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UNIVERSITY OF CAMBRIDGE

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SPring-8

ESRF The European Synchrotron

Marco Calvi :: Center for Photon Science :: Paul Scherrer Institute

A GdBCO Undulator for Tomographic Microscopy at the new Swiss Light Source, SI

LEAPS INNOVATION

CHART Swiss Accelerator Research and Technology

IFJ PAN – Polish academy of Science

Nov 28th 2024

SLS2.0

Overview

- Brief introduction to accelerator based light sources
- The tomographic microscopy beamline: TOMCAT ✉ I-TOMCAT
- The HTS (REBCO) bulk staggered array undulator
- The results on short samples:
  - Bulks & Tape-Stacks
- The status of the meter long HTS undulator prototype
- Conclusions

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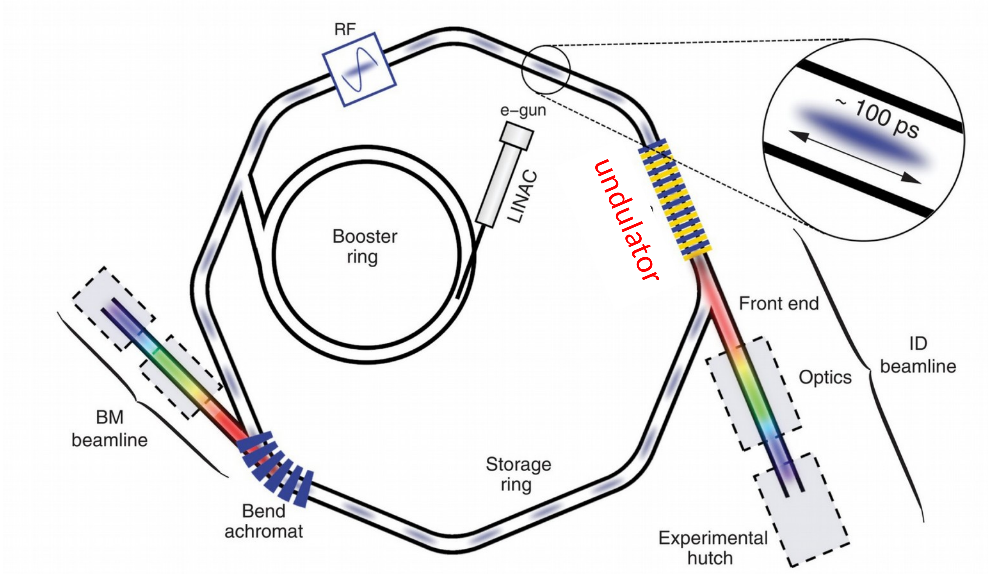
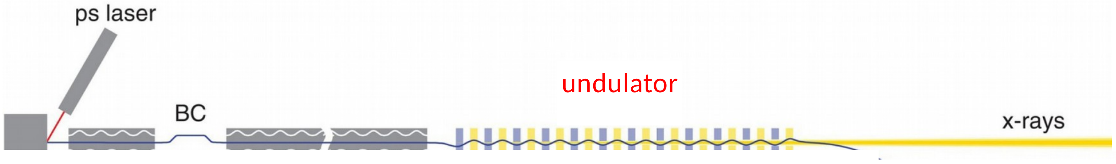
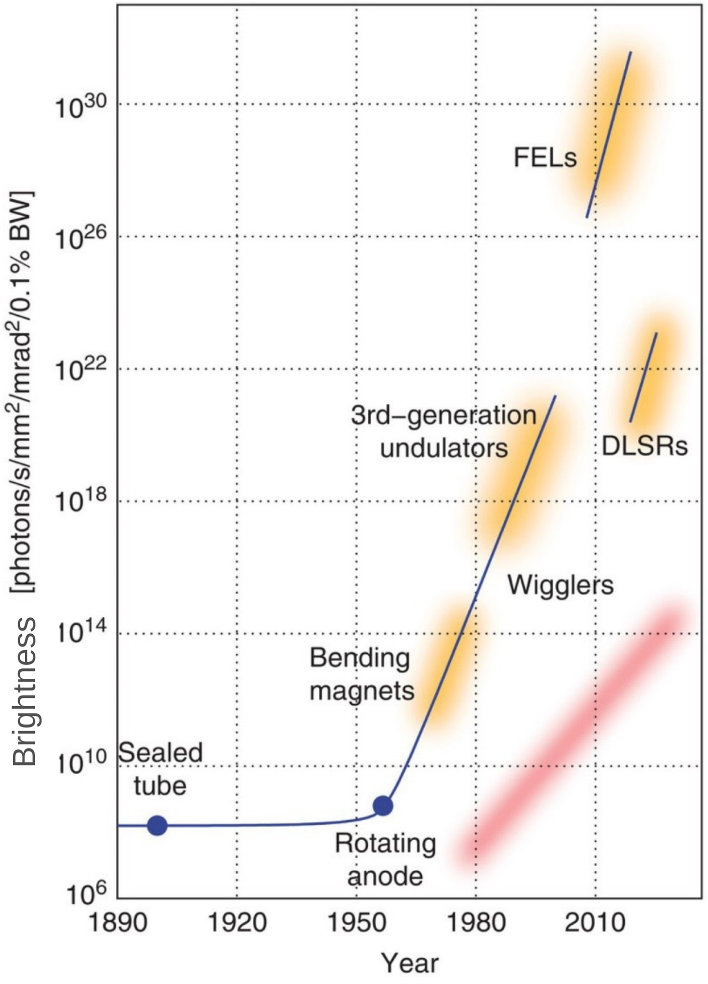
Introduction



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



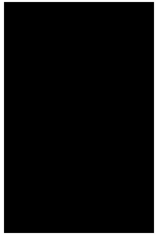


TOMCAT

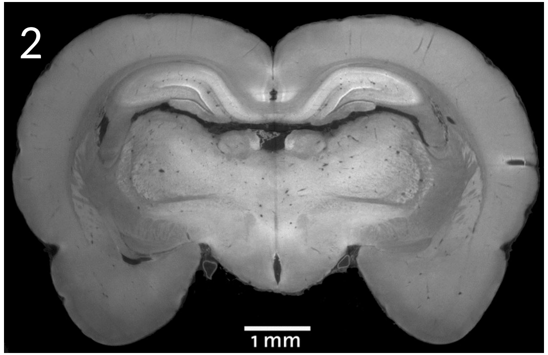
The X-ray tomographic microscopy beamline at the Swiss Light Source

Non-destructive, high-throughput, high-resolution, 3D imaging technique:

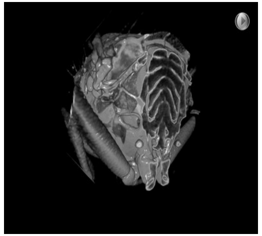
1. Wide spatial resolution: nano-micro-meso scales (0.1-10 µm)
2. High density resolution enhanced by phase contrast
3. Broad range of sample sizes (10 µm – 20 mm)
4. High temporal resolution: 3D data acquisition in less than 1 s
5. In-situ, operando, in-vivo investigations



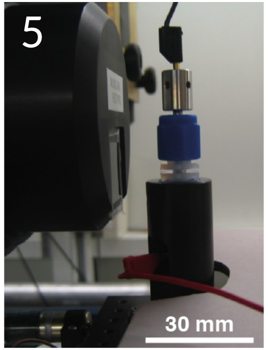
Spatial Resolution
10 microns – 0.1 microns



Density Resolution
Phase contrast imaging



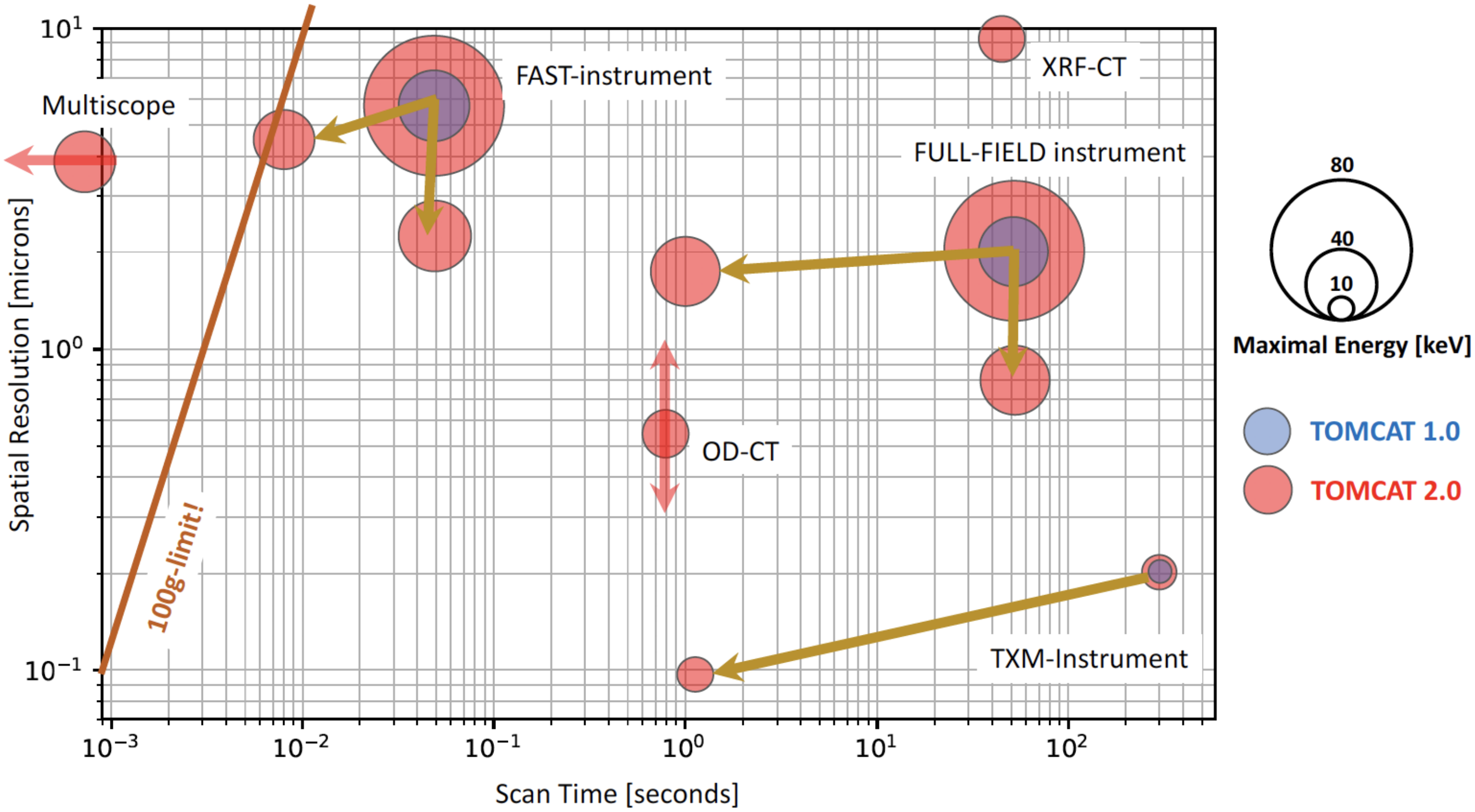
Ultra-fast tomography
Living fly



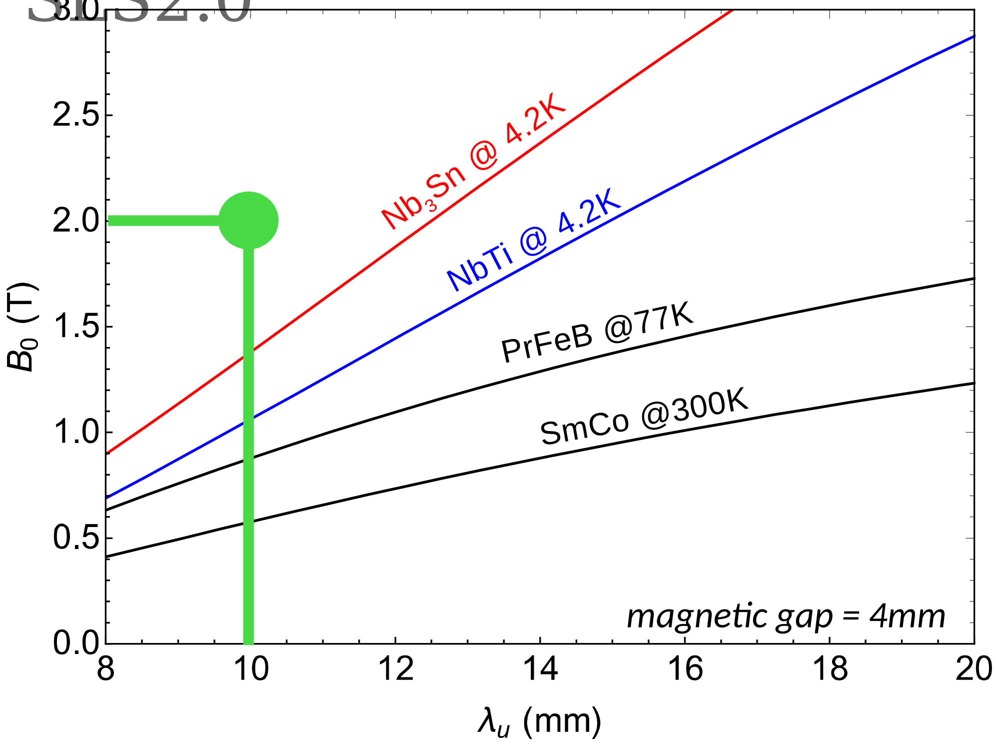
In-situ capabilities
Furnace/Cryo/Traction
Electrochemistry

TOMCAT ✉ I-TOMCAT @ SLS2.0

- Higher spatial and temporal resolution
- Larger samples, denser material
- More chemical information

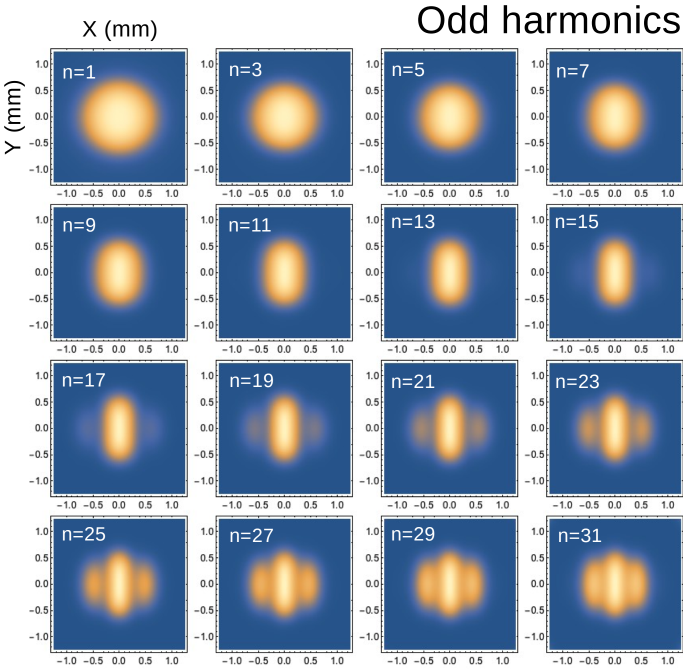


The new µ-Tomography beamline of SLS2.0

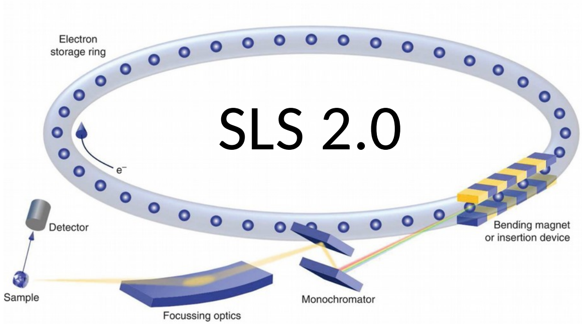


[Scaling laws: E.R. Moog, R.J. Dejus, and S. Sasaki, Light Source Note: ANL/APS/LS-348 James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator and Beams 17, 022401 (2014)]

HTSU10 with B_0=2.0 T



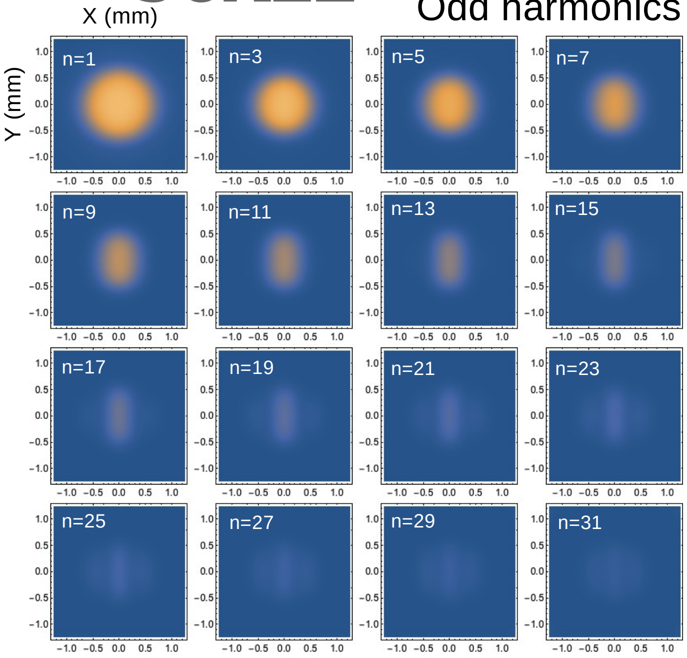
Flux at 30m from the source
to illuminate a sample of about 1mm^2

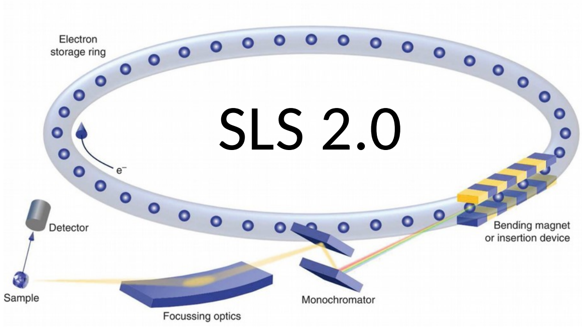


Calculations done for the future iTOMCAT beamline, dedicated to tomographic microscopy

CPMU14 with B_0=1.3 T – ABSOLUTE SCALE

Odd harmonics





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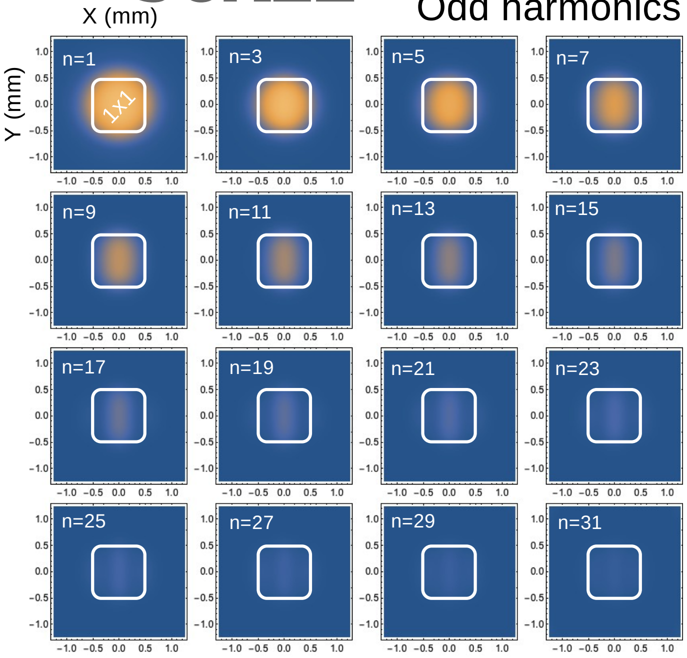

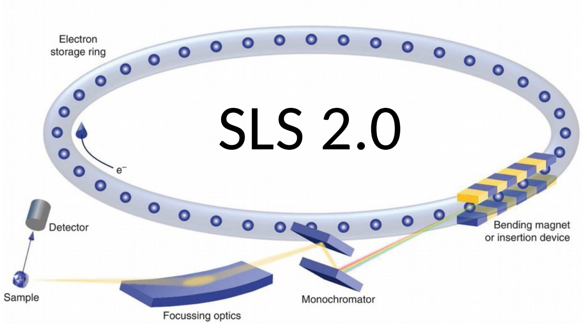

Calculations done for the future iTOMCAT beamline, dedicated to tomographic microscopy

