2023 Cryogenic Engineering Conference and International Cryogenic Materials Conference, July 9-13, Hawaii Convention Center, Honolulu, USA

Superconducting undulator development for synchrotrons and FELs

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July 10, 2023, Honolulu

Many thanks to the following people for providing materials used in this presentation or the SCU review Kai Zhang and Marco Calvi 2022 *Supercond. Sci. Technol.* 35 093001

Marco Calvi, Paul Scherrer Institute

Sara Casalbuoni, European XFEL

Efim Gluskin, Argonne National Laboratory

Qiaogen Zhou, Shanghai Advanced Research Institute, CAS

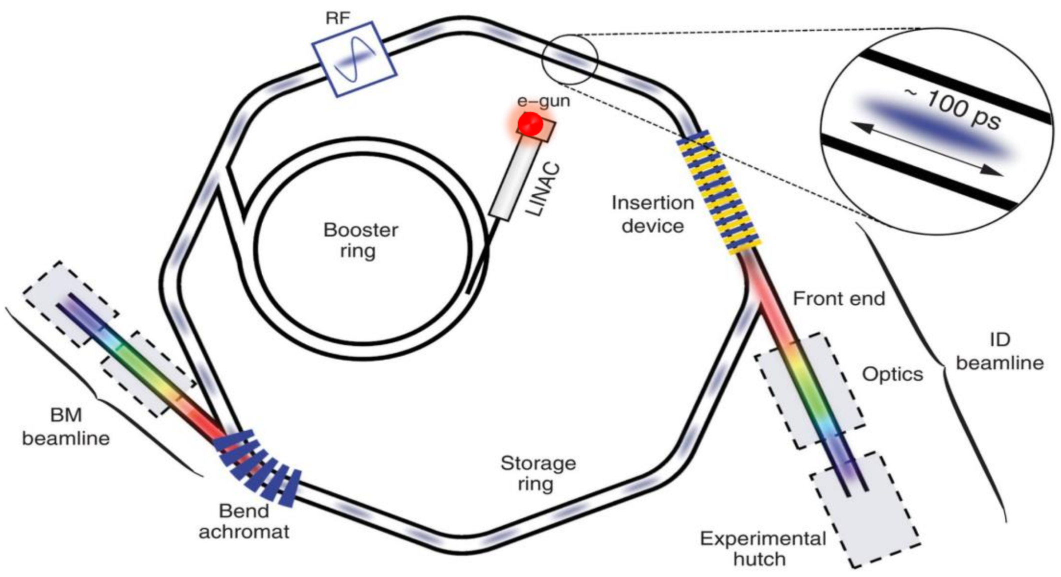
Yuhui Li, Institute of High Energy of Physics, CAS

Cristian Boffo, Fermi National Accelerator Laboratory

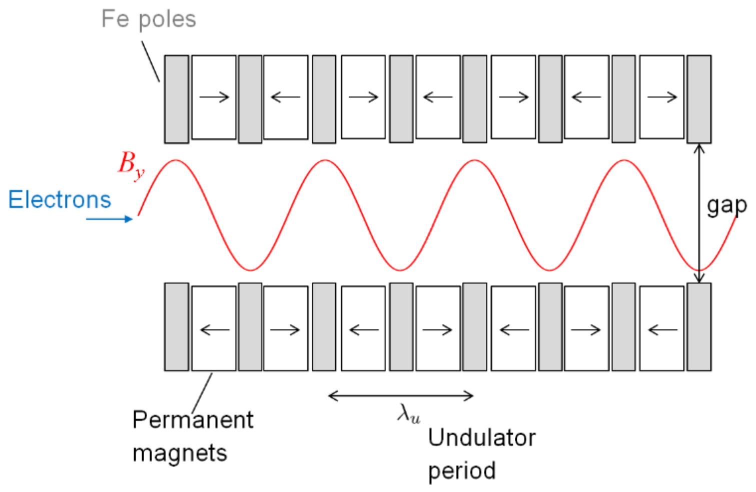
Overview

- Introduction to synchrotrons and FELs
- Why superconducting undulator (SCU)?
- Overview of SCU technique development and applications
- Ongoing SCU R&D activities
- HTS materials – opportunities and challenges
- Conclusions and outlooks

Introduction to Synchrotrons and Free-Electron Lasers



Synchrotron radiation light sources



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

$$K = \frac{B_0 e}{mc}\frac{\lambda_u}{2\pi}$$

Free Electron Lasers

- An adjustable deflection parameter *K* of up to 1~2 is generally required.
- To shorten the period length λ_u, the undulator field B_0 should be higher to keep *K* at the same level.
- Reduction in λ_u can either shorten the radiation wavelength or reduce the electron beam energy.

An introduction to Synchrotron Radiation: Techniques and Applications, Philip Willmott C © 2019 John Wiley & Sons Ltd.

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Synchrotron Radiation facilities

APS, 1995, USA: 7 GeV, 1104 m ring, 35 beamlines; to be upgraded to DLSR during 2023-2024

ESRF, 1994, France: 6 GeV, 844 m ring, 44 beamlines; was upgraded to ESRF-EBS in 2020

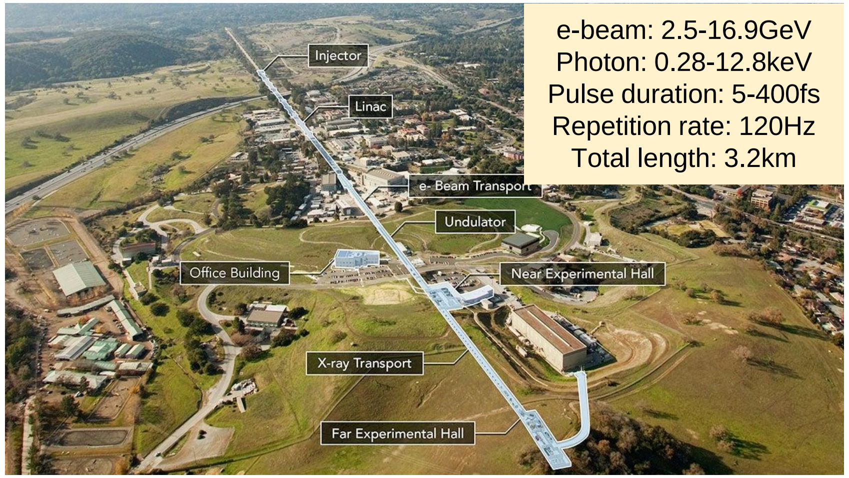
SPRING8, 1999, Japan: 8 GeV, 1436 m ring, 48 beamlines

ALS, 1993, USA: 1.9 GeV, 197 m storage ring, 40 beamlines, to be upgraded to DLSR during 2025-2026

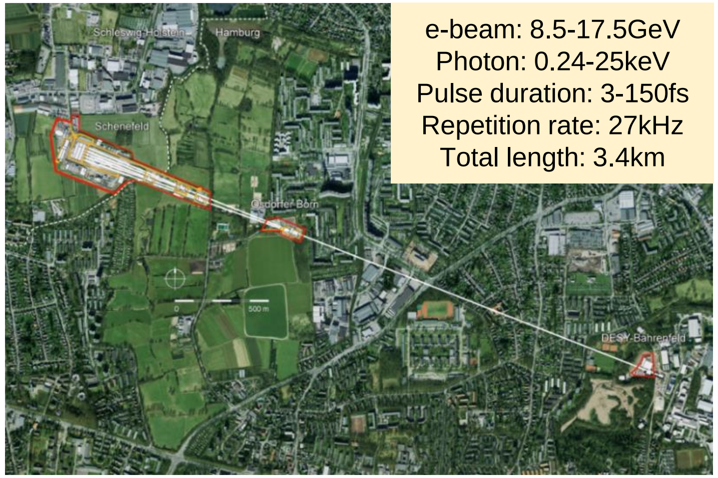
SLS, 2001, Switzerland: 2.4 GeV, 288 m ring, 16 beamlines, to be upgraded to DLSR during 2023-2025

SSRF, 2009, China: 3.5 GeV, 432 m ring, 16 beamlines

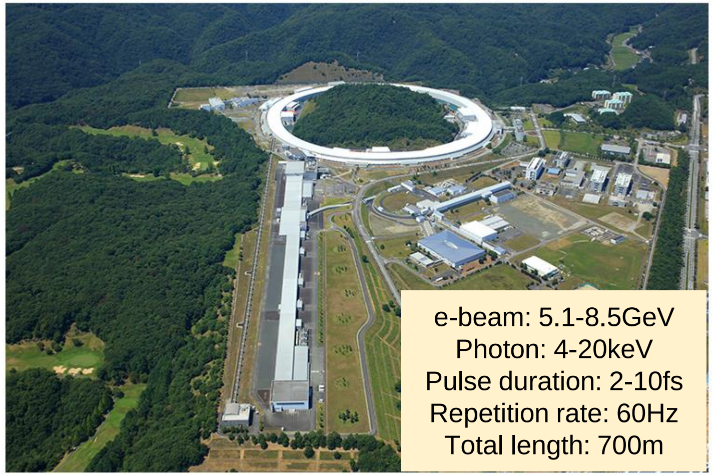
Free-Electron Laser facilities



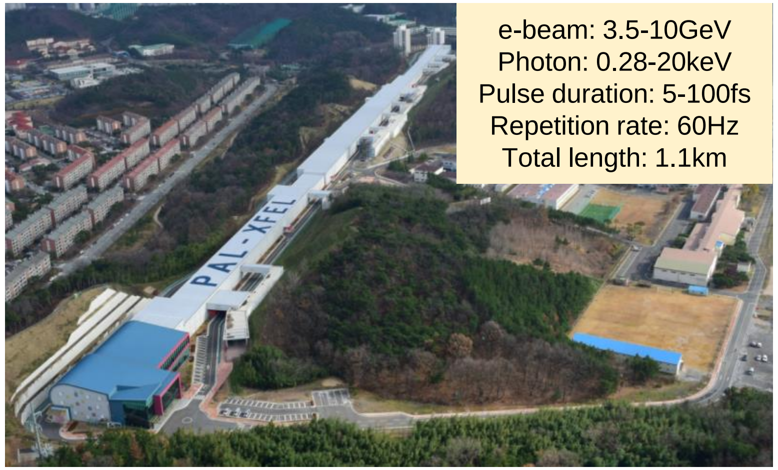
LCLS, 2009, USA; to be upgraded to LCLSII



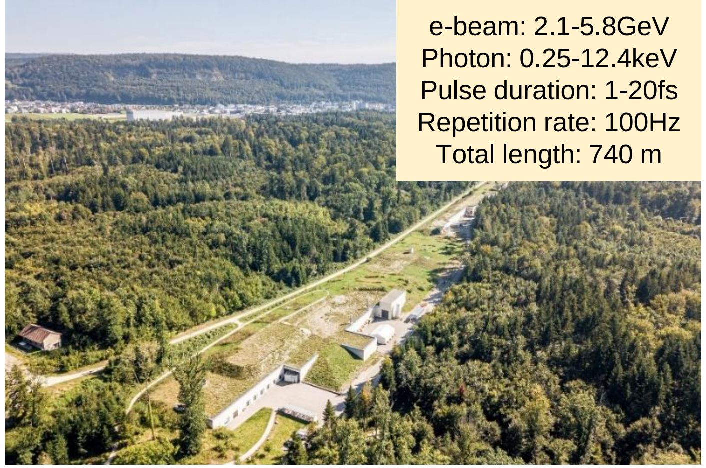
EuXFEL, 2017, Germany



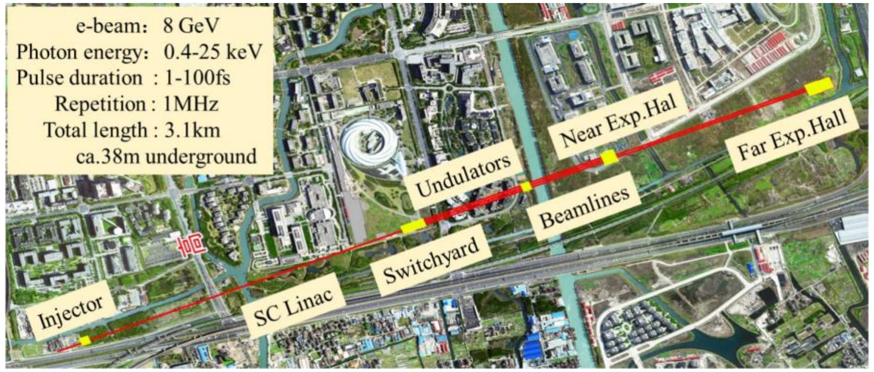
SACLA, 2011, Japan



PAL-XFEL, 2017, South Korea



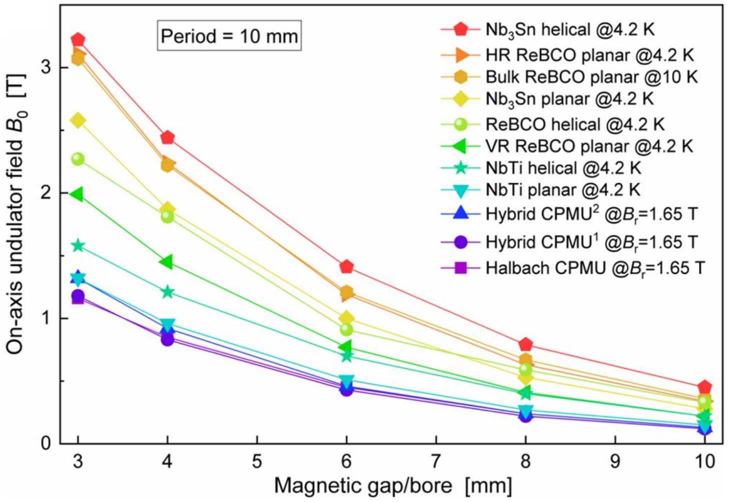
SwissFEL, 2018, Switzerland



SHINE, China, under construction

Why superconducting undulator (SCU)?

- ✓ Higher magnetic field at short period λ_u
- ✓ Lower sensitivity to radiation
- ✓ Simpler magnetic field control
- ✓ Variable polarizations are possible
- ✓ Reduced wakefield effects with cold bore
- ✓ Much lower vacuum pressure



Comparison between SCUs and PMUs at λ_u = 10 mm

Overview

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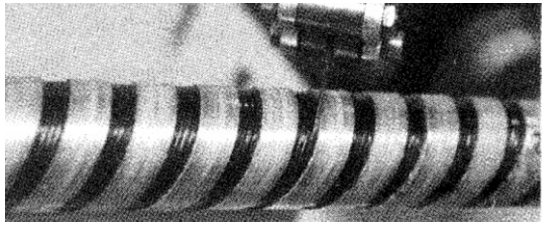
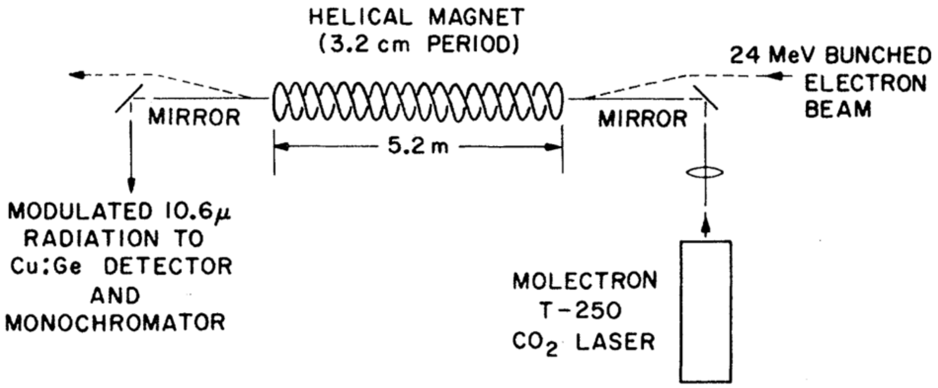
Ancient history

- The first helical undulators built in 1976 were superconducting, installed in a FEL oscillator proposed by Stanford University, demonstrating for the first time the possibility of high gain at 10.6 um radiation (infrared).

