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CORC® conductors with integrated fiberoptics and voltage wires for quench detection

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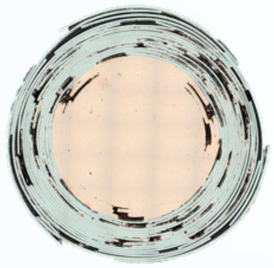
Applied Superconductivity Conference 2020
Wk1LOr2B-06 - Special Session:
Recent Cable Achievements for Fusion Magnets

Conductor-on-Round-Core (CORC®) magnet cables and wires wound from HTS ReBCO tapes



Transverse cross section

	CORC® wires		CORC® cables	
Conductor diameter	2.5 to 4.5 mm		5 to 8 mm	
Min bending radius	> 25 mm		> 50 mm	
Temperature, Field	**4.2 K, 20 T**	**30 K, 8 T**	**4.2 K, 20 T**	**30 K, 8 T**
Current	> 5,000 A	> 3,500 A	> 10,000 A	> 7,500 A
Current density	Up to 450 A/mm^2	Up to 340 A/mm^2	Up to 600 A/mm^2	Up to 450 A/mm^2

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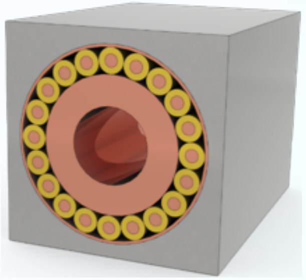


Courtesy of Tim Mulder

	CORC® wires		CORC® cables		CORC® Conductor-in-Conduit (CIC)	
Conductor diameter	2.5 to 4.5 mm		5 to 8 mm		20 to 45 mm	
Min bending radius	> 25 mm		> 50 mm		> 500 mm	
Temperature, Field	**4.2 K, 20 T**	**30 K, 8 T**	**4.2 K, 20 T**	**30 K, 8 T**	**4.2 K, 20 T**	**30 K, 8 T**
Current	> 5,000 A	> 3,500 A	> 10,000 A	> 7,500 A	> 60,000 A	> 45,000 A
Current density	Up to 450 A/mm²	Up to 340 A/mm²	Up to 600 A/mm²	Up to 450 A/mm²	> 50 A/mm²	> 30 A/mm²

Why is quench detection difficult with high-temperature superconductors (HTS)?

HTS is not LTS

Fundamental issues

- Temperature margin is high
- Magnet operation often far from critical surface $T_{opp} << T_c$

(actually good things)

Implications

Quench propagation velocity is (relatively) slow

- Heat capacity @ T_c >> than in LTS
- Non-propagating hot spots can develop
- Burnout?

Solutions?

Active diagnostics

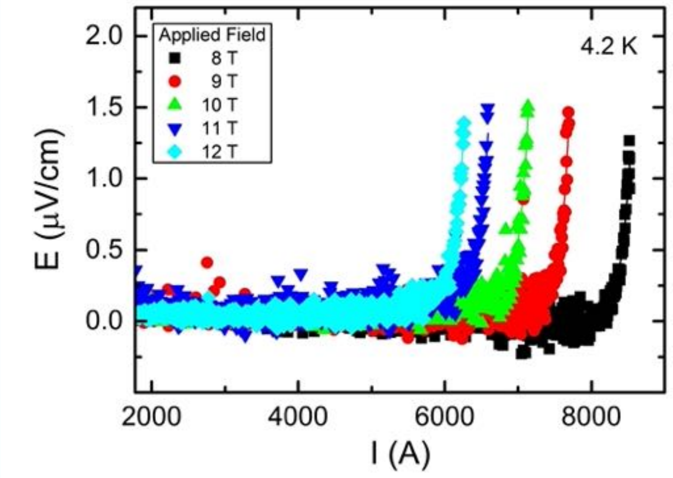
- Sensing electric field perturbations
  - Voltage taps are tried and true, but signals can be hidden by noise
- Sensing temperature/strain perturbations
  - Fiber optics
  - Acoustic thermometry
- Sensing magnetic field perturbations
  - Pickup coils
  - Hall sensors

Magnet protection

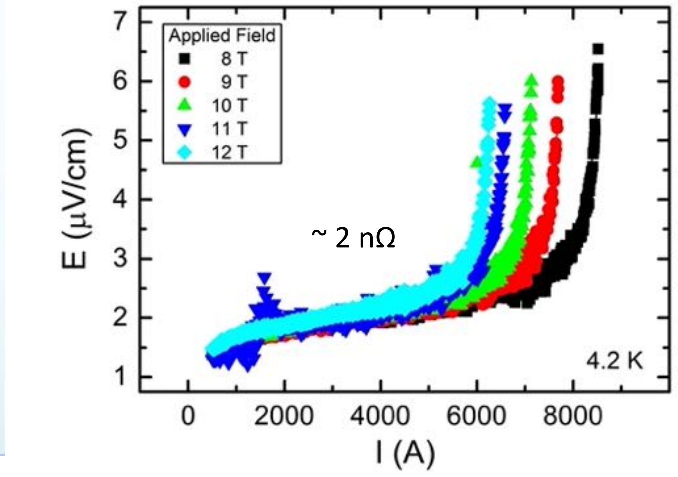
- Traditional protection schemes
  - Dump resistors, coupled inductors, etc
- Spread out the hot spot
  - Active protection (ex quench heaters)
    - Artificially improve quench propagation velocity (requires lots of energy)
  - Passive protection with current sharing
    - Keep voltage across hot-spots in single ReBCO strands low
    - High-currents and low inductance help

