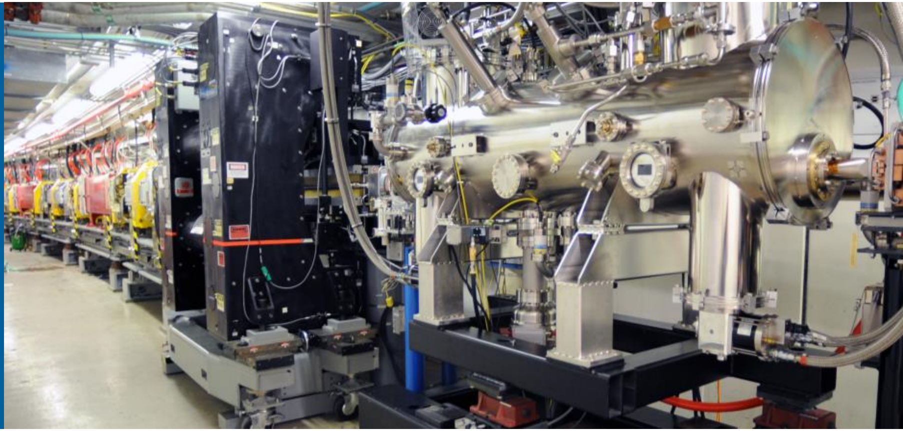
SUPERCONDUCTING UNDULATORS FOR POLARIZED POSITRON SOURCES



YURY IVANYUSHENKOV
Advanced Photon Source
Argonne National Laboratory

Snowmass Polarized Positron Sources Workshop, March 1, 2022

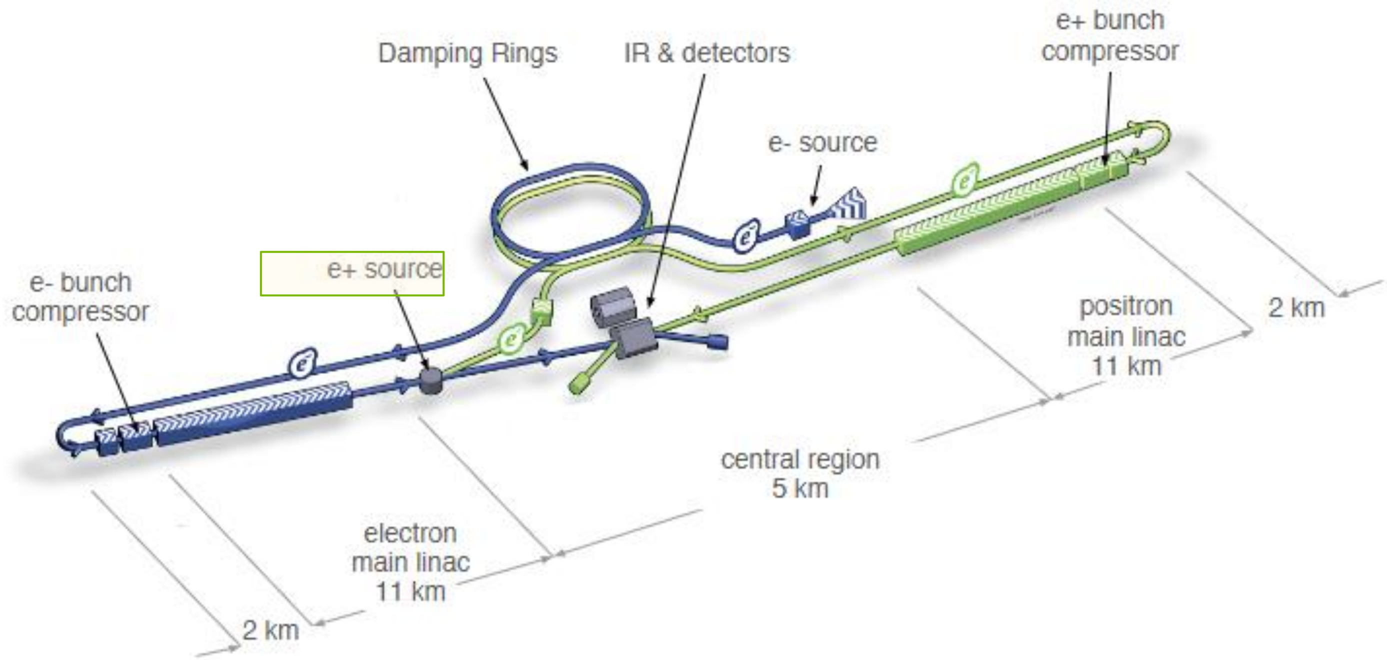
SCOPE

- ILC polarized positron source and helical superconducting undulator (HSCU)
- HSCU examples
- Polarized source HSCU enabling components
- Toward high field HSCU
- Polarized source HSCU roadmap
- Synergy with other projects
- Summary

ILC POLARIZED POSITRON SOURCE AND HELICAL SUPERCONDUCTING UNDULATOR (HSCU)

ILC POSITRON SOURCE

Schematic layout of the ILC, indicating all the major subsystems (not to scale) [1].

