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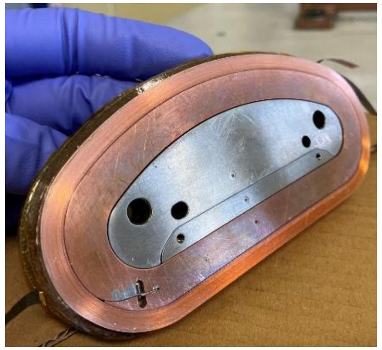

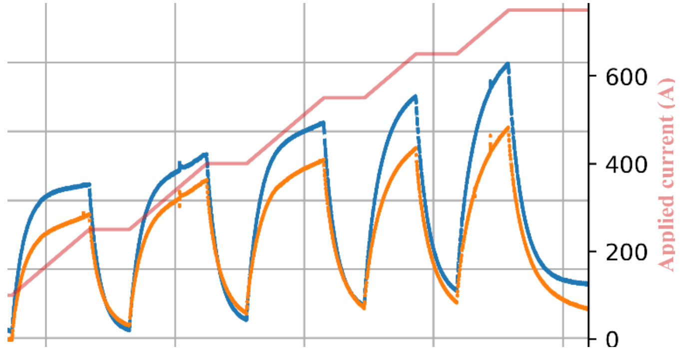

Powering test results of HTS undulator prototype coils for compact FELs at 4.2 K

Sebastian C. Richter[1,2], A. Ballarino[1], A. Bernhard[2], A. W. Grau[2], D. Saez de Jauregui[2] and A.-S. Müller[2]

1 CERN

2 KIT Karlsruhe Institute of Technology

* SPONSORED BY THE Federal Ministry of Education and Research

**

This work is supported by:

* The Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 05E15CHA)

** The DFG-funded Doctoral School „Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology"

CERN – The European Organization for Nuclear Research
KIT – The Research University in the Helmholtz Association

home.cern
www.kit.edu

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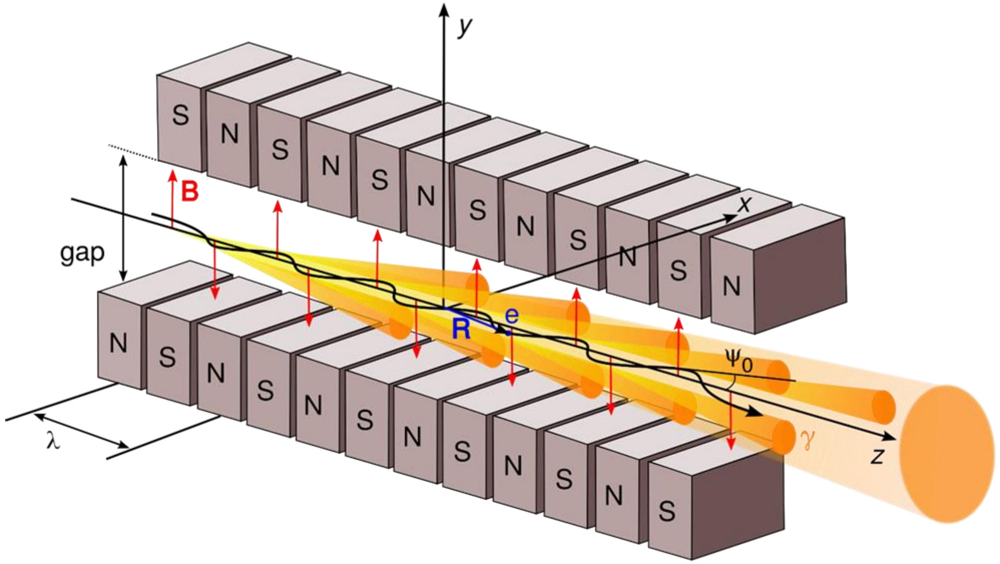

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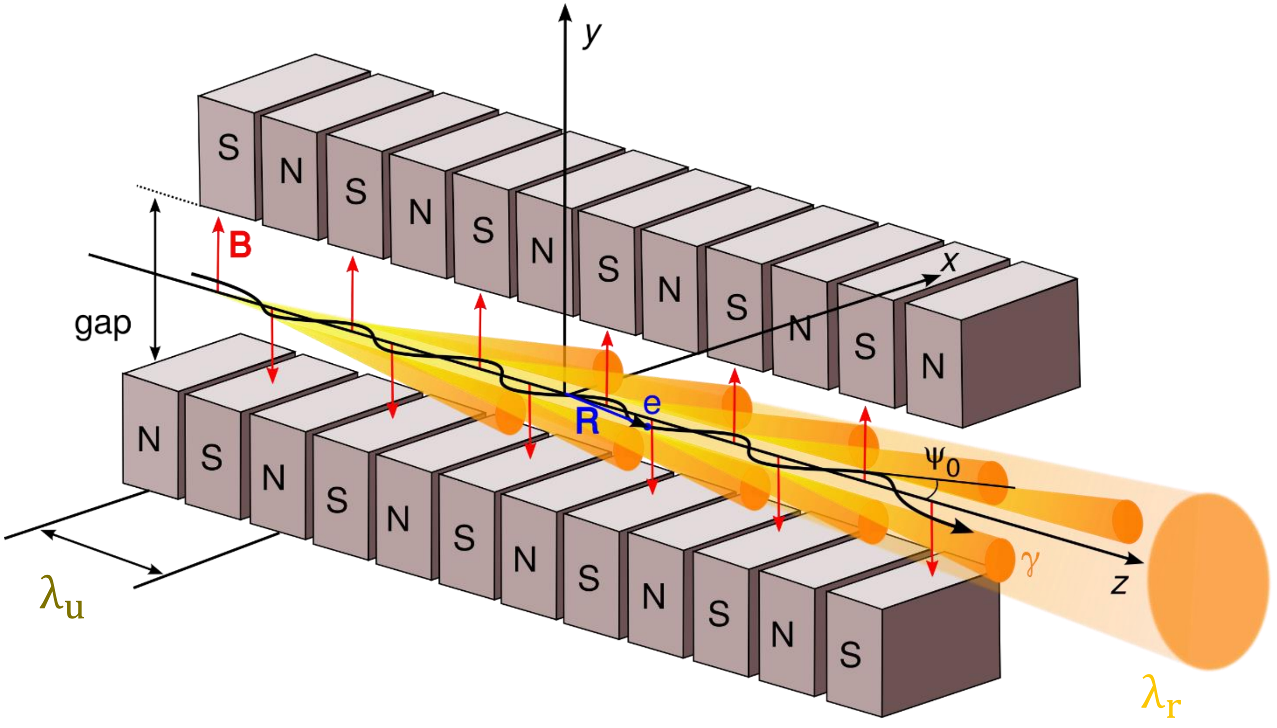
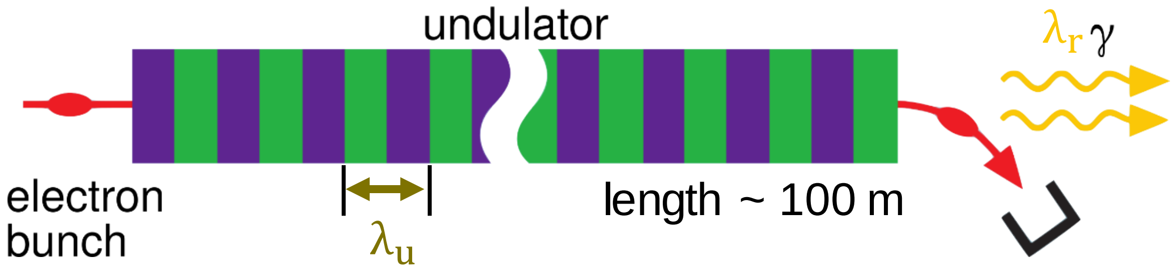
Background: free-electron laser (FEL)

The plain undulator…



… in an FEL



Self-amplified spontaneous emission (*SASE*)
→ Microbunching

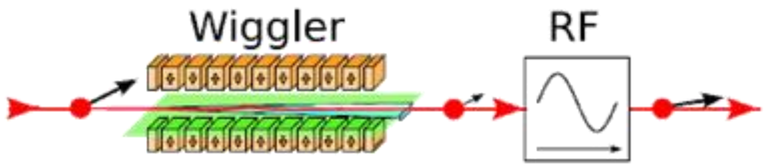
$$\lambda_r = \frac{\lambda_u}{2\gamma_r^2}\left(1 + \frac{K(B,\lambda_u)^2}{2}\right)$$

Schmüser, Dohlus, Rossbach; Ultraviolet and Soft X-Ray Free Electron Lasers, Springer (2008).

Background: damping undulator/wiggler

- Definition *undulator* vs. *wiggler:* K parameter → radiation spectrum,
  - $K_{\text{undulator}} \lesssim 1$,
  - $K_{\text{wiggler}} \gg 1$.

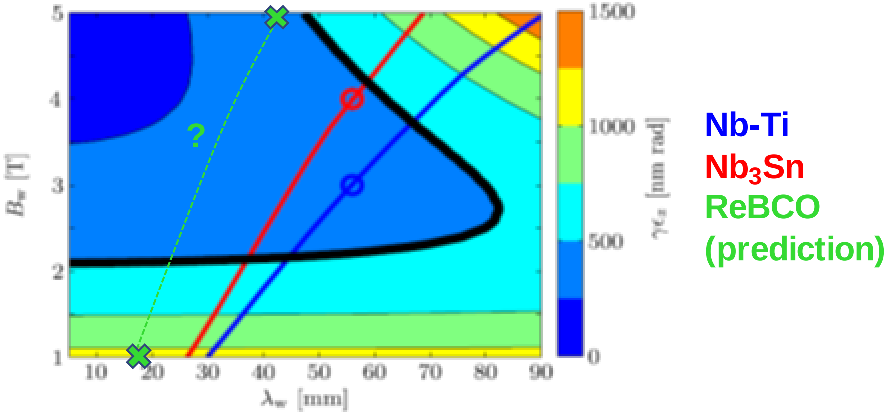
$$K = \frac{e \cdot B\lambda_u}{2\pi m_e c}$$



P. Peiffer, "The Status of the Damping Wiggler Project for the CLIC Damping Rings", The 16th Pan-American Synchrotron Radiation Instrumentation Conference, Chicago (2010).

- Particles lose energy via synchrotron radiation by additional dipole fields,
- Wigglers can easily be placed in straight sections of a ring,
  - $\int^L B\, dl = 0$.

- Link to CLIC and FCC-ee:
  - High magnetic fields (> 2 T),
  - Long period lengths (> 40 mm).



D. Schoerling *et al.*, "Design and system integration of the superconducting wiggler magnets for the Compact Linear Collider damping rings" (2012), doi: 10.1103/PhysRevSTAB.15.042401.