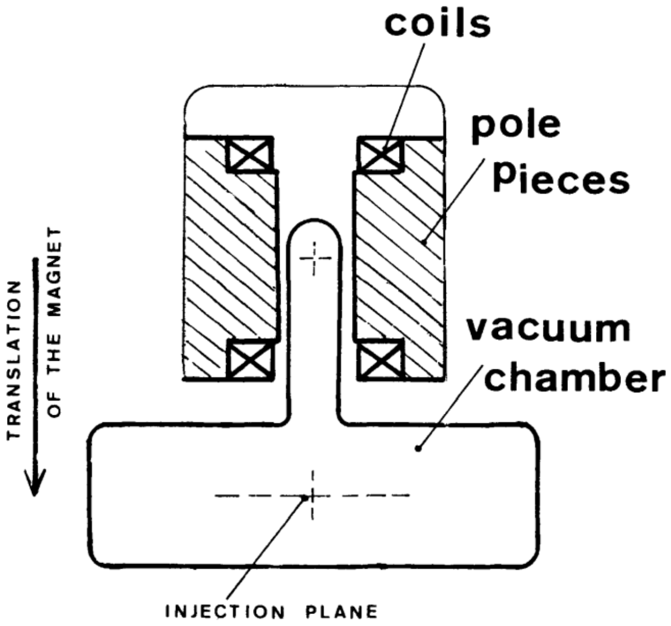


L R Elias et al 1976 *Phys. Rev. Lett.* 36(13) 717-20



FEL oscillator proposed by Stanford University

- The first planar undulators built in 1979 were superconducting with an inversed T-shape vacuum chamber, installed in the ACO storage ring in France, emitting ultra-violet radiation at beam energy 140-240 MeV.

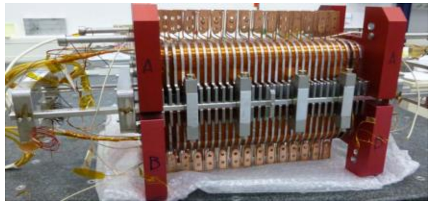


C Bazin et al 1980 *J. Physique - Letters* 41 547-50

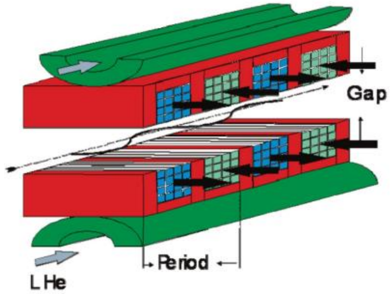
Transverse view of the planar SCU

Nb-Ti planar SCUs developed at KIT synchrotron

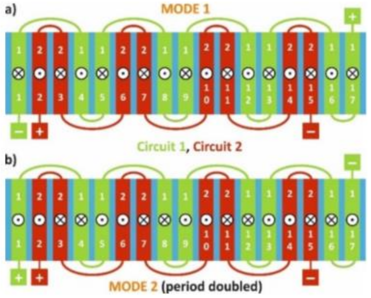
Year	Lab.	No. of periods	Period length	Magnetic gap	Vacuum gap	Undulator field B_0	
2003	KIT/ACCEL	10	14 mm	5 mm	-	1.33 T	Model
2006	KIT/ACCEL	100	14 mm	8	7.4	0.38 T	Device
2015	KIT/Noell	11.5	20 mm	8	-	0.93 T	Model
2016	KIT/Noell	100.5	15 mm	8	7	0.73 T	Device
2019	KIT/Noell	74.5	20 mm	8	7	1.18 T	Device
2019	KIT	24 or 12	17 mm or 34 mm	6	-	1.3 T or 2.3 T	model



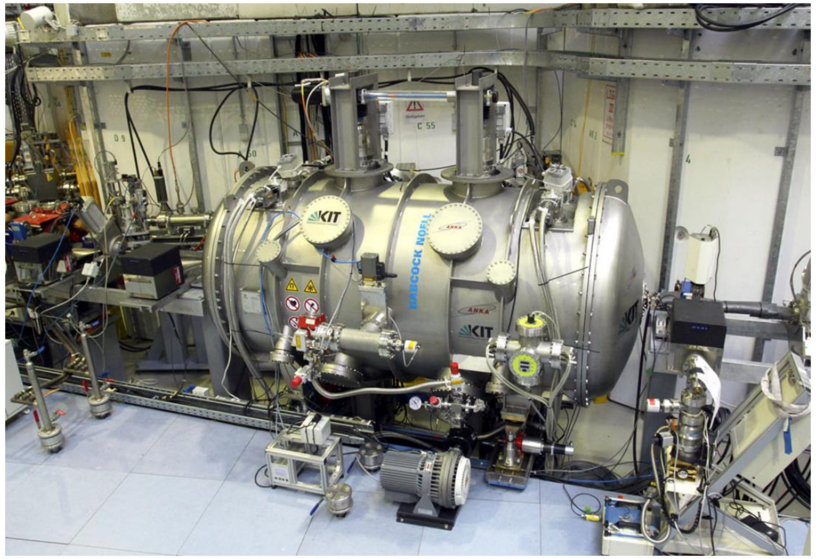
30 cm-long SCU20



1.5 m-long SCU14



SCU with switchable λu

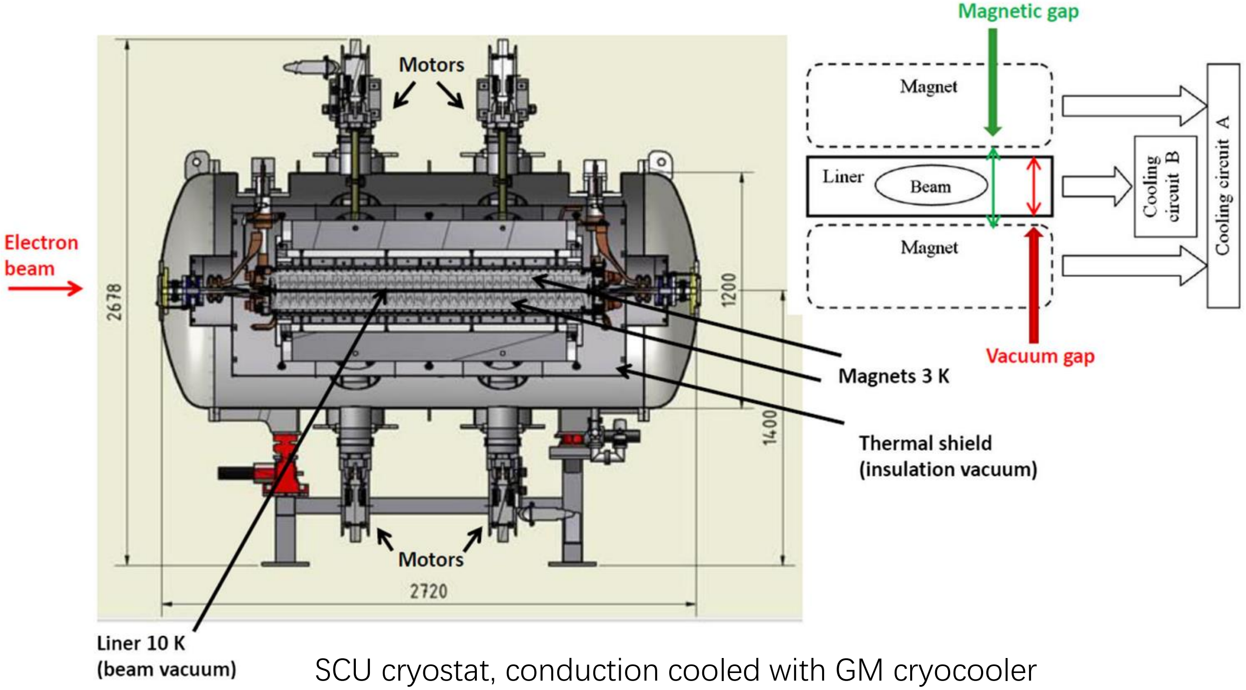


1.5 m-long SCU15, 2016

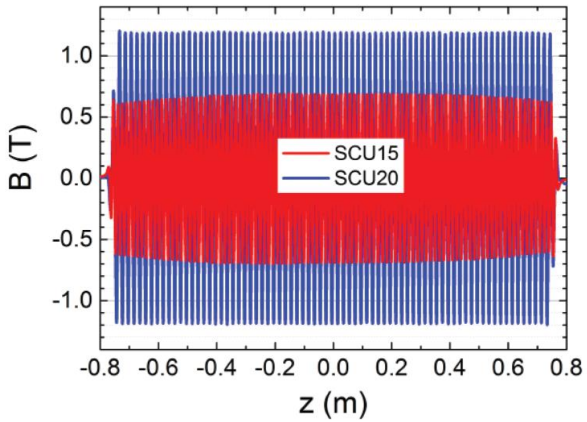
Casalbuoni S et al 2006 *Phys. Rev. ST Accel. Beams* 9 010702, Grau A et al 2016 *IEEE Trans. Appl. Supercond.* 26 4100804

Casalbuoni S et al 2019 *J. Phys.: Conf. Ser.* 1350 012024, Casalbuoni S et al 2016 *Phys. Rev. Accel. Beams* 19 110702

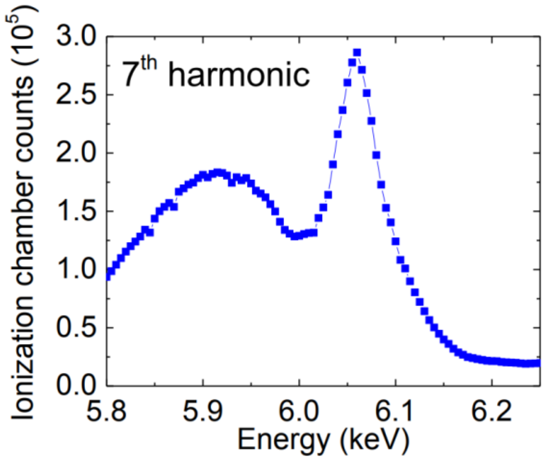
Nb-Ti planar SCUs developed at KIT synchrotron



SCU cryostat, conduction cooled with GM cryocooler



Magnetic field along z-axis



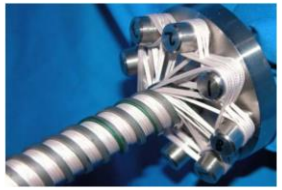
7^{th} harmonic of SCU20

- Liquid helium-free.
- Good thermal decouple between the vacuum chamber and SCU with merely 1 mm magnetic-mechanical gap difference.
- No quenches were observed during the operation of SCU15 and SCU20 in the storage ring of KIT synchrotron.
- The collaboration between KIT and Noell GmbH leads to a successful commercialization of SCUs.

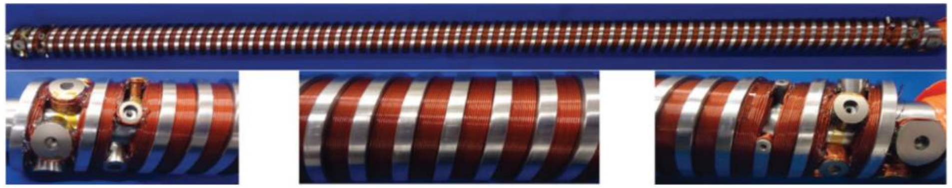
Casalbuoni S et al 2016 *Phys. Rev. Accel. Beams* 19 110702, Casalbuoni S et al 2018 *Synchrotron Radiation News* 31 24-28

SCUs developed at APS, ANL

Year	Type	No. of periods	Period length	Magnetic gap	Vacuum gap	Undulator field B_0	
2007	Nb_3Sn helical	17	14 mm	7.94 mm	-	0.9 T	Model
2013	Nb-Ti planar	20.5	16 mm	9.5 mm	7.2 mm	0.8 T	Device
2015	Nb-Ti planar	59.5	18 mm	9.5 mm	7.2 mm	0.98 T	Device
2017	ReBCO planar	5	16 mm	9.5 mm	-	0.2 T	Model
2018	Nb-Ti planar	70	21 mm	8 mm	-	1.67 T	Model
2018	Nb-Ti helical	38.5	31.5 mm	31 mm	8 mm	0.41 T	Device
2019	Nb-Ti SCAPE	15	30 mm	-	6 mm	0.6 T	Model
2021	Nb_3Sn planar	28.5	18 mm	9.5 mm	-	1.2 T	Model
2023	Nb_3Sn planar	61	18 mm	9.5 mm	7.2 mm	1.2 T	Device

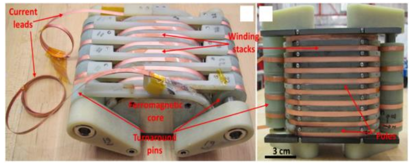


Nb_3Sn helical model

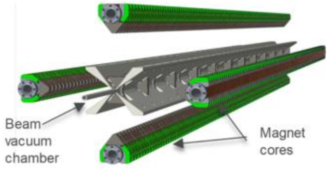


Nb-Ti helical SCU31.5 installed at APS

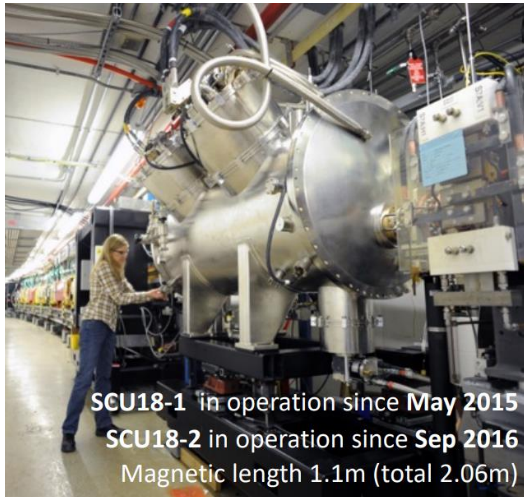
Nb_3Sn planar SCU18 model



Joint-free HTS planar model



SCAPE 3D design model



Kim S H et al 2007 *Proc. PAC2007 Conf.*, Albuquerque, USA 1136-38

Kesgin I et al 2021 *IEEE Trans. Appl. Supercond.* 31 4100205

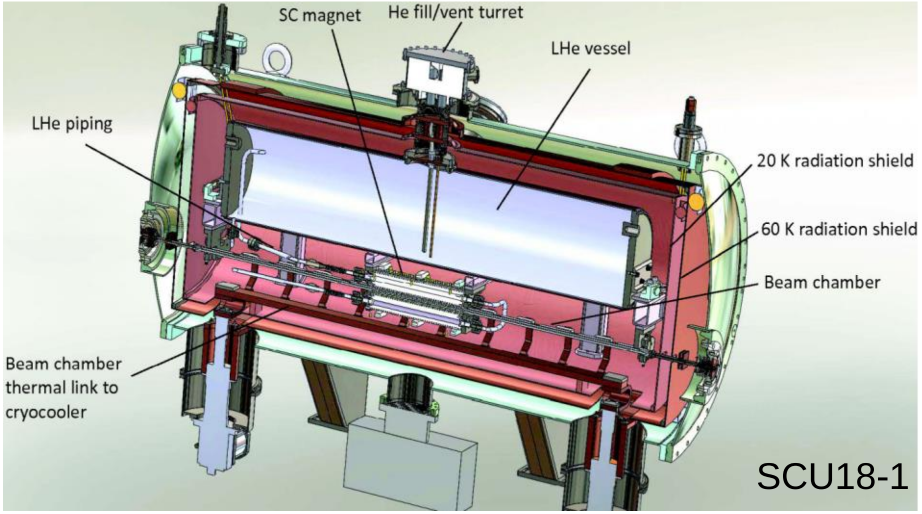
Kasa M et al 2020 *Phys. Rev. ST Accel. Beams* 23 050701

Kesgin I et al 2017 *Supercond. Sci. Technol.* 30 04LT01

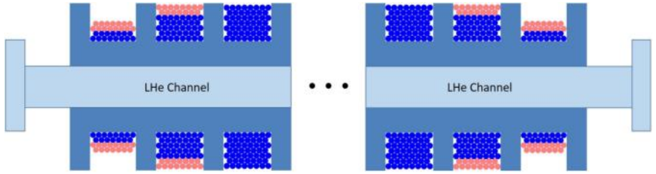
Ivanyushenkov Y et al 2017 *Proc. IPAC2017 Conf.*, Copenhagen, Denmark 1596-8

Ivanyushenkov Y 2017 *Phys. Rev. Accel. Beams* 20 100701

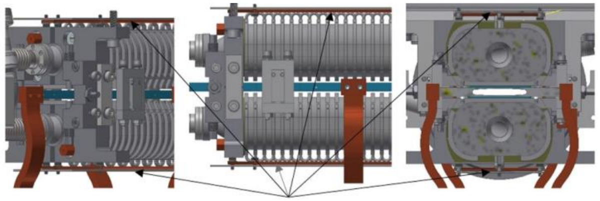
Nb-Ti planar SCUs developed at APS, ANL



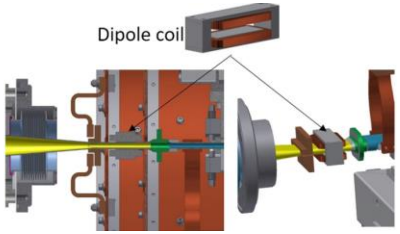
SCU cryostat at APS, indirectly cooled by LHe pipes



