Superconducting Undulator Development at European XFEL

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European XFEL

Outline

- Why superconducting undulators?
- Which technology?
- State of the art in storage rings
- Measurement systems
- Possible applications for XFELs
- Superconducting undulator development at European XFEL
  - Challenges for a hard X-ray FEL source
  - Present activities and future steps under study at European XFEL

Why superconducting undulators? Tunability!

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

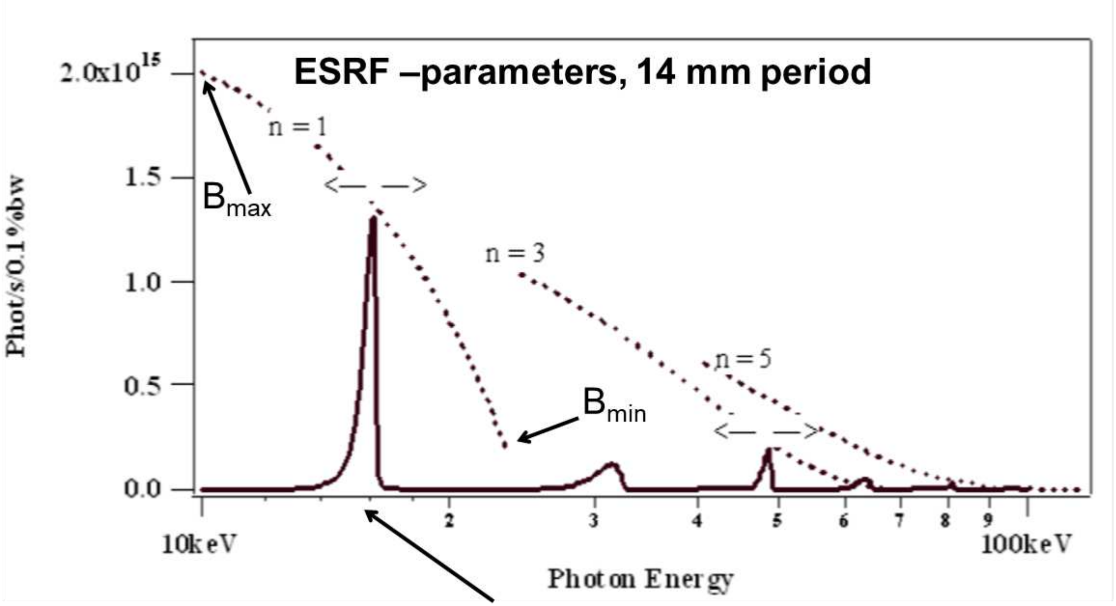
$$\lambda = \frac{\lambda_U}{2\,n\,\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad K = \frac{e}{2\pi mc} B_0\,\lambda_U = 0.9336\,B_0[T]\,\lambda_U[cm]$$

- To increase the tunability range of the photon energy

⇩

increase the peak field on axis B_0

- Important at XFELs because fewer beamlines



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

Why superconducting undulators?

Developments to increase B_{max}

Permanent magnet undulator LCLS, PAL-XFEL, SHINE, EuXFEL

↓

IVU= in-vacuum undulator SACLA, SwissFEL

↓

CPMU= cryogenic permanent magnet undulator

alternative technology to increase B_{max} further

↓

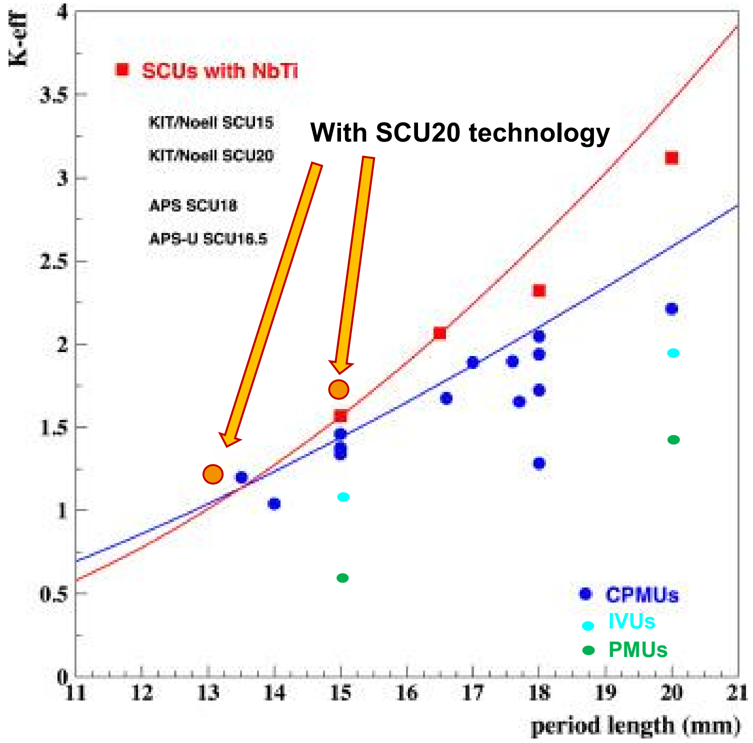
SCU=superconducting undulator Development for XFELs
LCLS with ANL and LBNL, SHINE, SwissFEL, EuXFEL

Why superconducting undulators?

Higher peak field on axis for the same gap and period length in operation with electron beam

All K-values are scaled to the same vertical vacuum aperture of 5.0 mm. The CPMU gap loss is 0.2 mm.
The SCU gap losses are 2.5 mm (SCU18), 1.8 mm (SCU16.5) and 1 mm for the KIT/Noell devices

IVUs (g=5.2 mm) and PMUs (g=7 mm)
P. Elleaume et. al NIM A 455 (2000) 503-523



SCUs have 3 times larger K with respect to PMUs for the same period and vacuum gap

Performance of SCUs and CPMUs

Facility	Start-Finish of Operations	λ_U(mm)	# of periods	Vacuum aperture (mm)	Gap loss (mm)	B (T)	Cooling
APS 2 SCUs	2015-current 2016-current	18	59.5	7.2	2.3	0.97	4 cryocoolers, LHe closed circuit
APS	2013-2016	16	20.5	7.2	2.3	0.8	4 cryocoolers, LHe closed circuit
KIT/Noell	2014-2015	15	100.5	7, 16 (open)	1	0.73	4 cryocoolers
KIT/Noell	2017-current	20	74.5	7, 15 (open)	1	1.18	4 cryocoolers

J. Bahrdt, E. Gluskin, NIMA (2018)

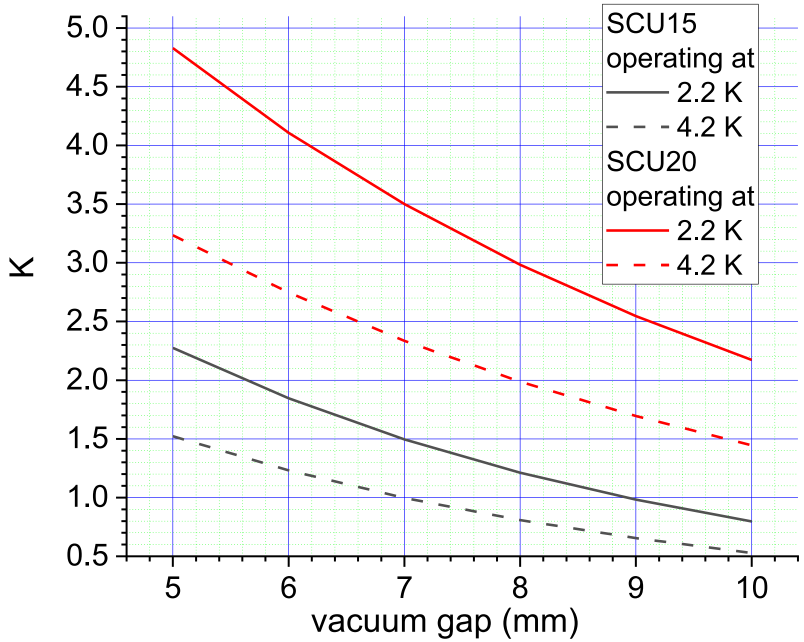
Further advantage is radiation hardness widely demonstrated for NbTi magnets (i.e. HERA, Tevatron, LHC)

Which technology?

- NbTi with operation at 4.2 K: advantage with respect to CPMU, proven in storage rings, radiation hard
- Can we do better?
  - Nb_3Sn
    - ► Not yet demonstrated in accelerator environment
    - ► Ongoing R&D at ANL in collaboration with FNAL
    - ► Brittle, requires heat treatment up to 600-700º C, hardly compatible with the small mechanical tolerances required to reach high magnetic field quality necessary for undulators
  - High Temperature Superconductors (HTS)
    - ► Not yet demonstrated in accelerator environment
    - ► Ongoing R&D at PSI and EuXFEL started
    - ► Uniformity, repeatability, mechanical properties, quench protection, available length for the tape, and production rate of high quality HTS

Which technology?

- For X-ray FELs with superconducting linac the most appealing technology seems NbTi operating at 2K
  - NbTi operating at **2 K**
    - ► Magnet can use the same design as the well demonstrated one for NbTi at 4 K
    - ► Cooling to be adapted, but 2K technology well known for operation of SC cavities
    - ► $\boldsymbol{B_0}$ **and K** value for the same λ_U **increased by about 50 % with respect to NbTi at 4K**



Simulations performed with FEMM
http://www.femm.info/wiki/HomePage

A 2 K operation margin is considered.
At 4.2 K operation margin ~55% in current.
At 2.2 K operation margin ~30% in current.