Voltage tap quench detection

E measured locally on 3.4 mm CORC® wire



E measured over terminals



V-taps work great for small separation distance, but we need to know where to put voltage taps and how often

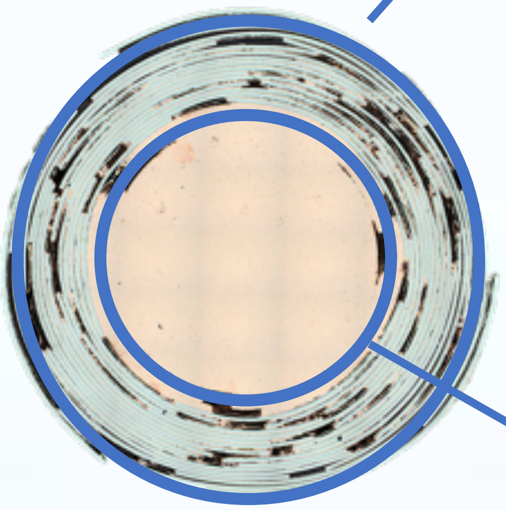
Signal to noise ratio of a localized quench attenuates with length between voltage taps

Measuring a coil is tricky because the large inductance of the coil makes voltage measurements very sensitive to small changes in field/current

Voltage tap wire can be co-wound with conductor to cancel out coil inductance, but this can be technically challenging, and any separation creates a loop

Weiss et al. *SUST,* **2020**
https://doi.org/10.1088/1361-6668/ab72c6

Present anatomy of a high Je CORC® wire



Transverse cross section

2 mm wide REBCO Tapes
(60-40% area)

- Hastelloy (51%)
- Copper (17%)
- Void/lubricant (17%)
- CORC® insulation (8%)
- Silver (4%)
- ReBCO (2-3%)

Core / former
(40-60% area)

- Typically OFHC copper
- Could be stronger
- Could be functional

Can we build diagnostic hardware into the CORC® core?

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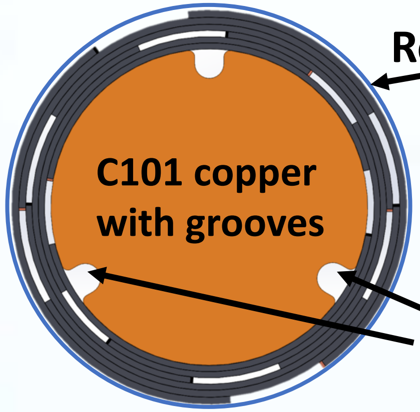
Integrated diagnostics

Smart conductors for complicated times

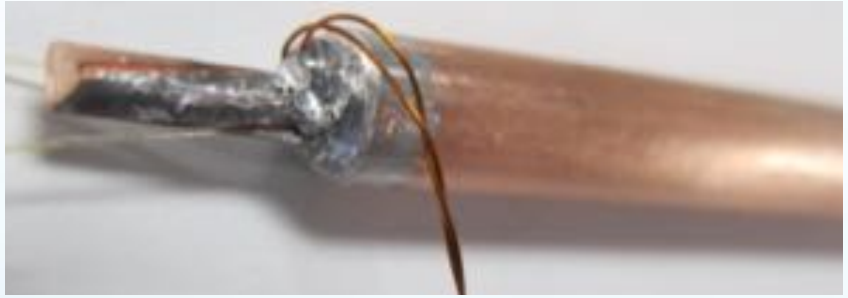
CORC® Wires with integrated diagnostics

Wire cross section



Grooved former allows integrated voltage taps, optical fibers, quench heaters, etc.

