PAUL SCHERRER INSTITUT PSI

IPAC23

Marco Calvi :: Photon Science Division :: Paul Scherrer Institute

Superconducting Undulators for Future Light Sources

14th International Particle Accelerator Conference
May 9th 2023 @ 14:30
Venice, Italy

CHART
Swiss Accelerator
Research and
Technology

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Many thanks to the following people for providing slides for this presentation:

Sara Calsalbuoni – EuXFEL

Efim Gluskin – ANL

Yury Ivanyushenkov – ANL

Ibrahim Kesgin – ANL

Patrick Krejcik – SLAC

Dinh Cong Nguyen – SLAC

Wolfgang Walter – Bilfinger Noell

CHART

Swiss Accelerator Research and Technology

Overview

- Synchrotron radiation sources
- Why SuperConducting Undulators (SCU)?
- Large SCU projects ongoing in EU & US:
  - The upgrade of APS: APS-U
  - The afterburner for SASE2 at the EuXFEL
  - SLAC-ANL FEL SCU Project
  - The HTSU10 for the I-Tomcat beamline of SLS2.0
- Brief overview of the ongoing R&D in LTS & HTS
- Conclusions

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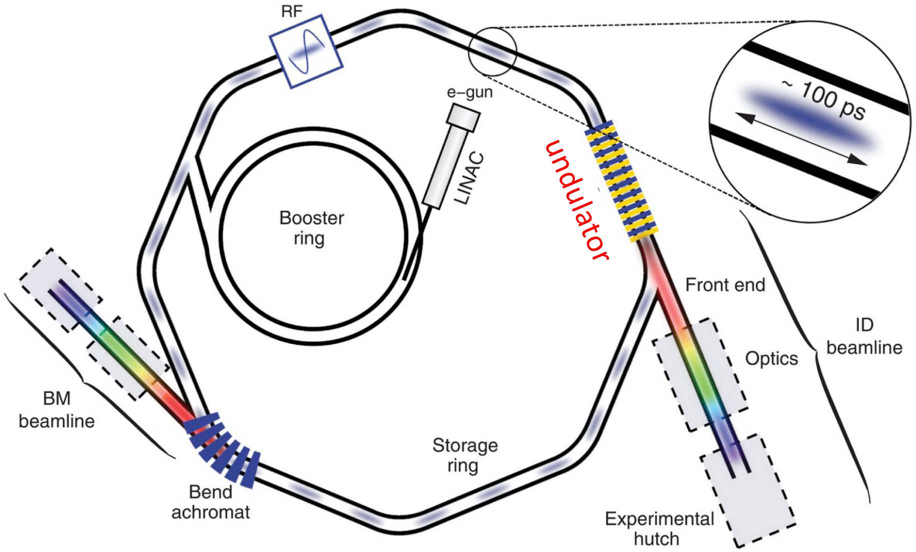
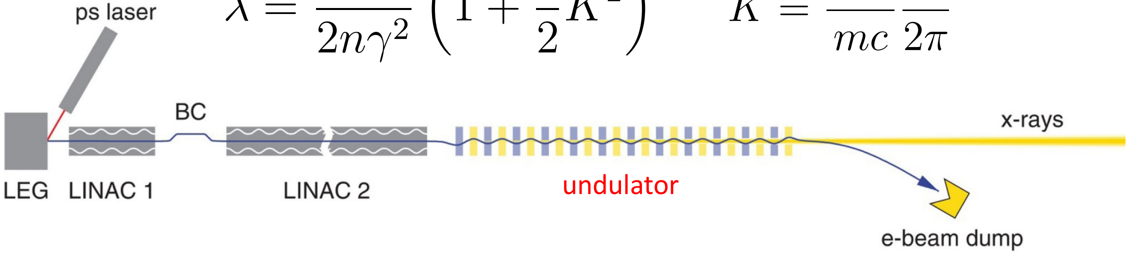
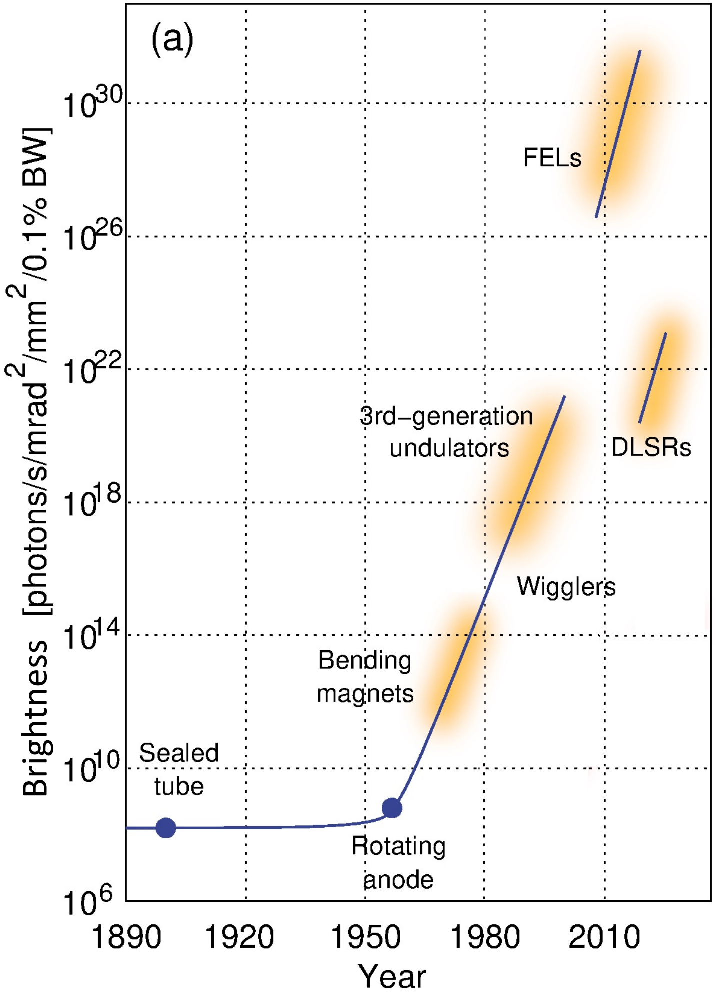
Introduction to SRS



$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{1}{2}K^2\right) \qquad K = \frac{B_0 e}{mc}\frac{\lambda_u}{2\pi}$$





An Introduction to Synchrotron Radiation: Techniques and Applications, Second Edition. Philip Willmott.

Hard X-ray beamline of SwissFEL

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PM Undulators of Aramis

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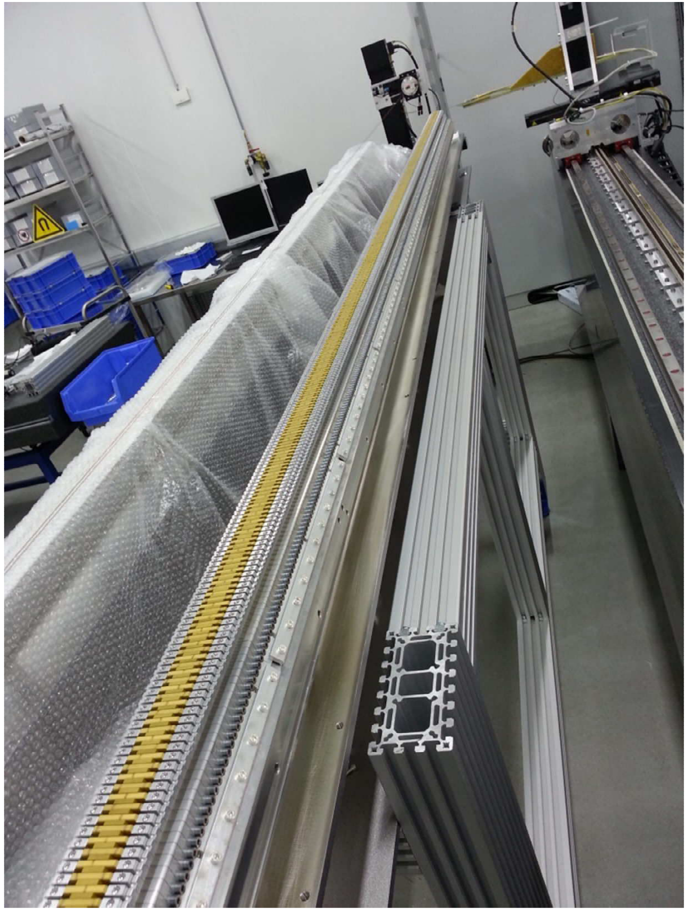
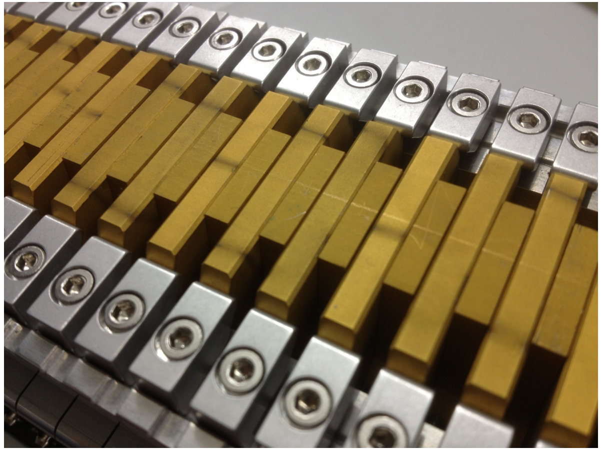
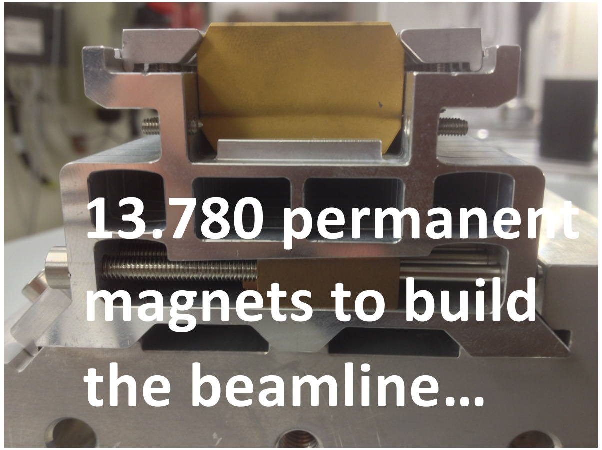
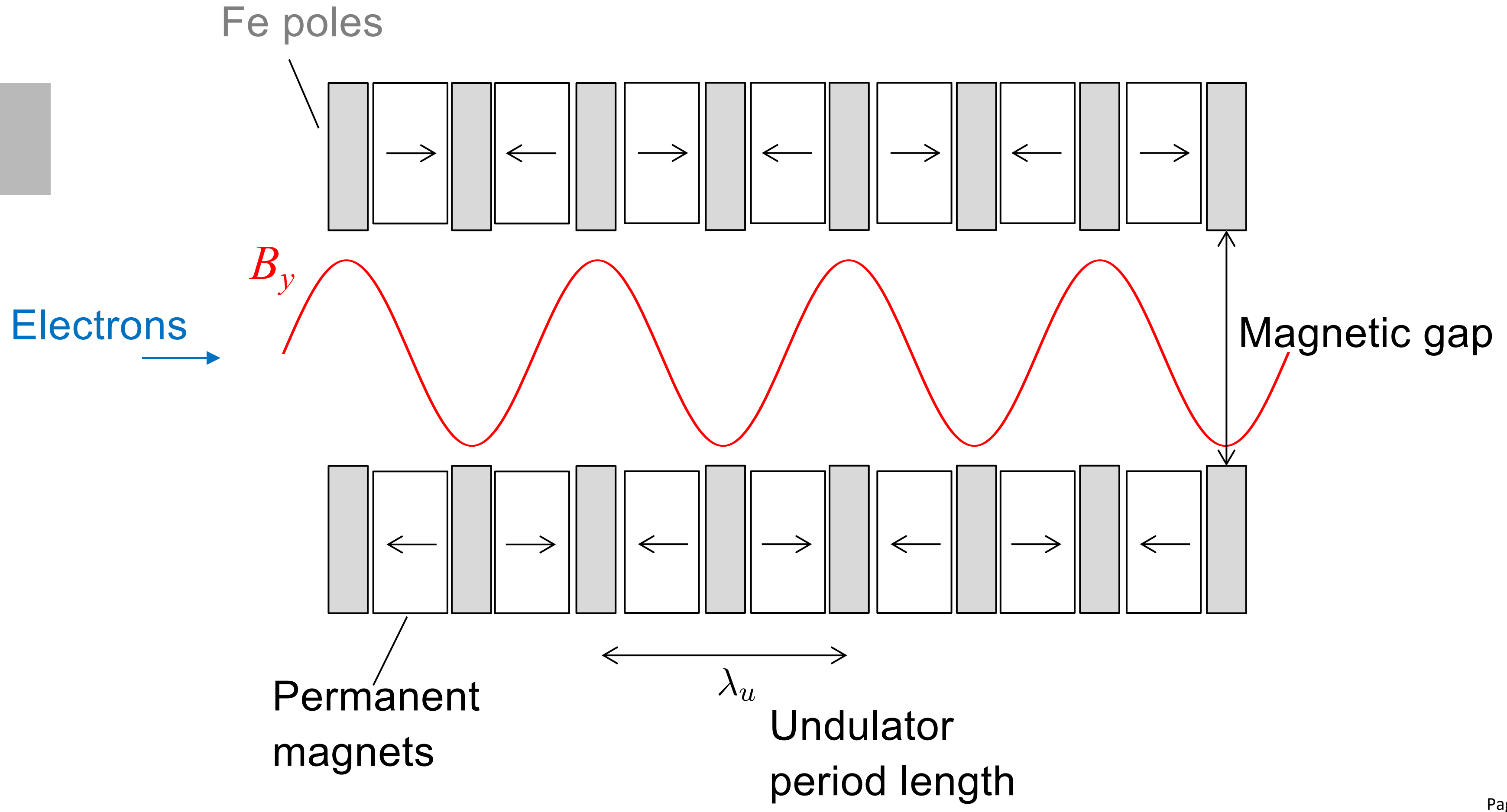


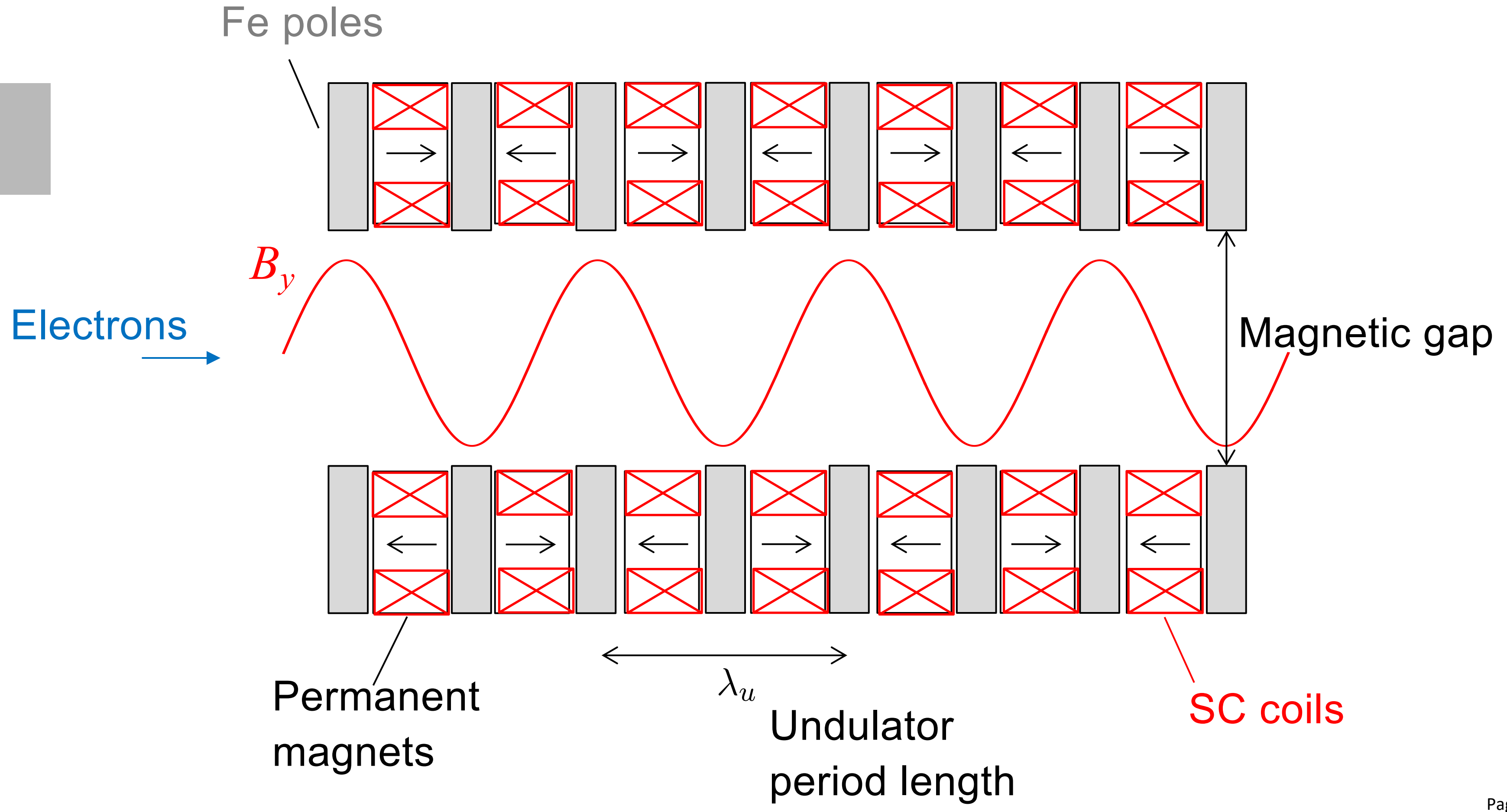




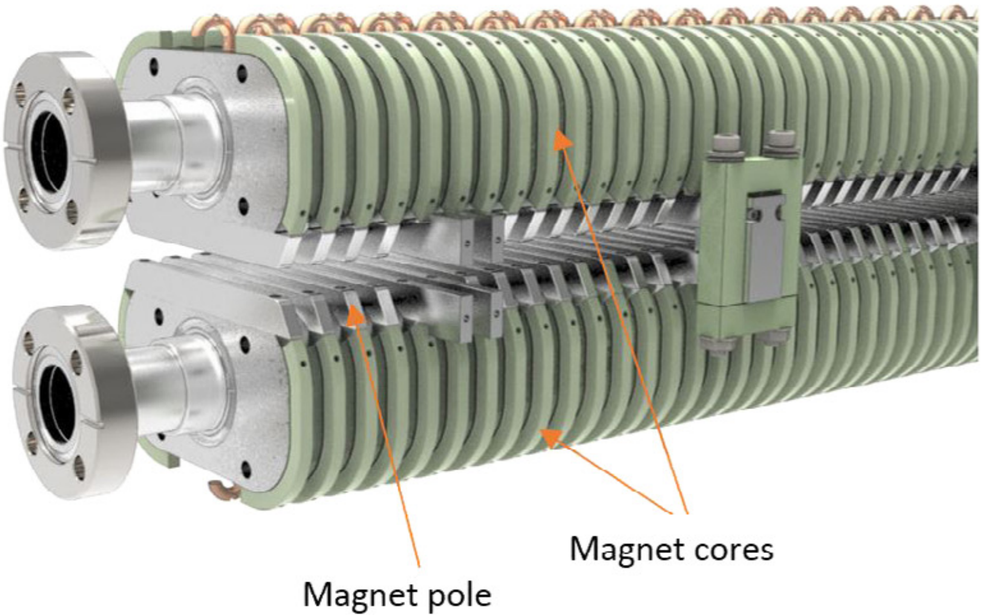
Permanent Magnet Undulator with Fe poles