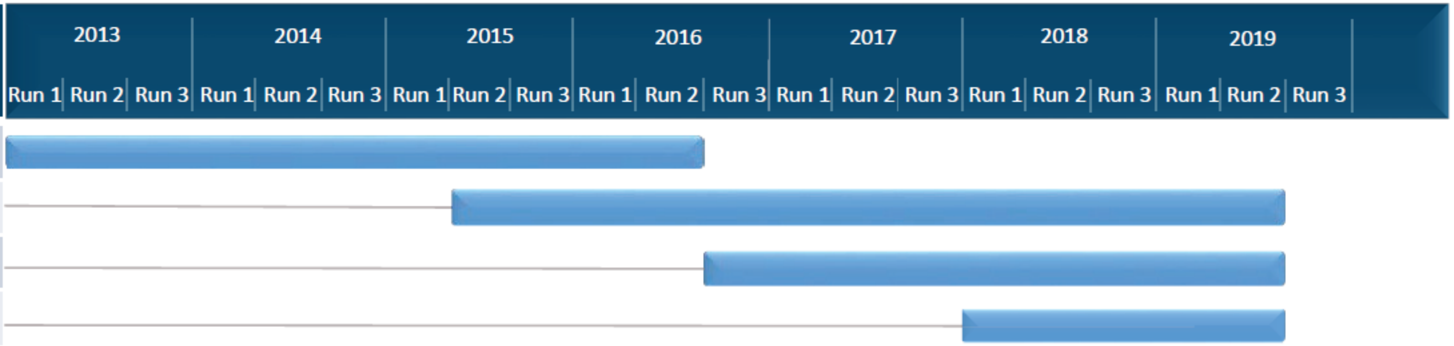
State of the art in storage rings: APS

K. Harkay, NAPAC2019, Lansing, Michigan, USA

SCUs IN OPERATION AT THE APS

Combined operating years > 11

Magnetic length	Device name	λ (mm)	# of periods	B (T)
0.33 m	SCU0	16	20.5	0.8
1.1 m	SCU1[1]	18	59.5	0.97
1.1 m	SCU6[2]	18	59.5	0.97
1.2 m	HSCU	31.5	38.5	0.41



[1] Also known as SCU18-1
[2] Also known as SCU18-2

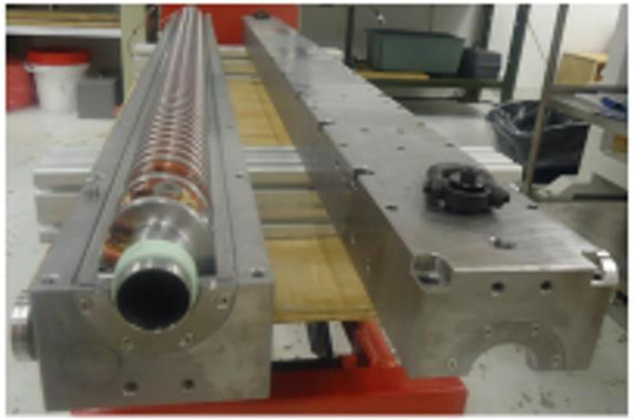
Table: M. Kasa

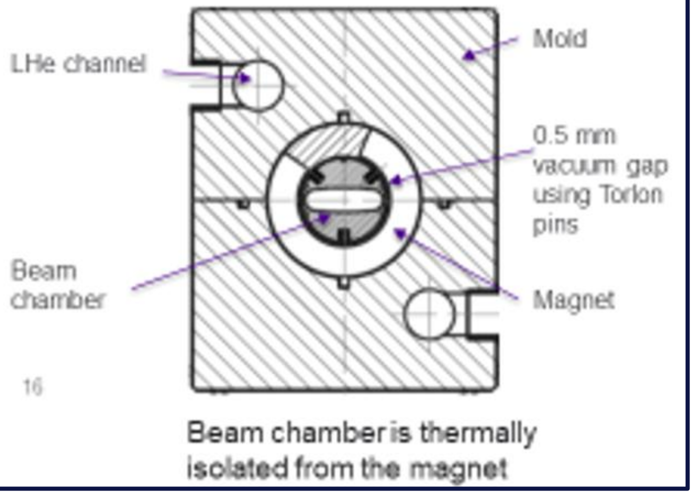
- Extensive commissioning plan was executed for SCU0 (5 days equivalent) [1].
- SCU1, SCU6, HSCU commissioning executed in fraction of time (1-2 days equivalent).
- All devices were turned over for beamline operations immediately after commissioning.

[1] K. Harkay, *NA-PAC'13*, 703.

State of the art in storage rings: APS

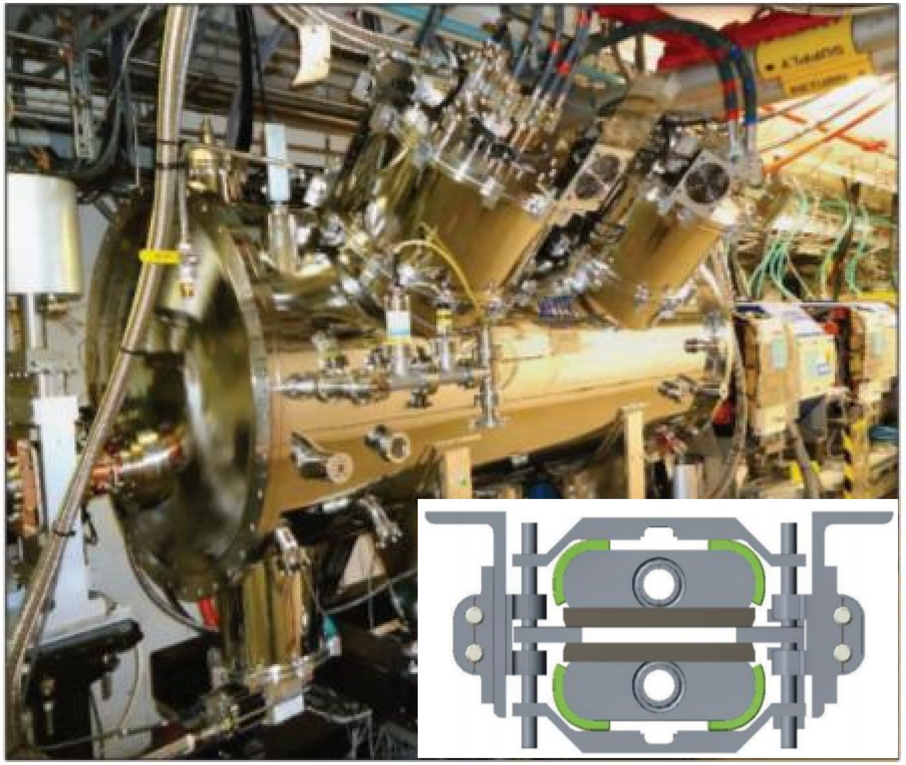
Helical



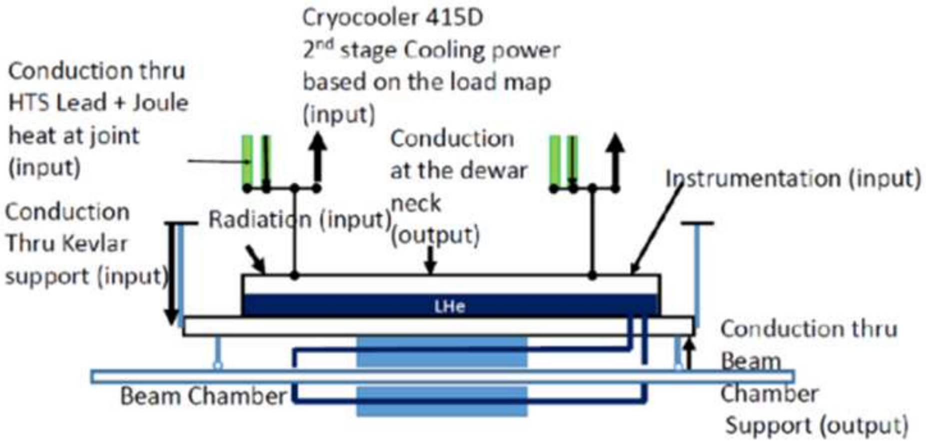


M. Kasa, SRI2018 Conf.

Planar



J. Fuerst et al., FLS2018 Conf.



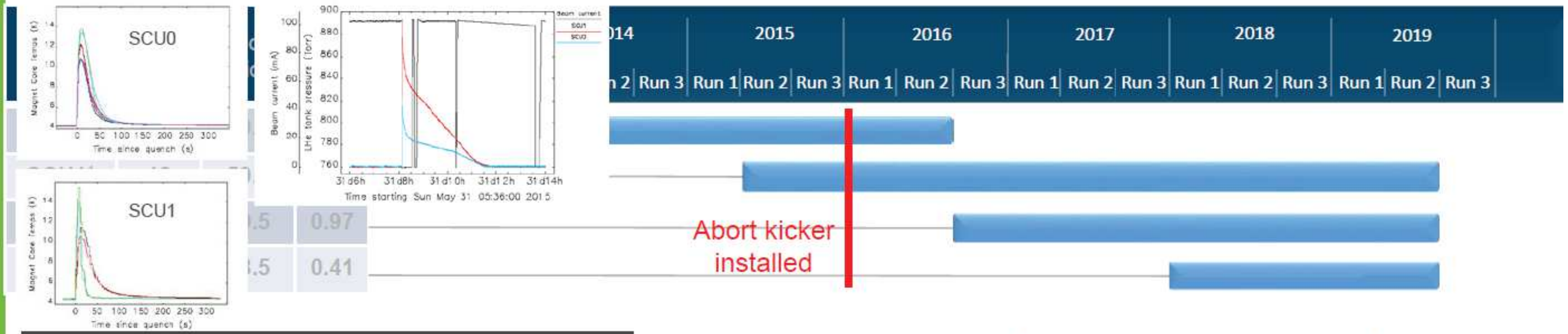
Y. Shironagi et al., IOP Conf. Ser.: Mater. Sci. Eng.278 012183 2017

State of the art in storage rings: APS

K. Harkay, NAPAC2019, Lansing, Michigan, USA

QUENCHES ARE TRANSPARENT

Most quenches occur during beam dumps; timely recovery [1]



Device name	# Quenches, beam dump	# Self-quenches
SCU0	98	6
SCU1	40	5
SCU6	32	3
HSCU	0	0

- Abort kicker significantly reduced rate of beam-dump-induced quenches.
- Self-quenches occur ~once a year per device
  - Perturbation of the storage ring beam orbit is minimal.
  - No self-quench has ever caused the beam to be lost.

