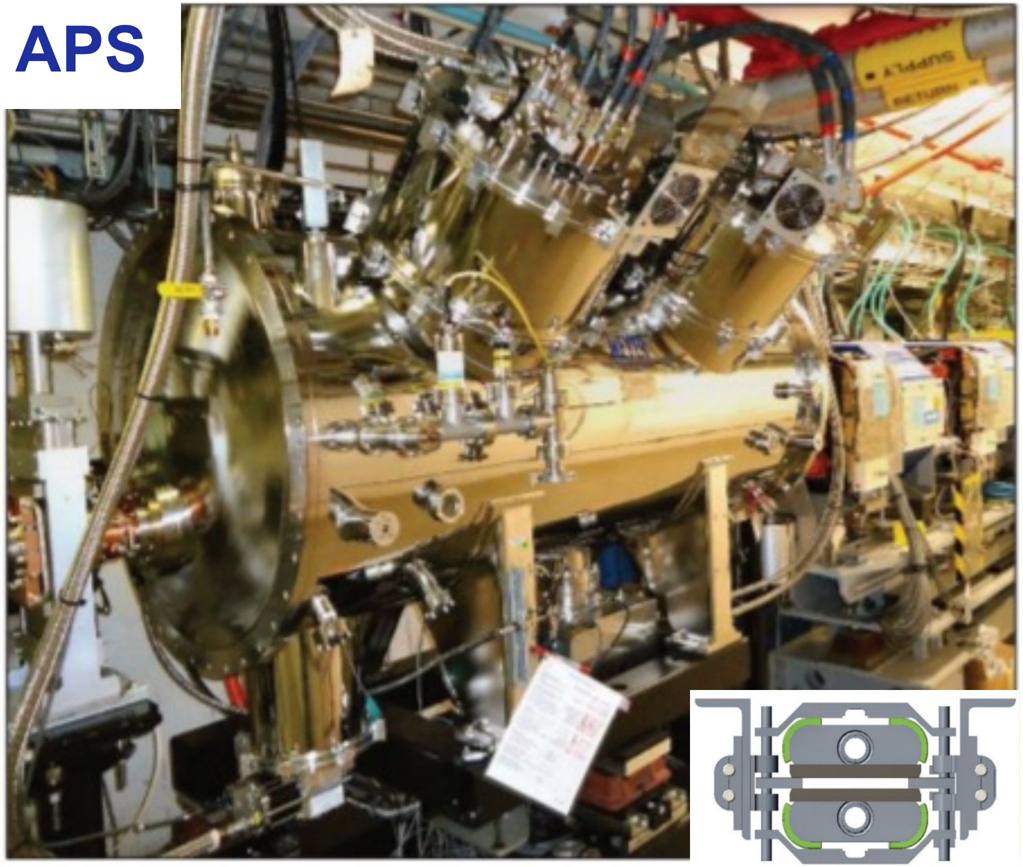
- Further advantage is radiation hardness widely demonstrated for NbTi magnets (i.e. HERA, Tevatron, LHC)