Voltage tap exits the CORC wire termination



CORC® Wires with integrated diagnostics

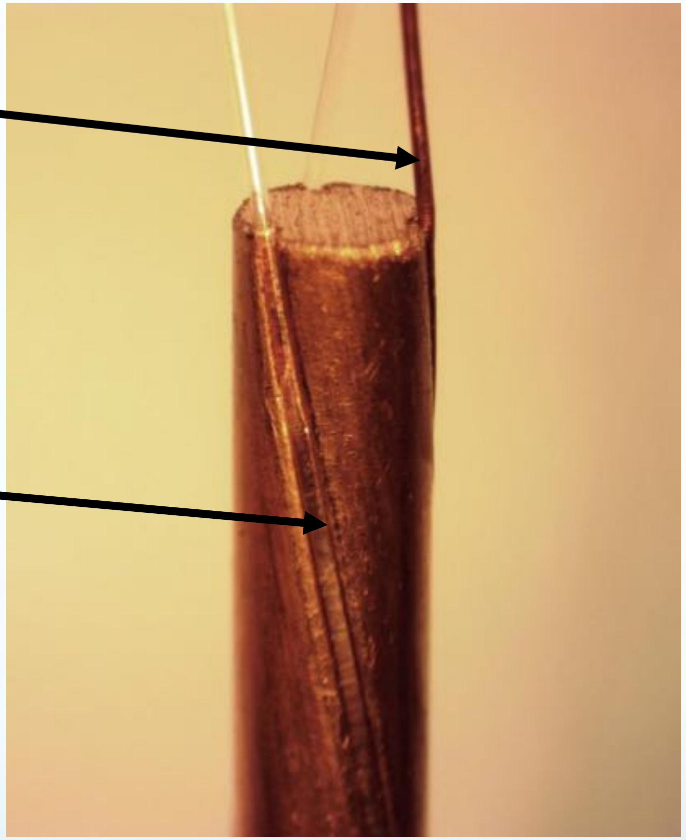
Grooved former allows integrated voltage taps, optical fibers, quench heaters, etc.

Voltage tap wires

- Polyimide insulated wire
- follows the same path as the CORC®
- Is protected by being embedded within the former

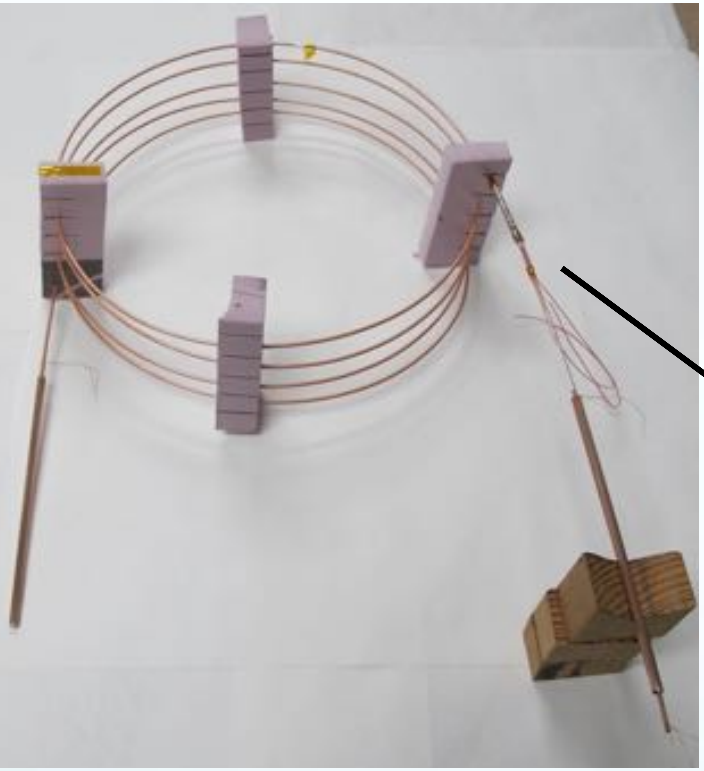
Fiber optic wire

- Uses Rayleigh scattering
- Distributed sensing of changes in strain/temperature along length of conductor
- Intimate contact within conductor



Two CORC® wire samples tested

Long 5 m sample



Short ~0.5 m sample

~5 mm heater

Long sample was tested and then cut into shorter sample to re-test, so heater sections are identical

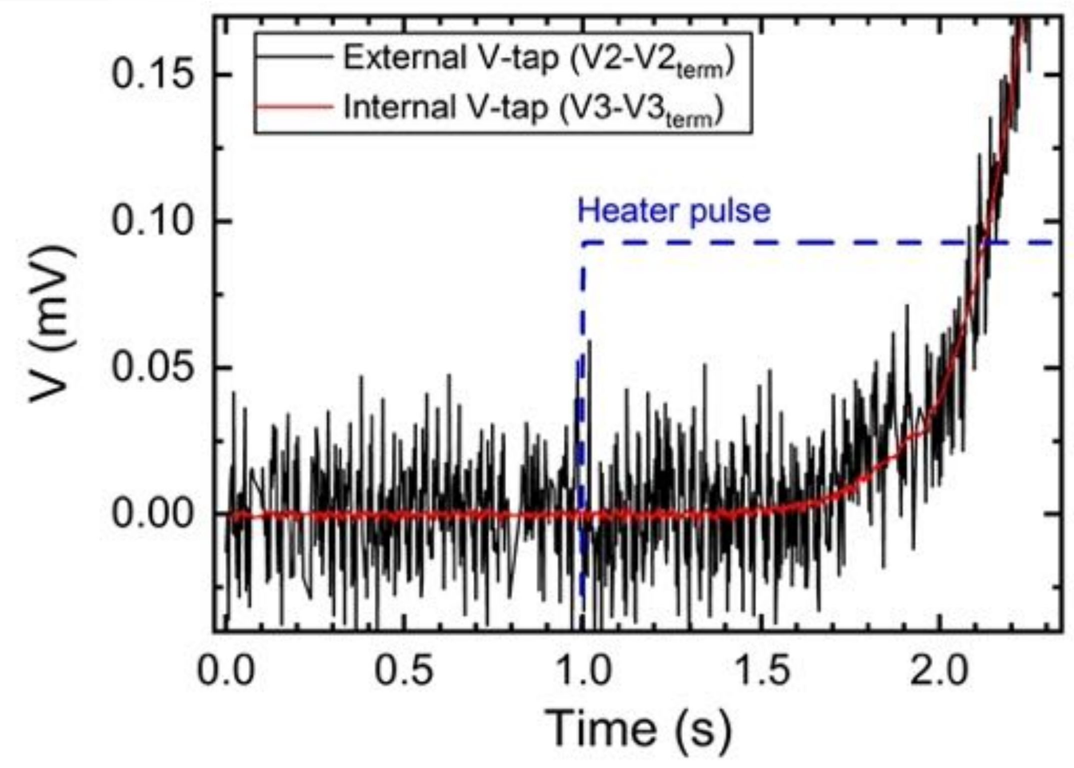
Two heaters:
5 mm long coiled heater
50 mm long strip heater