[1] Y. Ivanyushenkov et al., *PRAB* **20**, 100701.

State of the art in storage rings: APS

K. Harkay, NAPAC2019, Lansing, Michigan, USA

SCU AVAILABILITY IS > 99%

We maintain detailed operational statistics – I. Kesgin TUPLH01

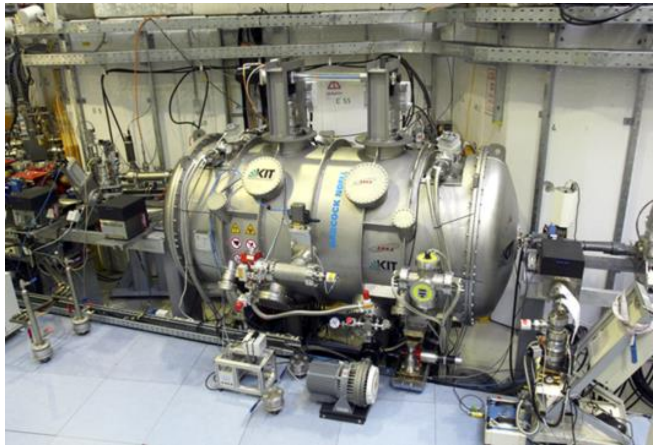
Device name	Availability %	Operation %
SCU0	98.9%	92.3%
SCU1	99.992%	96.6%
SCU6	99.89%	84.9%
HSCU	100%	14%

- Availability = ratio hours $\frac{\text{device powered}}{(\text{powered+down})}$
- Operation = ratio hours $\frac{\text{device powered}}{(\text{APS delivered beam})}$
- Sector 6 beamline down since Jan 2019 (unrelated to SCU6).
- HSCU demand relatively low so far.

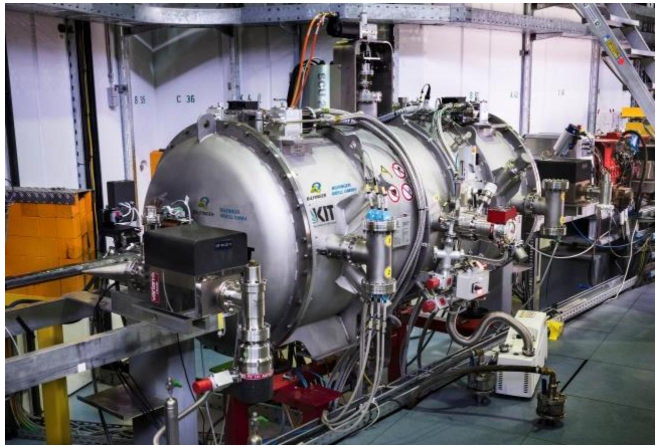
State of the art in storage rings: KIT synchrotron

BILFINGER BILFINGER NOELL GMBH KIT Karlsruhe Institute of Technology

- KIT and Noell development of SCUs for the KIT synchrotron and low emittance light sources
  - NbTi wire
  - Conduction cooling => no need of cryogenic fluids
  - Movable vacuum chamber: highly desirable during commissioning and “nice to have” during operation



SCU15



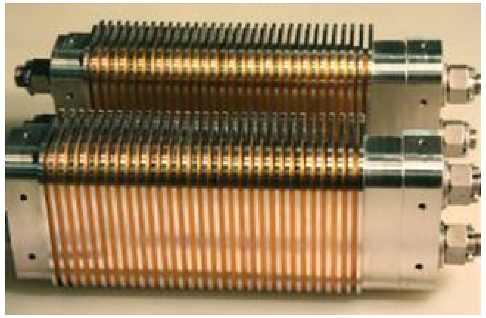
SCU20

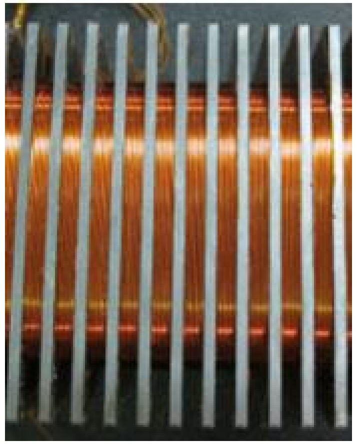
Parameter	SCU15	SCU20
period length	15 mm	20 mm
maximum peak field on axis	0.73 T	1.18 T
number of fully wound periods	100.5	74.5
magnetic length	1.555 m	1.554 m
magnetic gap	8 mm	8 mm
vacuum gap closed (open)	7 (15) mm	7 (15) mm

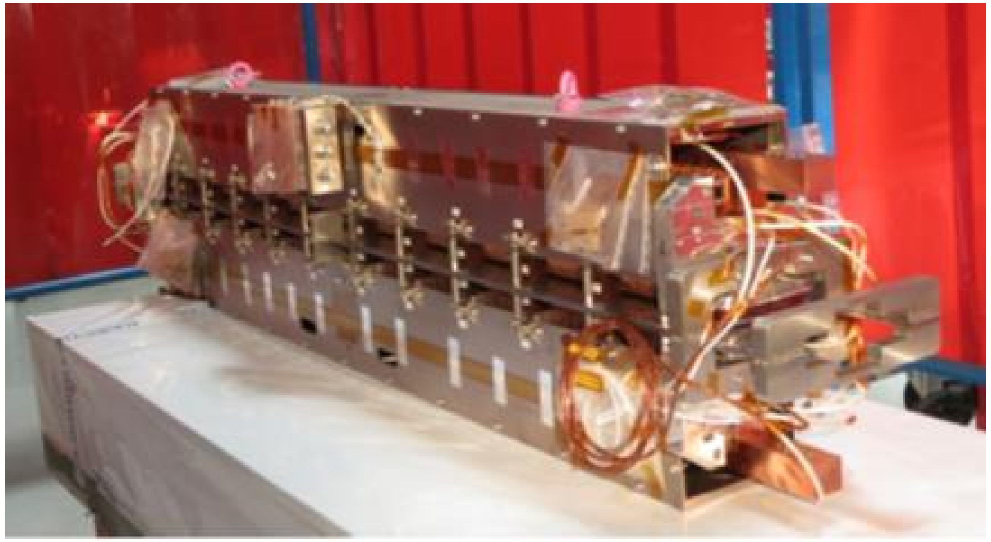
S. C. et al., Synchr. Rad. News, 31:3, 24-28 (2018)

State of the art in storage rings: KIT synchrotron

BILFINGER
BILFINGER NOELL GMBH
KIT Karlsruhe Institute of Technology





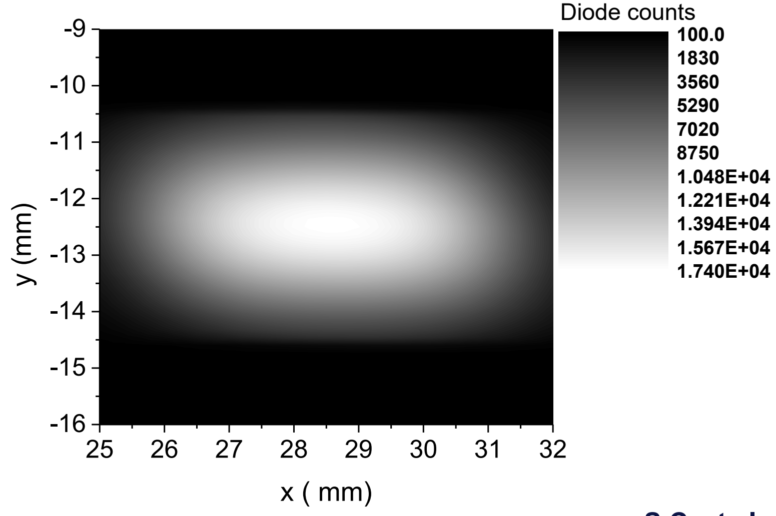


S. C. et al., Synchr. Rad. News, 31:3, 24-28 (2018)

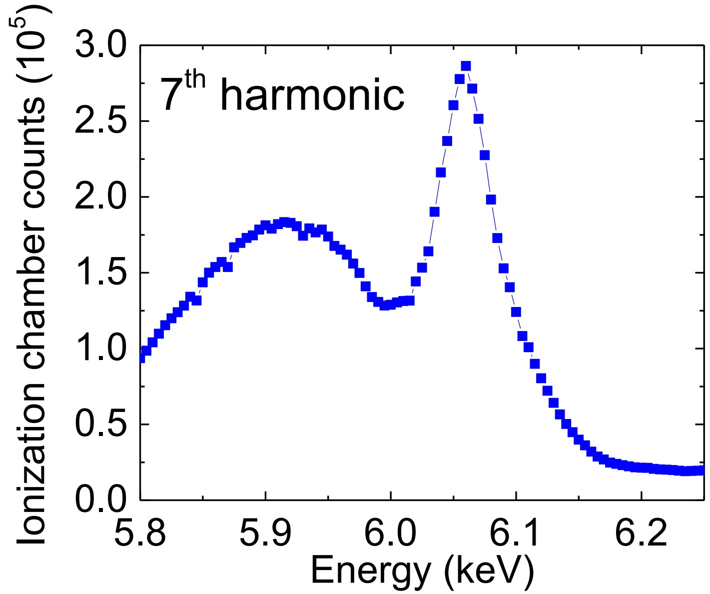
State of the art in storage rings: KIT synchrotron

- **SCU20 tests with beam**
  - Installation in December 2017
  - Successfully operating in the KIT synchrotron since January 2018 without quenches
  - First X-rays 10.1.2018