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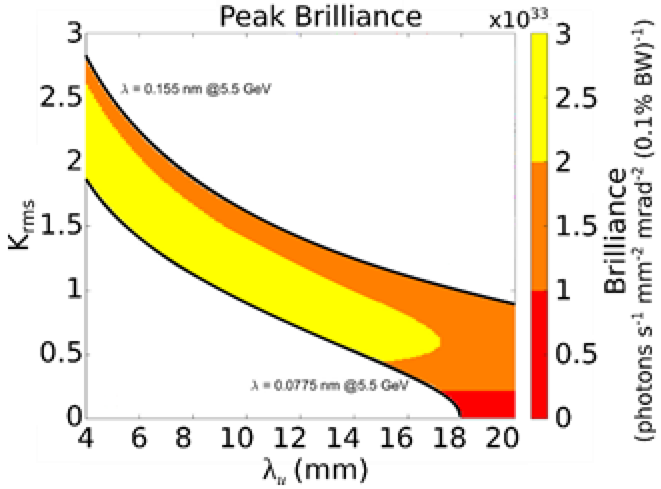
Background: use case

- The next generation of compact, highly brilliant light sources may profit from high-temperature superconducting (**HTS**) undulators:
  - Potential enhancement of undulator parameters, e.g., magnetic flux density (*B*) amplitude for given undulator period length (λ_u),
  - Facilitated operation compared to LTS, like Nb-Ti or Nb_3Sn → Relaxed cryogenic requirements (lower costs), larger margins.

- Link to CompactLight:
  - Hard X-ray FEL (< 1 nm),
  - Short-period undulators (~ 13 mm),
  - Low electron beam energy (2.5 to 5.5 GeV).

Funded by the European Union

Compact



F. Nguyen *et al.* “XLS - D5.1: Technologies for the CompactLight Undulator” (2019), doi: 10.5281/zenodo.5024409

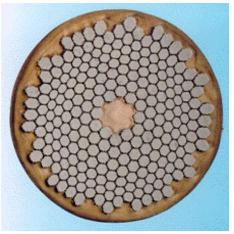
Background: different superconductors

Low-Temperature Superconductor (LTS)

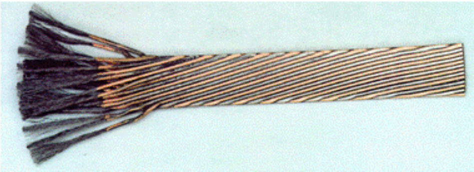
State-of-the-art: Nb-Ti (niobium-titanium)

$T_c \approx 10$ K

$B_{c2} \approx 14.5$ T



strand



*

cable

B to strand/cable orientation is not relevant.

Critical current is given by:

$$I_c(T, B)$$

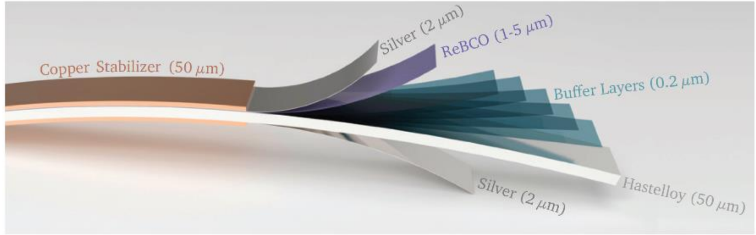
High-Temperature Superconductor (HTS)

Here: ReBCO (rare-earth barium copper oxide)

$T_c \approx 92$ K

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

**



Tape

$\boldsymbol{B}_\perp$: B ⊗ or ⊙, *J* →

$\boldsymbol{B}_\parallel$: B → or ↑, *J* →

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

More on superconductor's critical current densities: ASC Plot (by P. Lee)

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

** J. van Nugteren, High Temperature Superconductor Accelerator Magnets, PhD (2016)

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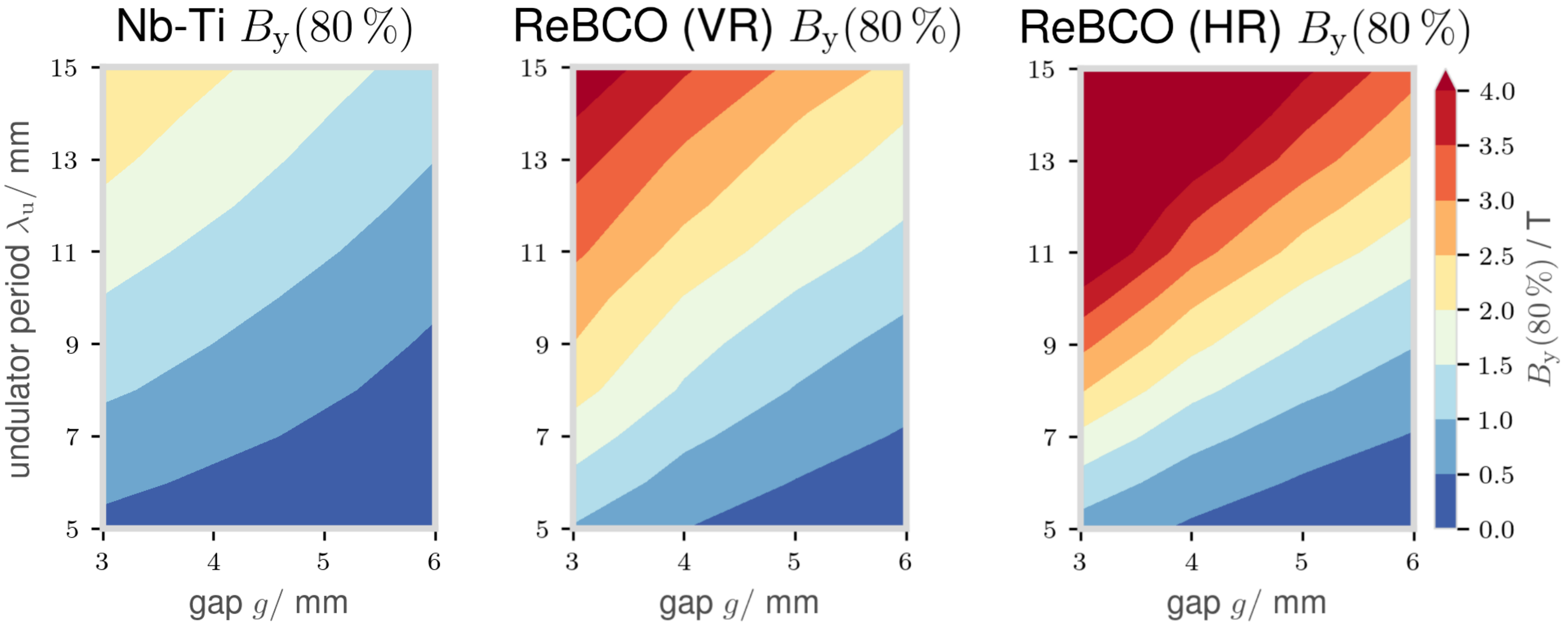
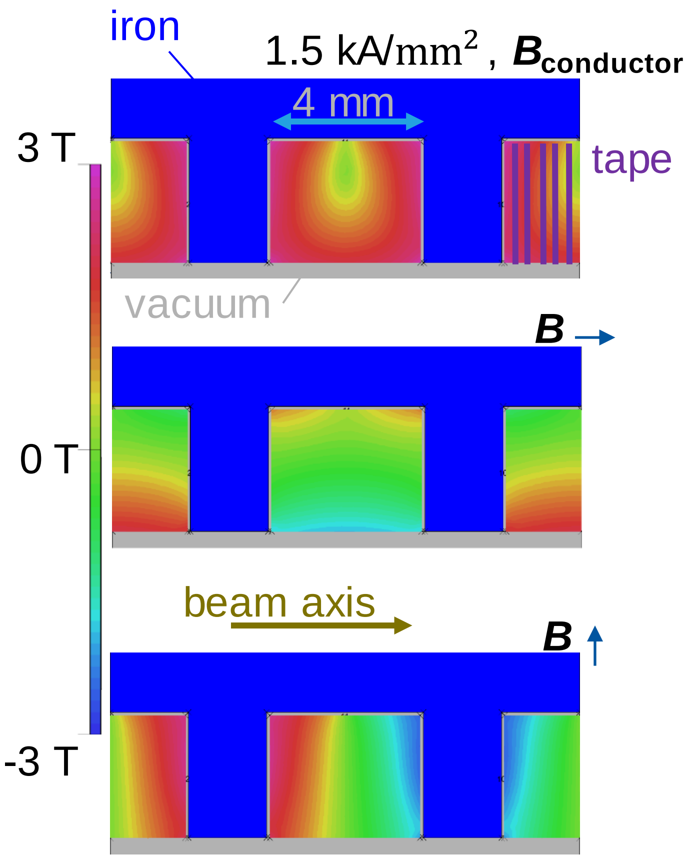
Motivation: 2D e/m-simulations



F. Nguyen *et al.* "XLS - D5.1: Technologies for the CompactLight Undulator" (2019), doi: 10.5281/zenodo.5024409



Example:
HR, 13 mm period, 6 mm gap

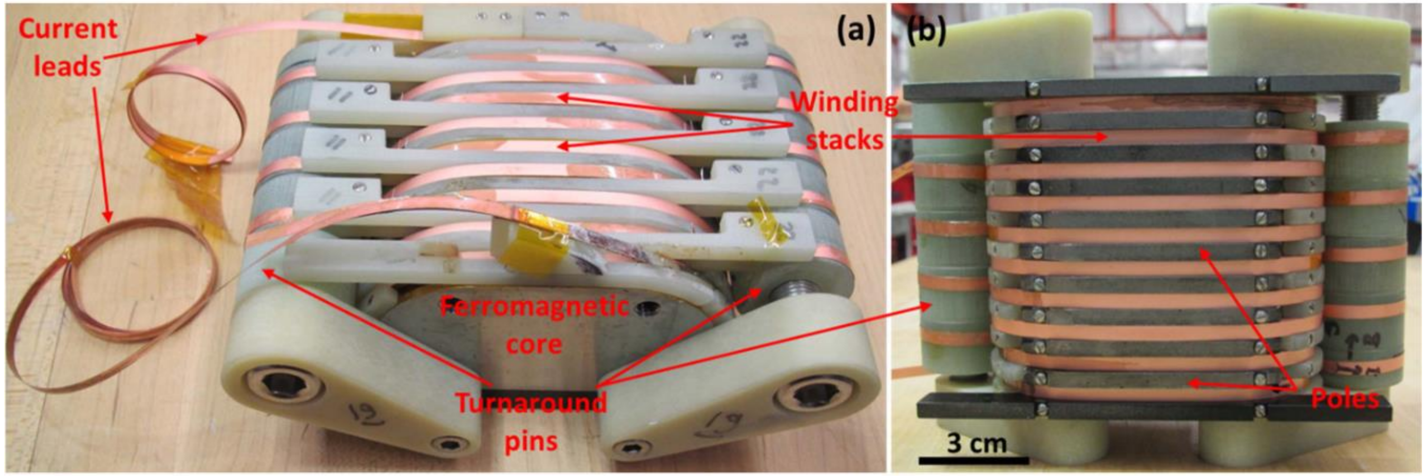
- Potential:
  - B-field amplitudes B_y ~ 2 T for λ_u ~ 13 mm feasible.