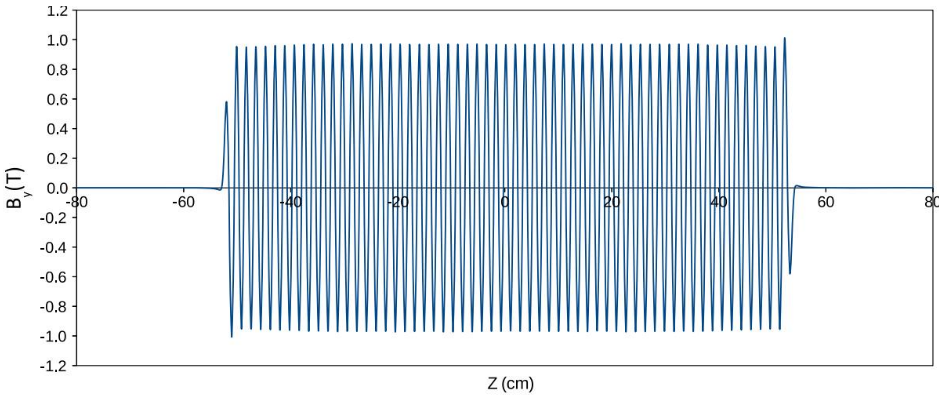
superconducting coil ends



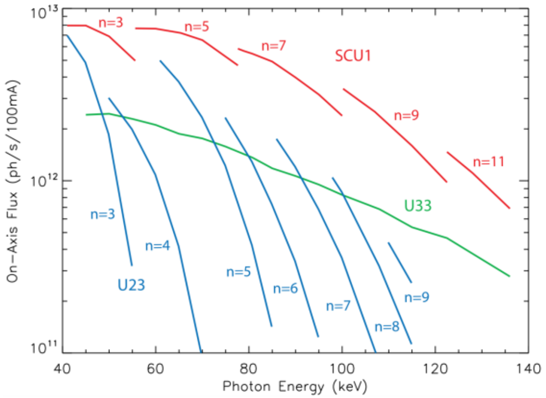
Helmholtz-like coil for correcting dipole field



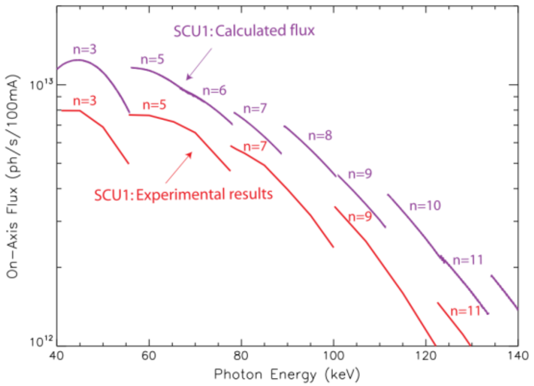
Dipole coils installed upstream and downstream of SCU



Magnetic field along the undulator length



Measured odd-harmonic tuning curves



Flux comparison

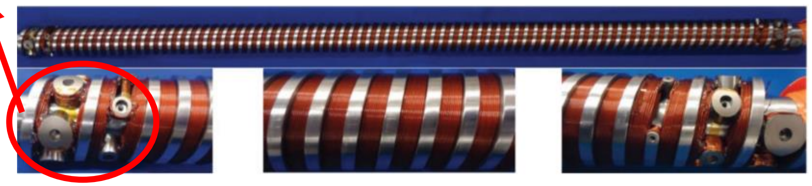
Ivanyushenkov Y et al 2015 *Phys. Rev. ST Accel. Beams* 18 040703, Ivanyushenkov Y 2017 *Phys. Rev. Accel. Beams* 20 100701

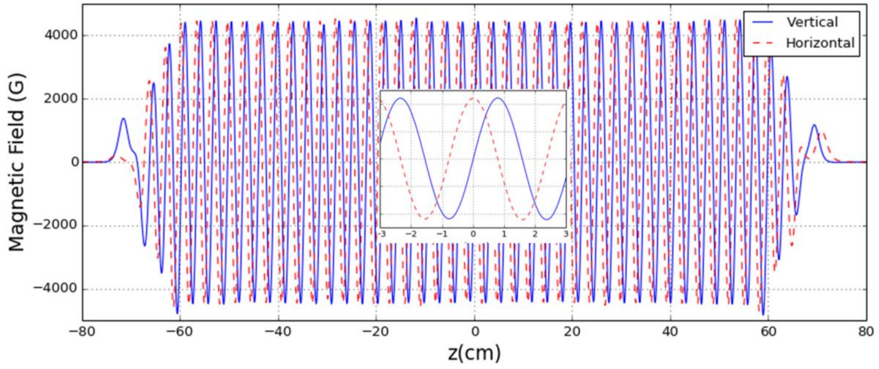
Nb-Ti helical SCUs developed at APS, ANL

- Period length: 31.5 mm
- Magnetic gap: 31 mm
- Vacuum gap: 8mm
- Undulator field: $B_x = B_y = 0.41$ T
- The first helical SCU served in the storage ring of synchrotrons
- Commissioned at APS, providing a single harmonic of about 6 keV X-rays

1.2 m-long helical SCU31.5 at APS, 2018

Continuous winding with turn around pins at the ends





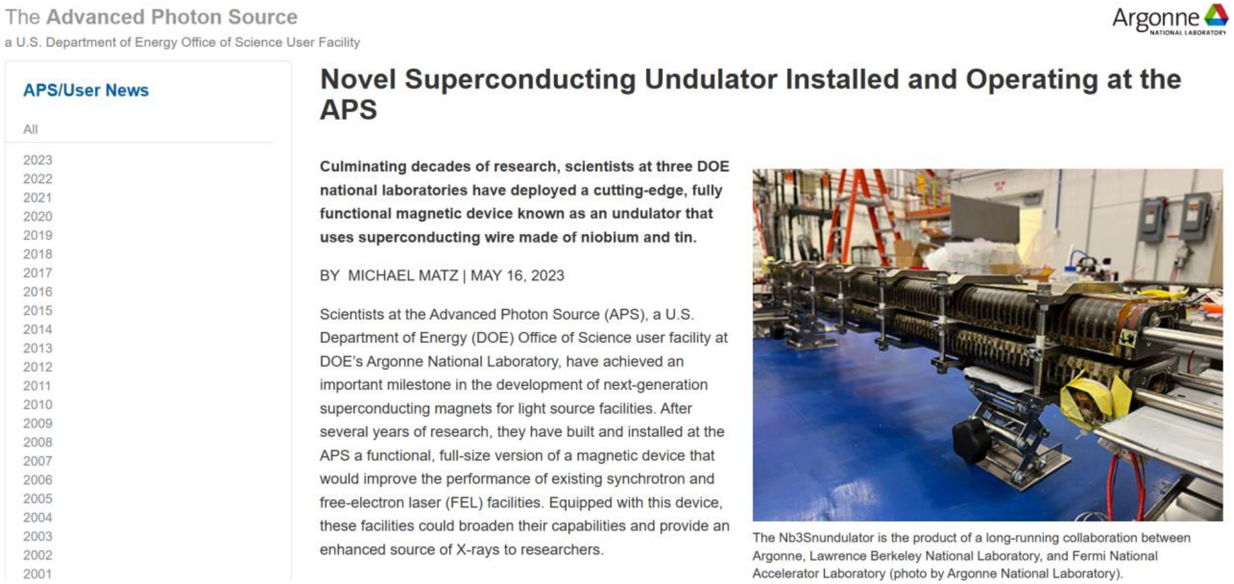
Magnetic field along the undulator length

M Kasa et al 2018 *Proc. IPAC2018 Conf.* Vancouver, Canada TUPMF008

Nb_3Sn planar SCUs developed at APS, ANL

R&D project in collaboration with FNAL and LBNL

- **Goal:** develop, build and install on the APS ring a Nb_3Sn undulator in a modified SCU0 cryostat a year before the APS-U 'dark time' starts
- **Technical route:** 84 mm-long Nb_3Sn SCU models → 0.5 m-long Nb_3Sn SCU models → 1.1 m-long Nb_3Sn SCU → Undulator assembly, test and installation in the APS ring



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APS/User News

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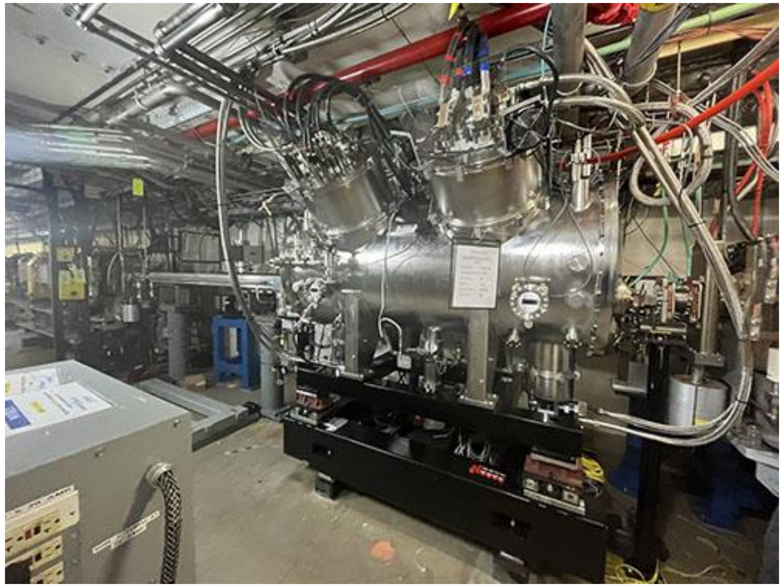
Novel Superconducting Undulator Installed and Operating at the APS

Culminating decades of research, scientists at three DOE national laboratories have deployed a cutting-edge, fully functional magnetic device known as an undulator that uses superconducting wire made of niobium and tin.

BY MICHAEL MATZ | MAY 16, 2023

Scientists at the Advanced Photon Source (APS), a U.S. Department of Energy (DOE) Office of Science user facility at DOE's Argonne National Laboratory, have achieved an important milestone in the development of next-generation superconducting magnets for light source facilities. After several years of research, they have built and installed at the APS a functional, full-size version of a magnetic device that would improve the performance of existing synchrotron and free-electron laser (FEL) facilities. Equipped with this device, these facilities could broaden their capabilities and provide an enhanced source of X-rays to researchers.

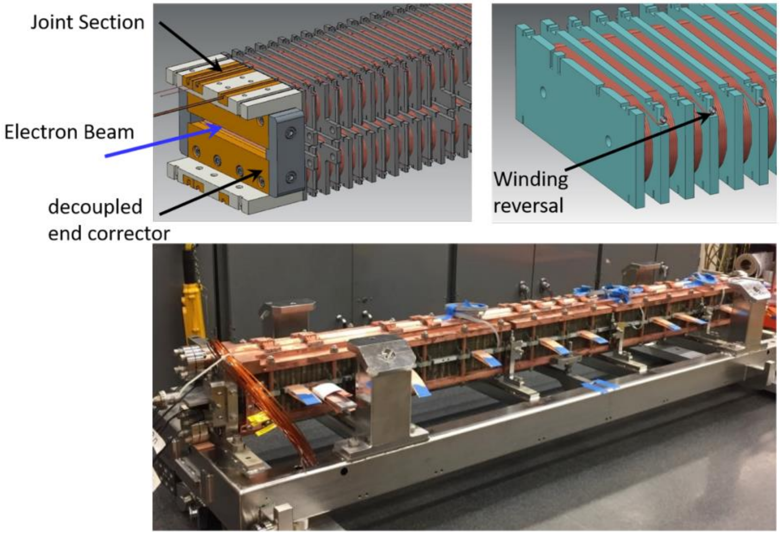
The Nb3Snundulator is the product of a long-running collaboration between Argonne, Lawrence Berkeley National Laboratory, and Fermi National Accelerator Laboratory (photo by Argonne National Laboratory).



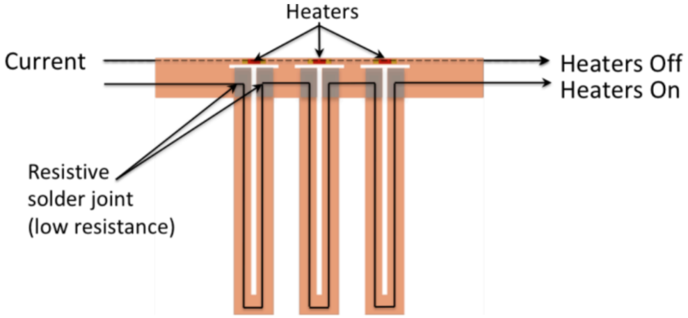
ANL news, May 2023, Commissioning of the first 1.1 m-long Nb_3Sn undulator at APS ring

For more details, please find from https://www.aps.anl.gov/APS-News/2023-05-16/novel-superconducting-undulator-installed-and-operating-at-the-aps/2023-05-16

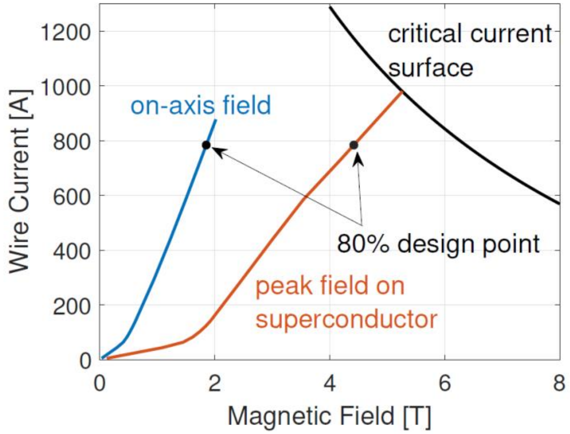
Nb_3Sn planar SCUs developed at LBNL



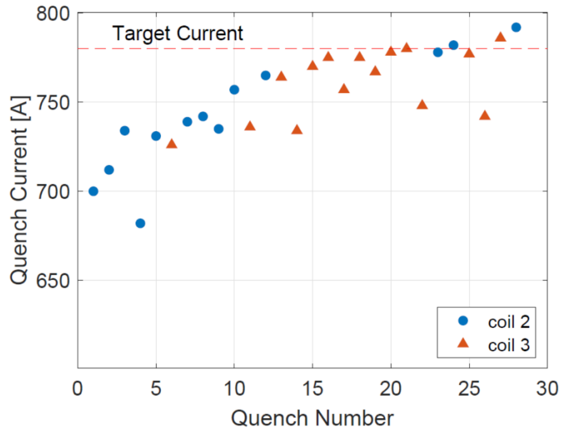
Magnet assembly with two undulator coils. 2018
(1.5 m long, 19 mm period, 8 mm magnetic gap, B_0=1.83 T)



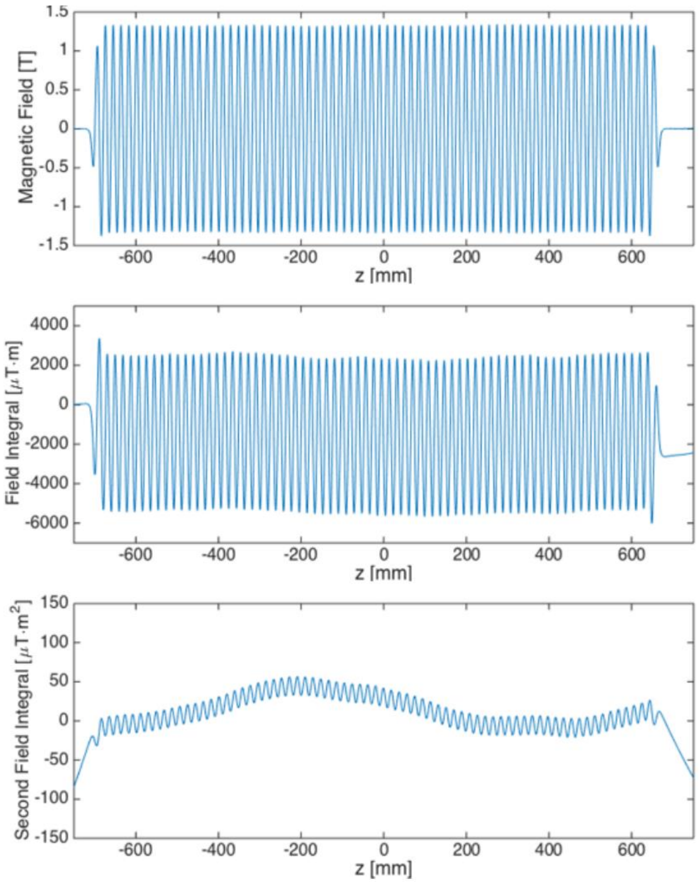
Novel field correction using YBCO current loops



SCU load line



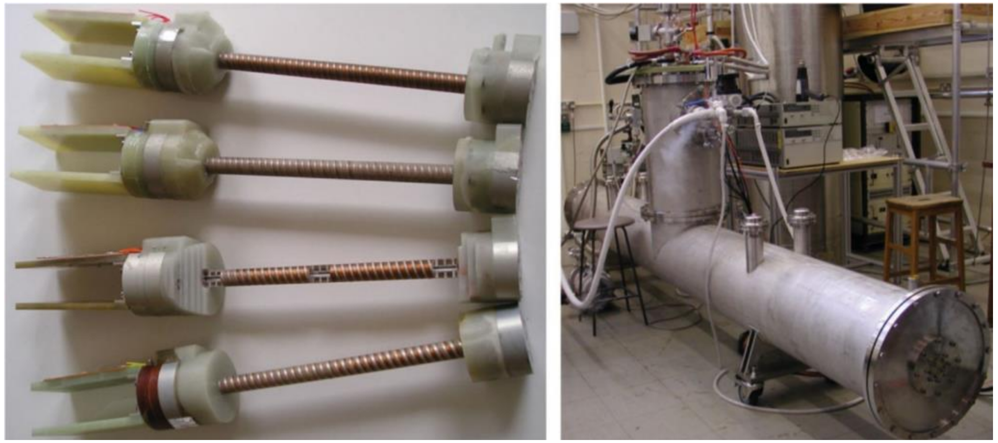
SCU training quenches



Magnetic field measurement at 500 A at ANL.
RMS Phase error < 5.4° after shimming

Arbelaez D et al 2018 *Synchrotron Radiat. News* 31 9-13, Beam dynamics newsletter 2019 78

Nb-Ti helical SCUs developed at STFC



Nb-Ti helical undulators developed at STFC. Left: short models; Right: 4 m-long device including two 1.74 m-long undulators

Continuous winding with return-peg design

Table Two 1.74 m-long Nb-Ti helical coils

Parameter	Magnet 1	Magnet 2
Field at 215 A (T)	0.88	0.89
RMS of Peak Field (T)	0.014	0.013
Period (mm)	11.48	11.46
RMS of Period (mm)	0.018	0.027
Maximum Field Achieved (T)	1.13	1.13
Maximum Current Achieved (A)	301	306

Since 2005, a series of Nb-Ti helical SCU models had been constructed and tested for the demonstration of being used in the International Linear Collider (ILC) for producing polarized positrons with circularly polarized γ-ray sources in excess of 10 MeV.