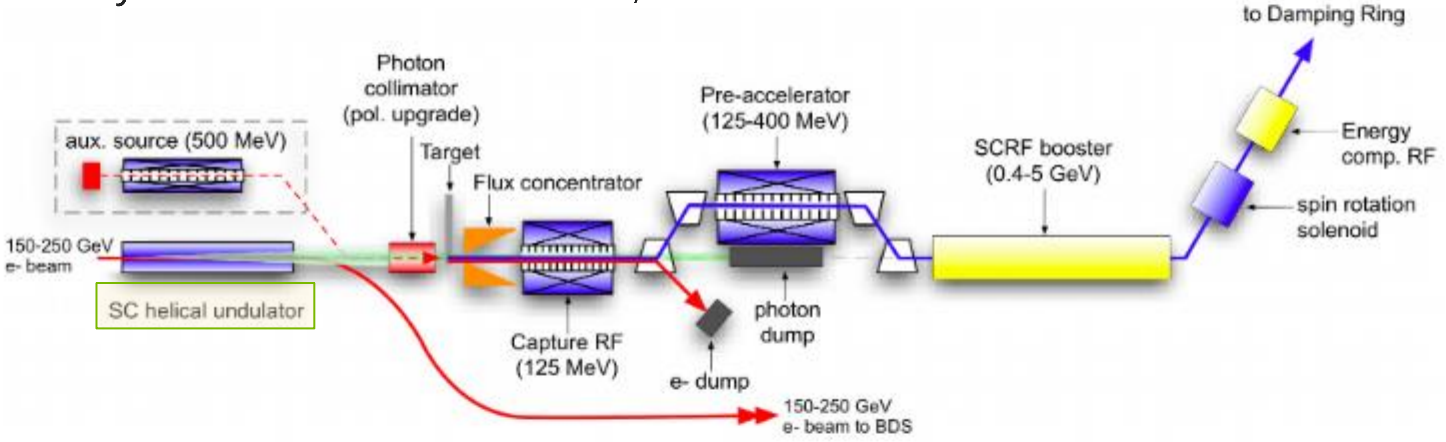


A polarised positron source in which positrons are obtained from electron-positron pairs by converting high-energy photons produced by passing the high-energy main electron beam through an undulator [1]

[1] THE INTERNATIONAL LINEAR COLLIDER, Technical Design Report, Vol.1

HELICAL UNDULATOR FOR ILC POSITRON SOURCE

Overall Layout of the Positron Source, located at the end of the electron Main Linac [1]



Parameter	units	350 GeV	500 GeV
Electron beam energy (e^+ prod.)	GeV	178	253
Bunches per pulse	N	1312	1312
Photon energy (first harmonic)	MeV	16.2	42.8
Photon openning angle ($=1/\gamma$)	µrad	2.9	2
Undulator length	m	147	147
Required undulator field	T	0.698	0.42
undulator period length	cm	1.15	1.15
undulator K		0.75	0.45
Electron energy loss in undulator	GeV	2.6	2

[1] THE INTERNATIONAL LINEAR COLLIDER, Technical Design Report, Vol.3

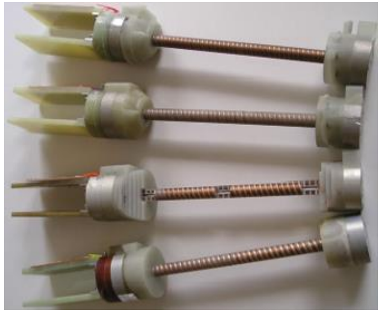
HELICAL SCU EXAMPLES

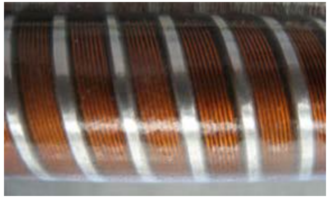
ILC HSCU PROTOTYPE BY UK HELICAL COLLABORATION

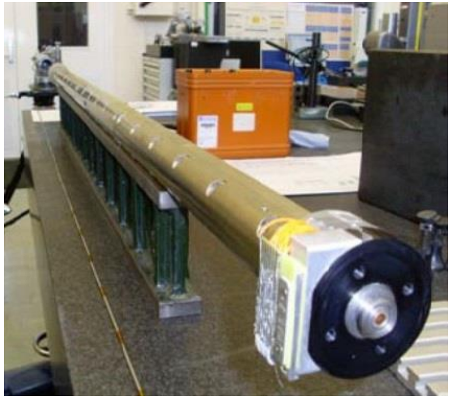
- In 2003-2010 HeLiCAl collaboration of Daresbury Lab, Rutherford Lab, University of Liverpool and University of Durham developed, fabricated and successfully tested ILC Helical SCU prototype [1]
- Field of 0.86 T was achieved in NbTi 11.5-mm period magnet
- Two 1.74-m magnets were assembled and tested in 4-m long cryostat

Parameter	Value
Cryostat length (m)	4
Magnetic length (m)	2 x 1.74
Period length (mm)	11.5
Field on axis (T)	0.86
Magnetic bore (mm)	6.35
Vacuum bore (mm)	5.85

[1] D.J. Scott et al., PRL 107, 174803 (2011)
[2] Y. Ivanyushenkov et al., Proceedings of PAC05, Knoxville, 2005, p. 2295.