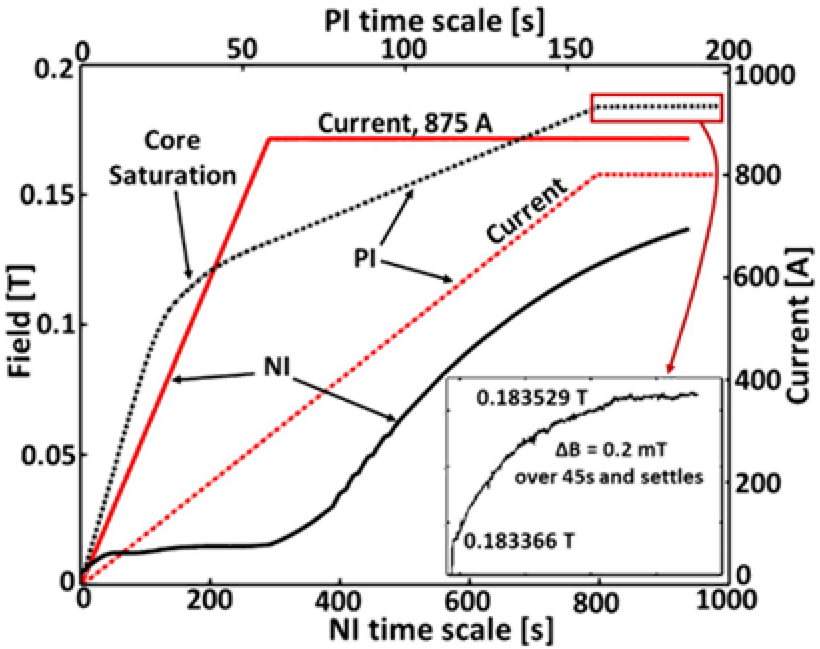
⇒ **Hard X-ray FEL** (λ < 1 nm)

Other HTS undulator approaches (I)

I. Kesgin *et al.*

- Continuous ReBCO tape winding (4 mm width, 95 µm thick),
- Non-insulated and partial-insulated jointless winding with U-turns:
  - Mirror-model with all VR coils wound from one tape,
  - $B_y \approx 1$ T for $\lambda_u = 16$ mm, g = 9.5 mm (I_{op}= 800 A → $J_{op} \approx 2.1$ kA/mm^2).





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

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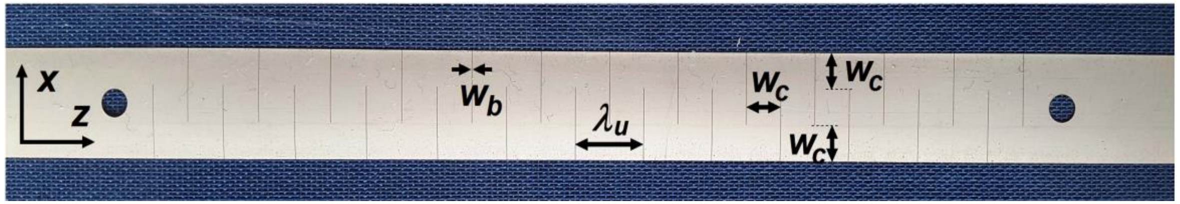
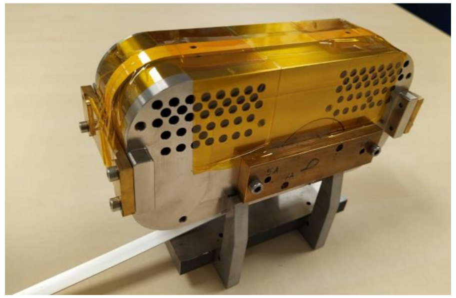
Karlsruher Institut für Technologie

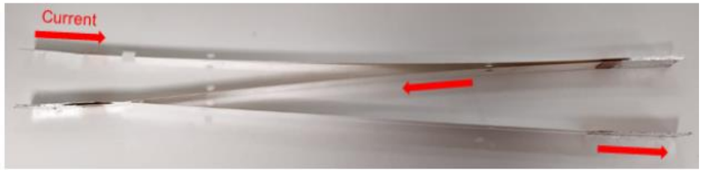
Other HTS undulator approaches (II)

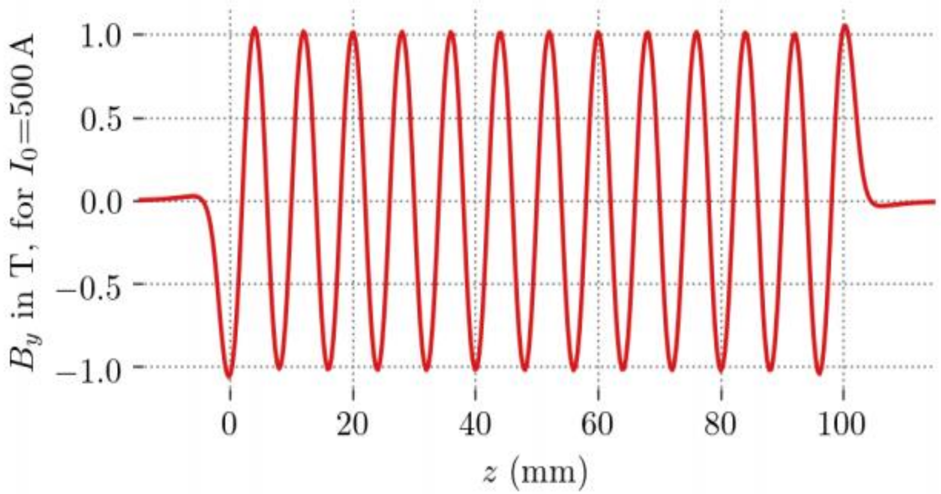
T. Holubek *et al.* and A. Will *et al.*

- 30 layers of laser-structured ReBCO tapes (12 mm width, 55 µm thick),
- Non-insulated jointless winding or soldered-stacked design:
  - The structure in each tape forces the current on a defined path,
  - $B_y = 1$ T for $\lambda_u = 8$ mm, g = 4 mm ($I_{op} = 500$ A $\rightarrow J_{op} \approx 2.2$ kA/mm^2).









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 Concepts of a Compact Undulator with Laser-Structured 2G-HTS Tapes" (2021), doi: 10.18429/JACoW-IPAC2021-THPAB048.

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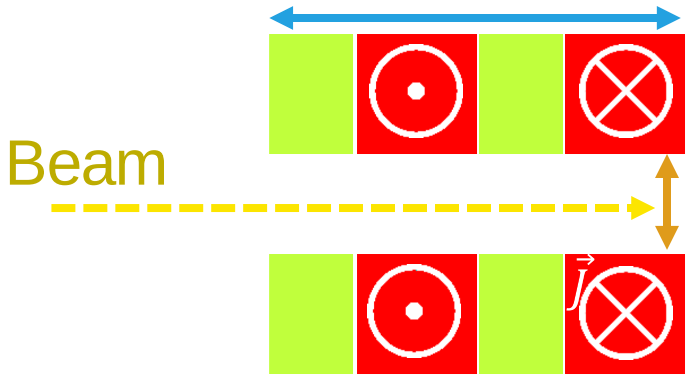
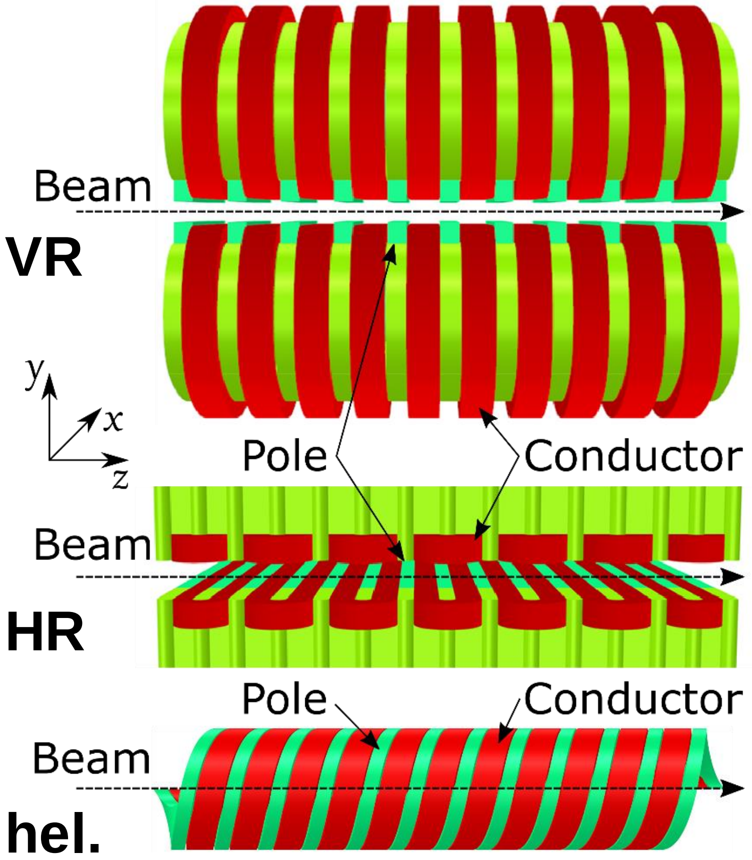
About the Project

- Investigation of 3 prototype coils:
  - Vertical racetrack (**VR**), — today
  - ~~Horizontal racetrack (**HR**),~~
  - Helical undulator (**hel.**).
- Non-insulated for quench protection.

λ_u = 13 mm
g = 6 mm





- Further investigations on bending radii < 5 mm.

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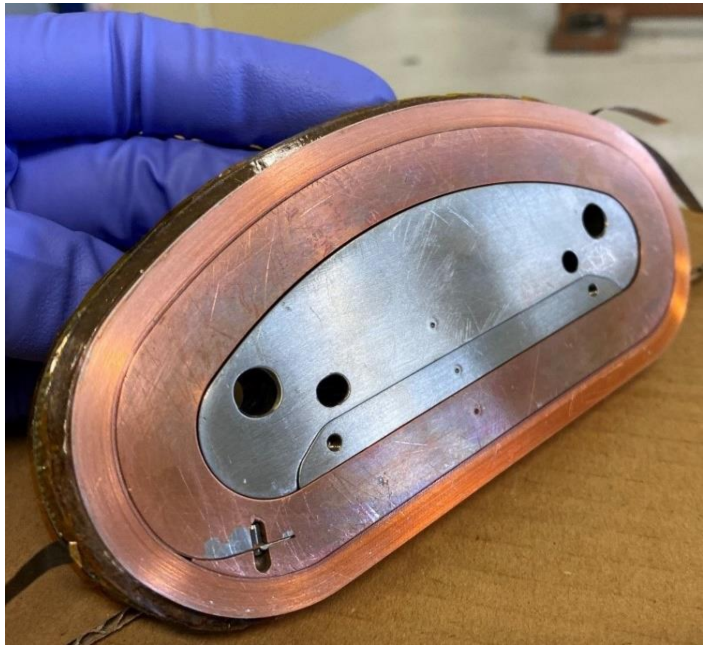

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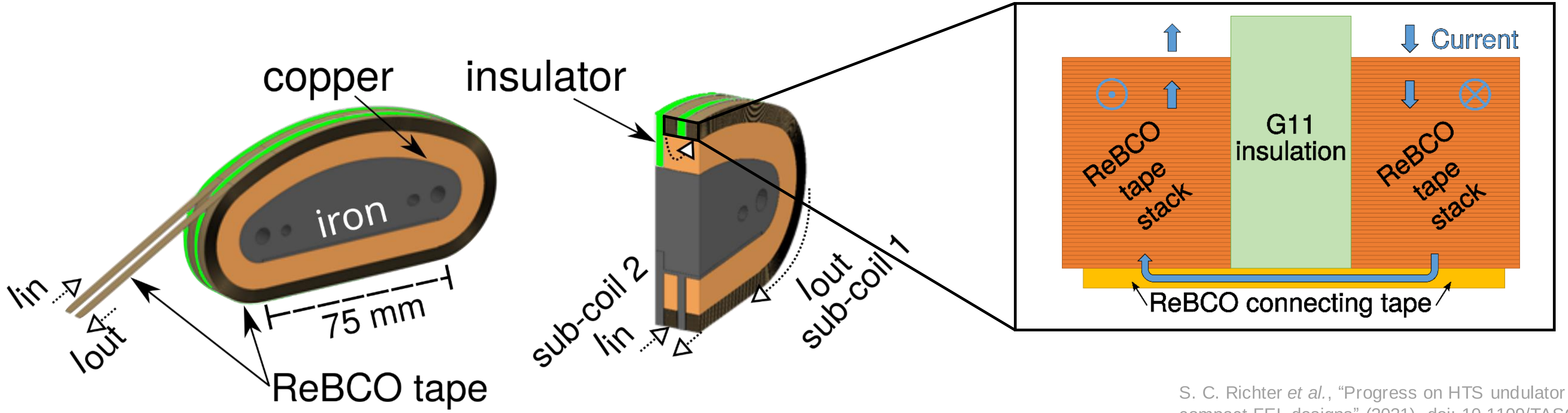
VR Undulator Coil: design

- Two non-insulated sub-coils with opposite current direction on the same winding body, separated by an insulator.
- Innermost turns of both sub-coils are soldered along the curved side to a 10 mm wide coated ReBCO tape (main electrical connection).
  - *Current flow*: sub-coil 1, spiral to its center, bridge to sub-coil 2, spiral out.