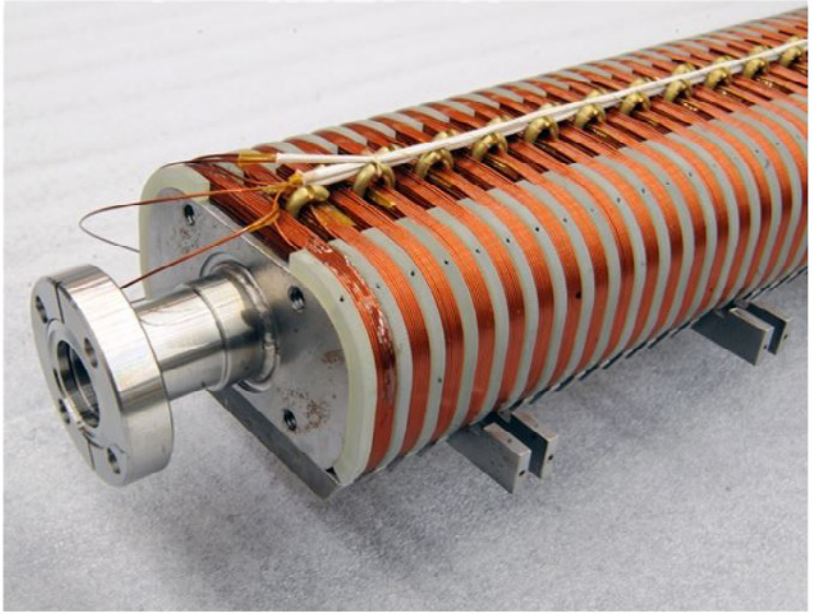


Superconducting Undulator with Fe poles



Superconducting Undulator with Fe poles





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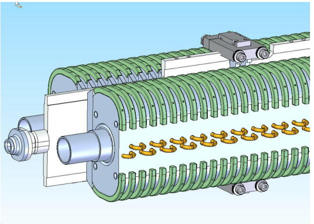
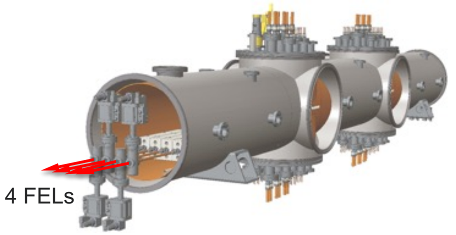
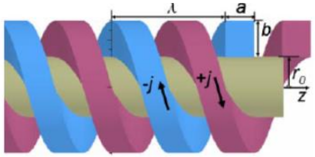
Why SuperConducting Undulators?

- Higher magnetic fields allow superior performance, or reduced undulator length.
- No permanent magnetic material to be damaged by radiation.
- Smaller footprint and simpler K-control than the typical massive adjustable-gap PMU.
- Easily oriented for vertical polarization
- Pure helical undulators are possible
- Compact variable polarisation undulator (replacing Apple)
- Reduced resistive wakefield with a cold bore
- Much lower vacuum pressure limits gas scattering.

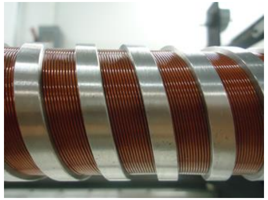




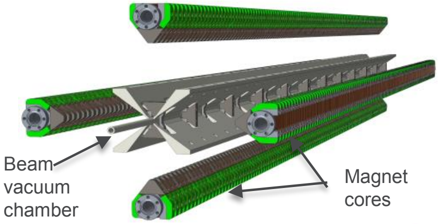
A concept of a cryomodule with four FELs.
Courtesy of J. Fuerst, ANL



Magnetic model of HSCU.



HSCU prototype coil winding.



KIT-Bilfinger NbTi-SCUs

	SCU15	SCU20	HEX-SCW	ANSTO-SCU16	EuXFEL	FLUTE	COMPASS	DLS SCW	Units
Period length	15	20	70	16	18	65	18	48	mm
Full periods	100.5	74.5	29	98	108 * 2	20	14	22.5	#
Max field on axis (min. gap)	0.73	1.19	4.3	1.1	1.82	0.88	1.82	4.2	T
K-Value (approx.)	1.0	2.2	28.1	1.6	3.1	5.3	3.1	18.8	
Location	KARA, KIT	KARA, KIT	NSLS II, BNL, US	Australian Synchrotron ANSTO	EuXFEL, DE	KIT DE	KIT DE	DLS UK	
Status	delivered 2014	delivered 2017	delivered 2022	delivered 2022	production	design	design	design	

The first commercially available undulator worldwide

Courtesy of W.Walter (Bilfinger NOELL)

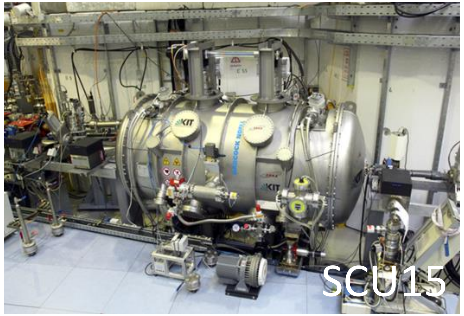
KIT-Bilfinger SCUs @ KARA

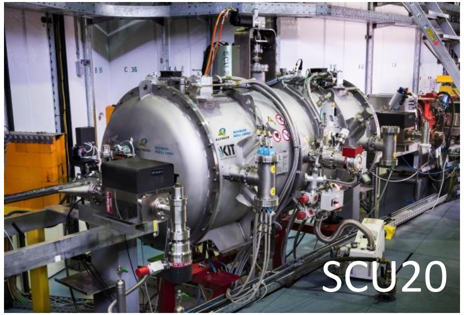
NbTi round wire

Conducting cooling

1.5m magnetic length

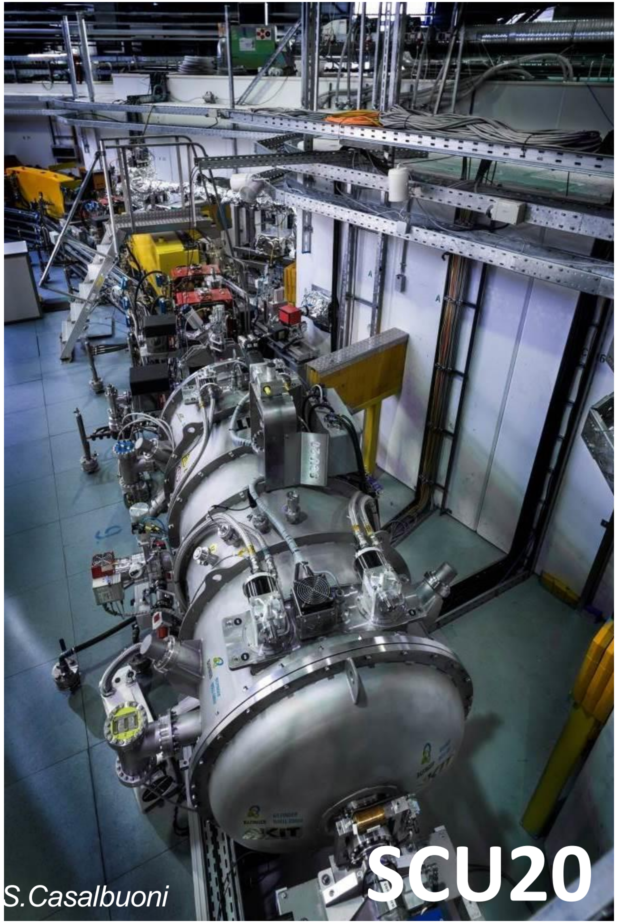
g_m-g_v = 1.0 mm





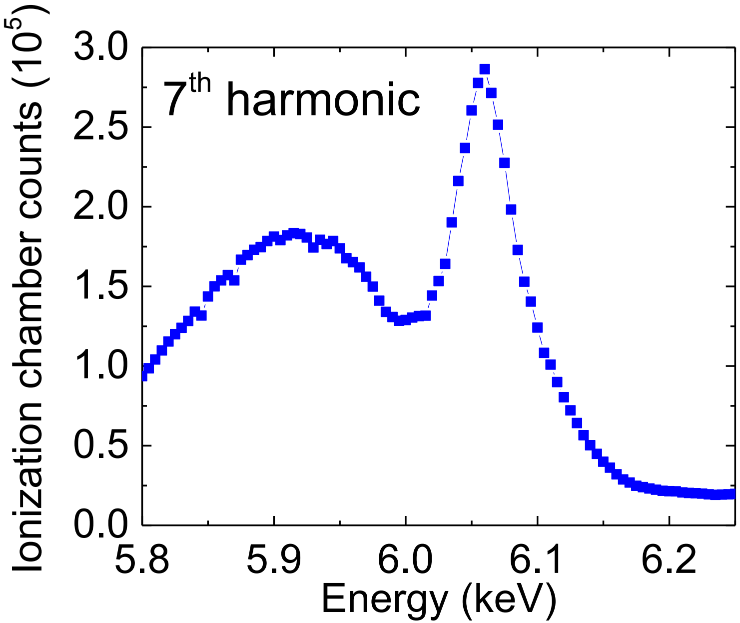
Courtesy of S.Casalbuoni

KIT-Bilfinger SCUs @ KARA



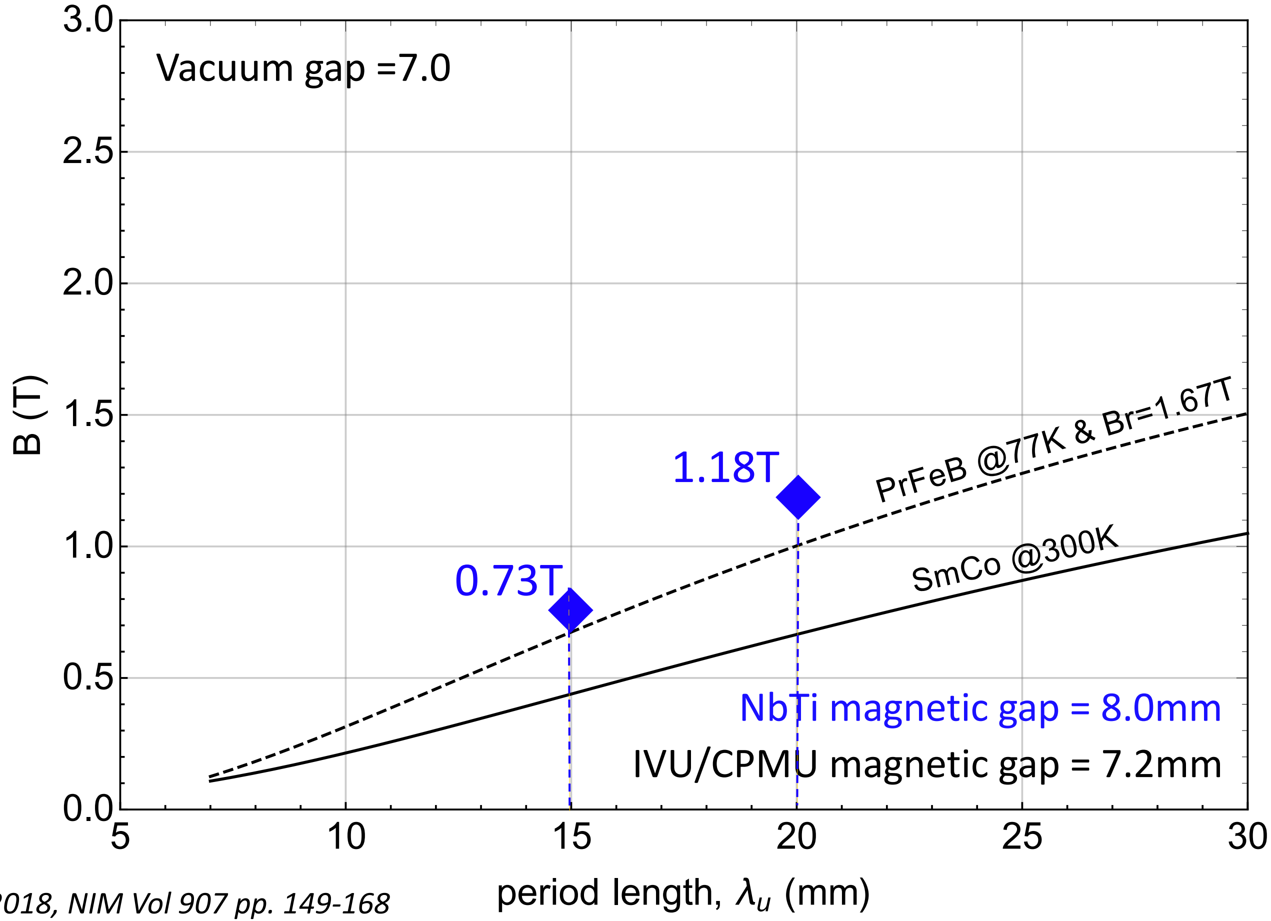
Courtesy of S.Casalbuoni

- Installed in December 2017
- First light January 2018
- Since then it is in operation @ KARA
- No quench observed



S.C. et al., AIP Conf. Proc. 2054, 030025 (2019)

KIT-Bilfinger SCUs @ KARA

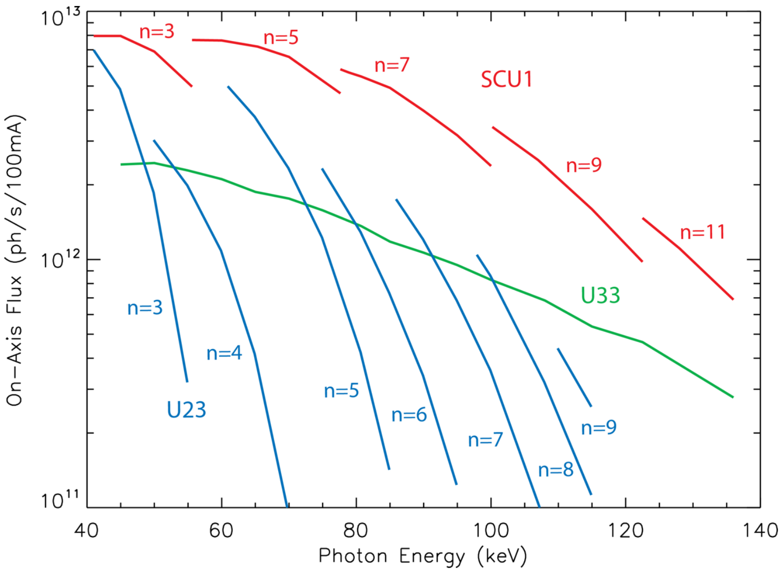


Bahrdt, J. Gluskin, E. 2018, NIM Vol 907 pp. 149-168

ANL NbTi-SCUs @ APS

Courtesy of Y.Ivanyushenkov

ANL NbTi-SCUs @ APS

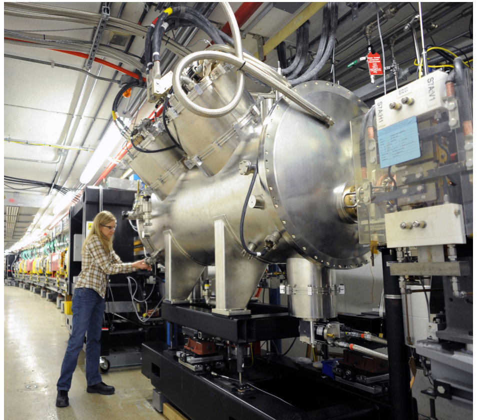


Measured SCU18-1 tuning curves in comparison with those of hybrid undulator U33 (Undulator A) and undulator U23.