Image of white beam scanning diode after 15 µm pinhole @ 17.1 m from the source and CVD diamond window 3mm x 2mm @ 8.3 m



- Tuning of SCU20 is compatible with the operation of all the beamlines of the KIT synchrotron while performing their most sensitive experiments
- Seventh harmonic of SCU20 measured at the NANO beamline through 70 µm x 30 µm at 17 m from the source with an ionization chamber at 2.5 GeV electron beam energy

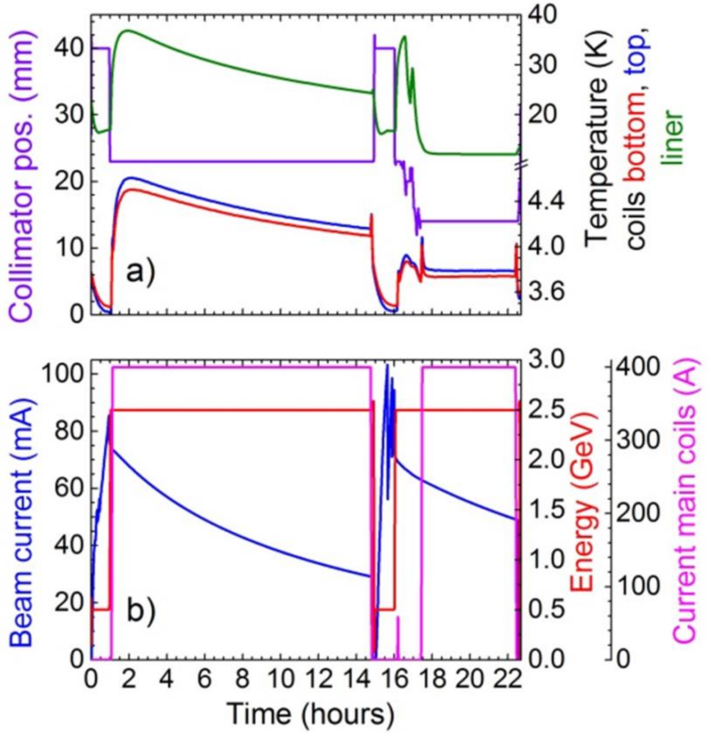


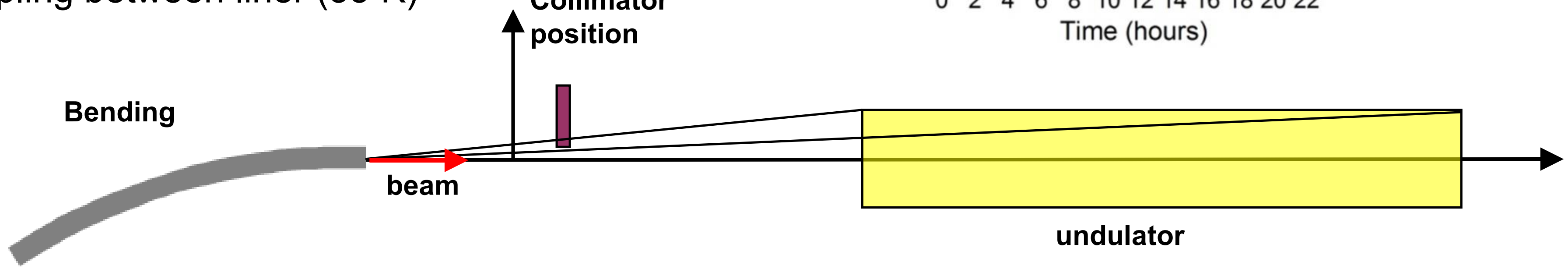
S.C. et al., AIP Conf. Proc. 2054, 030025 (2019)

State of the art in storage rings: KIT synchrotron

BiLFINGER BILFINGER NOELL GMBH KIT Karlsruhe Institute of Technology

- **SCU20 tests with beam**
  - Beam lifetime (23 h at 100 mA) was recovered in about 3 weeks of beam operation of the storage ring at 2.5 GeV
  - Transparent to electron beam with values of correctors very close to the ones measured in CASPER II
  - Adjustment of the currents in the vertical and horizontal correctors in few hours
  - Beam heat load 8 W
  - Operation temperature margin of at least 0.8 K (normal operation at 3.8 K, but working also at 4.6 K)
  - Excellent thermal decoupling between liner (35 K) and coils (4.6 K)



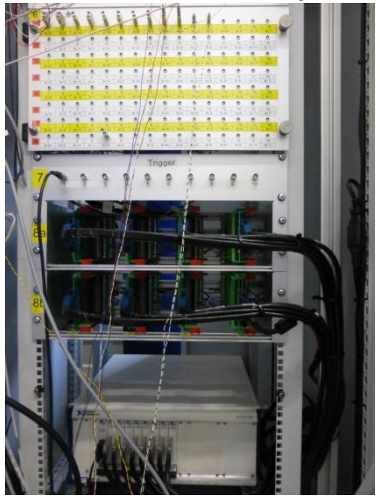


S.C. et al., AIP Conf. Proc. 2054, 030025 (2019)

Magnetic characterisation systems: CASPER II at KIT

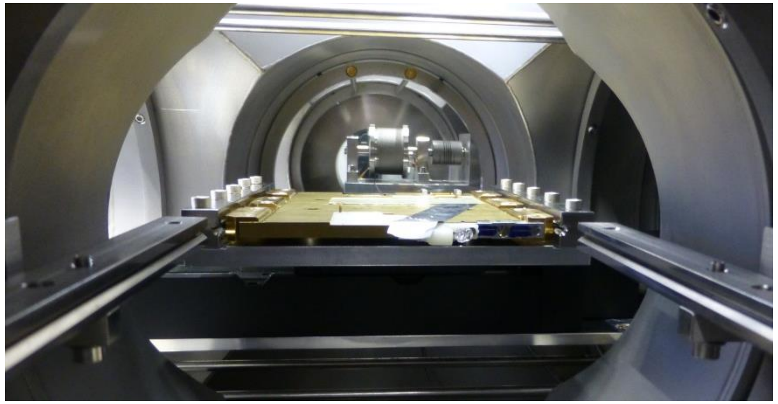
Horizontal cryogen free test stand to characterize conduction cooled undulator coils

Training:
- Quench detection
- Quench analysis

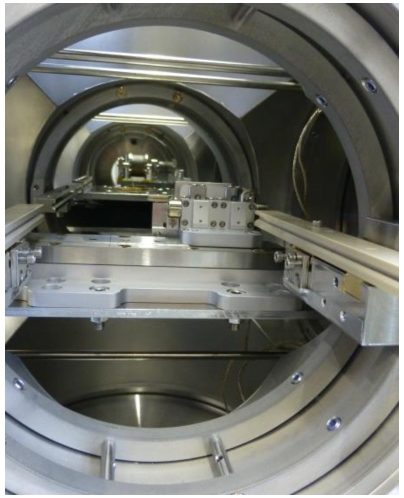


A. Grau et al., IEEE Trans. on Appl. Supercond. 2312-2315 Vol. 21-3 (2011)

Local field measurements:
- Hall probes

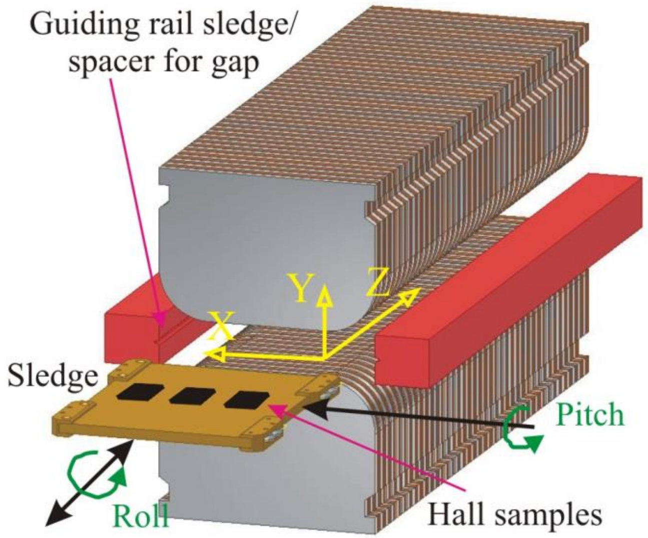


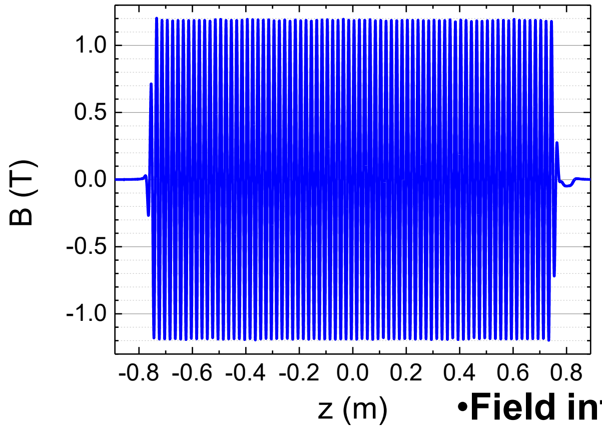
Integral field measurements:
- Moving wire



