
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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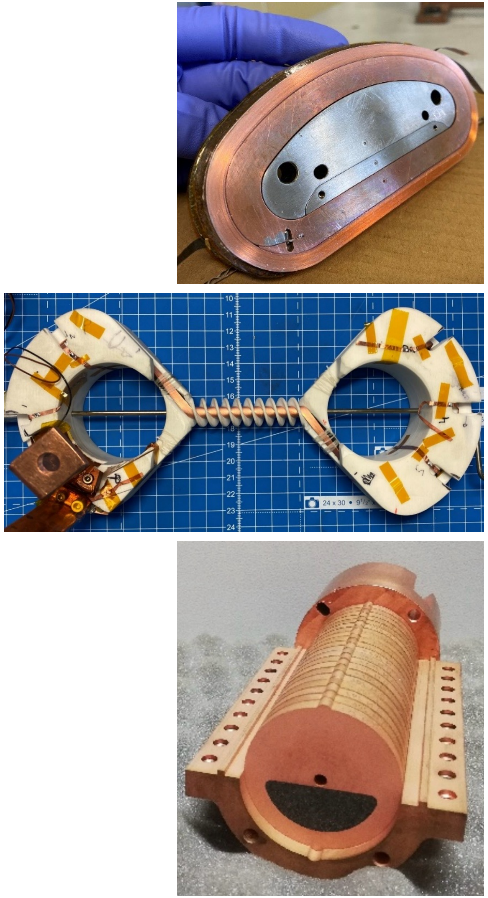
High-Temperature Superconducting Undulators: Potential, Status, and Application

9th Low Emittance Rings Workshop 13-16 February 2024, CERN, Geneva, Switzerland

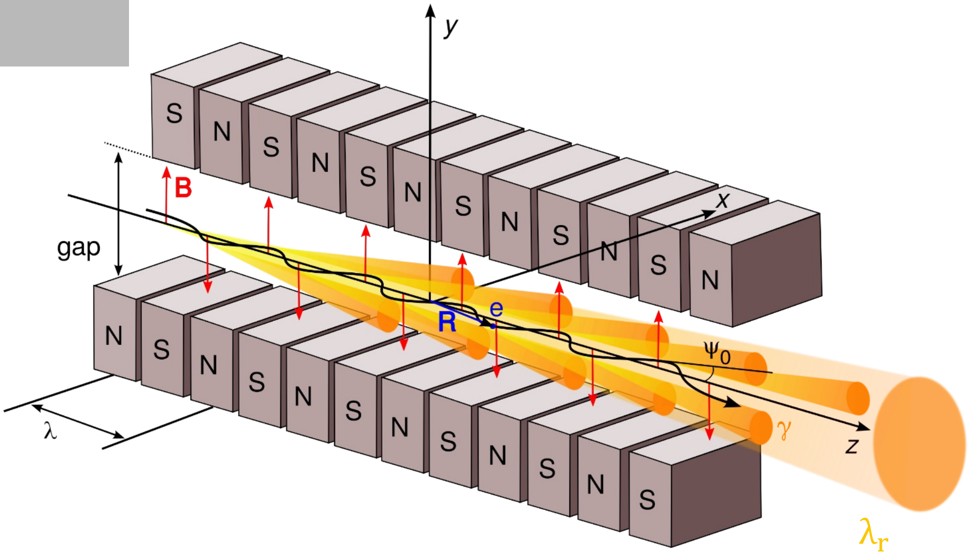
Outline

- Background and Motivation
- HTS Tape Undulator Study (CERN-KIT)
- HTS Bulk Undulator (PSI)
- Summary and Conclusion

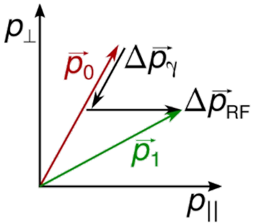


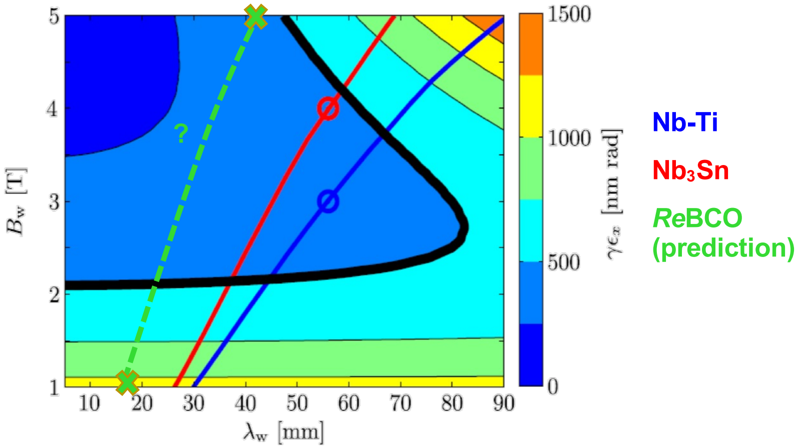
Undulator & Wiggler Magnets

The plain undulator as light source,



and for damping:





$$\lambda_r = \frac{\lambda_u}{2\gamma_r^2}\left(1 + \frac{K(B,\lambda_u)^2}{2}\right)$$

S. C. Richter, Ph.D. Thesis KIT (2023)

D. Schoerling *et al.*, (2012) *Phys. Rev. ST Accel. Beams* **15**, 042401

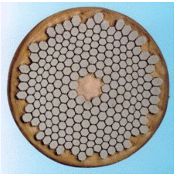
Background: different superconductors

Low-Temperature Superconductor (LTS)

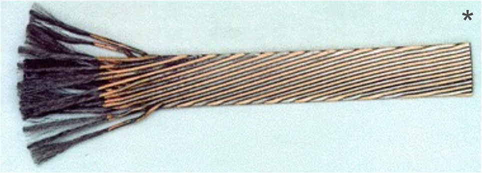
State-of-the-art: Nb-Ti (niobium-titanium)

$T_c \approx 10$ K

$B_{c2} \approx 14.5$ T



strand



*

cable

B to strand/cable orientation is not relevant

Critical current:

$$I_c(T, B)$$

High-Temperature Superconductor (HTS)

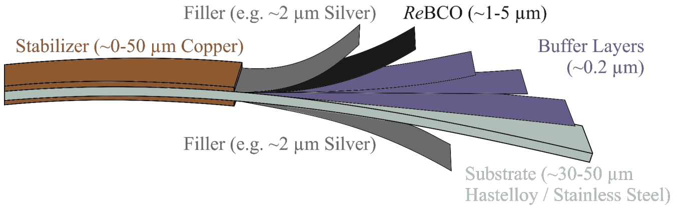
*Here: Re*BCO (*Rare-earth* $Ba_2Cu_3O_{7-\delta}$)

$T_c \approx 92$ K

$B_{c2\perp} \approx 110$ T, $B_{c2\parallel} > 240$ T

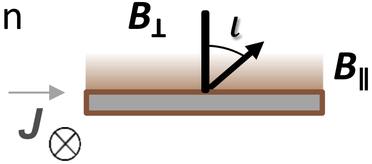
**

bulk



tape

Cross-section tape width



variation ≤ 50% I_c

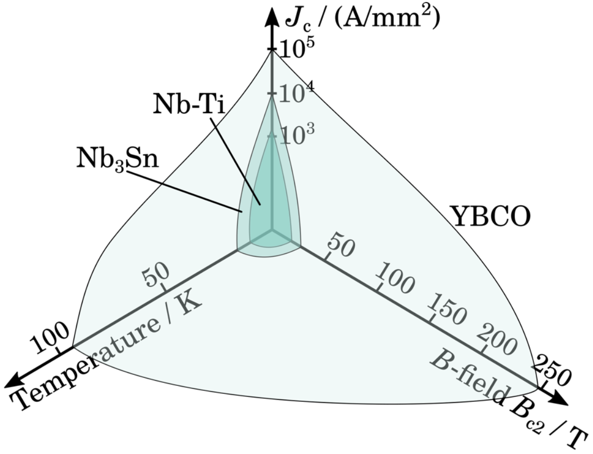
$$I_c(T, B, \iota)$$

* https://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/components/cable.htm

** https://shop.can-superconductors.com/

Background: why HTS?

- Potential enhancement of undulator parameters
  → More compact synchrotron light sources
  → Improved damping
- Facilitated operation compared to Nb-Ti or Nb_3Sn
  – larger margins
  → Relaxed cryogenic requirements (lower cost)



D. Schoerling *et al.* (2012) *Phys. Rev. ST Accel. Beams* **15**, 042401

- Link to CompactLight:

– Hard X-ray FEL	(< 1 nm),
– High-field, short-periods	(~ 13 mm, K>1),
– Low electron beam energy	(2.5 to 5.5 GeV).

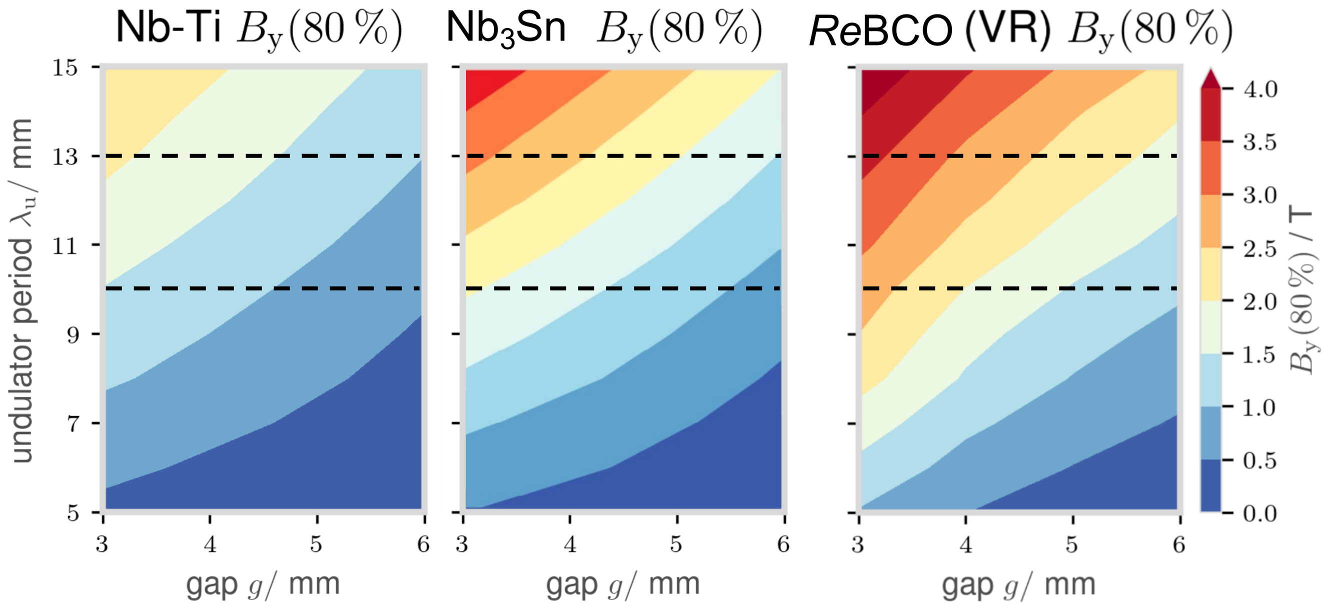
Funded by the European Union Compact

F. Nguyen *et al.* (2019) “XLS - D5.1: Technologies for the CompactLight Undulator”

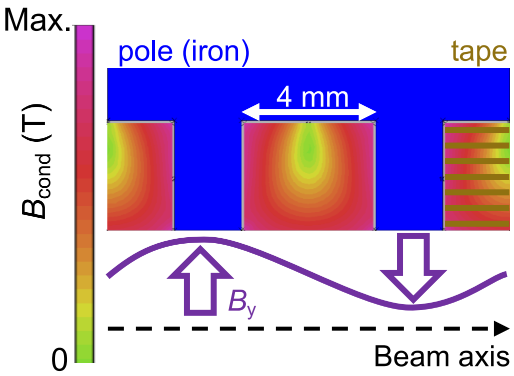
- Link to CLIC and FCC-ee:

– High magnetic fields	(> 2 T),
– Long-period wigglers	(> 40 mm).