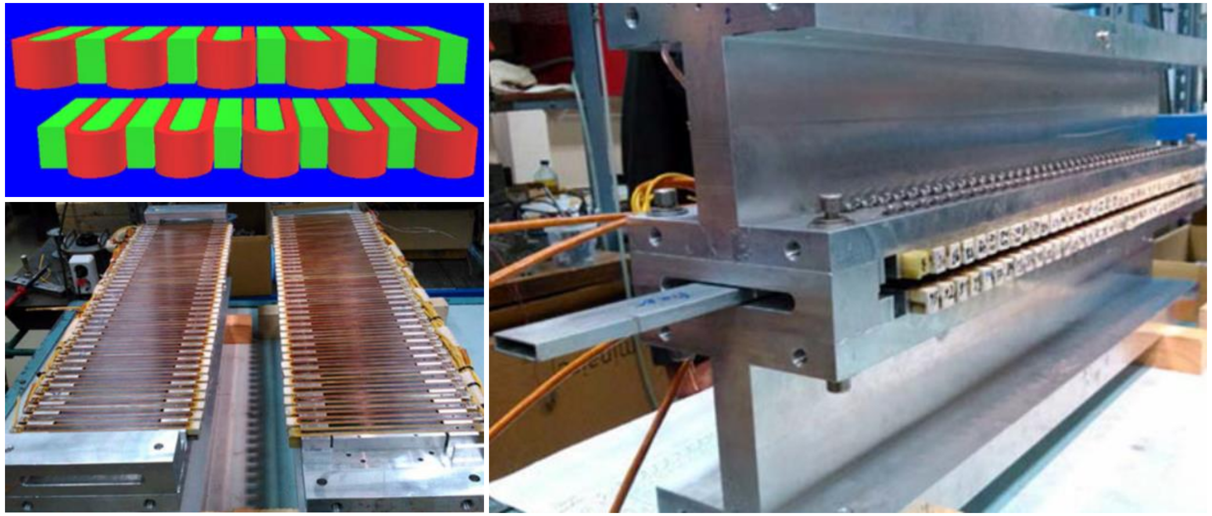
In 2008, Clarke et al reported the construction of a full scale SCU module for ILC and demonstrated that both two 1.74-m long helical SCU11.5 prototypes could reach a stable on-axis field B_0 of 0.86 T after training quenches (B_m~1.13 T).

In 2011, Scott et al experimentally demonstrated that a full-scale 4-m long working helical SCU module was suitable for future TeV-scale linear positron sources.

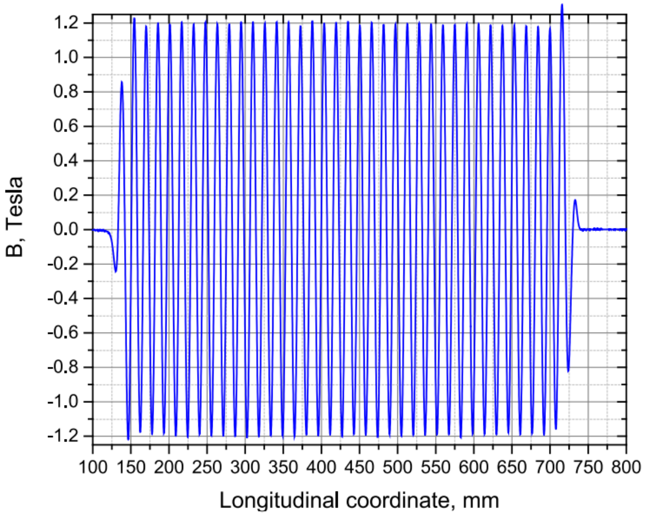
Clarke J A et al 2008 *Proc. EPAC2008 Conf.*, Genoa, Italy 709-11, Scott D J et al 2011 *Phys. Rev. Lett.* 107 174803

Nb-Ti planar SCUs developed at BINP

Year	No. of periods	Period length	Magnetic gap	Vacuum gap	Undulator field B_0	
2016	15	15.6 mm	8 mm	-	1.2 T	Model
2018	40	15.6 mm	8 mm	-	1.2 T	Model
2021	119	15.6 mm	8 mm	-	1.2 T	Model



Superconducting undulator coils with neutral poles



Magnetic field along a 40-period undulator. RMS phase error < 4° without shimming

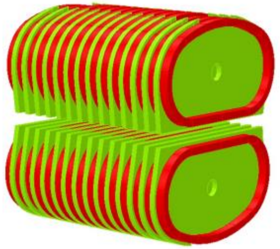
Bragin A et al 2018 *IEEE Trans. Appl. Supercond.* 28 4101904

Nb-Ti planar SCUs developed at SSRF

R&D project at SSRF started from 2013

- A 5-period SCU16 model was fabricated in 2016, obtaining B_0 = 0.93 T at 8 mm magnetic gap
- In 2021 a 50-period SCU16 device was successfully developed and tested in the SSRF storage ring, obtaining a stable on-axis field B_0 = 0.62 T at 7.5-mm vacuum gap (10-mm magnetic gap)
- No quenches occurred at the beam current of 200 mA
- The 50-period SCU16 device was later taken out from SSRF storage ring

Period Length	16 mm
Period Number	50
Magnetic Gap	9.5 mm
Peak Fields	0.67 T
SC Wire	NbTi/Cu, ϕ0.6
Current	400 A
Length of cryostat	1.8 m



SCU coil assembly

Shanghai Synchrotron Radiation Facility (SSRF)

SCU installed in SSRF storage ring

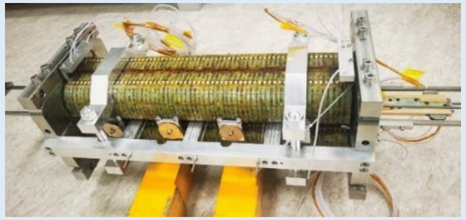
Zhang Z et al 2014 *IEEE Trans. Appl. Supercond.* 24 4101503, Xu J et al 2016 *AIP Conference Proceedings* 1741 020027

Xu Jet al 2017 *IEEE Trans. Appl. Supercond.* 27 4100304, CAS research news 2021 https://www.cas.cn/syky/202111/t20211115_4814175.shtml

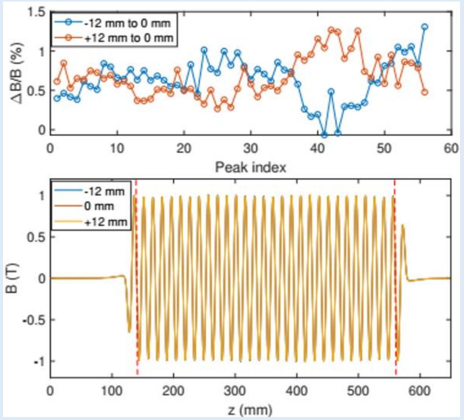
Nb-Ti planar SCUs developed at IHEP, CAS

R&D project at IHEP started in 2019

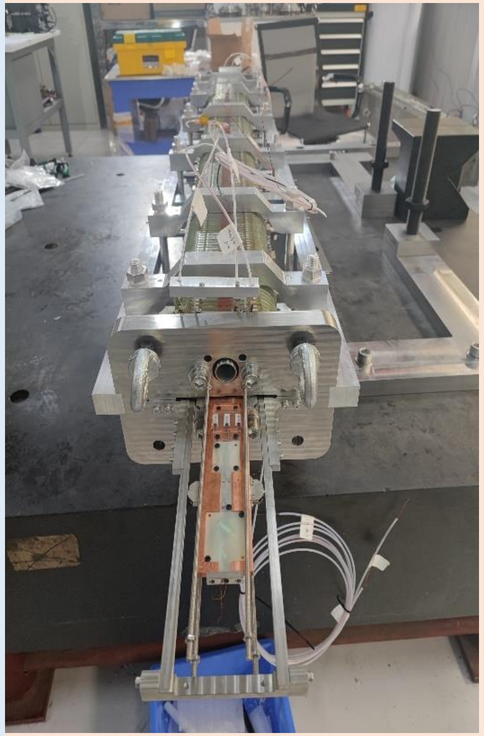
- In 2021 a 0.5 m-long SCU15 model was developed and tested, obtaining B_0 = 1.01 T at 7 mm magnetic gap and RMS phase error between 4º and 10º at I_{op} = 100 ~ 400 A
- In 2023 a 1.5 m-long SCU15 model was developed and tested, obtaining B_0 > 0.5 T at 9.5-mm magnetic gap. By adjusting pole heights, the RMS phase error was reduced from 16º@350 A to 6.4º@300 A



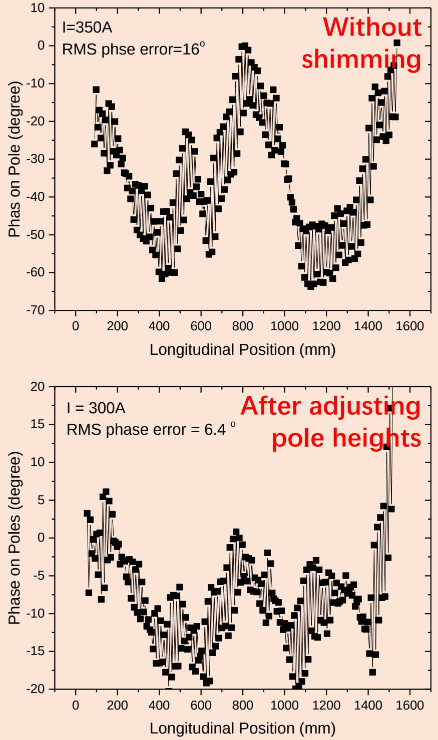
0.5 m-long SCU15 coil assembly



Measured magnetic field



1.5 m-long SCU15 coil assembly



Measured phase errors

Wei J et al 2022 *J. Synchrotron Rad.* 29, 997–1003, Chen Z et al 2022 *NIMA* 1047 167826, Chen Z et al 2022 *J. Inst.* 2022 17 T09008

Overview

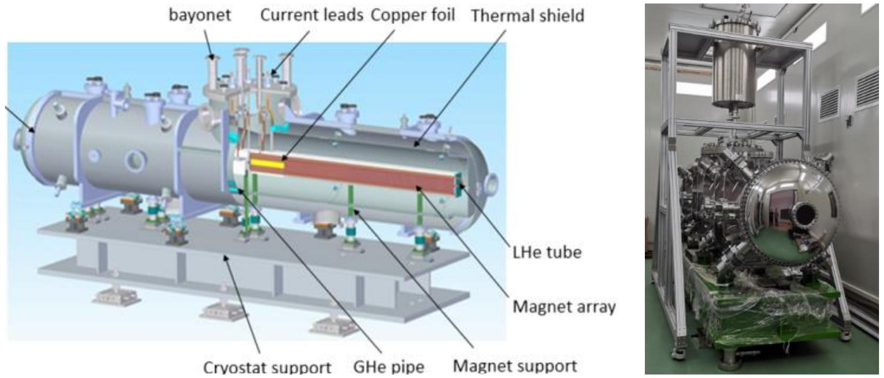
- Introduction to synchrotrons and FELs
- Why superconducting undulator (SCU)?
- Overview of SCU technique development and applications
- Ongoing SCU R&D activities
- HTS materials – opportunities and challenges
- Conclusions and outlooks

SCU R&D at SSRF –
4 m-long Nb-Ti planar SCU16 for SHINE

SCU R&D for SHINE started in 2018

- **SCU prototype demonstration.** To develop a 4 m-long in-vacuum SCU16 prototype with 5 mm-pole gap and 4 mm-beam gap, obtaining B_0 = 1.58 T at the designed operation current. The cryostat and SCU coil assembly are cooled by GHe and LHe pipes connected to the cryogenic plant.
- **Magnetic field measurement.** To measure the on-axis magnetic field with the Hall probe scanning and the pulsed wire magnetic field measurement system.
- **Field correction.** To minimize the phase error, two middle periods are designed as a “phase shifter”. The end coils are used to correct the first and second field integrals. Five power supplies will be used, two for the end coils, and three for the main coils including one for the “phase shifter”.
- **Series production.** To fabricate 40 SCU devices for the installation at FEL-III beamline for SHINE. The undulator field needs to be adjustable between 0.68 and 1.58 T for generating 10-25 keV photons with vertical polarization.

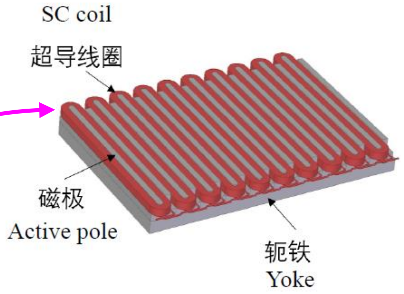
Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE)



SHINE superconducting undulator cryostat

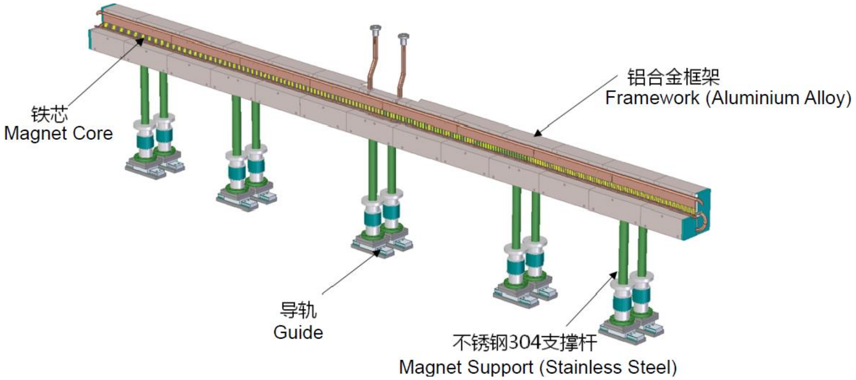
Tang Q et al 2020 *IEEE Trans. Appl. Supercond.* 30 4100104
Zhou Q and Mezentsev N 2021 R&D of SC Undulators in Asia/Russia, *Virtual Superconducting Undulators for Advanced Light Sources Workshop* Mon. 19/04

SCU R&D at SSRF –
4 m-long Nb-Ti planar SCU16 for SHINE

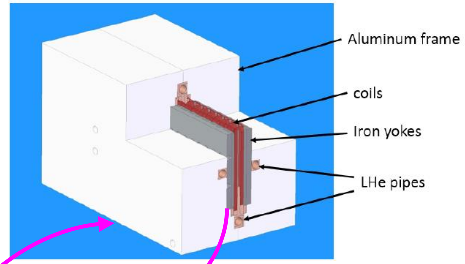


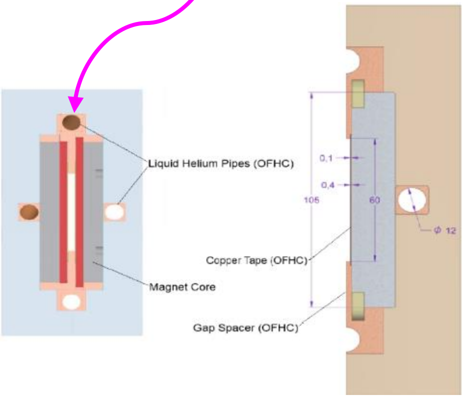
Two 4 m-long SC coil assemblies

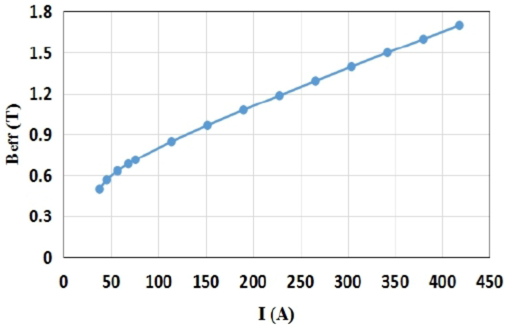
- Each assembly has 505 horizontal racetrack coils and 505 active poles
- 8-10 coils are wound with single wire, ~50 joints in one SC coil assembly



Magnet support structure, each magnet yoke is divided into 4 sections



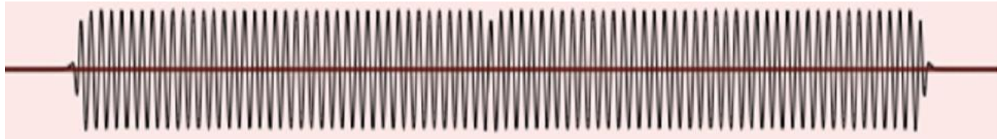




Undulator field vs. current

SC coils are indirectly cooled by 4 LHe copper pipes.