Voltage measured using external voltage taps, and internal (embedded) voltage taps

Van der Laan et al. **SUST**
https://doi.org/10.1088/1361-6668/ab9ad1

Voltage measured using heater induced hotspot

Voltage measured over the sample terminations



I ~ 350 A (85% of I_c)
76 K

Internal V-Tap wire is tightly confined within CORC® wire following the current-path with almost no separation

Noise is much lower for internal V-Tap compared to external V-tap

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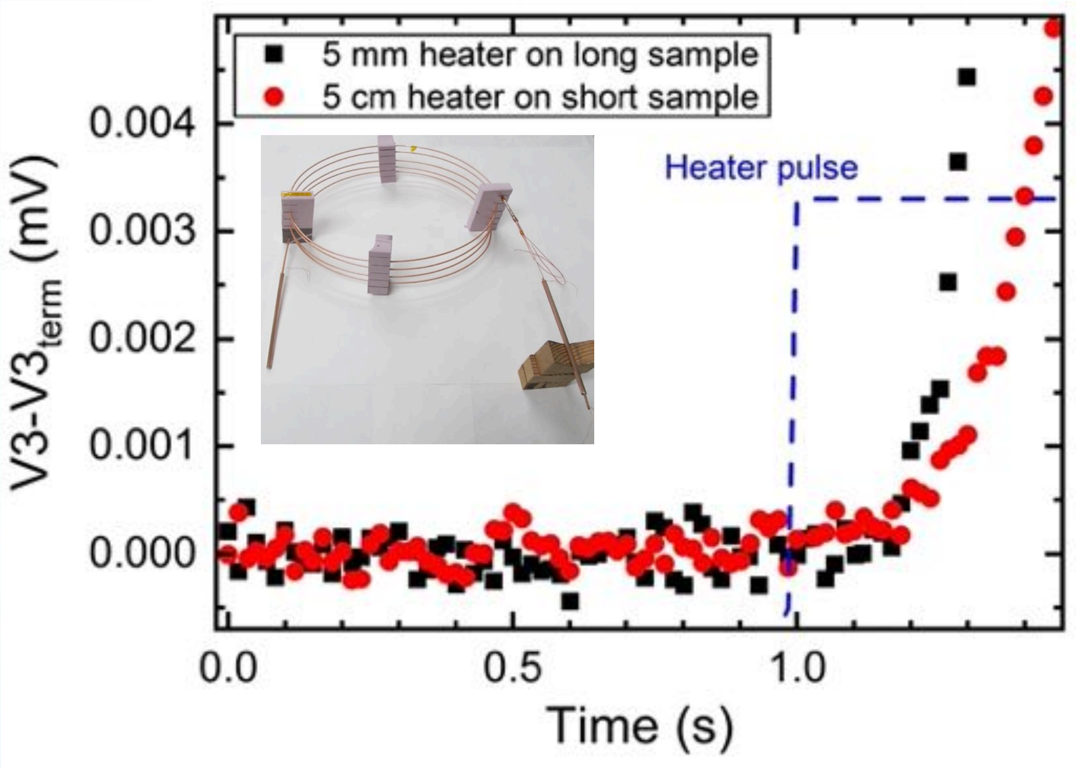

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Internal V-Tap wire is tightly confined within CORC® wire following the current-path with almost no separation