Motivation: 2D e/m-simulations (4.2 K)



Example: VR, $\lambda_u = 13$ mm



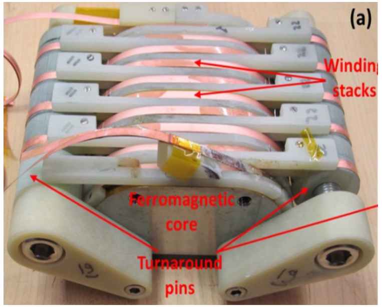
- *Re*BCO's potential:
  - *B*-field amplitudes $B_y \sim 2$ T for $\lambda_u \in [10,13]$ mm feasible.

⟺

Impossible with state-of-the-art technology

S. C. Richter, Ph.D. Thesis KIT (2023)

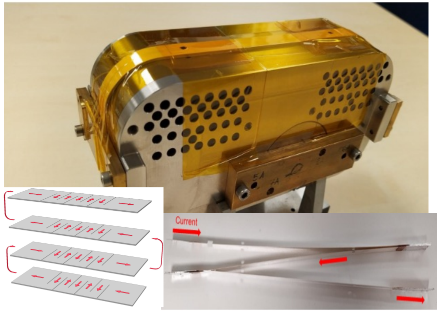
Other HTS undulator studies



<u>I. Kesgin *et al.*</u>

- Non- and partial-insulated, and Epoxy wet winding
- VR jointless winding
- Mirror model

I. Kesgin *et al.*, "High-temperature superconducting undulator magnets" (2017), doi: 10.1088/1361-6668/aa5d48.

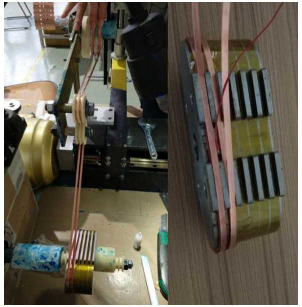


<u>T. Holubek *et al.*</u>, <u>A. Will *et al.*</u>

- Non-insulated, laser-structured
- Jointless and with joints (stack)
- Short model

T. Holubek *et al.*, "A novel concept of high temperature superconducting undulator" (2017), doi: 10.1088/1361-6668/aa87f1

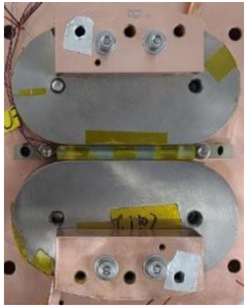
A. Will *et al.*, "Design and Fabrication Concept of a Compact Undulator with Laser Structured 2G-HTS Tapes" (2021), doi: 10.18429/JACoW-IPAC2021-THPAB048.



<u>S. Liu *et al.*</u>

- Non-insulated winding
- VR winding with joints
- Mirror model

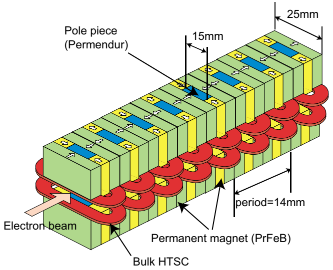
S. Liu *et al.*, "Development of a Short REBCO Undulator Magnet With Resistive Joints" (2019), doi:10.1109/TASC.2019.2896045



<u>J. Park *et al.*</u>

- Non-insulated winding
- VR winding
- Short model

J. Park *et al.*, "Conduction Cooling Test of Short Period NI HTS Undulator at Different Operating Temperatures" (2021), Presentation at MT27.



<u>T. Tanaka *et al.*</u>

- PMU + HTS: "Enhanced CPMU"
- *Re*BCO Bulks
- Short model

T. Tanaka *et al.*, *"Application of high-temperature super-conducting permanent magnets to synchrotron radiation sources"* (2004), doi: 10.1103/PhysRevSTAB.7.090704 .

Magnet protection..?!

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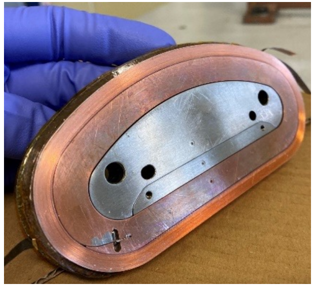

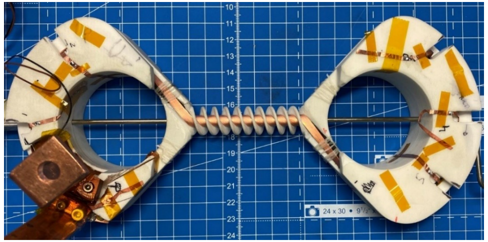

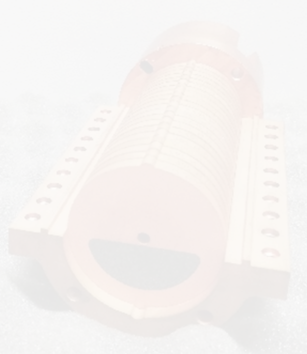

CERN

Karlsruhe Institute of Technology

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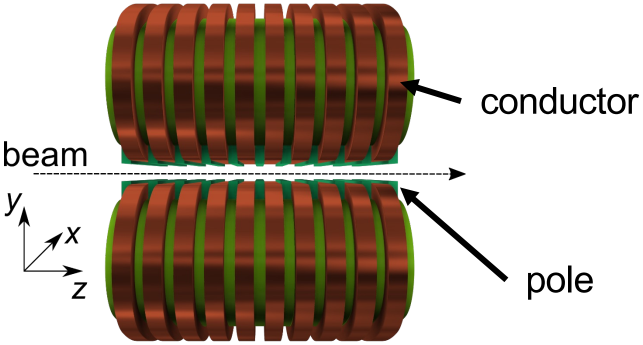
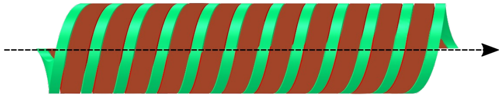
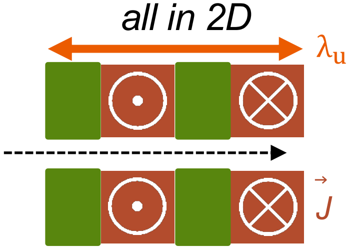
About the HTS Undulator Study (CERN-KIT)

- Investigation of prototype coils (λ_u = 13 mm)
  - Vertical Racetrack (**VR**)
  - Helical Undulator (**Hel.**)





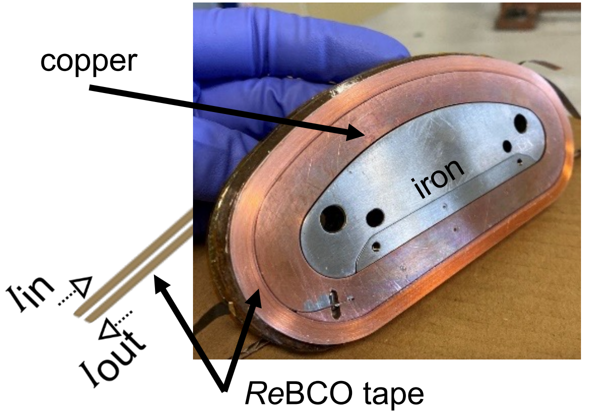


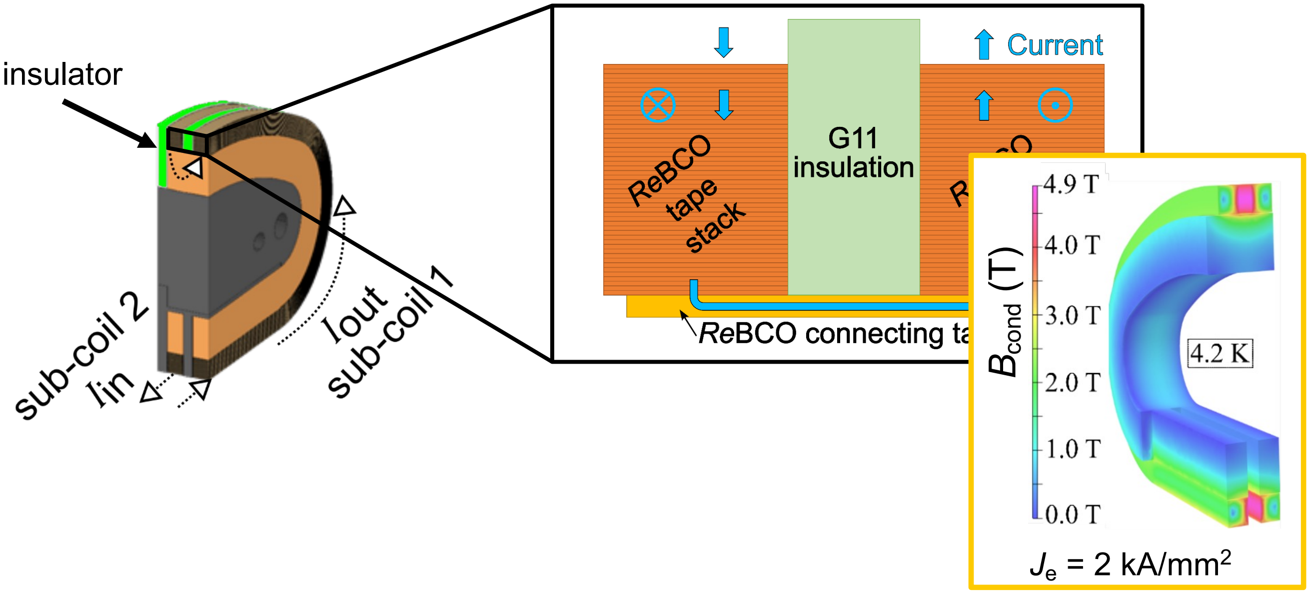
→ Non-insulated windings for high *J* quench protection
+ extra Cu as a stabilizer

VR Undulator Coil: design

One-period coil:

- Two non-insulated sub-coils with opposite current directions on the same winding body, with central insulators.