HSCU magnet prototypes [2]


Helical magnet winding [2]


3.4-m long magnet assembly


Cold test of HSCU at RAL

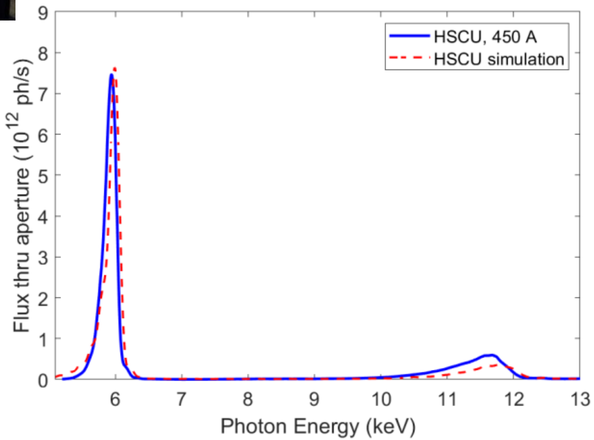
HELICAL SCU FOR APS AT ARGONNE

- SCU technology offers the possibility of building circular polarizing helical undulators
- A helical SCU (HSCU) was installed on APS ring in December 2017. In operation since January 2018
- X-ray photon correlation spectroscopy program at the APS benefits from the increased brilliance provided by an HSCU

HSCU in Sector 7 of APS storage ring [1].

Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2

[1] M. Kasa et al., Phys. Rev. Accel. Beams 23, 050701 (2020).

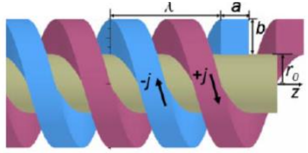


Simulated and measured spectrum of HSCU [1].

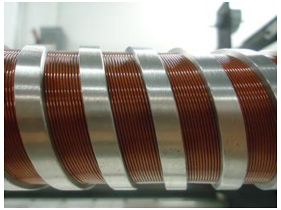
POLARIZED SOURCE HSCU ENABLING COMPONENTS

HSCU MAGNET

- Soft iron 1.2-m long magnet core (former)
- Novel winding scheme with NbTi wire
- Epoxy resin impregnation mold serves as a mold and as a strong back
- Magnet is cooled with LHe contained in the strongback channel. 4-K magnet is thermally isolated from ‘warm’ beam chamber.
- Successfully operates in APS HSCU since January 2018 [1]

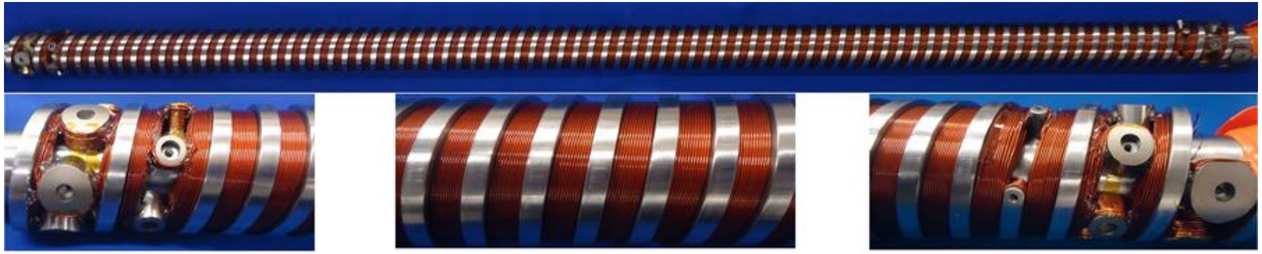


Magnetic model of HSCU.



HSCU prototype coil winding.

HSCU magnet core prototype.