Noise is much lower for internal V-Tap compared to external V-tap

5 m Long sample compared to 0.5 m Long sample show similar noise floor

Very little inductive pick-up, even at very high current ramping

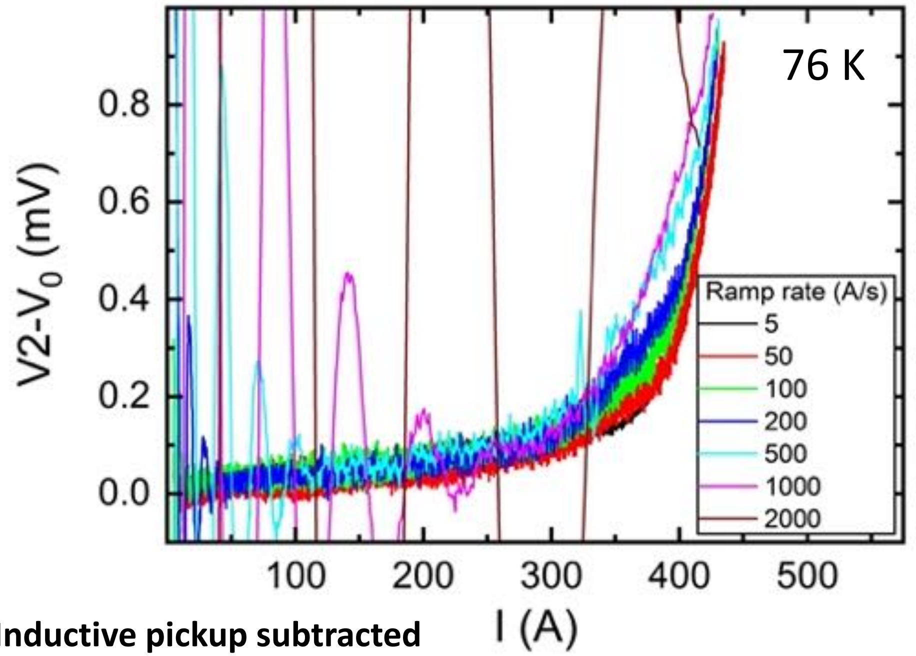
Van der Laan et al. *SUST,* **2020**
https://doi.org/10.1088/1361-6668/ab9ad1

Ramp-rate dependence of V(I) data

Data taken on Long (5m) sample

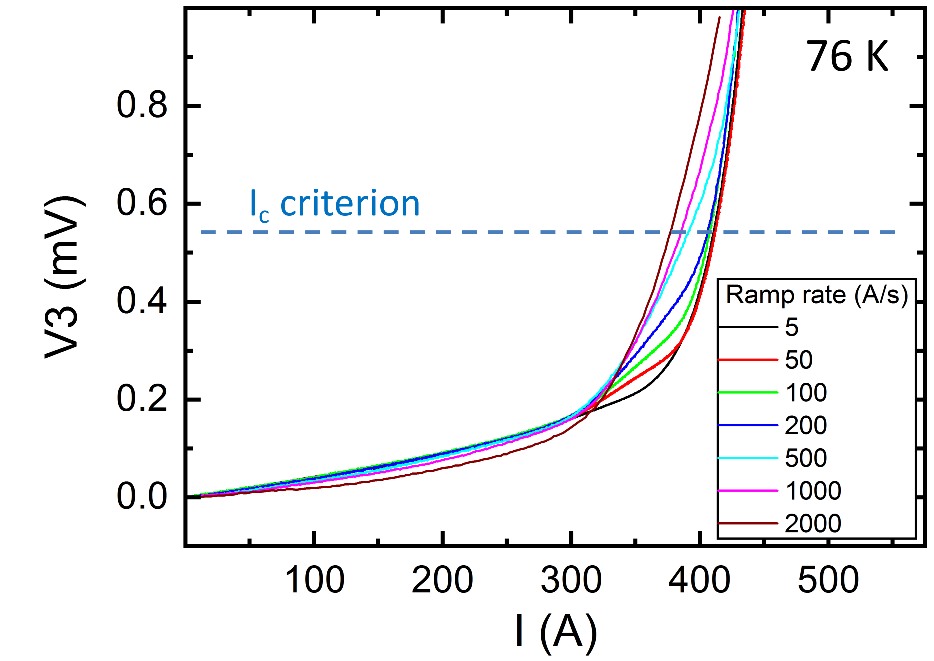
External V-tap measures inductive pickup and data in general is noisier than that taken with internal V-taps