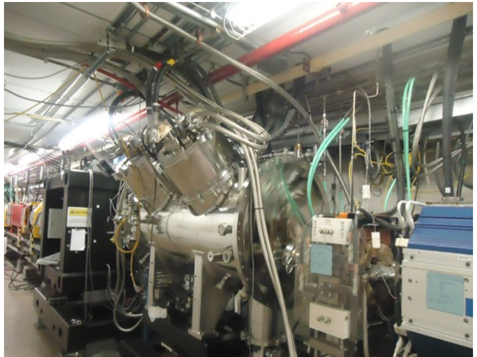
Courtesy of Y.Ivanyushenkov

Operational experience in the APS ring

- SCU field integrals satisfy the physics specifications
- SCU quench produces only small beam motion and does not cause loss of the beam
- Position of the SCU vacuum chamber is stable and does not require realignment
- SCU cryocooler vibrations do not affect beam stability
- SCU operation does not affect the beam lifetime
- Overall SCUs availability for users is 99%



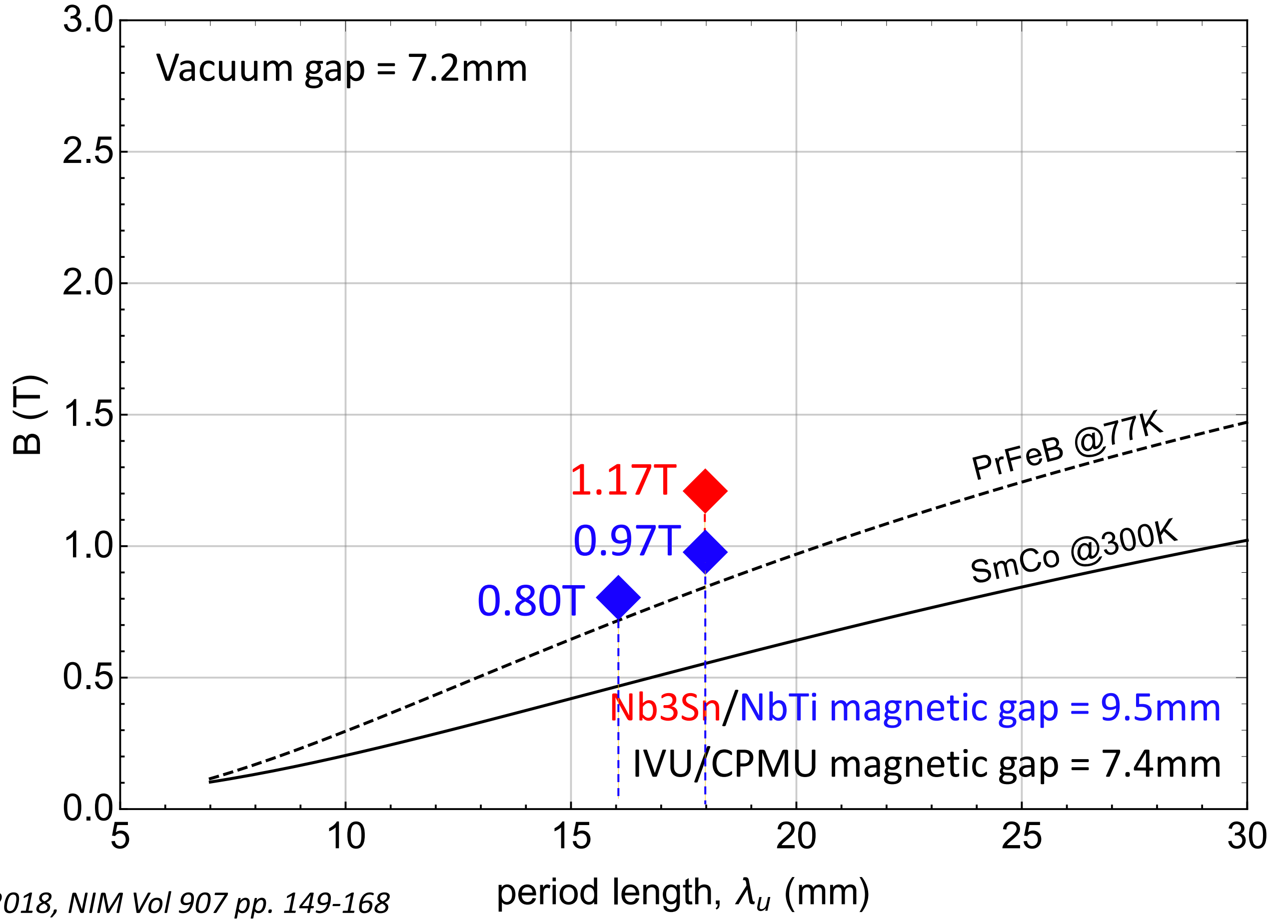
SCU18-1 in Sector 1 of the APS ring.



SCU18-2 in Sector 6 of the APS ring.

Courtesy of Y.Ivanyushenkov

ANL SCUs @ APS



Bahrdt, J. Gluskin, E. 2018, NIM Vol 907 pp. 149-168

Nb_3Sn undulator @ APS

A 3-year project supported by the DOE's Accelerator & Detector Research Program

Collaboration among 3 US National Labs

ANL (lead intuition)

FNAL (heat treatment)

LBNL (quench detection & protection)

Project breakdown:

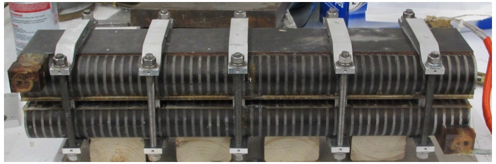
R&D Phase: Build and test short prototypes and scaled to a 0.5-meter lengths

Construct a full-scale magnet (1.1 meters long)
Modify an existing cryostat to accommodate the Nb_3Sn undulator magnets

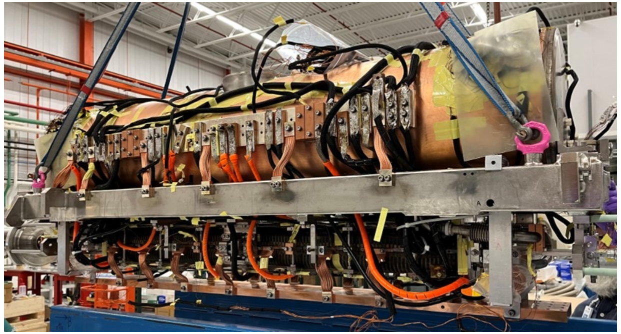
Undulator assembly, testing, magnetic characterizations and installation on the APS

0.084 m

0.5 m



1.1 m

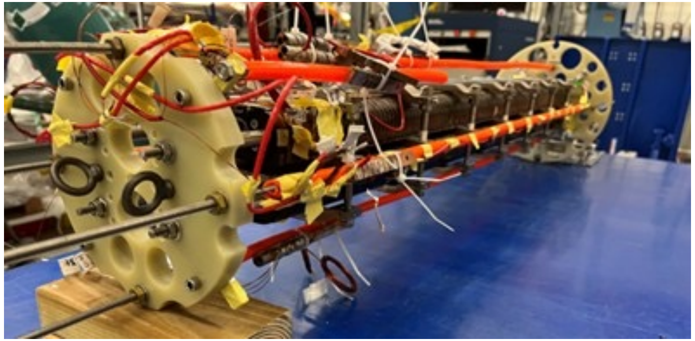


Undulator specifications	NbTi	Nb_3Sn
Undulator Field, T	0.97	1.17
K-value	1.6	2.0
Design current, A (80 and 70% of the I_c) @4.2 K	450	800
Period length, mm	18	18
Magnetic gap, mm	9.5	9.5
Vacuum gap, mm	7.2	7.2
Magnetic length, m	1.1	1.1

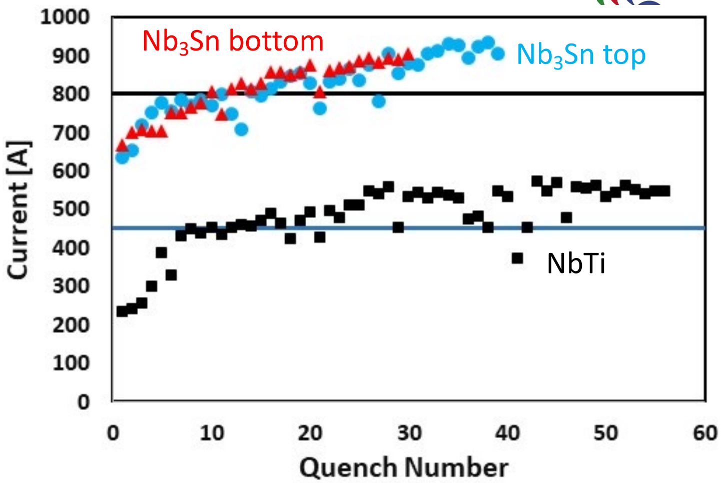
Courtesy of I. Kesgin

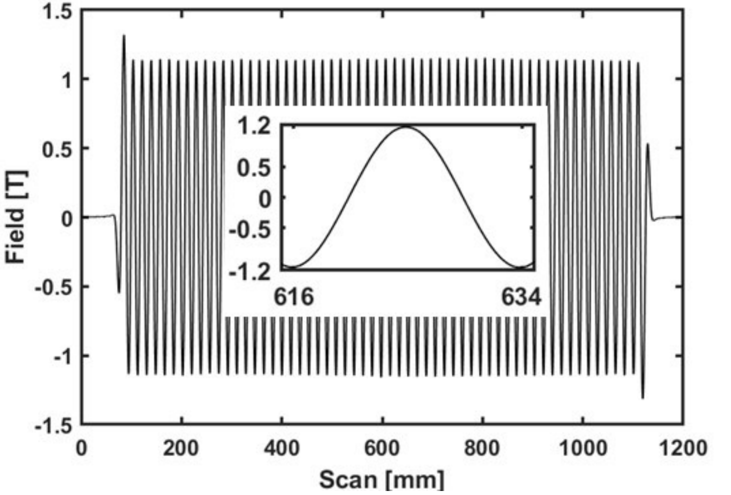
Undulator training & field measurements

Courtesy of I. Kesgin



- 1.1m SCU magnets assembled in undulator configuration with diagnostic elements
- Undulator achieved design field without requiring additional training during the second cooldown
- **Phase error of <6 degrees achieved up to the maximum operating current**





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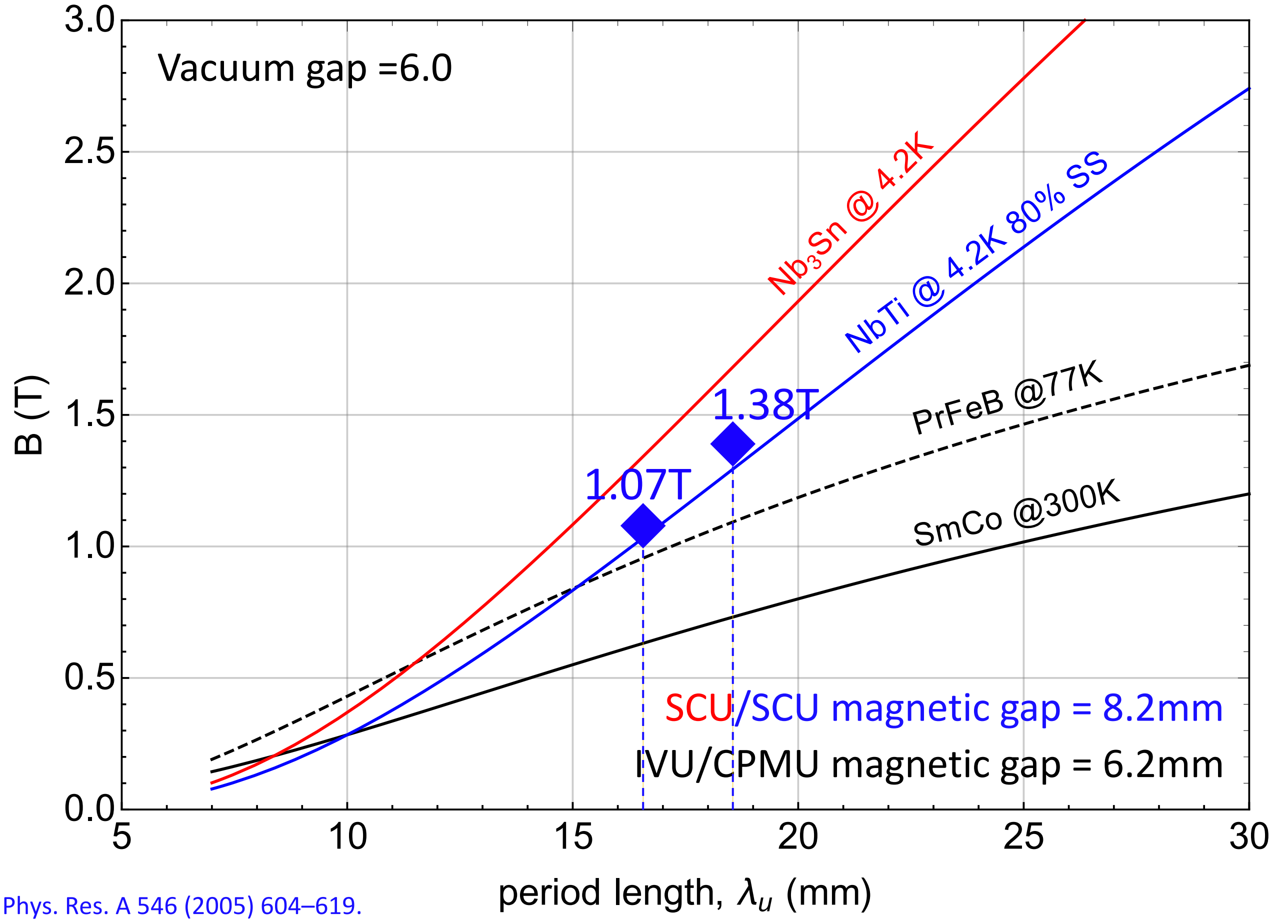
SCUs for APS Upgrade



S. Kim, Nucl. Instr. Meth. Phys. Res. A 546 (2005) 604–619.

SCUs for APS-U(pgrade)

FOUR cryomodules 4.8 m long 20" diameter vacuum vessel with **EIGHT** SCUs:

- Two with *inline* SCUs
  (one long undulator source)
- Two with *canted* SCUs
  (two canted undulator sources)

Location	Conf	Vacuum gap	Magnetic gap	Period length	Length
		mm	*mm*	*mm*	*m*
01-ID	Inline	6.0	8.2	16.5	2x1.9
11-ID	canted	6.0	8.2	16.5	2x1.5
20-ID	Inline	6.0	8.2	16.5	2x1.9
28-ID	canted	6.0	8.2	18.5	2x1.3

Courtesy of Y.Ivanyushenkov

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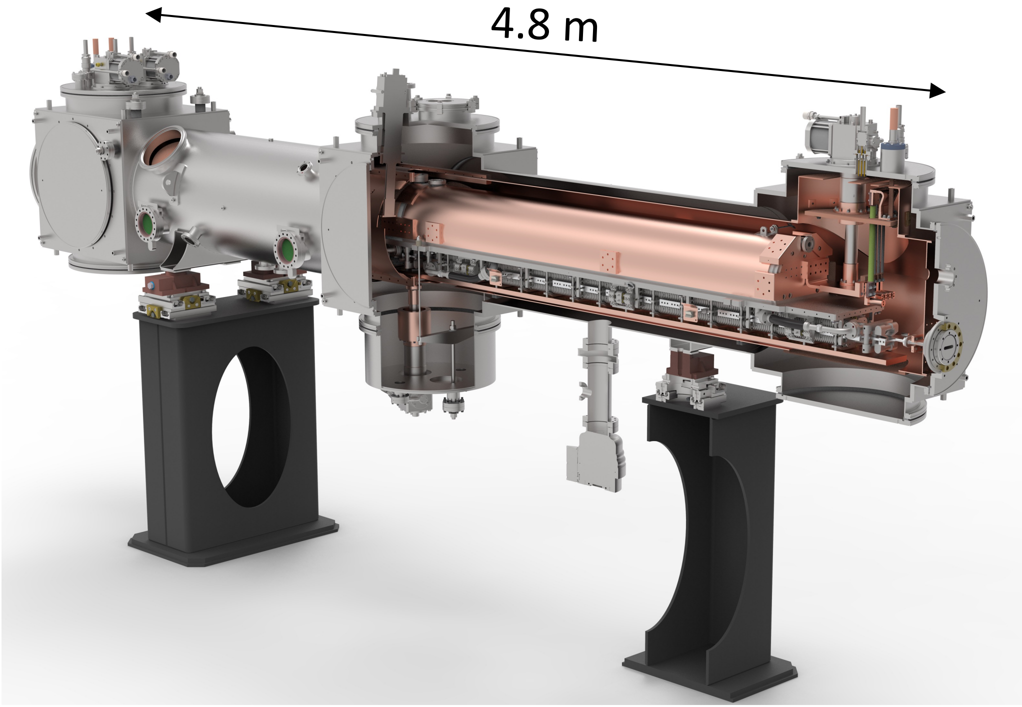

Design model of APS-U ID straight section with an SCU cryomodule: single thermal shield; off-shelf vacuum components; three thermal stages (4K – 20K – 40K); 6(+1) cryocoolers;

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Courtesy of Y.Ivanyushenkov

Cryostat vacuum vessel

SCUs for APS-U(pgrade)

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LHe Tank

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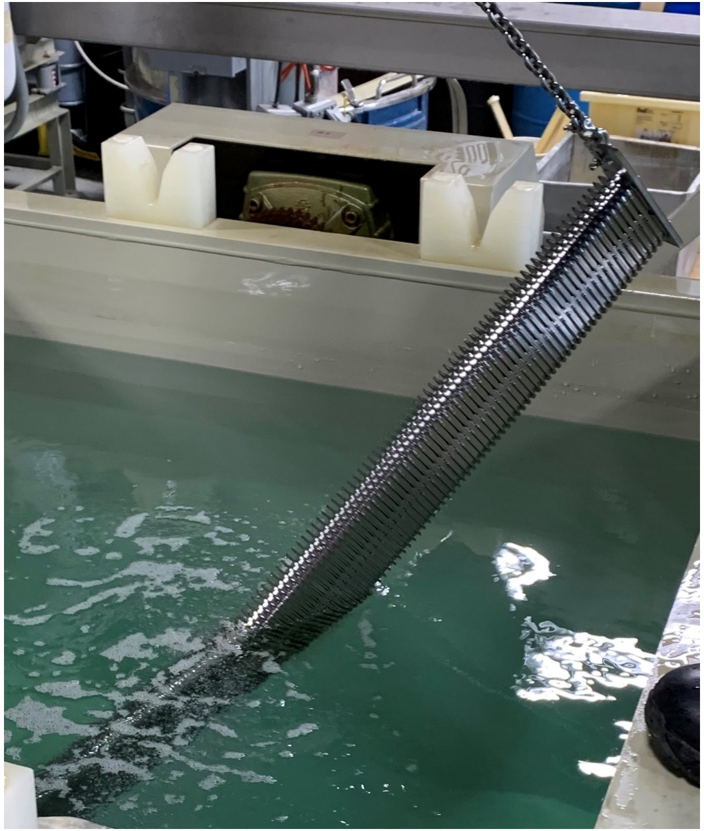