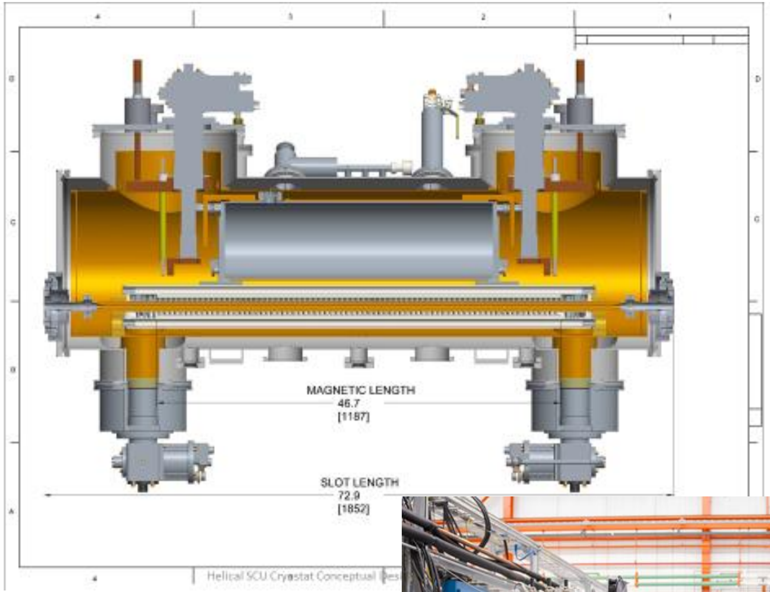


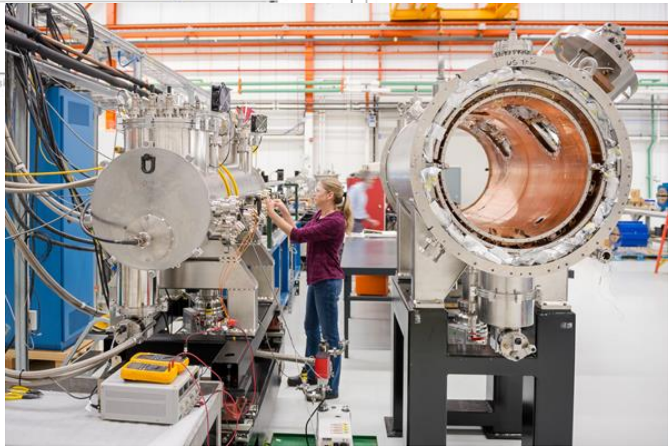
Wound 1.2-m long HSCU magnet core

[1] M. Kasa et al., Phys. Rev. Accel. Beams 23, 050701 (2020).

APS HSCU CRYOSTAT

- The 2nd generation cryostat has been developed at the APS for HSCU
- One thermal shield
- Four RDK415D cryocoolers
- Two temperature stages
- Reduced diameter of the vacuum vessel
- Vertical turrets
- Standard flanges for the end covers
- Simplified design of He filling port



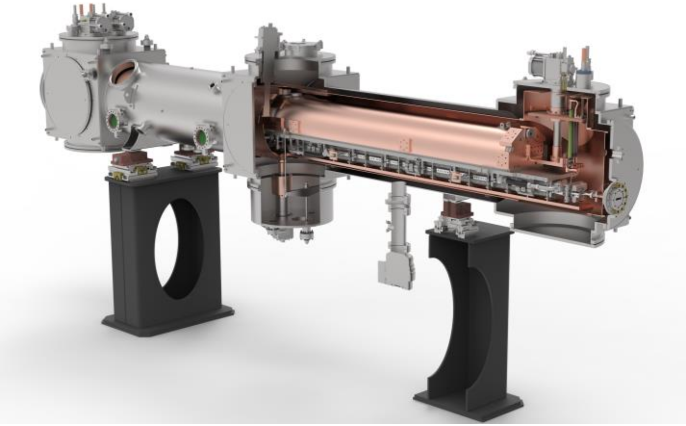


HSCU cryostat (left) and SCU0/SCU1 cryostat (right)

J. Fuerst et al., “A second-generation superconducting undulator cryostat for the APS,” Proceedings of CEC-ICMC 2017, Madison, 2017.

APS UPGRADE SCU CRYOSTAT

- Two SCU cryomodules are under fabrication for the APS Upgrade project
- Cryostat design is based on a proven design of the 2-m cryostat for Helical SCU:
  - 4.8-m long 20”-diameter vacuum vessel;
  - single thermal shield;
  - off-shelf vacuum components;
  - three thermal stages (4K – 20K – 40K);
  - 6 cryocoolers (two types)



Cryostat design model

Cryostat vacuum vessel

LHe tank

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DESIGN OF MODULAR AND FLEXIBLE SCU SYSTEMS AT FNAL

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

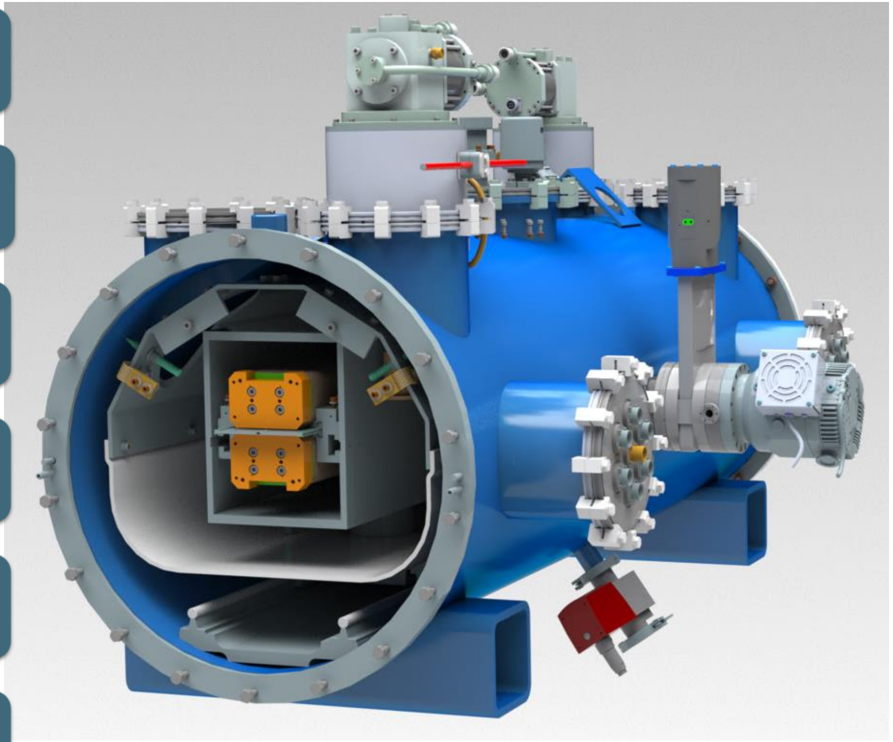
Cooling system compatible with both conduction cooled (cryocoolers) and LHe operations (SRF CM Style).