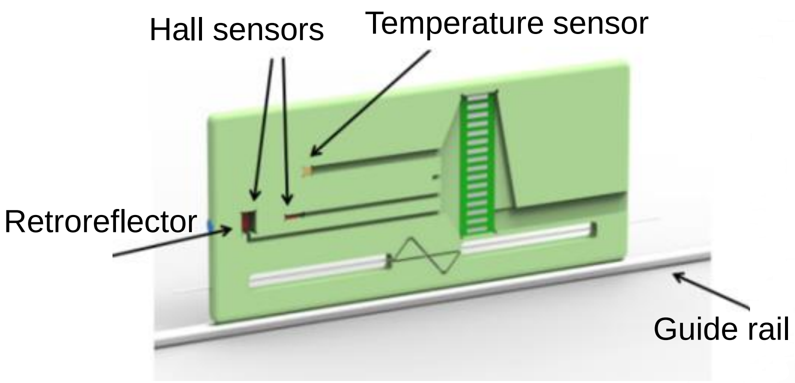
The beam heat load ~10 W is absorbed by 100 um thick copper tape which is connected to LHe pipes



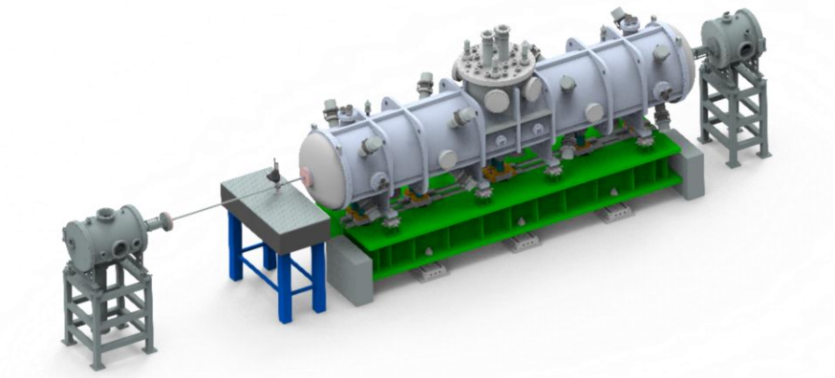
To minimize the Phase error, two middle periods are designed as a "phase shifter"

Zhou Q and Mezentsev N 2021 R&D of SC Undulators in Asia/Russia Virtual Superconducting Undulators for Advanced Light Sources Workshop Mon. 19/04

SCU R&D at SSRF –
4 m-long Nb-Ti planar SCU16 for SHINE



Hall probe sledge based scanning measurement



Pulse-wire magnetic field measurement system

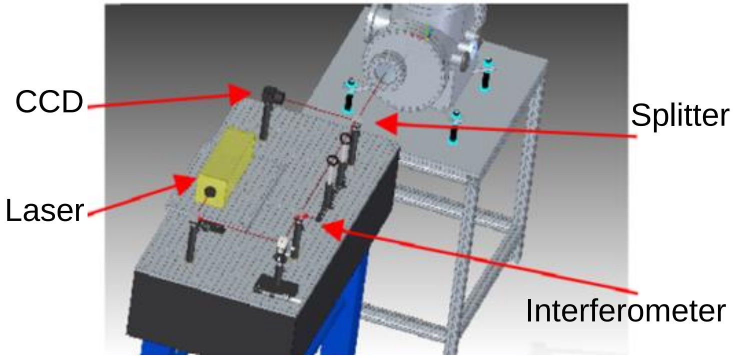
Method 1: Partial difference equations

$$\mu\frac{\partial^2 u}{\partial t^2} - T\frac{\partial^2 u}{\partial x^2} + EI_w\frac{\partial^4 u}{\partial x^4} = 0$$

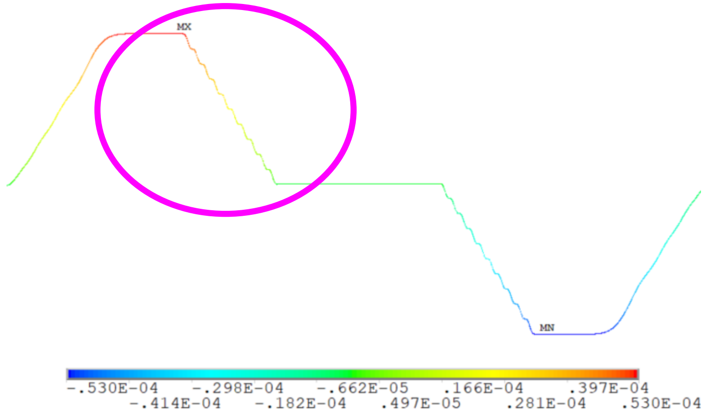
Method 2: FEM – solving the multi-physics coupled mechanical impact dynamics

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\}$$

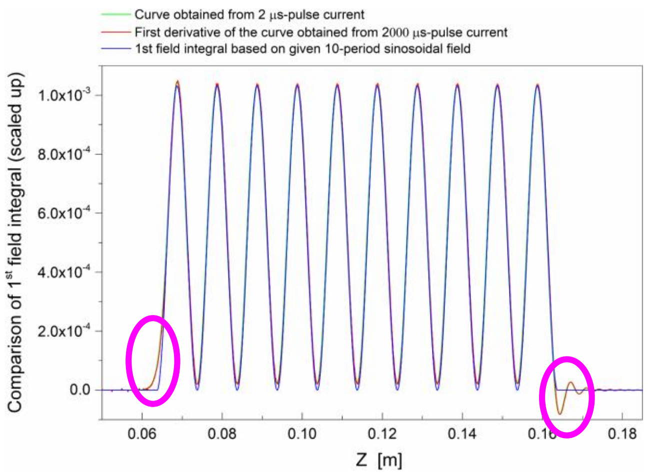
Mass Damping Stiffness



The interferometer can offer the probe's displacement in z-direction. The Splitter and CCD can offer the probe's displacement in x or y-direction.



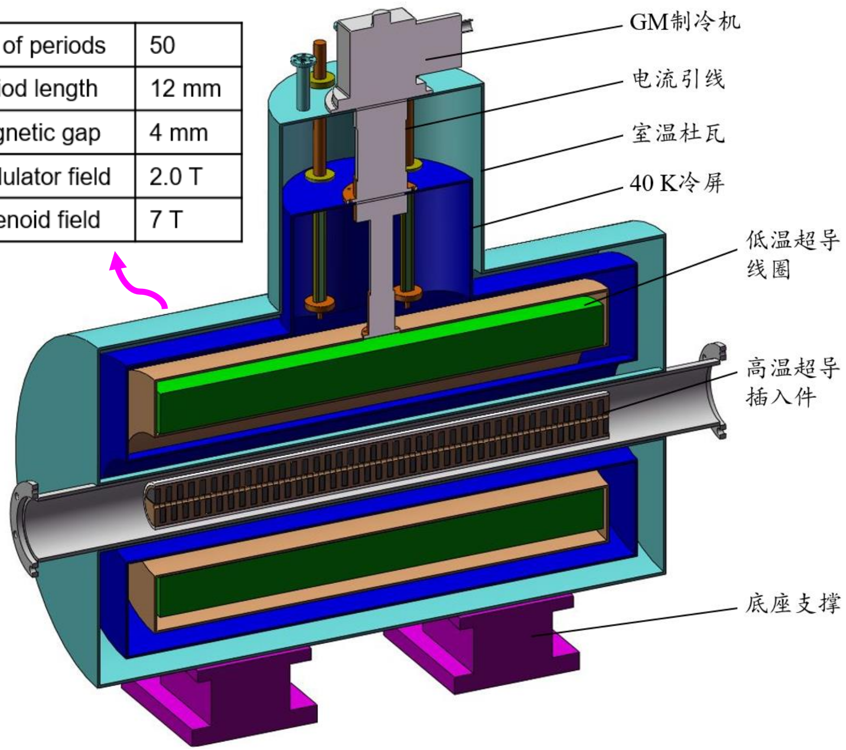
2 ms-pulse current gives the 2nd field integral information (multi-physics simulation with ANSYS APDL codes to understand the sag, temperature gradient and dispersion effects)



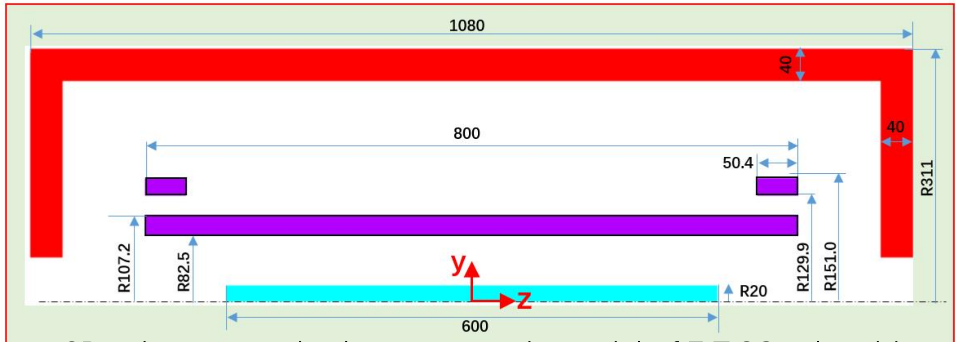
Comparison of simulated 1st field integral with APDL codes

SCU R&D at SSRF –
0.6 m-long bulk HTSU12 prototype

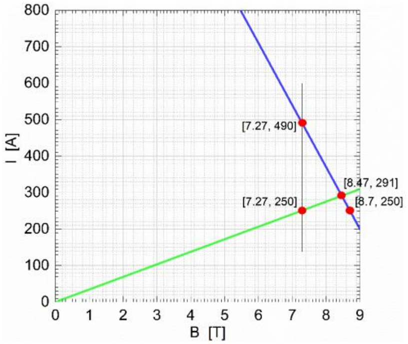
No. of periods	50
Period length	12 mm
Magnetic gap	4 mm
Undulator field	2.0 T
Solenoid field	7 T



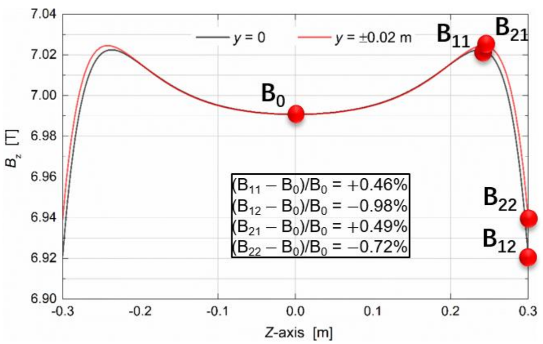
Conceptual design of a HTSU12 prototype



2D axis-symmetric electromagnetic model of 7 T SC solenoid



SC solenoid load line



Solenoidal field B_z along the axis

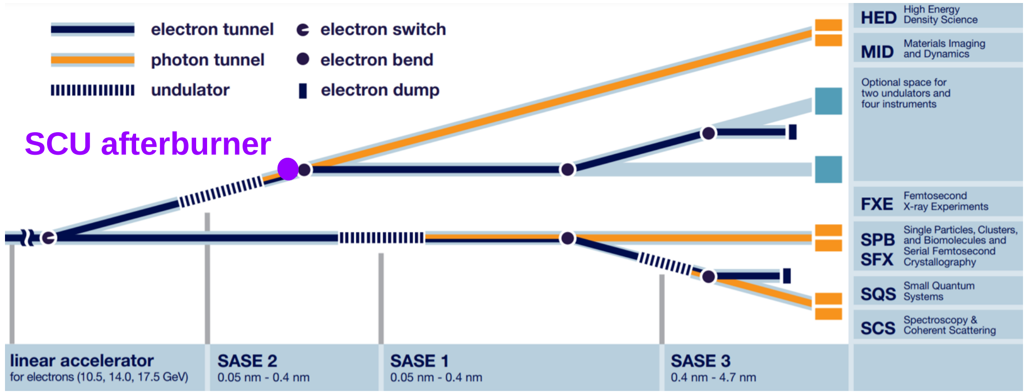
- The HTSU12 prototype consists of a 7 T SC solenoid and 100 pieces of staggered-array ReBCO bulk superconductors.
- The 7 T SC solenoid provides a homogeneous magnetic field within Φ40 mm × 600 mm.
- This novel HTS undulator technology is considered as a candidate option for future beamlines at SHINE.
- More details about the staggered-array bulk HTS undulator will be presented later …

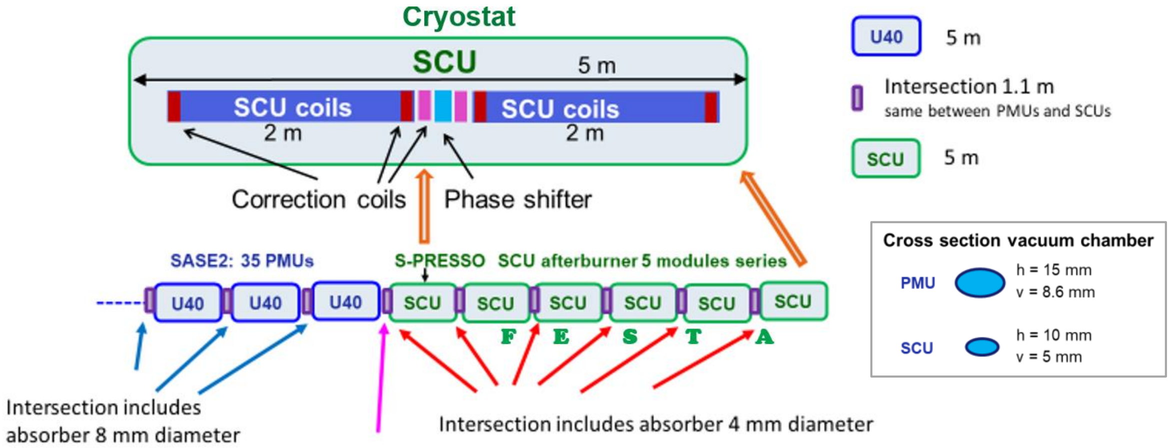
张江实验室
ZHANGJIANG LABORATORY

SCU R&D at EuXFEL – SASE2 SCU Afterburner

CEC ICMC 23 HONOLULU JULY 9-13

- The CW operation mode upgrade under consideration at the EuXFEL limits the electron beam energy to 7-8 GeV. EuXFEL plans to develop the technology of SCUs as part of its facility development program.
- SCU afterburner for SASE2 undulator line will
  - allow lasing at photon energies 30-60 keV
  - benefit EuXFEL strategic plans
    - Enabling lasing at photon energies up to 60 keV, fully exploiting the capability of the FEL linac with 17.5 GeV LINAC
    - a SASE SCU line with λu = 18 mm would allow to cover the same photon energy range from 3.1 to 24.8 keV with 8 GeV LINAC as provided now by the installed PMUs with 17.5 GeV LINAC





Only this intersection includes RF valve increasing by few cm the length of the intersection