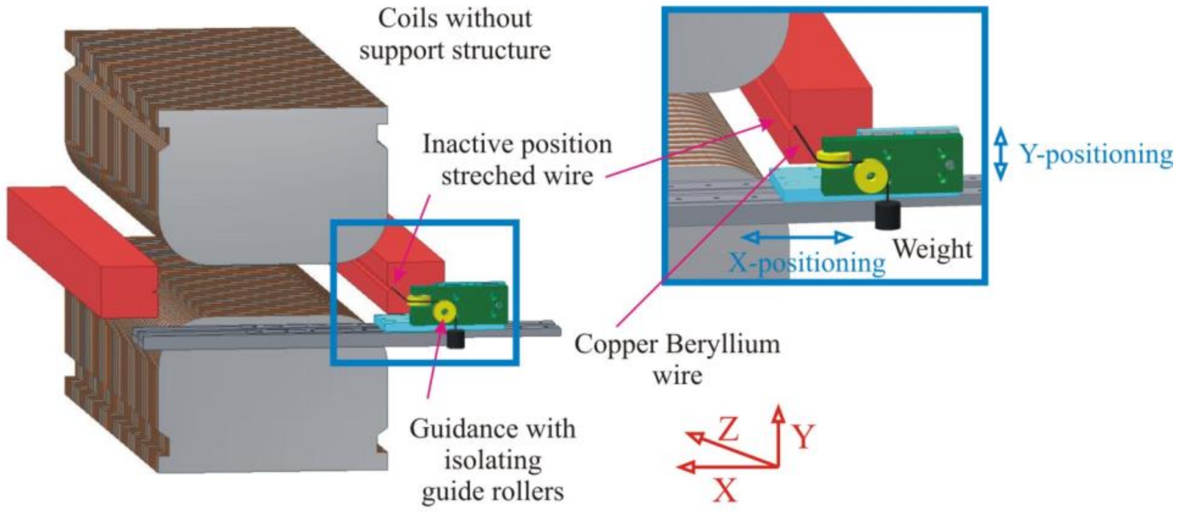
Magnetic characterisation systems: CASPER II at KIT

- **Local field measurements with Hall probes**





- **Field integral measurements with moving wire**



Local and integral field measurements can be performed during the same cool down

A. Grau et al., IEEE Trans. on Appl. Supercond. 9001504 Vol. 22-3 (2012)

Magnetic characterisation systems: CASPER II at KIT

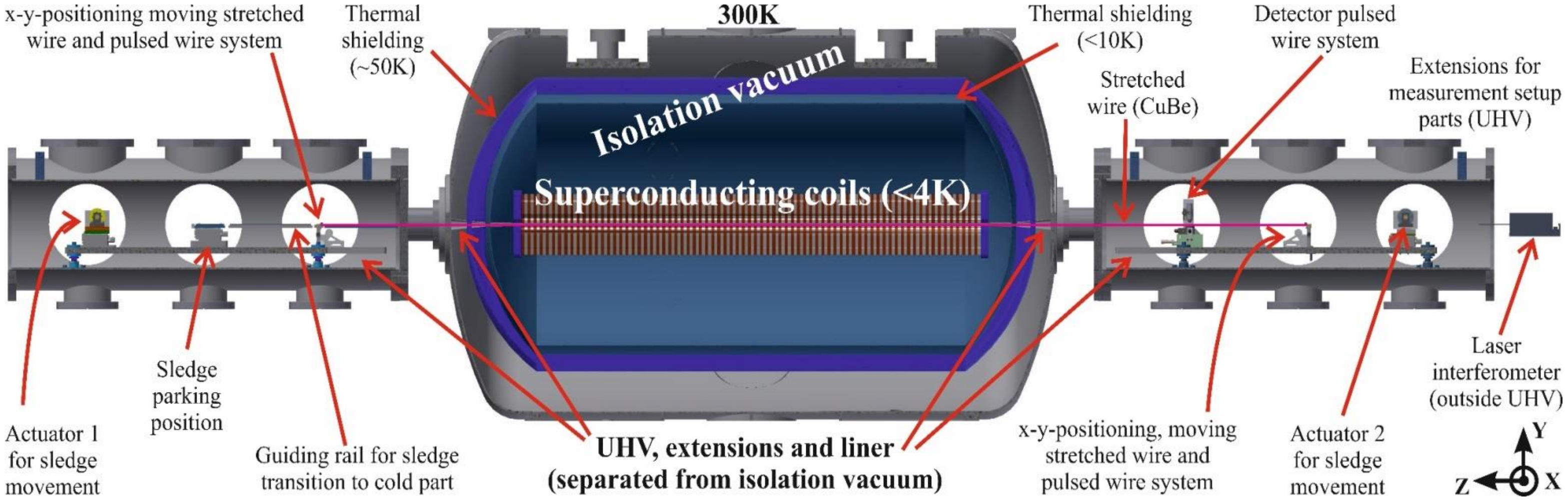
Karlsruhe Institute of Technology

- **Local field measurements**
  - Hall probe mounted on a sledge moving along the undulator length sliding on precisely machined guiding rails
  - Hall probe calibrated to ± 90 µT
  - Longitudinal position measured with a laser interferometer with sub µm resolution

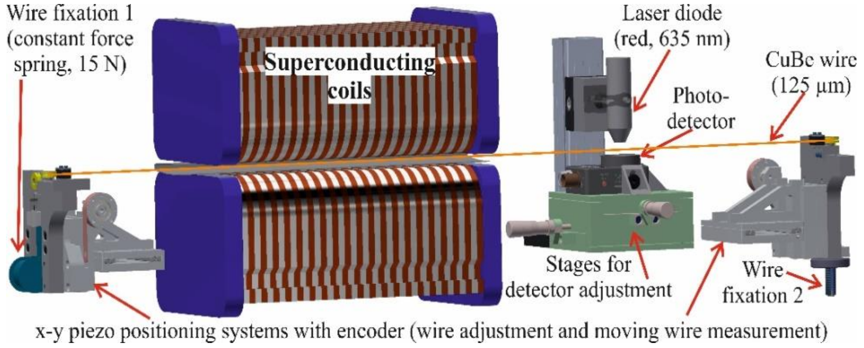
- **Integral field measurements**
  - CuBe wire with a diameter of 125 µm is stretched between two stages placed at a distance of 2.7 m (strain force 6 N)
  - Alignment coils magnetic plane to stretched wire movements measured only at room temperature with a precision of 50 µm
  - Reproducibility of I_1 is ± 3.5×10^{-6} T mm and of I_2 is ± 1×10^{-5} T mm^2

Magnetic characterisation systems: at KIT

Lessons learned in CASPER II integrated in the measurement system for the final cryostat

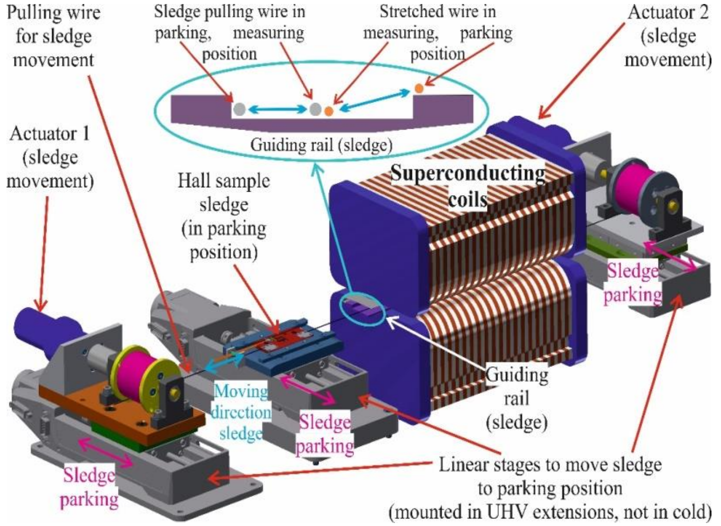


Field integral measurements with stretched wire



- Moving wire
- Pulsed wire

Local field measurements with Hall probe



A. Grau et al., IPAC19, Melbourne, Australia

Magnetic characterisation systems: at Argonne

Local field measurements

- Similar as for SC wiggler system from Budker

Ti tubing “warm bore” as a guide tube for the carbon fiber Hall probe assembly

Integral field measurements

- Rotating/flipping coil method
- Coil: 100 μm CuBe wire 2 m long and width 4 mm
- Lower spatial resolution than in CASPER II, where

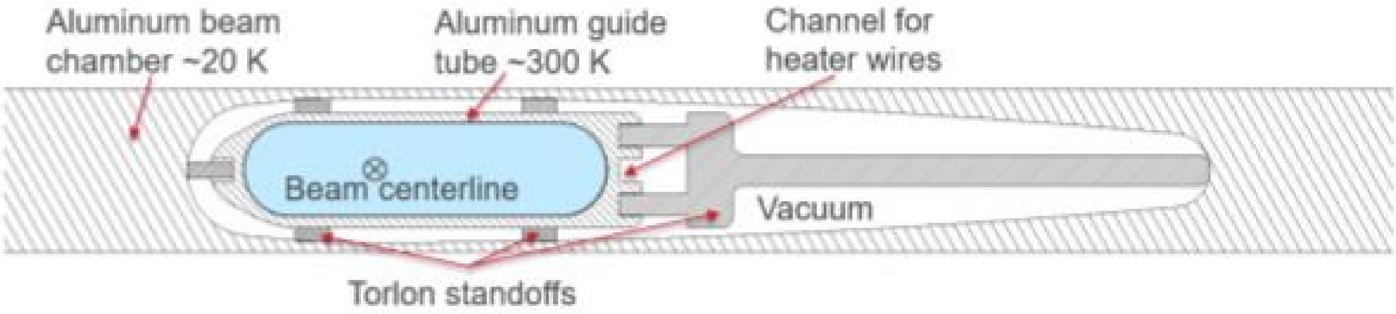
the flux change is obtained by moving the wire by ±0.5 mm, instead of through a width of 4 mm

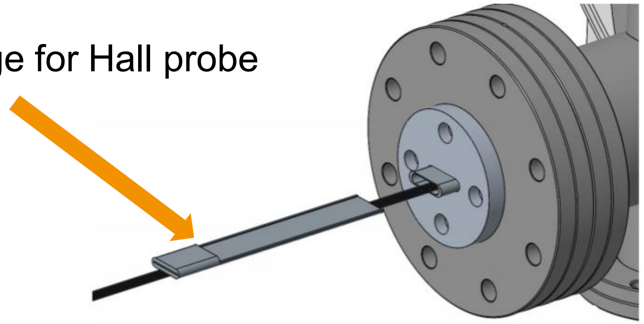
- Possible to measure dynamic field integrals

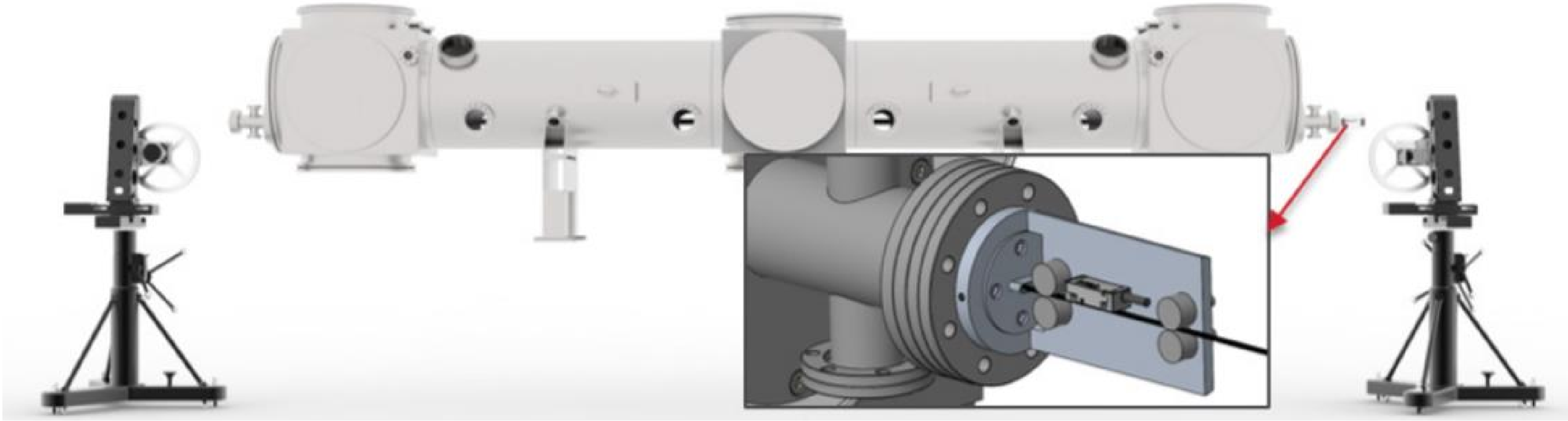
C. Doose and M. Kasa, NAPAC13, Pasadena, CA, USA

Magnetic characterisation systems: at Argonne

Upgrade of local field measurements to improve precision



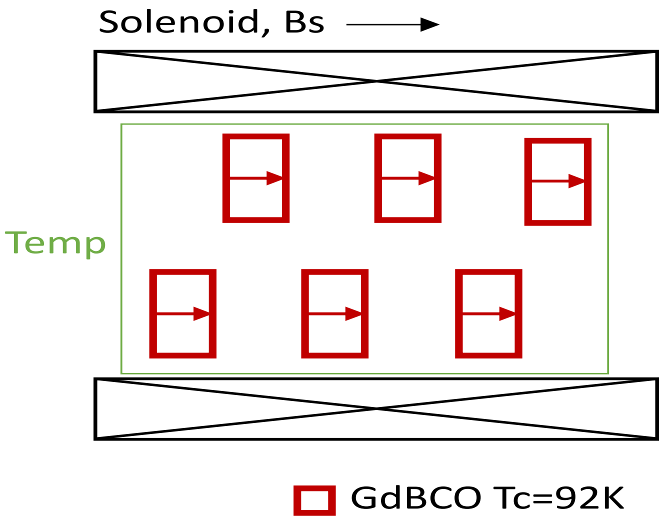


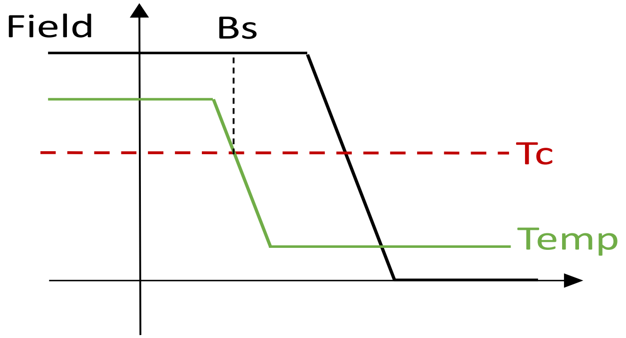


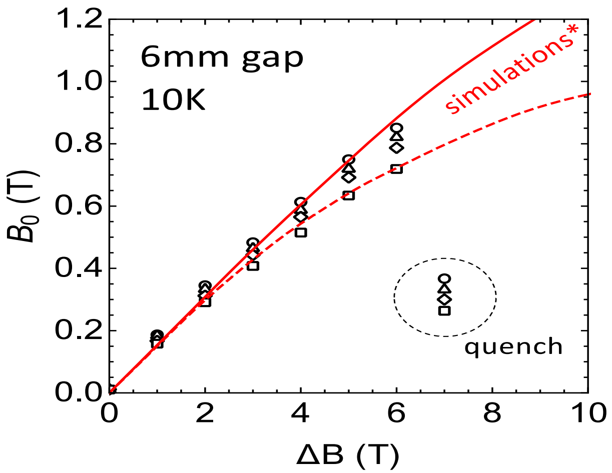
M. Kasa et al., IPAC19, Melbourne, Australia

HTS Undulator Project @ PSI

The first idea from the University of Kyoto 2006. A staggered array of HTS bulks magnetised by an external solenoid. First experimental results 2008 (Kinjo' PhD defence). 2018, PSI started a theoretical investigation of the limits of this approach and estabilished that a 10 mm period undulator with 4 mm magnetic gap could generate a 2T field on axis if magnetised with a 10T solendal (*field cooling*). A collaboration agreement was established with the University of Cambridge to carry out the high filed tests (up to 12T). First results August 2019 on a 6mm gap sample. A series test campaign is planned to investigate different bulk and tape maufactures to choose the most performing and reliable approach for the first meter long demonstrator prototype. This device will be test in SLS 2.0 at the new microscopy tomogaphy beamline.







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

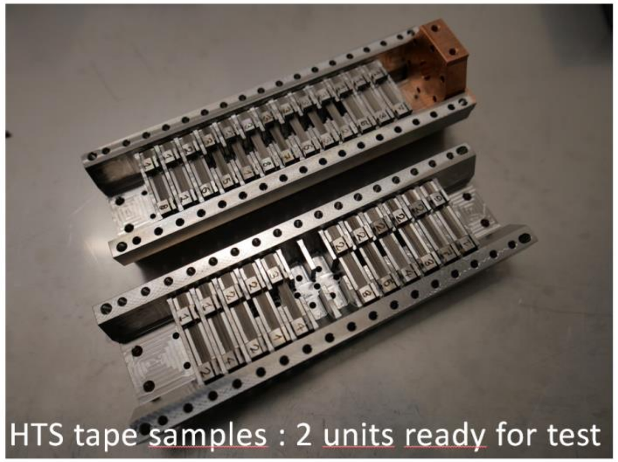
Courtesy of Marco Calvi (PSI)

PAUL SCHERRER INSTITUT PSI

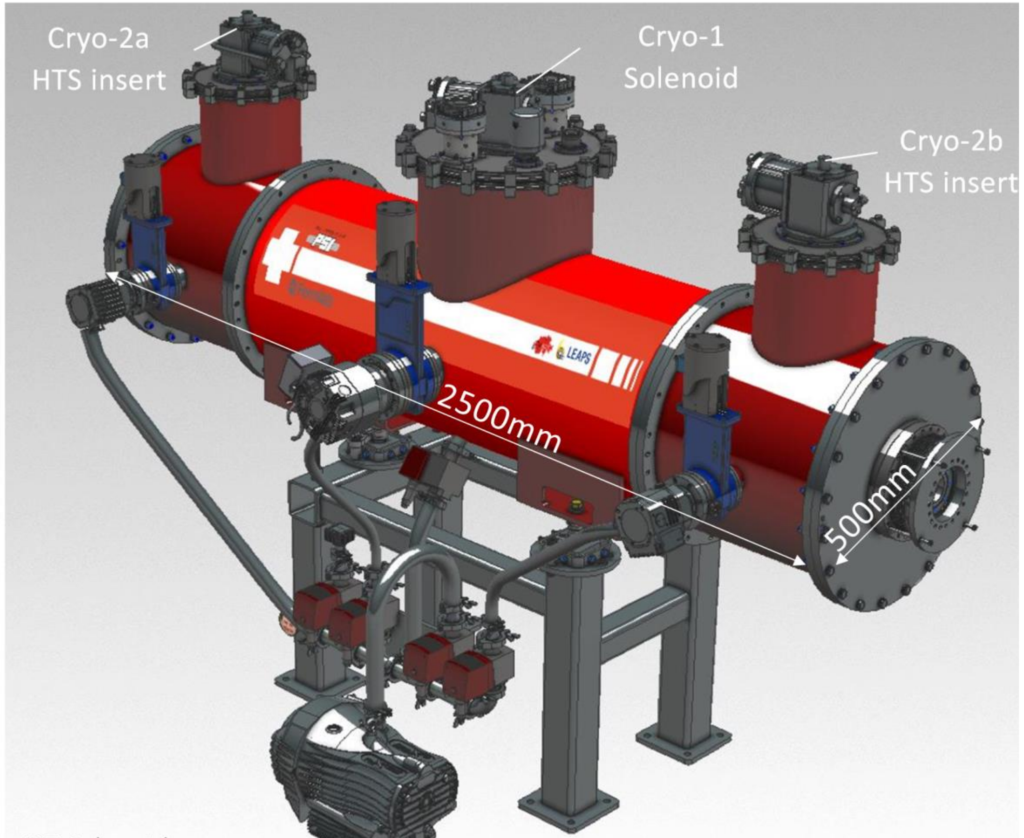
HTS Undulator – Short sample tests and Engineering work

HTS Bulk samples : 5 units are in preparation

Short sample tests consists of 10 period undulator units, prepared with HTS bulks and tapes from different manufactu-res. For the bulks also with different materal: YBCO, GdBCO, EuBCO



HTS tape samples : 2 units ready for test



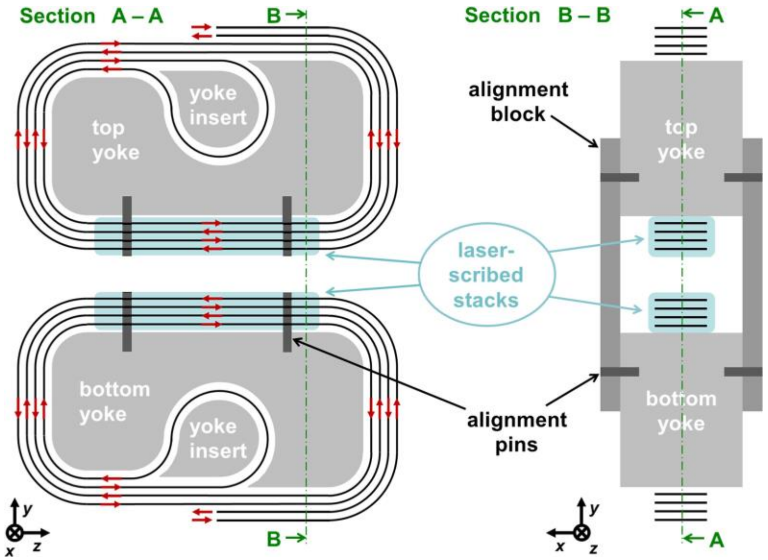
12T Solenoid
design and manufacture in collaboration with Fermilab contract in preparation

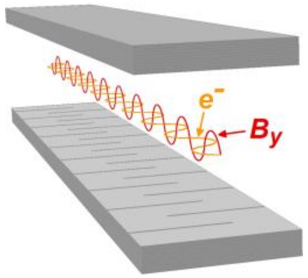
HTS INSERT

Courtesy of Marco Calvi (PSI)

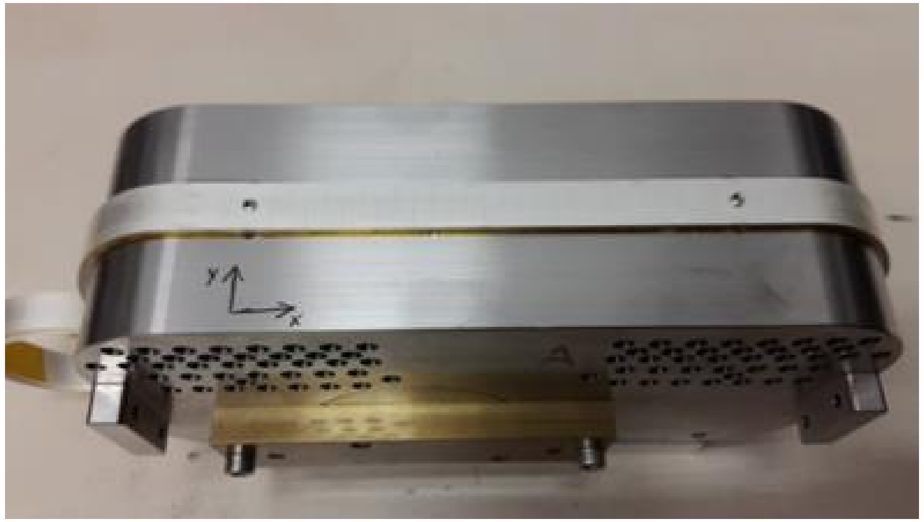
HTS structured undulator for X-ray FELs

- Promising for narrow gap ~ 2 mm, short period < 10 mm regimes. Natural transverse gradient.





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



Laser structuring using TRUMPF picosec YAG - IR laser, programmable beam control used for Roebel cables at KIT ITEP

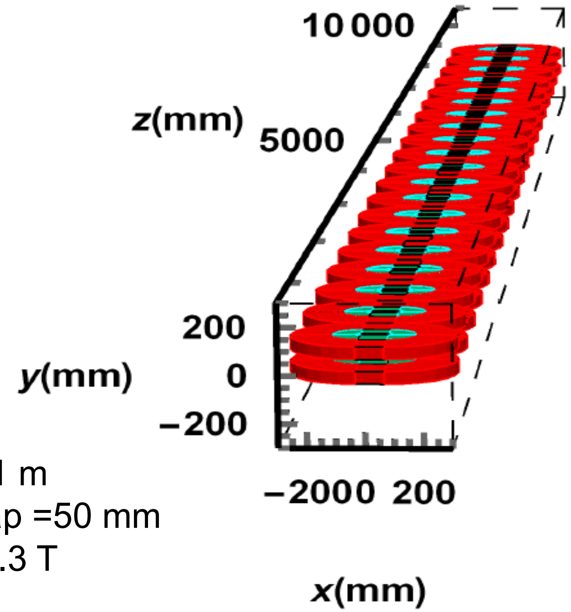
- Photon energies > 12 (42) keV for electron beam energies of 3.5 (8) GeV

S. Prestemon et al., IEEE Trans. on Appl. Supercond. 1880 Vol. 21-3 (2011)
T. Holubek et al., Supercond. Sci. Technol. 30 115002 (2017)

SCUs for European XFEL: THz SCU

Dual use of the ultra-short GeV electron bunches, possible by a rather minor extension of the infrastructure. **X-ray movies of THz-driven mode-selective chemistry**

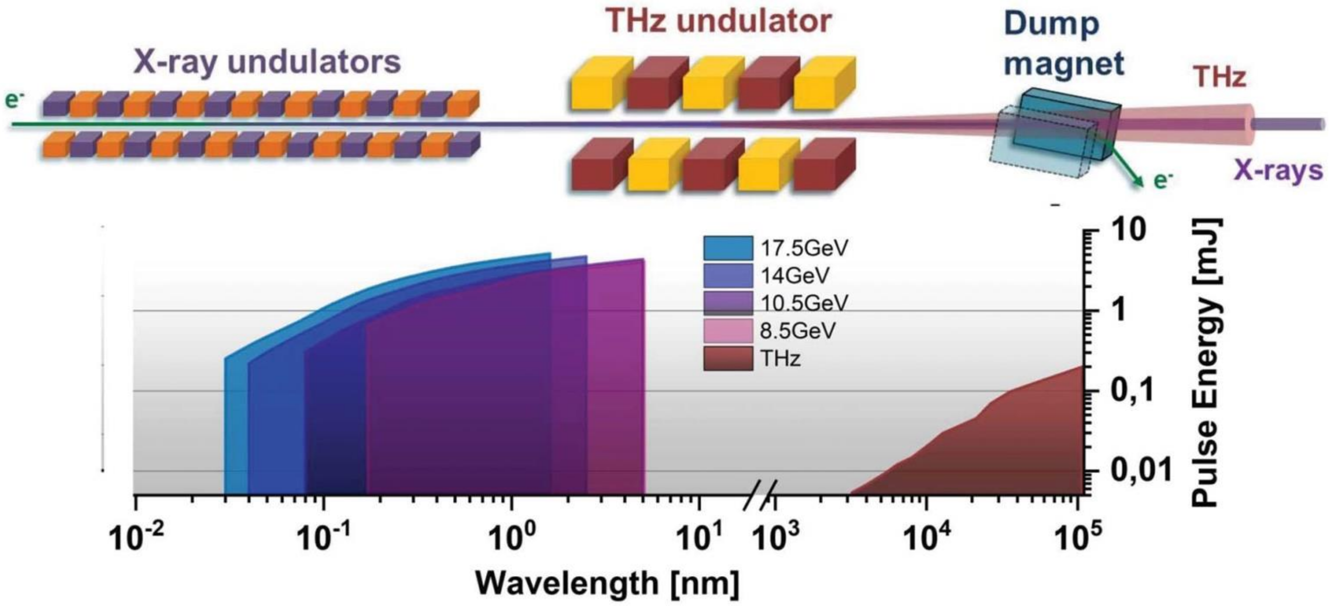
Superradiant THz undulator based on NbTi



λ_U = 1 m
m. gap =50 mm
B = 7.3 T

T. Tanikawa et al., JINST 14 P05024 (2019)

SCUs can produce the same peak magnetic field as PMUs using a larger vacuum gap, which allows to reduce the frequency cut off of the vacuum chamber, and to transmit most of the THz radiation of interest