Core chemical polishing

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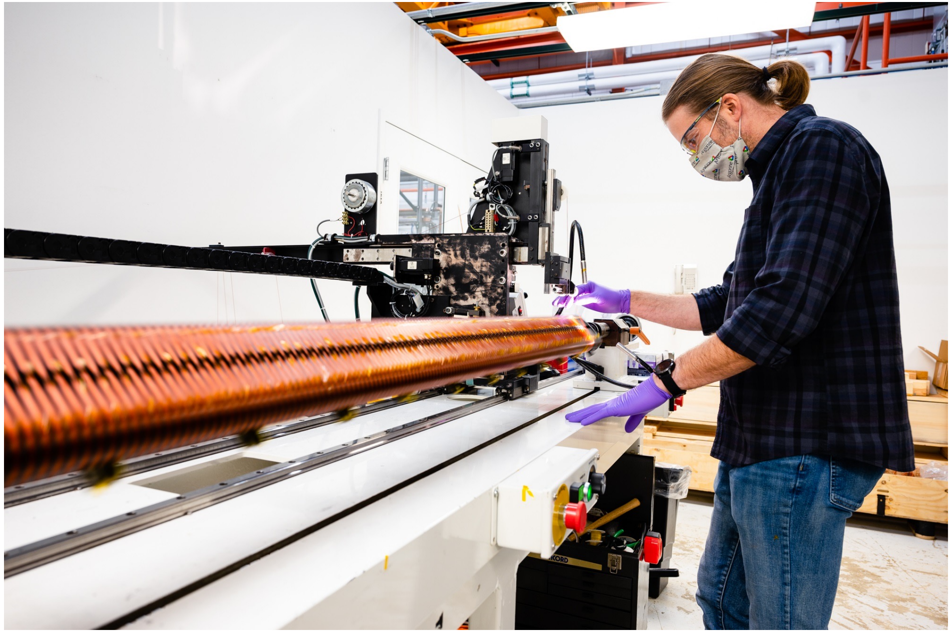

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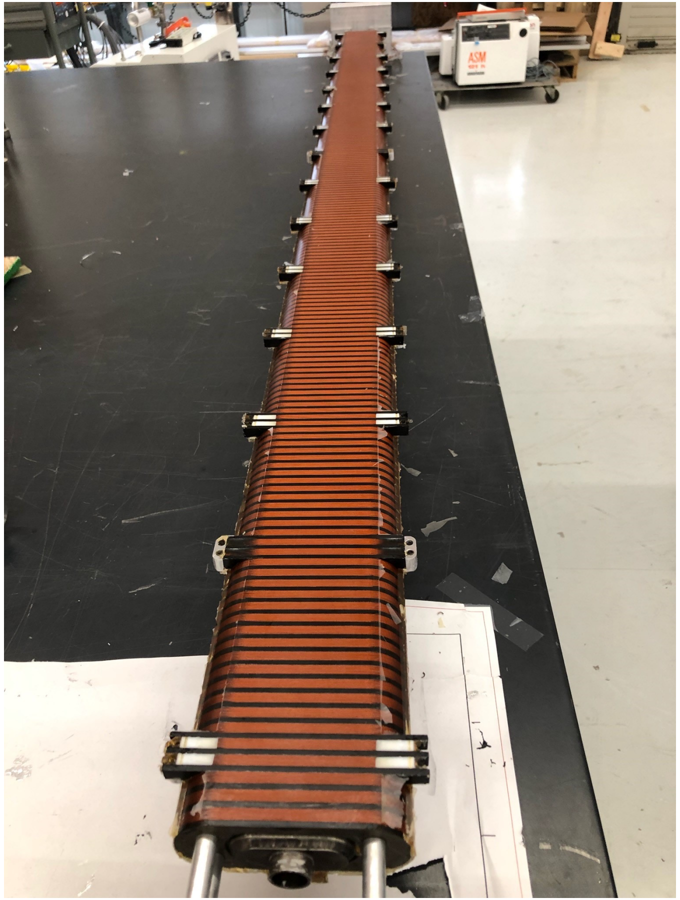

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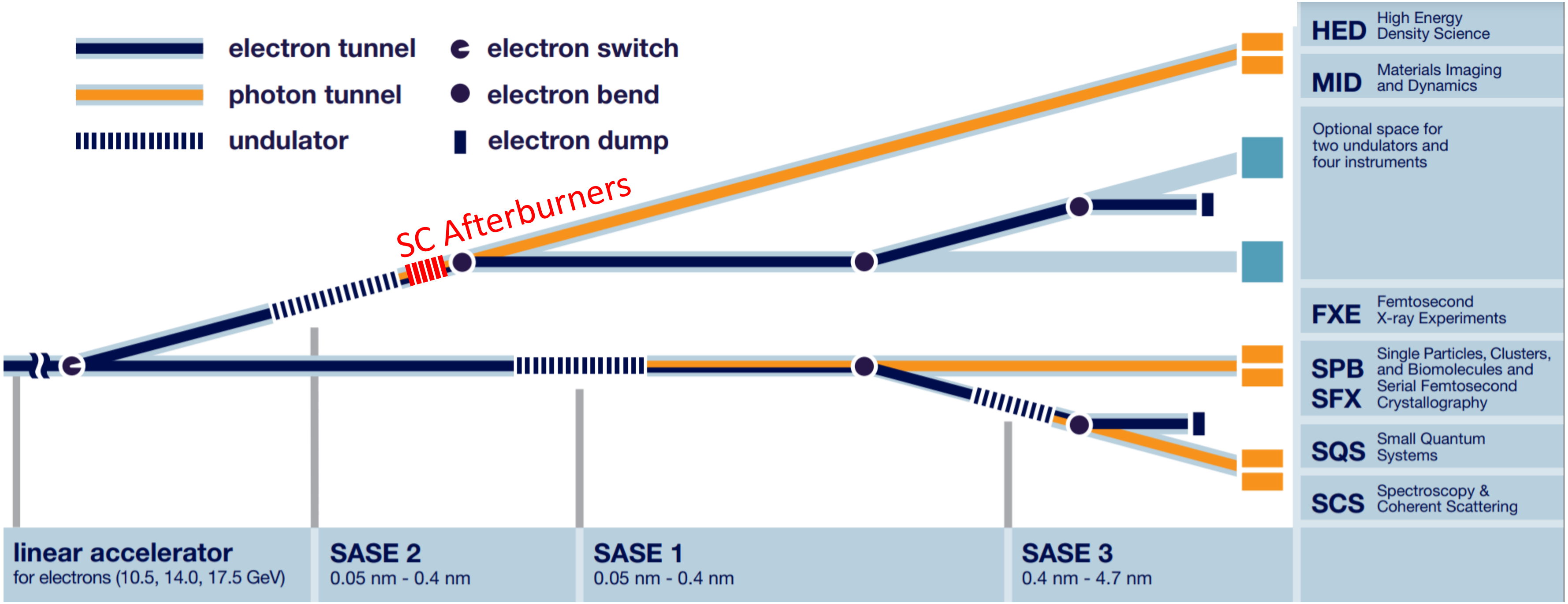
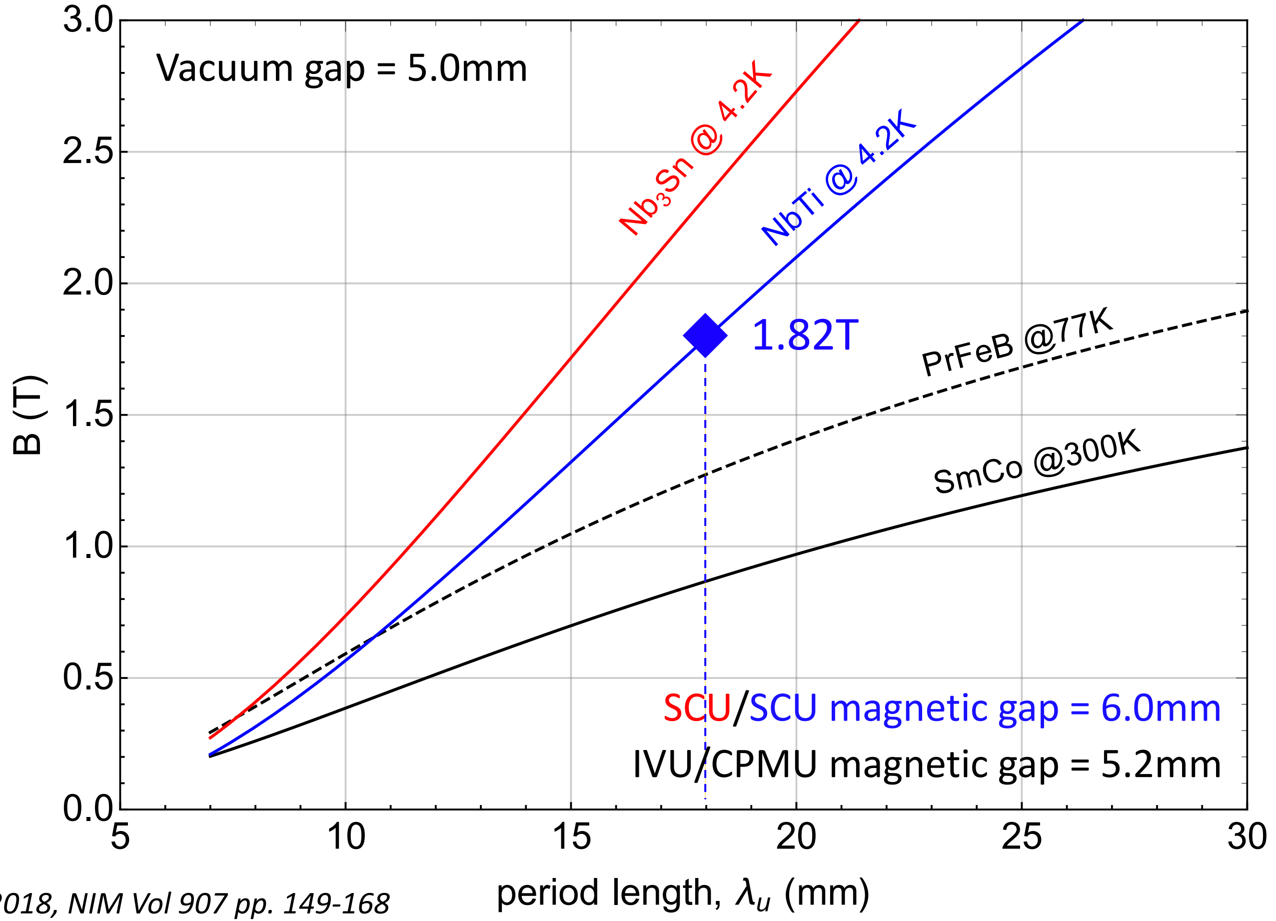
EUXFEL SASE2 SC Afterburner

1. Enabling lasing at photon energies up to ~60 keV with 17.5GeV linac
2. After the upgrade to CW linac (<8GeV) the SCA will allow to cover the same photon energy then today (3.1-24.8keV)



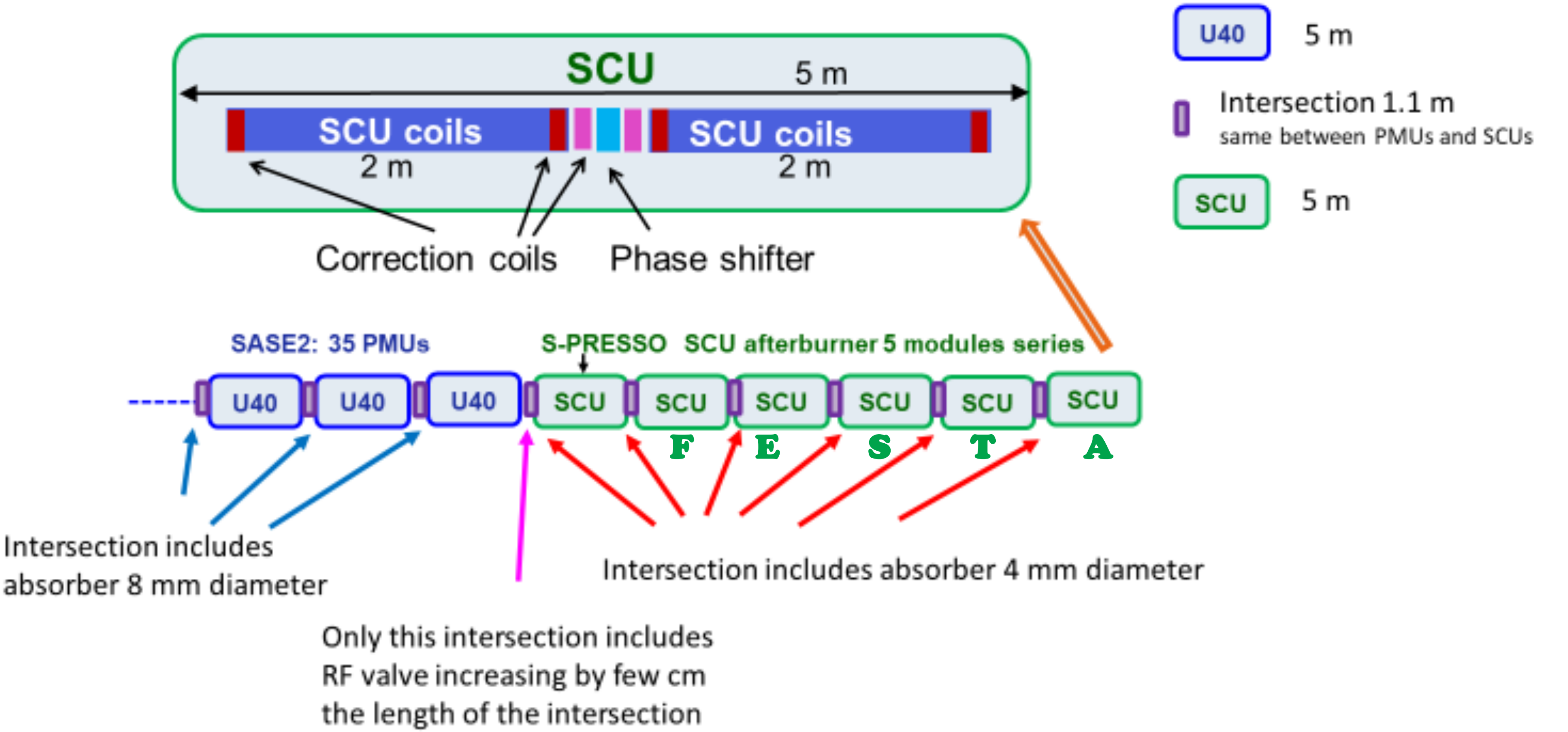
Courtesy of S.Casalbuoni

EUXFEL SASE2 SC Afterburner



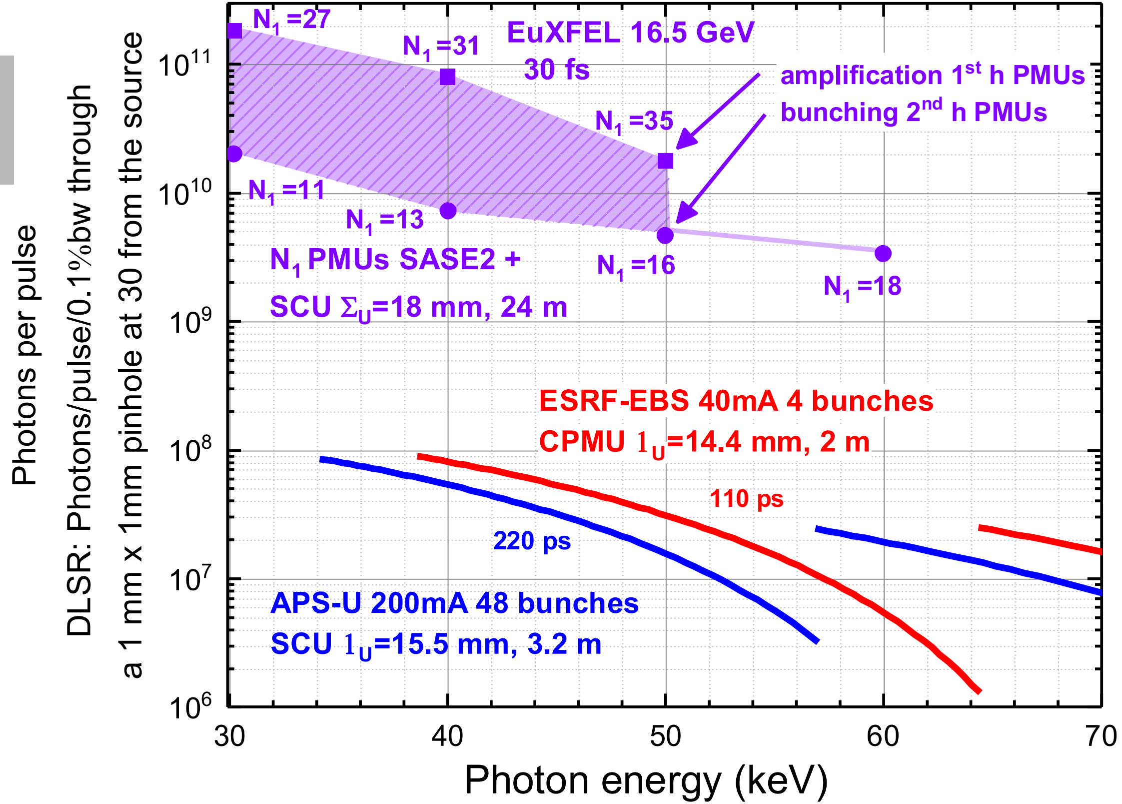
Bahrdt, J. Gluskin, E. 2018, NIM Vol 907 pp. 149-168

EUXFEL SASE2 SC Afterburner



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

EUXFEL SASE2 SC Afterburner



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

Figure 2. Photons per pulse generated by the afterburner, made of six SCU modules with 18 mm period length and a magnetic length of 24 m, are shown as a function of the photon beam energy. The calculation has been done using the code GENESIS 1.3 v.2 [8], with the electron beam parameters shown in Table 1. The number of photons per pulse are compared to the one calculated using SPECTRA [9] from typical short period undulators at the ESRF-EBS [10] and APS-U [11] through a pinhole of 1 mm × 1 mm at 30 m from the source.