Casalbuoni S et al 2022 *J. Phys.: Conf. Ser.* 2830 012012

Casalbuoni S 20.02.2023, Fermilab, Batavia, IL

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

S-PRESSO: **S**uperconducting undulator **PRE-S**erie**S** m**O**dule

FESTA: Free Electron Laser Superconducting Afterburner

SCU R&D at EuXFEL –
SASE2 SCU Afterburner

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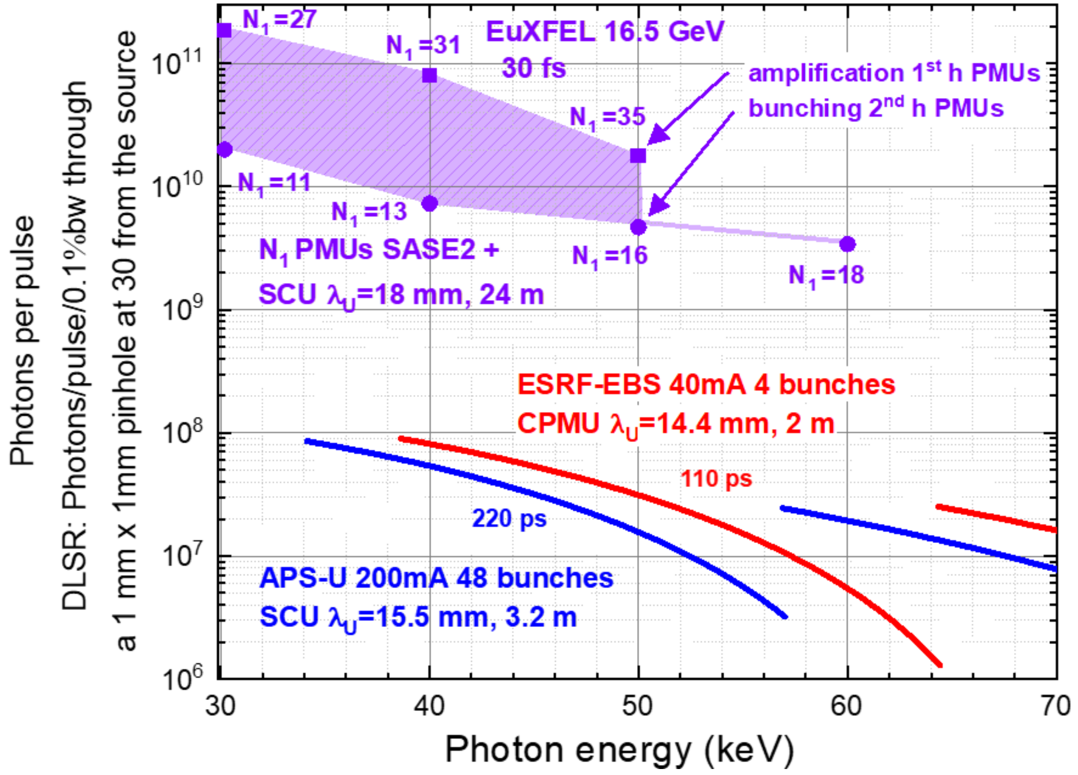
ZHANGJIANG LABORATORY

CEC ICMC 23 HONOLULU JULY 9-13



The number of photons per pulse are calculated using GENESIS 1.3v2 and compared to the ones calculated using SPECTRA from typical short period undulators at the ESRF-EBS and APS-U through a pinhole of 1 mm × 1 mm at 30 m from the source

Energy	16.5 GeV
Normalized emittance	0.4 mm mrad
Initial energy spread	3 MeV
Current	5 kA
Bunch length	30 fs

- Estimated range of photons per pulse achievable by tuning the SCU afterburner on the fundamental
  - amplifying the output of the fundamental of the PMUs
  - using the bunching of the second harmonic of the PMUs
- More detailed studies considering wake-fields, tapering, ‘real’ bunch distribution and optimized electron bunch properties are ongoing

Casalbuoni S et al 2022 *J. Phys.: Conf. Ser.* 2830 012012

张江实验室
ZHANGJIANG LABORATORY

SCU R&D at EuXFEL – Superconducting undulator PRE-SerieS mOdule

CEC ICMC 23 HONOLULU JULY 9-13

- **S-PRESSO: S**uperconducting undulator **PRE**-**S**erie**S** m**O**dule, has been specified, the contract has been assigned to Bilfinger Noell GmbH, and TDR received.
- The cooling scheme of **S-PRESSO** and of the afterburner modules will be based on cryocoolers as from the KIT/Noell design.
- Aims of **S-PRESSO** are to test
  - the alignment of the two 2 m long SCU coils in the 5 m long cryostat
  - the mechanical tolerances necessary for the FEL process
  - the implementation of the module in the accelerator
- **S-PRESSO** will be used to further amplify the fundamental produced by the PMUs of SASE2 in the hardest X-ray part of the spectrum which they can generate. In this configuration it will be possible to measure the contribution of the SCUs to the FEL amplification process at specific photon energies. Moreover, harmonic configuration tests at larger photon energies are planned.

S PRESSO
SUPERCONDUCTING UNDULATOR PRE-SERIES MODULE

Period	18 mm
Peak field	1.82 T
K	3.06
Vacuum gap	5 mm
First field int. (x,y)	< 0.004 T mm
Second field int. (x,y)	< 100 T mm^2
$\Delta K/K$ rms	<0.0015
Roll off at ± 2 mm	$< 5 \times 10^{-5}$
Beam heat load	10 W
Pressure beam vacuum chamber at room temperature	$< 10^{-7}$ mbar

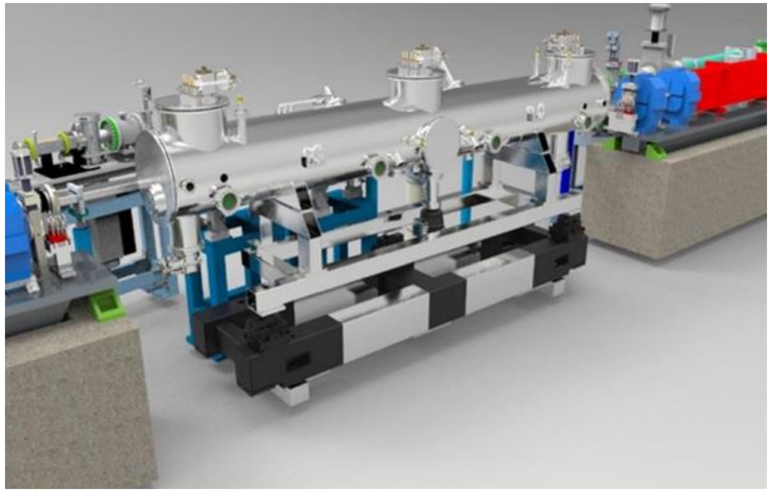
Casalbuoni S et al 2022 *J. Phys.: Conf. Ser.* 2830 012012

SCU R&D at ANL –
SCUs for APS upgrade

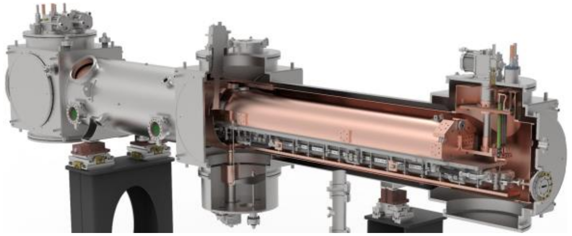
SCU R&D for APS-U started in 2019

- The new Nb-Ti planar SCU device for APS-U employs a 4.8 m-long cryostat for the installation of two SC coil assemblies (2×1.9 m, …)
- Two SCU devices are with "in-line" configuration in which two SC coil assemblies behave as one radiation source
- Two SCU devices are with "canted" configuration in which two SC coil assemblies are operated independently

Location	Configuration	Upstream device	Downstream device
01-ID	Dual Inline in Long Cryostat	SCU 1.65	SCU 1.65
11-ID	Canted in Long Cryostat	SCU 1.65	SCU 1.65
20-ID	Dual Inline in Long Cryostat	SCU 1.65	SCU 1.65
28-ID	Canted in Long Cryostat	SCU 1.85	SCU 1.85

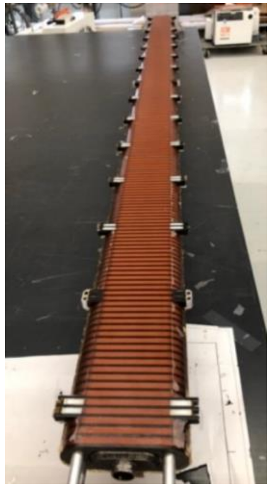


3D sketch of APS-U ID straight section with SCU installation

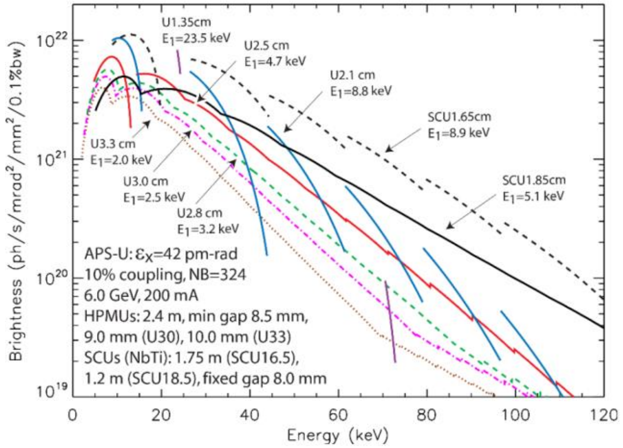


4.8-meter long SCU cryostat, 20" diameter vacuum vessel

3D Model of the planar SCU assembly



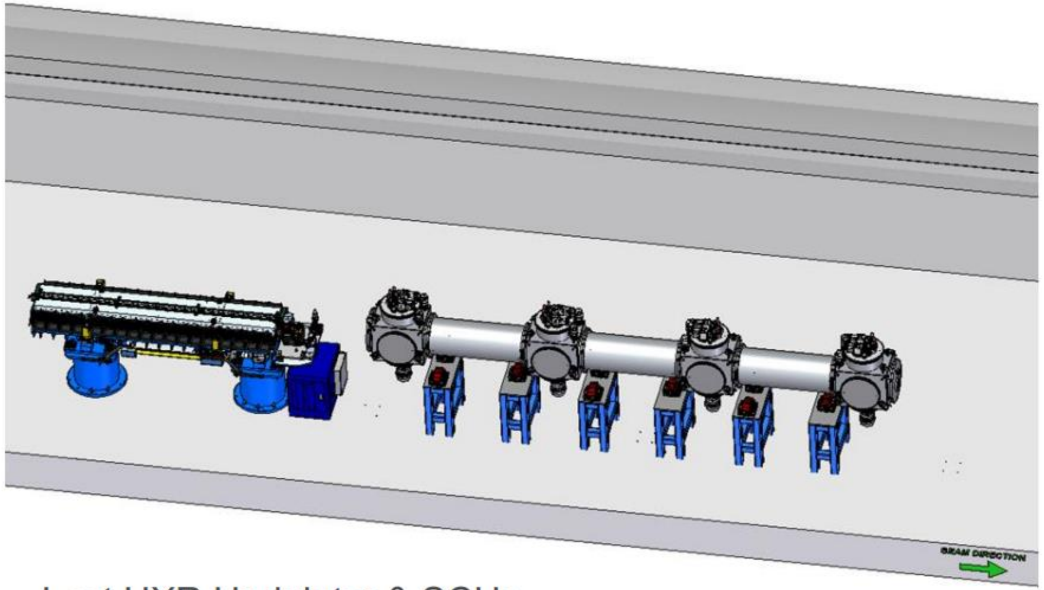
1.9 m-long SC coil



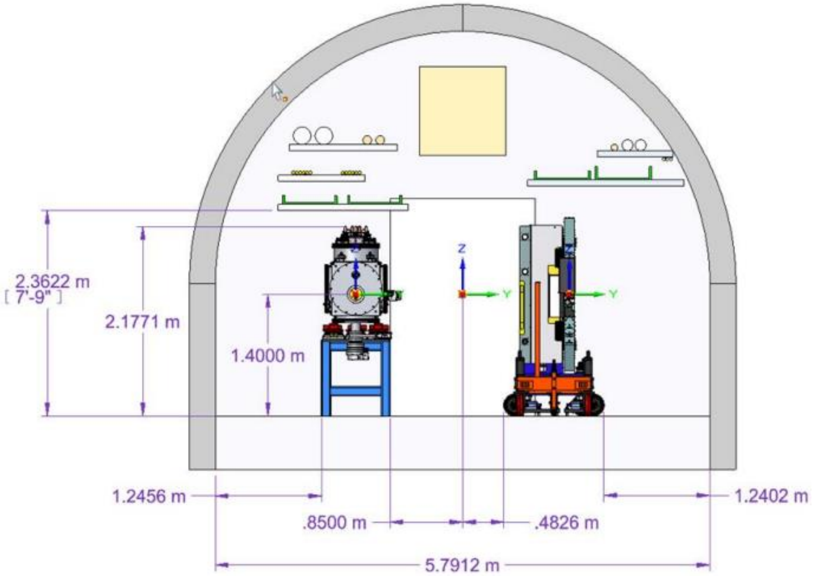
Comparison of calculated brightness tuning curves between PMUs and SCUs for APS-U

Kasa M et al 2019 *IPAC* TUPRB095, Ivanyushenkov Y *Superconducting Undulators for Advanced Light Sources Virtual Workshop*, April 19-21, 2021

SLAC and ANL propose to test SCU FEL performance at LCLS. Nb-Ti planar SCUs will be installed at the Hard X-ray Undulator beamline and operated as an Afterburner to test alignment and to measure FEL gain.



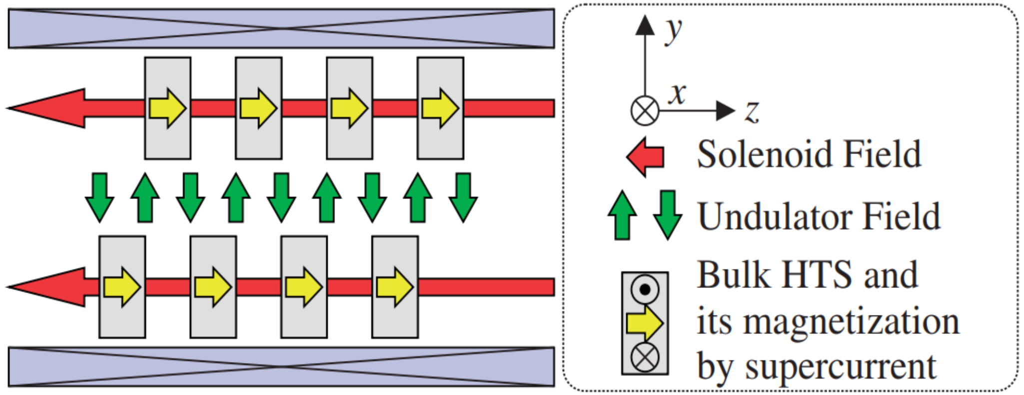
Last HXR Undulator & SCUs



Undulator Hall cross-section

Ivanyushenkov Y, *Superconducting Undulators for Advanced Light Sources Virtual Workshop*, April 19-21, 2021

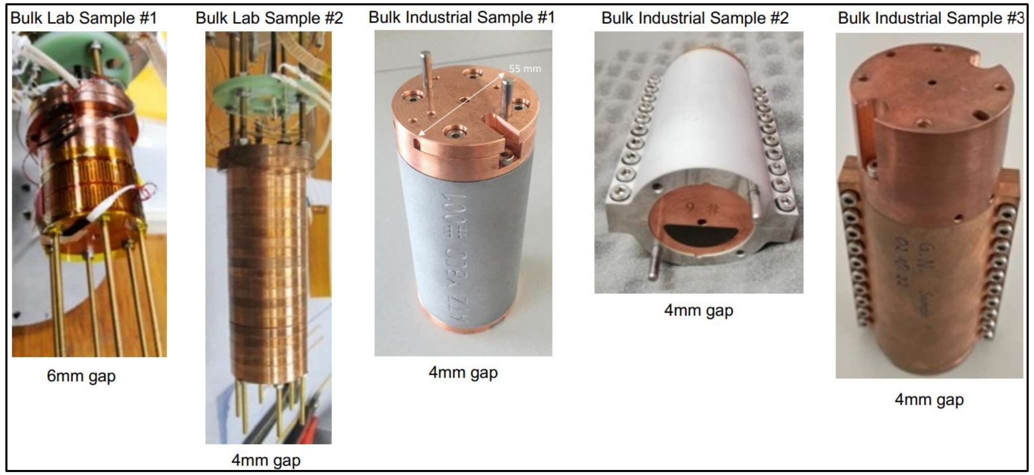
SCU R&D at PSI –
Short bulk HTSU models

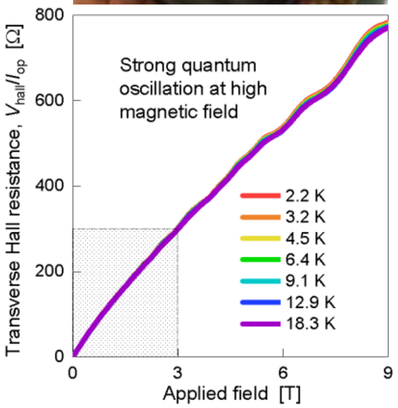


T Kii, et al 2006 *Proc. FEL2006 Conf.*, Berlin, Germany 653-5

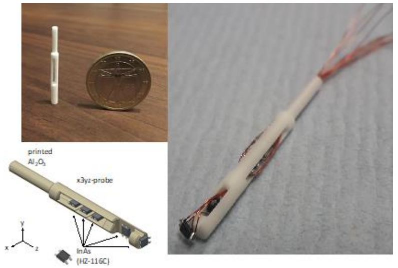
R Kinjo et al 2013 *Appl. Phys. Express* 6 042701