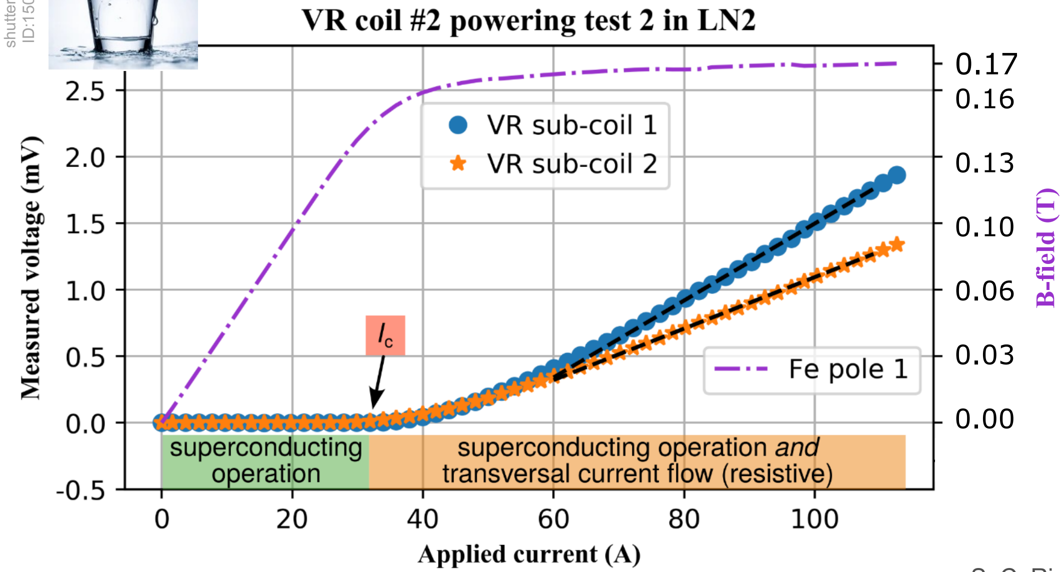


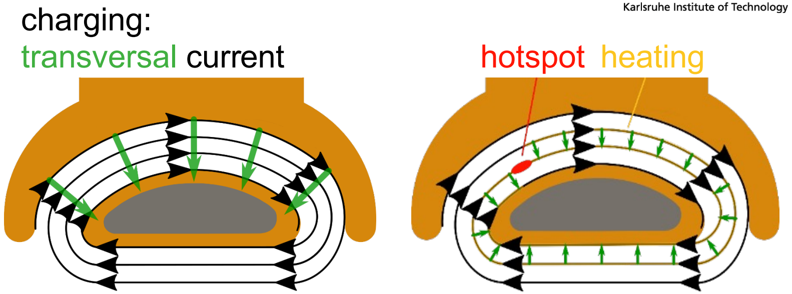
S. C. Richter *et al.* (2022) *IEEE Trans. Appl. Supercond.* **32**(4) 4100305

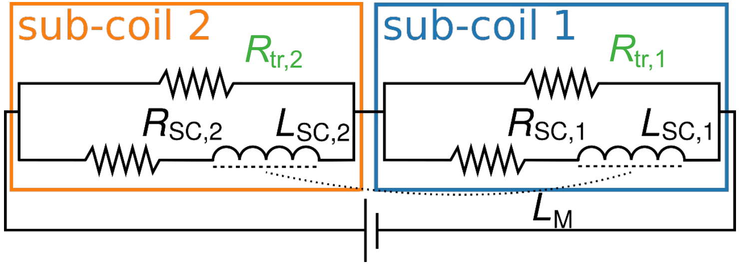
VR Undulator Coil: powering at 77 K (LN_2)

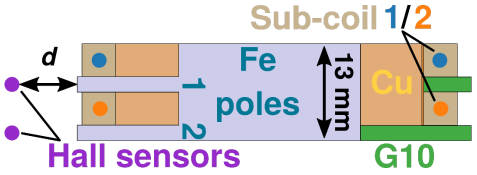
1) Current steps and overflow:
   - Steps of 2 A with a 300 s decay time,
   - Up to ≈ 300% I_c, ending in stable resistances R_{tr} .

shutterstock.com, ID:150919655



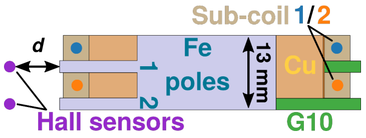






S. C. Richter *et al.* (2023) *IEEE Trans. Appl. Supercond.* ***33****(5)* 4100207

VR Undulator Coil: powering at 4.2 K (LHe)

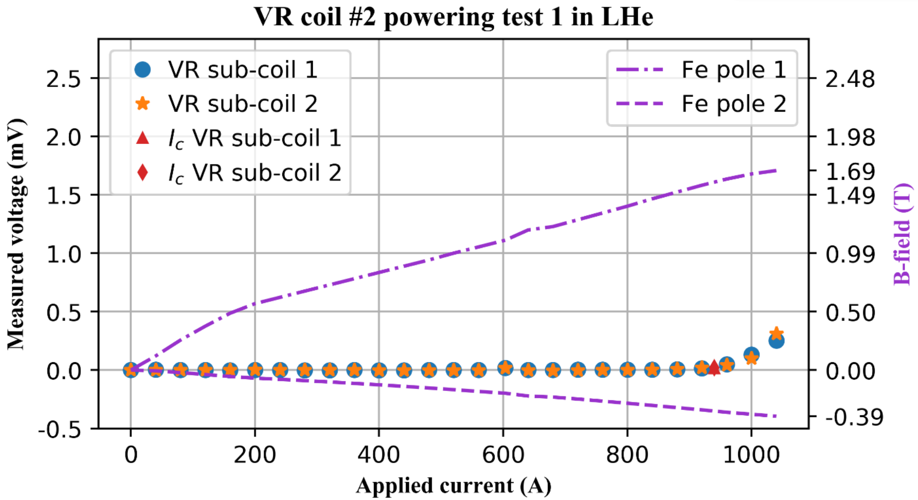


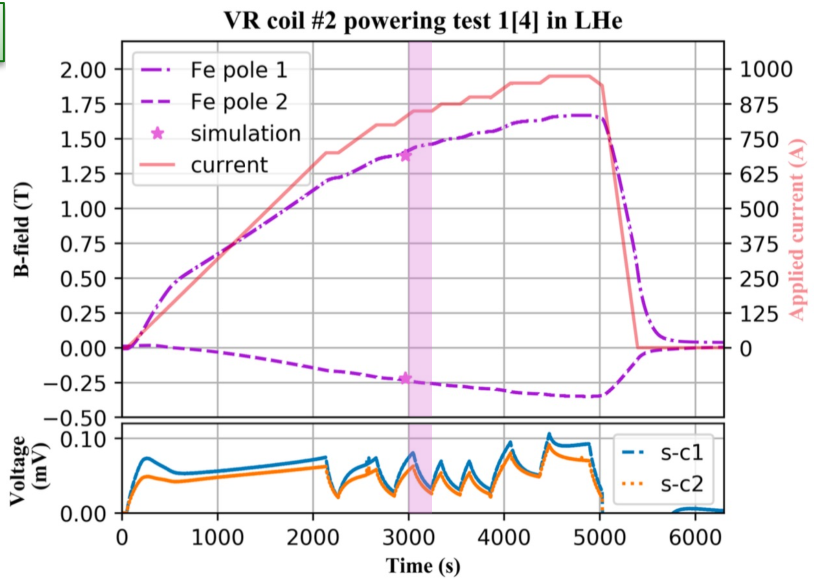
2) Current steps, magnetic field, and overflow:

- 40 A steps with a 300 s decay time
- 828 A operation → 1.4 T in 3.5 mm (7 mm gap)

I_c	930 A	930 A

→ $J_{en} \approx 2.3$ kA/mm²



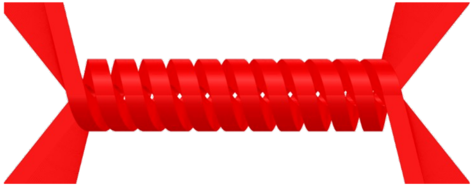


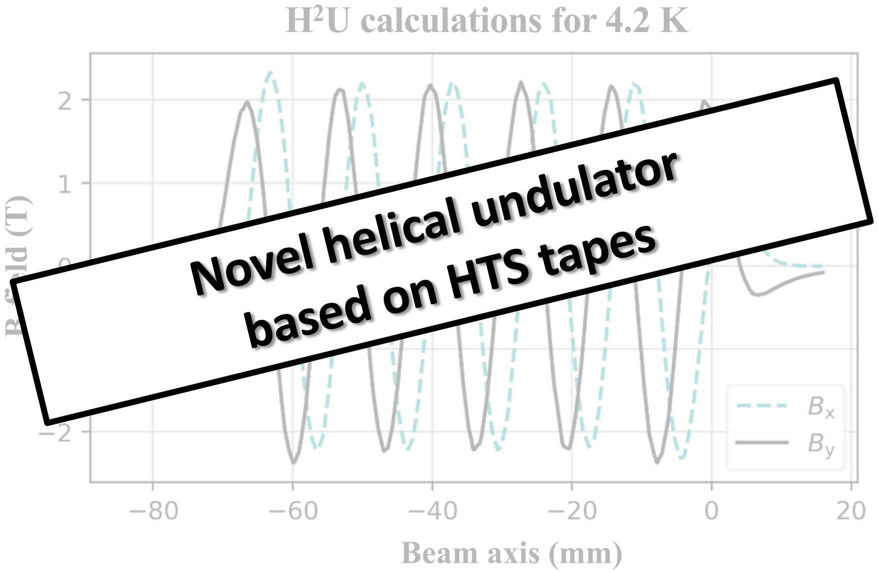
S. C. Richter *et al.* (2023) *IEEE Trans. Appl. Supercond.* ***33****(5)* 4100207

HTS Helical Undulator (H²U) Demonstrator

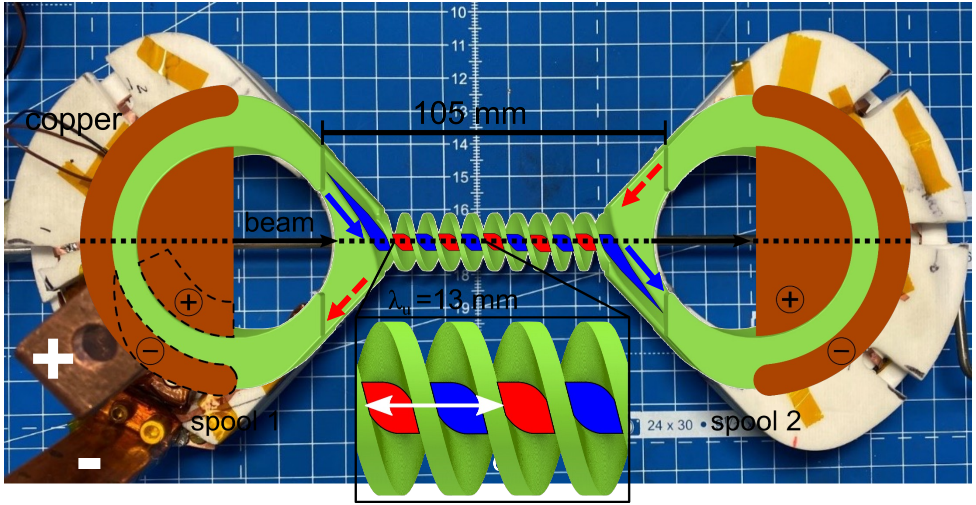
Why? → More compact and efficient!