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

Superconducting undulator PRE-SerieS mOdule

SUPERCONDUCTING UNDULATOR PRE-SERIES MODULE

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;
- to measure the contribution of the SCUs to the FEL amplification process at specific photon energies;
- To test harmonic configurations at larger photon energies up to 60keV;

SPECs:

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

Courtesy of S.Casalbuoni

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

Overview

- Synchrotron radiation sources
- Why SuperConducting Undulators (SCU)?
- Large SCU projects ongoing in EU & US:
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  - The afterburner for SASE2 at the EuXFEL
  - SLAC-ANL FEL SCU Project
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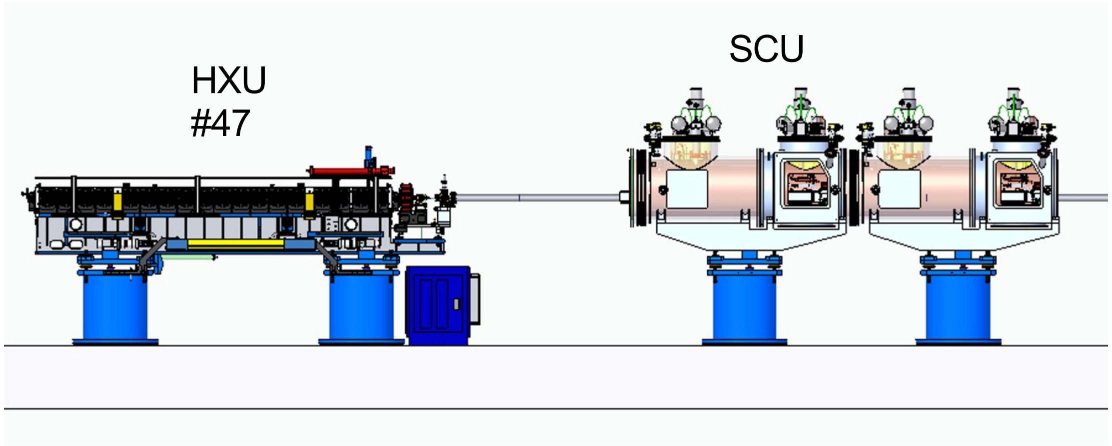
SLAC-ANL FEL SCU Project

ANL and **SLAC** team together to design, build and test *21mm period length* **NbTi** SCU at the end of the LCLS Hard X-ray Undulator (HXU) beam line at SLAC.

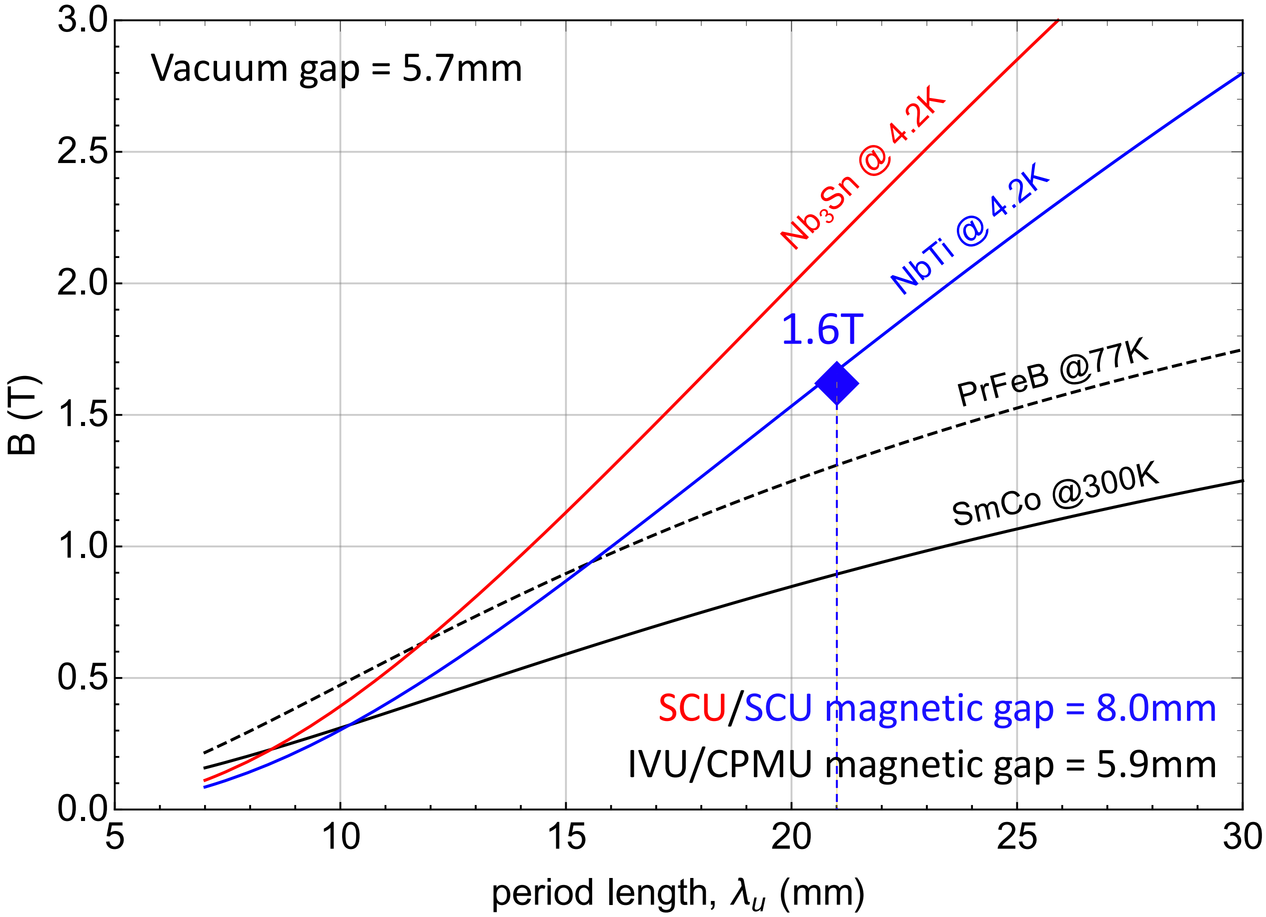


Courtesy of D.Nguyen

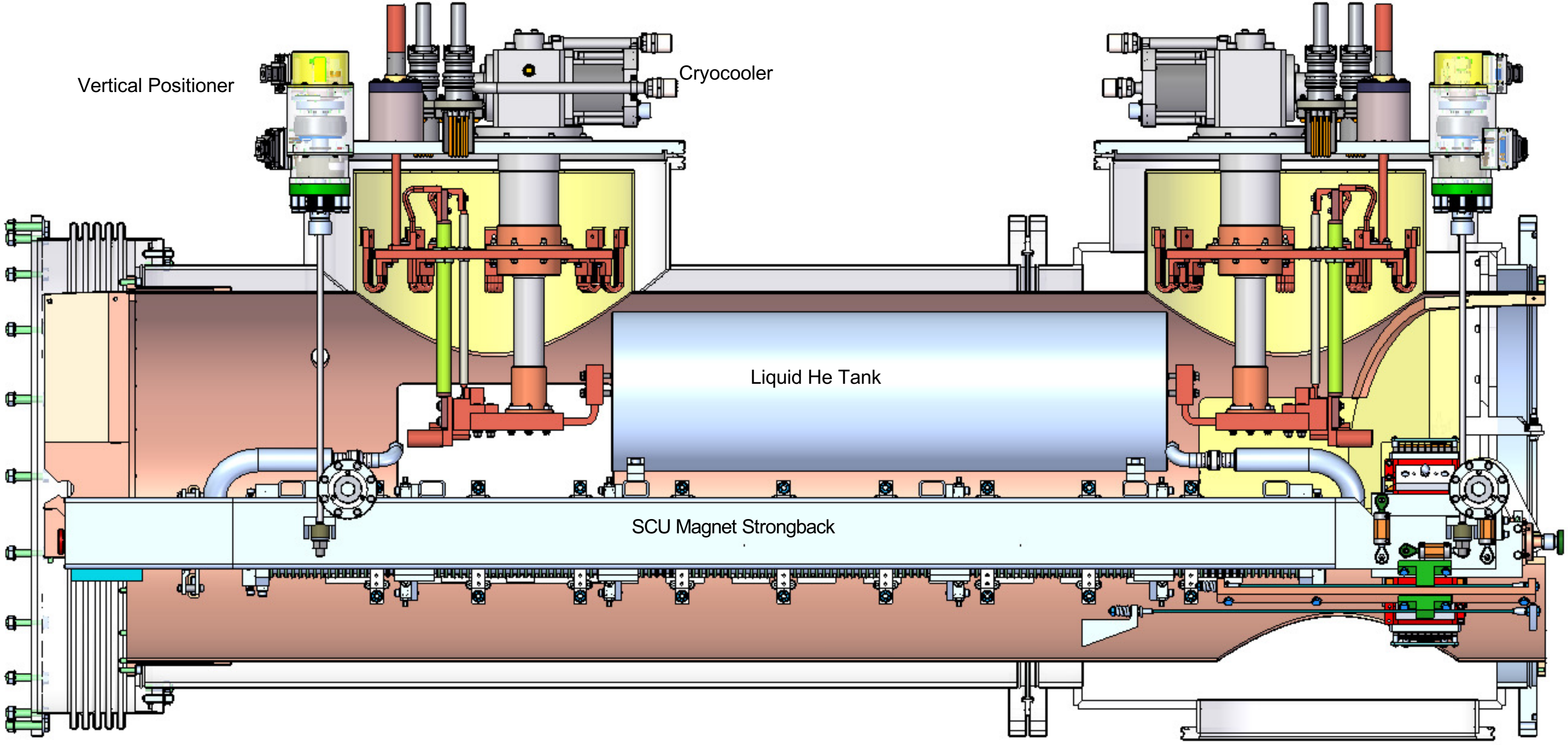
OBJECTIVES:

- Develop an SCU design with integrated beamline components (quad, BPM, phase shifter)
- Demonstrate beam-based alignment (BBA) to micron-level precision
- Demonstrate FEL gain in SCUs with electron beams pre-bunched in the HXUs
- Select an SCU period that resonates with HXUs over the entire LCLS tuning range.

SLAC-ANL FEL SCU Project



FEL SCU Cryomodule Design

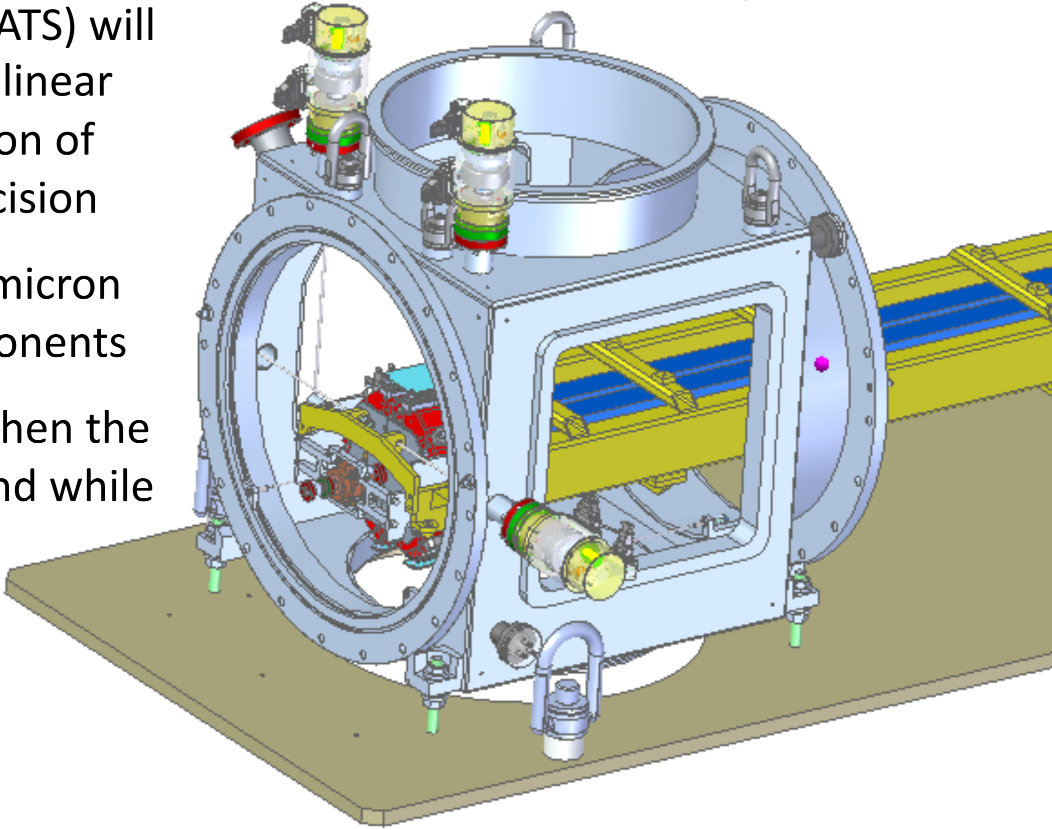


Courtesy of D.Nguyen

Prototype Fabrication & Assembly

- Precision Alignment Test Stand (PATS) will test the ability of the direct-drive linear actuators in controlling the position of SCU magnets to micron-level precision
- PATS will be used to validate the micron precision alignment of SCU components
- SCU motions will be monitored when the chamber pressure is evacuated and while the SCU is cooled to cryogenic temperatures.

Precision Alignment Test Stand



Courtesy of D.Nguyen

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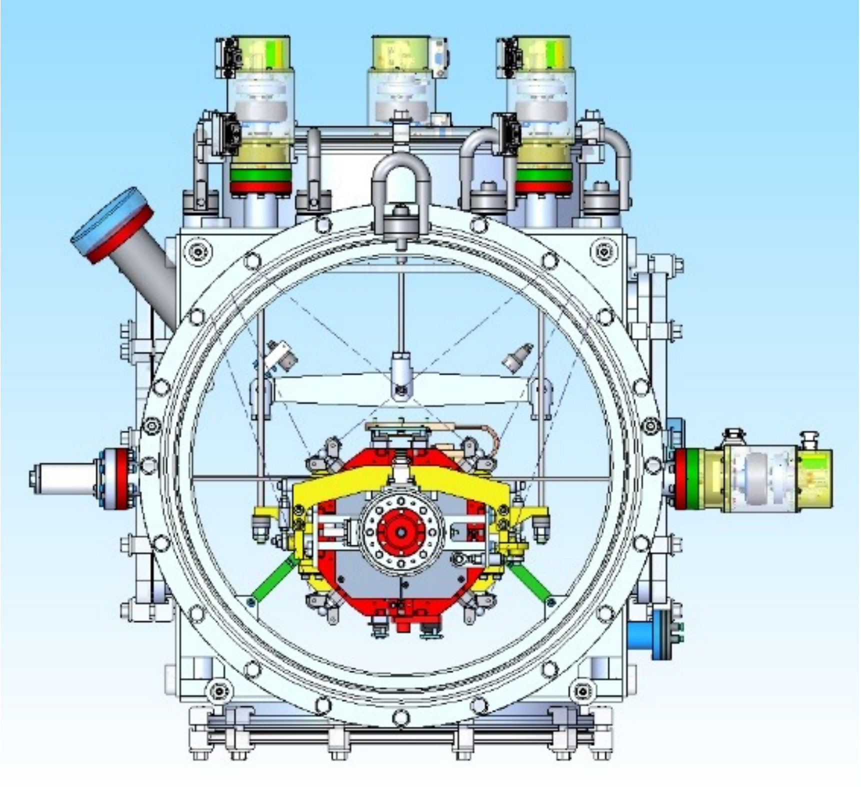
PATS end view showing optical paths (---)