External V-tap measurement

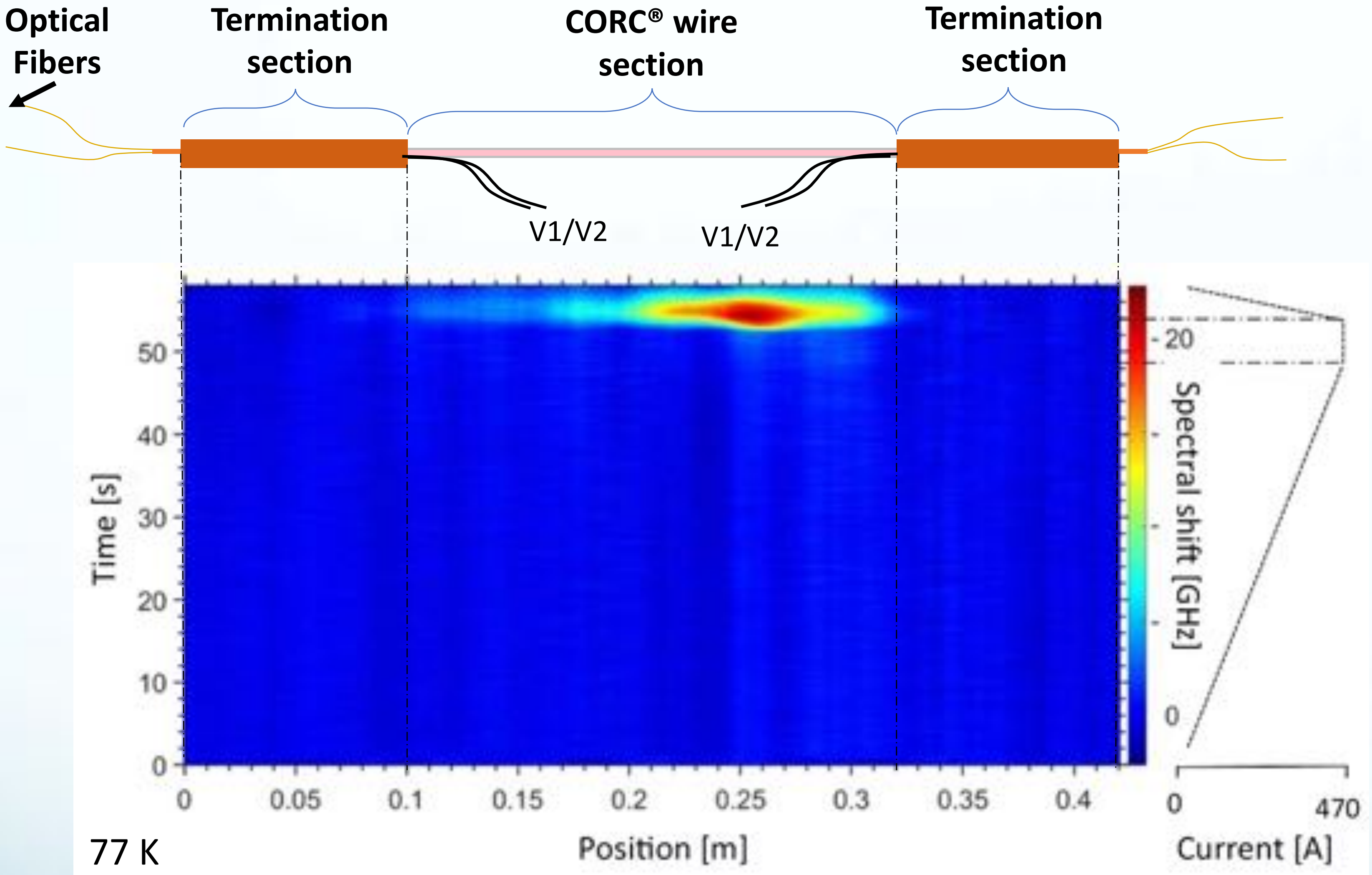


Inductive pickup subtracted

Internal V-tap measurement



Temperature rise measured via optical fibers



Current ramped over 48 s to 470 A (140% I_c) and held constant as hot spot develops and propagates