- *4.2 K:* $B_y \geq 2$ T for $\lambda_u = 13$ mm, $g = 5$ mm,
- 77 K: stable operation up to 107% I_c





Novel helical undulator based on HTS tapes



S. C. Richter *et al.* (2023) *IEEE Trans. Appl. Supercond.* ***34***(3) 4101507

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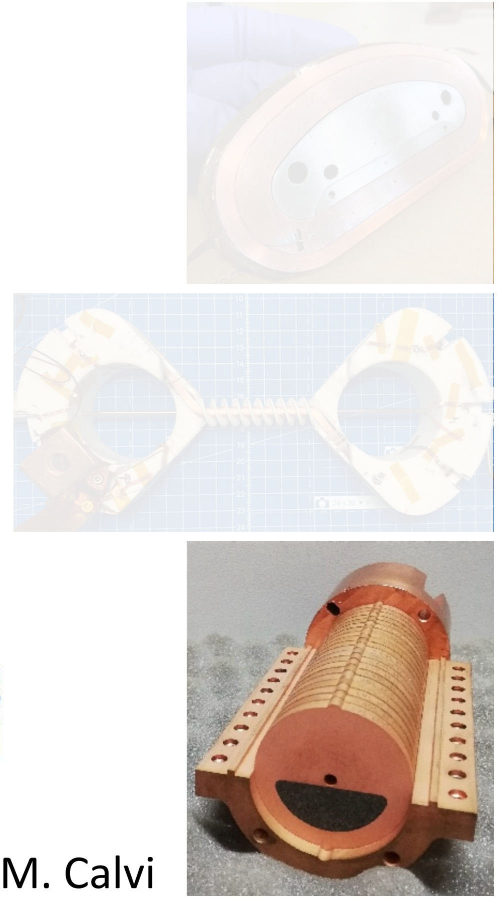
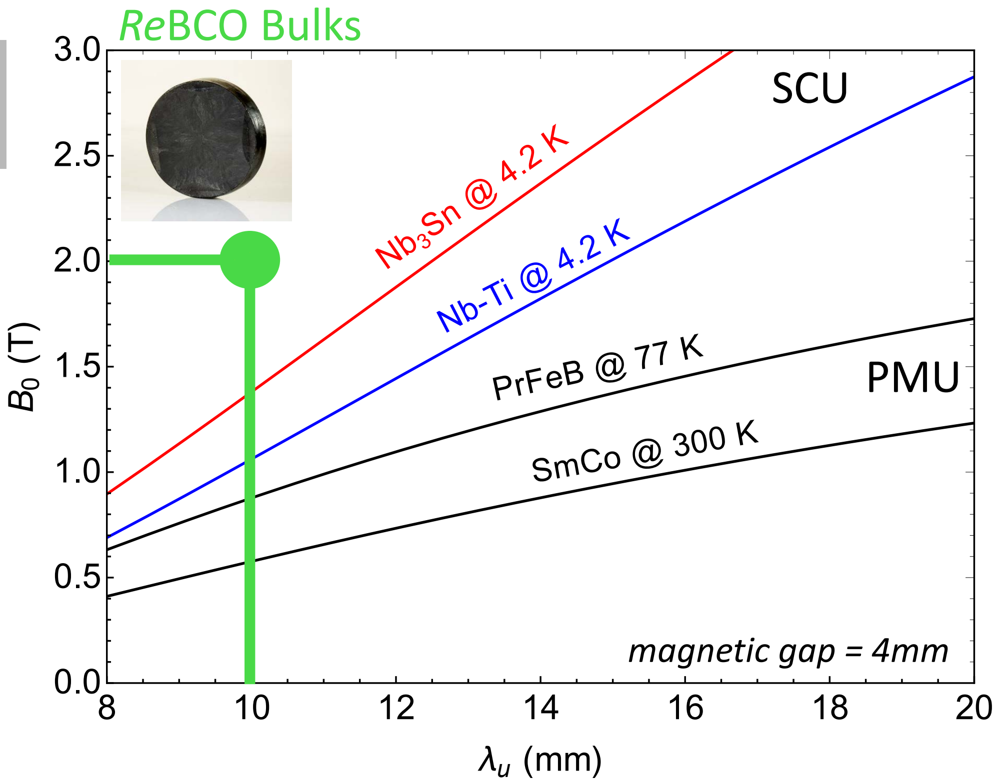


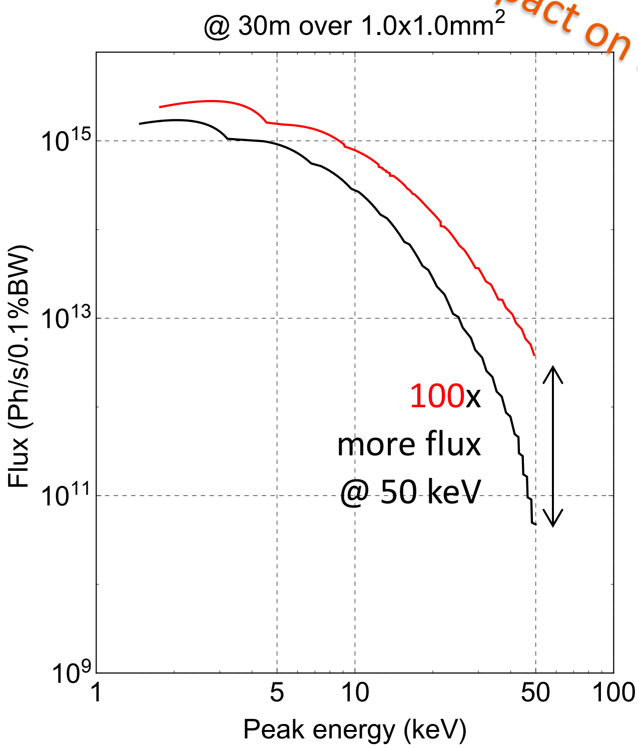
Swiss Accelerator
Research and
Technology

Courtesy of M. Calvi

About the HTS Bulk Undulator at PSI for SLS2.0



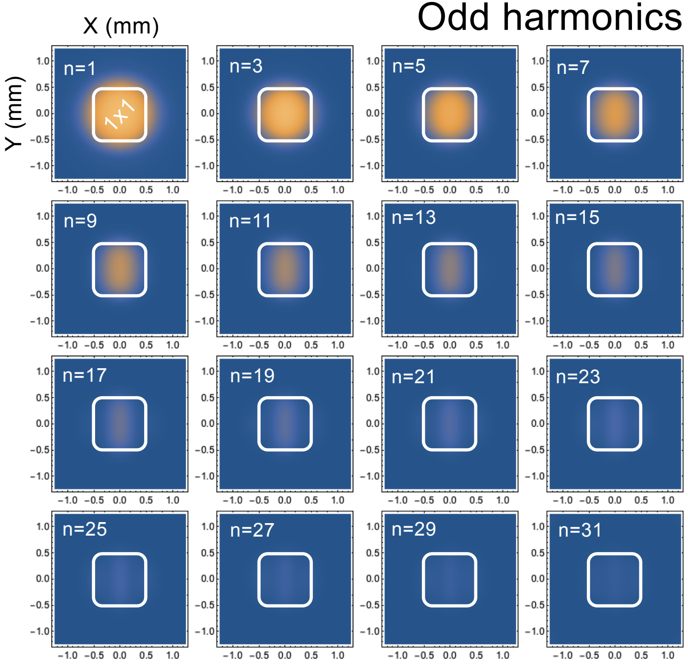
Impact on SLS2.0



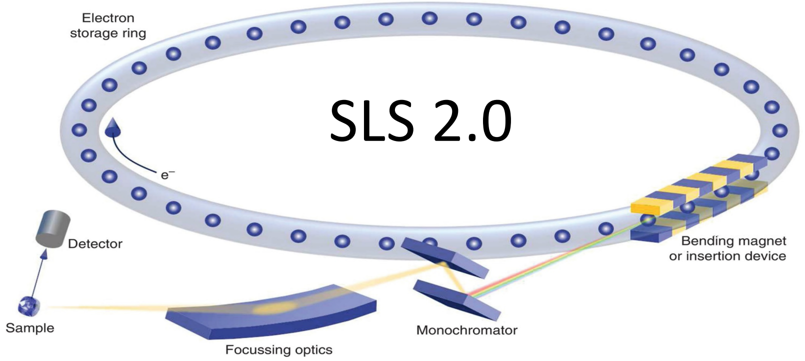
[Scaling laws: E.R. Moog, R.J. Dejus, and S. Sasaki , Light Source Note: ANL/APS/LS-348
James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator
and Beams 17, 022401 (2014)]

CPMU14 with B_0=1.3 T

Odd harmonics



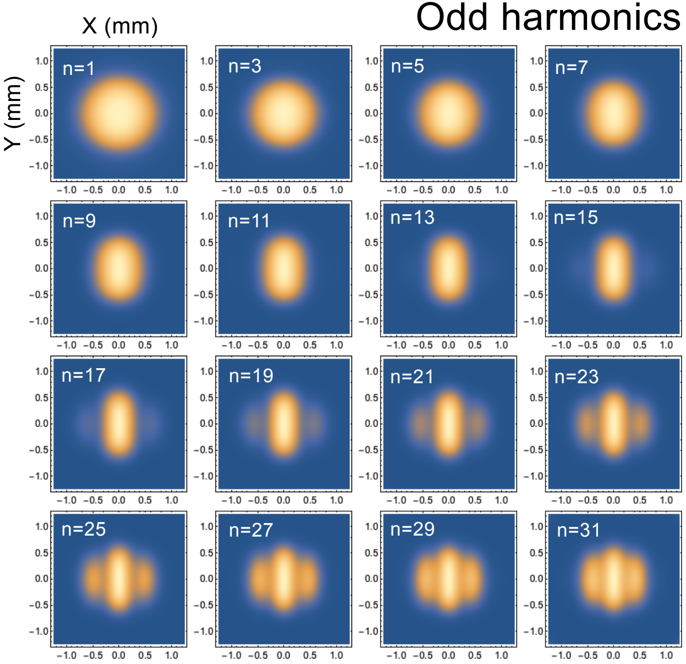
Flux at 30 m from the source
to illuminate a sample of about 1 mm^2