S. C. Richter *et al.*, “Progress on HTS undulator prototype coils for compact FEL designs” (2021), doi: 10.1109/TASC.2022.3150288.

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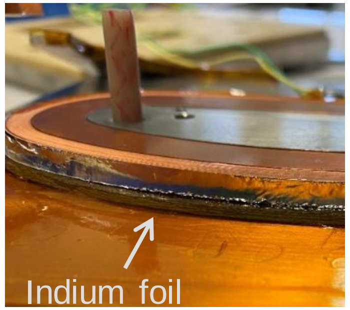
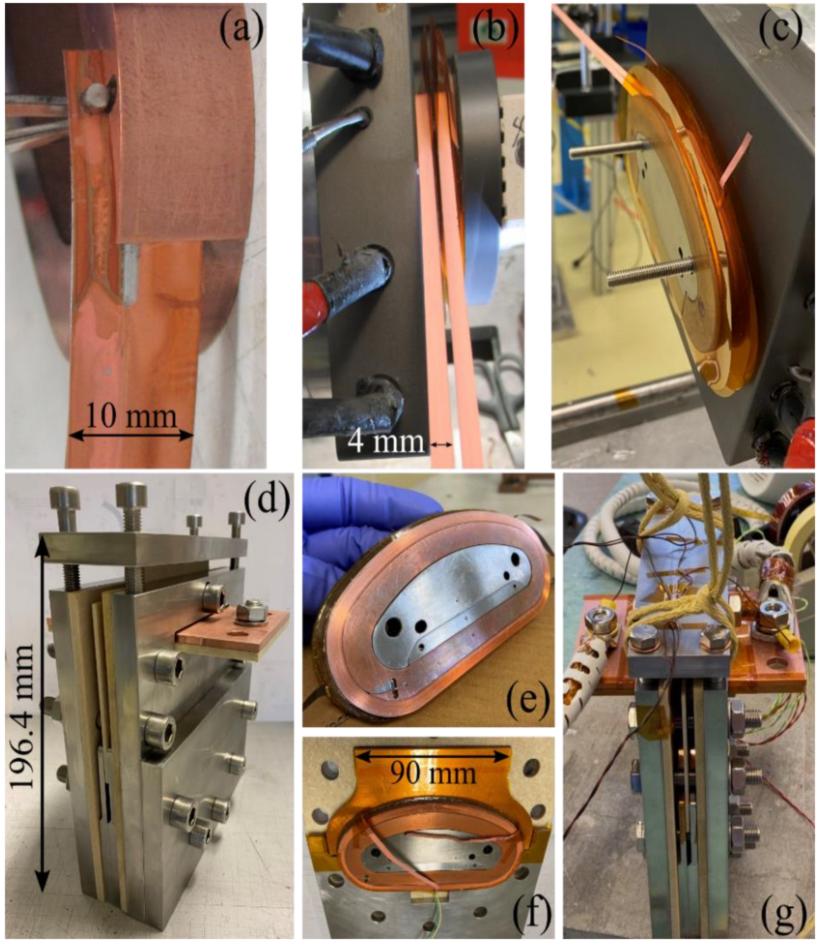
VR Undulator Coil: manufacturing

- 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).





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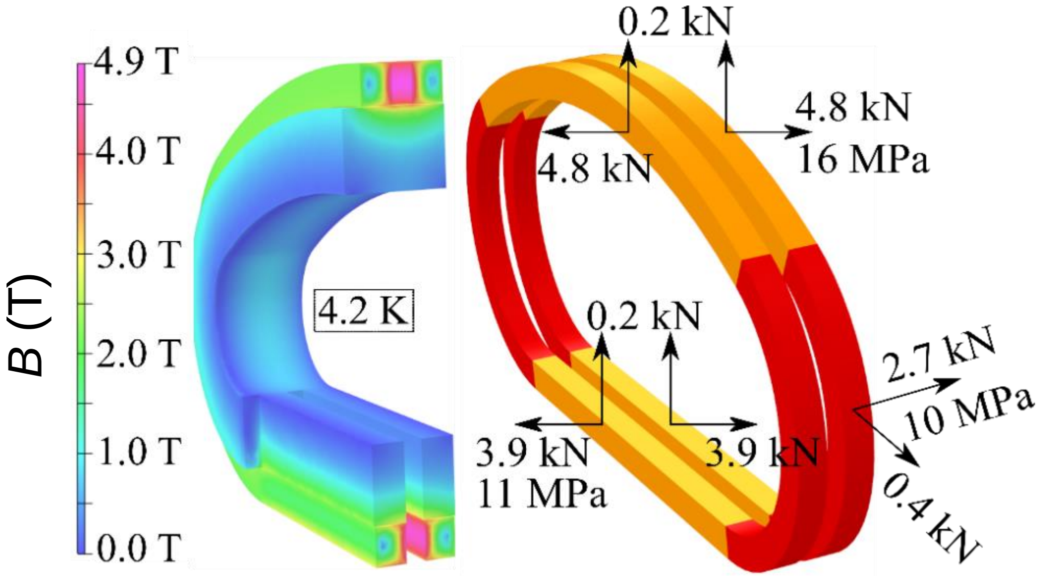
VR Undulator Coil: 3D modelling

- J_c was defined by considering the worst-case scenario:
  the max. magnetic field on the conductor B_{cond} perpendicular to the tape plane,
  - At 4.2 K: max. $B_{\perp} \approx 99.95\% \, B_{cond}$.



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

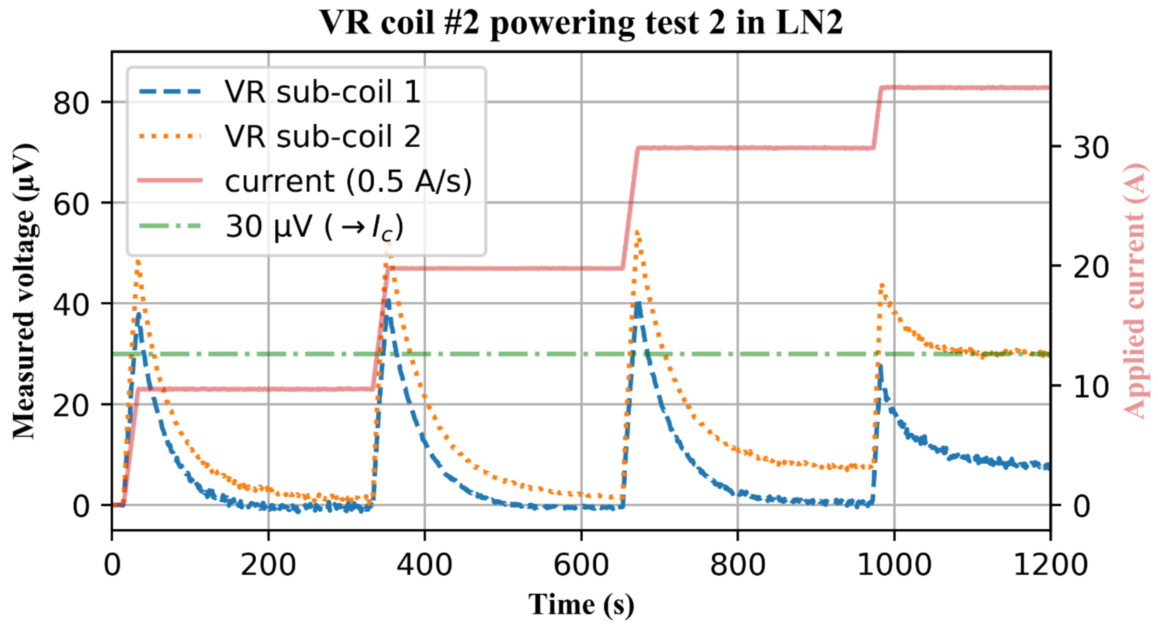
	VR coil #2	VR coil #3
Undulator period λ_u	13 mm	
Sub-coil x-section	4 mm × 5 mm	4 mm × 4.6 mm
HTS conductor	Bruker HTS	SuperPower
with dimensions	4 mm x 100 μm	4 mm x 45 μm
Number of turns	51	102
$J_{op, sim}$ (4.9 T, 4.2 K)	2071 A/mm^2	2222 A/mm^2
$I_{op, sim}$ (4.9 T, 4.2 K)	828 A	400 A
$B_{y,1}(I_{c,sim}$,d = 3.5 mm)	1.38 T	1.24 T

Opera 2020
Based on the Biot–Savart law

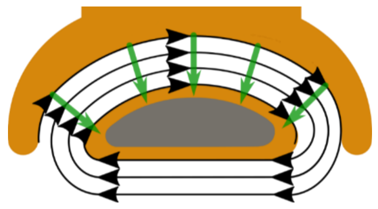
S. C. Richter *et al.*, "Progress on HTS undulator prototype coils for compact FEL designs" (2021), doi: 10.1109/TASC.2022.3150288.

VR Undulator Coil: signal tests at 77 K (LN2)

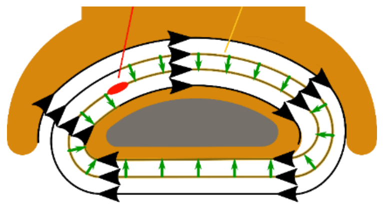
- current ramping with 0.05 A/s and 0.5 A/s until a drift in voltage was measured.
- With an outermost turn length of 30 cm:
  - I_c(30 µV) ↔ E_c=1 µV/cm

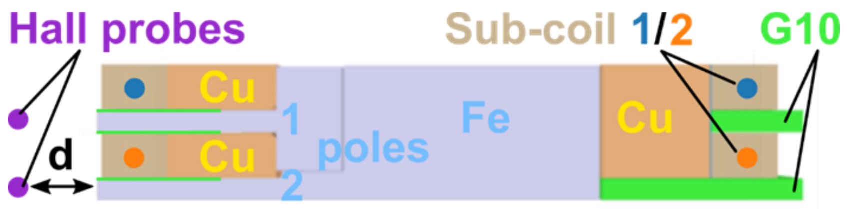


charging:
transversal current



hotspot heating





S. C. Richter *et al.*, "Powering Test Results of HTS Undulator Coils at 77 K for Compact FEL Designs" (2022), doi: 10.18429/JACoW-IPAC2022-THPOPT058.