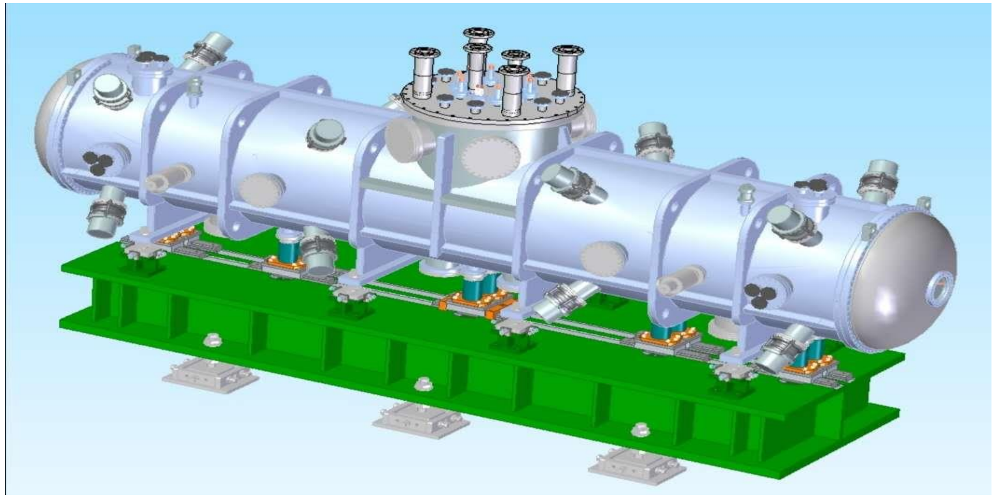


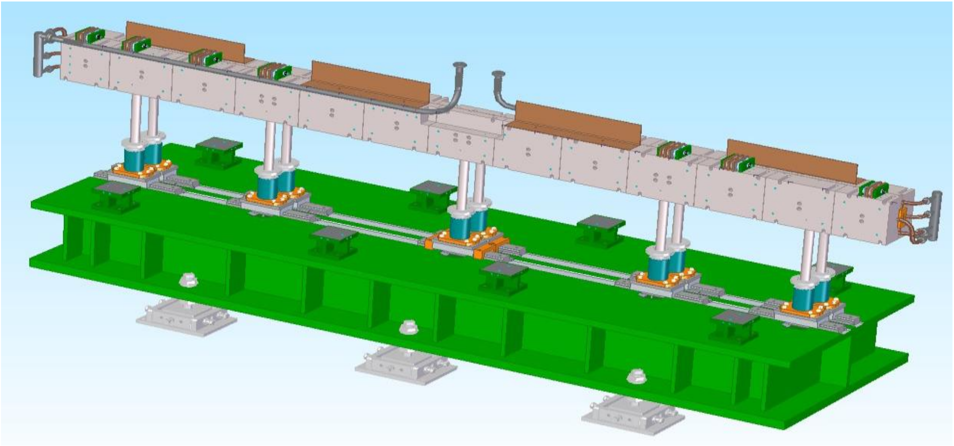
T. Tanikawa et al., J. Synchrotron Rad. (2020). 27, 796

SHINE SCUs

Quantity	40
Period Length	16 mm
Magnetic Length	4 m
Period Number	250
Beam Gap	4 mm
Peak Fields	0.682 – 1.583 T
Beam Energy	8 GeV
Photon Energy	10 – 25 keV

- SHINE project will use 40 in-vacuum SCUs to produce the photon energy range of 10-25keV with the vertical polarization.
- 504 vertical racetrack superconducting coils wound on the active poles are used for one undulator and are inserted in the yokes with neutral poles.
- The cooling of the magnet is forced by the liquid helium pipes. In order to reduce the thermal radiation from the vacuum chamber, a 65K shielding cooled by the gas helium pipe is designed.
- To minimize the phase error, two periods in the middle of the undulator are designed as a phase shifter and are excited magnetically by one power supply. Other two 124-periods before and after are excited by two power supplies respectively.





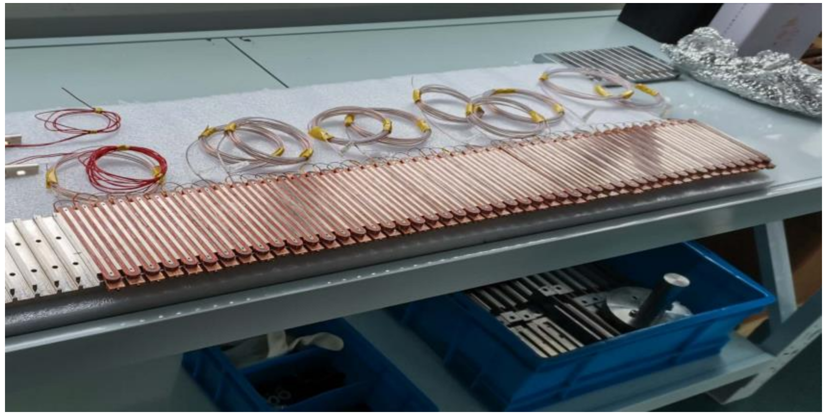
Courtesy of Zhou Qiaogen (SINAP)

The Progress of The Prototype (2018-2020)

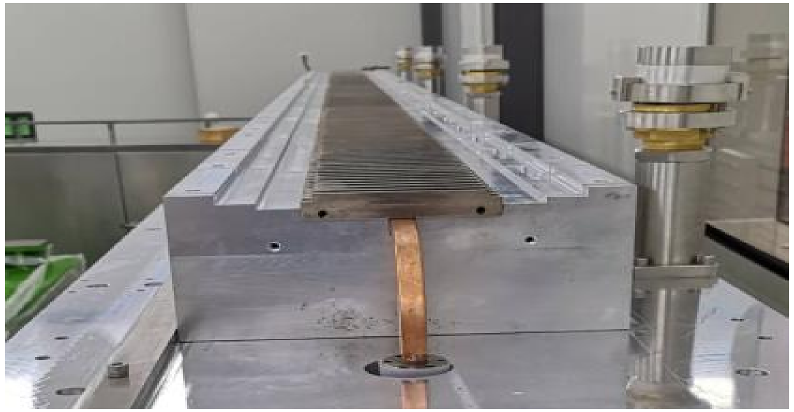
Cryostat

Coil Series

Support



Magnet Arrays



Aluminum Frame of Magnet

Courtesy of Zhou Qiaogen (SINAP)

Superconducting undulators development for European XFEL

- The development of SCUs will enable
  - to build the know how inside the facility to the state-of-the-art technology
  - to further improve the know how to be later on transferred to industry

- Benefit EuXFEL strategic plans
  - SCU SASE line(s) to lase at photon energies **> 50 keV**, offering a unique source worldwide
    - ► MHz rate X-ray microscopy can reveal bulk dynamics in material such as crack propagation or shockwave propagation previously possible to observe only ex-situ
    - ► NbTi SCU@2K 15mm period 5 mm vacuum gap 54-100 keV
  - Soft X-ray SASE lines with SCUs significantly enlarged tunability
    - ► NbTi SCU 70mm period 7 mm vacuum gap 0.25-3 keV
  - CW upgrade with lower electron beam energy (7 GeV) with SCU SASE line(s) can cover about the same photon energy range as by the presently installed PMU
    - ► NbTi SCU@2K 15mm period 5 mm vacuum gap 8.6-25 keV

Challenges for short period SCUs for XFELs

- Cooling
- Number of undulators in one cooling unit?
- Relative alignment of the SCUs inside one cryostat along the SASE line
- Functionality and field quality including measurement system in the final cryostat
- Tunnel and accelerator infrastructure
- Industrialization

Present activities at European XFEL

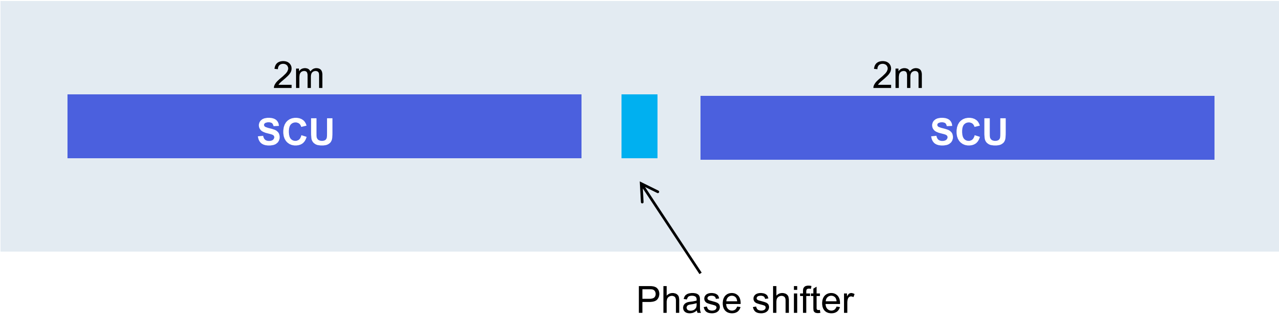
- Undulator Hall at EuXFEL
- EuXFEL R&D project on Advanced SCU Coils.
  Postdoc: Vanessa Grattoni started 1.10.20
- LEAPS-INNOV activity on pulsed wire method to determine the magnetic field profile of long structures (~2-4 m) with short periods (<20 mm). Postdoc: Johann Baader started on 1.6.20
- Vertical measurement setup to measure undulator coils up to 2m length @4K and @2K in collaboration with DESY


Courtesy of Barbara Marchetti

48m x 19m x 10m

Plans at European XFEL: SCU afterburner for SASE2

- SCU afterburner to be installed at the end of SASE2: 5 modules with about the same length as the installed permanent magnet undulators (5 m)



- Use of same intersections
- period length = 15 mm and vacuum gap = 5 mm
- up to 10^9 photons/pulse targeted at > 50 keV

Courtesy of Massimiliano Di Felice

Main components for SCU project at European XFEL

- **Vertical cryostat:** functionality and field quality of **R&D on advanced SCU coils** and of 2 m SCU coils before installation in final cryostat

- **Horizontal magnetic measurement system:** functionality, field quality and alignment in final cryostat

- **Pre-series prototype module** — Start 2021
  - Address the issues of **cooling** and **alignment**
  - **Test horizontal magnetic measurement system** setup for final module
  - **Lessons learned** to be implemented in the 5 modules for SASE2

- **Cryogenic plant** to cool the 5 modules to be installed during the long shutdown

- **SCU afterburner to be installed at the end of SASE2. Small series production of 5 modules** — Installation in WS 2027/28
  - Demonstration of the **functionality of SCUs at a X-ray FEL**
  - Set up of the needed **infrastructure** to characterize and operate SCUs
  - **Industrialization** of SCUs and reduction of the price per module

Collaborators to the SCU for European XFEL project

European XFEL Undulator group	European XFEL	DESY	RAK Industrial Consulting	KIT
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S. Casalbuoni	H. Sinn	W. Leemans		
V. Grattoni	T. Tanikawa	R. Ramalingam		
S. Karabekyan	T. Tschentscher	D. Sellmann		
B. Marchetti	M. Vannoni	T. Schnautz		
F. Preisskorn	M. Wünschel			
M. Yakopov				
P. Ziolkowski				

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Thank you for your attention !