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

HTSU10 with B_0=2.0 T

Odd harmonics



Flux at 30 m from the source
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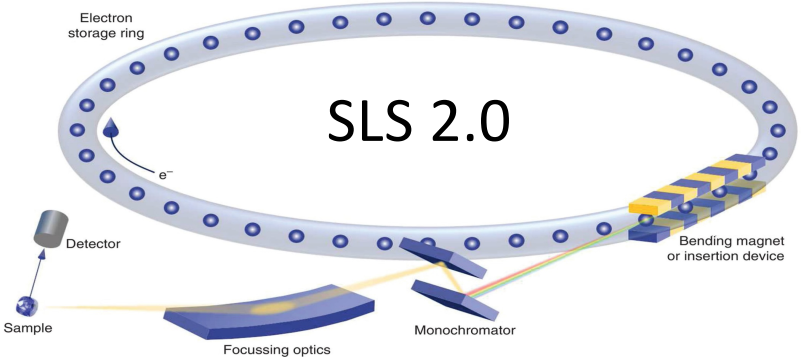
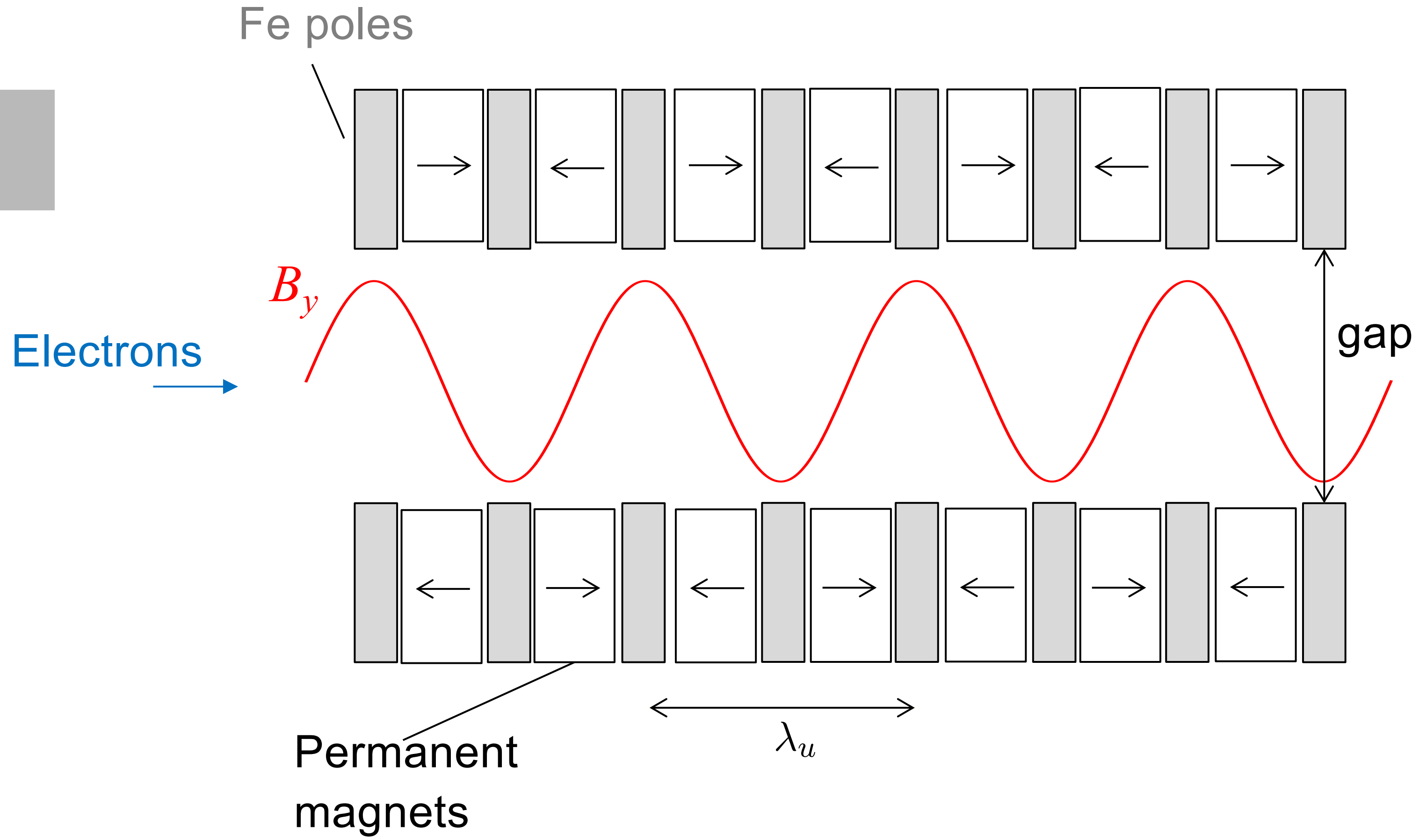
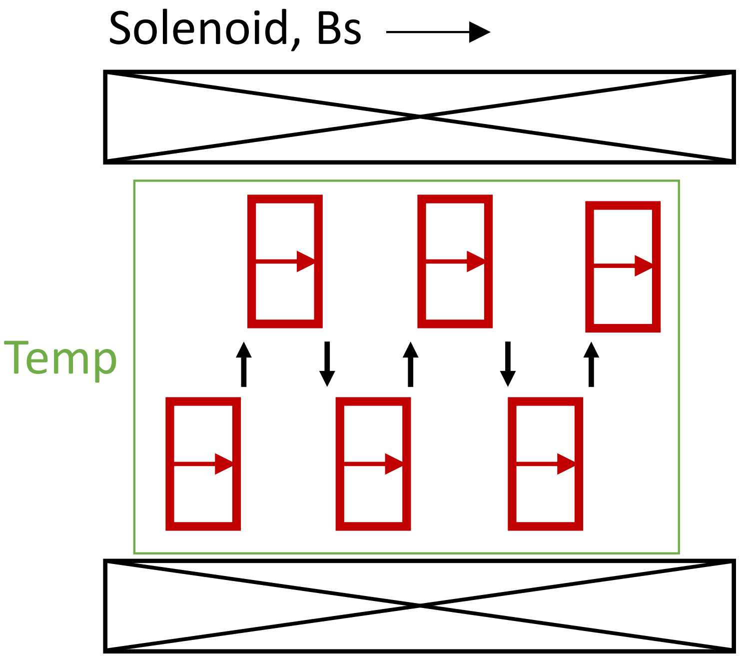


Calculations done for the future iTOMCAT beamline, dedicated to tomographic microscopy

Permanent Magnet Undulator with Fe poles

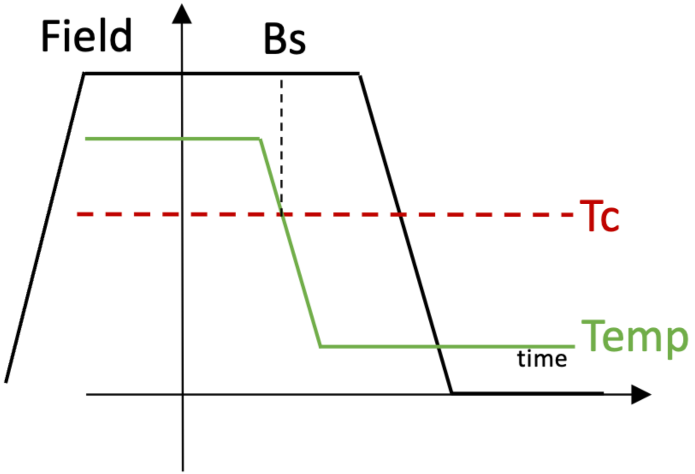


Superconducting Staggered Array Undulator



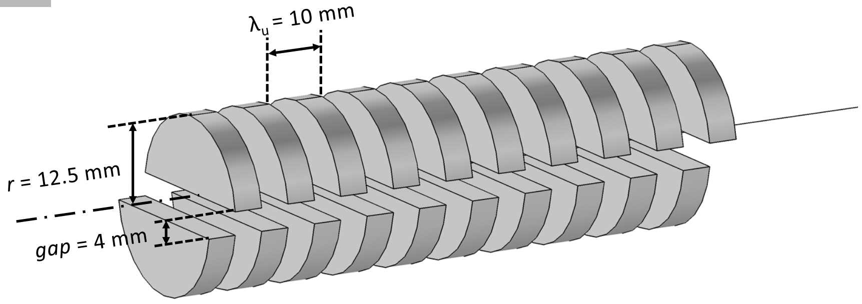
□ GdBCO Tc=92K

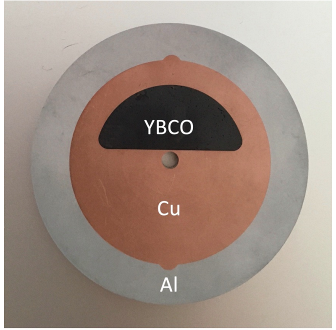
Example of *field cooling* magnetization