M Calvi et al 2020 Supercond. Sci. Technol. 33 014004





Hall sensor calibration



Hall sensors mounted on a 3D printed Al_2O_3 holder

Short bulk HTSU models tested at Cambridge University

SCU R&D at PSI –
Short bulk HTSU models

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Letters
Superconductor Science and Technology
Supercond. Sci. Technol. **36** (2023) 05LT01 (7pp)
https://doi.org/10.1088/1361-6668/acc1a8

Letter

Record field in a 10 mm-period bulk high-temperature superconducting undulator

Kai Zhang[1,7], Andrew Pirotta[1,2], Xiaoyang Liang[1,3], Sebastian Hellmann[1], Marek Bartkowiak[4], Thomas Schmidt[1], Anthony Dennis[5], Mark Ainslie[6], John Durrell[5] and Marco Calvi[1,*]

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[7] Now with Zhangjiang Laboratory, Shanghai 201210, People's Republic of China

E-mail: marco.calvi@psi.ch

Received 28 November 2022, revised 16 February 2023
Accepted for publication 6 March 2023
Published 15 March 2023

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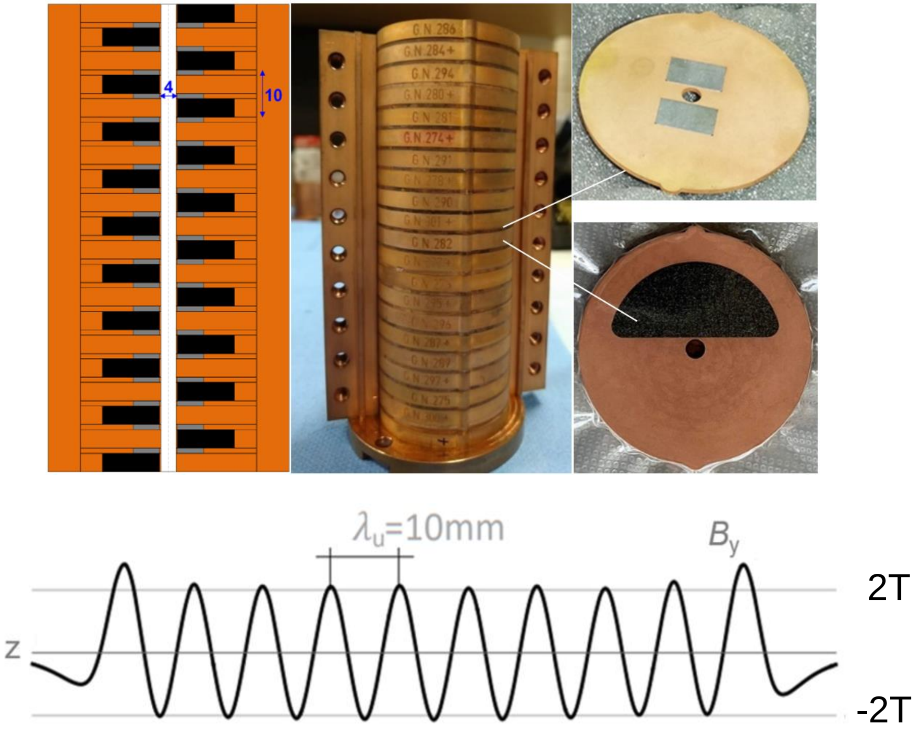
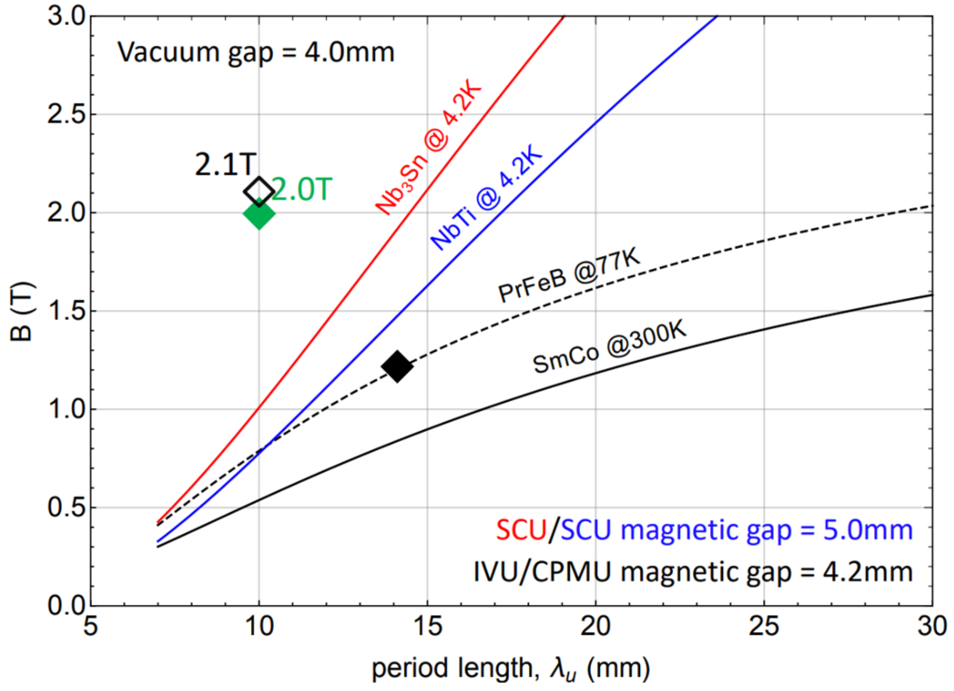
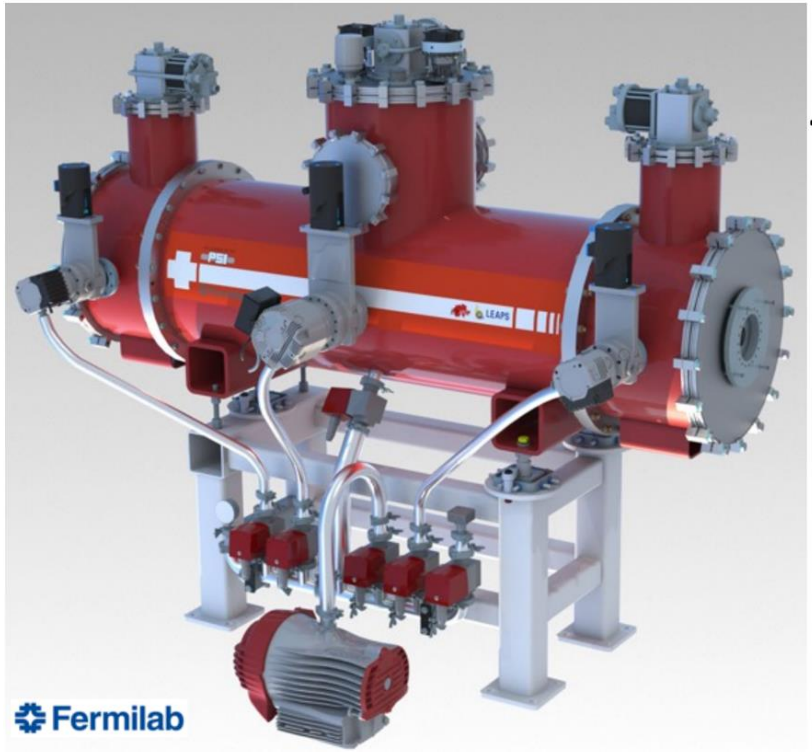


Kai Zhang et al 2023 *Supercond. Sci. Technol.* 36 05LT01

SCU R&D at PSI –
1 m-long HTSU for ITOMCAT beamline at SLS2.0



Bahrdt J and Gluskin E 2018 *NIMA* 907 149-168



THE METER LONG PROTOTYPE

Active length : 1.0 m

Total length : < 2m

period length : 10.5 mm

magnetic gap : 4.5mm

B_0 ~ 1.8T

Cryocoolers

HTS temp 10K

LTS temp 4.0K

Calvi M 2023 Superconducting Undulators for Future Light Sources 14th *International Particle Accelerator Conference*, Venice, Italy

Overview

- Introduction to synchrotrons and FELs
- Why superconducting undulator (SCU)?
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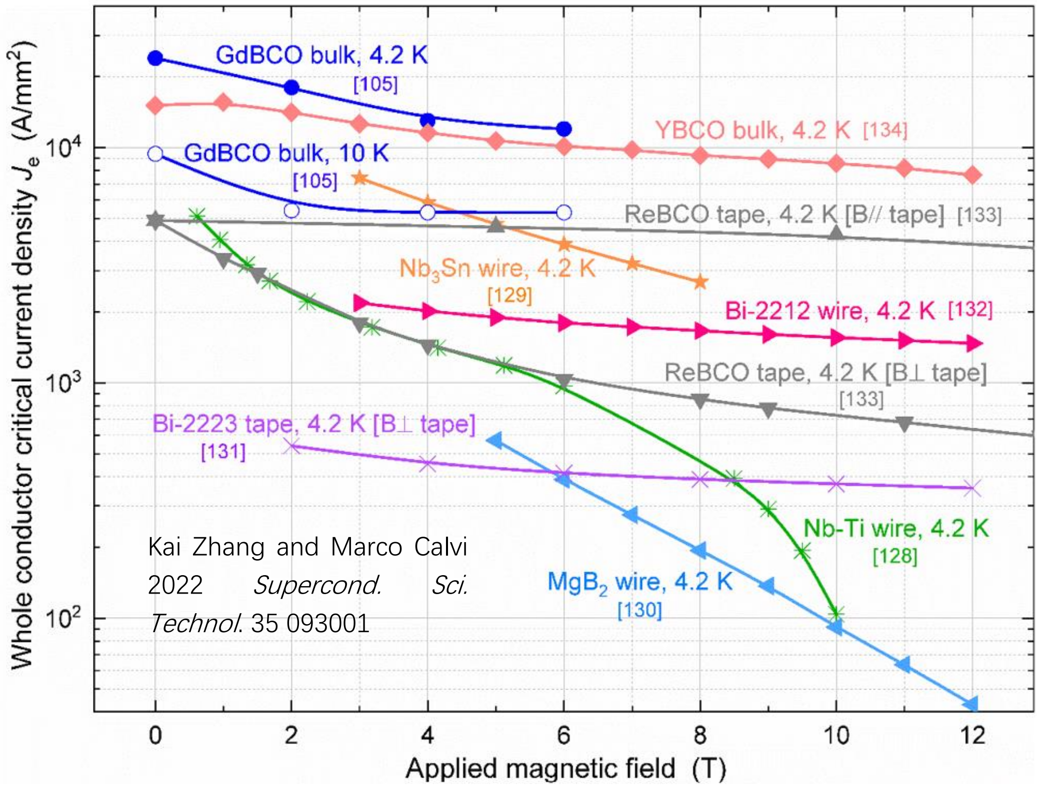
- HTS materials – opportunities and challenges
- Conclusions and outlooks

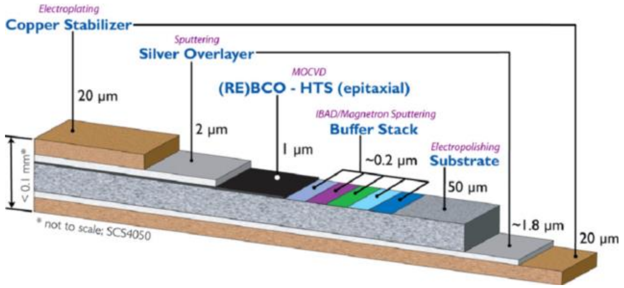
HTS materials – opportunities and challenges



Comparison of whole conductor critical current density

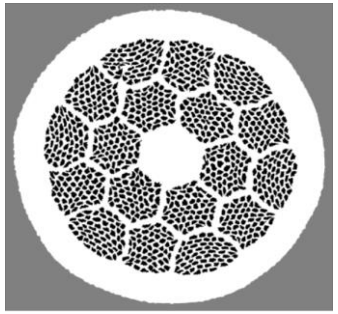
ReBCO bulk superconductor

- Highest J_e
- Mechanically brittle
- Inhomogeneous



ReBCO coated conductor

- High J_e
- Mechanically robust
- Anisotropic
- Low quench propagation velocity
- Inevitable screening current effects



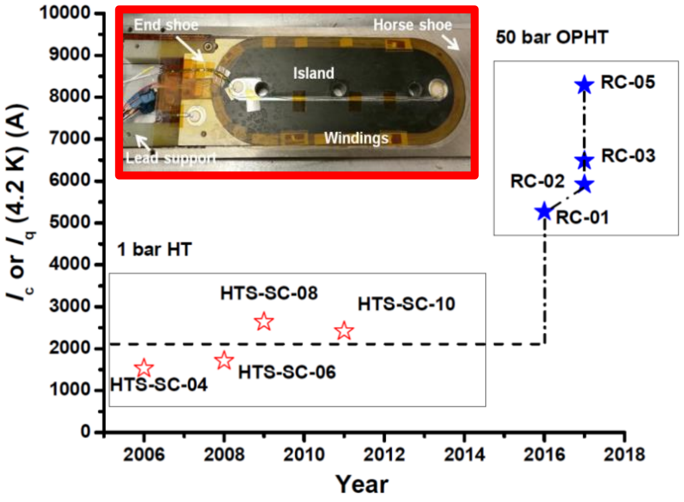
Bi-2212 round wire

- Low J_e
- Isotropic
- Heat treatment required
- Strain sensitive
- Low quench propagation velocity
- Minimized magnetization effects

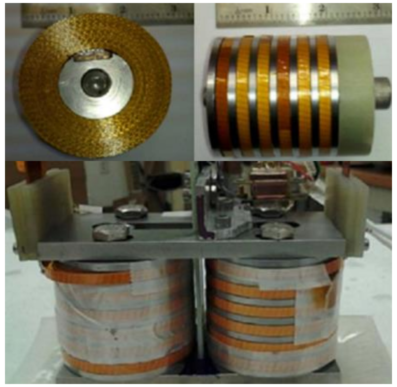
See presentations at CEC/ICMC2023

Lance cooley et al M2Or3I-01
Naoyuki Amemiya et al M4Or1A-02
Tengming Shen et al M2Or3I-04

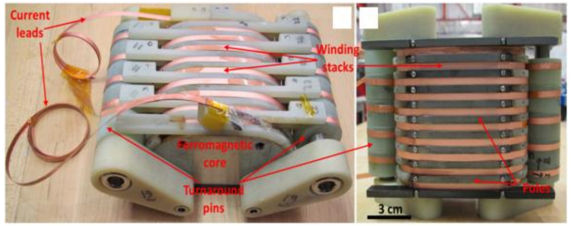
ReBCO coated conductor based SCU models



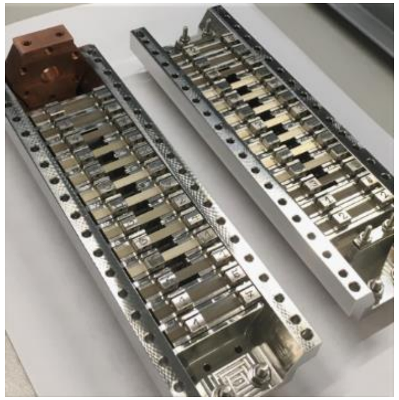
LBNL, 2017: Bi-2212 racetrack coil, J_e > 1000 A/mm^2 @4.2K



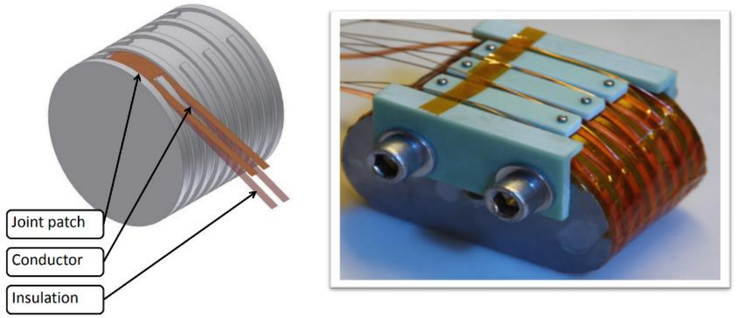
LANL, 2014: ReBCO planar, λ_u = 14 mm, B_0 = 0.77 T, 3.2 mm gap