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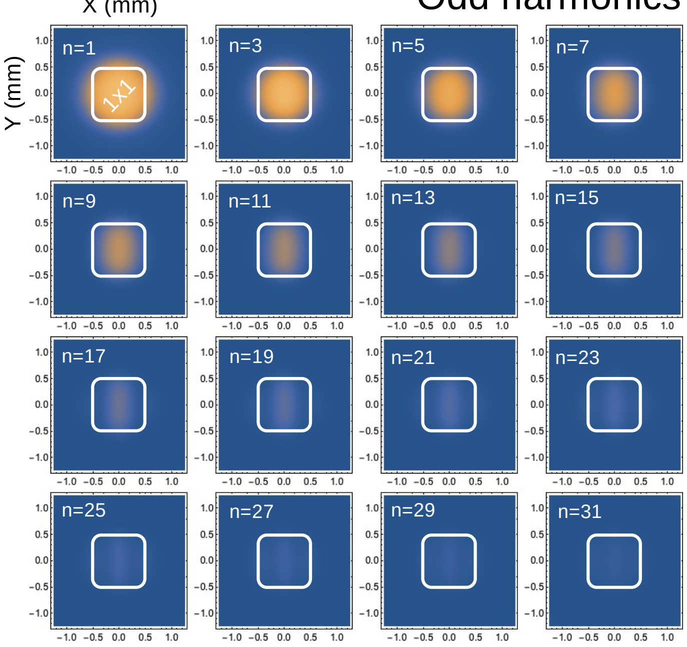
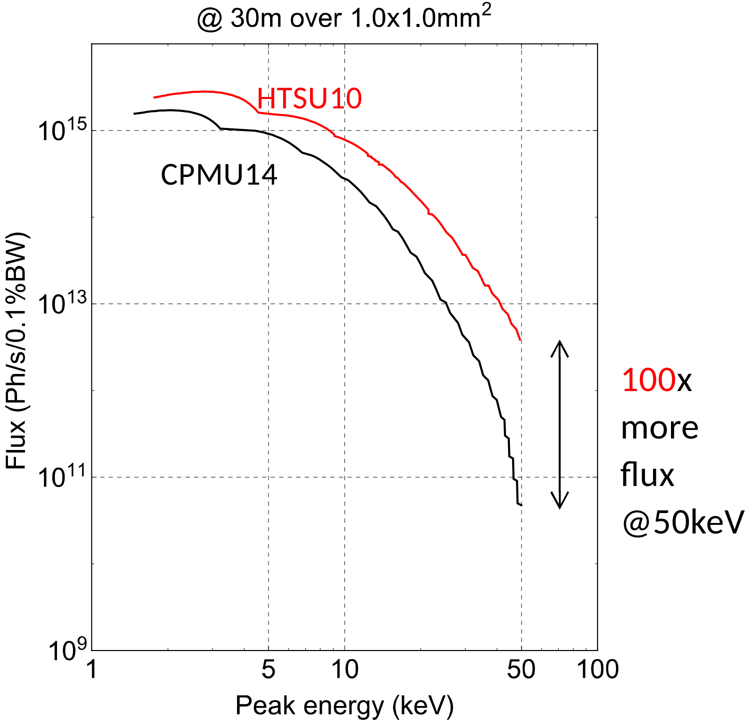
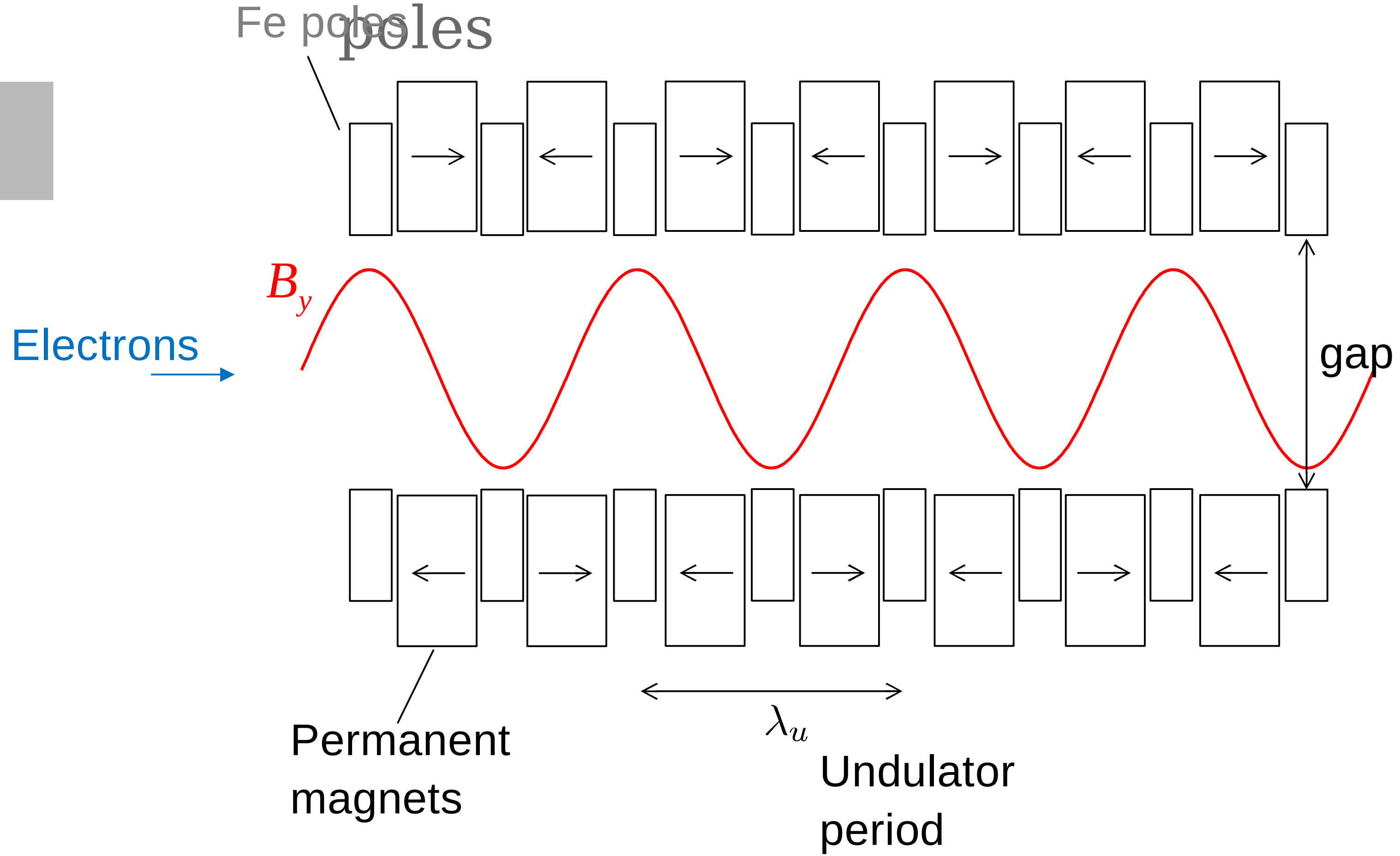




Flux at 30m from the source
to illuminate a sample of about 1mm^2

Permanent Magnet Undulator with Fe poles



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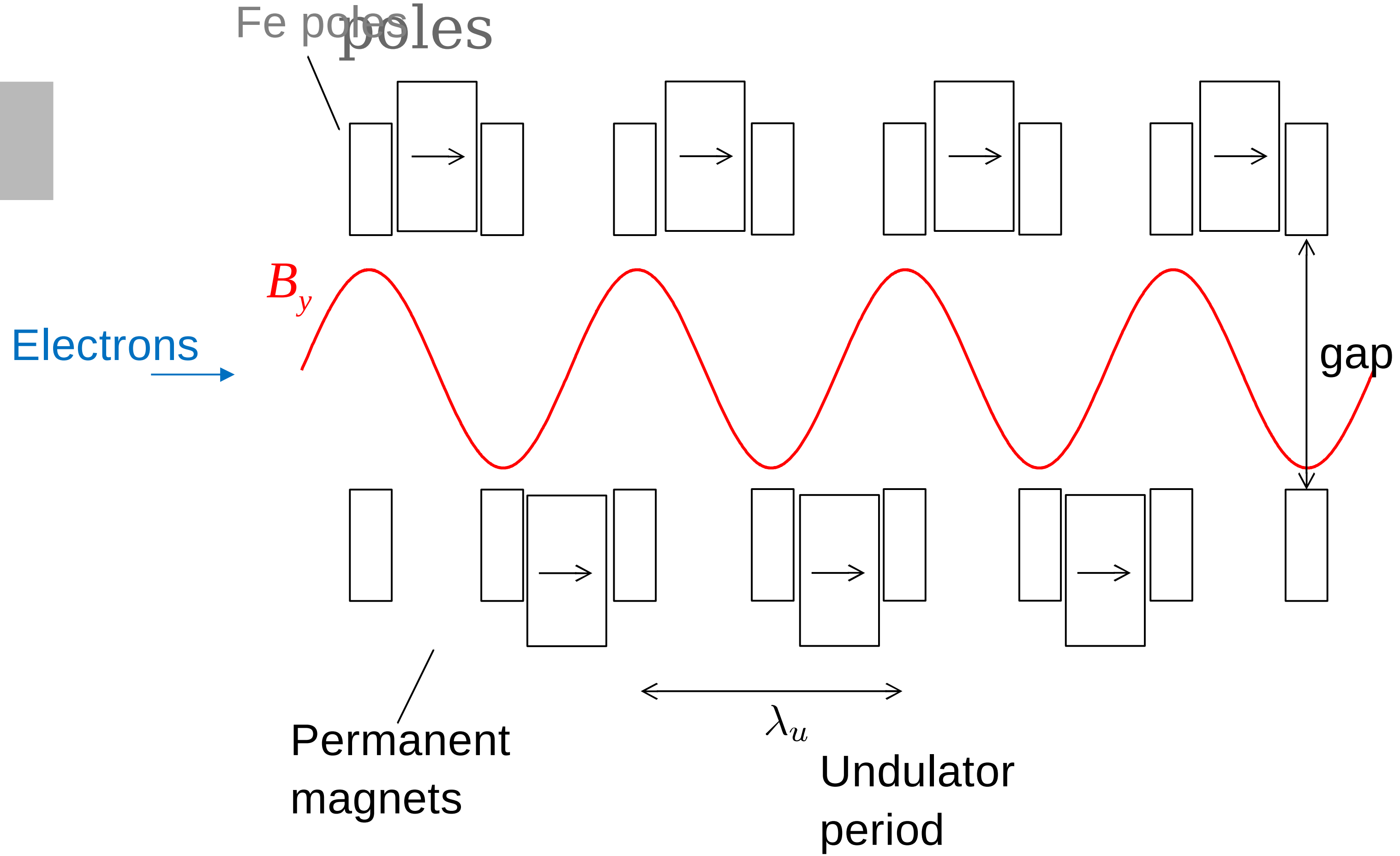
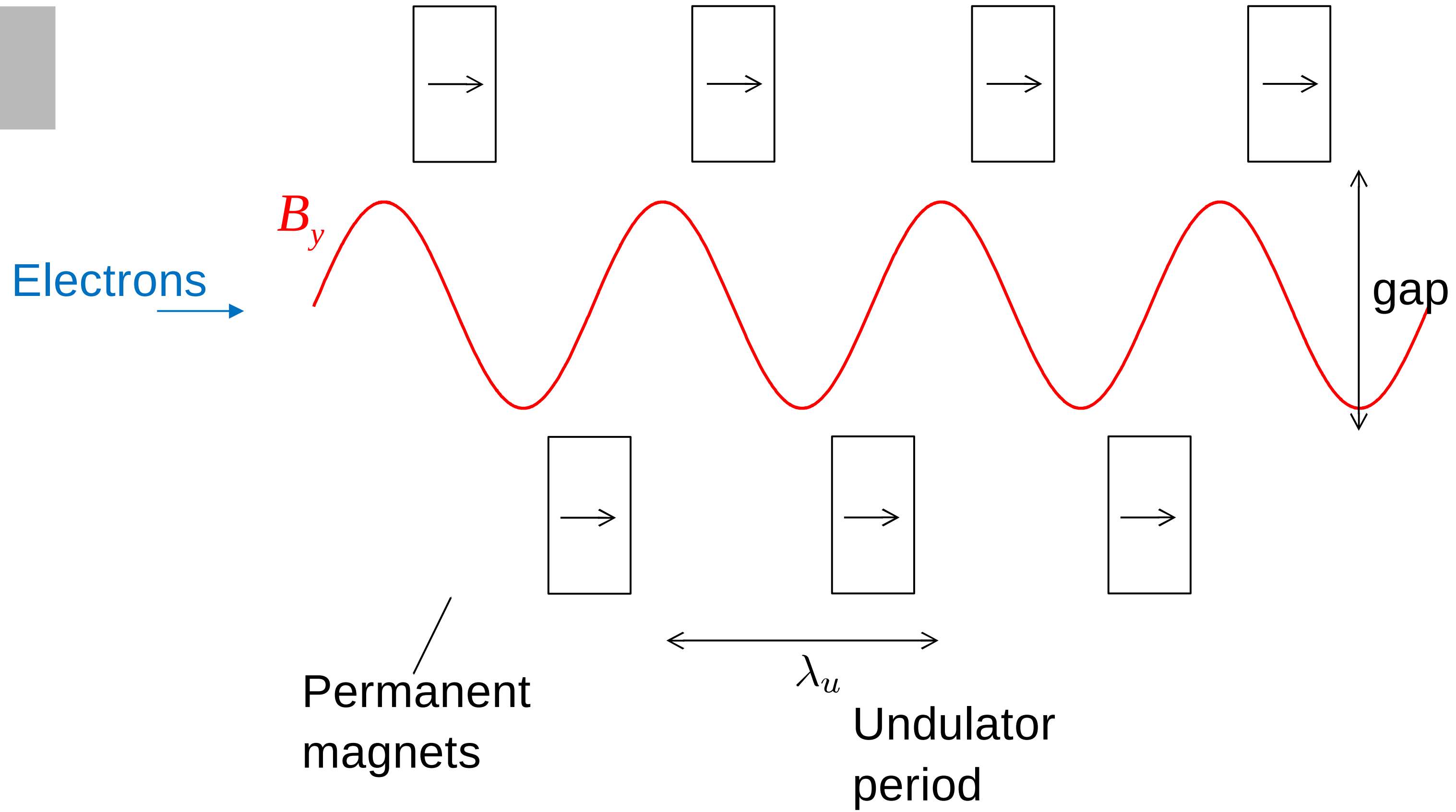
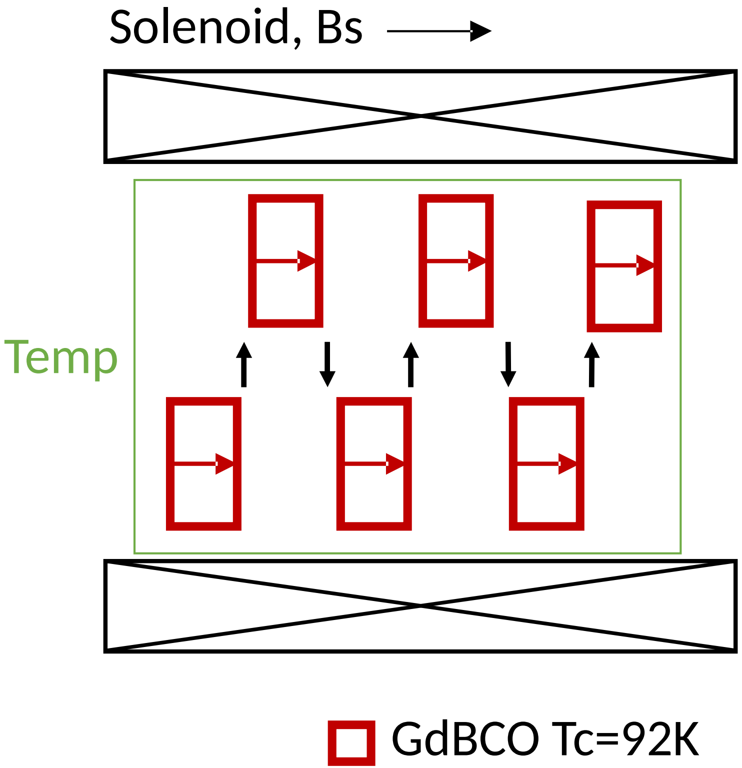


Permanent Magnet Undulator with Fe poles

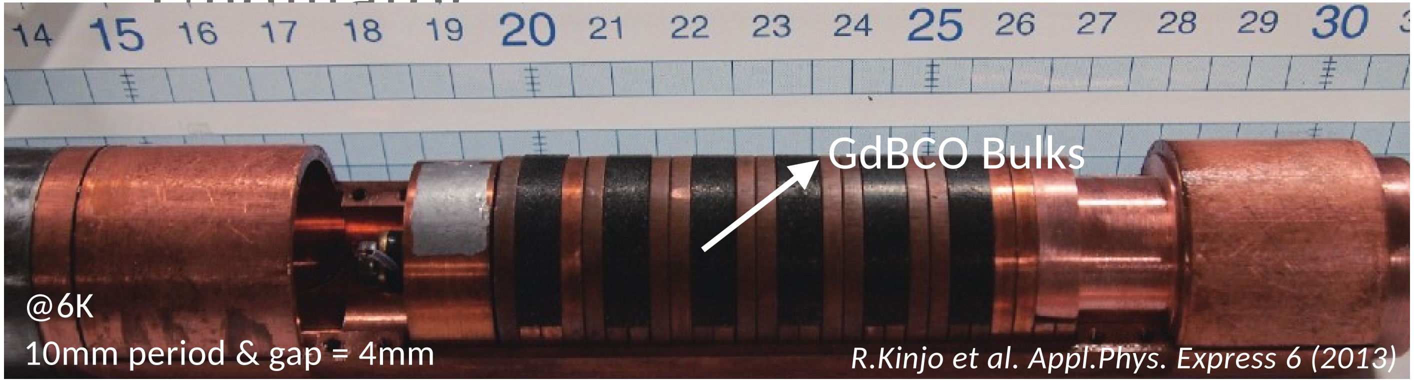


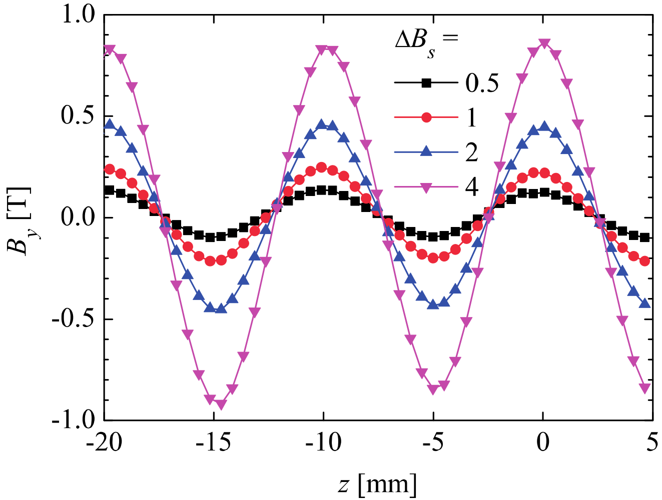
Superconducting Staggered Array Undulator

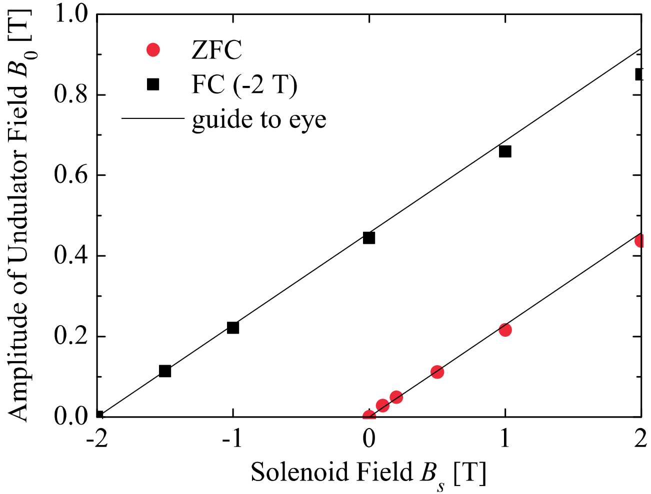


T. Kii, et al.: Proc. FEL2006 (2006) p. 653.

Superconducting Staggered Array Undulator





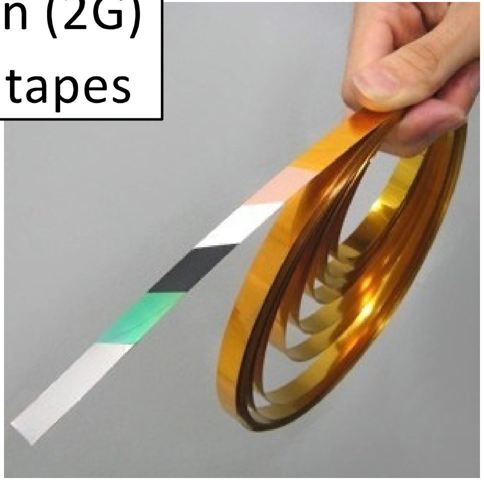


0.85T

HTS ✉ REBCO

- CAN Superconductor
- Adelwitz Technologiezentrum
- Nippon Steel

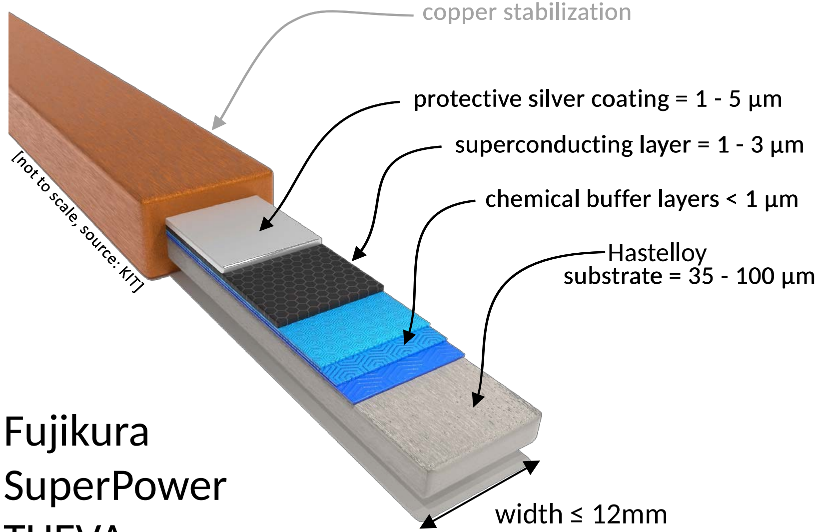
2nd generation (2G) thin-film HTS tapes



- Fujikura
- SuperPower
- THEVA
- SuNAM
- AMSC
- Deutsche Nanoschicht/BASF
- SuperOX
- BRUKER

HTS ✉ REBCO

2nd generation (2G) thin-film HTS tapes



- CAN Superconductor
- Adelwitz Technologiezentrum
- Nippon Steel

- Fujikura
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- Deutsche Nanoschicht/BASF
- SuperOX
- BRUKER