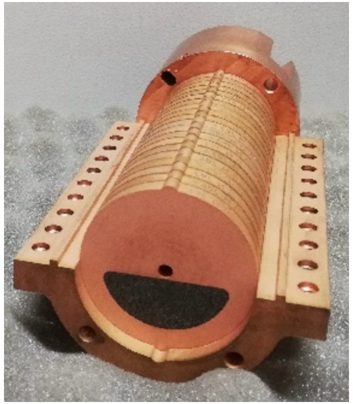


T. Kii, *et al.* (2006) Proc. FEL2006 p. 653.
R. Kinjo *et al. (2013) Appl. Phys. Express* ***6*** *042701*

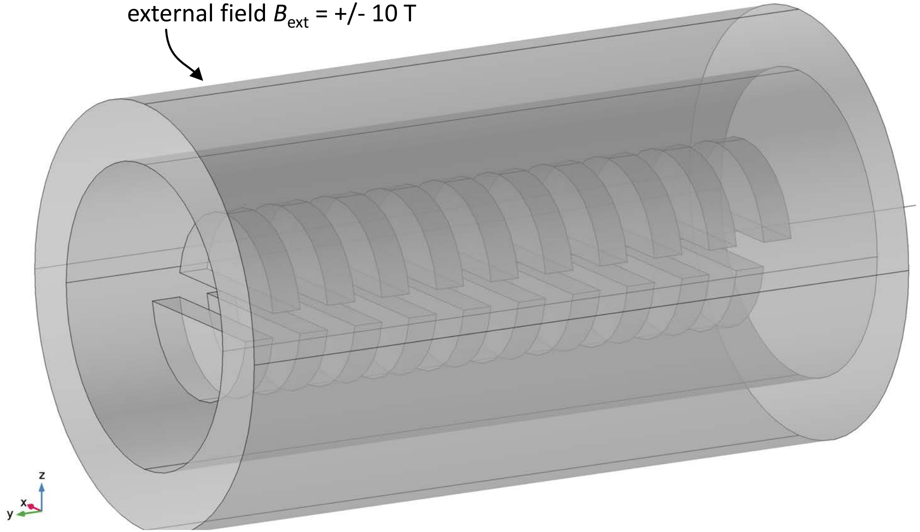
Short bulk HTSU samples: design





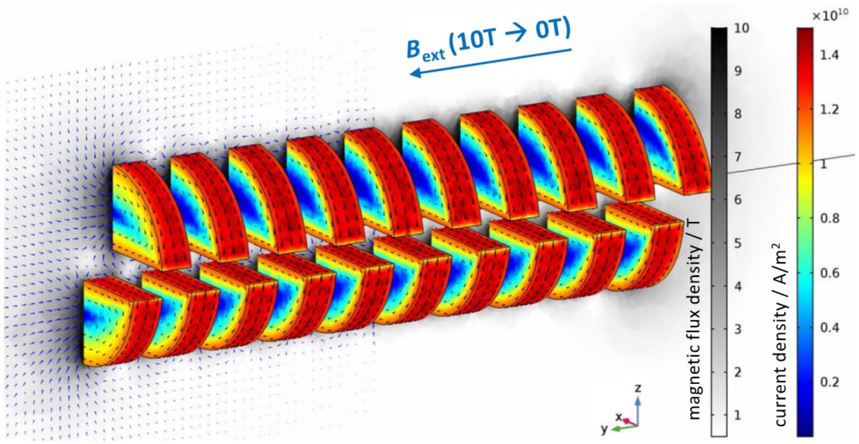


- Superconducting solenoid providing external field B_{ext} = +/- 10 T

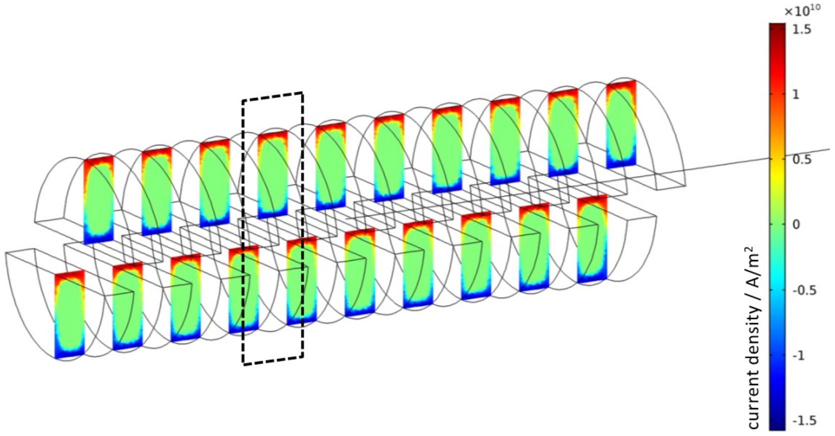


Short bulk HTSU sample: calculations

Field Cooling magnetization from 10 T to 0 T



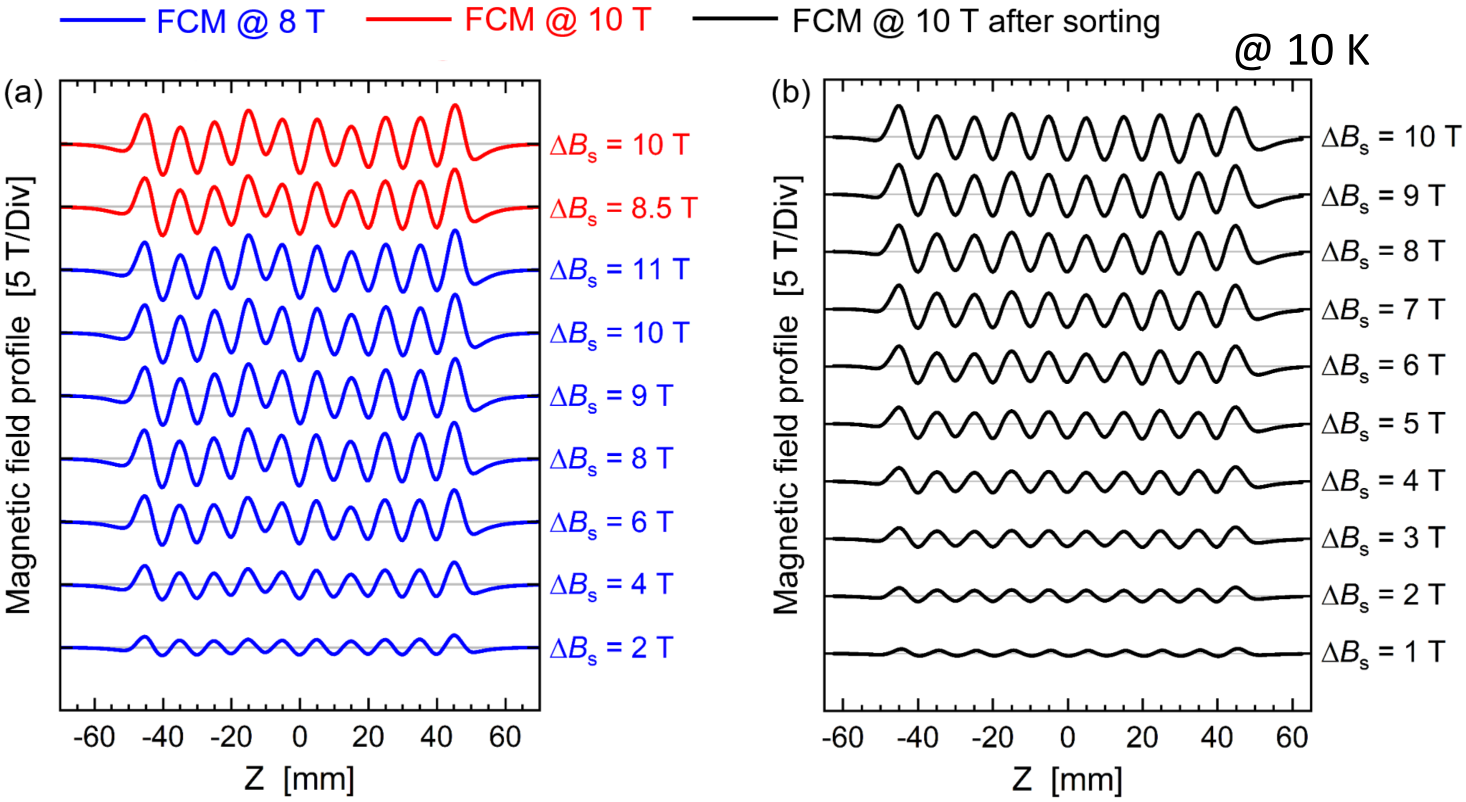
Surface current density and magnetic field



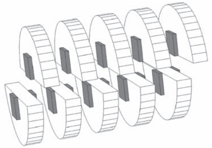
Magnetization current density in the mid-plane

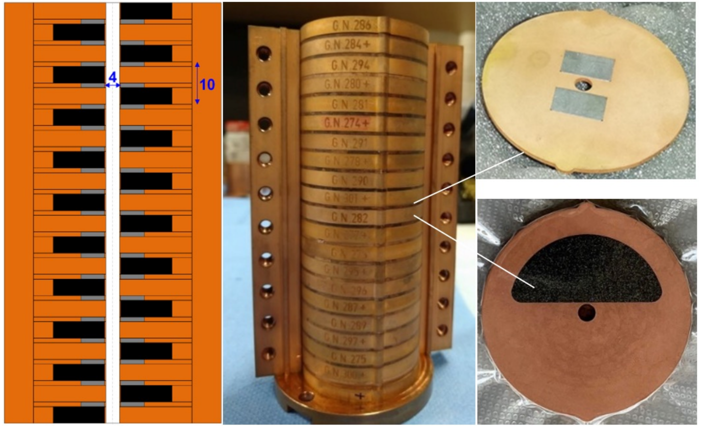
up to ~15 kA/mm^2 (!)

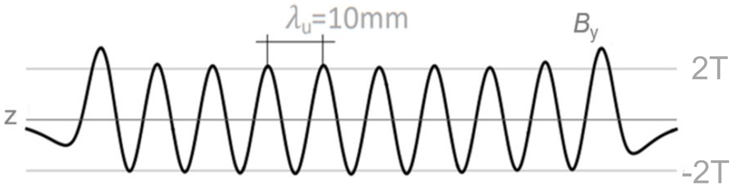
Planar Hybrid: bulk sorting



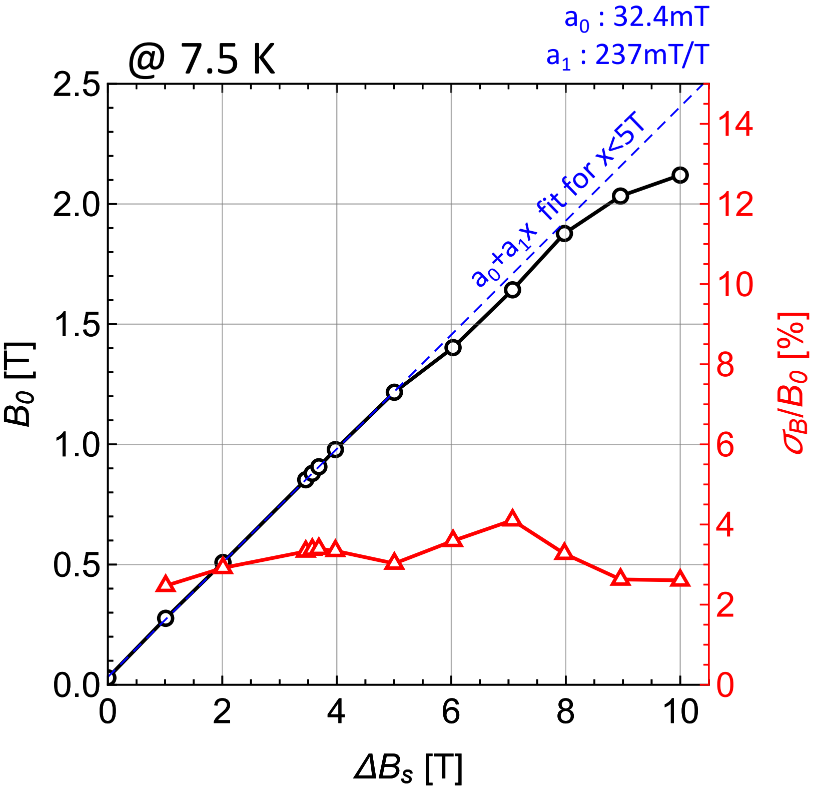
Planar Hybrid: *B*-field (Nippon Steel)







Very high-quality bulks: no optimization, yet



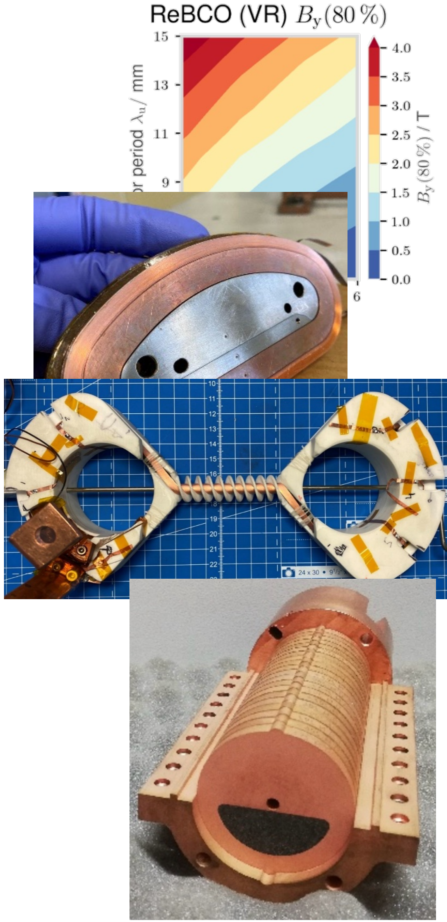
→ also possible with a different setup: helical field

K. Zhang *et al.* (2023) Supercond. Sci. Technol. **36**
M. Calvi *et al.* (2023) Phys. Rev. Research **5**

Summary and Conclusion

HTS has demonstrated potential and feasibility for undulators

- VR prototype coils demonstrated *high magnetic fields*
  - Stable operation up to I_c, and beyond (77 K, 4.2 K)
- *Re*BCO tape-based helical undulator demonstrator: *novel design*
- Short model bulk undulator demonstrated *high magnetic fields*
  - Stable operation with optimized *B*-field (7.5 K, 10 K),
  - Design ready: first full HTS undulator (1 m) at PSI for SLS2.0 in 2026 (!)