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

System independent from superconductor technology and coil configuration (planar vs helical)

Ongoing development for a prototype SCU to be installed in EuPRAXIA@SPARC_LAB (LNF-INFN Frascati)

This technology can be transferred to polarized source undulators to help reduce costs and improve integration

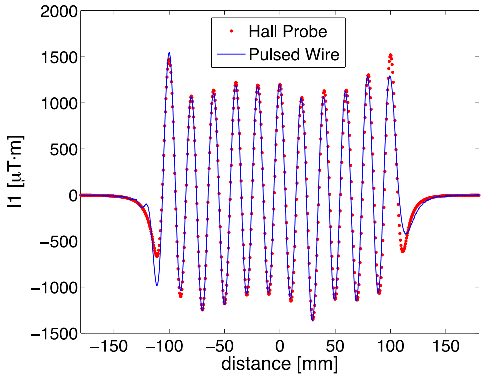


SCU for EuPRAXIA@SPARC_LAB INFN Frascati

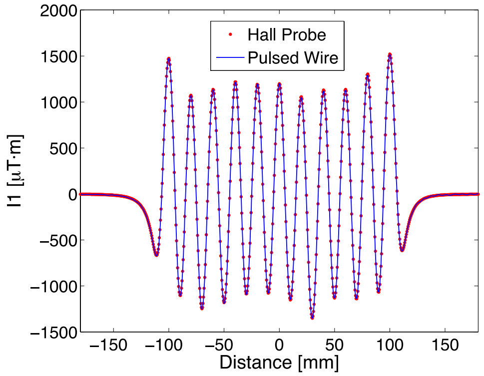
HSCU MAGNETIC MEASUREMENTS: PULSED WIRE METHOD ADVANCEMENTS

- The pulsed wire method can be beneficial to measure undulators where measurement access is difficult
- Developed pulsed wire equipment for in and out of vacuum measurements
- Developed algorithms to correct signal distortions due to finite current pulse width and the wire flexural rigidity (dispersion)

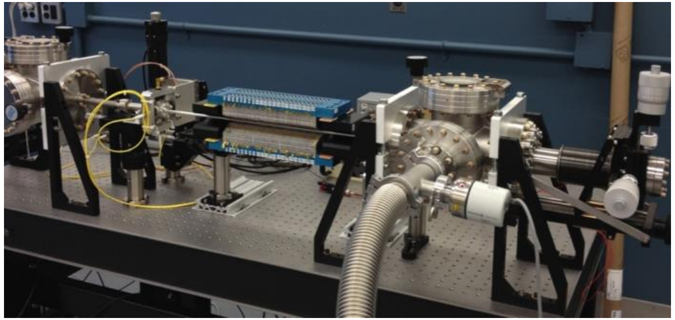
Before Correction Algorithm



After Correction Algorithm



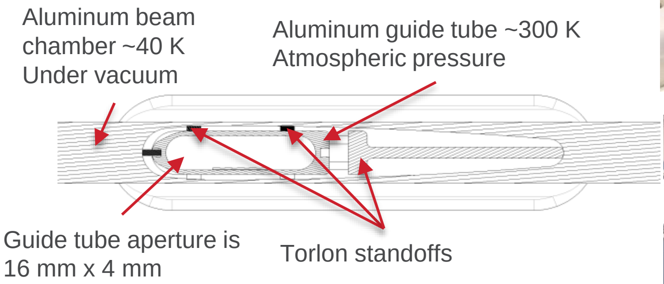
In-vacuum Pulsed Wire System

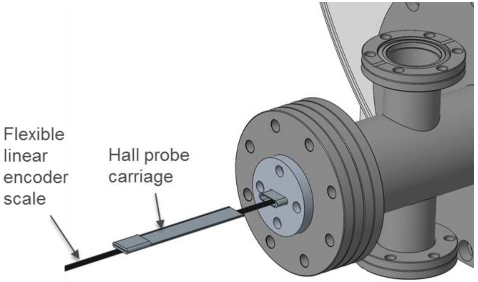


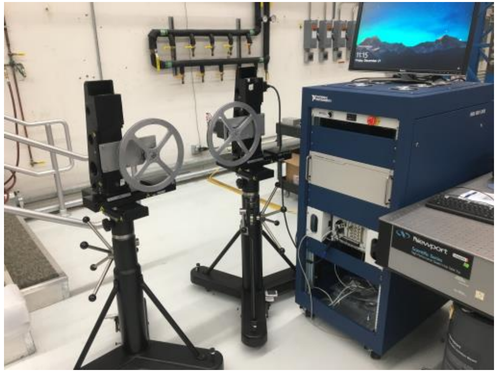
D. Arbelaez et al, Nucl. Inst. & Meth. A, Vol. 716