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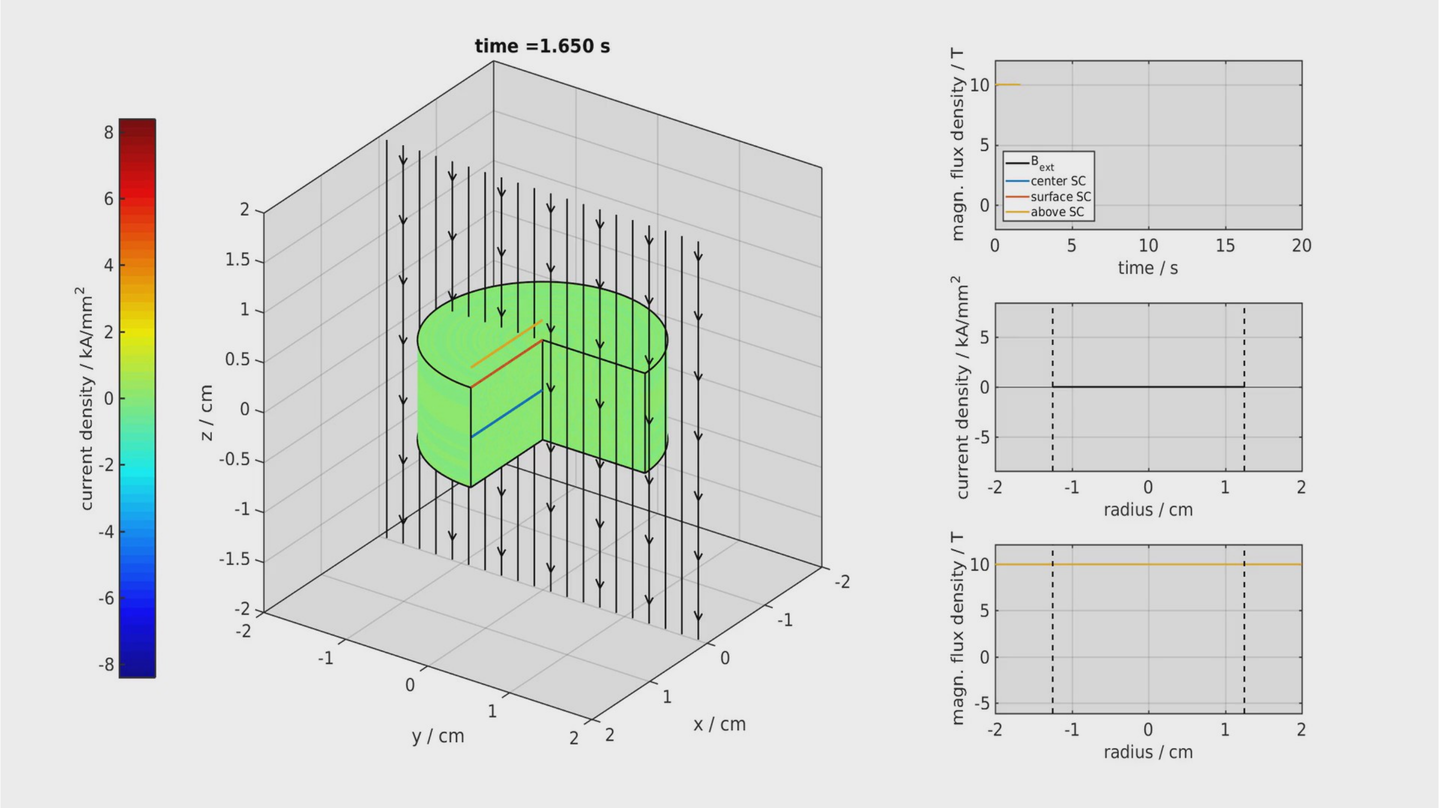
HTS ✉ REBCO

REBCO Bulks

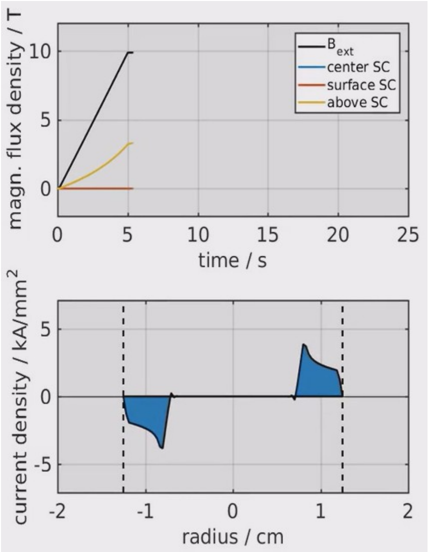
- CAN Superconductor
- Adelwitz Technologiezentrum
- Nippon Steel

Example of Field Cooling (FC)

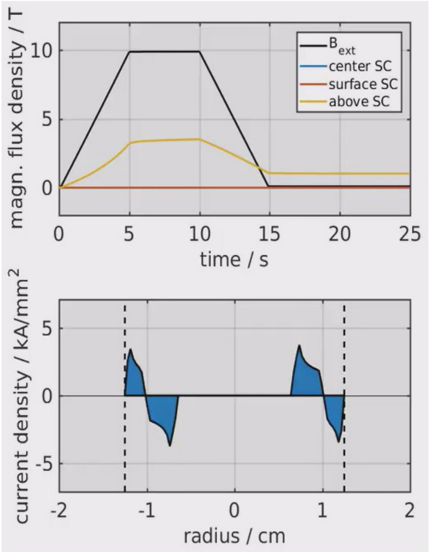


ZFC versus FC

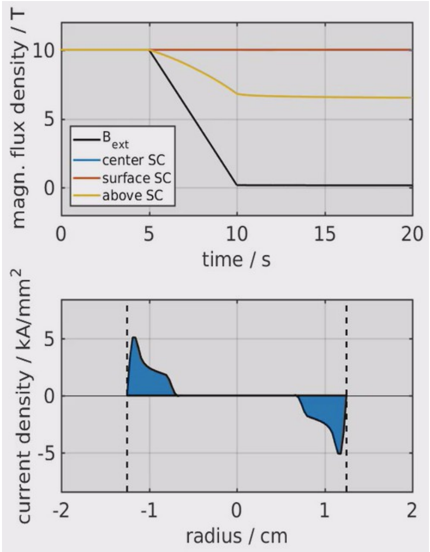
ZFC - 1



ZFC - 2

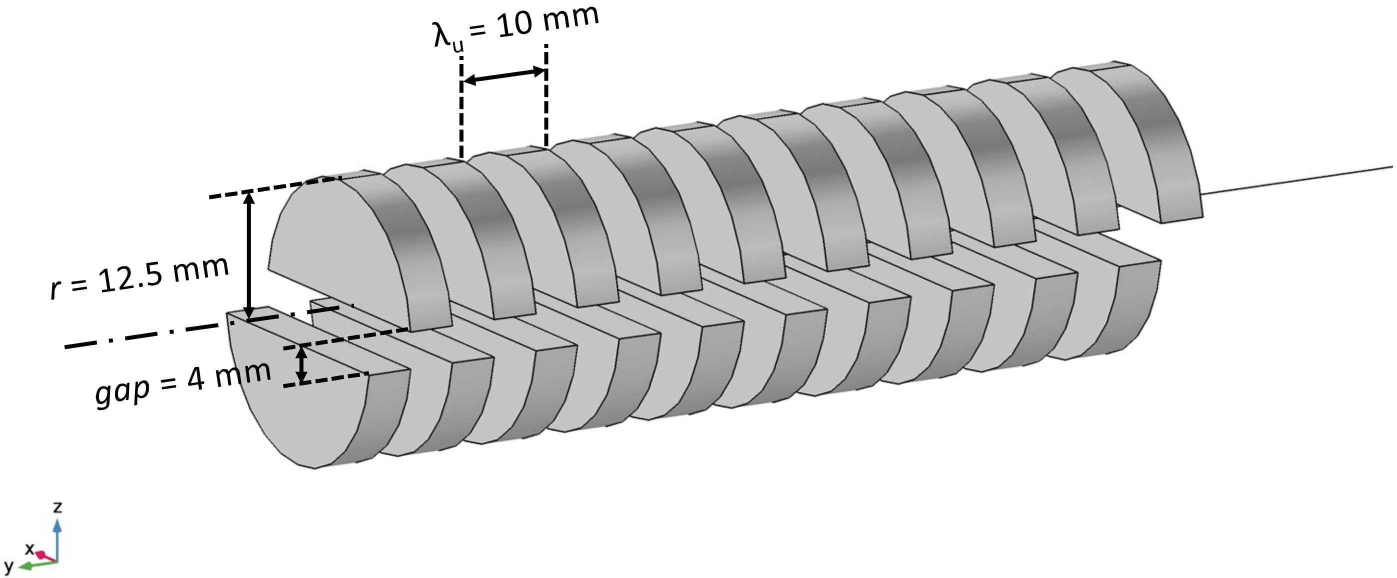


Field Cooling



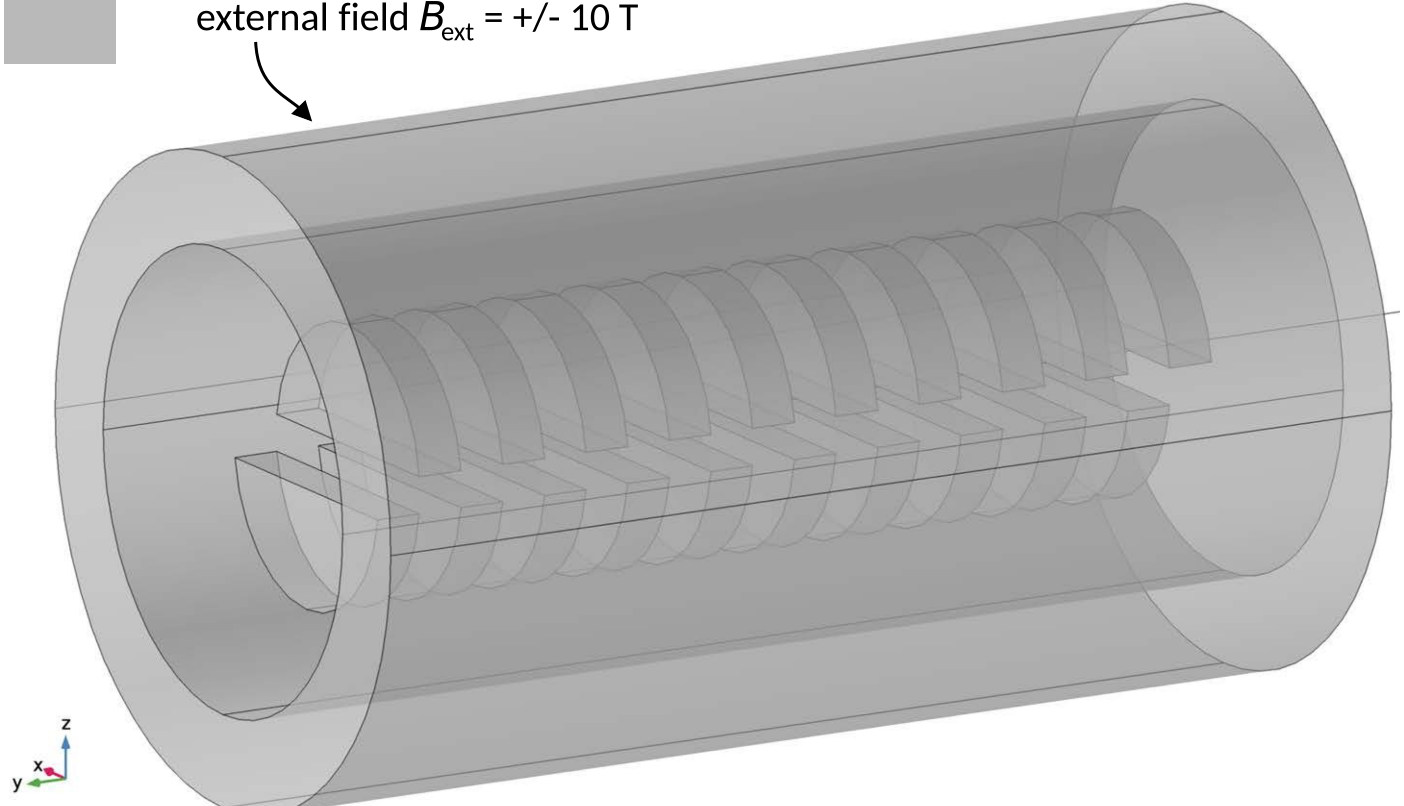
Field cooling is what fits better for this application

Superconducting Staggered Array



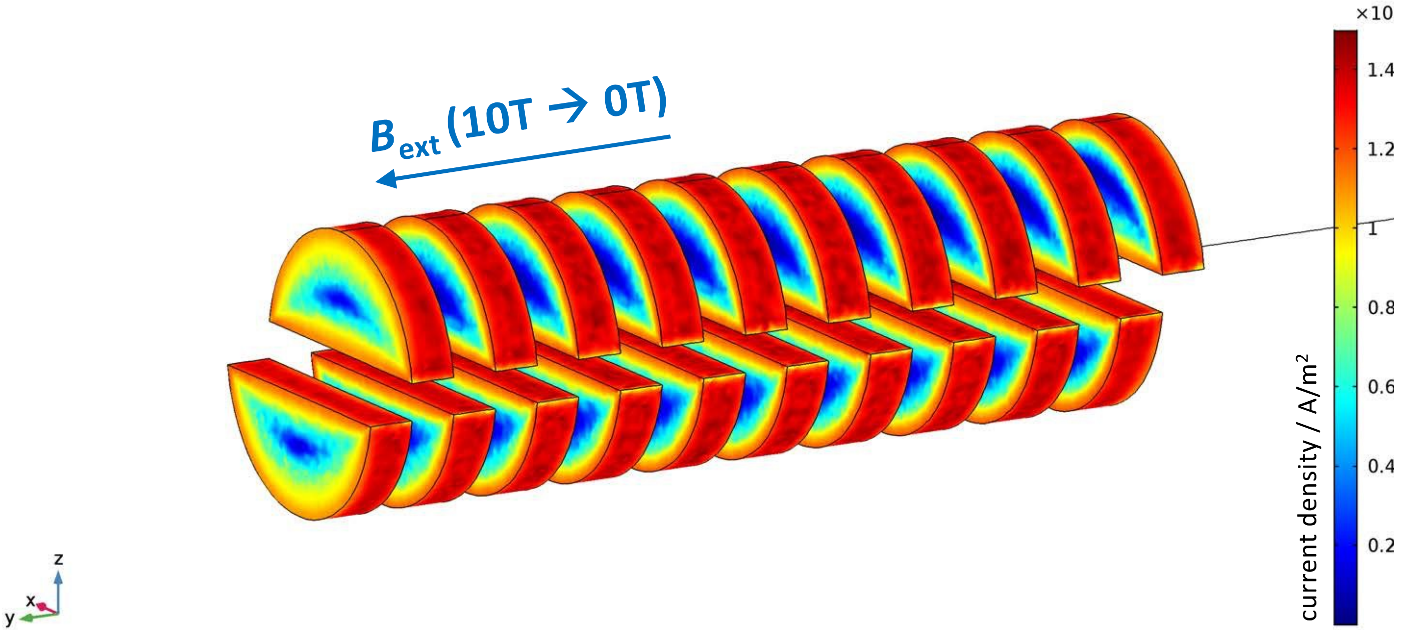
Superconducting Staggered Array

- Superconducting solenoid providing external field B_{ext} = +/- 10 T



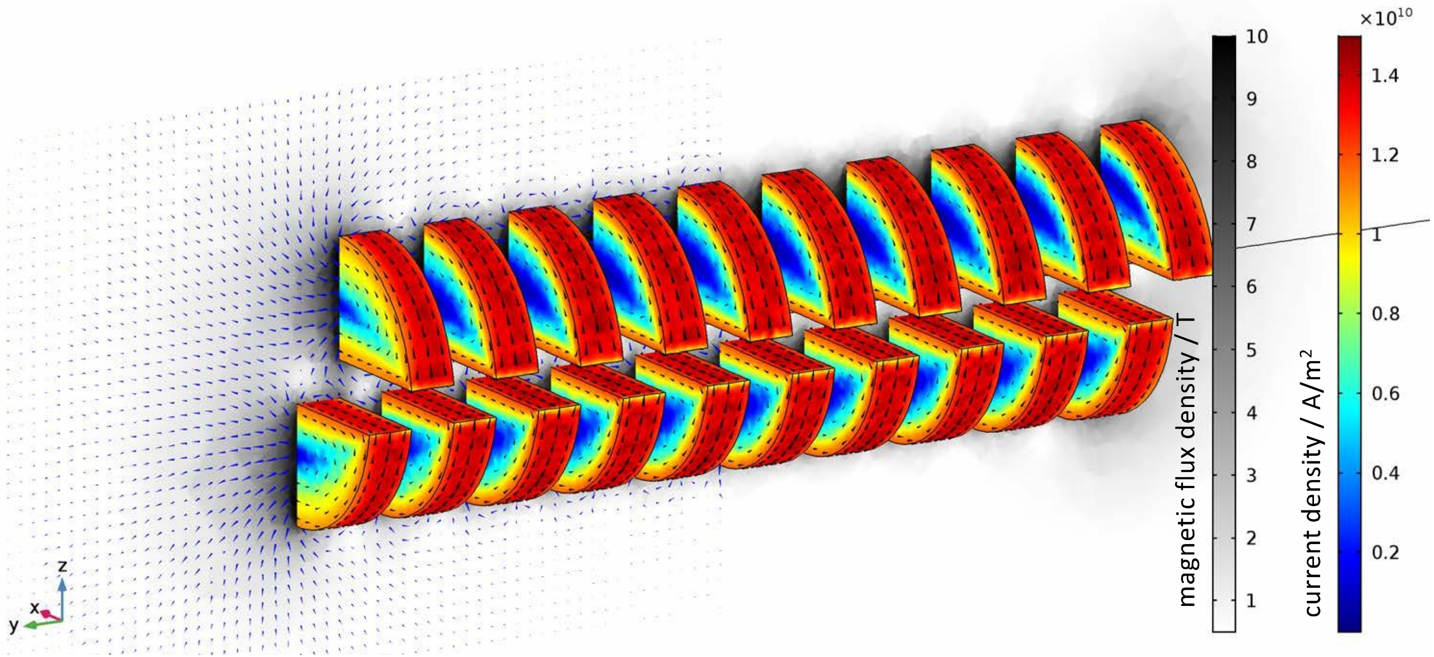
Superconducting Staggered Array

- Surface current density after magnetization with field 10T → 0T:



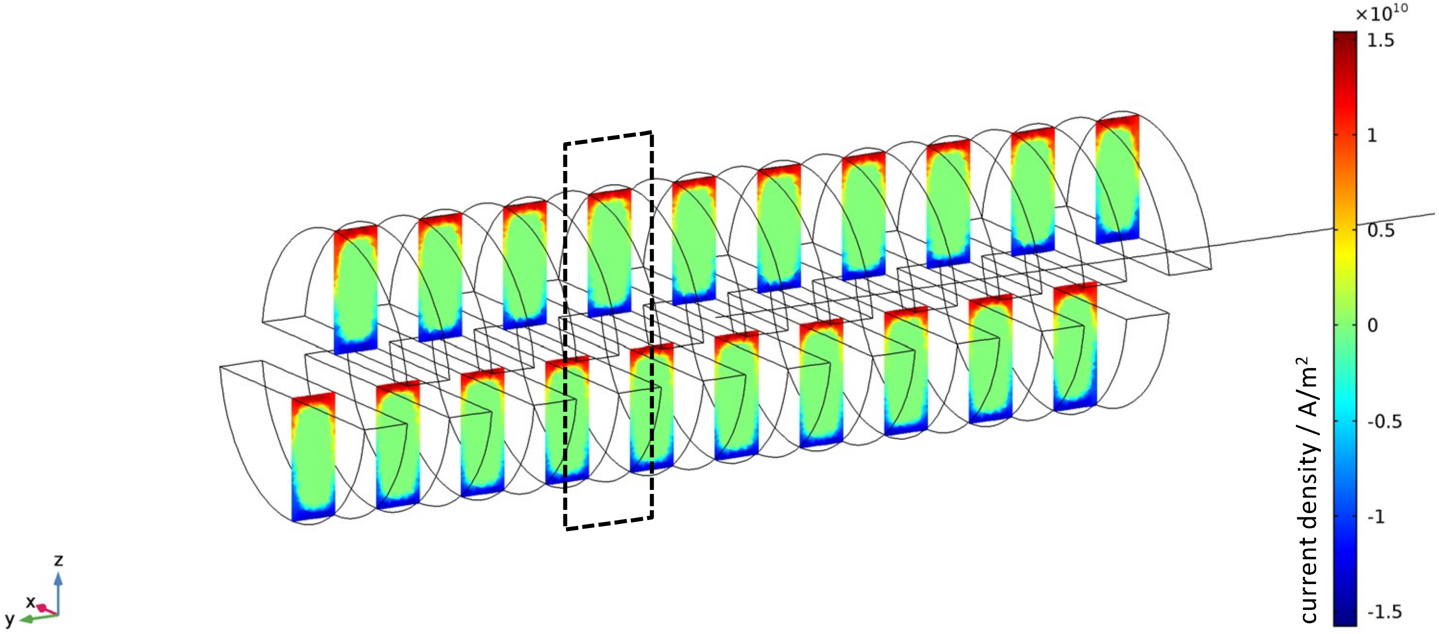
Superconducting Staggered Array

- Surface current density and trapped magnetic field after magnetization with field 10T → 0T:



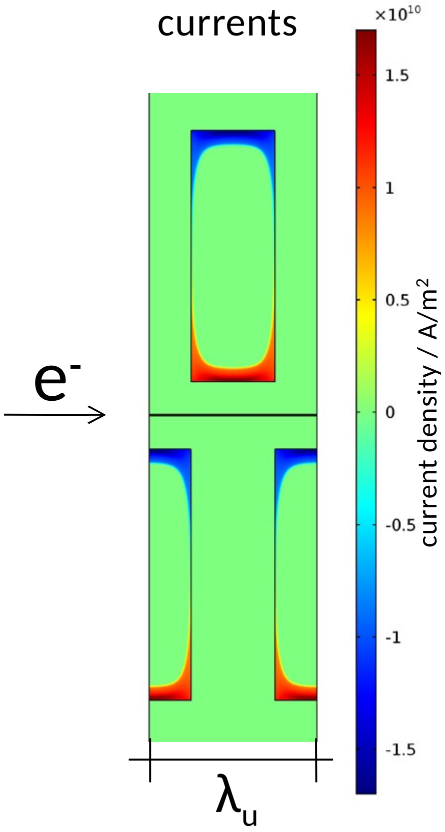
Superconducting Staggered Array

- Internal current density after magnetization with field 10T → 0T:

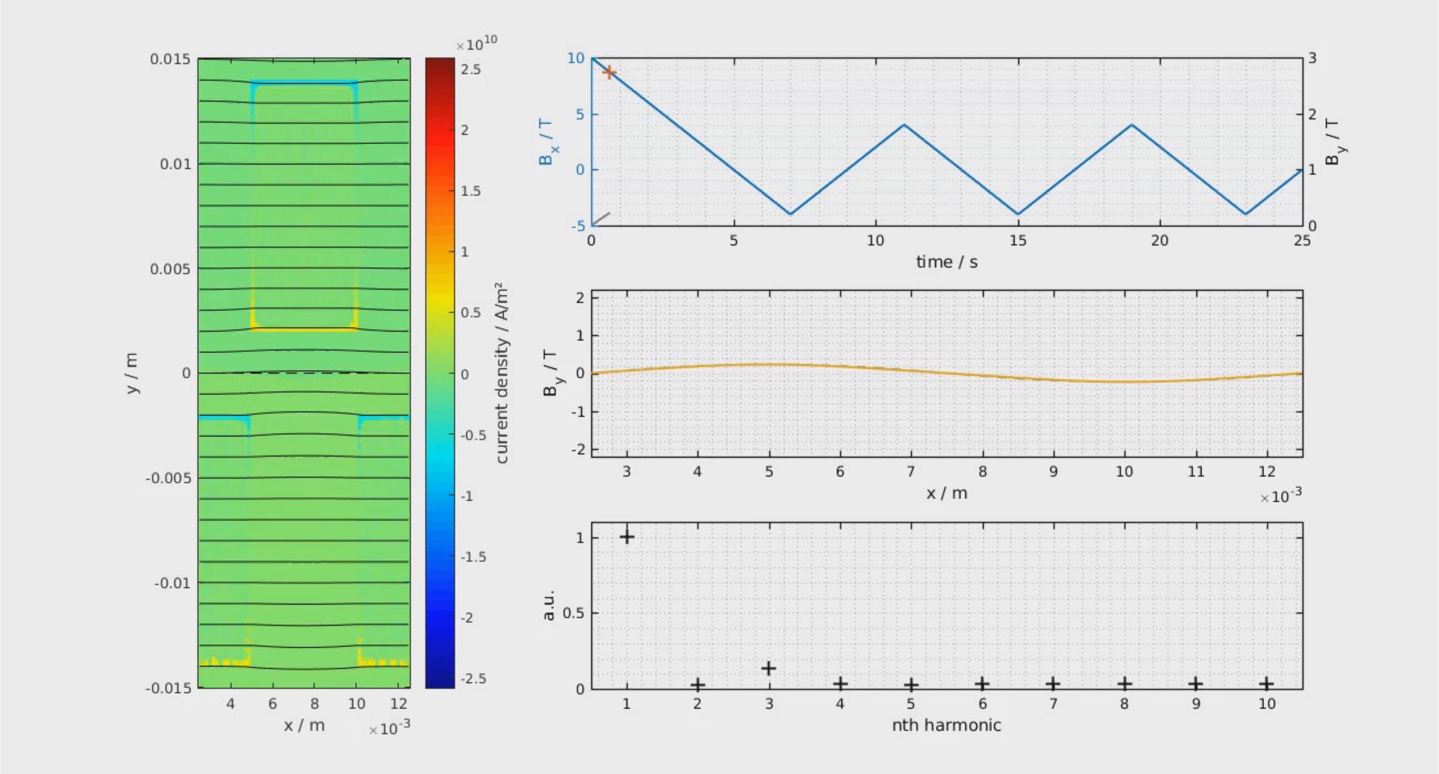


Superconducting Staggered Array

Trapped
currents



Example of operation: K-tuning

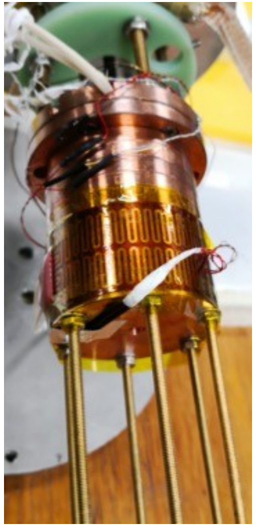


Overview

- Brief introduction to accelerator based light sources
- The Tomographic Microscopy beamline: TOMCAT ✉ I-TOMCAT
- The HTS (REBCO) bulk Staggered Array undulator
- The results on short samples:
  - Bulks & Tape-Stacks
- The status of the meter long HTS Undulator prototype
- Conclusions

Samples Overview

1^{st} Bulk Sample



6mm gap

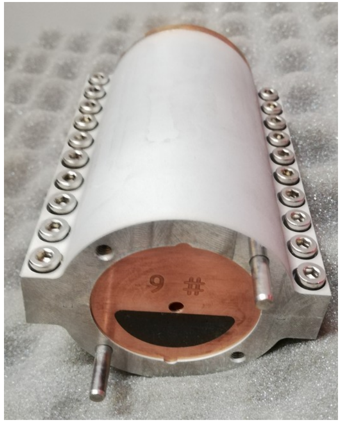
2^{nd} Bulk Sample

4mm gap

Bulk Industrial Sample

4mm gap

Bulk Simplified Sample



4mm gap

2019

2023

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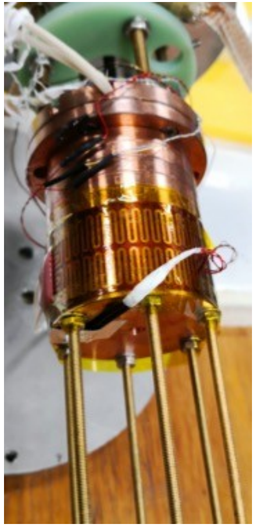
Samples Overview

1st Bulk Sample



6mm gap

2nd Bulk Sample

4mm gap

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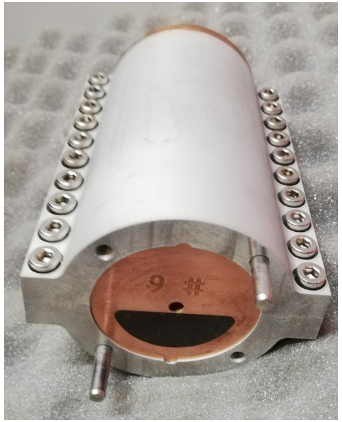


4mm gap

The “Good” Sample

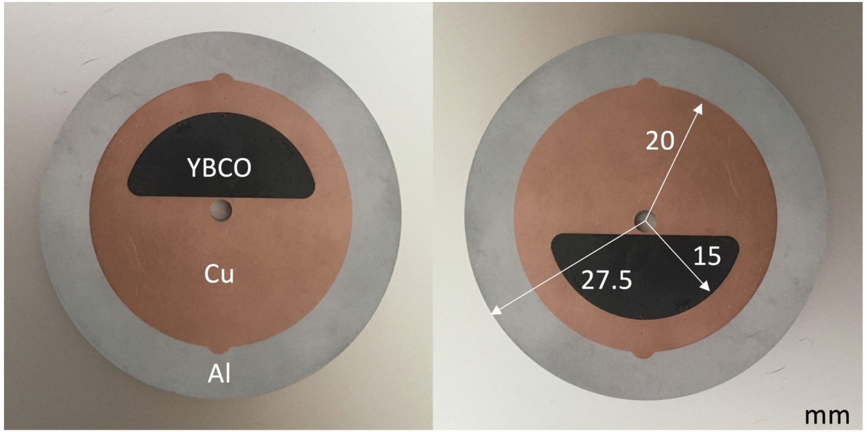
4mm gap

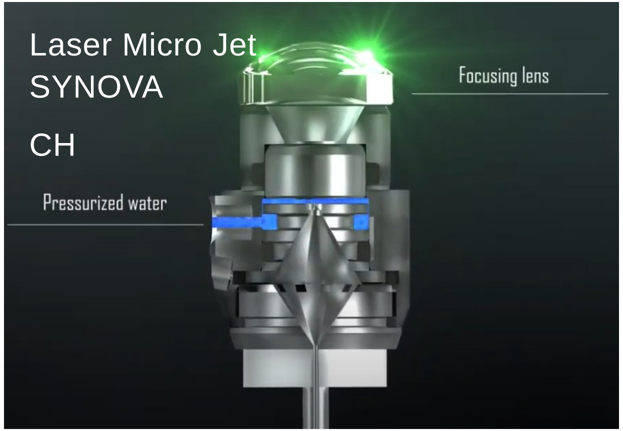
2019

2021

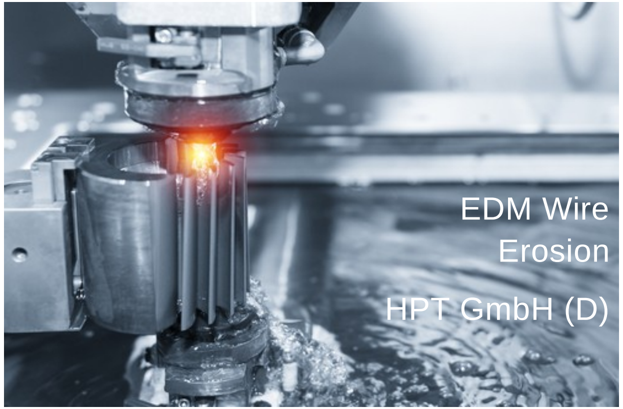
2023

Industrial Sample

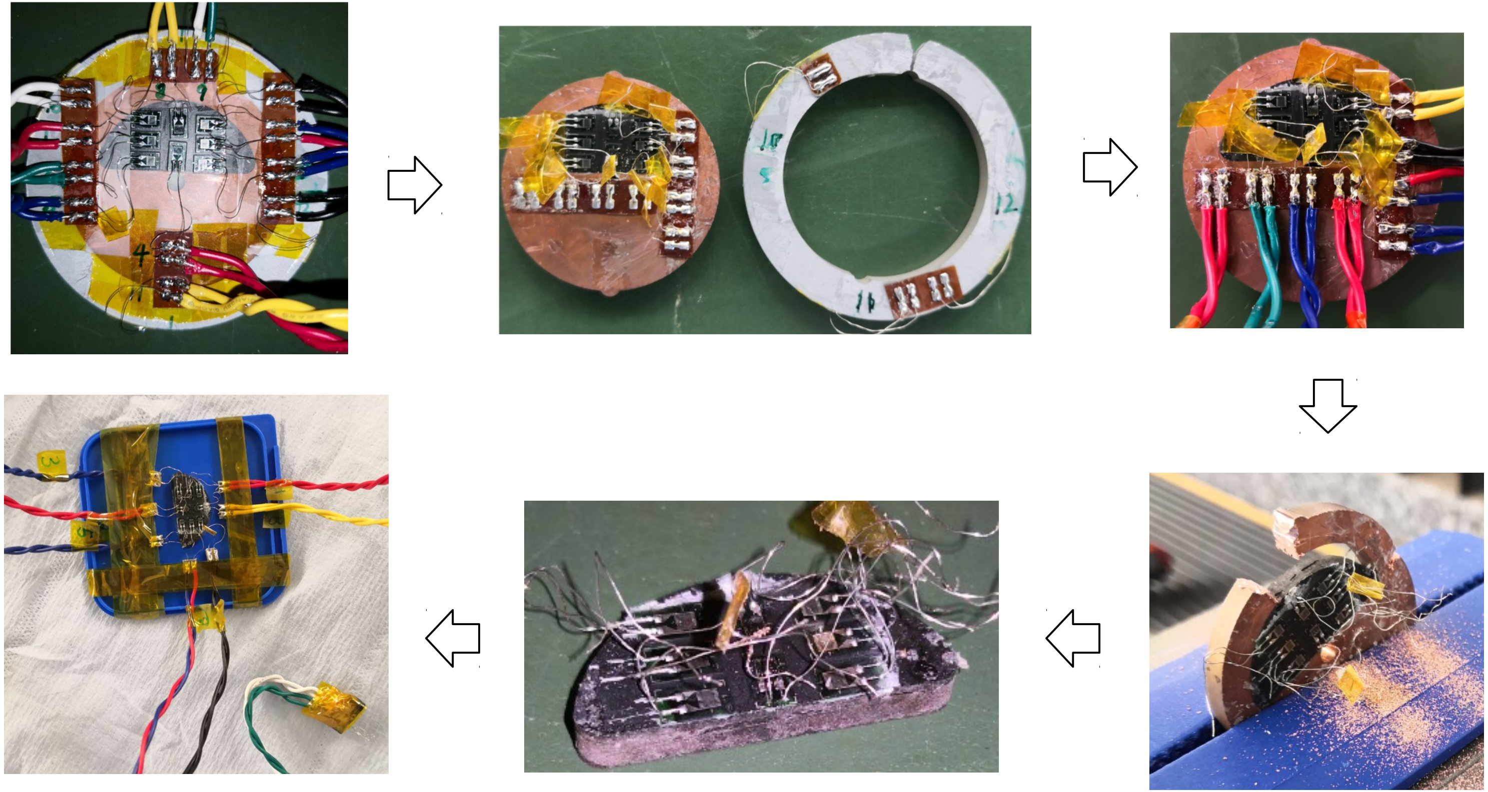




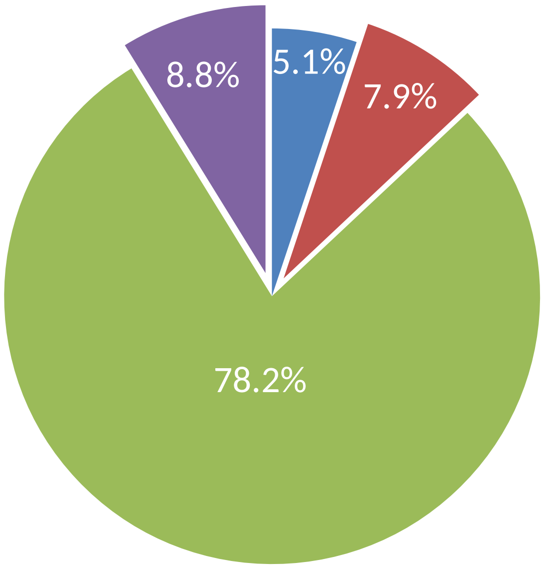
The HTS crystals are embedded (schrink-fit) into a copper matrix with micro-meter accuracy, to be mechanical and thermally stabilised. An additional Aluminium shrinking cylinder is used to precisely assemble the undulator array
(in the picture only a cross section)



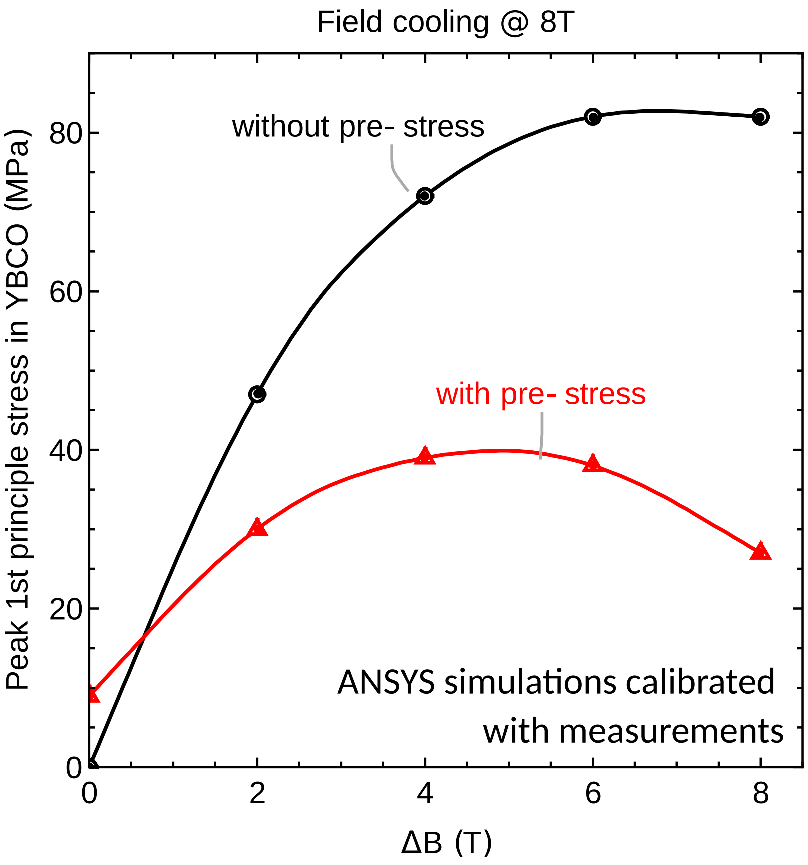
Prestress Measurements @ 77K



Contributions to the pre-stress in YBCO bulk

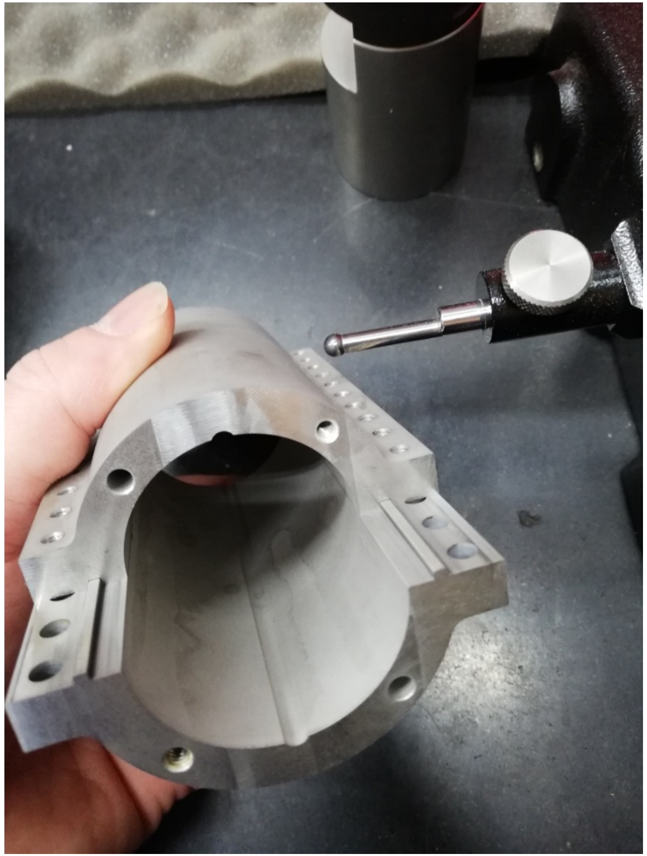


- by the shrink-fit into the Cu disk
- by the shrink-fit into the Al shell
- by the shrinking force provided by the Cu disk @ 77 K
- by the shrinking force provided by the Al shell @ 77 K



Industrial Sample

Simplified Industrial Sample



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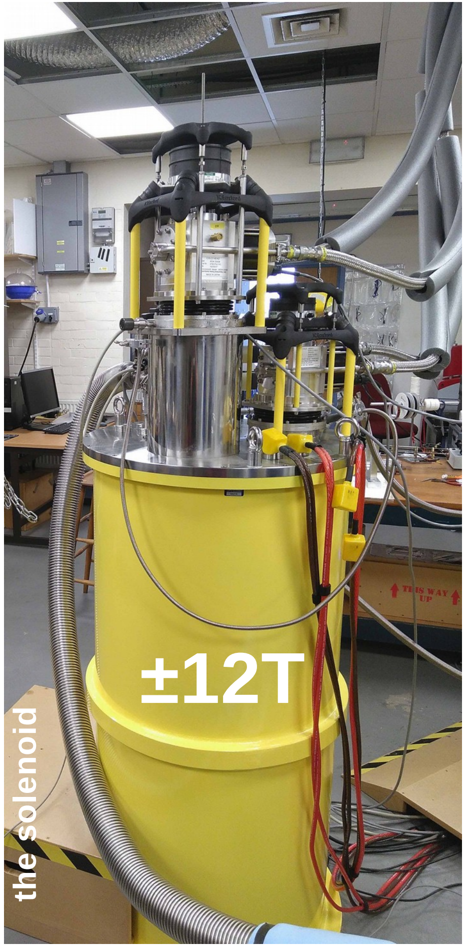
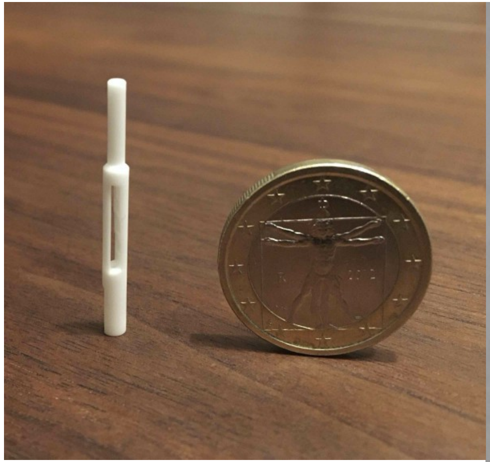
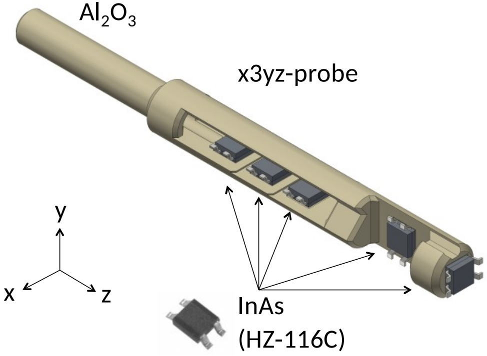
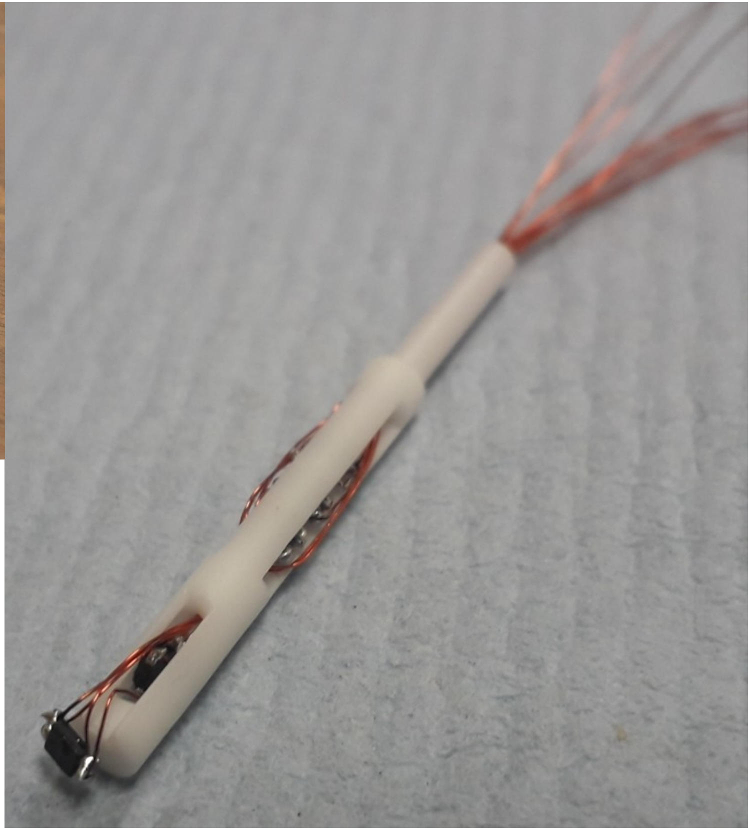


Our Second Short Sample – Oct 2020



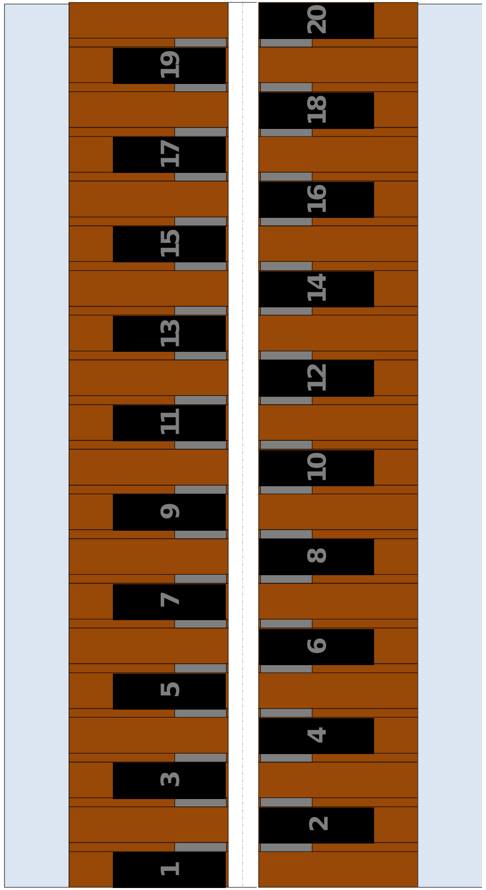


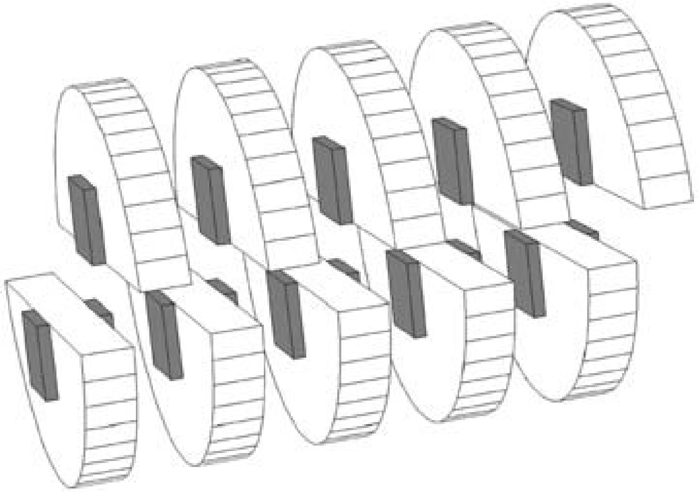


Staggered Array With CoFe Poles

4mm gap

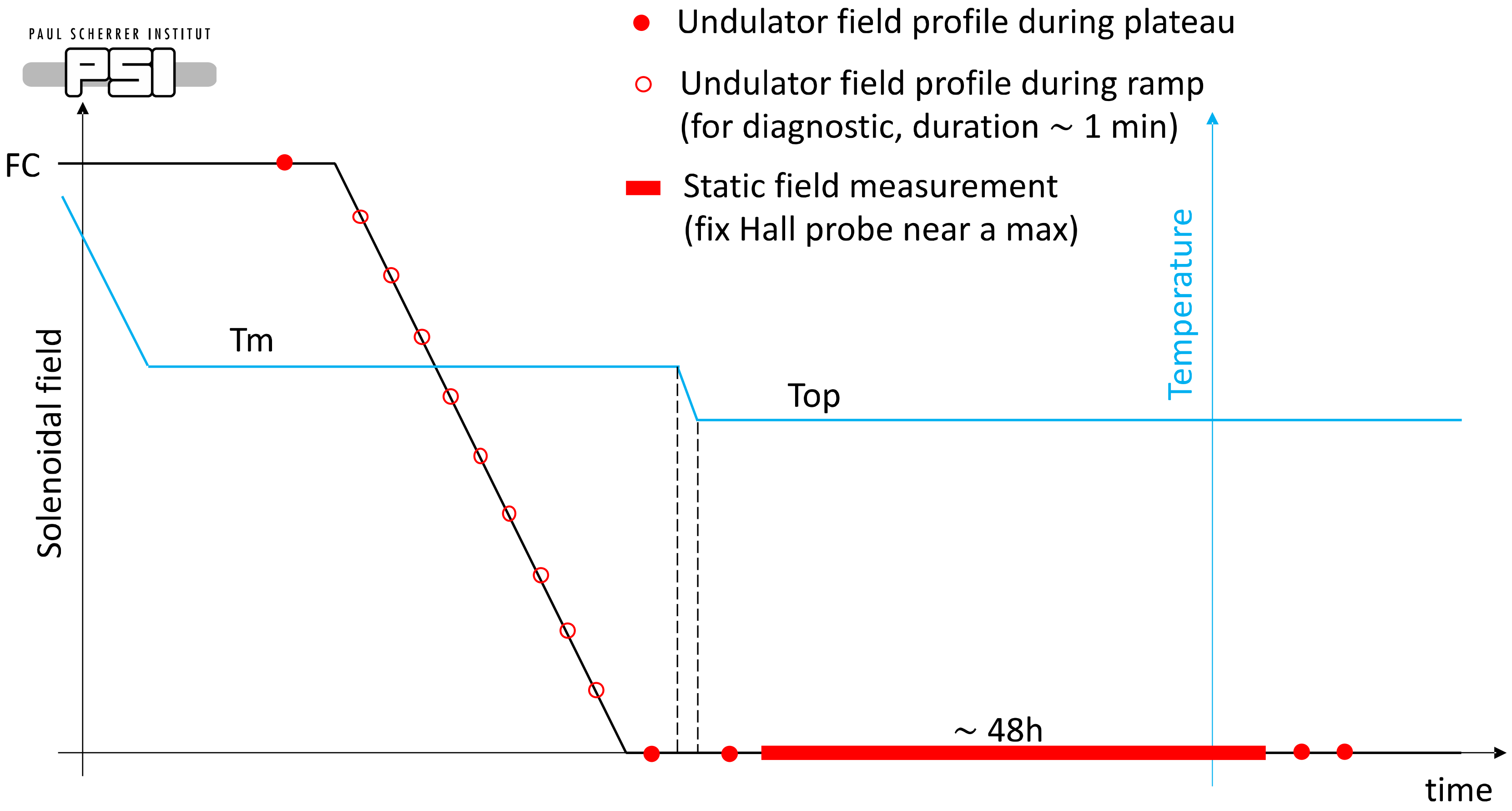
10 mm period





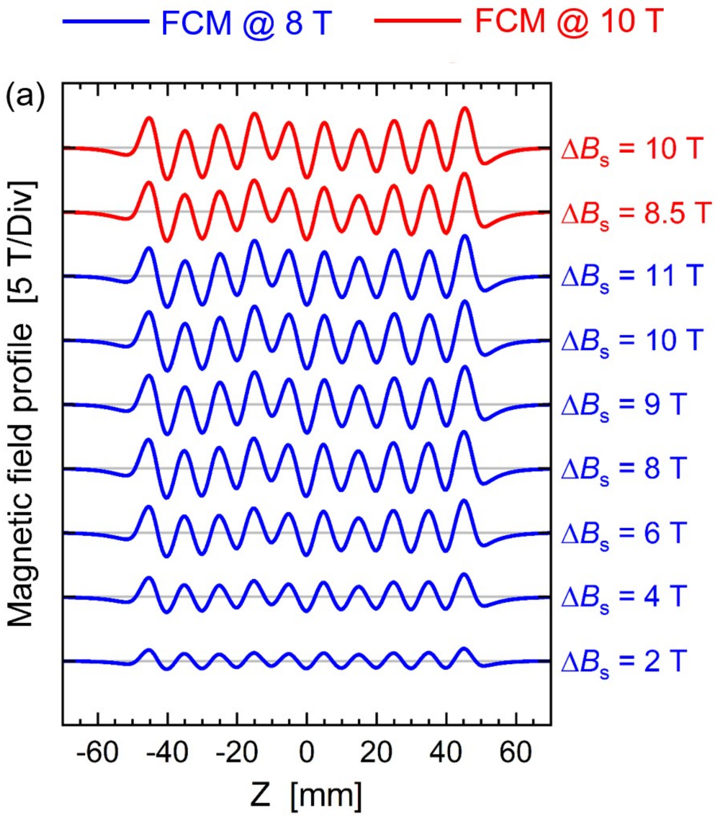
With additional ferromagnetic poles :

CoFe $\Delta B_0 = +0.20$ T



FC, Field Cooling magnetisation level, 10T
Tm, magnetisation temperature ~ 10K
Top, operational temperature ~ 7K

Experimental results - YBCO from ATZ



PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 100702 (2024)

Experimental results of a YBCO bulk superconducting undulator magnetic optimization

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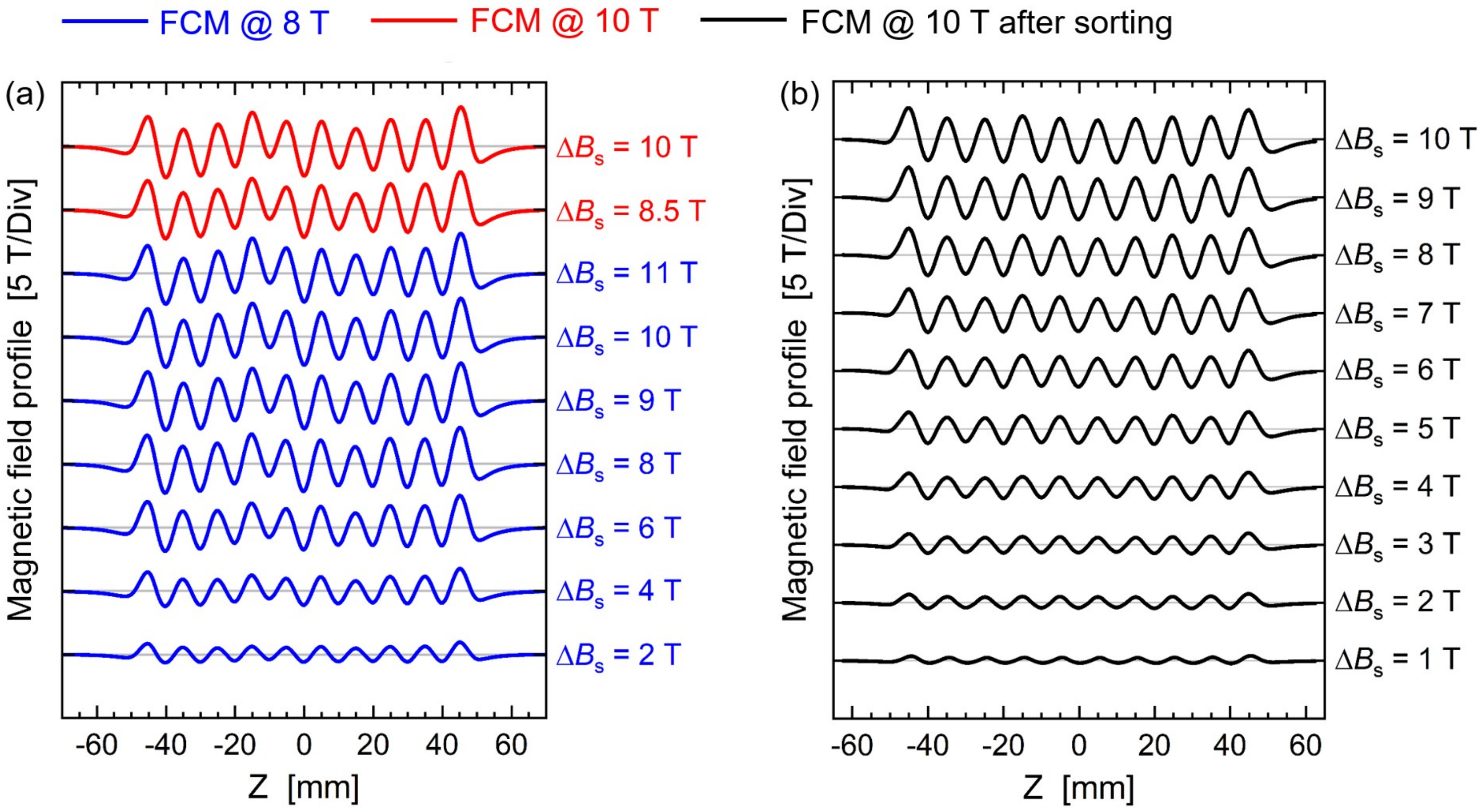
(Received 18 July 2024; accepted 3 September 2024; published 10 October 2024)

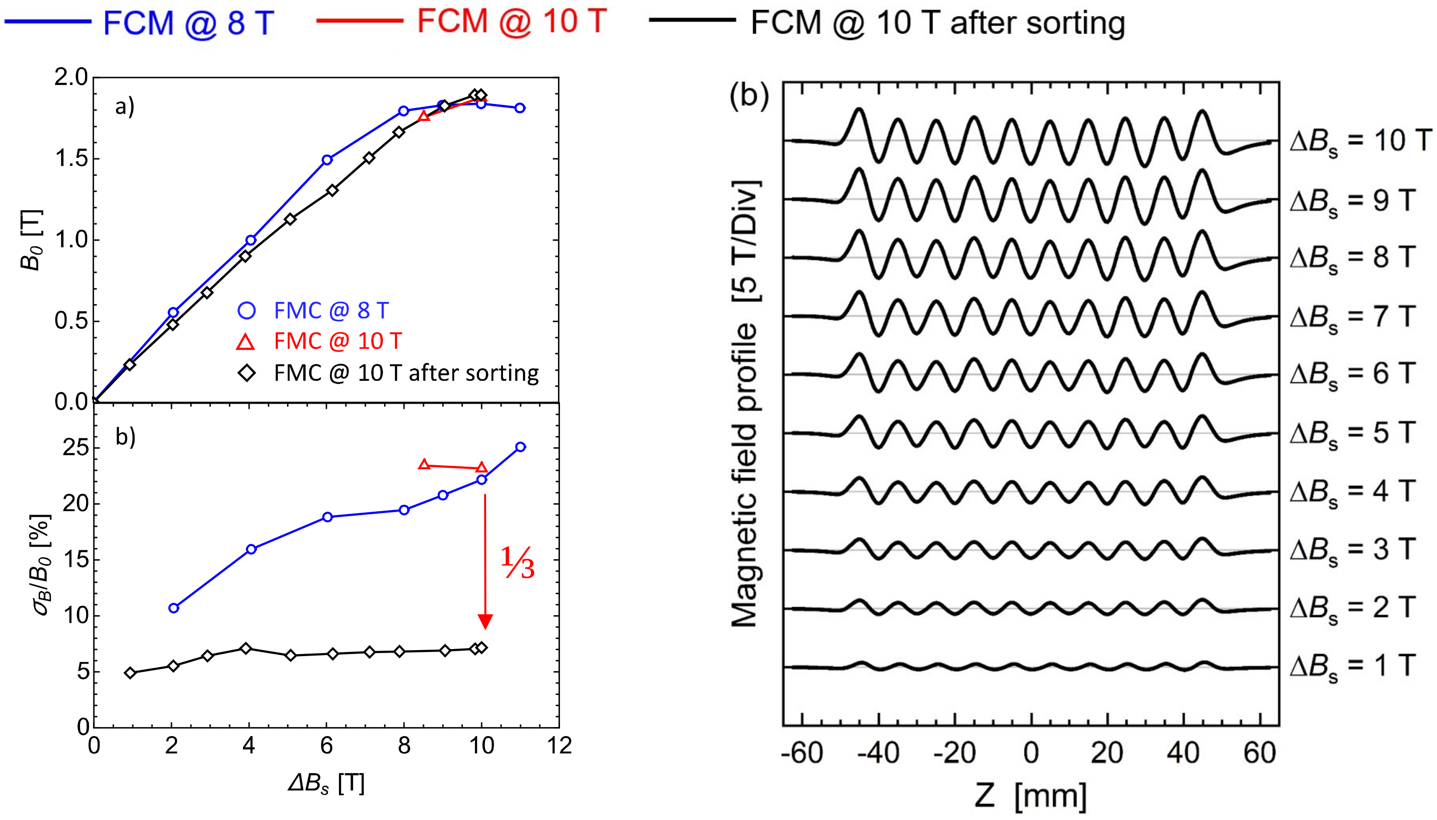
The magnetic field optimization of RE-Ba-Cu-O (REBCO, RE = rare earth) bulk superconducting undulators is a fundamental step toward their implementation in an accelerator driven photon source, like a synchrotron or a free electron laser. In this article, we propose a sorting algorithm to reduce the undulator's phase error based on the reconstruction of the trapped current inside the bulks of a staggered array undulator. The results obtained with a YBCO short prototype field-cooled down to 10 K in a 10 T magnetic field are reported. Finally, its performance is critically discussed in light of 2D magnetic field maps of its individual components, obtained at LN_2 after the magnetization tests.

DOI: 10.1103/PhysRevAccelBeams.27.100702

Experimental results - YBCO from ATZ



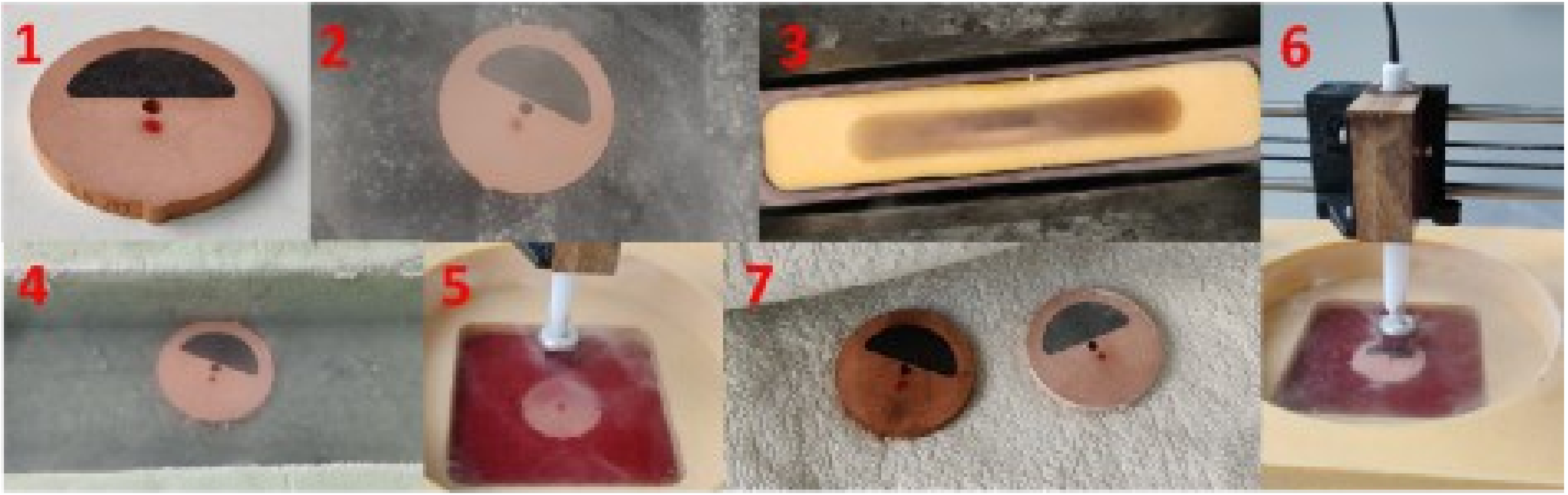
Experimental results - YBCO from ATZ



Single Disk characterisation

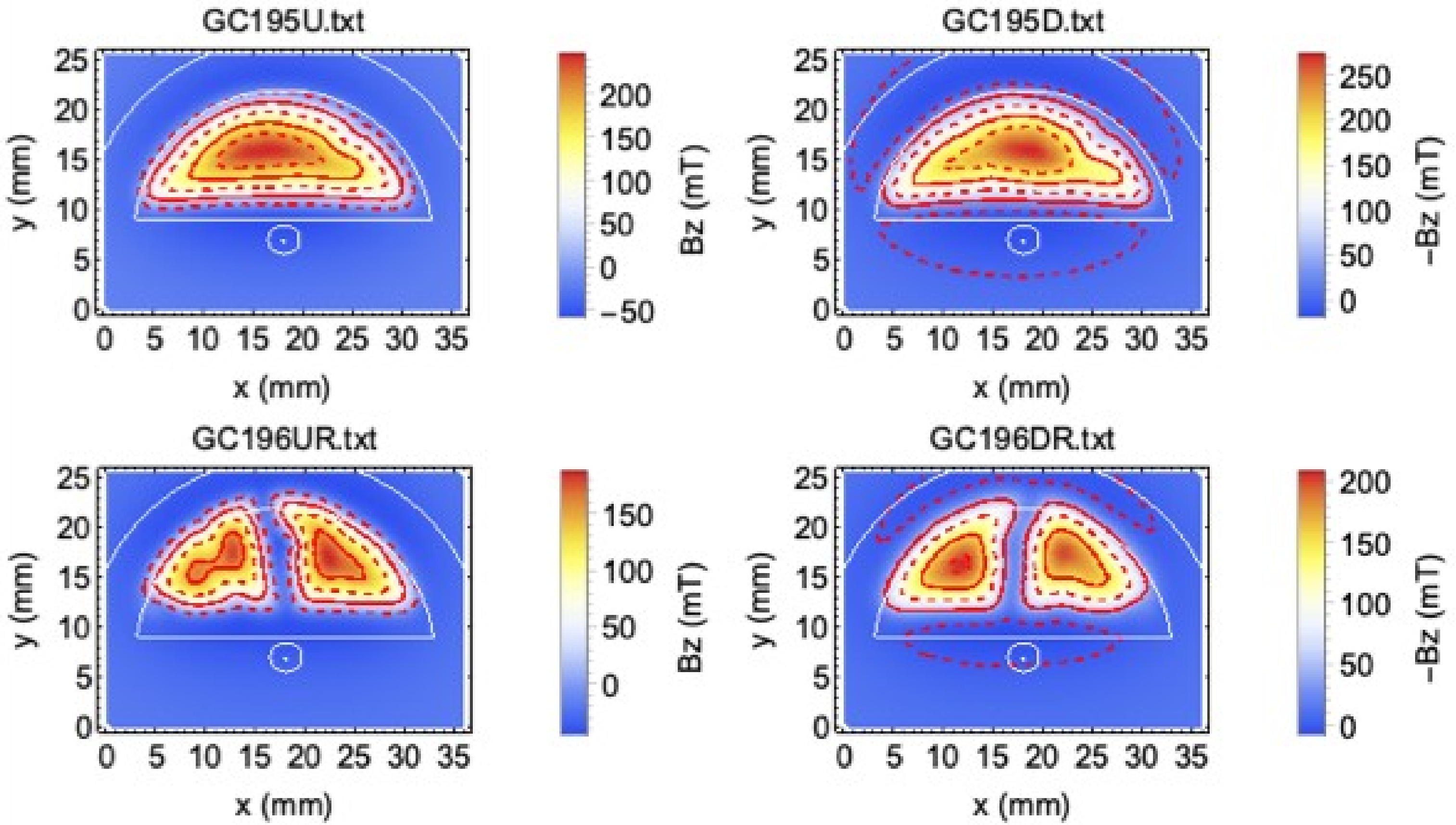
We have manufactured additional 200 disks from CAN-GdBCO / EuBCO & NS-GdBCO

All of them will be individually cooled in 1T down to LN2 and 2D field mapped, on both sides, with the aim to spot the broken ones / and to pre-sort them with respect to their strength

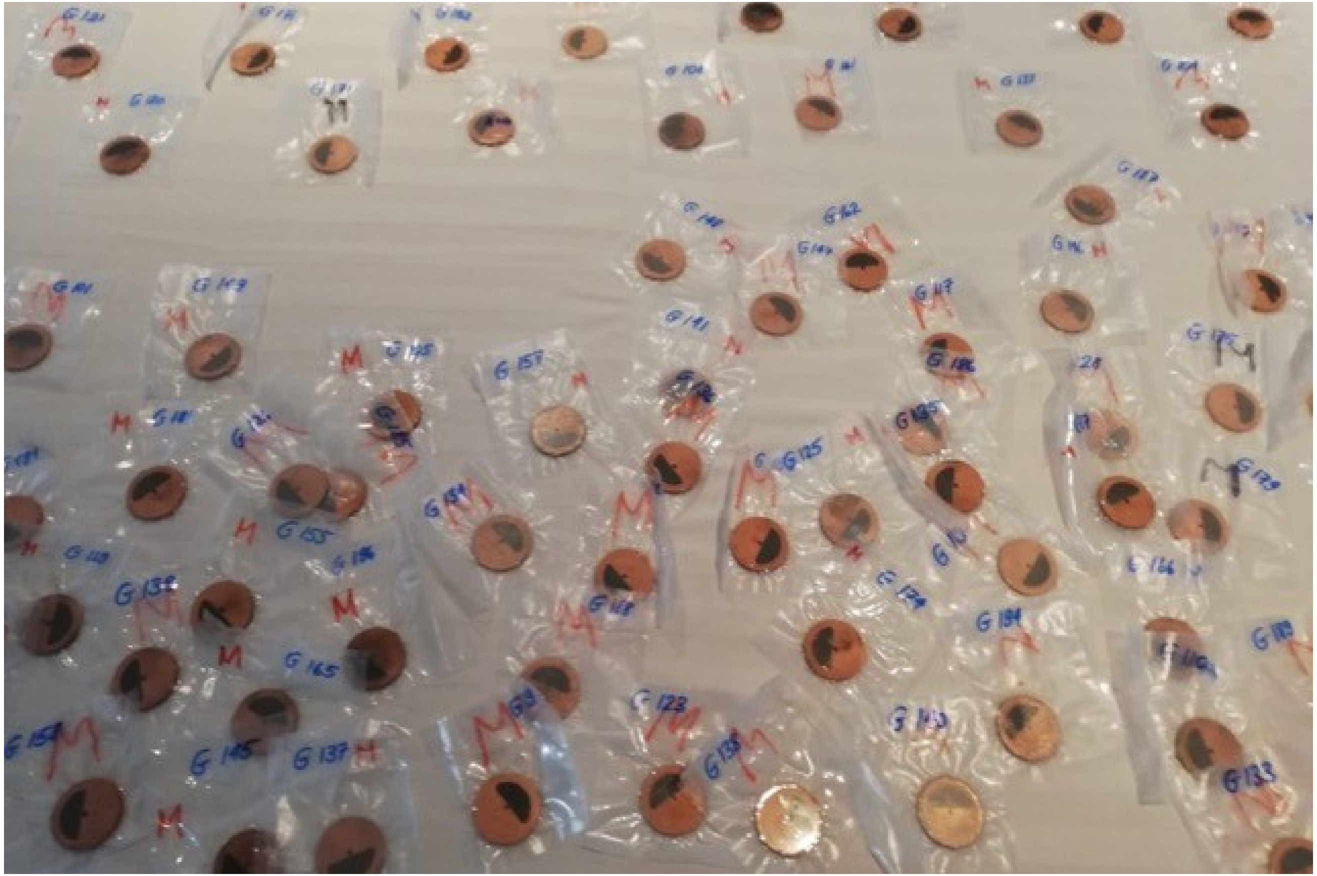


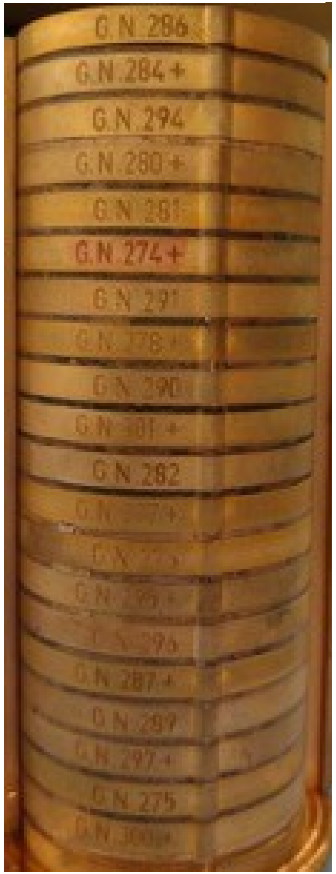
[1]the disk [2]pre-cooling [3]field Cooling [4]flux creep [5]disk support [6]2D field map [7]drying

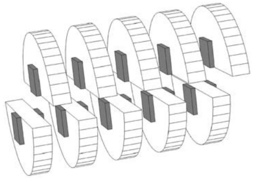
2D Field map


GC195U.txt
GC195D.txt
GC196UR.txt
GC196DR.txt
y (mm)
x (mm)
Bz (mT)
-Bz (mT)

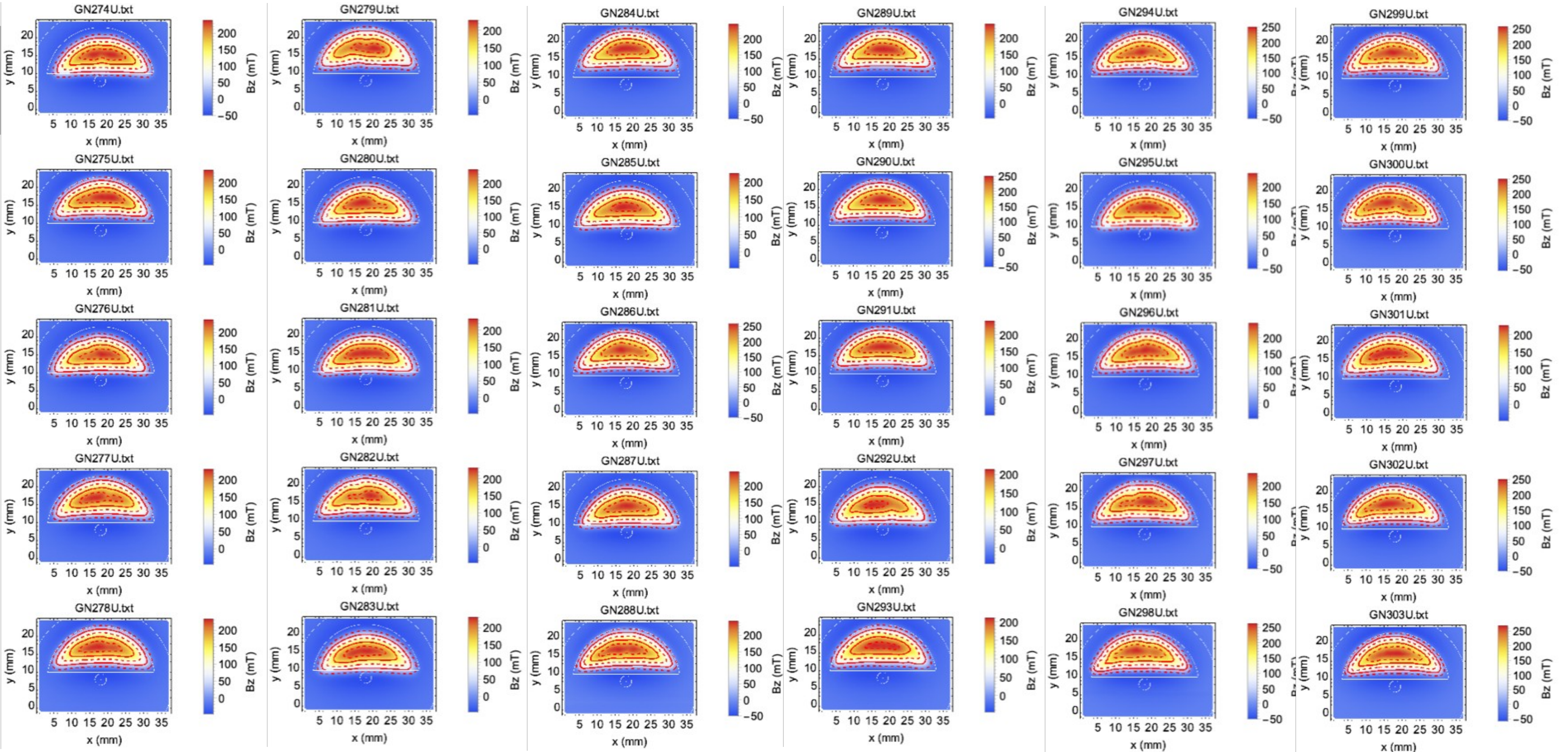
Pre-sorting / Stacking

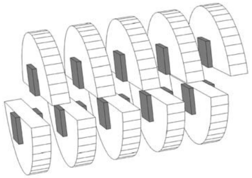






Planar Hybrid: Nippon Steel





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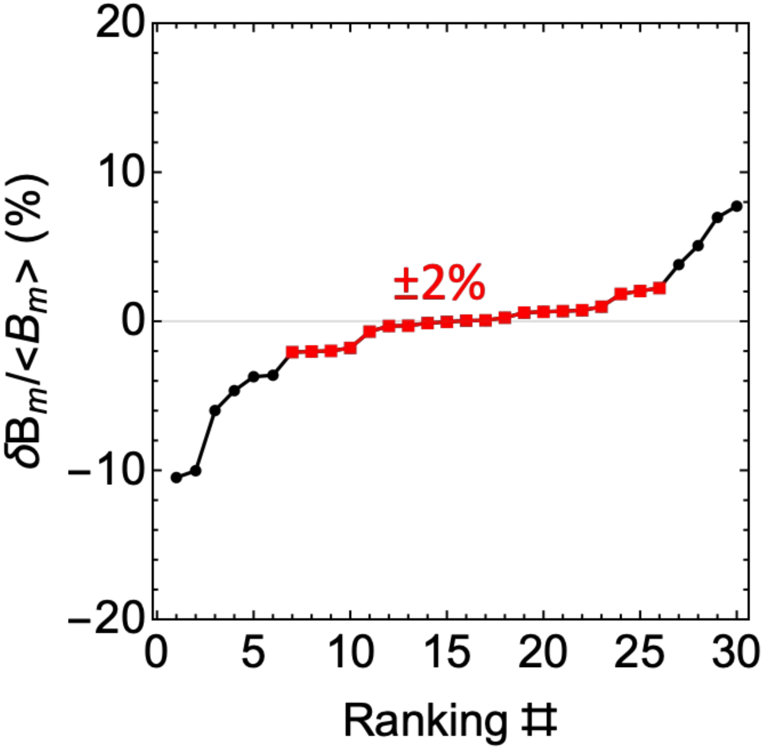

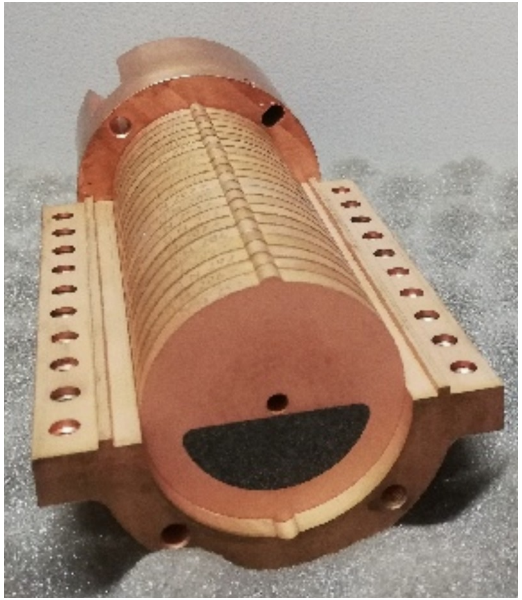

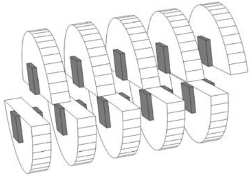

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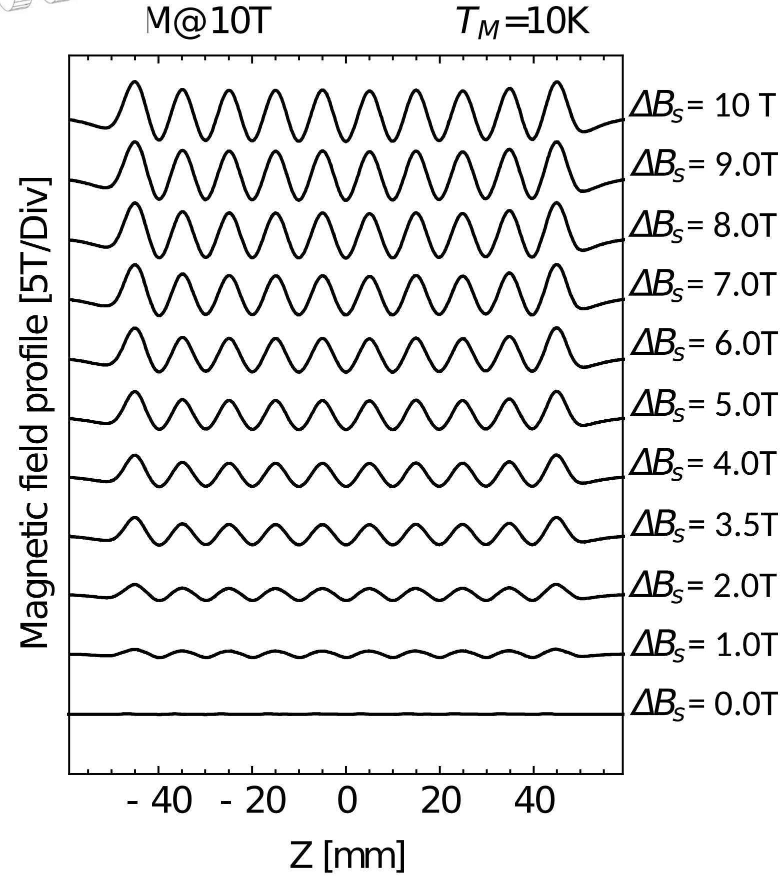

Zhang, K., Pirotta, A., Liang, X., Hellmann, S., Bartkowiak, M., Schmidt, T., Dennis, A., Ainslie, M., Durrell, J. & Calvi, M. Record field in a 10 mm-period bulk high-temperature superconducting undulator. *Superconductor Science and Technology* **36**, 05LT01. https://doi.org/10.1088/1361-6668/acc1a8 (Mar. 2023).

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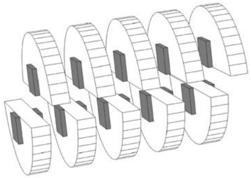

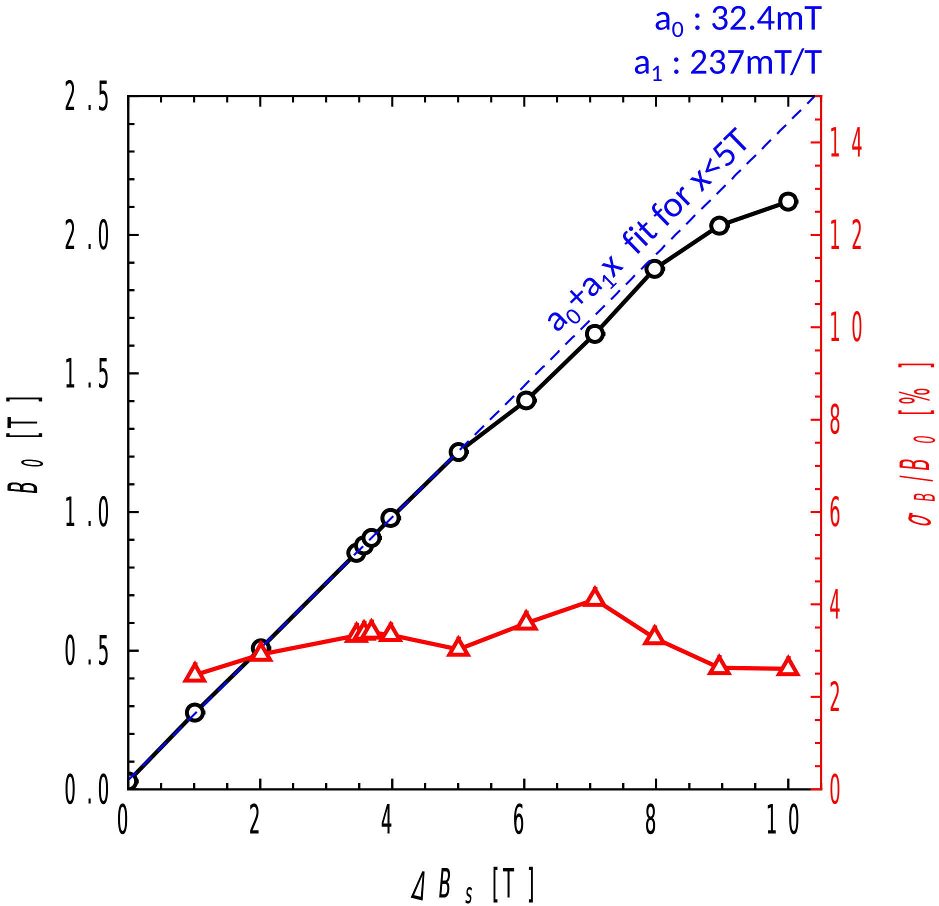

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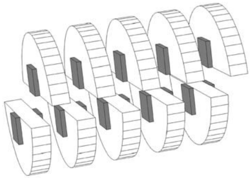

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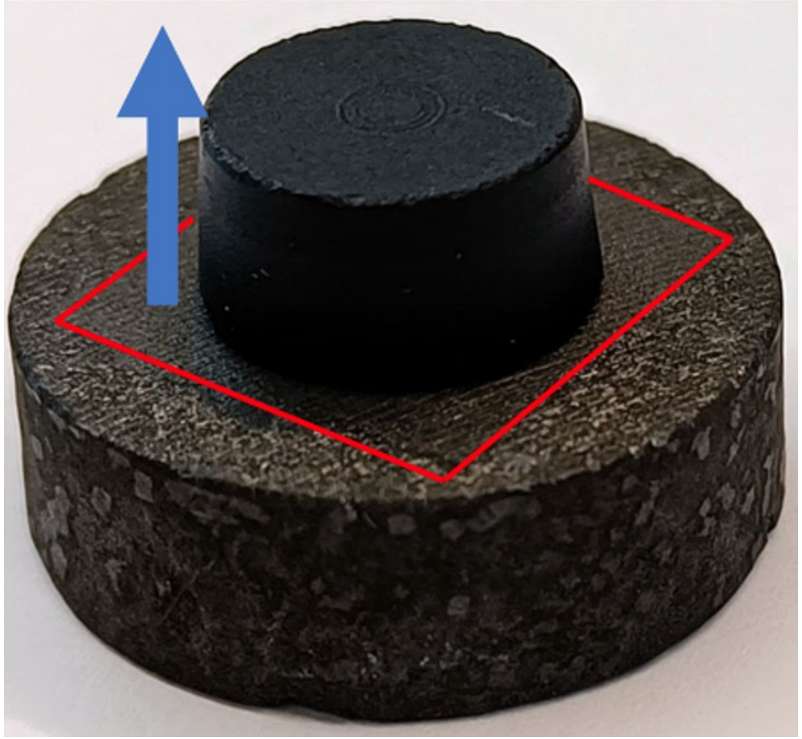
It looks a prefect result… BUT:

- “We” paid the raw-bulks about 2600 € each
- NS does not deliver REBCO bulks outside Japan…
- Since 2023 NS decided not to deliver anymore bulks to customers also in Japan… they are keeping this activity as an internal R&D.

ARE WE BACK TO SQUARE ONE????