S. Casalbuoni et al., Front. Phys. Sec. Interdisciplinary Physics Volume 11 - 2023

State of the art in storage rings of NbTi based SCUs

- KIT/Noell development: successful commercialization

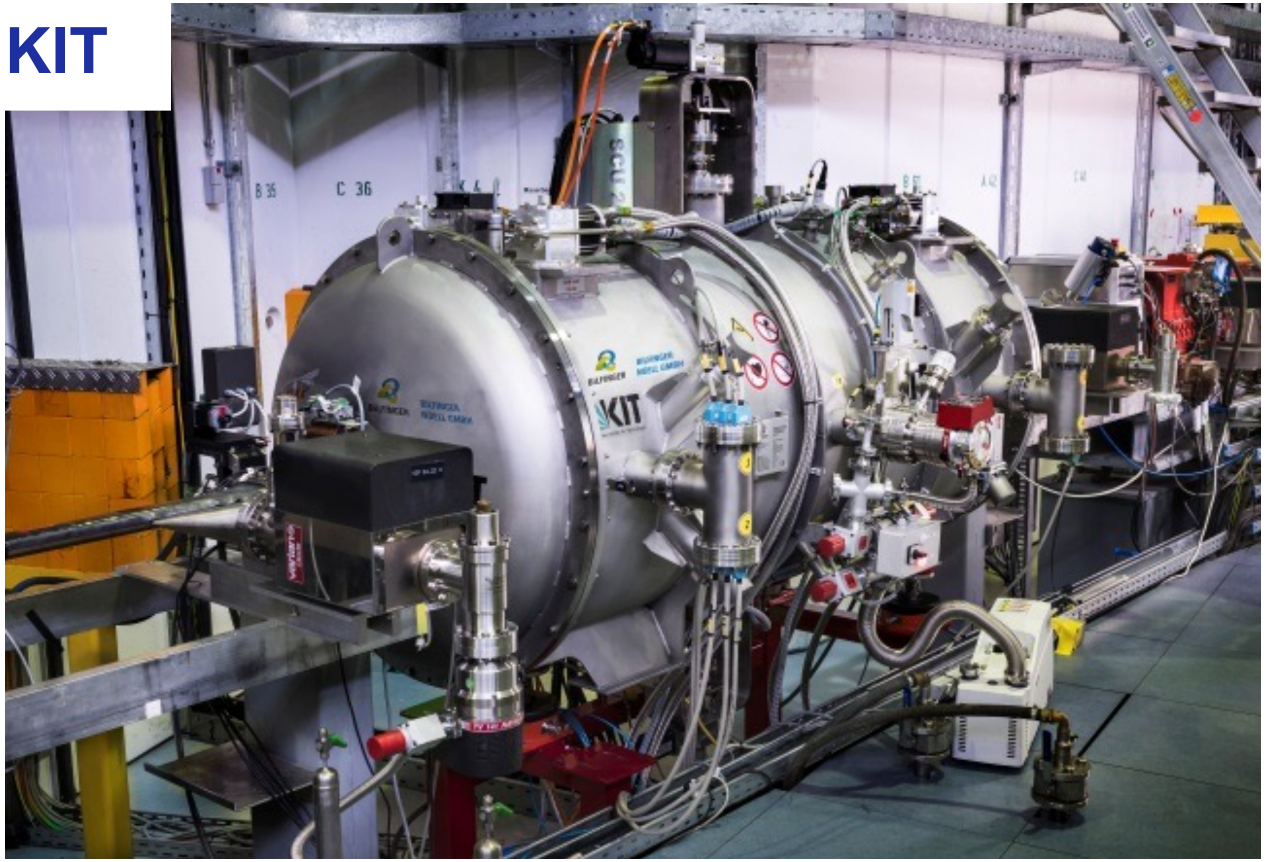
APS



Thermosyphon with LHe tank + cryocoolers

J. Fuerst et al., FLS2018 Conf.

KIT



Cryogen-free: only cryocoolers

S. Casalbuoni et al., Synchr. Rad. News, 31:3, 24-28 (2018)

Projects at XFELs

All based on NbTi at ~4K

SHINE

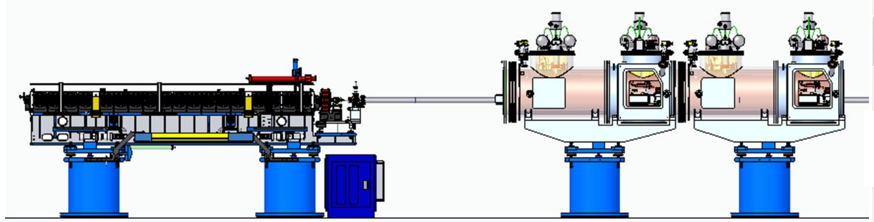
- complete undulator line
- room temperature intersections
- in vacuum SCUs, cryoplant, thermosyphon

Quantity	40
Period Length	16 mm
Magnetic Length	4 m
Period Number	250
Beam Gap	4 mm
Peak Fields	0.682 – 1.583 T

Courtesy of Zhou Qiaogen (SINAP)

LCLS II

- R&D for modular SCU line with cold intersections
- test for FEL demonstration
- two 1.47 m SCU coils
- thermosyphon + cryocoolers, ANL design



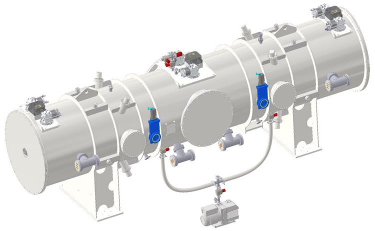
P. Krejcik,FLS23, Luzern, Switzerland

Parameter	Baseline
Superconductor	NbTi
Period length (mm)	21
Number of periods / SCU	≥ 71 *
SCU magnet length (m)	≥ 1.5 m *
Magnetic gap	8 mm
Vacuum gap	5.7 mm
Magnetic field at 600 A (T)	1.6
K_{peak} at 600 A	3.14

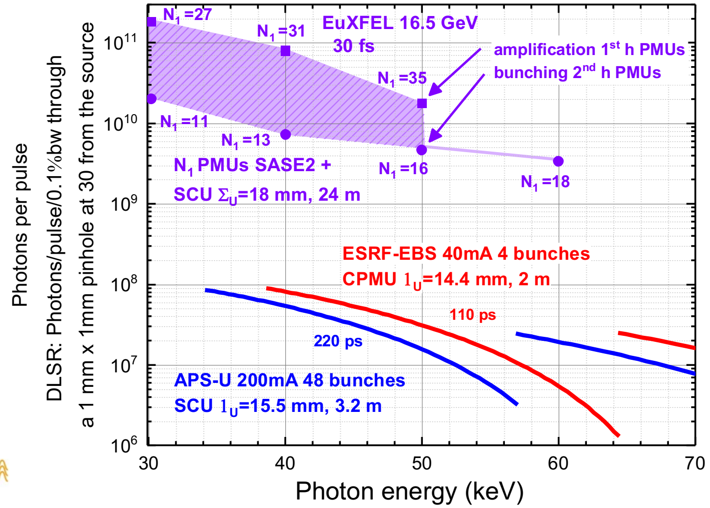
EuXFEL

- S-PRESSO in production by Noell
- cryogen-free with room temp. intersections
- test for FEL demonstration
- planned additional 5 modules
- two 2 m SCU coils + sc phase shifter