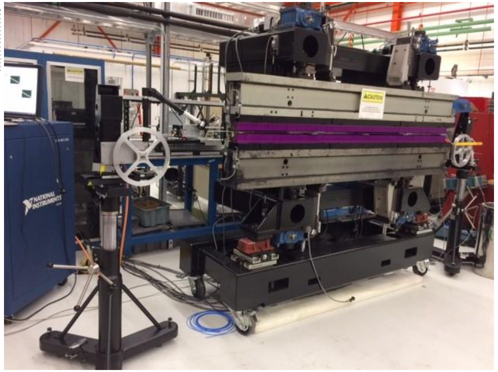
NEW SCU MEASUREMENT SYSTEM AT APS

- New design is based on experience of using a 2-m long measurement system for the APS SCUs [1]:
  - a proven concept of a warm guiding tube
  - Hall probe carriage is moved with a flexible linear encoder scale [2]
  - does not require a long holder attached to a long travel linear stage
- System is fabricated, assembled and tested. It's being used to measure a well characterized HPMU and APSU SCU Article#1
- System can be modified for measuring HSCUs









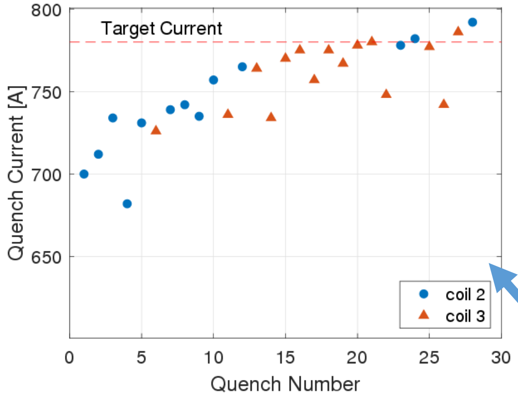
[1] M. Kasa and Y. Ivanyushenkov, "Magnetic measurement system being developed for SCU program at the APS", presented at IMMW21, Grenoble, France, June 2019.
[2] M. Kasa et al., U.S. patent No.10,908,231, 2021

TOWARD HIGH FIELD HSCU

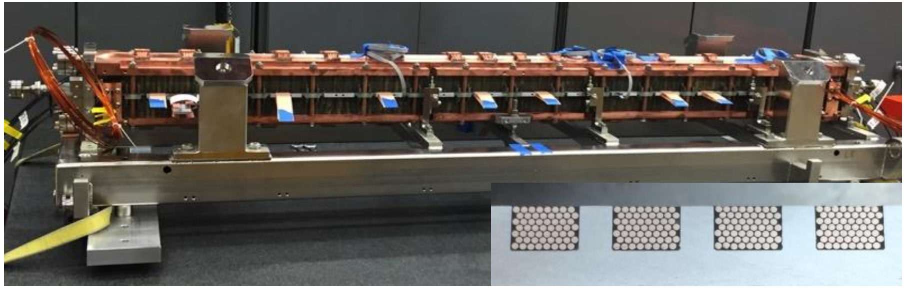
DEVELOPMENT OF NB_3SN UNDULATORS AT LBNL

- 6 period prototype in 2006 reached 98% of short sample after three quenches
  - Demonstrated stability at high current density (7.6 kA/mm^2 non-Cu Jc) with 0.48 mm MJR strand
  - Demonstrated magnet protection at high Cu current densities (8.0 kA/mm^2 in Cu)
- 1.5 m long prototype reached target field (80% of short sample limit) in 2017
  - Developed fabrication methods for “long” Nb_3Sn undulators
  - Demonstrated conductor stability with modern 132/169 RRP conductor (0.6 mm diameter)
  - Developed fast quench protection system and demonstrated that full length Nb_3Sn undulator can be protected

Training curve For Full 1.5 m SCU



1.5 m Long Nb_3Sn Superconducting Undulator Prototype



6 Period Prototype

D. Arbelaez et al, ICFA Beam Dynamics Newsletter, NO. 78.

D.R. Dietderich et al, IEEE Trans on Applied Superconductivity VOL. 17, NO. 2

ANL-FNAL COLLABORATION ON Nb_3Sn UNDULATOR FOR APS

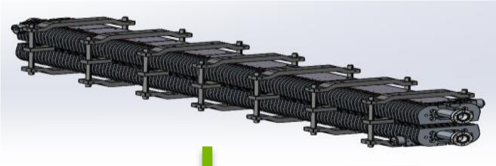
- Goal: Develop, build and install on the APS ring a Nb_3Sn undulator (in a modified SCU0 cryostat) in 2022
- Collaboration with FNAL and LBNL
- Plan:
  - R&D phase – build and test short magnet models (complete)
  - 0.5-m long prototype (complete)
  - Full scale magnet and cryostat (in process)
  - Undulator assembly, test, installation on the APS ring

- **Achieved:**
- Improved conductor stability to achieve 100% of short sample limit
- Demonstrated performance reproducibility both in short coil R&D and in scale-up

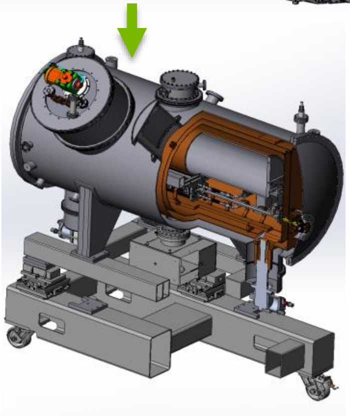
I. Kesgin et al., *IEEE Transact. on Applied Supercond.*, vol. 31,no 5.

84 mm

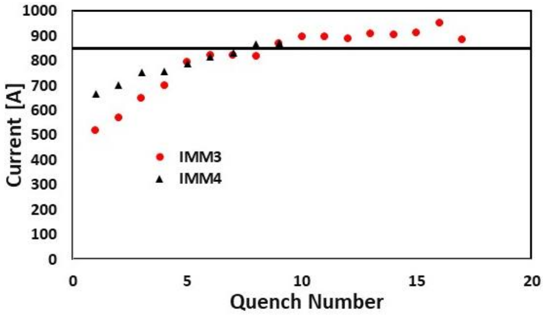
0.5 m



1.1 m

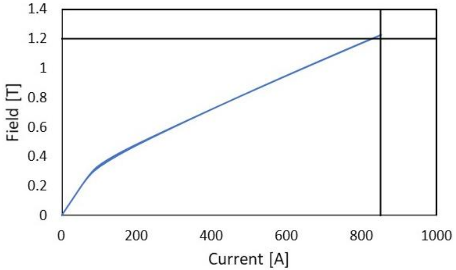


Quench training profile of individual cores



Nb_3Sn SCU did not require any training to reach the design current in 2nd cooldown and demonstrated excellent training memory.

Excitation curve of 0.5-m long Nb_3Sn SCU



The performance exceeded the design current and undulator field of ~850 A and 1.2 T, respectively. The magnetic field simulations agreed well with the measured field values. Nb_3Sn SCU offers at least 20% undulator field increase compared to a NbTi SCU with the same magnetic gap (9.5 mm) and period length (18 mm).

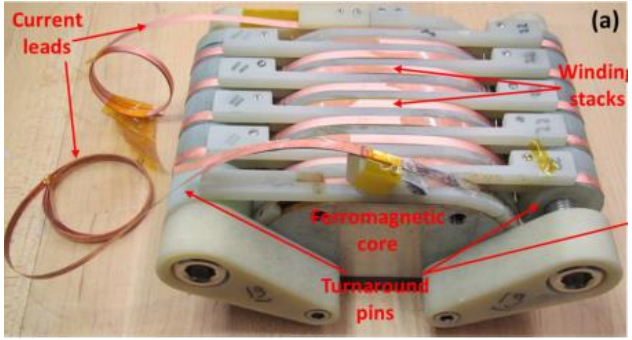
Argonne NATIONAL LABORATORY

R&D ON HTS SCU AT THE APS

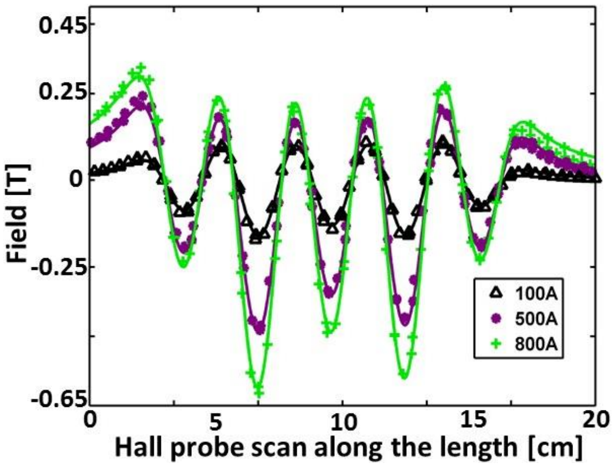
A Laboratory Directed R&D on HTS SCU demonstrated that 2G HTS conductors are suitable for fabrication of undulator magnets:

- A technique of winding an undulator magnet with HTS tape without electrical joins is developed [1].
- Partial interlayer insulation reduces charging delay [2].
- Prototype undulator shows superior performance at 4.2 K compared to NbTi counterparts (2.1 kA/mm^2 versus 1.4 kA/mm^2 for NbTi). This is power supply limit, not superconductor.
- Simulations confirm the measured field profiles. Estimated field value of HTS undulator is about 30% greater than analogous NbTi undulator magnets.
- Availability of long length wire with uniform I_cs and weak mechanical properties are the remaining issues that are currently being addressed by the multiple HTS manufactures.