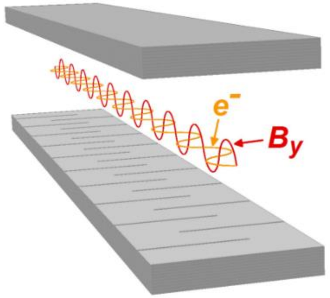
ANL, 2017: Joint-free HTS planar SCU model



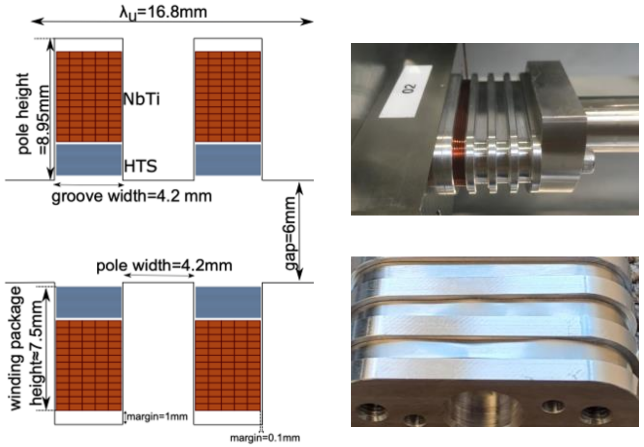
PSI, 2019: HTS tape-stack undulator model



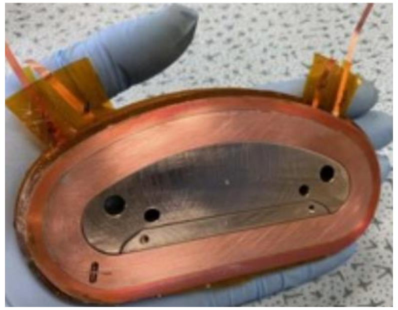
Noell/KIT, 2010: ReBCO Planar, J_e=700A/mm^2@4.2K



LBNL (2009) – KIT (2017): HTS Meander-type



EuXFEL, 2023: Hybrid NbTi/HTS undulator



KIT, 2022: ReBCO racetrack coil

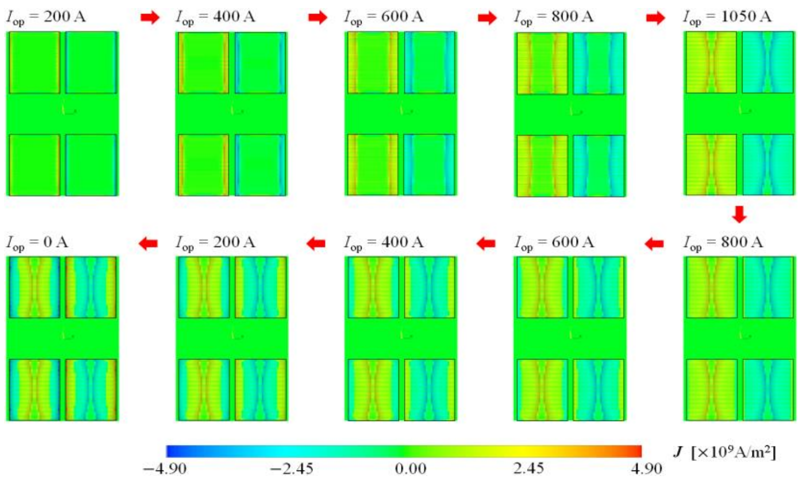
Kesgin I et al 2017 *Supercond. Sci. Technol.* 30 04LT01, Boffo C 2010 Design and test of an HTS planar undulator prototype, *Applied Superconductivity Conference*, Washington, USA

Prestemon S et al 2009 *Proc. PAC2009 Conf.*, Vancouver, Canada 2438-40, Holubek T et al 2017 *Supercond. Sci. Technol.* 30 115002, Nguyen D N et al 2014 *IEEE Trans. Appl. Supercond.* 24 4602805

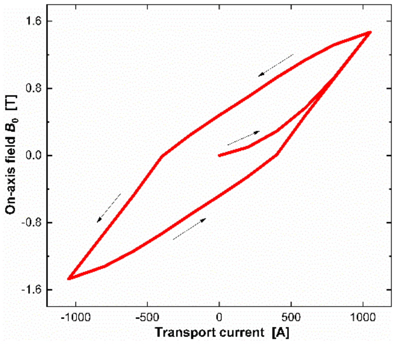
Casalbuoni S 20.02.2023, Fermilab, Batavia, IL, Richter S C 2023 et al *IEEE Trans. Appl. Supercond.* 33 4100207, Shen T et al 2019 *Sci. Rep.* 9 10170, Grattoni V et al 2023 *IEEE Trans. Appl. Supercond.* 33 4100405

ReBCO coated conductor based SCUs – Screening current induced field effects

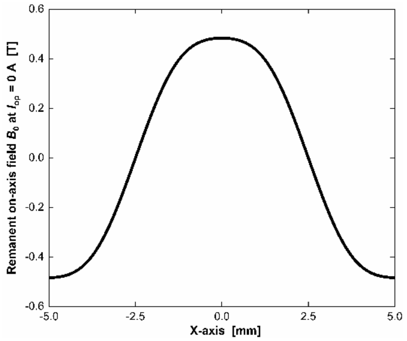
- Unlike multi-filamentary twisted Nb-Ti/Nb_3Sn conductors whose magnetization effects are minimized, the transport current in a ReBCO coated conductor is not distributed evenly. For example, during charging a single ReBCO tape slowly, the applied transport current always want to shield the tape to reserve the initial zero field as much as possible and thus flows along the edge of the ReBCO tape.
- This screening current induced field (SCIF) effect has been widely studied in ReBCO coils in NMR and accelerator magnets however, not yet considered in ReBCO coils based undulator in which the SCIF effect can be much more severe due to the much smaller magnetic gap/bore.



Current distribution in 2D periodical VR ReBCO SCU during charging I_{op} linearly: 0 A - 1050 A - 0 A.



Hysteresis loop of on-axis B_0



Remanent on-axis B_0

Kai Zhang and Marco Calvi 2022 *Supercond. Sci. Technol.* 35 093001

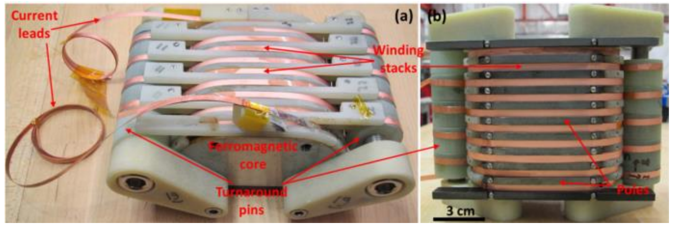
ReBCO coated conductor based SCUs – Non- and Partial insulation technology

- The quench propagation velocity of HTS coils is of the order of cm/s (~100 times lower than LTS), not friendly for quench detection or protection.

- Non-insulation (NI) HTS coil technology was first proposed by Hahn et al in 2010 and became a hot research topic later for two main reasons: a) more compact and better thermal stability - the elimination of insulation layers can enhance the overall coil current density and the radial thermal conductivity in the HTS coils; b) self-quench protection mechanism – the NI-HTS coil can survive when the transport current I_{op} exceeds the critical current I_c because a certain amount of current will bypass its original superconducting spiral path through turn-to-turn contact.

- However, the NI-HTS coil often has an obvious charge or discharge delay, for example, the central magnetic field needs longer time to stabilize after charging the coils.

- The partial insulation (PI) HTS technology by insulating the HTS coils every several layers is a potential solution to speed up the charge-discharge rate while retain the self-quench protection characteristic in the meantime.



ANL, 2017: Joint-free HTS planar SCU model

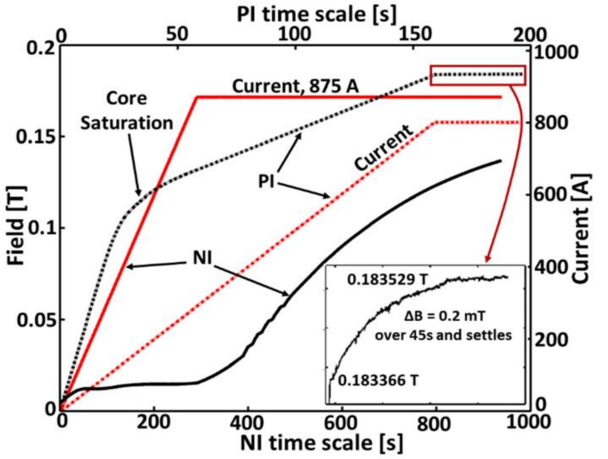
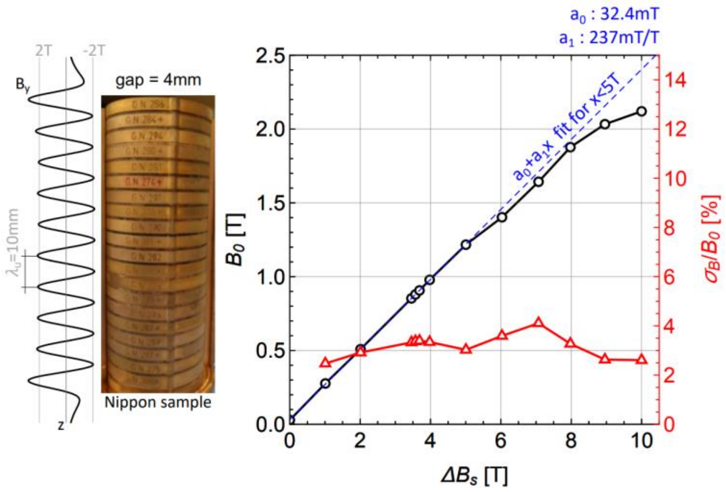


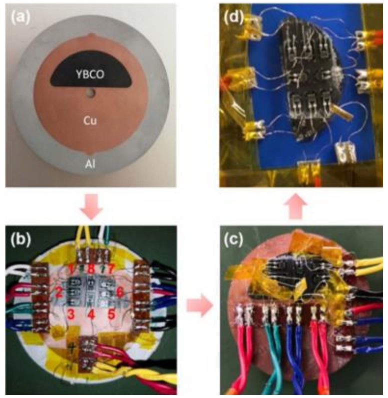
Figure 3. Time traces of the magnetic field and current of partial (PI) (top *x*-axis) and no insulation (NI) (bottom *x*-axis) magnets at 4.2 K. The settle time of the field at the end of the current ramp for the PI (dashed lines) magnet is sufficiently short for use in an undulator, while it is unacceptably long for the NI (solid lines) magnet. The inset shows an expanded view of the constant current region for the PI magnet revealing that the field changes by only 0.2 mT and essentially constant after 45 s.

Kesgin I et al 2017 *Supercond. Sci. Technol.* 30 04LT01

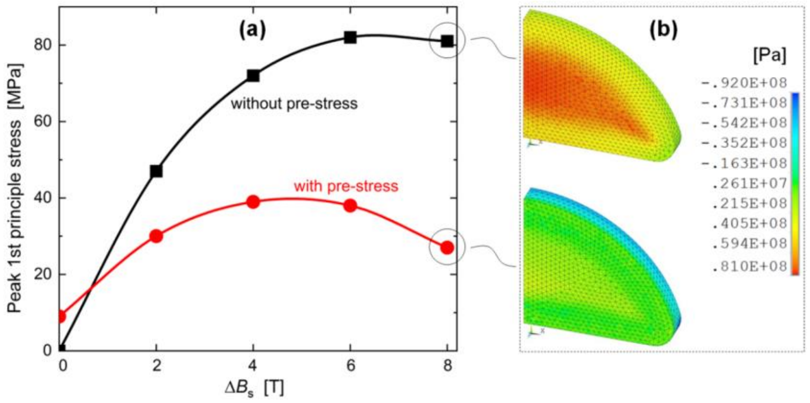
ReBCO bulk superconductor based SCUs



Relation between B_0 and ΔB_0



Strain characterization of pre-stressed ReBCO bulk



Comparison of peak 1st principle stresses in the half-moon shaped GdBCO disk with and without pre-stress

$$\mathbf{AL} = \mathbf{B}$$

$$\Downarrow$$

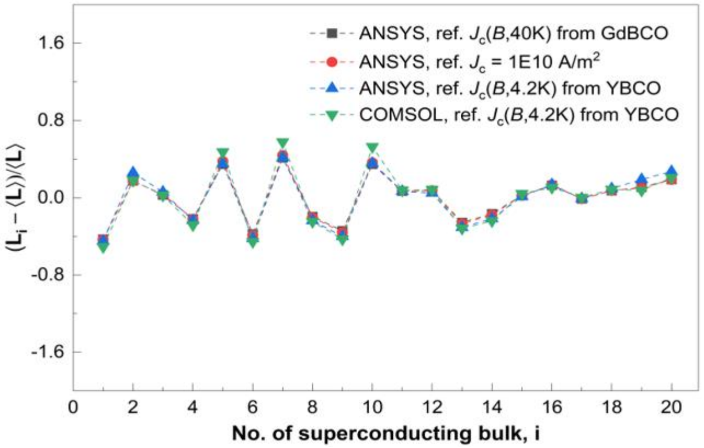
$$\Delta B_i^k = B_{m,i} - B_{s,i}^k$$

$$\Downarrow$$

$$\Delta \mathbf{L}^k = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\Delta \mathbf{B}^k$$

$$\Downarrow$$

$$\mathbf{L}^{k+1} = \mathbf{L}^k + f_d \cdot \Delta \mathbf{L}^k$$



Inverse analysis of each ReBCO bulk's J_e based on measured undulator field

Key technologies to be addressed:

- ☐ Minimization of the temperature gradient along the long bulk HTS insert.
- ☐ Flux creeping effects. Flux freezing the ReBCO bulks is necessary to avoid the decay of the undulator field.
- ☐ In-vacuum small gap magnetic field measurement.
- ☐ Field shimming. Local field needs to be corrected by sorting ReBCO bulks and adjusting poles' heights.

Kinjo R et al 2022 *Phys. Rev. Accel. Beams* 25 043502

Conclusions & Outlooks

- Nb-Ti SCUs, with either planar or helical type, have now reached impressive performances at the KIT synchrontron and APS storage rings, demonstrating **reliable operation** without quenches or with stable electron beams in case of a quench.
- One can buy Nb-Ti SCUs from industry now as for ANSTO who has a contract with Noell GmbH.
- Very recently, a 1.1 m-long Nb_3Sn planar undulator has been installed in the APS storage ring successfully.
- There are plans to apply Nb-Ti SCUs as developed for storage rings to EuXFEL, LCLS II and SHINE.
- Several HTS undulator prototypes wound with 2G ReBCO coated conductors were made world-wide but none of them reached a practical level of undulator field. Open questions like the **screening current effects** and the **non-insulation** technology remained to be answered.
- Very recent R&D on staggered-array bulk ReBCO undulator at PSI/Cambridge obtained an on-axis field B_0 of as high as **2.1 T** @ 10 K at **10 mm short period** and 4-mm magnetic gap, showing great potential for its application in FELs and DLSRs where small magnetic gap is allowed.
- R&D on SCUs with tunable K-value up to ~2 and period length as short as possible is of continuing interest world-wide for either reducing the total costs (shortening the length of the linear accelerators) or enhancing the photon energy.
- R&D on variably polarized SCU, for example the SCAPE, is another hot research topic for both synchrotrons and FELs.

Acknowledgements

For providing materials

Marco Calvi, Paul Scherrer Institute

Sara Casalbuoni, European XFEL,

Efim Gluskin, Argonne National Laboratory

Qiaogen Zhou, Shanghai Advanced Research Institute, CAS

Yuhui Li, Institute of High Energy of Physics, CAS

For R&D activities at SSRF

Qiaogen Zhou, Yi Ding, Jidong Zhang, Qisheng Tang, Zezhou Wu, Jinya Chen, Lei Han, Bo Zhang, Zhiqiang Jiang, Pengcheng Dong, Ziqiang Feng, Dabing Wei

Postdoc and PhD positions at Zhangjiang Laboratory

张江实验室
ZHANGJIANG LABORATORY

中国科学院大学
University of Chinese Academy of Sciences

One Postdoc position and one PhD position are currently open at Zhangjiang Laboratory to work on the research and development of a 0.6 m-long, 12 mm-period bulk HTS undulator

*Eligible PhD student will receive a Doctoral Degree from the University of Chinese Academy of Sciences

For supervisor information, please check https://people.ucas.edu.cn/~kai.zhang

For more details, please contact zhangkai@zjlab.ac.cn