Upcoming research:

tapes

- Controlled inter-turn resistance
  - NI, PI, or variable resistance?
- Field quality and tuning
- Holmium poles
- Bulks: Single-direction melt growth (SDMG)

HTS is superior to LTS in absolute on-axis field

Acknowledgements

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WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Sebastian Richter :: Photon Science Division - Insertion Devices :: Paul Scherrer Institute

High-Temperature Superconducting Undulators:
Potential, Status, and Application

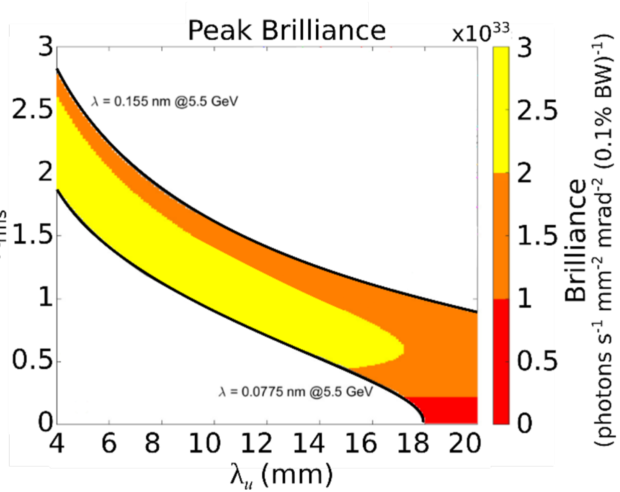
THANK YOU FOR YOUR ATTENTION

9th Low Emittance Rings Workshop 13-16 February 2024, CERN, Geneva, Switzerland

Backup: Undulator & Wiggler Magnets

Light source:

CompactLight

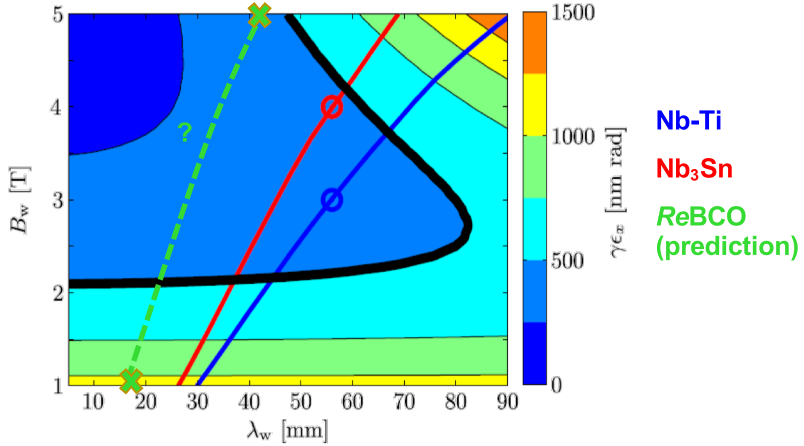


Funded by the European Union

Compact

Collider:

CLIC



F. Nguyen *et al.* (2019) “XLS - D5.1: Technologies for the CompactLight Undulator”

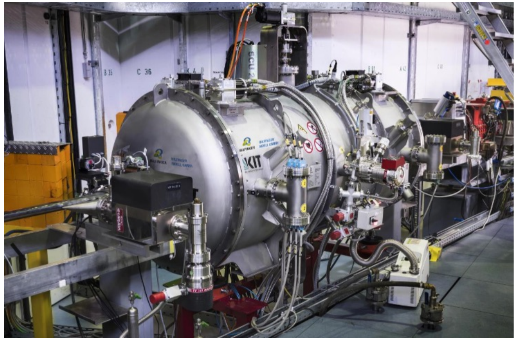
D. Schoerling *et al.*, (2012) *Phys. Rev. ST Accel. Beams* **15**, 042401

Backup: overview of today's SCUs

State-of-the-art technology: Low-Temperature Sc (LTS)

- Higher magnetic fields / reduced undulator length
- Simple *K*-control via current (vs. massive PMU)
- Small footprint
- Cryogenics and quench protection are crucial
- High-field, short-period examples:

B	**λ_u**	**gap**	**material**	**location**
1.18 T	20 mm	7 mm	Nb-Ti	KARA (KIT), DE
1.17 T	18 mm	9.5 mm	Nb_3Sn	APS (ANL), US
1.82 T	18 mm	6 mm	Nb-Ti	EuXFEL/Bilfinger, DE *in production*



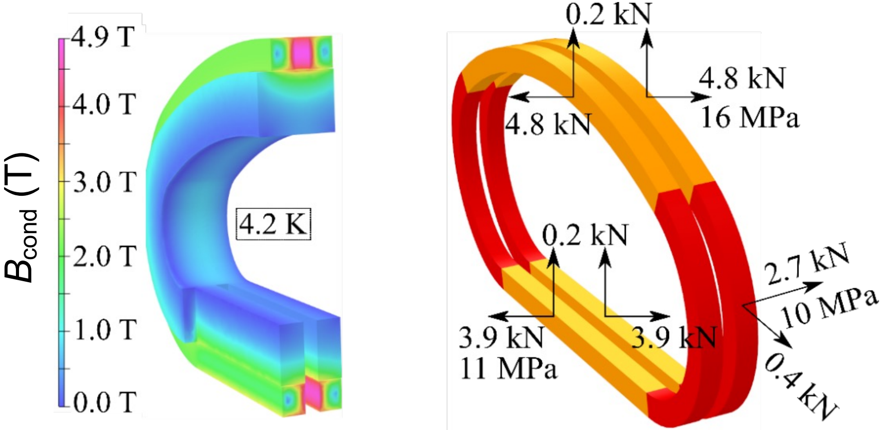
SCU20 (KIT),
S. Casalbuoni *et al.* (2019) *AIP Conf. Proc.* ***2054***

SCU18 (ANL),
Y. Ivanyushenkov *et al.* (2015) *Proc. IPAC 2015*

Backup: VR Undulator Coil – 3D modelling

J-anisotropy → considering the worst-case scenario defined J_c:

- Max. B_{cond} perpendicular to the tape's plane,
- At 4.2 K: max. $B_{\perp} \approx 99.95\%\ B_{cond}$.



J_e(4.2 K) = 2071 A/mm^2

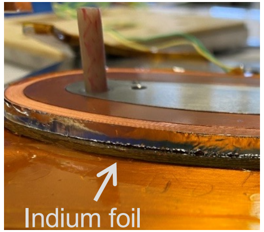
	VR coil
Undulator period λ_u	13 mm
Sub-coil x-section	4 mm × 5 mm
HTS conductor	Bruker HTS
with dimensions	4 mm x 100 µm
Number of turns	51
$J_{op,\ sim}$ (4.9 T, 4.2 K)	2071 A/mm^2
$I_{op,\ sim}$ (4.9 T, 4.2 K)	828 A
$B_{y,1}(I_{c,sim}$, @3.5 mm)	1.38 T

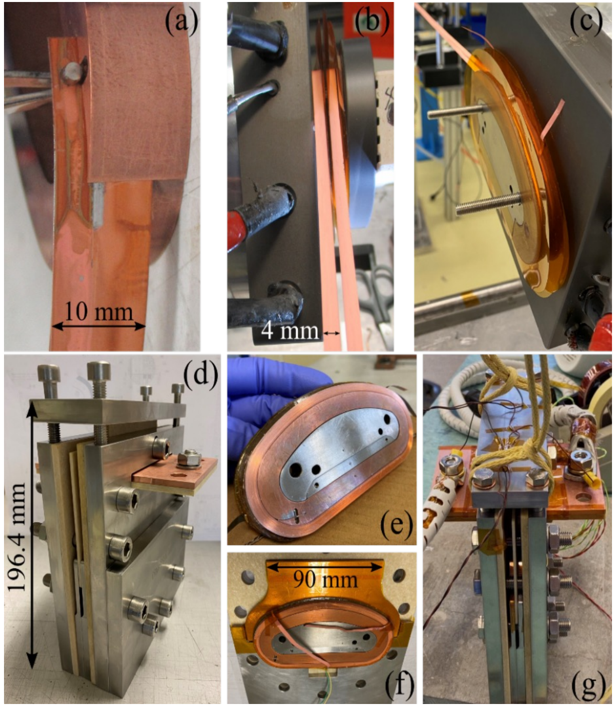
S. C. Richter *et al.* (2022) *IEEE Trans. Appl. Supercond.* **32**(*4*) 4100305

Backup: VR undulator coil manufacturing

- 4 mm wide and
  - 100 µm thick Bruker HTS tape (VR coil #1 and #2),
  - 45 µm thick SuperPower tape (VR coil #3).
- The first turn was fixed by a pin and soldered along the curved side to the 10 mm tape,
  - Sn62Pb36Ag2 solder paste @ 185 °C for 5 min.
- Winding with controlled winding tension {30 N, 25 N}.
- The last turn was soldered along the curved side,
  - 97In3Ag solder paste @ 155 °C for 5 min.

- Contact: copper lead with indium foil,
- 4 voltage taps (sub-coil's start and end).



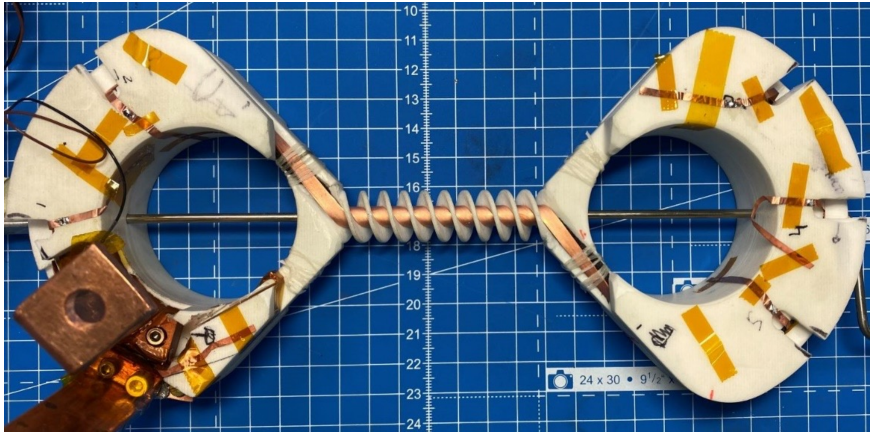


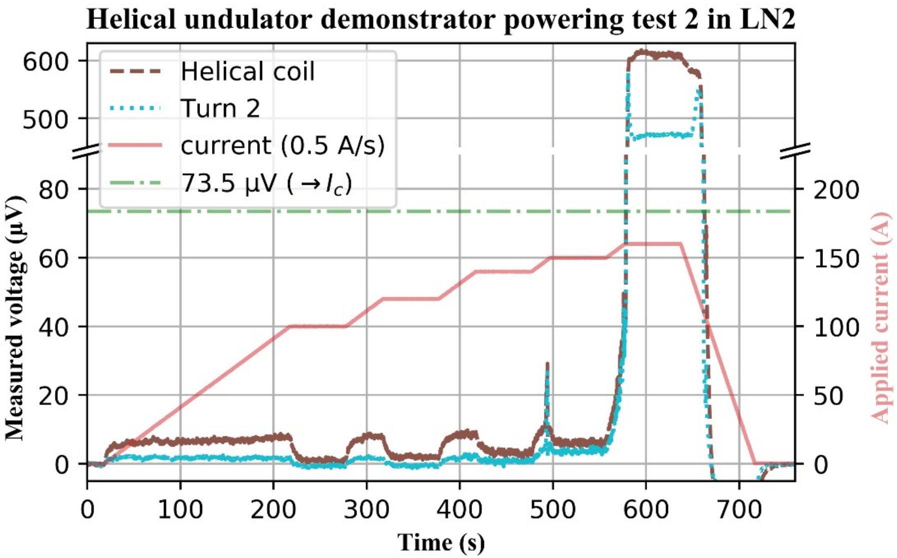
S. C. Richter *et al.* (2022) *IEEE Trans. Appl. Supercond.* ***32****(4)* 4100305

Backup: H^{2}U demonstrator

- $B_y \geq 2$ T for $\boldsymbol{\lambda_u}$ = 13 mm, g = 5 mm,
- Wound with 4 mm wide *Re*BCO tape.

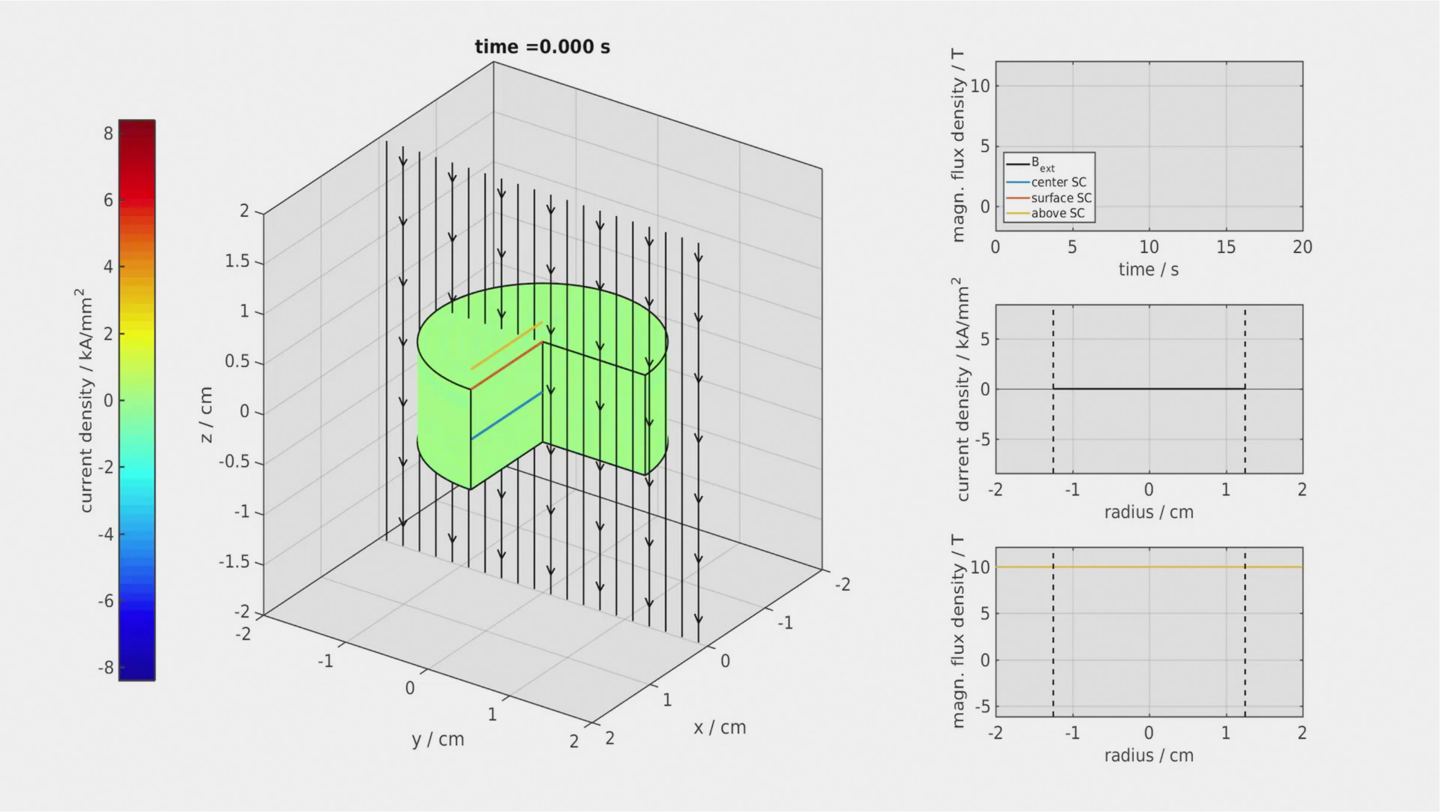
Very first helical undulator with superconducting tapes
→ novel winding scheme and challenges!



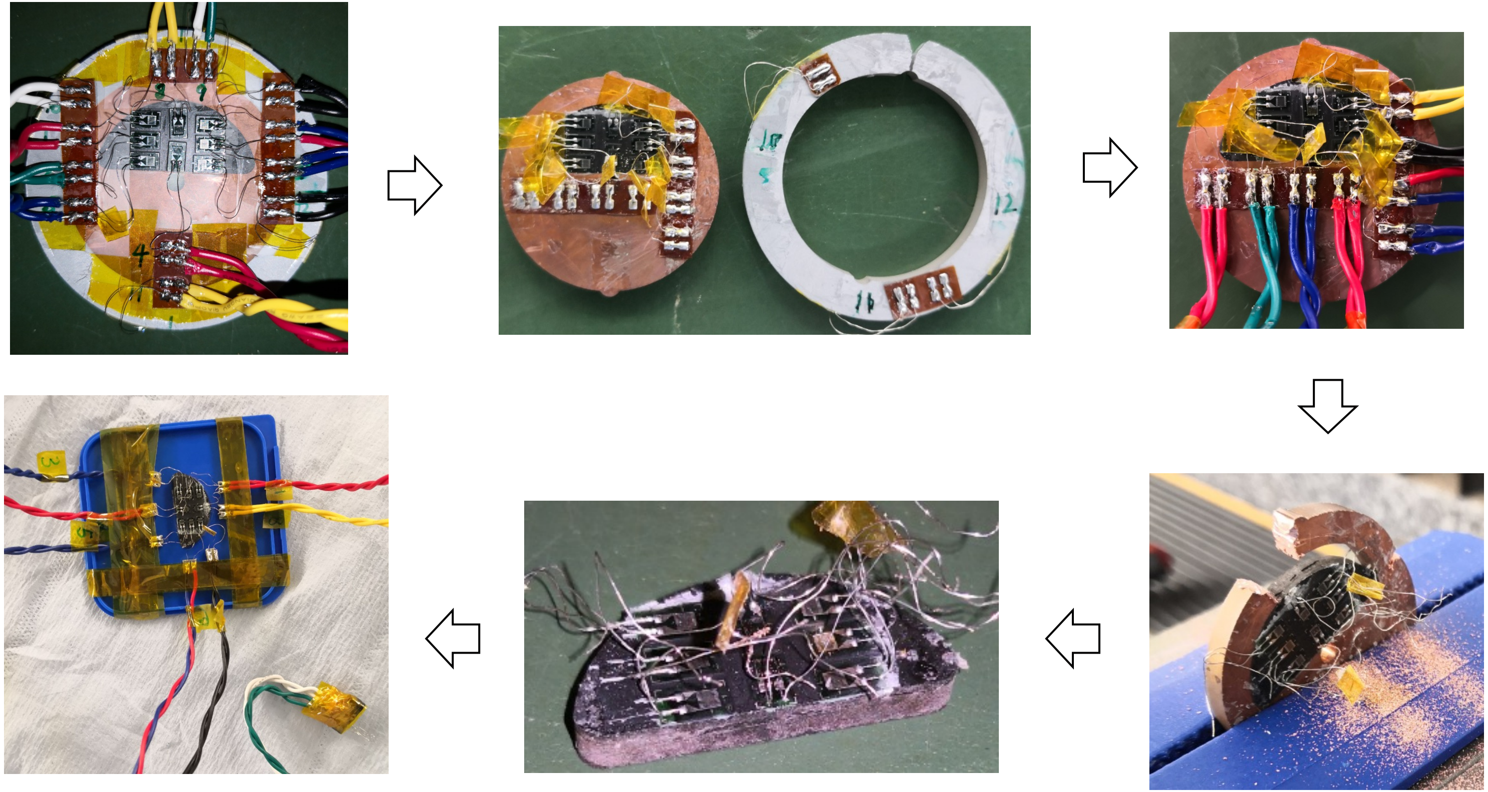


S. C. Richter *et al.* (2023) *IEEE Trans. Appl. Supercond.* ***34****(3)* 4101507

Backup: example of Field Cooling (FC)

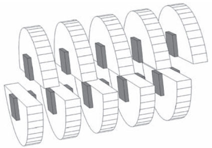


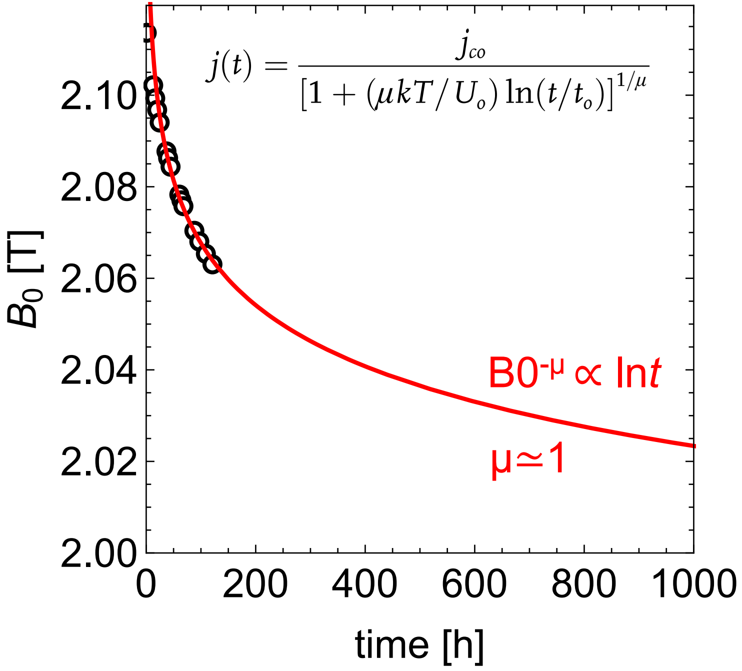
Backup: prestress measurements at 77 K

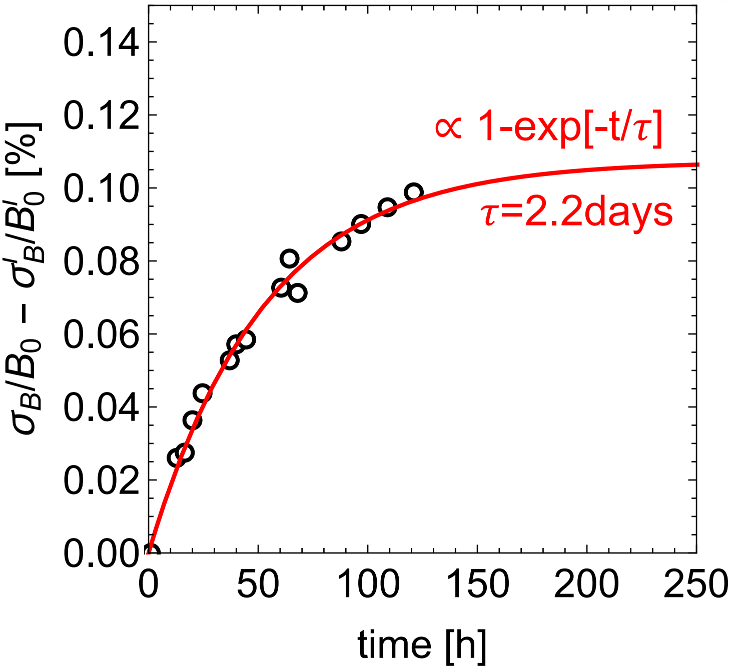


K. Zhang *et al.* (2023) Supercond. Sci. Technol. **36**

Backup: Planar Hybrid – *B* decay (Nippon Steel)







K. Zhang *et al.* (2023) Supercond. Sci. Technol. **36**