Courtesy of D.Nguyen

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IPAC23

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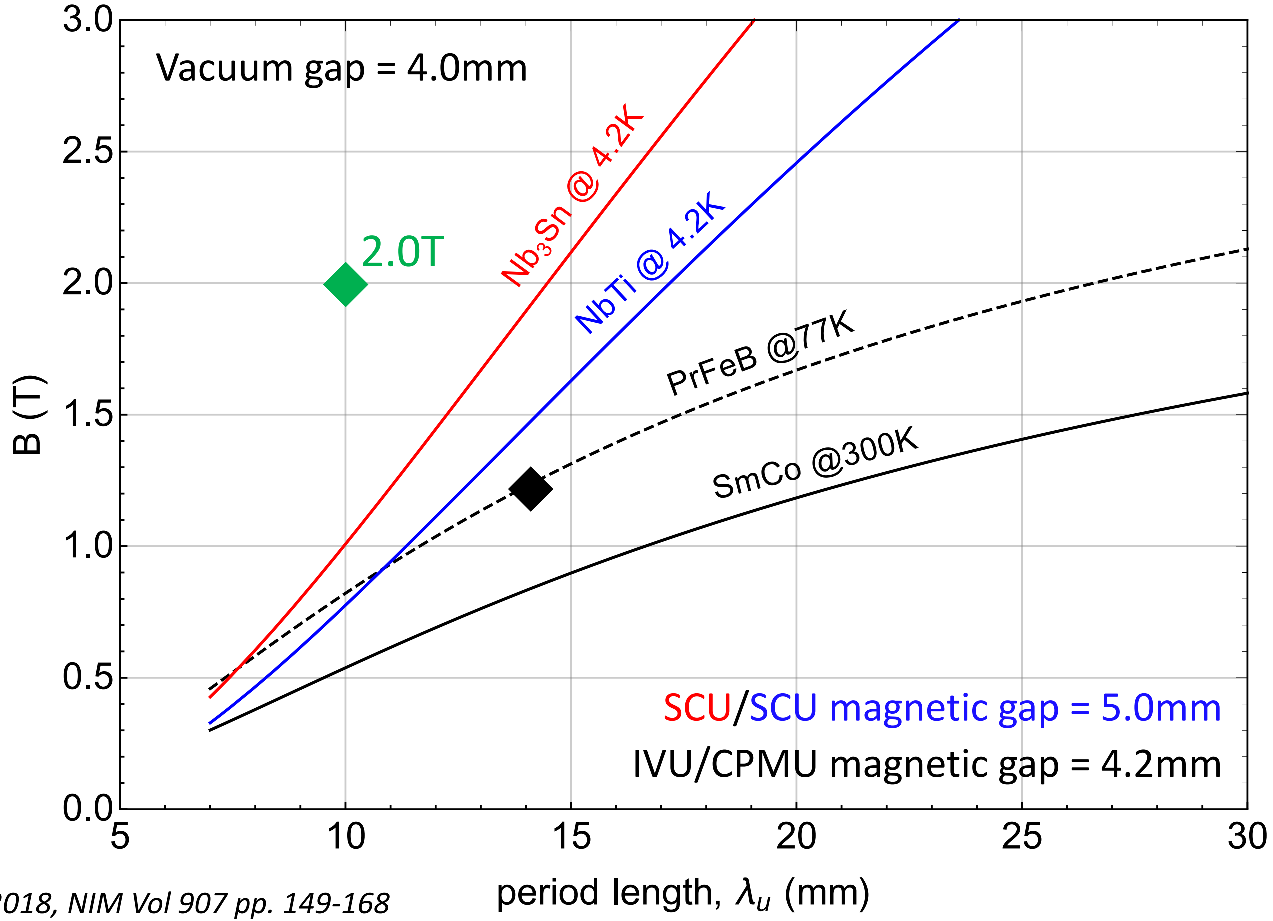
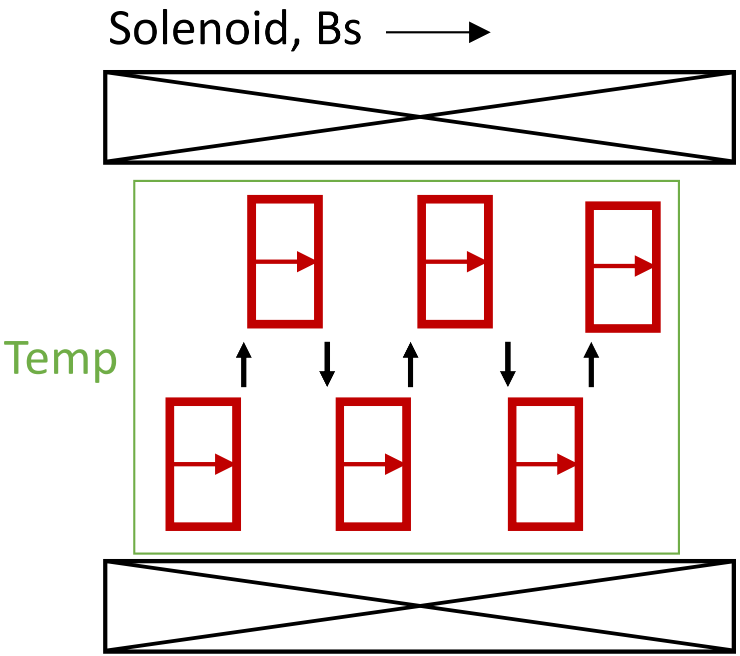
I-Tomcat beamline of SLS2.0



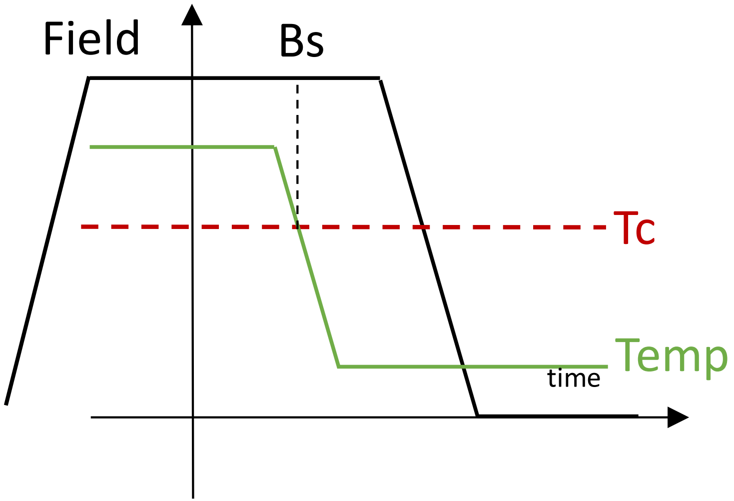
Bahrdt, J. Gluskin, E. 2018, NIM Vol 907 pp. 149-168

Superconducting Staggered Array Undulator



GdBCO Tc=92K

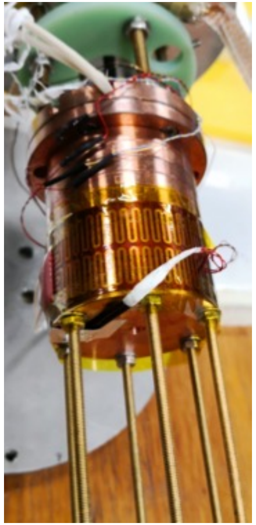
Example of *field cooling* magnetisation



T. Kii, et al.: Proc. FEL2006 (2006) p. 653.

Samples Overview

Bulk Lab Sample #1

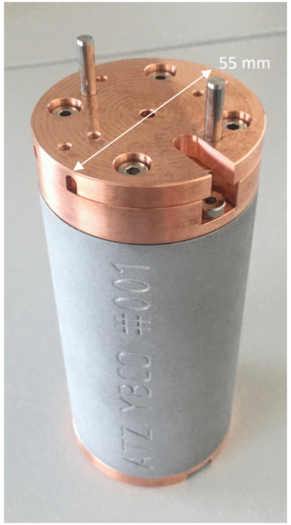


6mm gap

Bulk Lab Sample #2

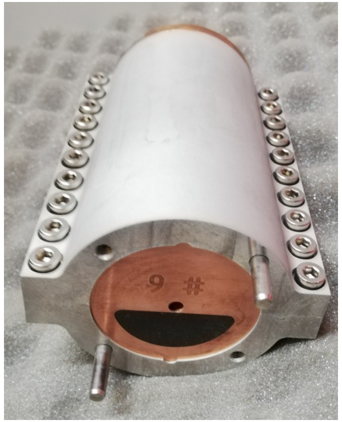
4mm gap

Bulk Industrial Sample #1



4mm gap

Bulk Industrial Sample #2



4mm gap

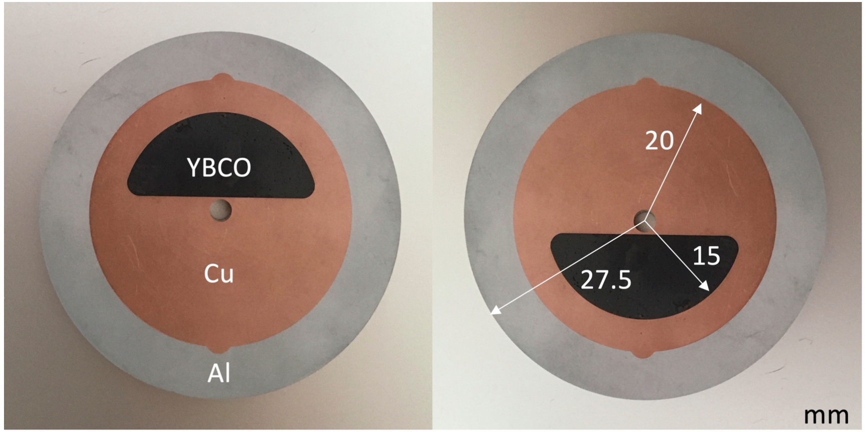
Bulk Industrial Sample #3

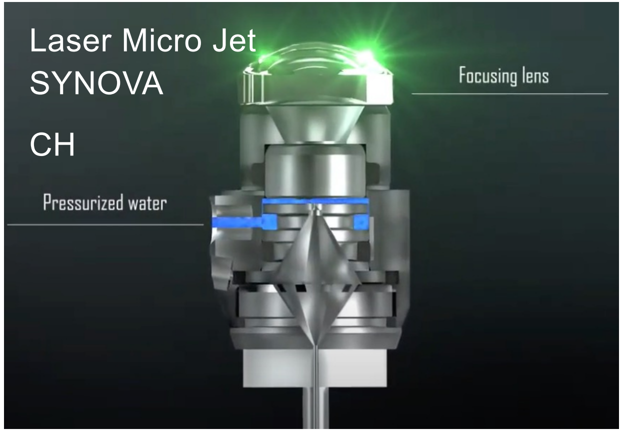
4mm gap

2019

2023

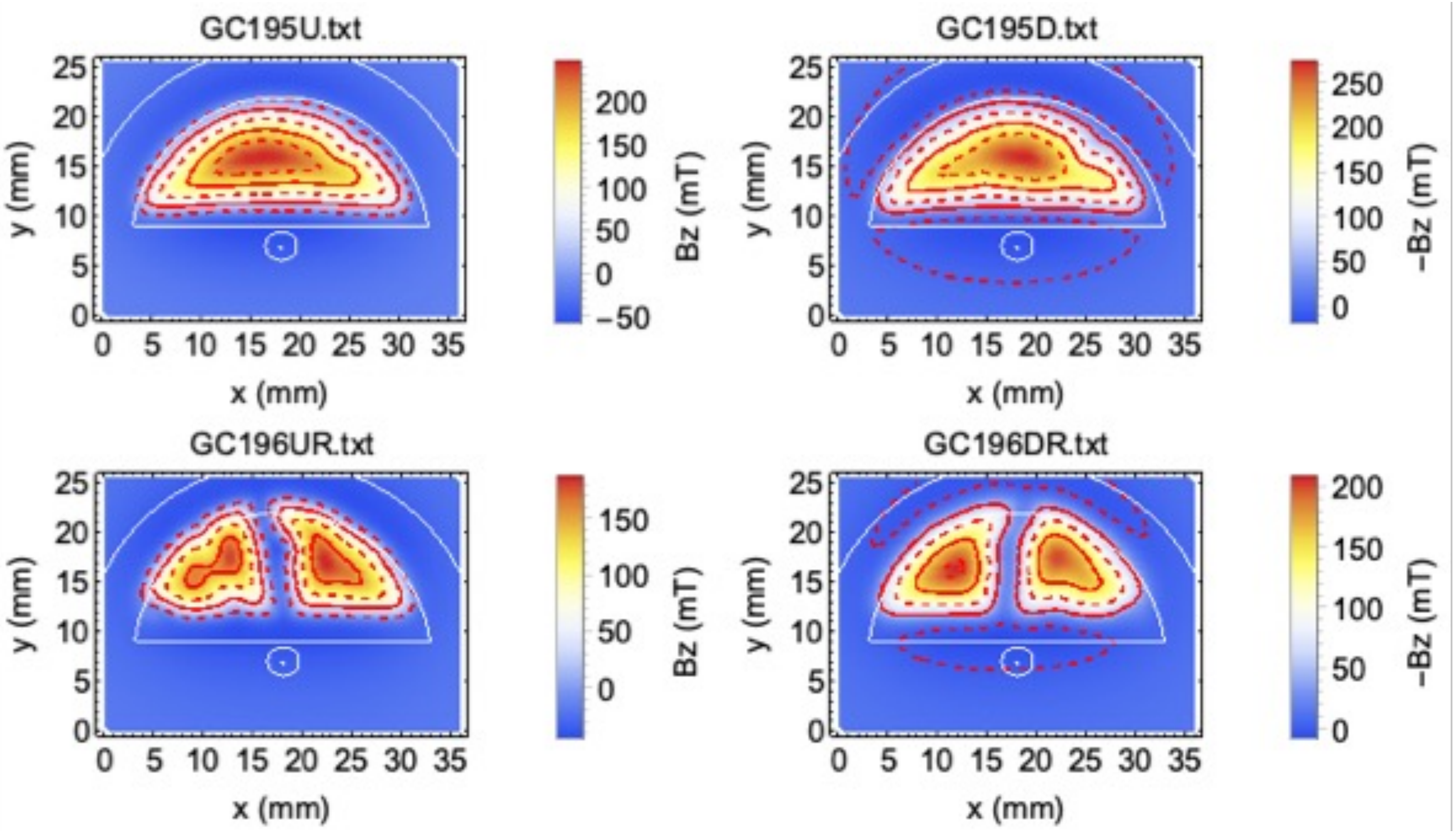
Industrial Sample





The HTS crystals are embedded (schrink-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
(in the picture only a cross section)

2D Field map @ LN2



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Pre-sorting / Stacking

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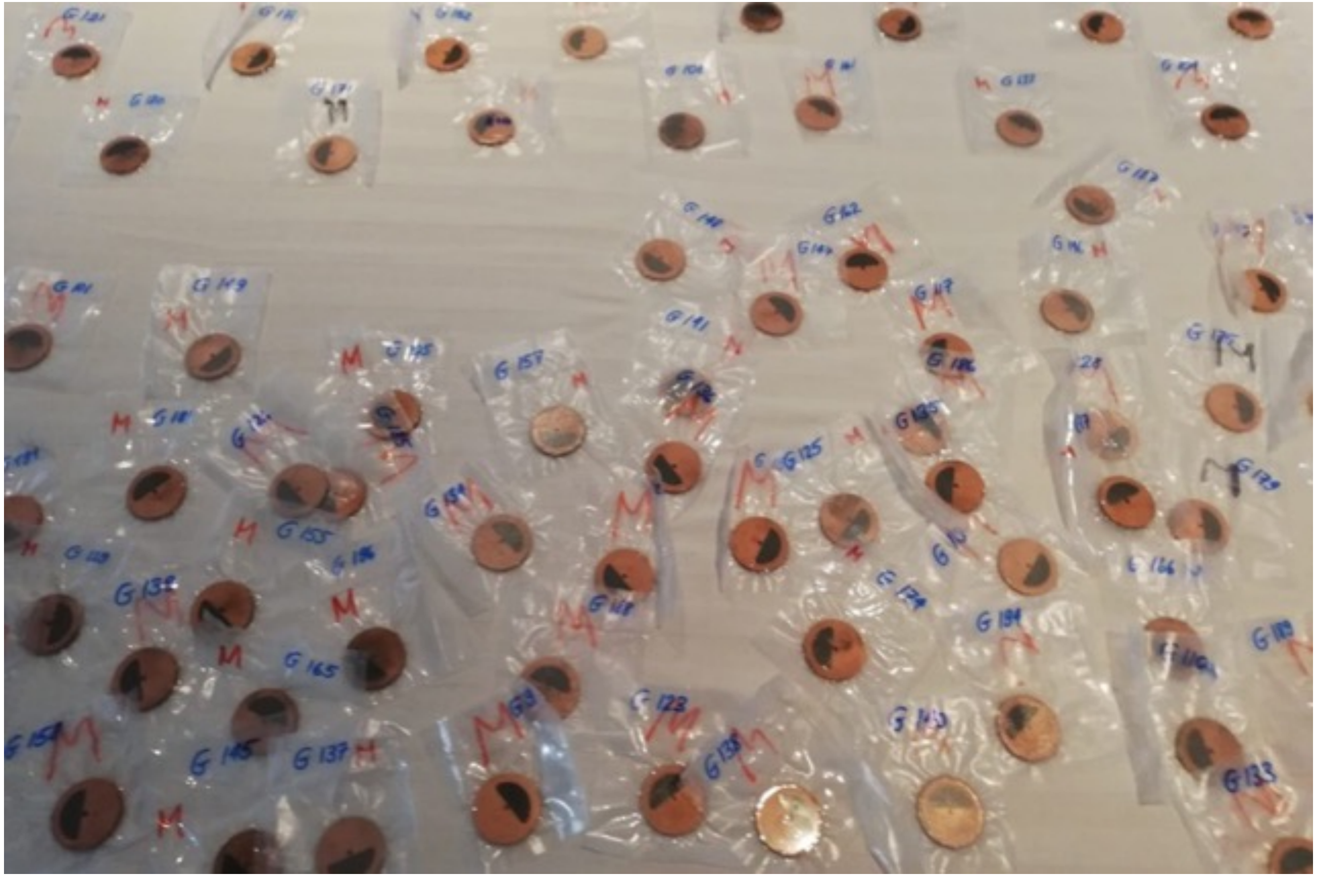
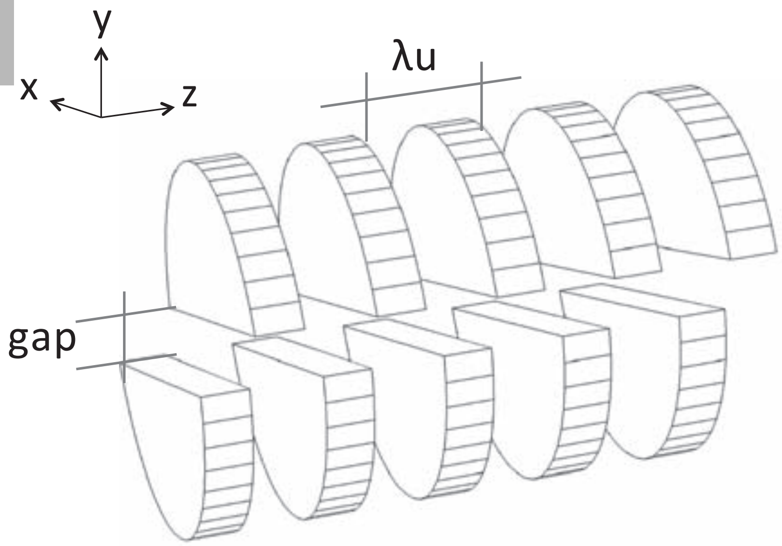
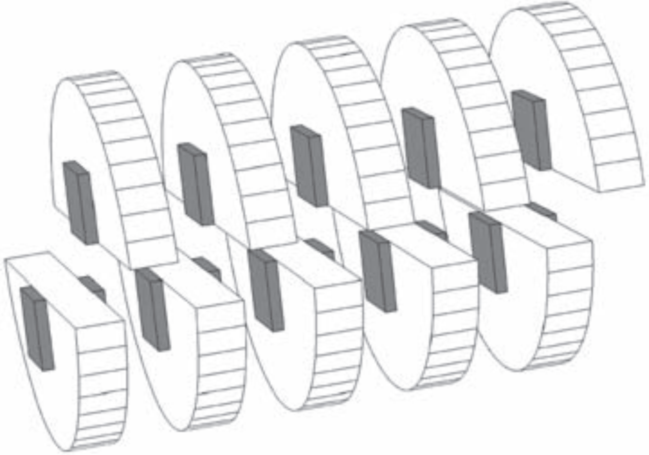
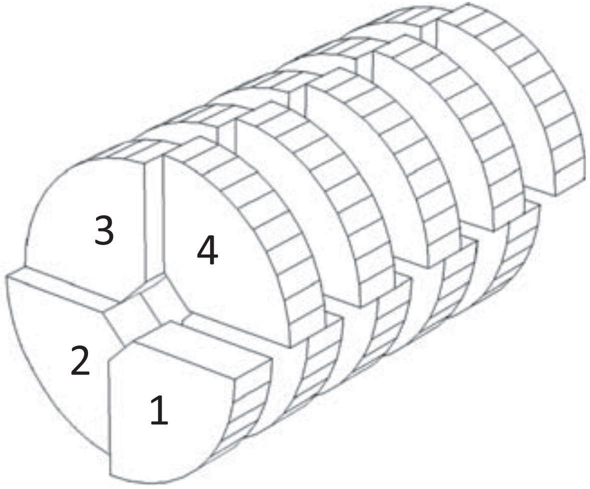
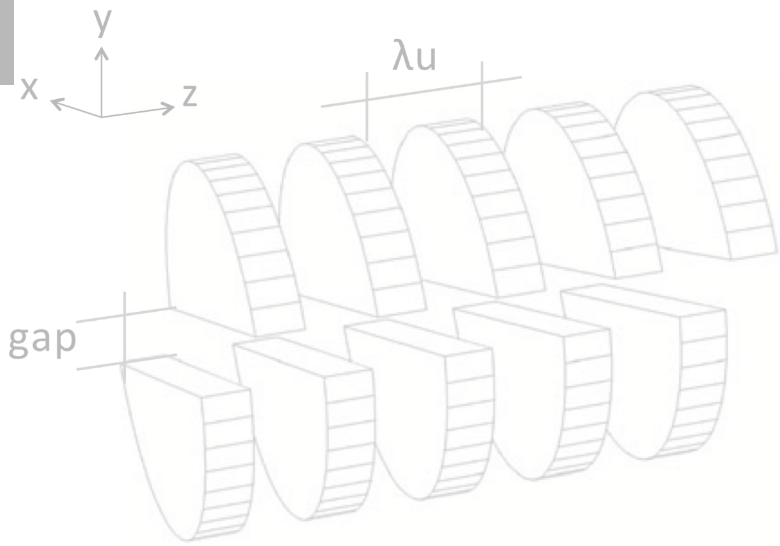



y
x
z
λu
gap




3
4
2
1



y
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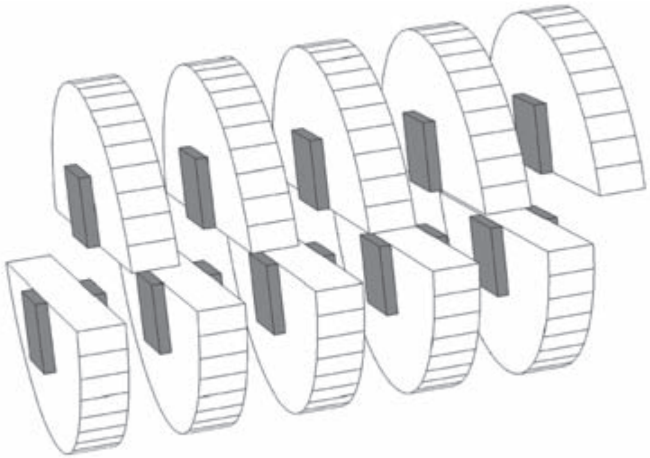
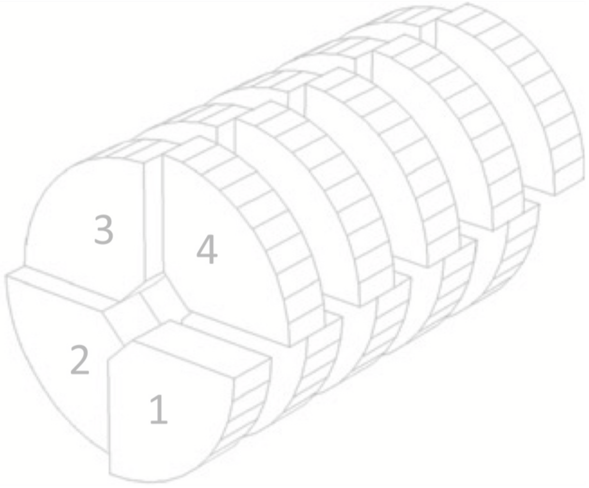
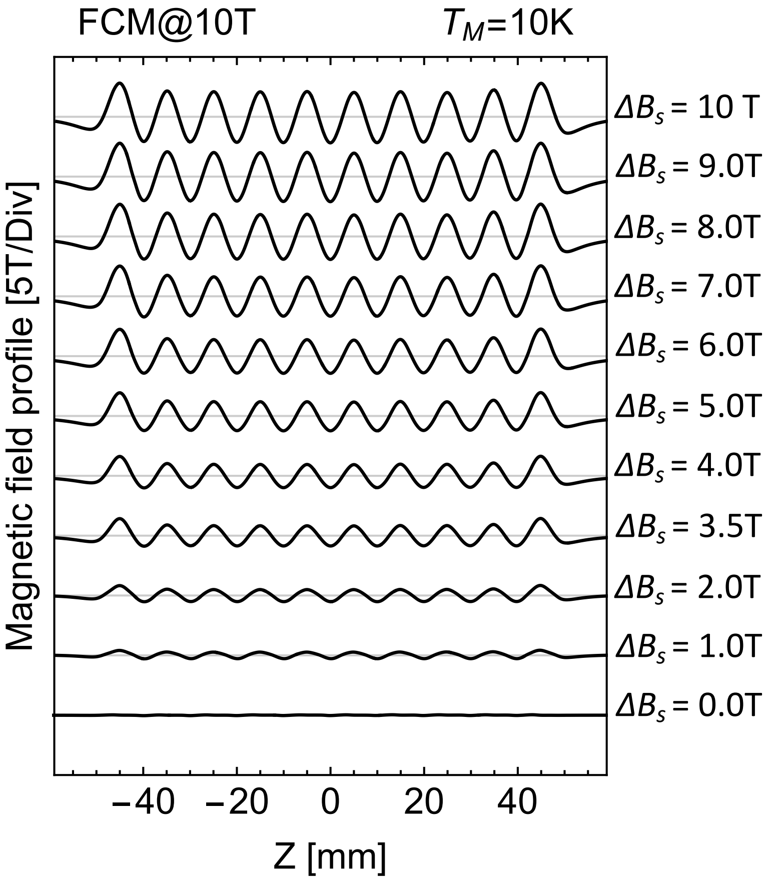




3
4
2
1

Planar Hybrid: Nippon Steel



Supercond. Sci. Technol. 36 (2023) 05LT01

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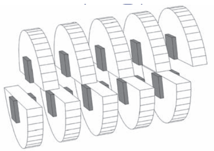
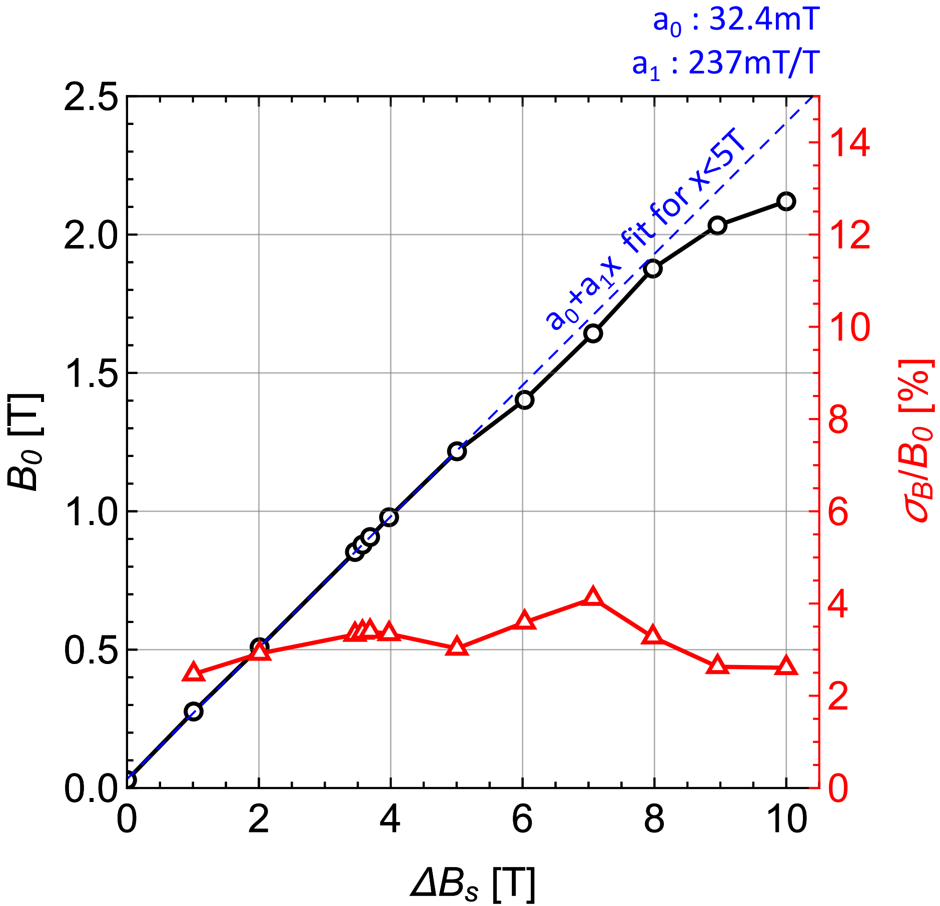
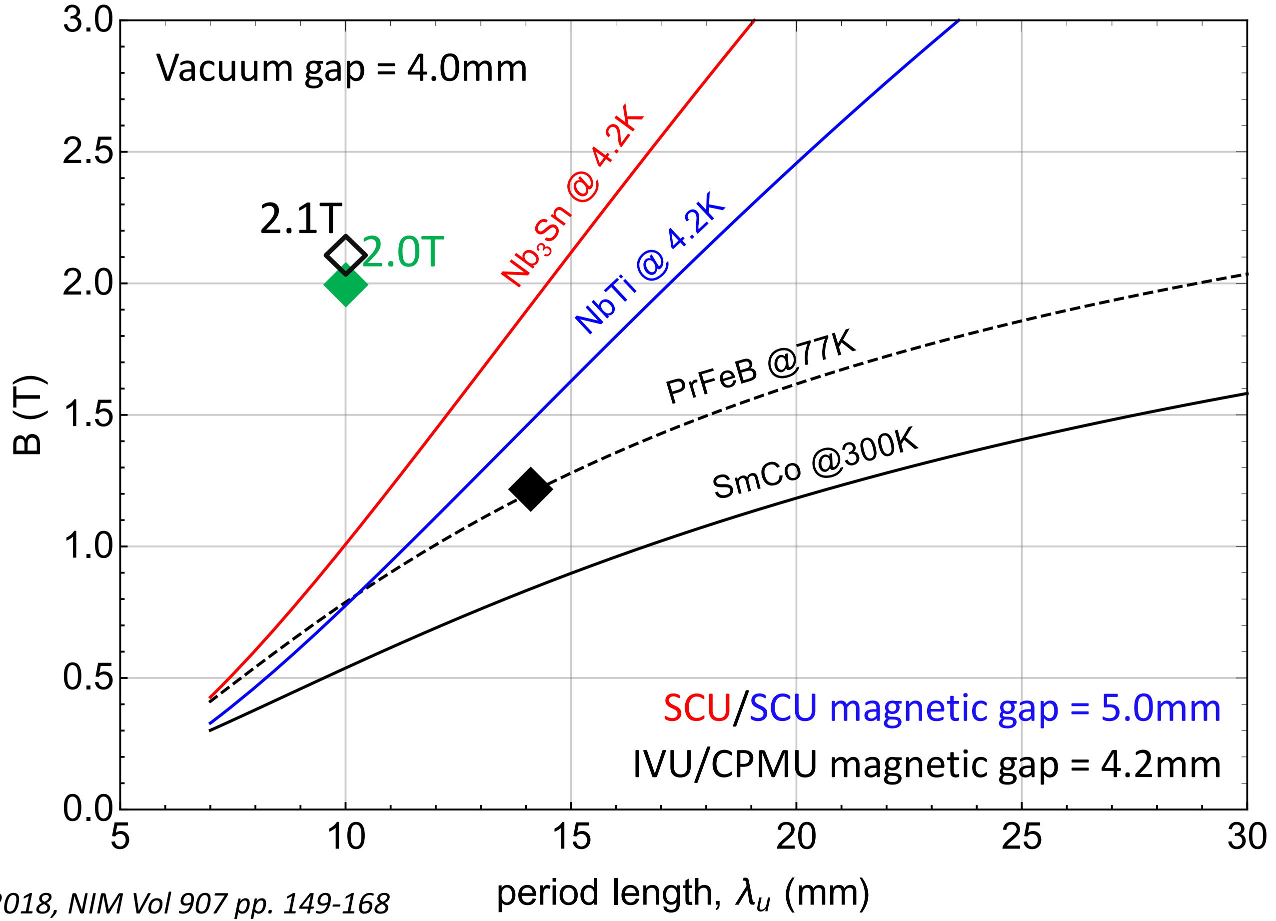