Van der Laan et al. **SUST** https://doi.org/10.1088/1361-6668/ab9ad1

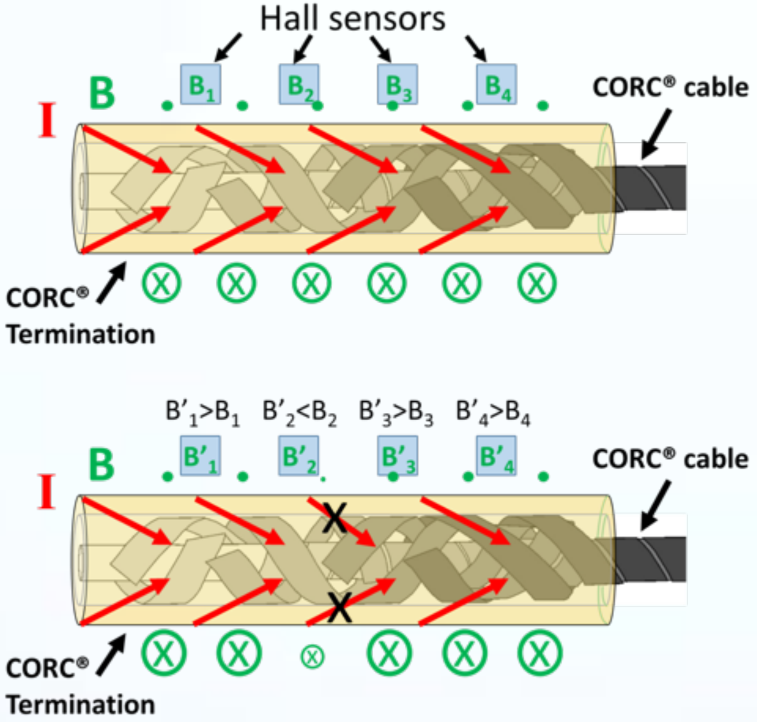
Curtesy of F. Scurti

Terminal integrated diagnostics

Measuring current redistribution between CICC strands due to hot-spots

Magnetic field perturbations measured by Hall sensors when current redistributes

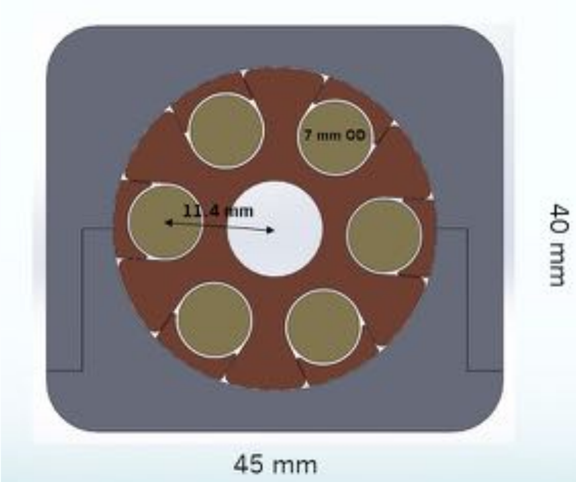
In single cable/wire terminations

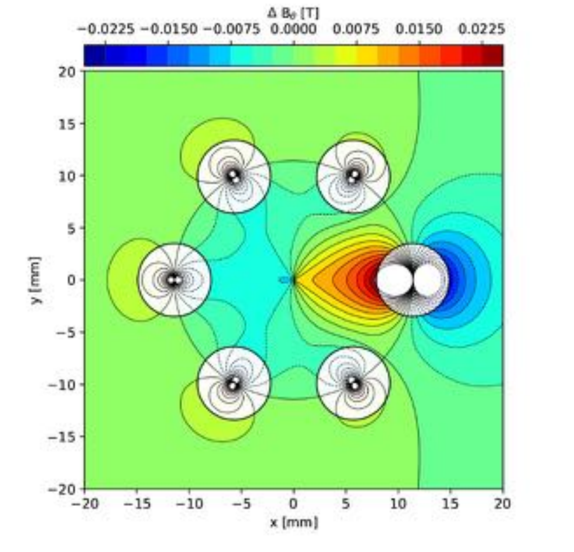


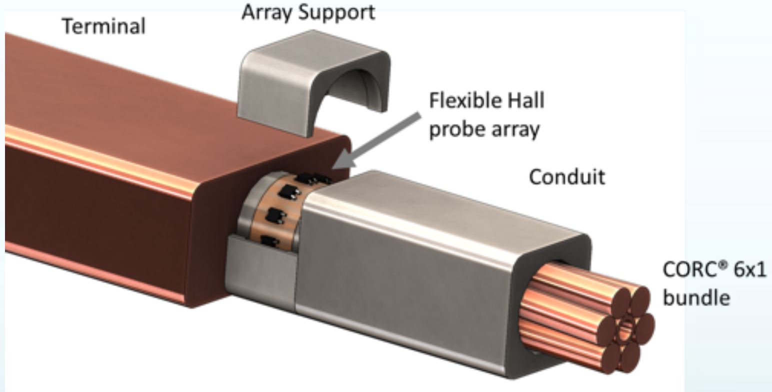
See talk by **Reed Teyber**: Wk1LOr5A-03 - CORC® Cable Terminations with Integrated Hall Arrays for Quench Detection

Teyber et al. *SUST*, **2020**
https://doi.org/10.1088/1361-6668/ab9ef3

In CICC terminations







Weiss et al. *SUST*, **2020**
https://doi.org/10.1088/1361-6668/abaec2

Summary

CORC® wires and cables with integrated diagnostics, a promising innovation

- CORC® Cables and wires with embedded sensors have many advantages
  - Accurate voltage measurements
    - Compensated inductance
    - Elimination of sample-length dependent noise
  - Distributed strain and temperature sensing with optical fibers
    - Can localize where hotspots begin
    - Can follow evolution of quench propagation
  - Mechanical protection of sensing wires
- Terminations with integrated Hall sensors also being explored
  - Effective diagnostic tool
  - Potential quench detection strategy for HTS

See Federico Scurti's talk for more on Optical Fiber measurements: Wk1LOr4C-03

Recent CORC® Publications

Topical review on 10 years of CORC® progress (2009-2019)

- Covers everything from conductor development to joints and magnets
- https://doi.org/10.1088/2F1361-6668/2Faafc82

Recent publications (2019-2020)