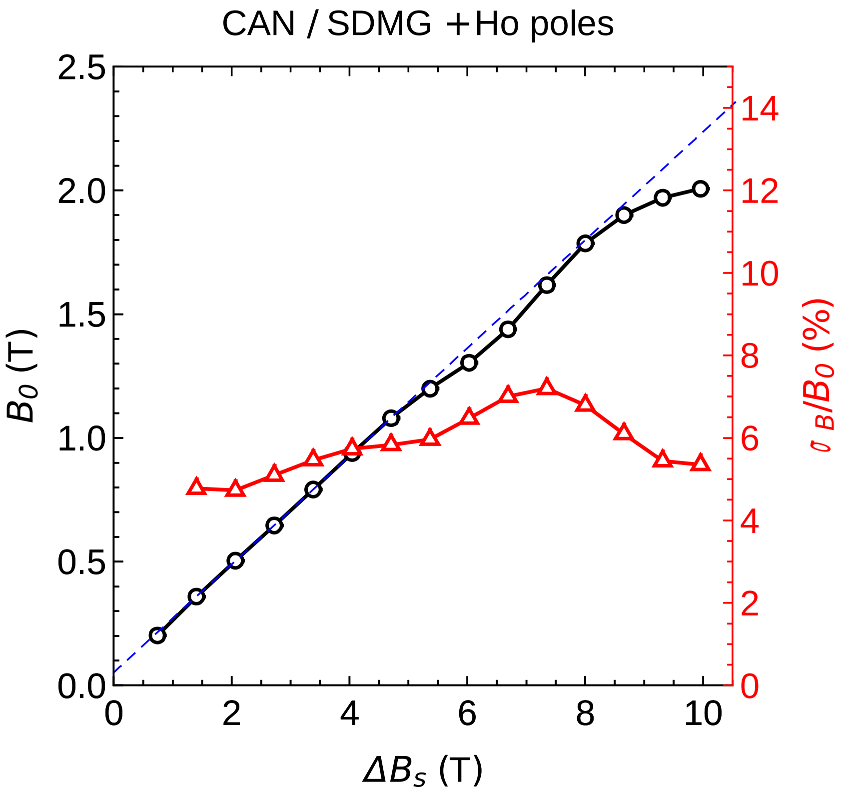
CAN-SUPERCONDUCTOR: SDMG



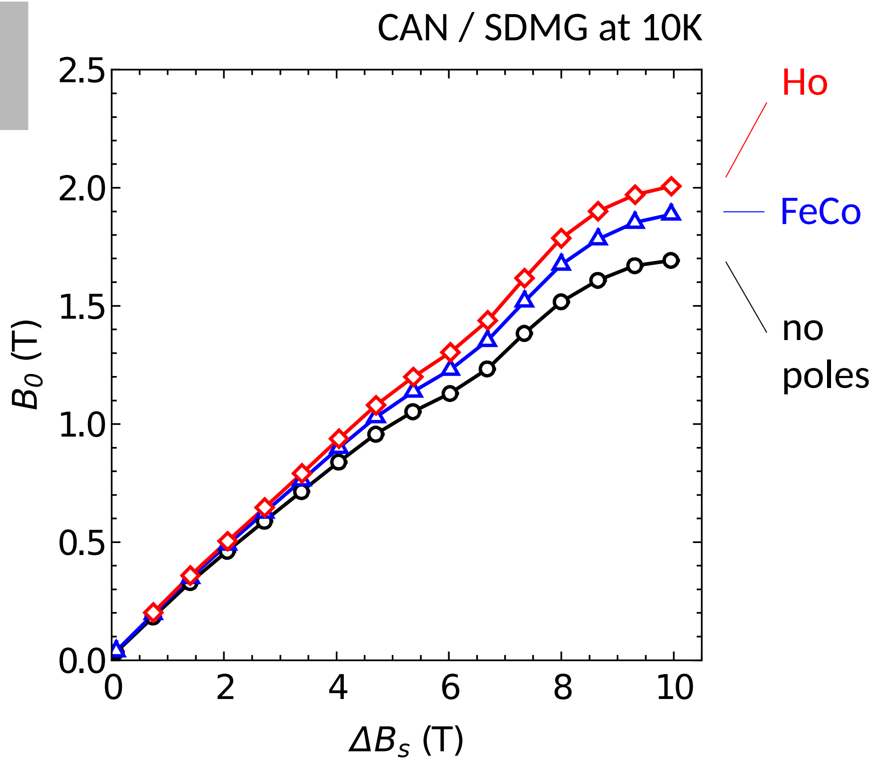
Courtesy of Dr *Tomáš Hlásek (CAN)*

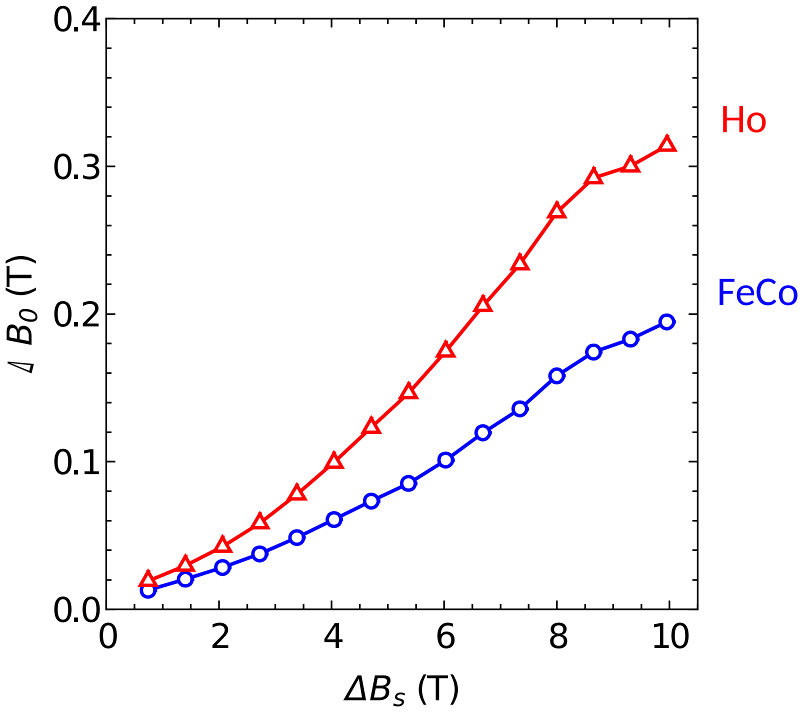
- **Single-direction Melt Growth** (SDMG) is a novel approach for REBCO single-domain bulk growth, where a grown bulk from a REBCO system with higher peritectic temperature is used to seed the grown bulk (instead of a NdBCO thin-film seed, which is used for both TSMG and TSIG). The main advantage of this approach is that the bulk is composed exclusively of the c-growth region, unlike TSMG-grown bulks. Therefore, the expected homogeneity is significantly higher in SDMG-grown bulks, as no growth interfaces are present in the bulks.

CAN / SDMG + Ho poles



Impact of the poles





Swiss Accelerator Research and Technology

PAUL SCHERRER INSTITUT

Summary of the planar staggered array with:

Company	RE	type	Undulator field, B (T) with different pole's material			σ/B
			w/o	FeCo	Ho	
ATZ	**Y**BCO	TSMG	1.67*	1.90	-	23%
Nippon	**Gd**BCO	TSMG	-	2.10	-	3%
CAN	**Gd**BCO	TSMG	-	2.02	-	7%
CAN	**Eu**BCO	TSMG	-	1.90	-	6%
CAN	**Gd**BCO	SDMG	1.69	1.89	2.01	5%
THEVA	**Gd**BCO	tape	0.78	0.88	-	8%
SuperOx	**Y**BCO	tape	0.74	-	-	8%

*The two ATZ samples are not the same thus the one with and the one w/o poles are not directly comparable

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*The two ATZ samples are not the same thus the one with and the one w/o poles are not directly comparable

†Those are not measurements but just extrapolations

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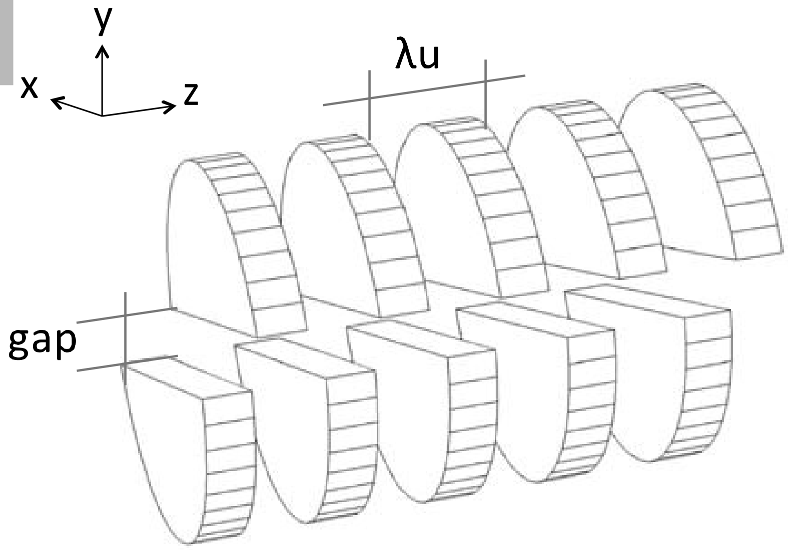
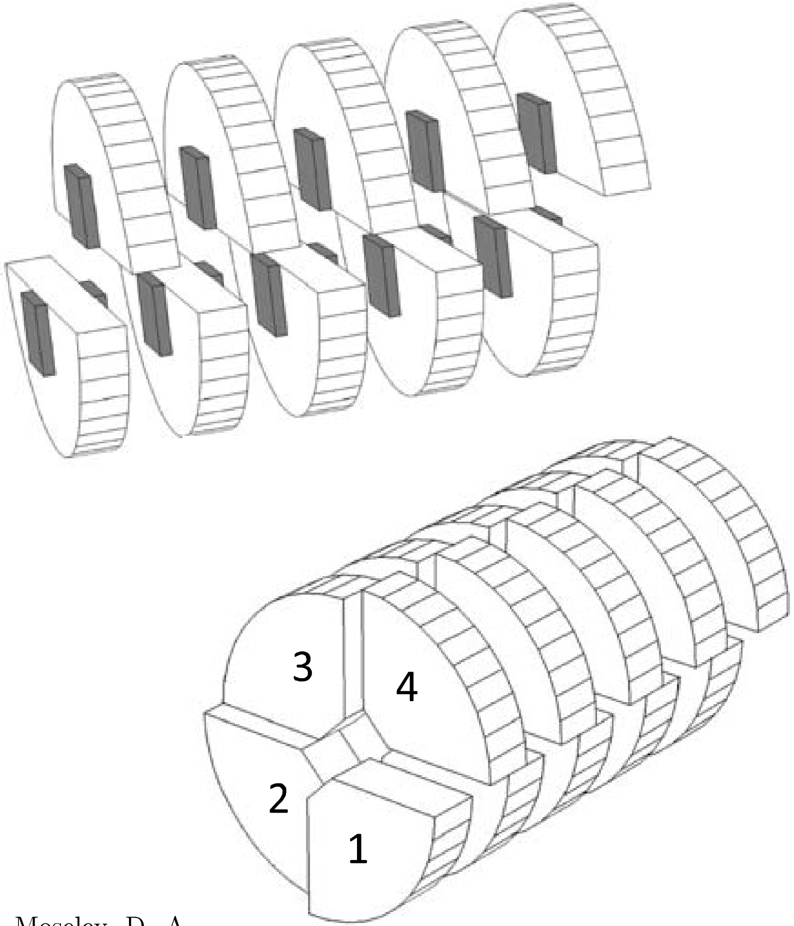
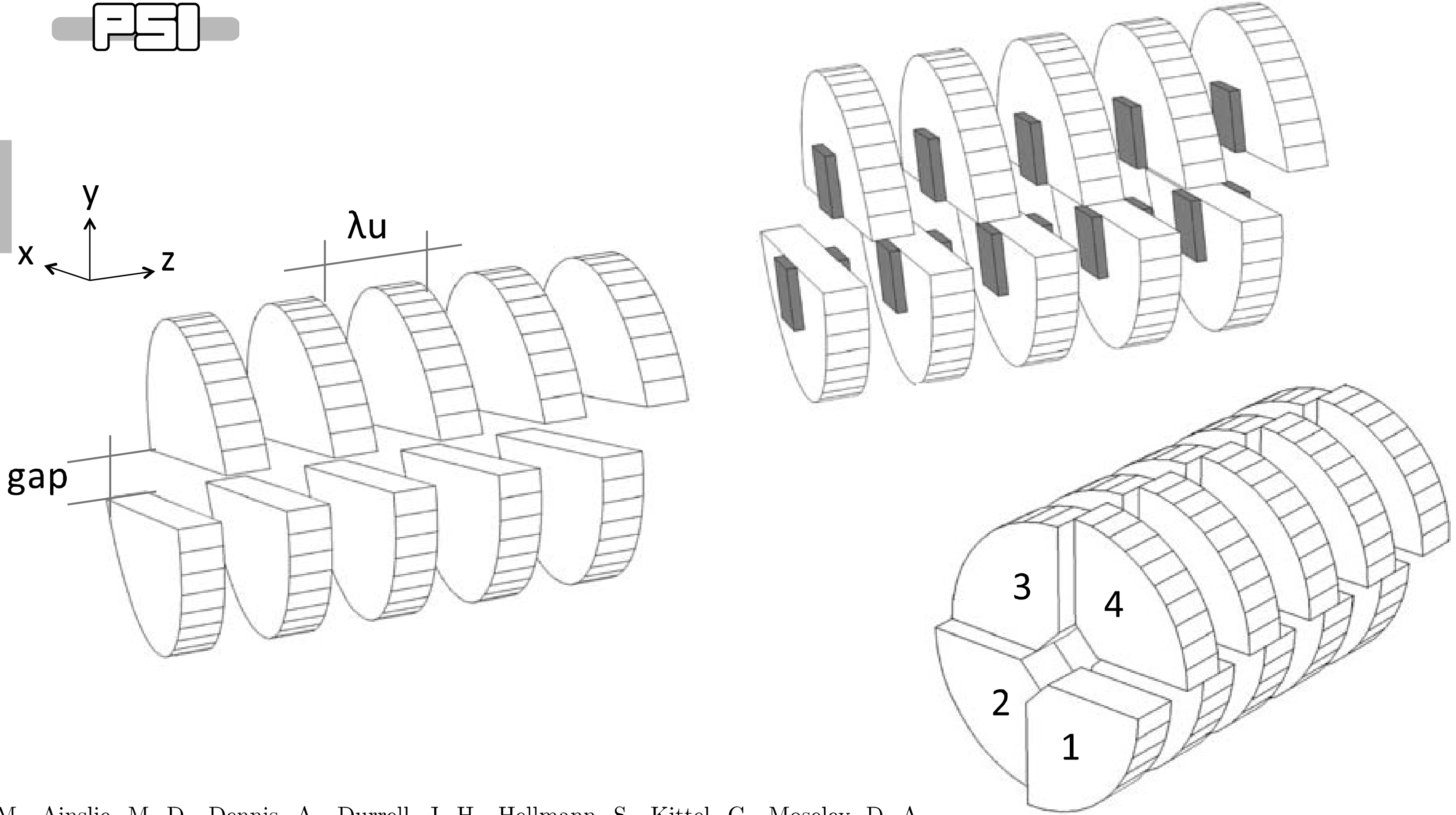
PSI





Calvi, M., Ainslie, M. D., Dennis, A., Durrell, J. H., Hellmann, S., Kittel, C., Moseley, D. A., Schmidt, T., Shi, Y. & Zhang, K. A GdBCO bulk staggered array undulator. *Superconductor Science and Technology* **33,** 014004. `https://doi.org/10.1088/1361-66682Fab5b37` (Dec. 2019).



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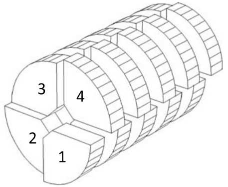

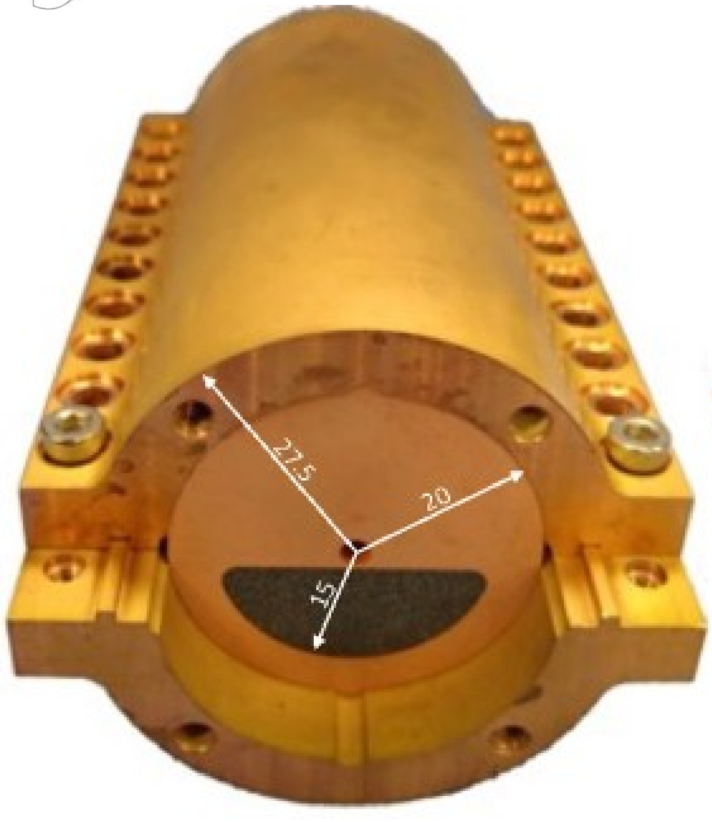

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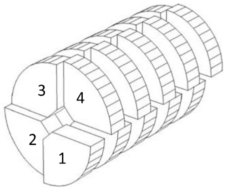

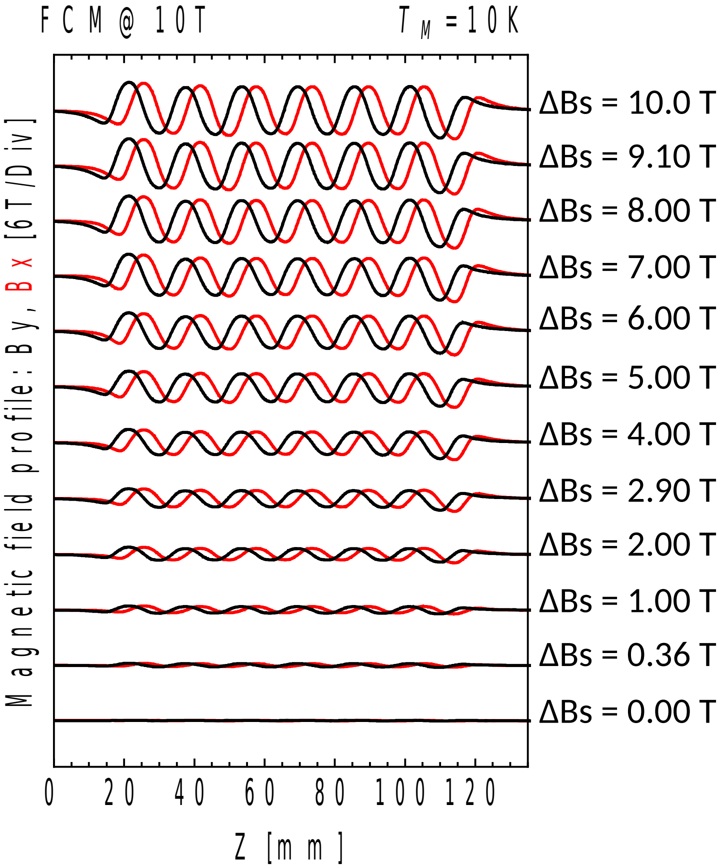

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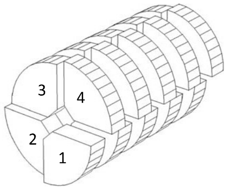

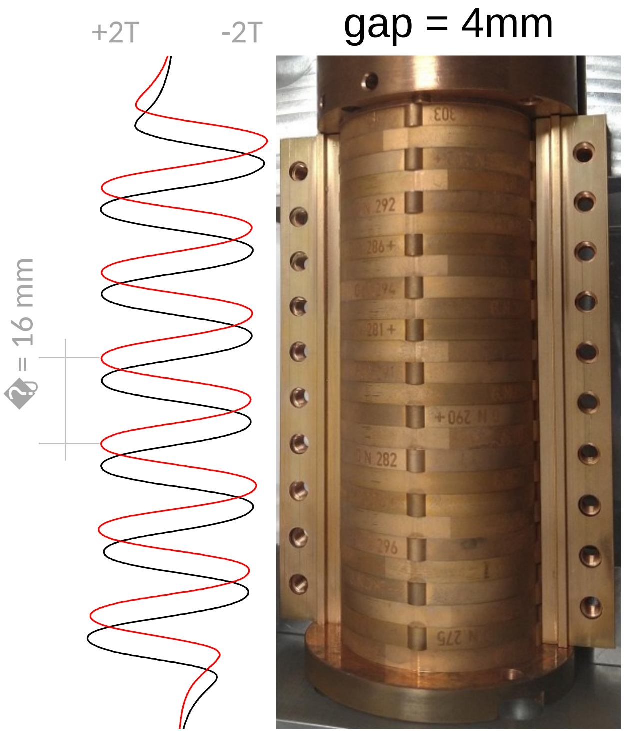

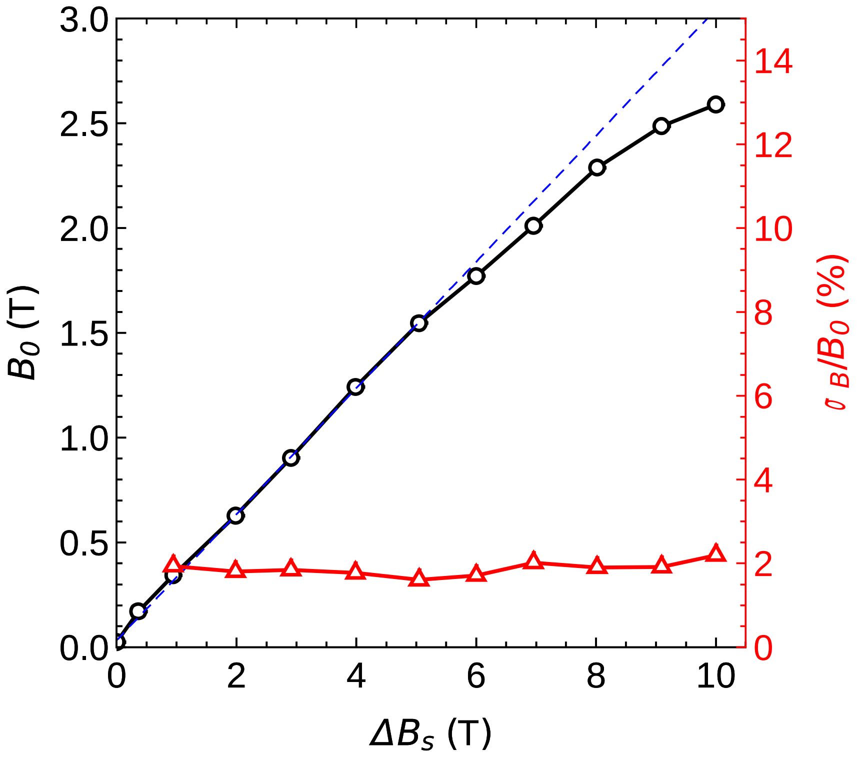

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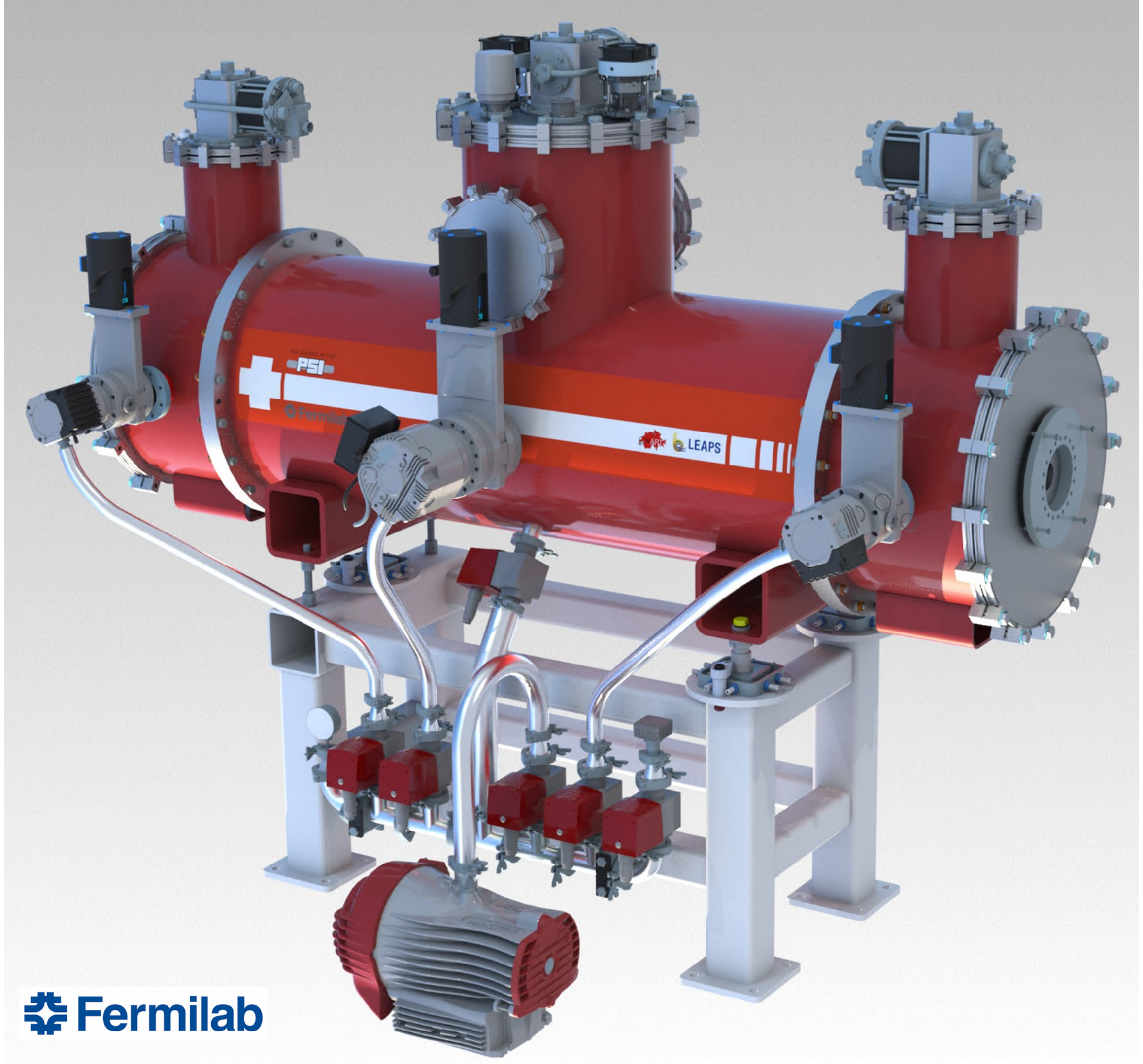
Overview

- Brief introduction to accelerator based light sources
- The Tomographic Microscopy beamline: TOMCAT ✉ I-TOMCAT
- The HTS (REBCO) bulk Staggered Array undulator
- The results on short samples:
  - Bulks & Tapes
- The status of the meter long HTS Undulator prototype
- Conclusions



THE METER LONG PROTOTYPE

Active length : 1.0 m

Total length : < 2m

period length : 10 mm

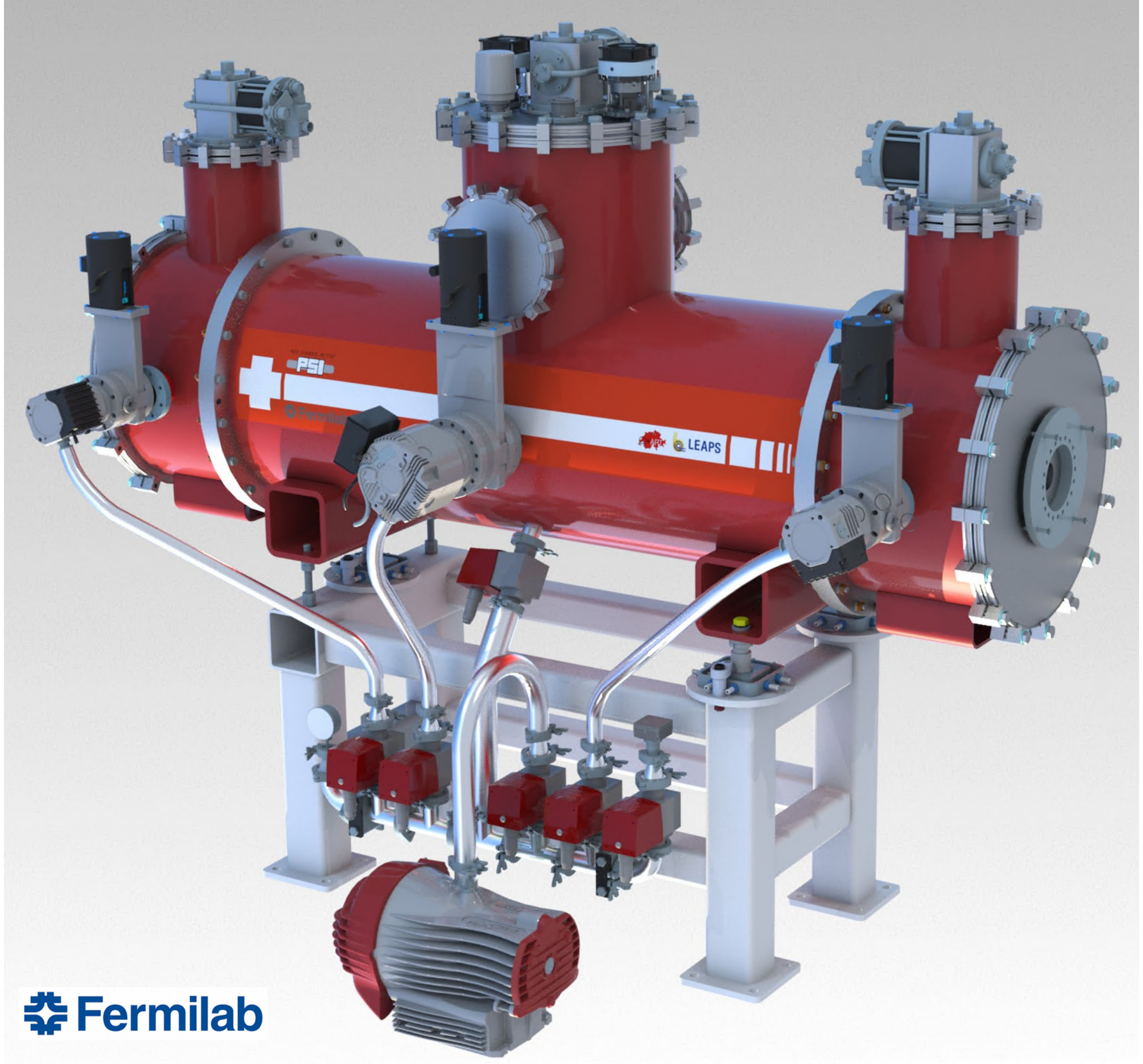
magnetic gap : 4.0mm

B_0 ~ 2.0

Cryocoolers

HTS Mag-temp 10K

LTS temp 4.0K



THE METER LONG PROTOTYPE

Active length : 1.0 m

Total length : < 2m

period length : **10.5** mm

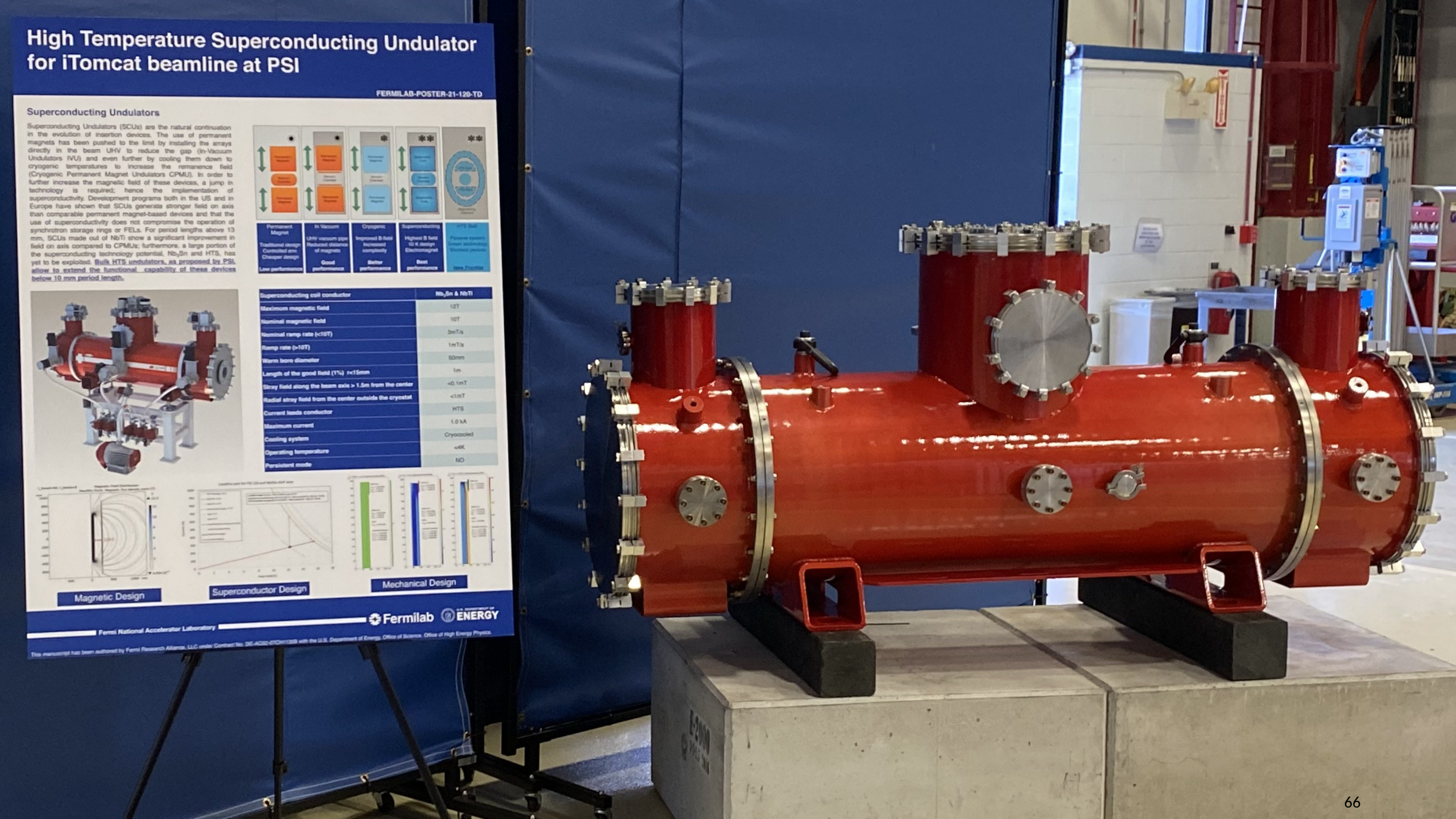
magnetic gap : **4.5** mm

B_0 ~ **1.8** T

Cryocoolers

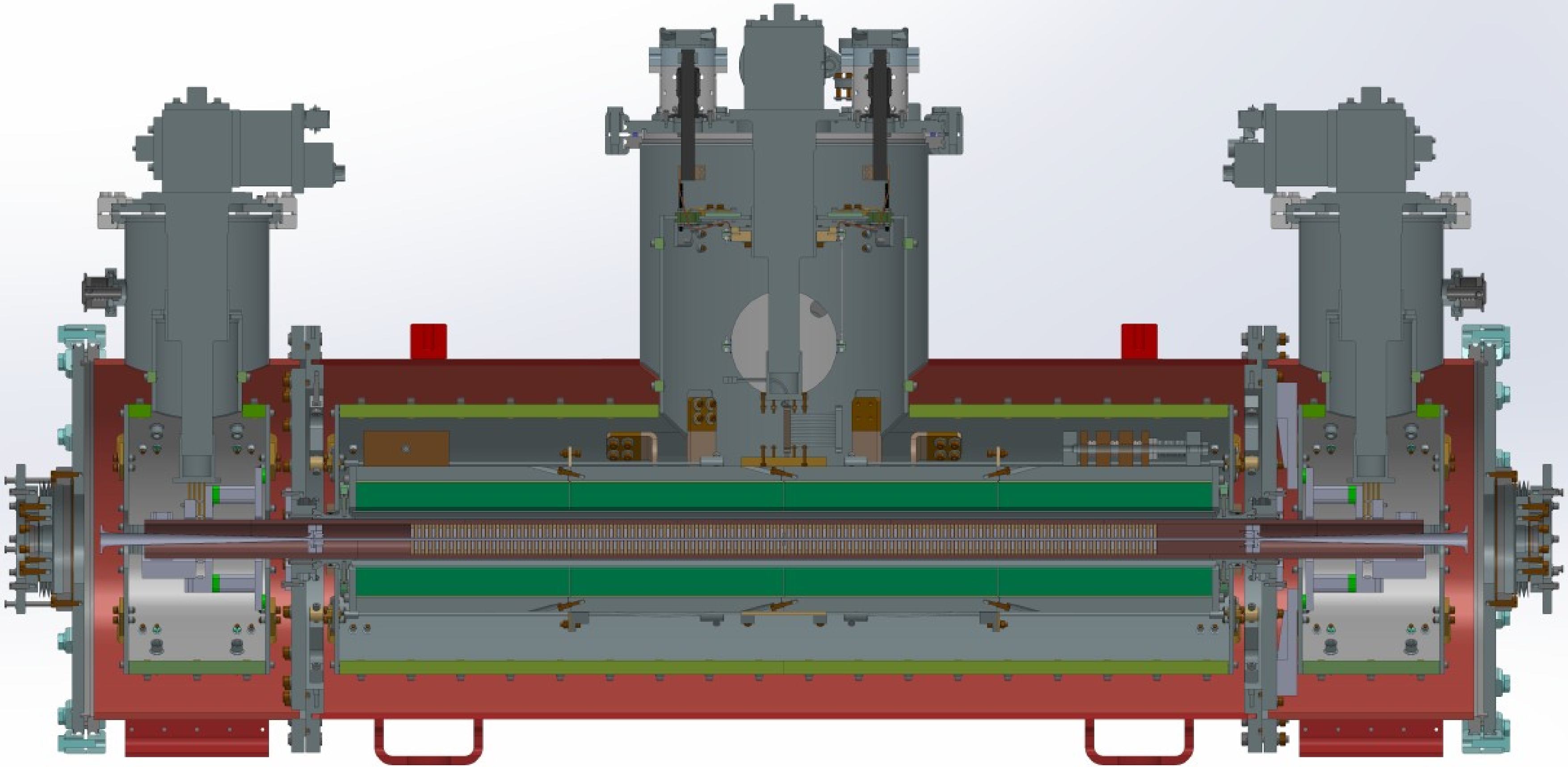
HTS Mag-temp 10K

LTS temp 4.0K


High Temperature Superconducting Undulator for iTomcat beamline at PSI
FERMILAB-POSTER-21-120-TD
Superconducting Undulators
Superconducting Undulators (SCUs) are the natural continuation in the evolution of insertion devices. The use of permanent magnets has been pushed to the limit by installing the arrays directly in the beam UHV to reduce the gap (In-Vacuum Undulators IVU) and even further by cooling them down to cryogenic temperatures to increase the remanence field (Cryogenic Permanent Magnet Undulators CPMU). In order to further increase the magnetic field of these devices, a jump in technology is required; hence the implementation of superconductivity. Development programs both in the US and in Europe have shown that SCUs generate stronger field on axis than comparable permanent magnet-based devices and that the use of superconductivity does not compromise the operation of synchrotron storage rings or FELs. For period lengths above 13 mm, SCUs made out of NbTi show a significant improvement in field on axis compared to CPMUs; furthermore, a large portion of the superconducting technology potential, Nb3Sn and HTS, has yet to be exploited. Bulk HTS undulators, as proposed by PSI, allow to extend the functional capability of these devices below 10 mm period length.
Low performance
Good performance
Better performance
Best performance
Superconducting coil conductor | Nb3Sn & NbTi
Maximum magnetic field | 12T
Nominal magnetic field | 10T
Nominal ramp rate (<10T) | 3mT/s
Ramp rate (>10T) | 1mT/s
Warm bore diameter | 50mm
Length of the good field (1%) r<15mm | 1m
Stray field along the beam axis > 1.5m from the center | <0.1mT
Radial stray field from the center outside the cryostat | <1mT
Current leads conductor | HTS
Maximum current | 1.0 kA
Cooling system | Cryocooled
Operating temperature | <4K
Persistent mode | NO
Magnetic Design
Superconductor Design
Mechanical Design
Fermilab
U.S. DEPARTMENT OF ENERGY
Fermi National Accelerator Laboratory


High Temperature Superconducting Undulator for iTomcat beamline at PSI
PSI
Fermilab
LEAPS INNOVATION

Vacuum chamber R&D

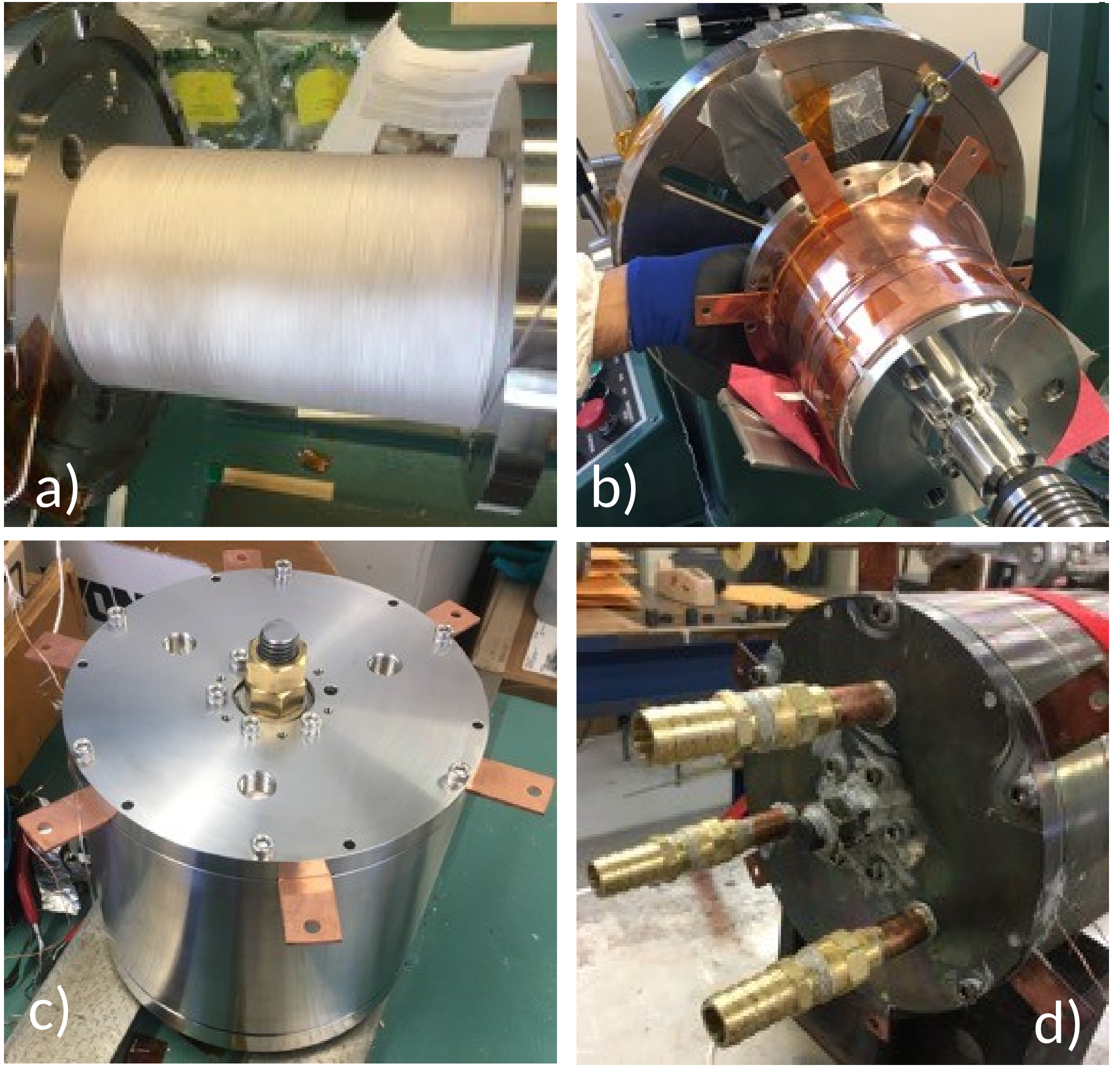


a) Winding phase of the solenoid with a glass fiber insulated RRP Nb_3Sn wire;

b) assembly of the copper sleeve for conduction cooling;

c) after the installation of the SS outer cylinder, ready for the Heat Treatment (650°C);

d) after HT, ready for potting with epoxy resin;



Conclusions & Outlooks

- We demonstrated high magnetic field (2T) in a short sample staggered array undulator made of GdBCO bulks HTS with 10mm period length and 4mm gap.
- Tape stacking is not giving the expected lower phase error and the field strength is substantially lower than bulks.
- The GdBCO bulk made by CAN out of the novel SDMG process are now our baseline
- Holmium poles deliver higher fields than FeCo even if they are not single crystals…
- A preliminary optimisation of the charging reduced the time required from 10 to 4h
- The delivery of the “Cryo-Solenoid” to PSI is planned for 2Q 2025, then we will start an intense measurement campaign to demonstrate a phase error as low as few degrees before installing the device in SLS2.0 at the beginning of 2026.

Acknowledgements

- *PSI* : K.Zhang, X.Liang, S.Hellmann, Th.Schmidt, L.Huber, S.Reiche, M.Bartkowiak, C.Calzolaio, Prof. M. Stampanoni, Prof L.Patthey, F. Marone & G.Lovric
- *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
- *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, V.Martinez, J.Hayman
- *CERN*: L.Bottura & B.Bordini