Period	18 mm
Peak field	1.82 T
K	3.06
Vacuum gap	5 mm



S-PRESSO SUPERCONDUCTING UNDULATOR PRE-SERIES MODULE + FESTA FREE ELECTRON LASER SUPERCONDUCTING AFTERBURNER

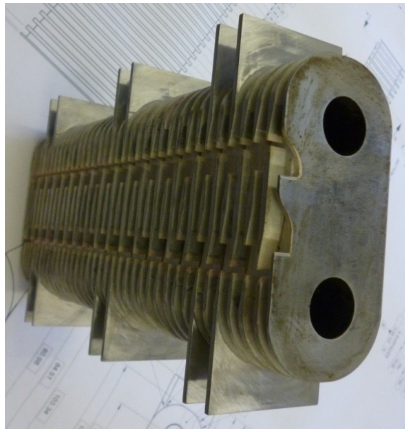


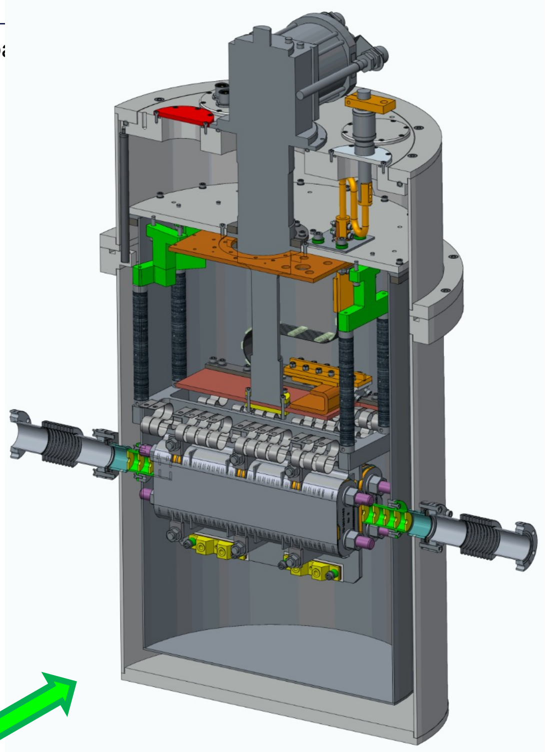
S. Casalbuoni et al 2022 J. Phys.: Conf. Ser. 2380 012012

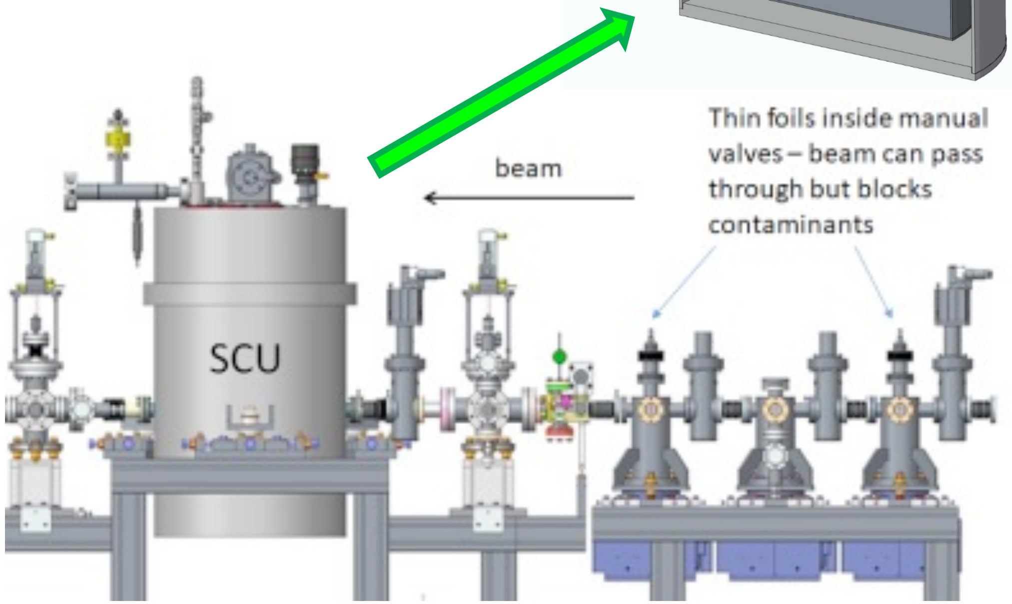
SCU Tests on CLARA

- **mini-undulator** from four 30 cm modules, and installed it in a cryostat into a 50 MeV test accelerator, CLARA
- **First ever test** of an in-vacuum planar SCU on an accelerator
  - Four weeks of **beam time** during CLARA exploitation period in 2019 (including two for setup)
    Thin foils blocking contamination from 10^{-6} mbar in SCU to 10^{-8} mbar in CLARA
  - Expected IR spectrum, not observed due to strong kick to the beam even at low currents

Period =15.5 mm
Mag. gap = vac. gap= 7.4 mm
B = 1.05 T
Operated at 4.2 K





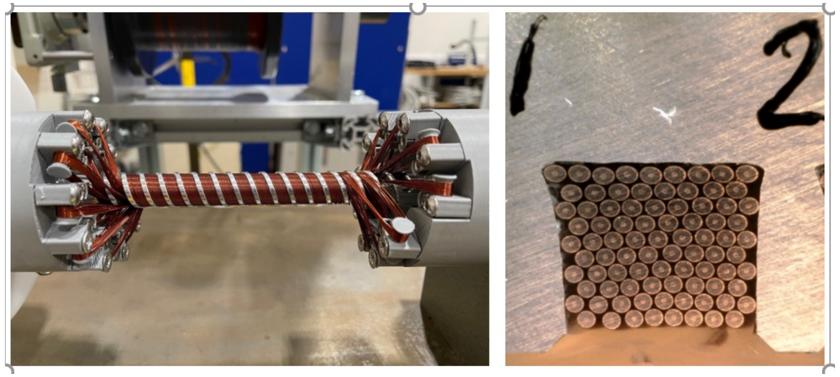


J. Clarke et al., ICFA Beam Dynamics New Letter 78, 2019

B. Shepherd, Workshop on Superconducting Undulators for Advanced Light Sources, 19-21.04.2021, on zoom

SCU plans for CompactLight and EuPRAXIA@SPARCLab FEL

Compact

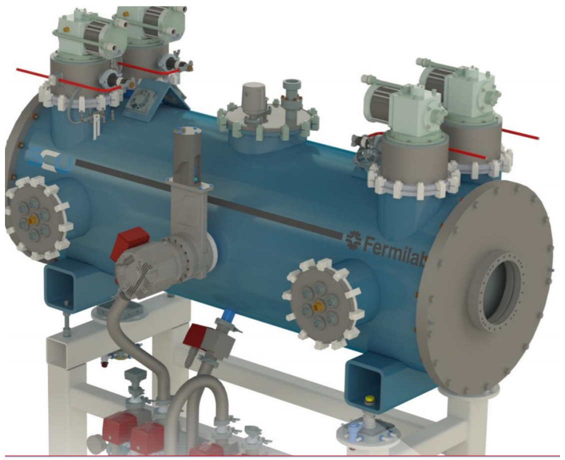


- STFC working on a design for a **helical SCU** with the following parameters (aimed towards **CompactLight**, 5.5 GeV, 8-16 keV photons):
  - **Period** 13 mm
  - Minimum **winding diameter** 5 mm
  - Beam pipe **bore diameter** 4 mm
  - **Peak field** on axis 1.10 T

B. Shepherd, Workshop on Superconducting Undulators for Advanced Light Sources, 19-21.04.2021, on zoom

- Plans for NbTi planar SCU at the EuPRAXIA@SPARCLab FEL in collaboration with FNAL

Parameter	Value	Unit
Period	< 16	mm
Beam stay clear	5	mm
FEL wavelength	~3	nm
K-value	>1.2	-
Ramp to operating field	<600	s
Cooling	Cryocoolers	-
Operating temperature	4.2	K
Magnet length	1.5	m
Flange to flange length	<2.0	m
Beam height	1.1	m
Vacuum vessel diameter	0.6	m
Insulation vacuum	$1*10^{-5}$	mbar
Cooldown time	<7	days

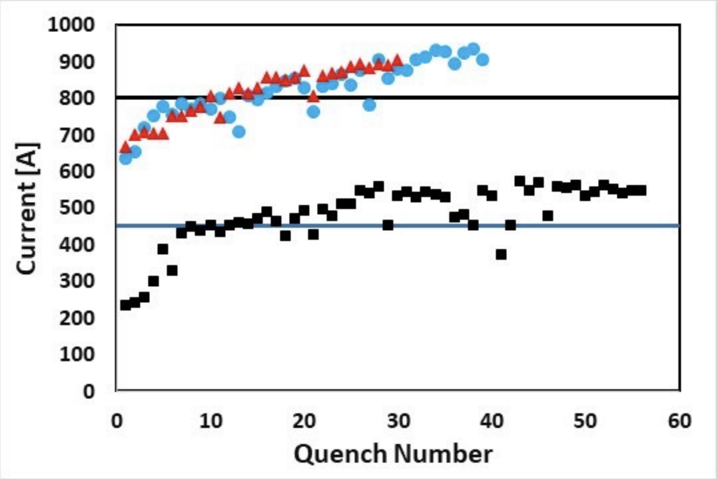


Courtesy of C. Boffo and M. Turenne (FNAL)

Nb_3Sn @ ~ 4 K

- Nb_3Sn 1.1 m coils tested in APS January-April 2023

Undulator specifications	NbTi	Nb_3Sn
Undulator Field, T	0.97	1.17
K-value	1.6	2.0
Design current, A (80 and 70% of the I_c) @4.2 K	450	800
Period length, mm	18	18
Magnetic gap, mm	9.5	9.5
Vacuum gap, mm	7.2	7.2
Magnetic length, m	1.1	1.1



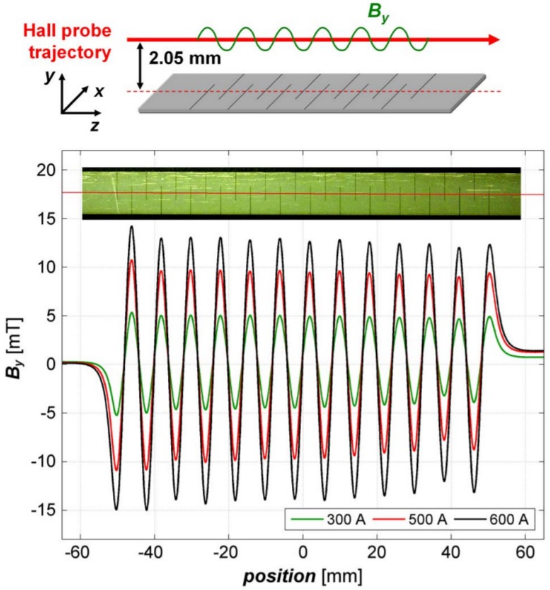
Courtesy of I. Kesgin

Phase error of <6 degrees achieved up to the maximum operating current

HTS undulators

- HTS (High Temperature Superconducting) tapes and bulks
  - Not yet demonstrated in accelerator environment
  - HTS tape: Noell, KIT, ANL, FNAL and EuXFEL started
  - HTS bulk: PSI for SLS II
  - Uniformity, repeatability, mechanical properties, quench protection, available length for the tape, and production rate of high quality HTS tape and bulk

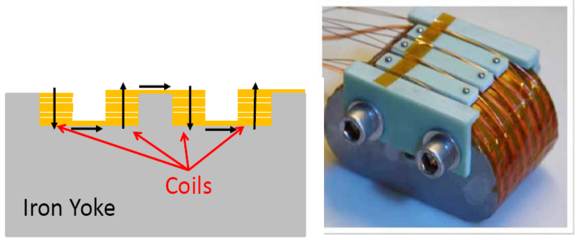
HTS structured SCU



Period length = 8 mm
m. gap = 2.5 mm
Estimated
w =12 mm B = 1.0 T
w > 20 mm B = 1.4 T

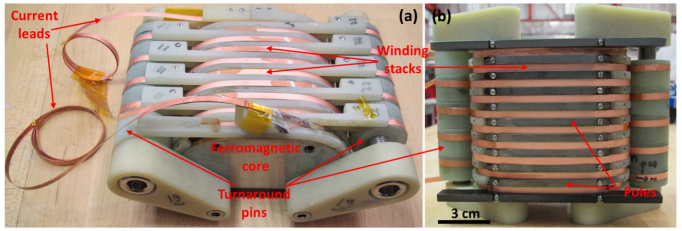
T. Holubek et al., IEEE Trans. on Appl. Supercond. 4602204 Vol. 23-3 (2013)

Planar HTS SCUs



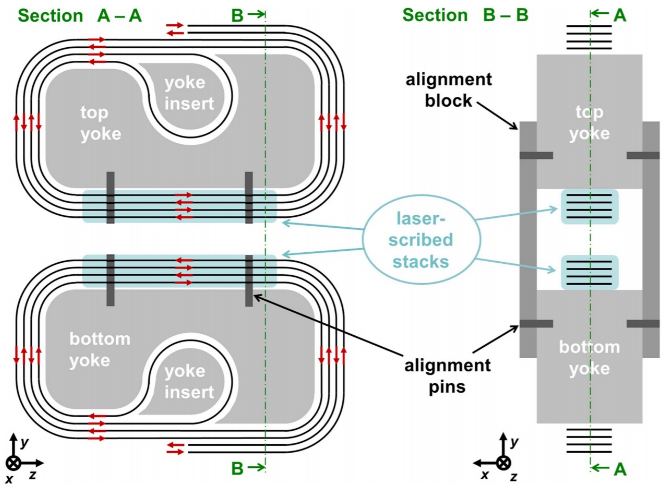
C. Boffo IDMAX10 Workshop, Lund 2010
C. Boffo, Th. Gerhard, PCT/EP2010/004656

European XFEL



I. Kesgin et al., SUST 30 04LT01 2017

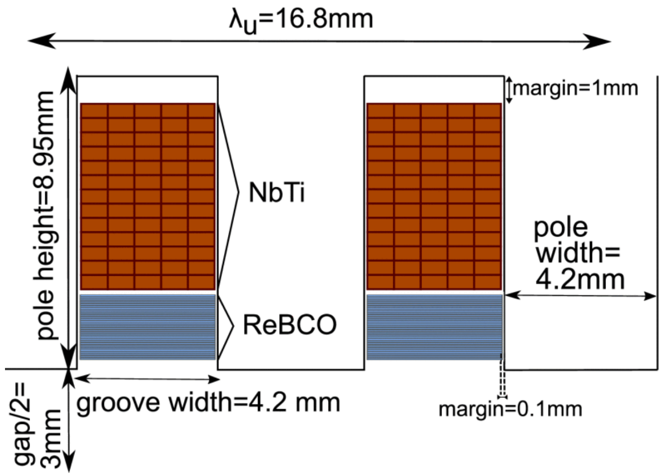
Period length = 16 mm
m. gap = 9.5 mm
Estimated
B = 1.0 T more than 30% NbTi@4K

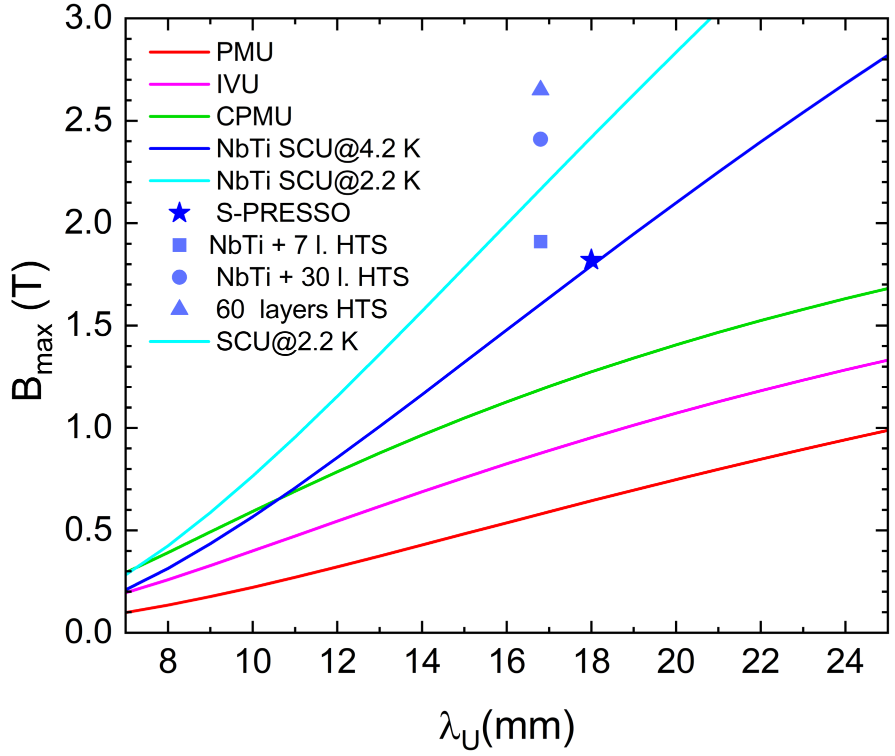


T. Holubek et al., SUST 30 115002 2017

Hybrid SCU/HTS tape

- ReBCO tapes are commercially available in lengths up to about 100 m
- Reduce cost. ReBCO tapes are about 10 times more expensive than NbTi wire
- Take advantage of the high current density and large temperature margin of the ReBCO tape



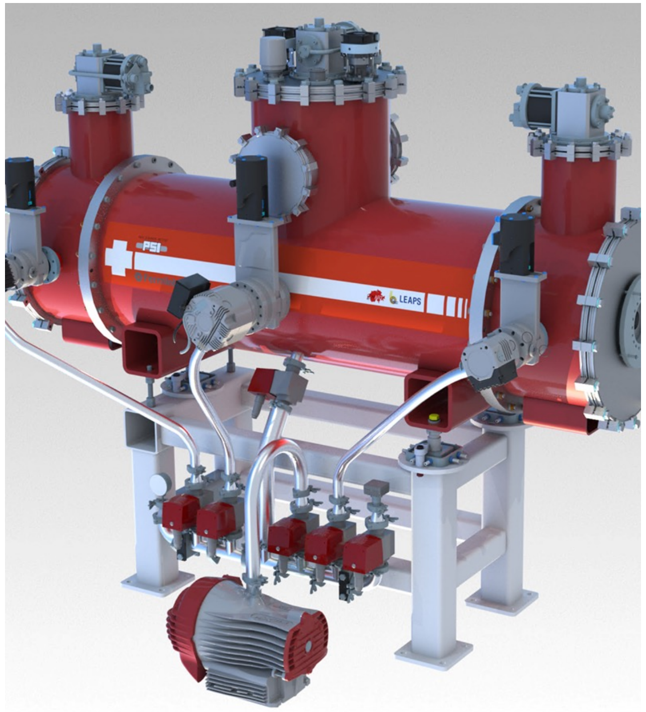


V. Grattoni and S. Casalbuoni, IEEE Trans. on Appl. Supercond. vol. 33, no. 5, pp. 1-5,. 2023

PAUL SCHERRER INSTITUT PSI

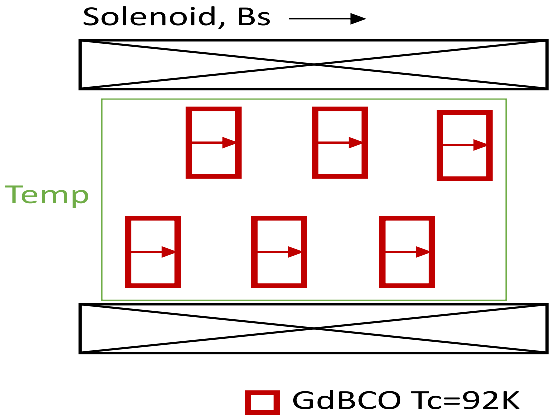
HTS Undulator Project @ PSI

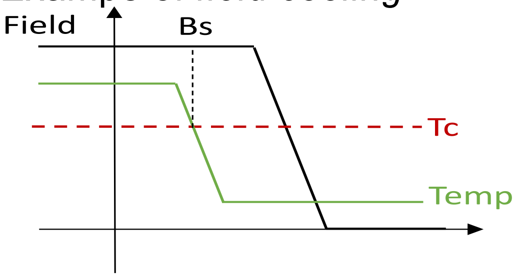
Conduction cooled cryostat

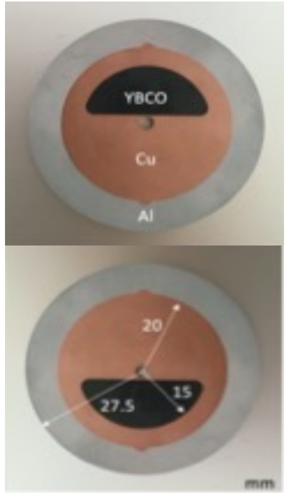


This device will be test in SLS 2.0 at the new microscopy tomogaphy beamline.

Courtesy of Marco Calvi (PSI)







Active length : 1.0 m
Total length : < 2 m
period length : 10 mm
magnetic gap : 4.0 mm
B_{max} ~ 2 T
Cryocoolers HTS temp 10 K
LTS temp 4.0 K

Magnetic arrays with

Planar geometry reached 2.1T

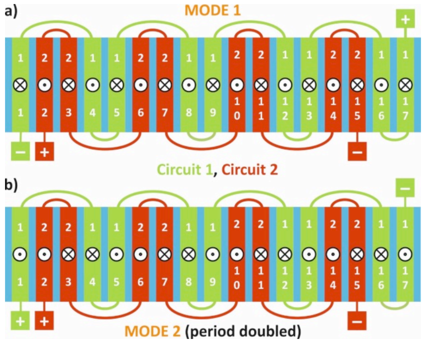
K. Zhang et al., SUST 36 05LT01 2023

Helical geometry reached B= 2.57 T

M. Calvi et al., Phys. Rev. Research 5, L032020 2023

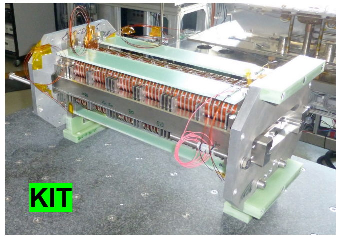
Different geometries

Period doubling

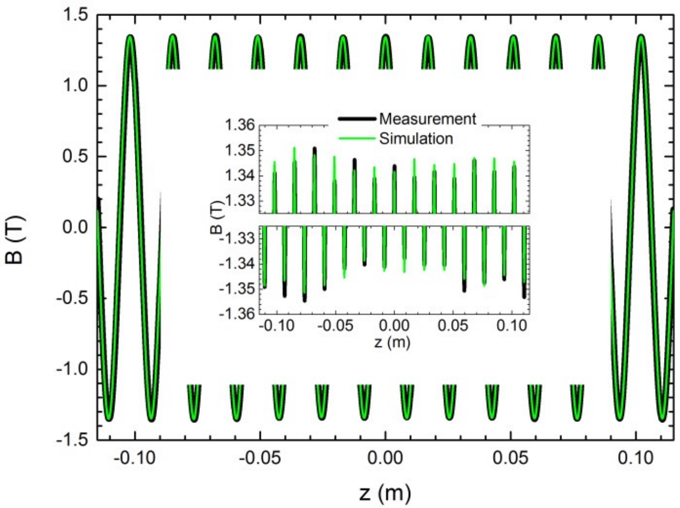


Period length: 17/34 mm
Magnetic length: 410 mm
Magnetic gap: 6 mm
NbTi wire, 1x0.5mm, 60 turns stacked in 12 layers

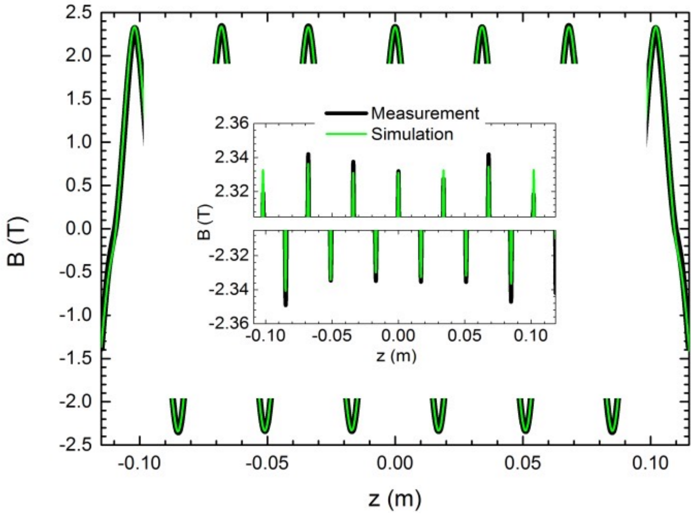
S. Casalbuoni et al., IPAC19 TUPGW017



Current: 500 A

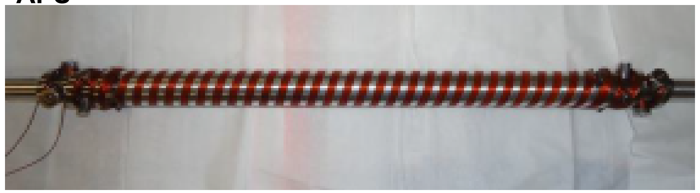


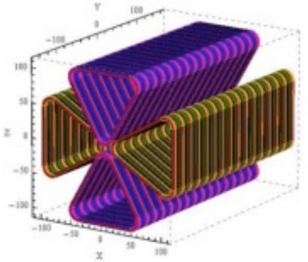
Current: 370 A



Helical, variable polarization

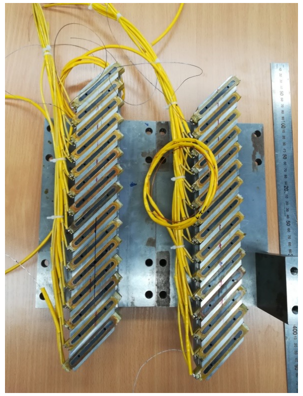
APS

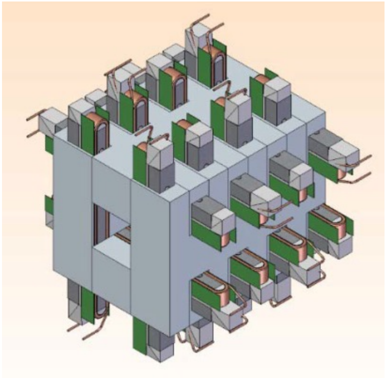




Y. Ivanyushenkov, Workshop on Superconducting Undulators for Advanced Light Sources, 19-21.04.2021, on zoom

N. Mezentsev, Workshop on Superconducting Undulators for Advanced Light Sources, 19-21.04.2021, on zoom





BINP

Summary

- Tremendous progress has been done in the past years on SCU development
- Planar NbTi SCUs are becoming a mature technology and they are commercially available
- The number of labs working on SCUs is increasing as well as the interest of the light sources community in this technology
- Many R&D projects are ongoing to explore alternative geometries and materials
- **Very exciting field!**

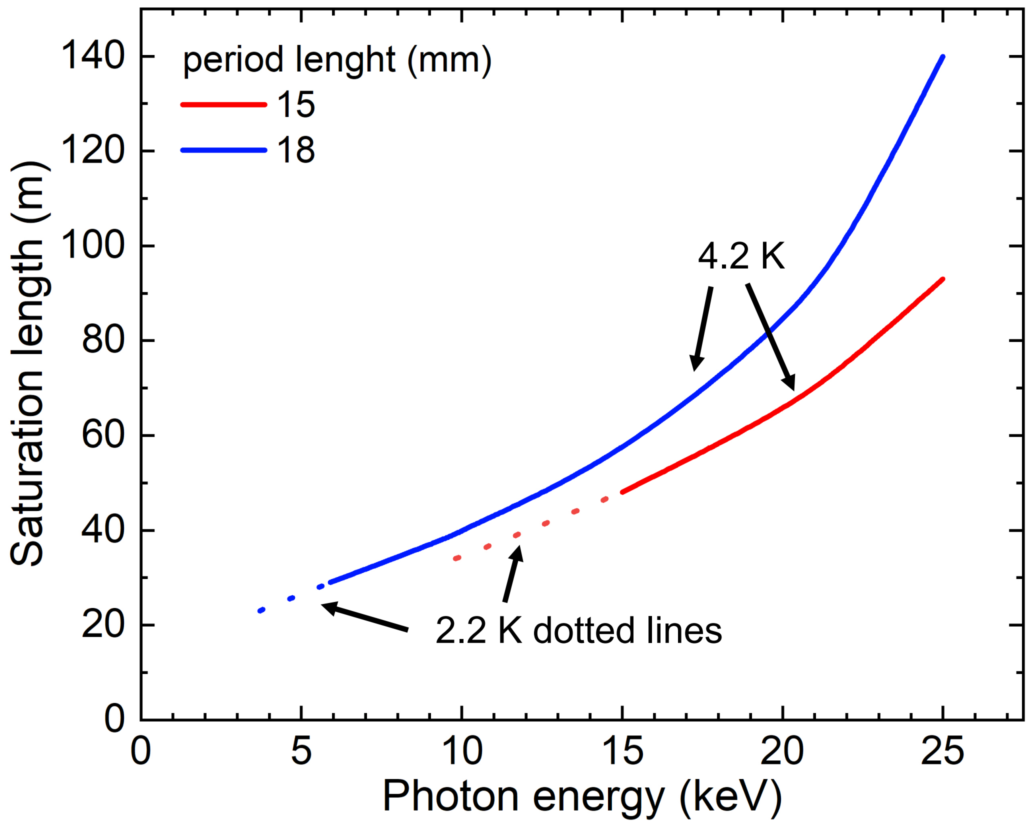
For more info Workshop on SCUs at ALSs, 19-21 April 2021
https://indico.desy.de/event/28501/overview

Thank you for your attention !

Back-up slides

SCUs for CW operation mode upgrade

beam energy = 8 GeV
peak current = 5 kA
normalized emittance =0.4 mm mrad
rms energy spread = 3 MeV
βx = βy = 16 m



In order to cover a similar photon energy range as now covered with an electron beam energy of 17.5 GeV and the PMUs with 40 mm period length would be necessary to use undulators with a shorter period length.

SCUs with a period length between 15 and 18 mm will allow to cover the same photon energy range.

S. Casalbuoni et al., Front. Phys. Sec. Interdisciplinary Physics Volume 11 - 2023

The classic Peter Lee plot

BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots#engineering