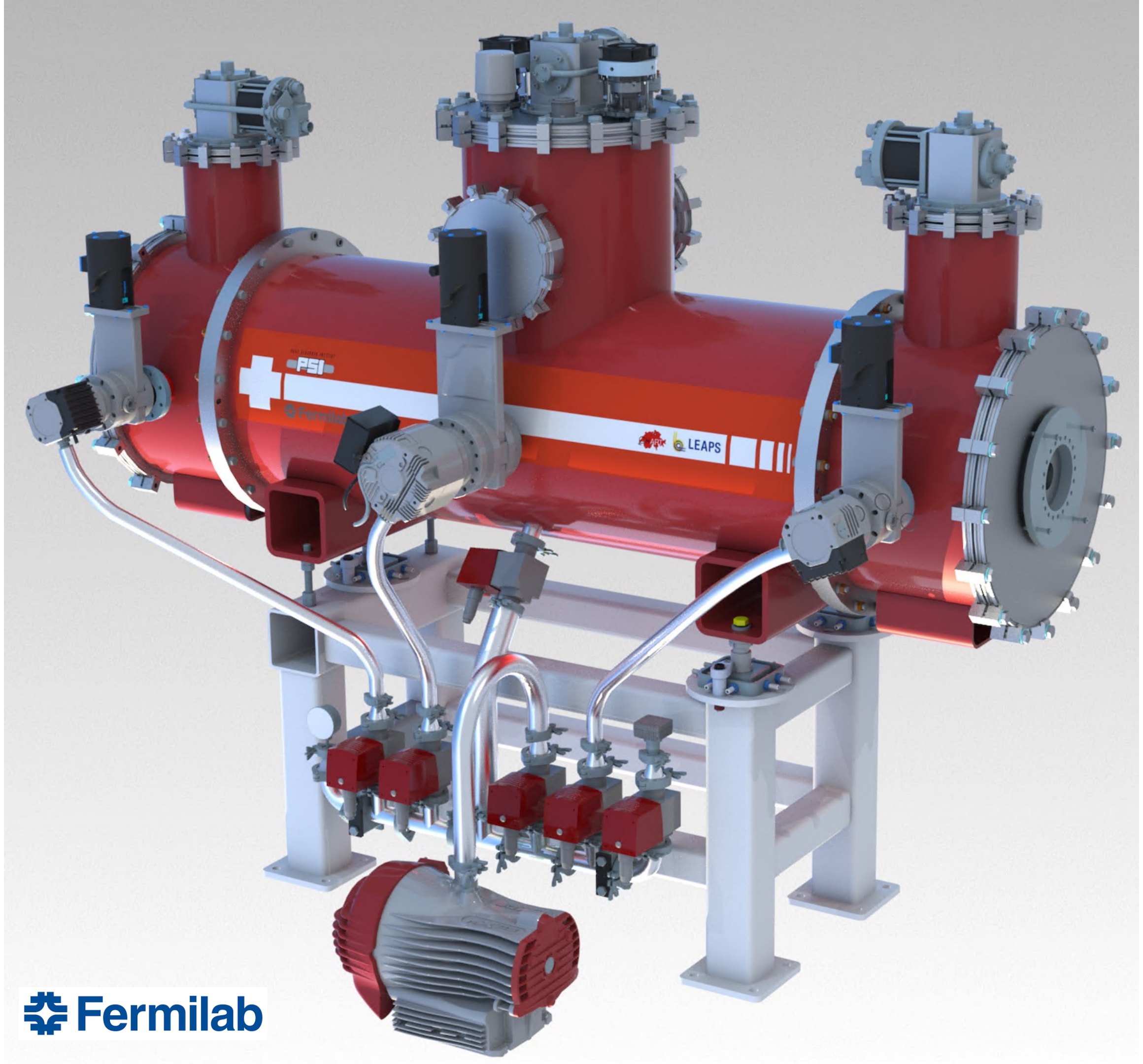


Supercond. Sci. Technol. 36 (2023) 05LT01

I-Tomcat beamline of SLS2.0



Bahrdt, J. Gluskin, E. 2018, NIM Vol 907 pp. 149-168



THE METER LONG PROTOTYPE

Active length : 1.0 m

Total length : < 2m

period length : 10.5 mm

magnetic gap : 4.5mm

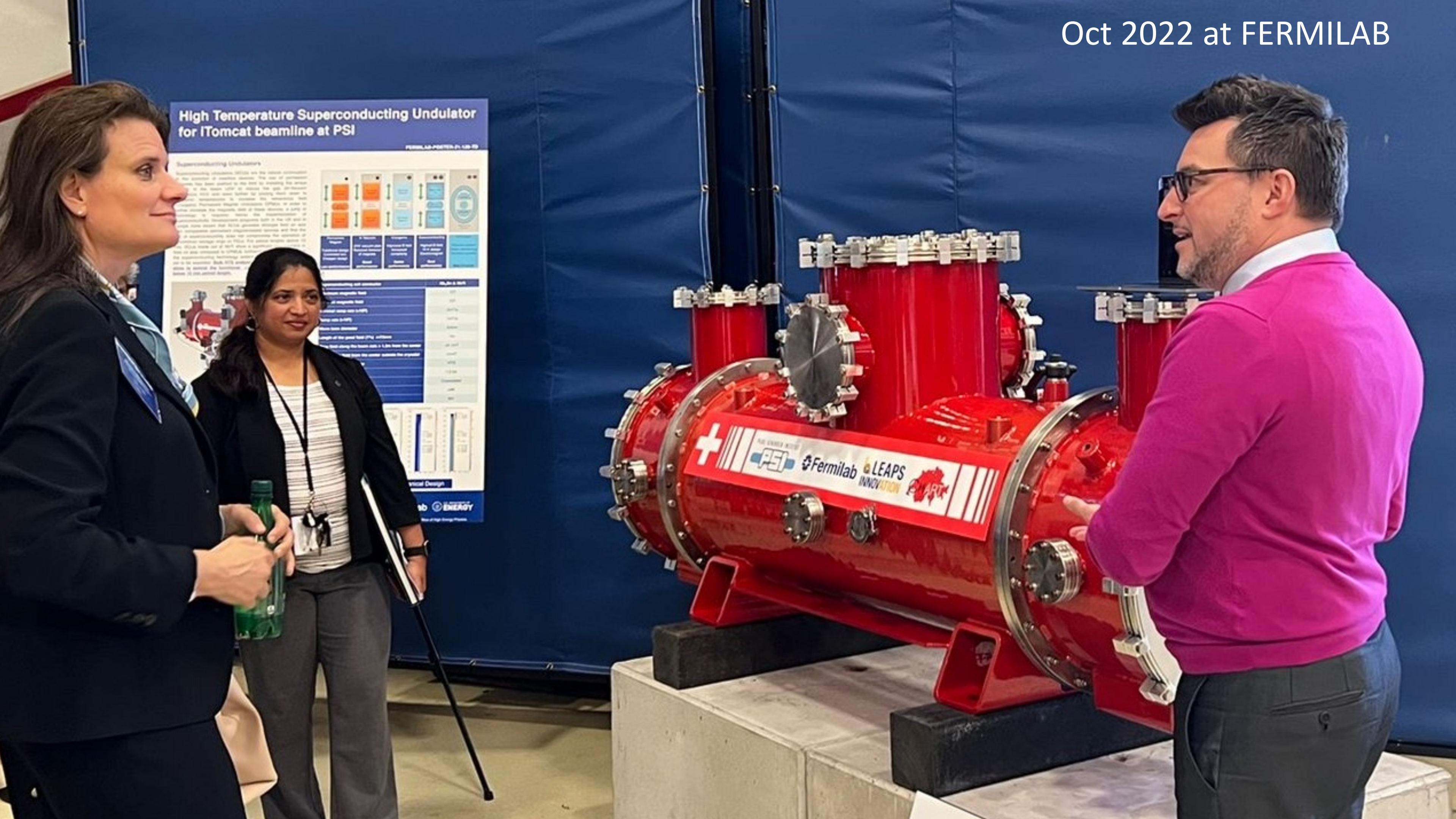
$B_0 \sim 1.8$T

Cryocoolers

HTS temp 10K

LTS temp 4.0K

Oct 2022 at FERMILAB



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R&D Activities

- EuXFEL:
  - hybrid NbTi + HTS tapes
- CERN+KIT:
  - HTS tapes planar
  - HTS tapes helical
  - HTS meanders
- ANL:
  - SCAPE
  - HTS tapes (PNI)
- Daresbury:
  - Helical NbTi
- PSI:
  - HTS REBCO Bulks: helical
  - HTS tapes: Wind & Shape

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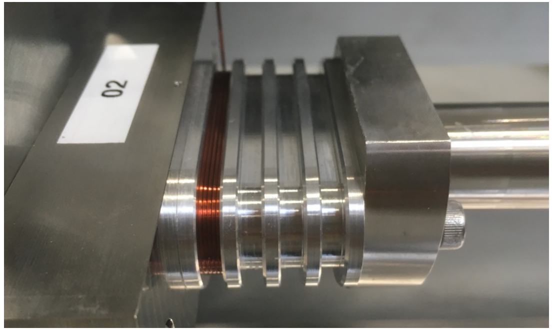

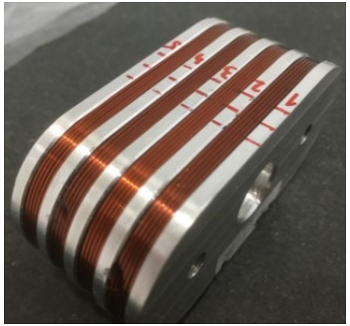

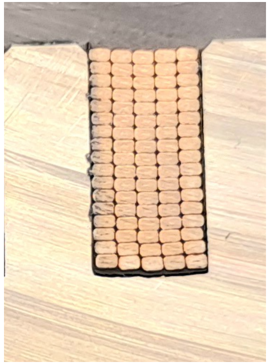

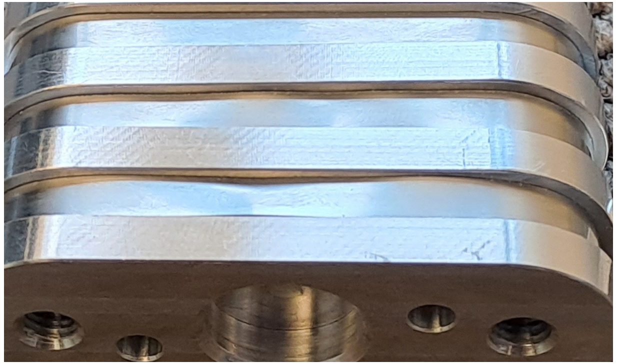

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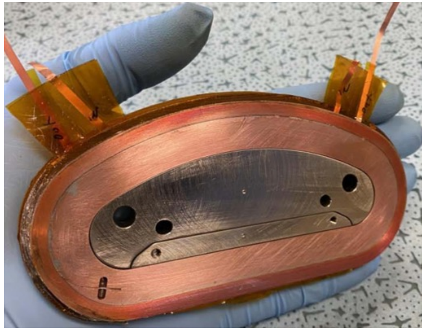

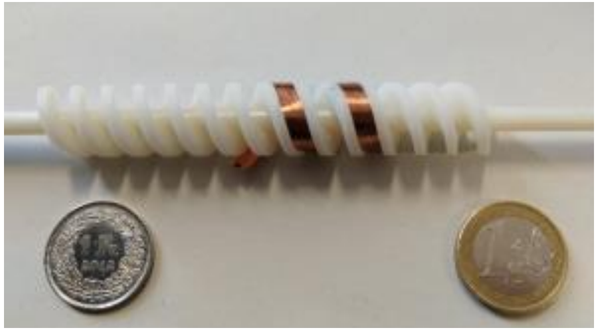

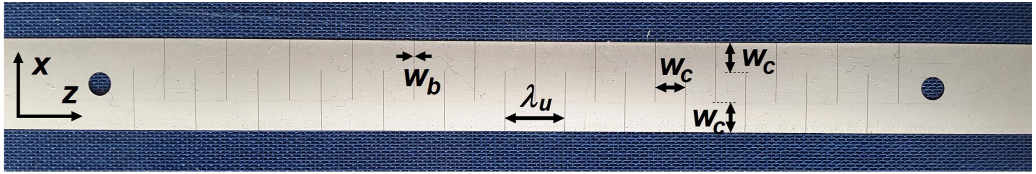

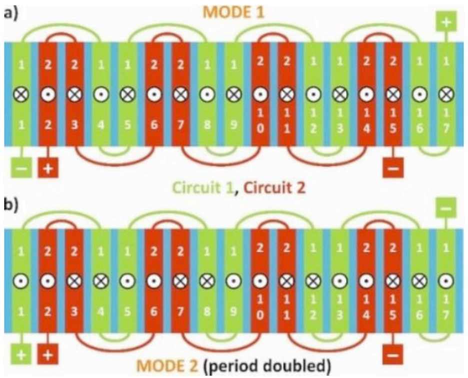

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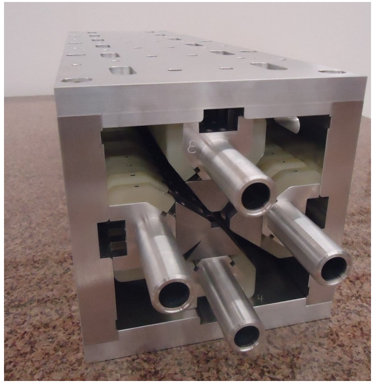

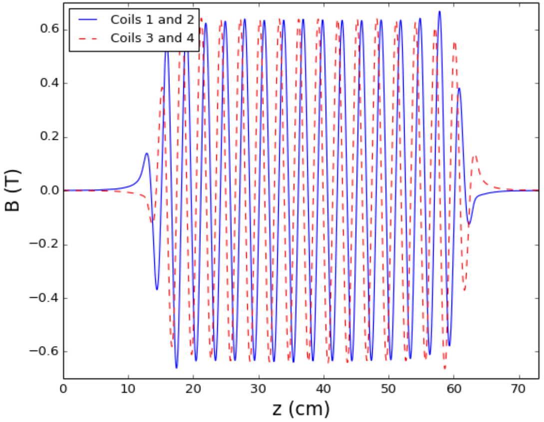

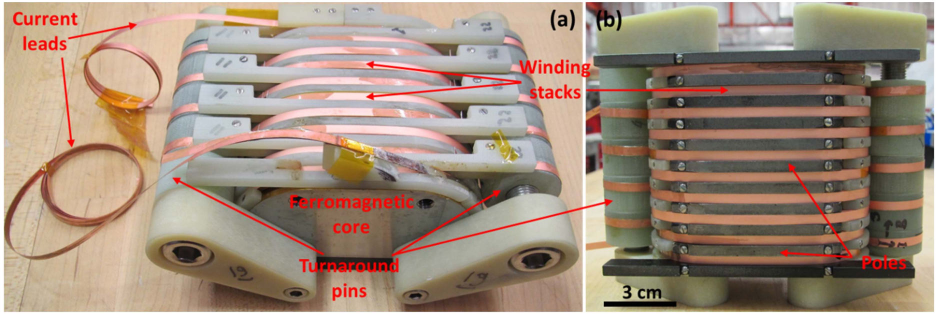

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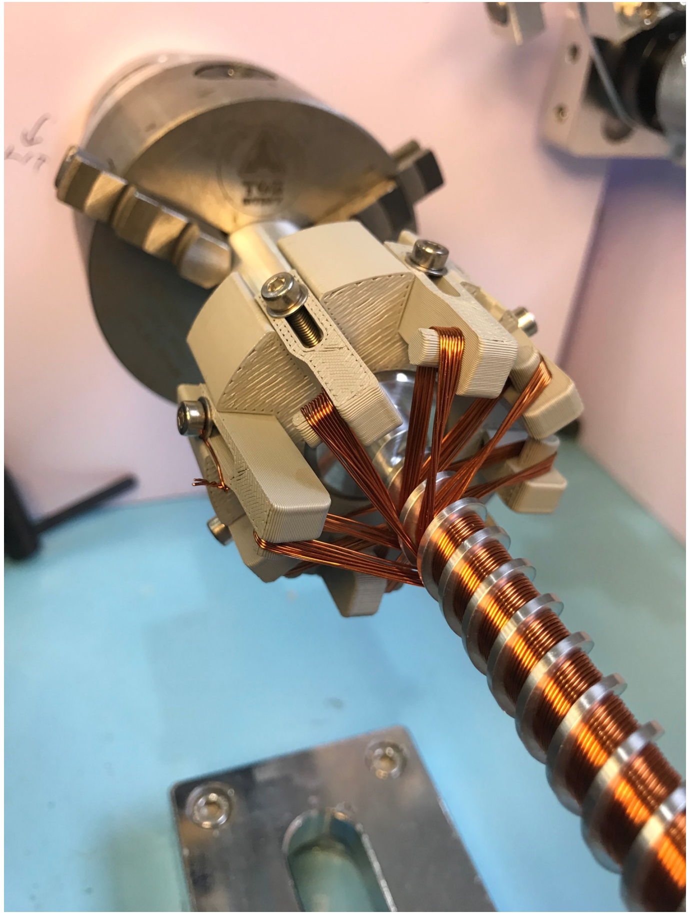

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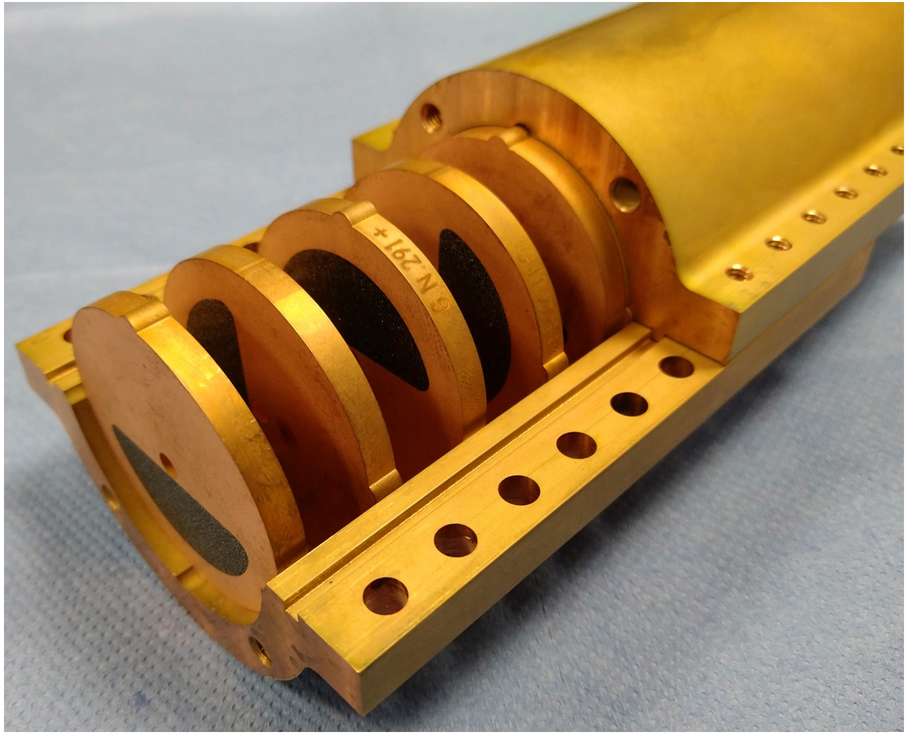

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Conclusions & outlooks

- Superconductivity brings clearly an added value in all projects presented
- NbTi SCU is a mature technology both available in labs and industry (Bilfinger Noell)
- Large experience gained in the operation of SCU in user facility during the last decade
- Nb_3Sn and HTS (REBCO) are exciting and active fields of research
- Non-insulated (or partially non-insulated) HTS tape technology is a sound technology for some applications: both to increase the engineering current density and simplify the quench protection
- Vacuum technology (thinner chambers) is essential to further improve the impact of SCUs
- REBCO bulks could share the same vacuum of the e-beam with a suitable coating: giving a chance to the technology of “in-vacuum-SCU”…

… *to be continued*

Acknowledgements

For providing materials used in this presentation:
S.Calsalbuoni, E.Gluskin, Y.Ivanyushenkov , I.Kesgin, P.Krejcik , D.Nguyen, Wolfgang Walter.

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- *CHART* : Prof. H.R.Ott & Prof. L.Rivkin
- *Uni Cambridge* : J.Durrell, A.Dennis, Y. Shi
- *King's College London*: M.Ainslie
- *ESRF* : G. Le Bec & J.Chavanne
- *Spring8* : T.Ishikawa, M.Yabashi, H.Tanaka
- *UniKyoto* : R.Kinjo, T.Kii, H.Ohgaki
- *Uni Malta* : N.Sammut, A.Sammut, J.Cassar
- *SENIS* : Prof.R.Popovic, S.Spasic, S.Dimitrijevic
- *KIT* : Prof. M.Noe
- *Fermilab*: C.Boffo, M.Turenne, F.McConologue