[1] I. Kesgin et al., US patent # US 10,249,420 B2
[2] I. Kesgin et al., 2017 Supercond. Sci. Technol. 30 04LT01



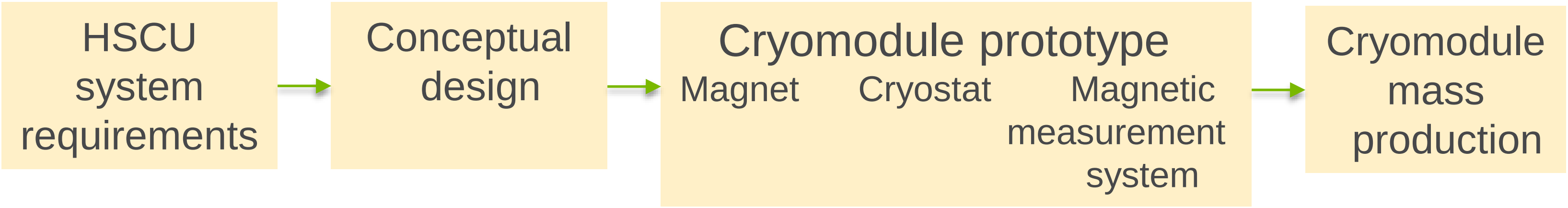
Continuously wound HTS undulator prototype.



Measured field of HTS undulator prototype.

POLARIZED SOURCE HSCU ROADMAP

POLARIZED SOURCE SCU ROADMAP

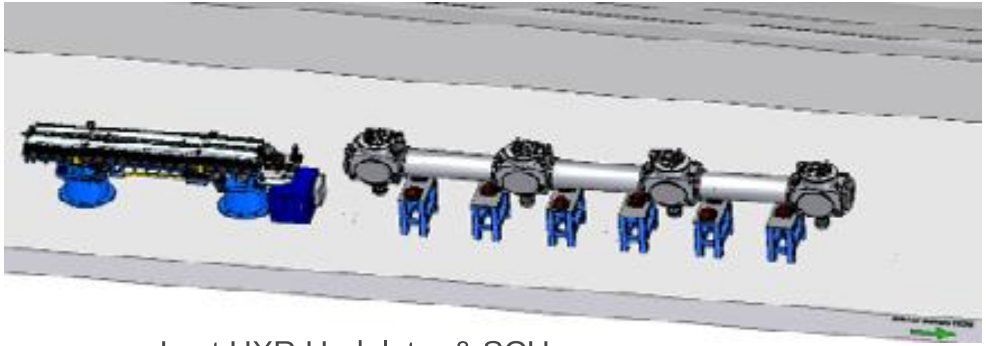


SYNERGY WITH OTHER PROJECTS

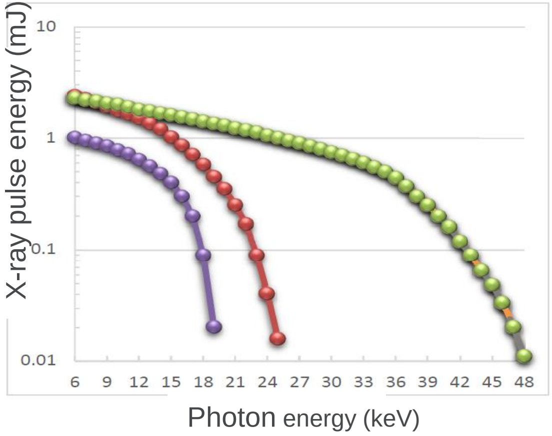
BENEFITS OF SCUs FOR FELs

- Stronger magnetic fields, higher FEL performance.
- No mechanical motions for wavelength controls.
- Cryo-pumped e-beam pipes provide excellent vacuum.
- SCUs increase the high X-ray energy reach for XFELs. Example: LCLS Cu linac with SCU can reach 48 keV.
- Combined with the high-repetition-rate SRF linac, SCU XFELs will increase the average coherent X-ray flux

SLAC-ANL collaboration is working on FEL SCU Demo project with the goal of fabricating and testing SCUs on LCLS Hard X-ray Undulator beamline



Last HXR Undulator & SCUs



LCLS-II-HE can produce 2 mJ pulse energy with low emittance e- beams and SCUs (green curve)

SUMMARY

- THE US HAS ACCUMULATED EXPERIENCE IN:
  - BUILDING HSCU FOR APS LIGHT SOURCE
  - DEVELOPING SMALL-BORE MAGNETIC MEASUREMENT TECHNIQUES
  - BUILDING CRYOCOOLER-BASED AND CRYOPLANT-BASED CRYOMODULES
  - DEVELOPING NB3SN AND HTS MAGNETS AND SCU PROTOTYPES

- THE US CAN TAKE A LEADING ROLE IN DEVELOPING AND BUILDING POLARIZED SOURCE SUPERCONDUCTING UNDULATOR SYSTEM

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  ** NOW WITH SLAC

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