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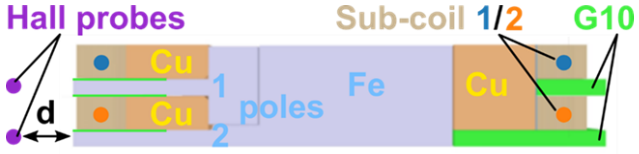
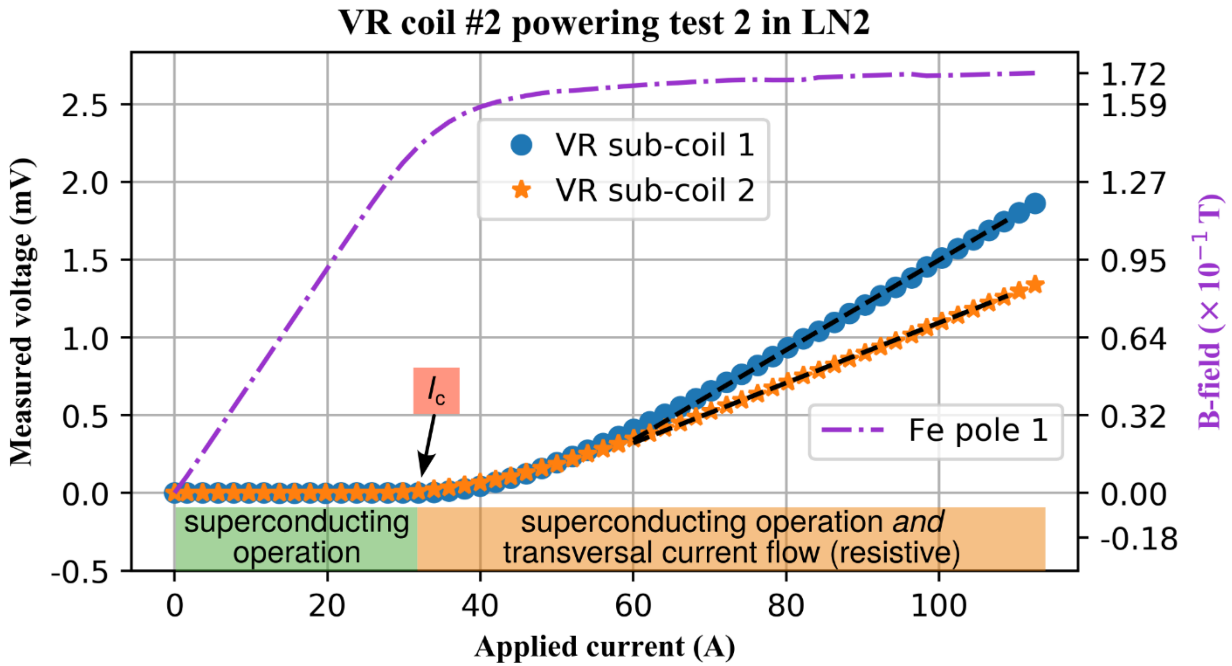
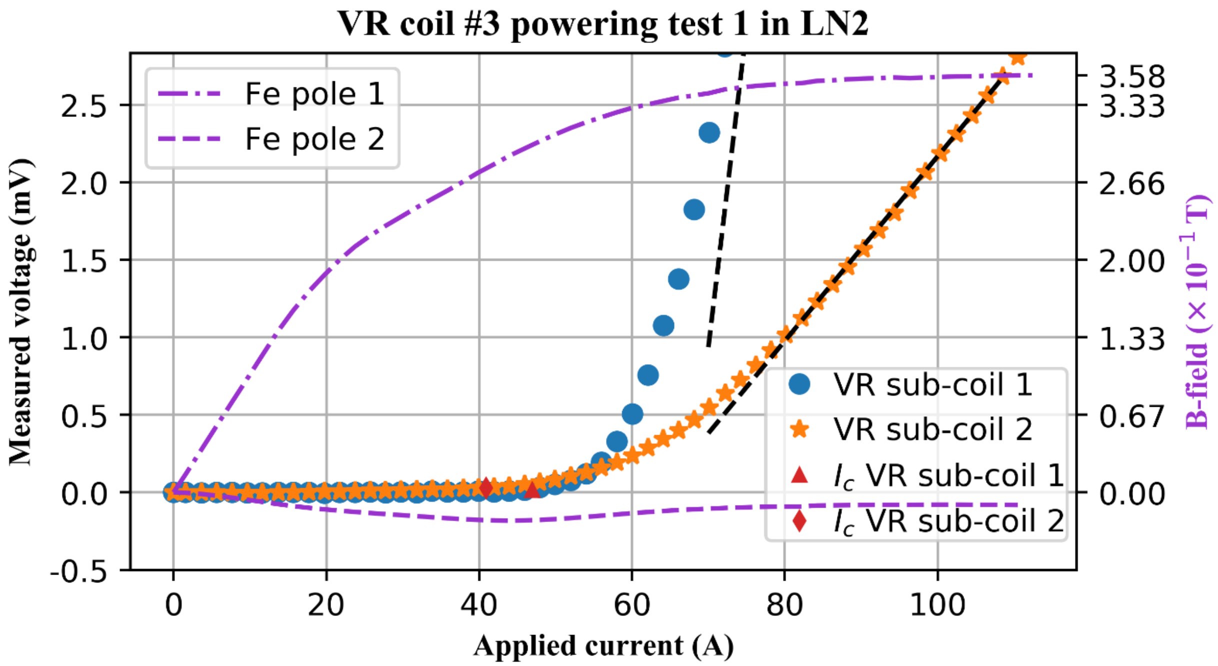
VR Undulator Coil: signal tests at 77 K (LN2)

- Current steps of 2 A with a 300 s decay time
  - up to ≈ 300% I_c
- For I > 80 A all sub-coils showed a stable resistance R_t .







S. C. Richter *et al.*, "Powering Test Results of HTS Undulator Coils at 77 K for Compact FEL Designs" (2022), doi: 10.18429/JACoW-IPAC2022-THPOPT058.

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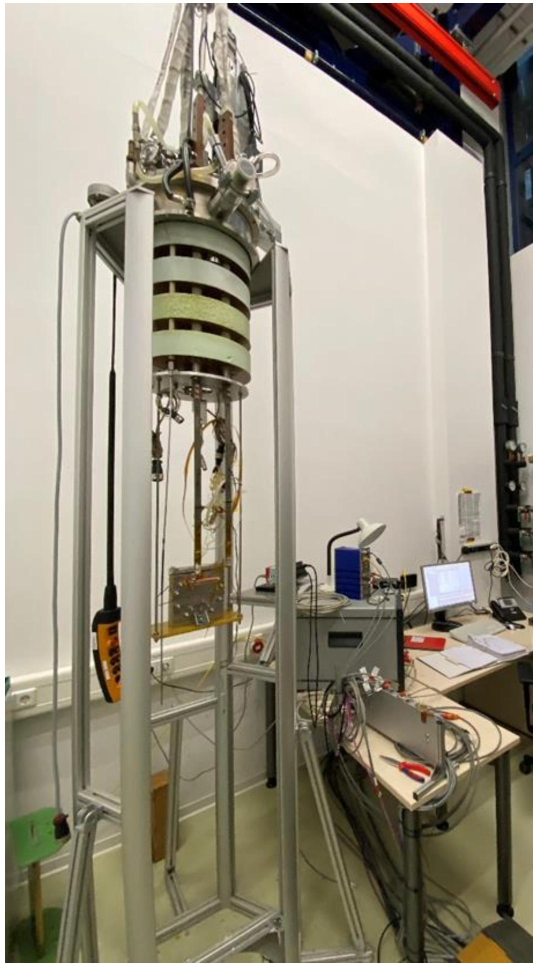
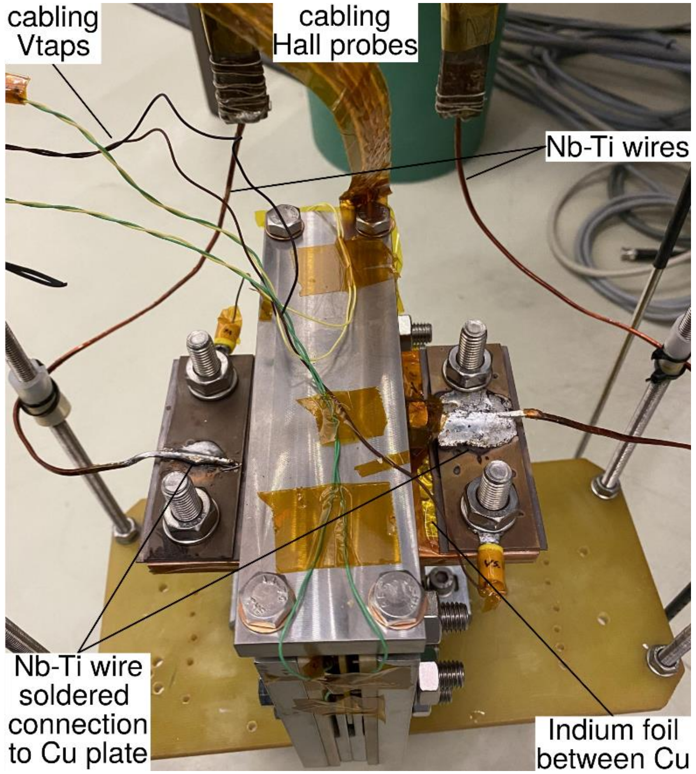
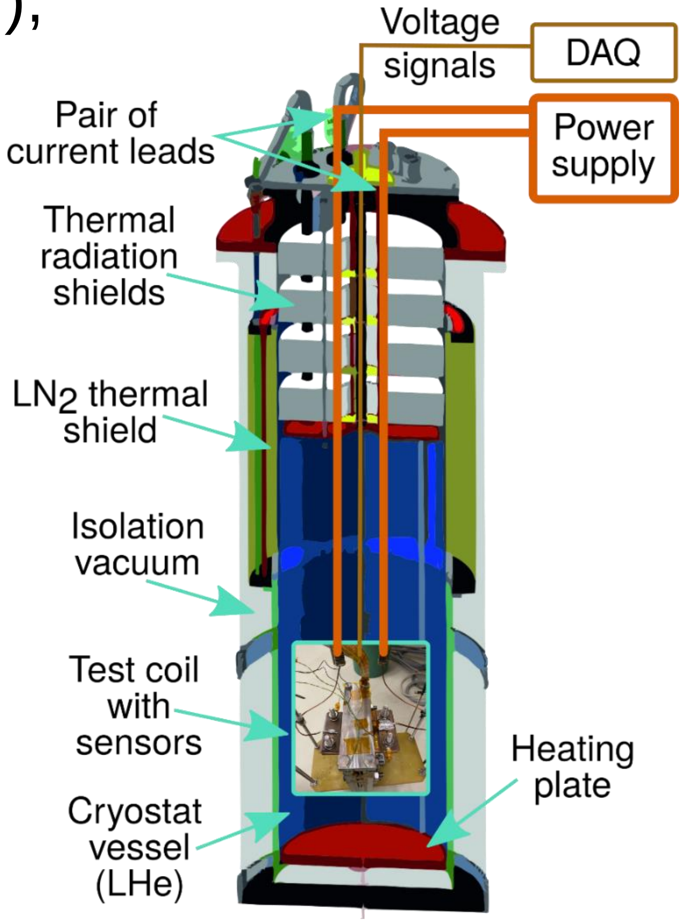


VR Undulator Coil: LHe setup

- CASPER I* test station with liquid helium cryostat (at KIT),
  - Current: 1500 A / ±5 V and 500 A / ±5 V power supplies,
  - Quench detector for coil protection,
    - 1 mV (later 4 mV),
    - 10 Hz DAQ time.



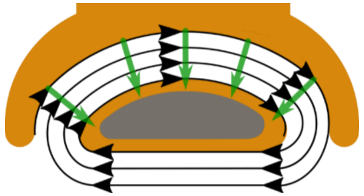


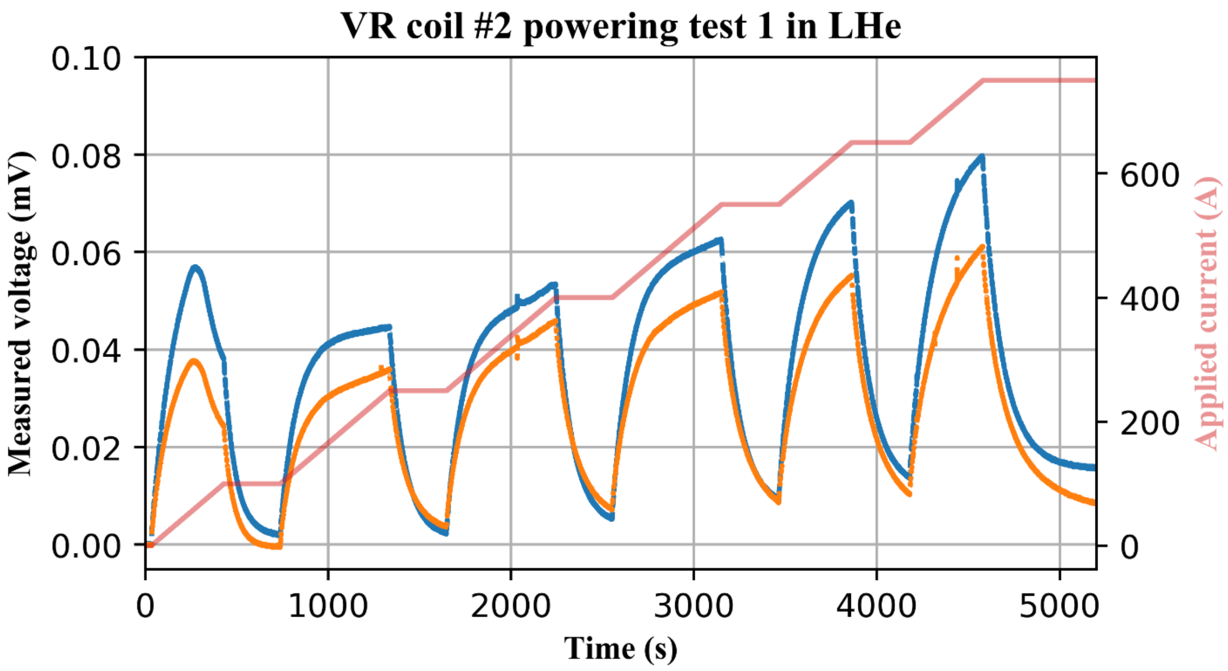
* E. M. Mashkina *et al.*, "Magnetic Measurement Device for Superconductive Undulator Mock-up Coils at ANKA" (2008), WEPC121 in Proc. EPAC'08, paper WEPC121 (2008).

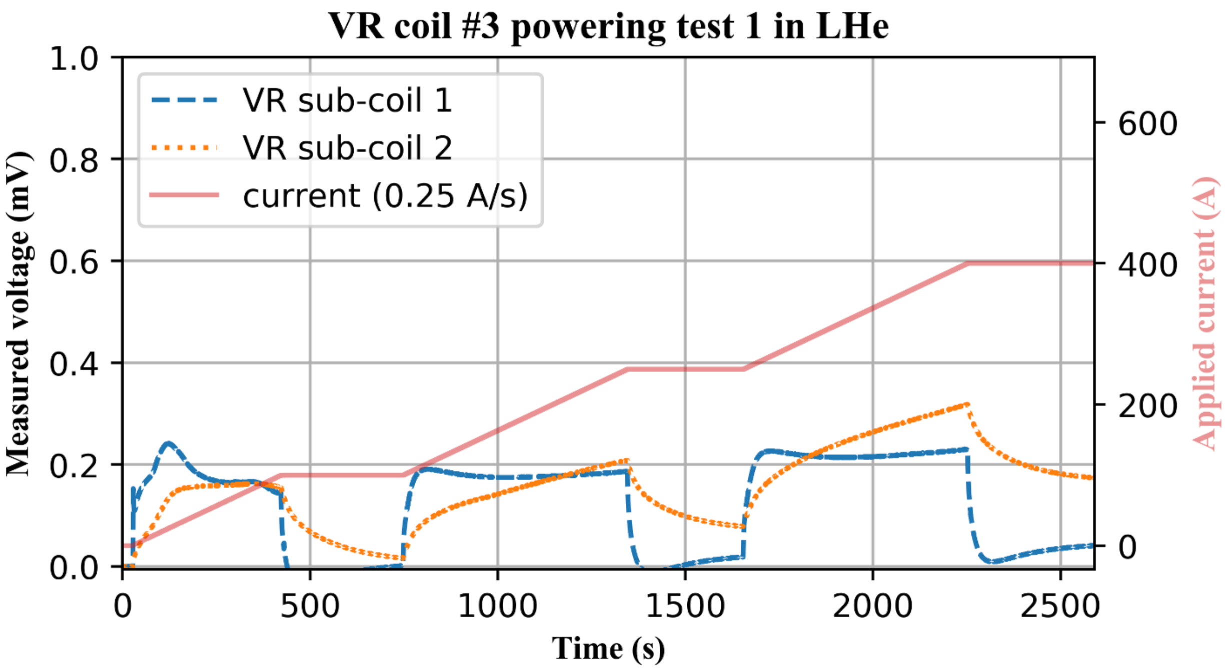
VR Undulator Coil: powering in LHe

1) Current ramping with 0.25 A/s
   - Voltage peaks,
   - drifts in decayed voltage.

charging:
transversal current





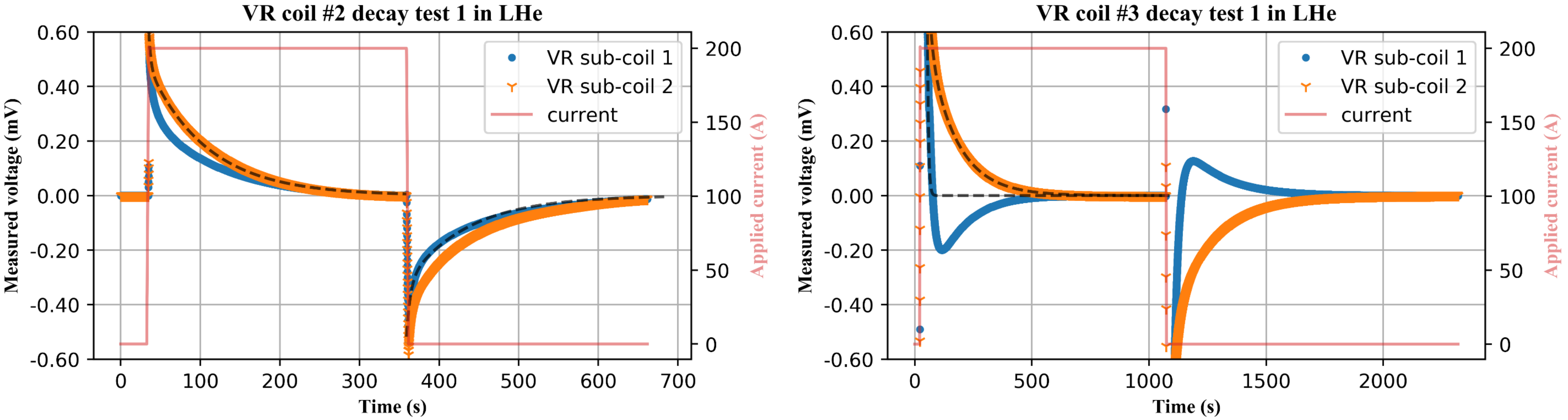


VR Undulator Coil: powering in LHe

2) Effective time constant τ:

- Current step function (0 A - 200 A),
- Measure voltage decay over time: $U \approx a \cdot e^{-t/\tau_i} + b \cdot e^{-t/\tau_{avg}}$

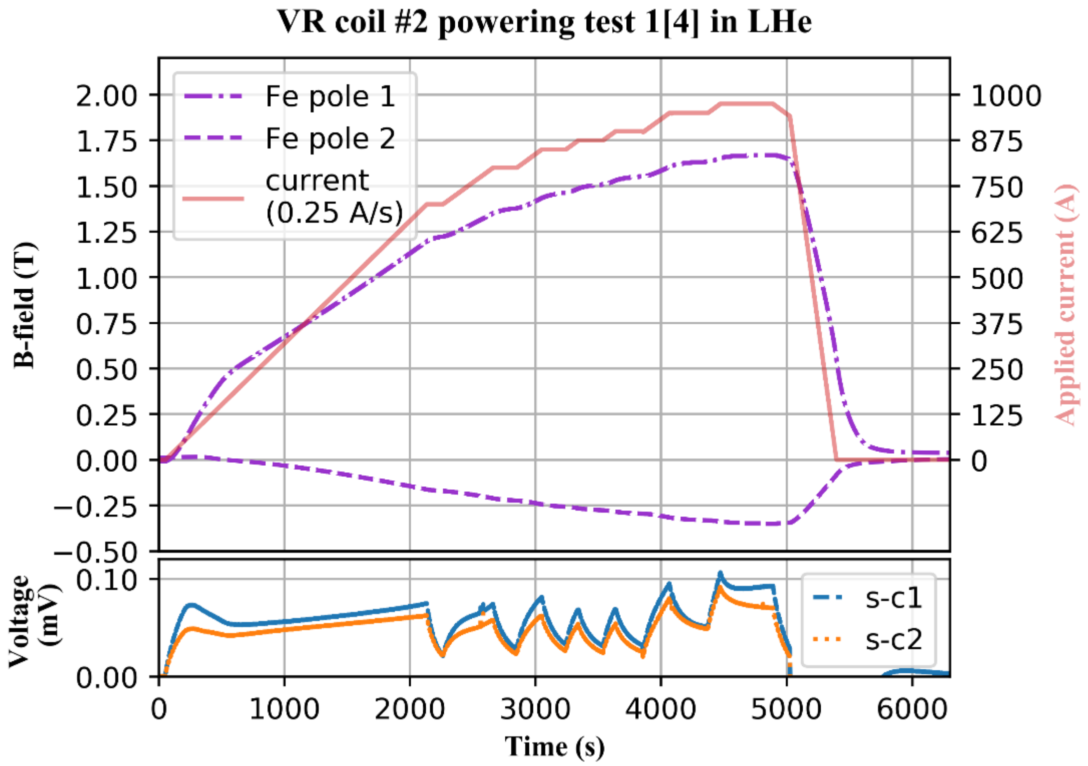
	VR coil #2		VR coil #3	
τ	76 s	74 s	(5 s)	121 s

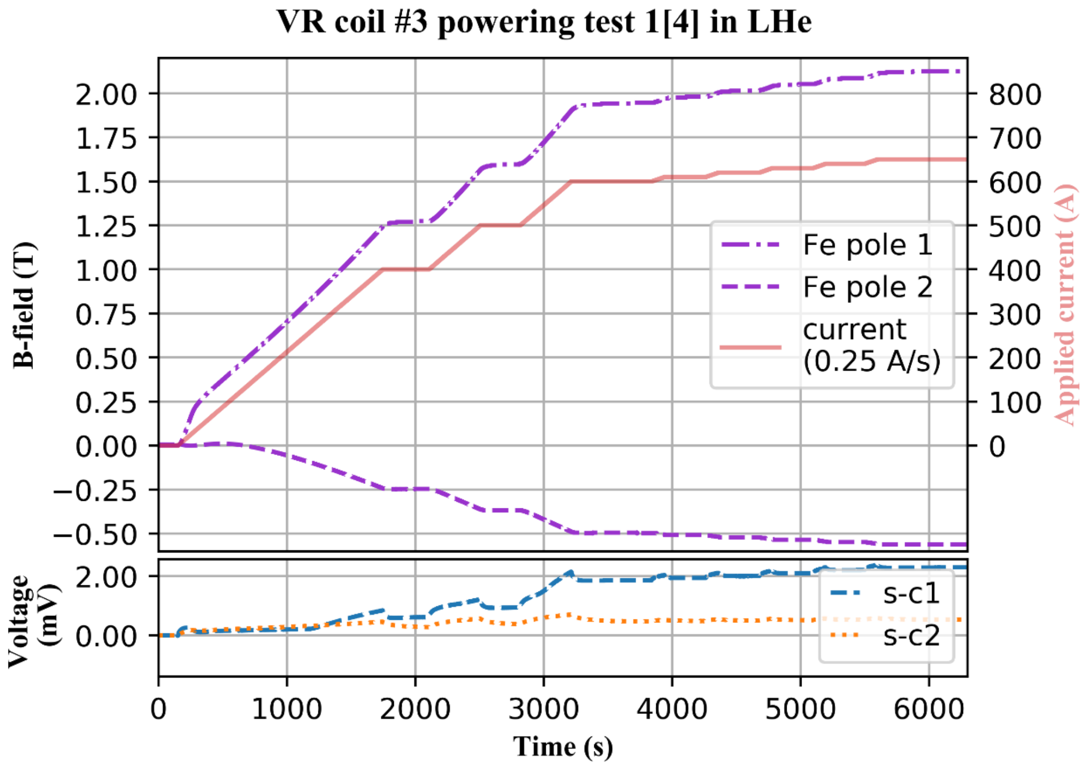


VR Undulator Coil: powering in LHe

3) Magnetic field build-up:
- Hall sensor signal

d = 3.5 mm	VR coil #2 (828 A)	VR coil #3 (400 A)
$B_{y,1}(I_{c,sim})$	1.38 T	1.24 T
$B_{y,1}(I_{c,exp})$	1.40 T	1.26 T





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VR Undulator Coil: powering in LHe

4) Current steps and overflow:

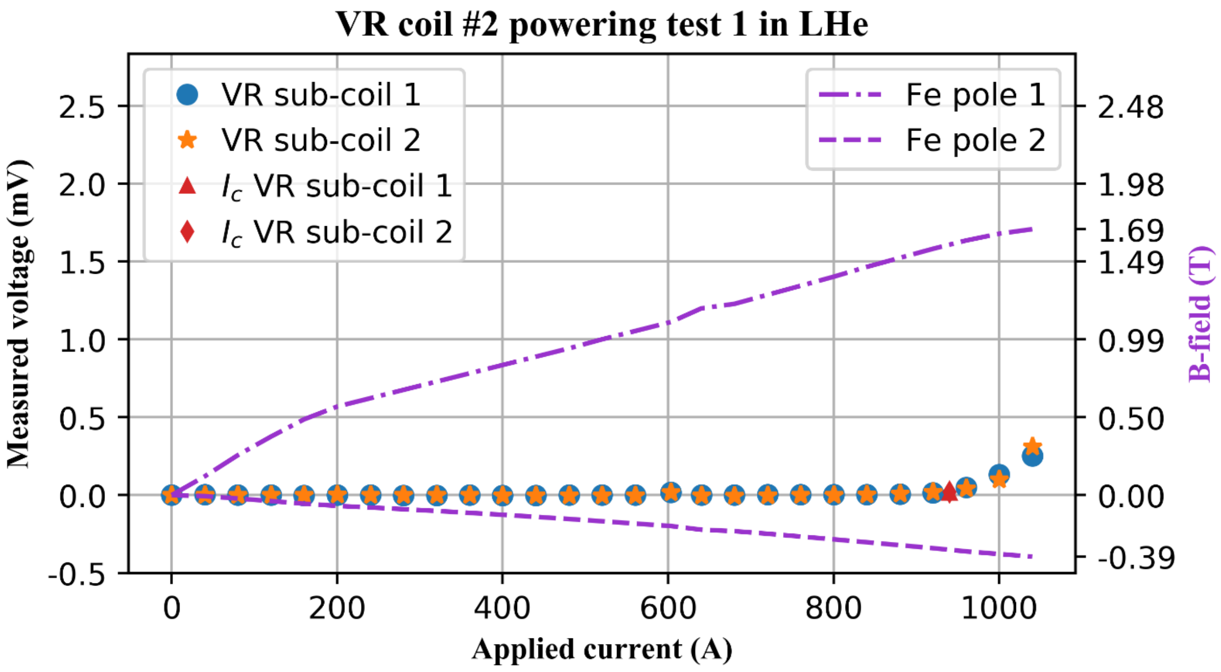
- Current steps of 40 A (VRC#2) and 20 A (VRC#3) with a 300 s decay time

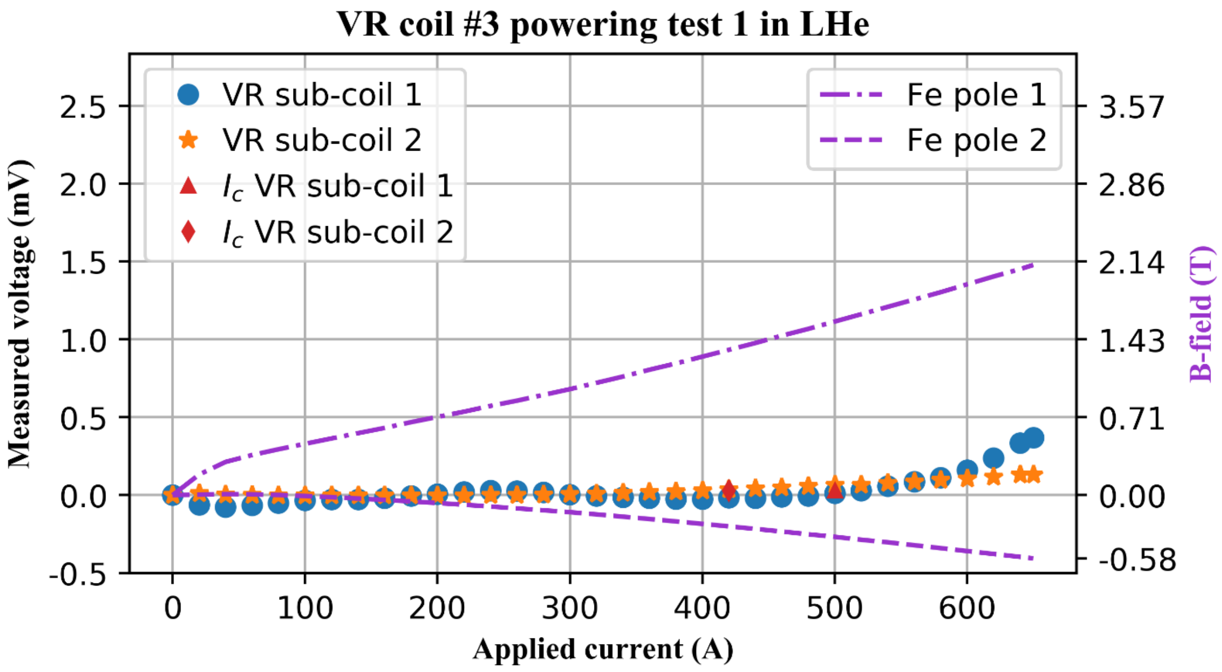
→ ***too short*** and ***30 µV too conservative for 30 m of tape?***

I_c	930 A	930 A

→ ≈ 2.3 kA/mm² ←

I_c	500 A	420 A

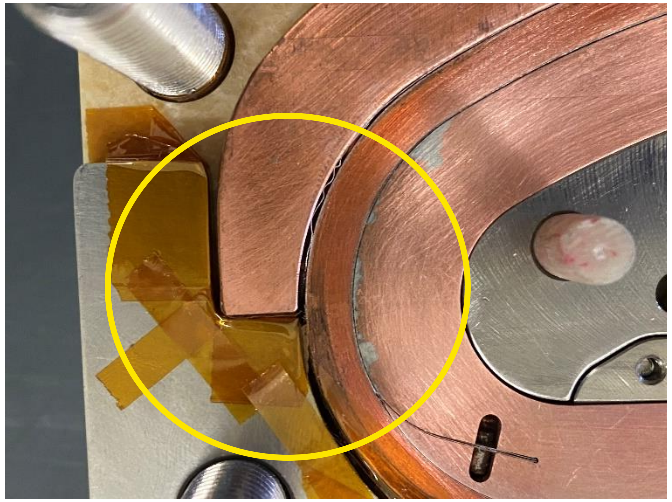


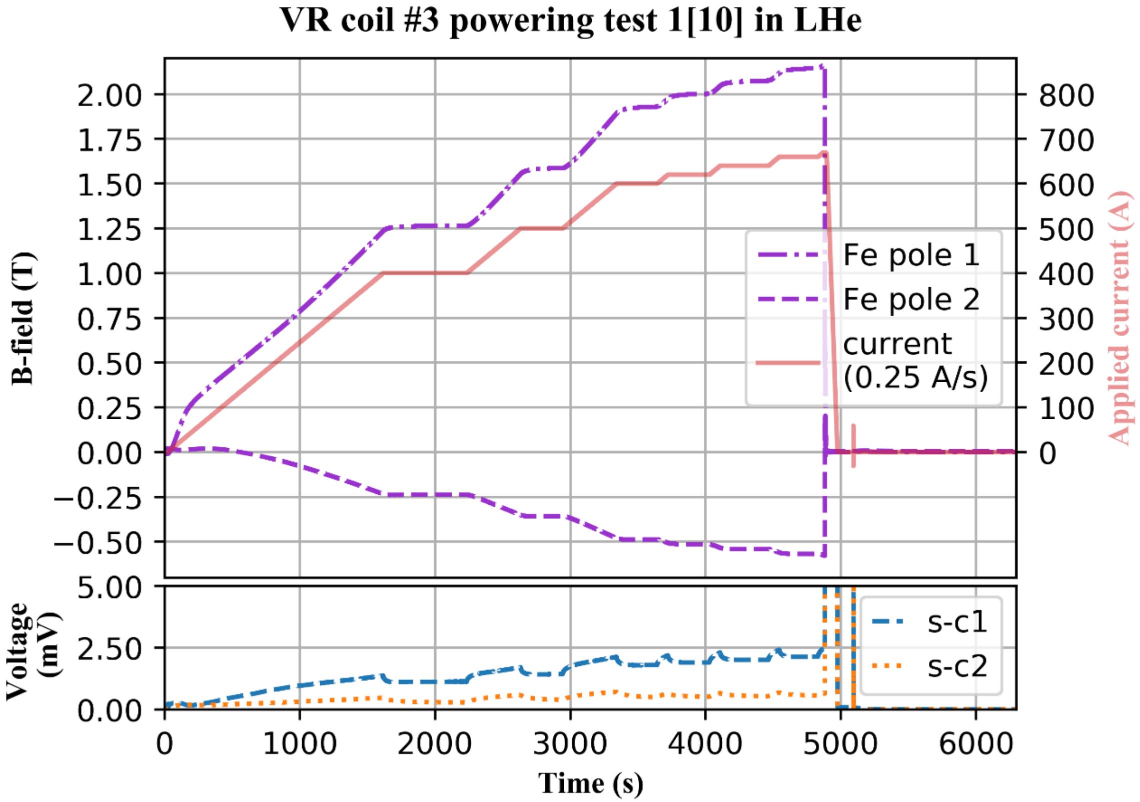


VR Undulator Coil: powering in LHe

5) Overflow and quench

- Current steps continued until *U* runaway.
- VRC#2: no value (defect Nb-Ti current lead),
- VRC#3 at 660 A (~3.6 kA/mm²).





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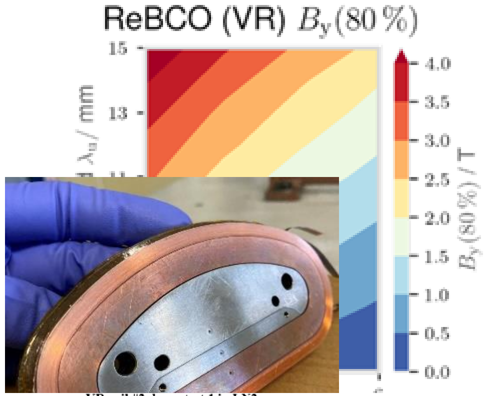
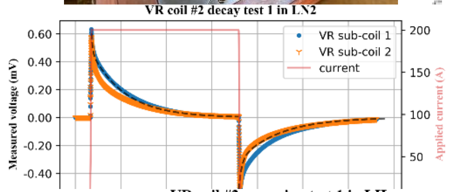
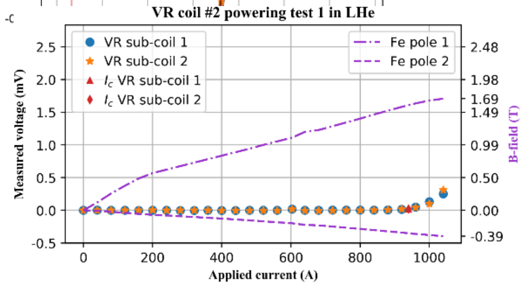
Summary and Conclusion

- The technical potential of HTS for undulators has been demonstrated.
- 3 VR prototype coils were manufactured and tested in LN2 and 2 in LHe.
  - Simulations matched the experiment,
  - Stable operation at the designed current,
  - Stable up to I_c and beyond without any degradation,
  - Tunable undulators may be challenging without metal/partial insulation.







Next steps:

- Controlled turn-to-turn resistance:
  - Higher resistance is preferred at 4.2 K.
- Investigation of
  - Mechanical margins,
  - Field quality (+ ramping),
  - Beam tracking.

Future plans:

- 3 VR coil short model,
- Manufacture the world's first ReBCO tape helical undulator (demonstrator).

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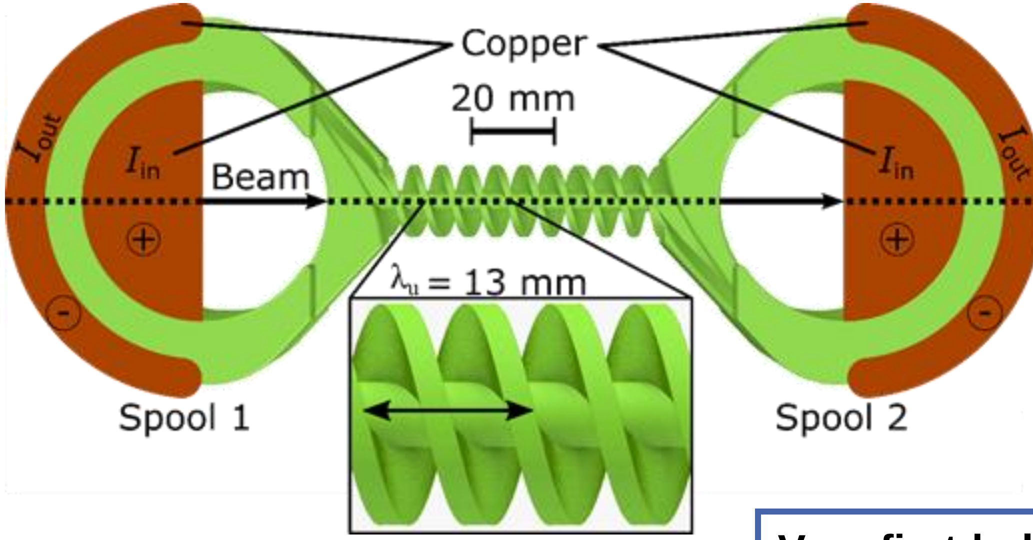
What's next?
Appetizer: helical HTS undulator

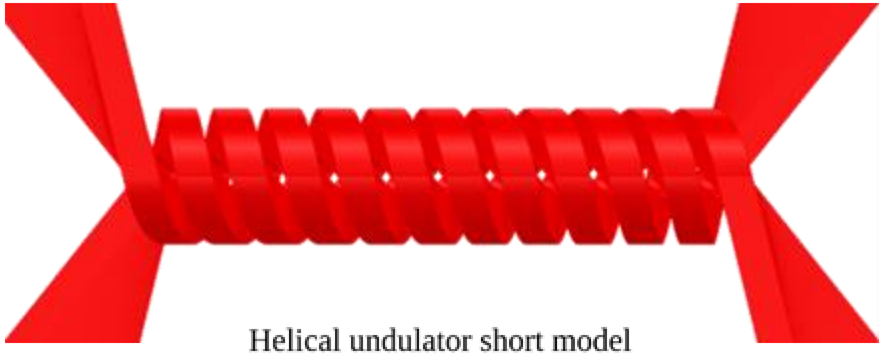
Why a helical undulator?

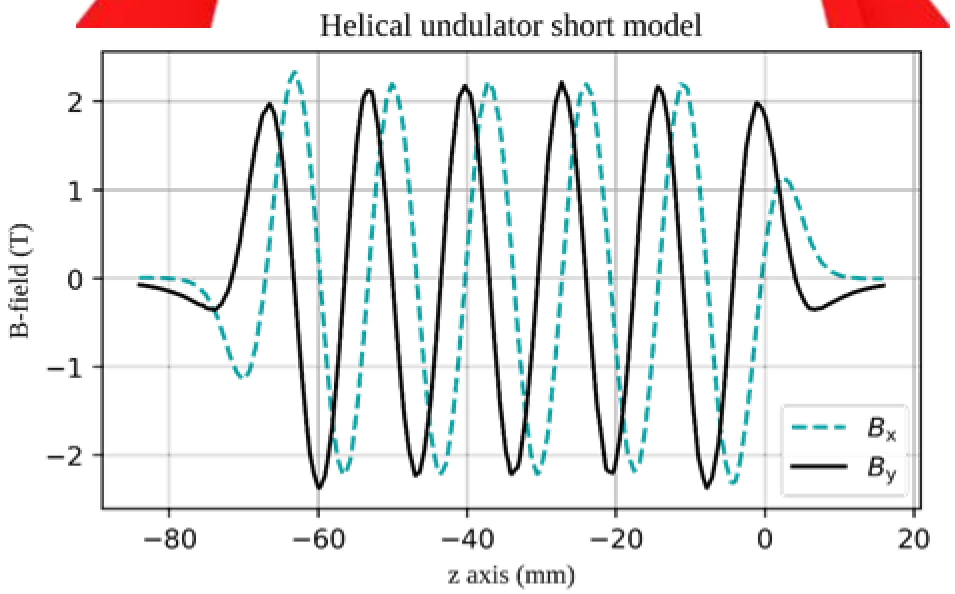
→ *More compact and efficient!*

- $B_y \geq 2.3$ T for $\lambda_u = 13$ mm, g = 5 mm,
- Wound with 4 mm wide ReBCO tape.



S. C. Richter *et al.*, "Status of a Prototype HTS Helical Undulator Coil for Compact FELs", IPAC'22 (2022), doi: 10.13140/RG.2.2.28578.91844.





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

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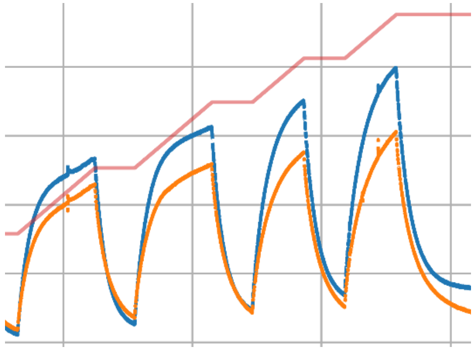

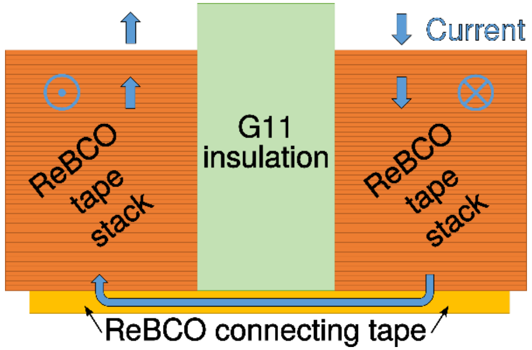

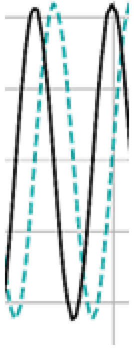

Powering test results of HTS undulator prototype coils for compact FELs at 4.2 K

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Many thanks to D. Schoerling[1], T. H. Nes[1], B. Krasch[2] and N. Glamann[2] as well as to the CERN teams of TE/MSC-SCD and -SMT for their support!

1 CERN

2 KIT Karlsruhe Institute of Technology

* SPONSORED BY THE Federal Ministry of Education and Research

**

This work is supported by:
* The Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 05E15CHA)
** The DFG-funded Doctoral School „Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology“

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