- CORC® CICC with integrated Hall sensors, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/abaec2
- CORC® terminals with integrated Hall sensors, Teyber et al **SUST** https://doi.org/10.1088/1361-6668/ab9ef3
- CORC® solenoid magnet tested in 14 T LTS outsert, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab7fbe
- AC loss and contact resistance studies, Yagotintsev et al **SUST** https://doi.org/10.1088/1361-6668/ab97ff
- CORC® wires with integrated Fibers and V-taps, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab9ad1
- CORC® wires made with 25um Sub tapes, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/ab72c6
- Progress on CORC® CICC development, Mulder et al **IEEE** https://doi.org/10.1109/TASC.2020.2968251
- Development of CORC® for FCL applications, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/aafaa7
- 1.2 T CCT magnet demonstrator, Wang et al **SUST** https://doi.org/10.1088/1361-6668/ab0eba
- Axial tension and fatigue testing, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab06a3

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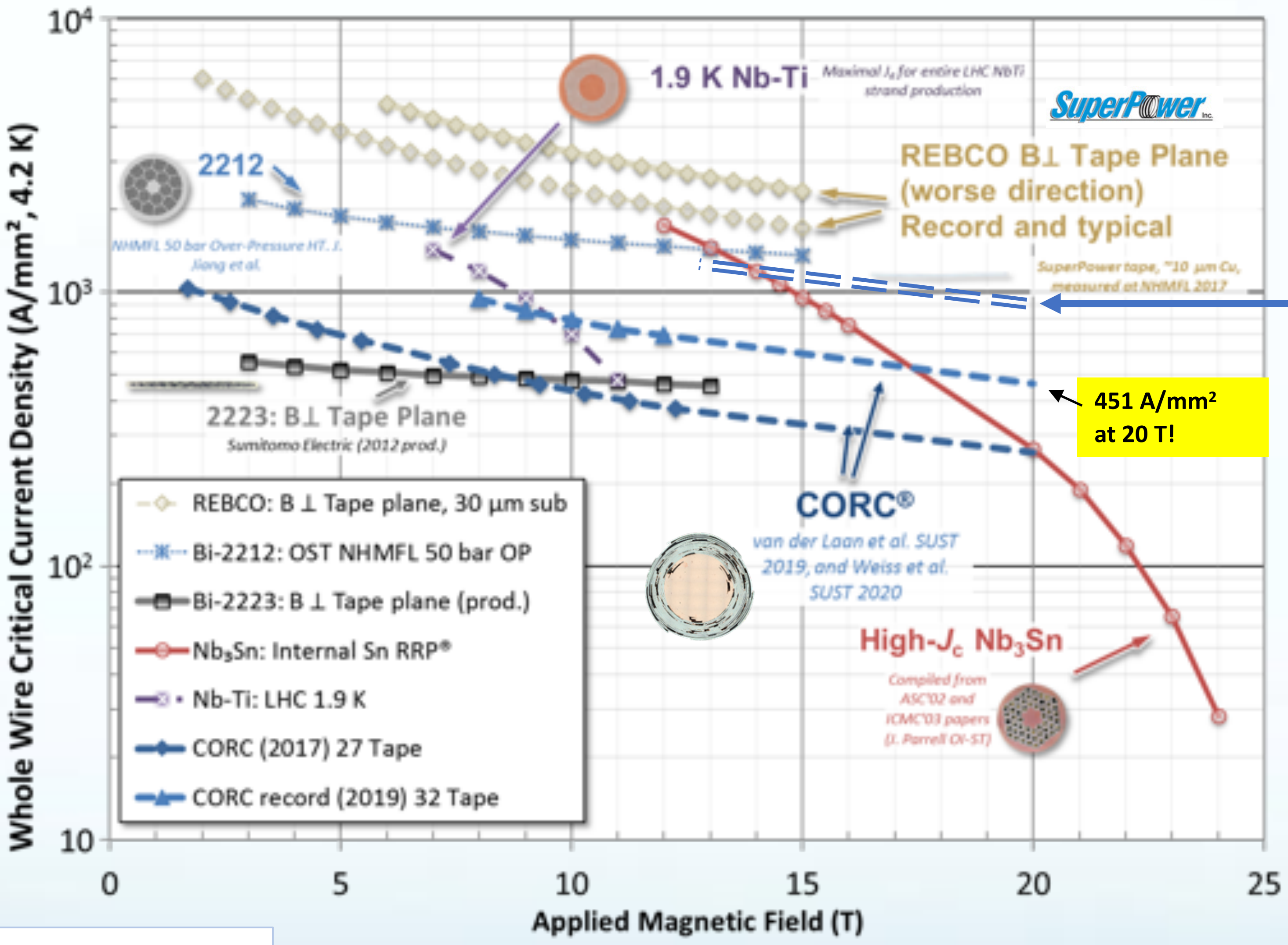
Not possible without the support of DOE, the US Navy, and various collaborators. Thank you!

CORC® J_e comparison to high-field magnet wires



CORC®
Potential using tapes with 20 μm substrates best pinning received

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Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots