# Quench detection for HTS conductors and coils using acoustic thermometry

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# Quench in HTS conductors



**Long lengths of HTS conductors with $I_e$ > 500 A/mm$^2$ in 20 T background field are becoming a reality, thus opening up prospects of next generation high-field magnets**

**Large temperature margin and heat capacity rising with temperature guarantee HTS conductor stability:** Minimal quench energies in HTS are 2-3 order of magnitude larger than those in LTS

## Why would an HTS magnet quench?

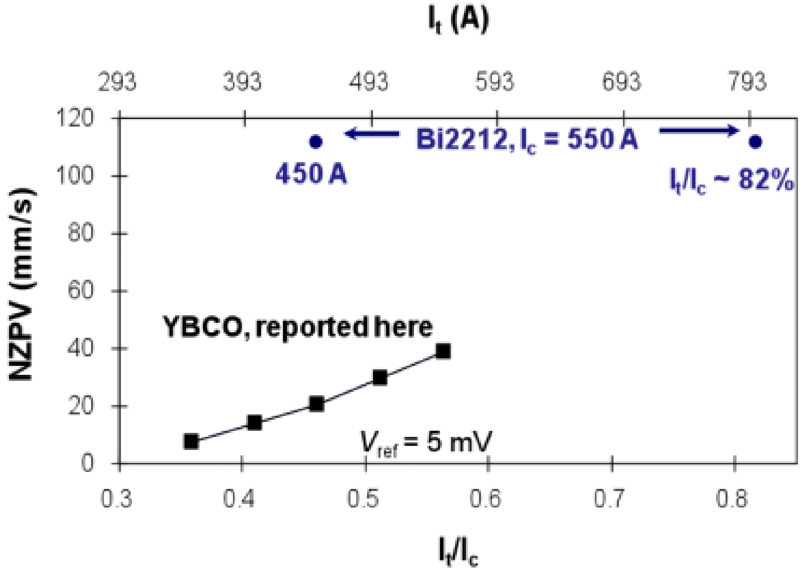
- **Over-heating**: insufficient cooling resulting in a thermal runaway (splices, ac loss, etc.)
- **Over-current**: current density goes overcritical due too:
  - conductor inhomogeneity
  - degradation due to stress (delamination, hairline cracks, edge defects in ReBCO or micro-cracks and leakage in Bi-2212

**We need quench detection!**

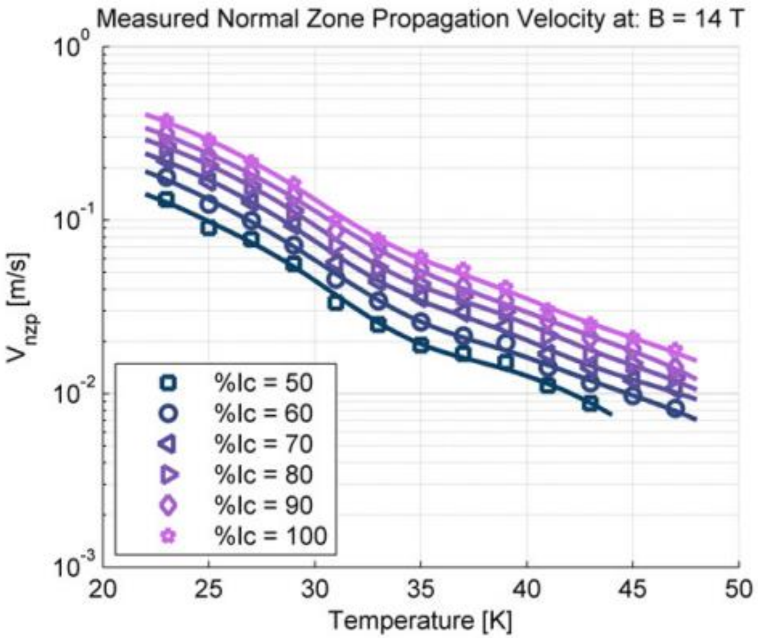
# Normal zone propagation in HTS is slow



## Same factors that cause stability with respect to quenching are impeding quench propagation




*H. H. Song and J. Schwartz, "Stability and Quench Behavior of YBa2Cu3O7-x Coated Conductor at 4.2 K, Self-Field," IEEE Trans. Appl. Supercond., 19, pp. 3735-3743, (2009).*




J. van Nugteren, "Normal Zone Propagation in a YBCO Superconducting Tape" MSc Thesis, Univ. of Twente, 2012

- **Quench propagation velocity is < 50 mm/s at best circumstances, and typically much less.**

A consequence of the slow NZPV is that a significant ΔT yields only a modest resistive voltage that is hard to detect in a noisy background => **conductor damage may occur before a voltage-based quench detection system is triggered.**

# Non-voltage quench detection approaches



- Inductive "quench antennas": current re-distribution around quench zone via magnetic transient. Non-invasive, quench localization. NZPV may be too slow for the quench antennas to be effective.
- Current balance measurement between halves of the split conductor – can be very sensitive, at nanoVolt level. Requires conductor striation, or a specific winding geometry.
- Acoustic emission: transient thermally-induced stress. Non-invasive. May be not efficient in non-impregnated / non-insulated coils. Non-specific (will also detect cracking, vibrations, etc…).
- FBG optical sensors - detect thermally-induced stress. Sensitive and immune to electromagnetic noise. Only localized measurement at specified locations *(poster 2LP2-02 by S. Chiochiolo et al.)*
- Rayleigh-backscattering fiber interrogation technique: thermally-induced stress. Distributed measurement, precise hotspot localization. Optical fiber has to be co-wound with or embedded into a conductor. *(poster 1EP2-20, by F. Scurti et al.)*
- Capacitive: change in stray capacitance of insulation and surrounding cryogenic liquid

  *(Poster **3LP4** by E. Ravaioli et al.)*

$\Delta T$

# The conductor itself as a temperature sensor?



**This approach has important advantages of being:**

- ✓ **fast,**
- ✓ **non-invasive**
- ✓ **adaptable to existing coils and magnet systems**.

**The key temperature-dependent quantity is the Young's modulus:**

Sound velocity: $v = \sqrt{\frac{E}{\rho}}$, where Young's modulus E exhibits the strongest temperature dependence:

$$E(T) = E_0 - s/\left[e^{t/T} - 1\right] \quad (s, t \text{ – adjustable parameters})$$

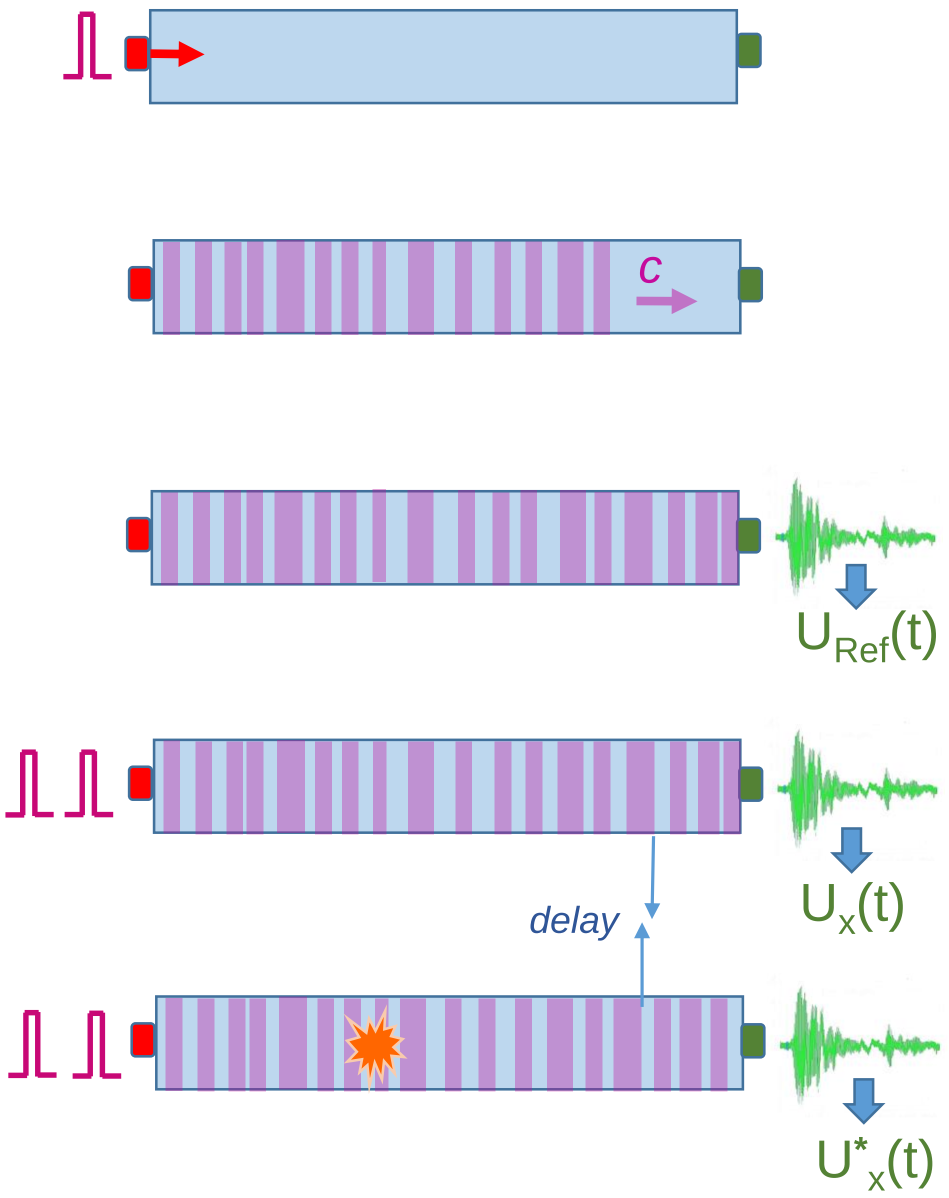
The E(T) dependence is **weak**: just ~$10^{-4}$-$10^{-5}$ $K^{-1}$ at 77 K and even less at lower temperatures. But it is still **measurable** using high-frequency ($10^5$-$10^6$ Hz) vibrational Eigenmodes of the body, and taking advantage of its high (>100) mechanical Q-factor

We do it by monitoring **transient acoustic response**

# Operational principle

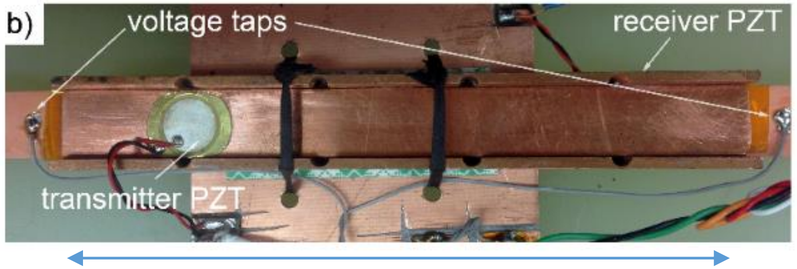


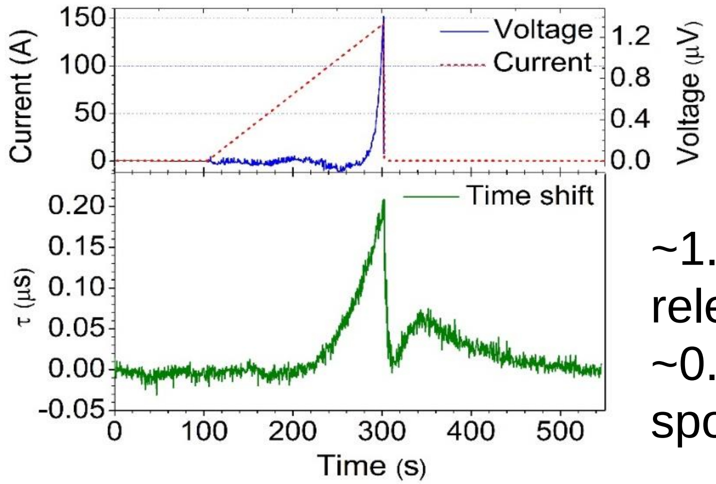
1. A body is **pulsed** by a sender transducer
2. A **“ring-down” transient waveform propagates and reverberates** multiple times
3. Transient oscillation **is acquired** by a receiver transducer; and **stored as “reference”** $U_{Ref}$ (t). Its shape is **uniquely defined** by the body geometry, density and elastic modulus E(T)
4. Pulsing and transient acquisitions are repeated periodically; every new transient $U_x(t)$ is compared to $U_{Ref}(t)$ using cross-correlation: $A(\boldsymbol{\Delta t}) = U_x(t+\boldsymbol{\Delta t}) * U_{Ref}(t)$. The time shift **Δt** yielding the **maximal cross-correlation**: is calculated for every new pulse
5. When a hot spot develops, E(T) decreases locally, delaying the wave passing through it. This proportionally **increases Δt**.



# Past results and new challenges






~1.27 mJ heat release
~0.6 K estimated spot temperature

*"Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks,"* *M. Marchevsky and S. A. Gourlay, Appl. Phys. Lett. 110, 2017 doi:10.1063/1.4973466*

- For a short conductor in quasi-adiabatic conditions the technique works really well… but what about:

  - Longer lengths (> 1 m)?

    - Acoustic damping is high at longer distances
    - Relative hot spot volume is small

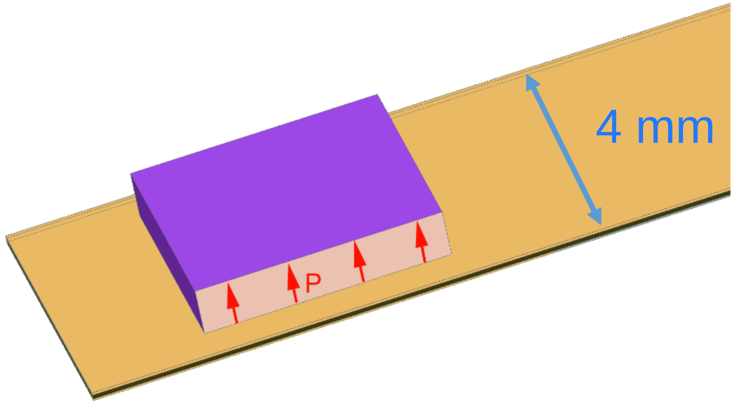
  - Varying thermal background?

    - Local $\Delta$T can be <1 K at nucleate boiling conditions, while background the temperature may fluctuate

  - Can we do localization as well as detection?

# Transient propagation in HTS tape



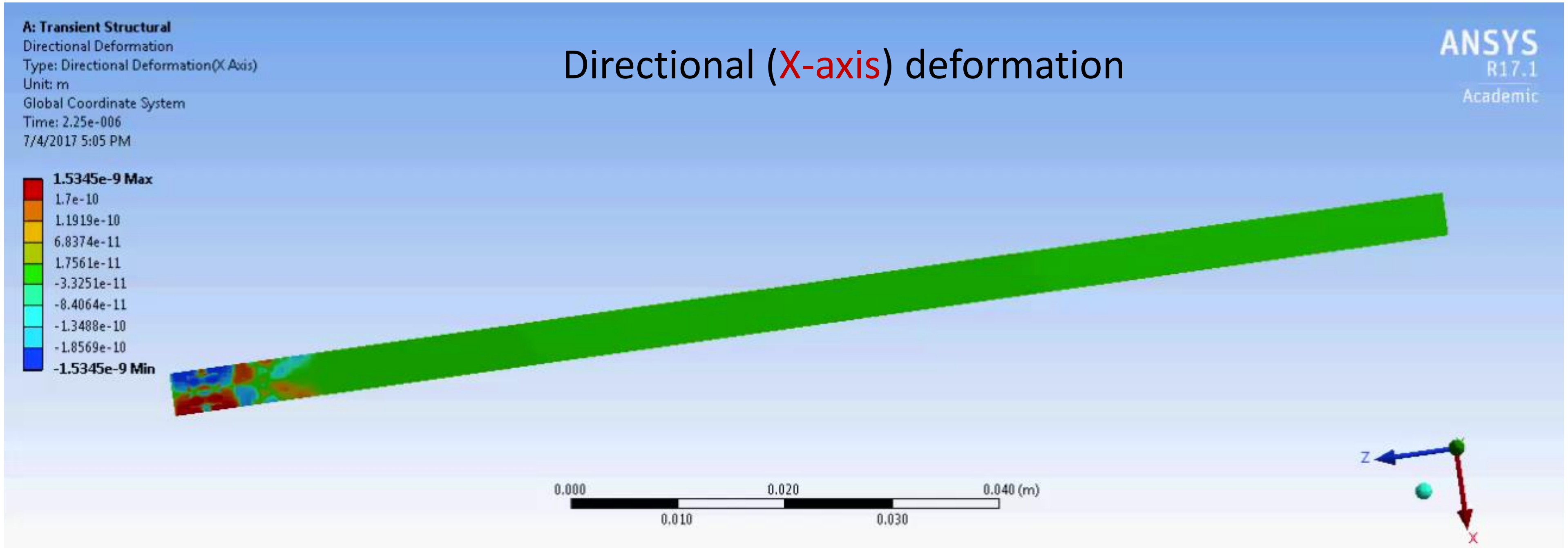



*- 30 (Cu)-50 (SS)-20 (Cu) $\mu$m tape cross-section*

*- 0.2 $\mu$s rectangular pulse voltage is applied to the transmitter piezo-transducer*

- **In-plane** shear waves and **out-of-plane** waves are excited

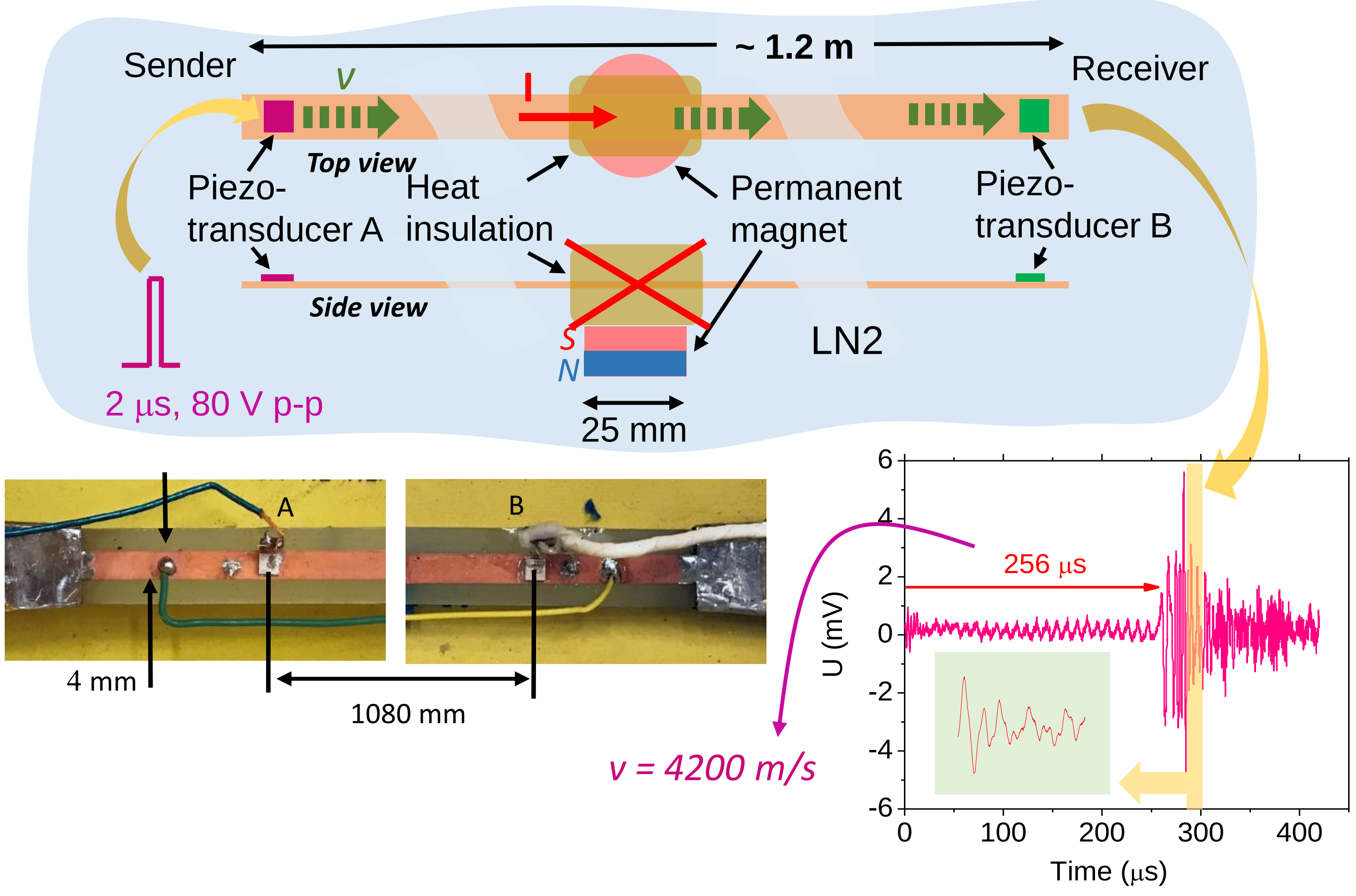
The in-plane wave modes interact less with a supporting structure and do not couple to the cryogen bath due to absence of shear vibrations in liquids. **Beneficial for the detection!**

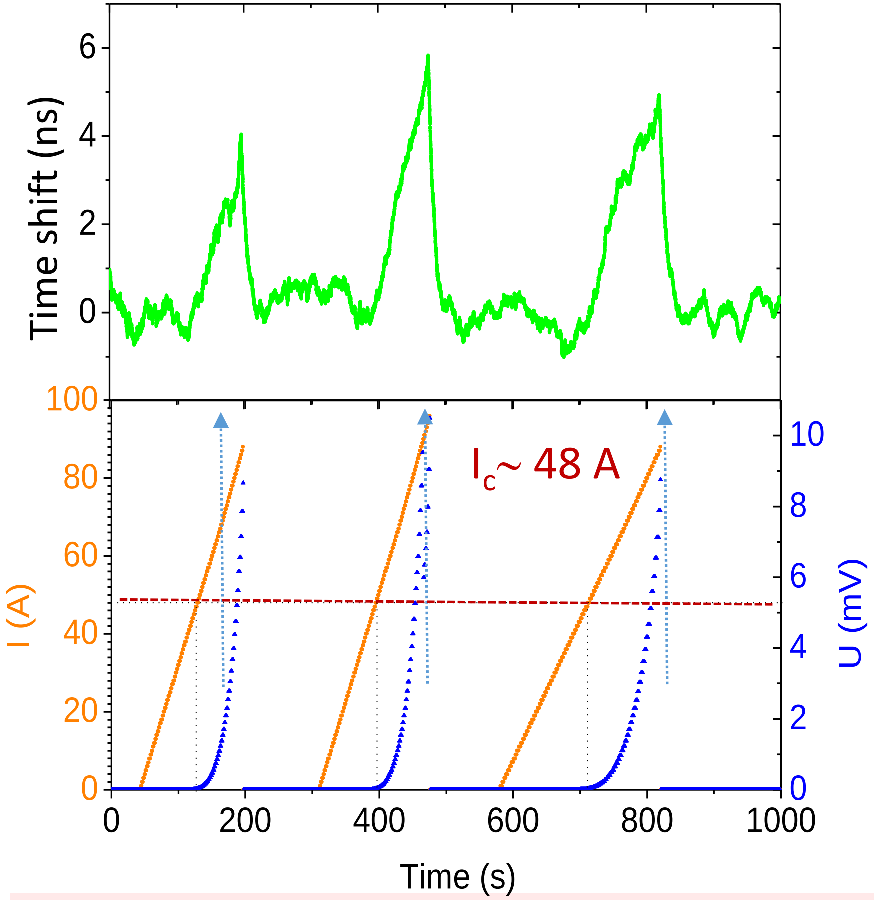


# Quench detection (adiabatic) in a ReBCO tape



A ~1.2 m-long, 4 mm wide SCS4050 tape (SuperPower); $I_c$ = 95 A (1 μV/cm), n = 34




However, once the heat insulation piece was removed from the tape, acoustic time shift was no longer observed…

- Noise level of ~ 1 ns corresponds to the tape voltage of ~ 1.6 mV (or ~ 13.3 μV/cm, or ~ 25 mW of power dissipation)

# How to improve detection sensitivity ?



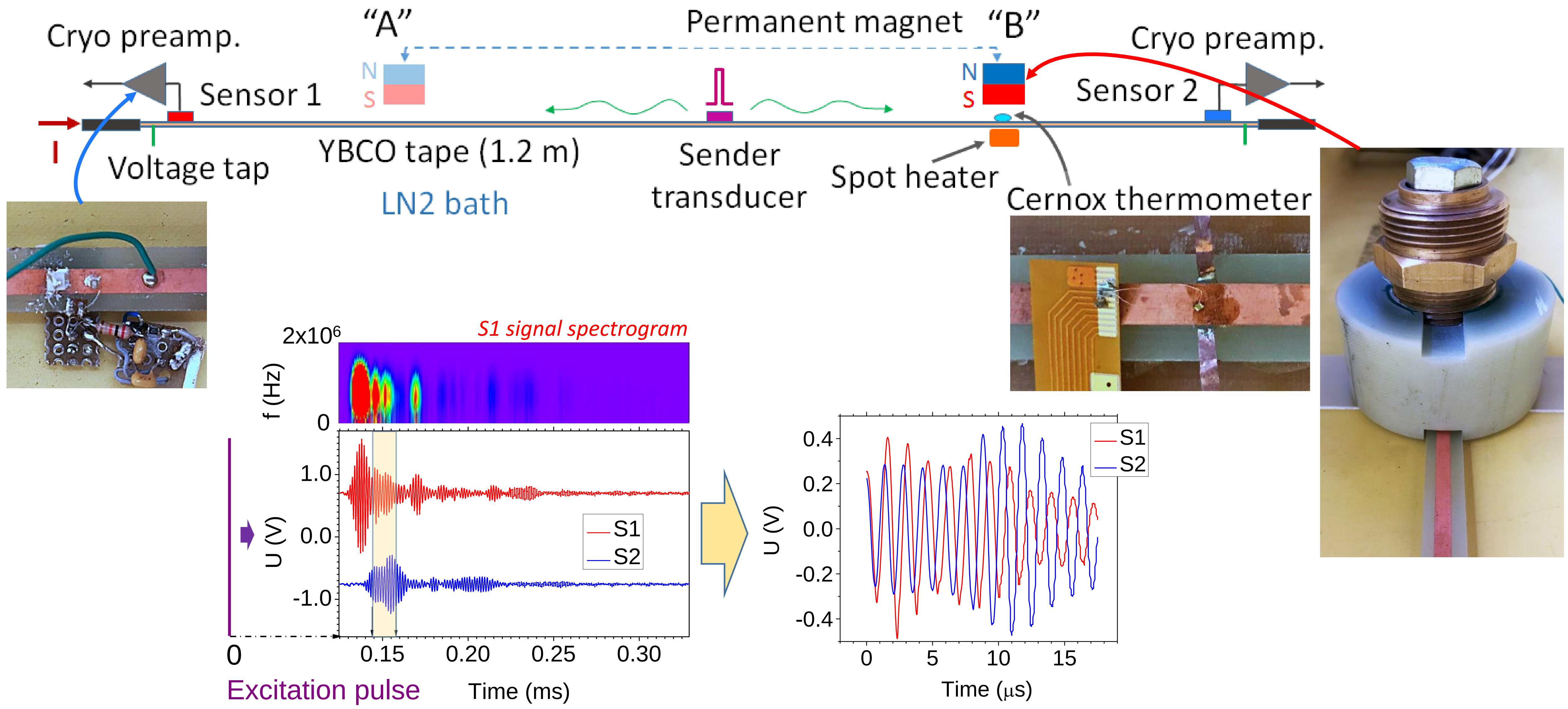
- Improve signal to noise ratio:
  - Cryogenic broadband preamplifiers (4.2 – 300 K), 1 MHz bandwidth
- Compensate for the ambient temperature variations
  - Differential measurement technique

By analogy to the voltage differential measurement, one could install two sensors ("A "and "B") at the opposite ends of the tape, and detect variation of ($\Delta t_B - \Delta t_A$) rather than the absolute $\Delta t$.

- This eliminates noise due to ambient thermal drifts
- The sign of ($\Delta t_B - \Delta t_A$) will point to the segment (adjacent to "A" or "B") where the hot spot is developing

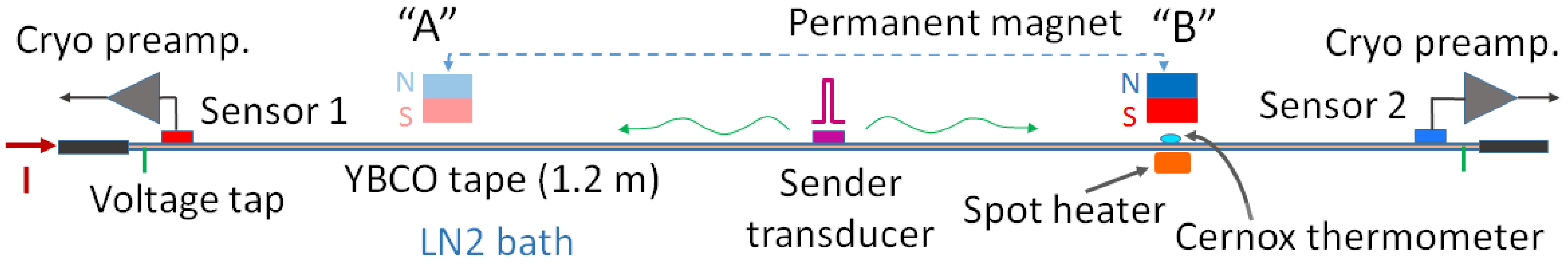
# Setup for the differential acoustic detection

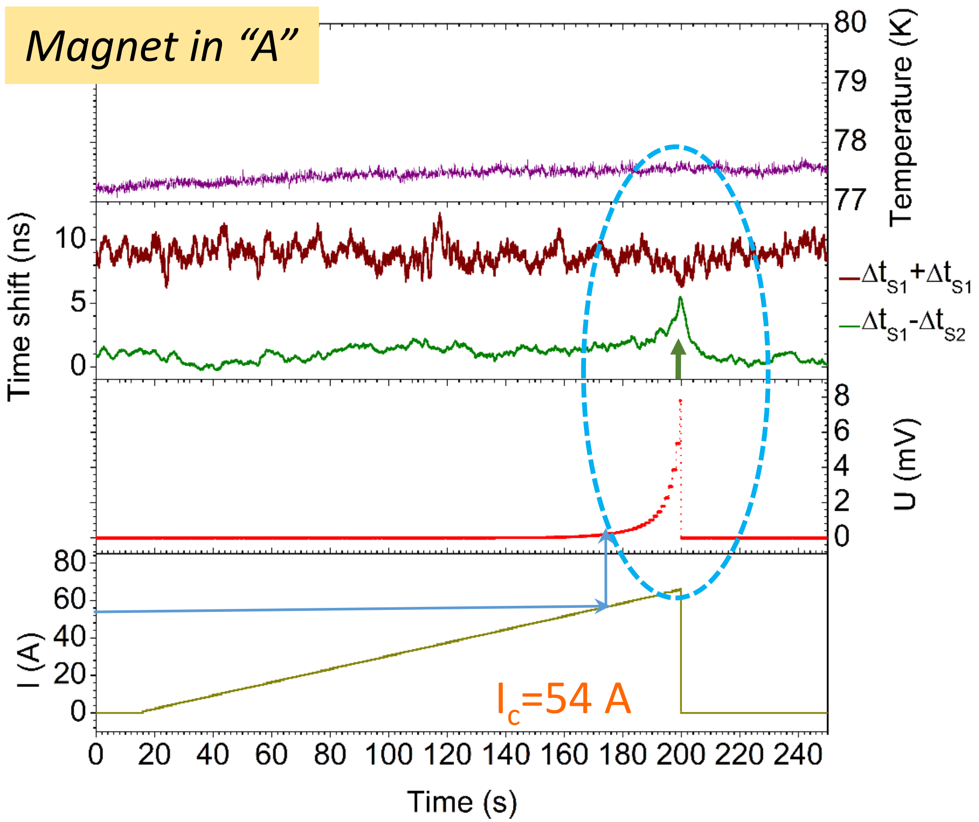


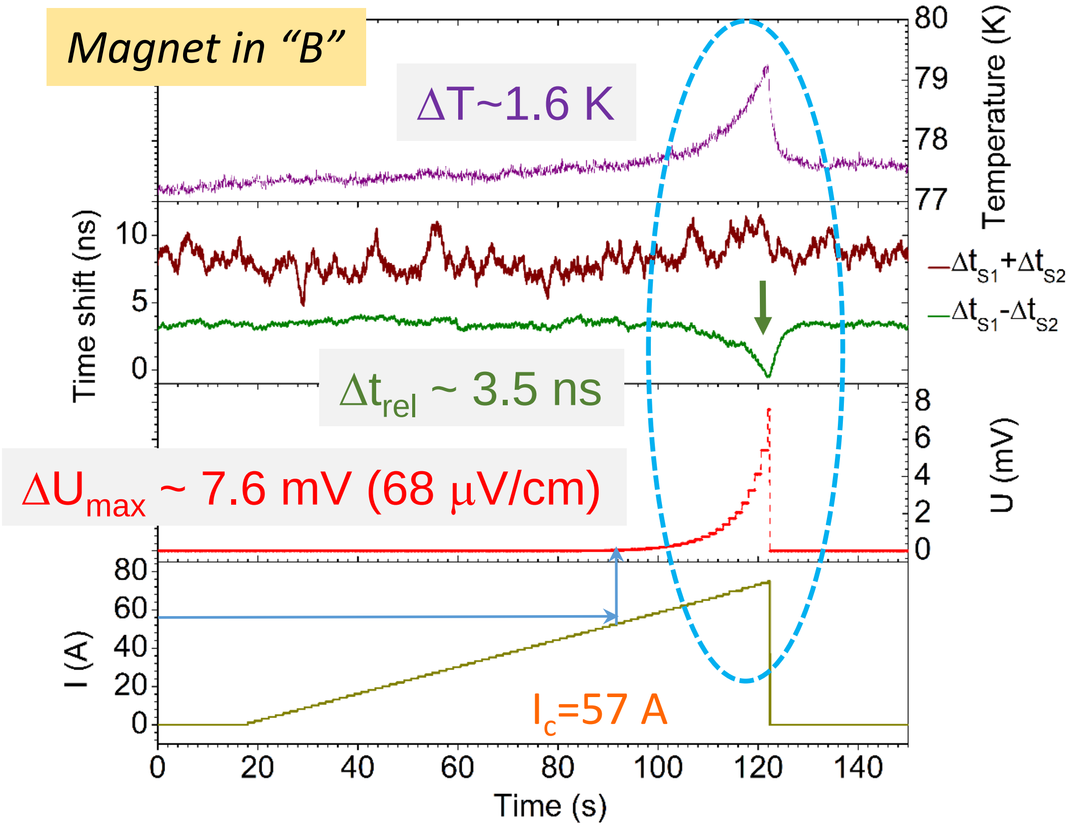


# Differential acoustic quench detection: results



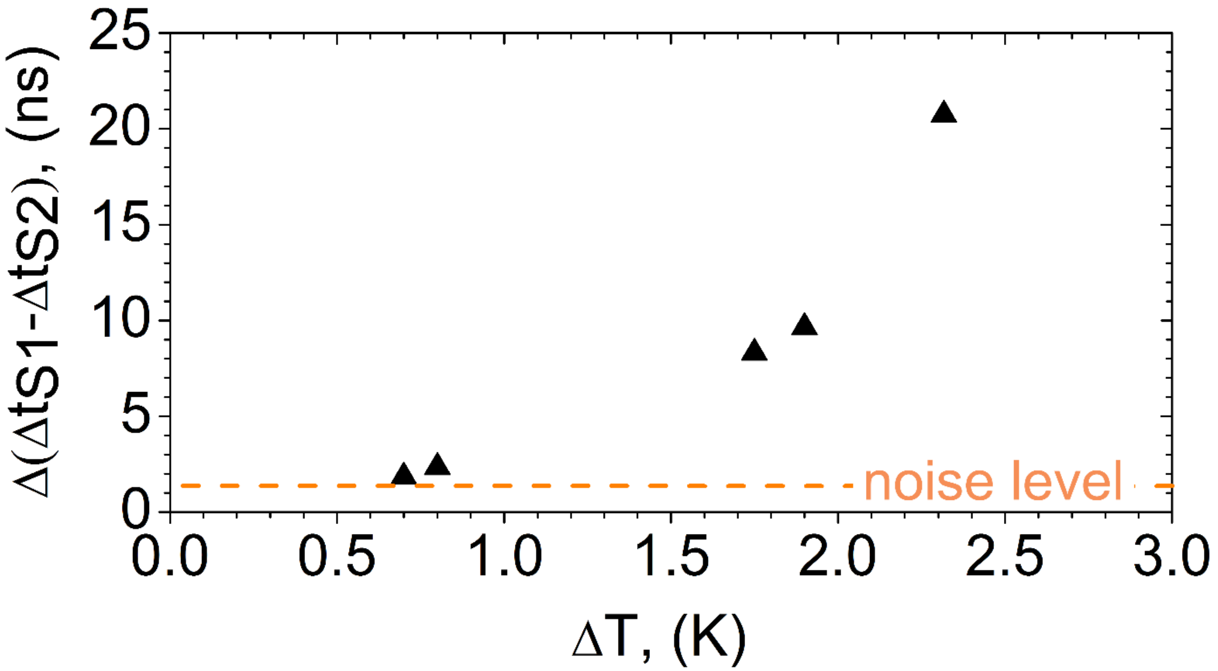


# Sensitivity calibration using spot heater

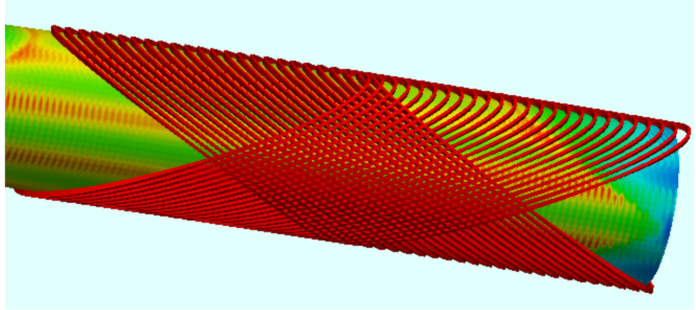
- Spot heater was fired at 4.0, 4.6, 4.8, 5 and 6 V; for 5-8 s, until temperature and acoustic signal equilibrated
- No current in the tape and magnet removed




**Thermal contribution to the acoustic time shift is clearly distinguishable above the noise background for $\Delta T > 0.7$ K**

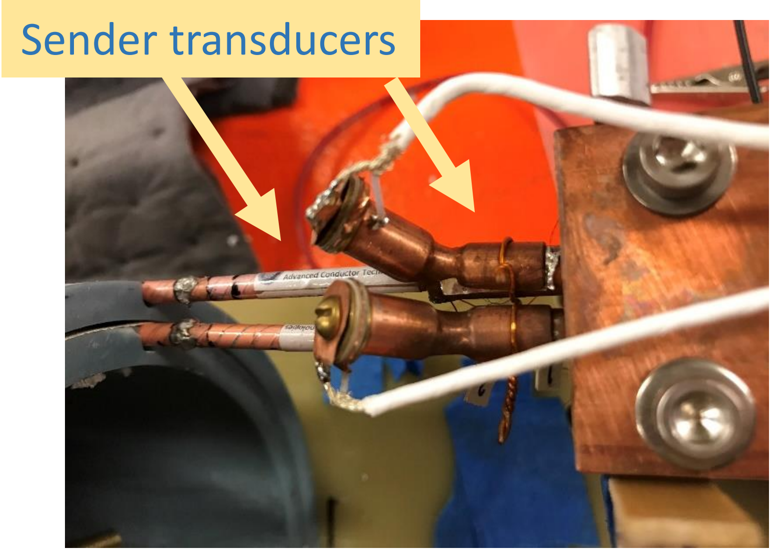
# Canted-cosθ sub-scale coil using CORC conductor

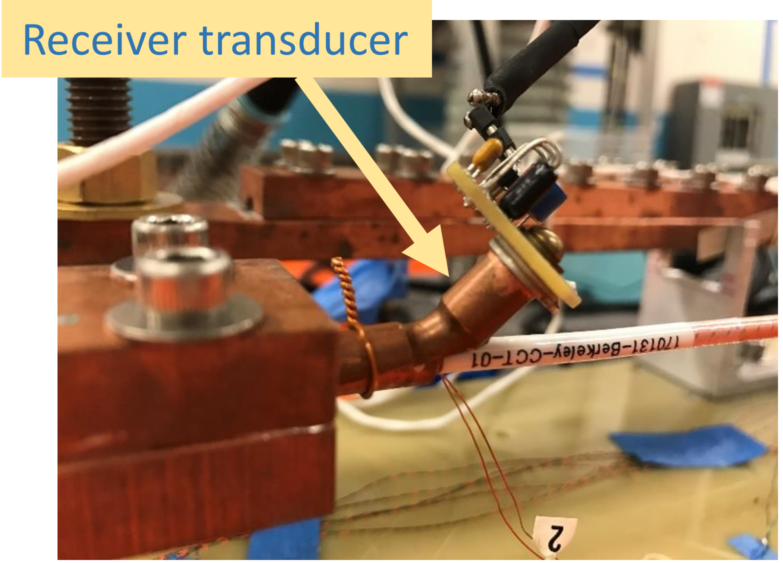
- CORC-based HTS dipole sub-scales are built by LBNL in the framework of US Magnet Development Program, and in collaboration with Advanced Conductor Technologies. Recent progress: *talk **3L02-04** by J. Weiss et al.*



- CORC® conductor :

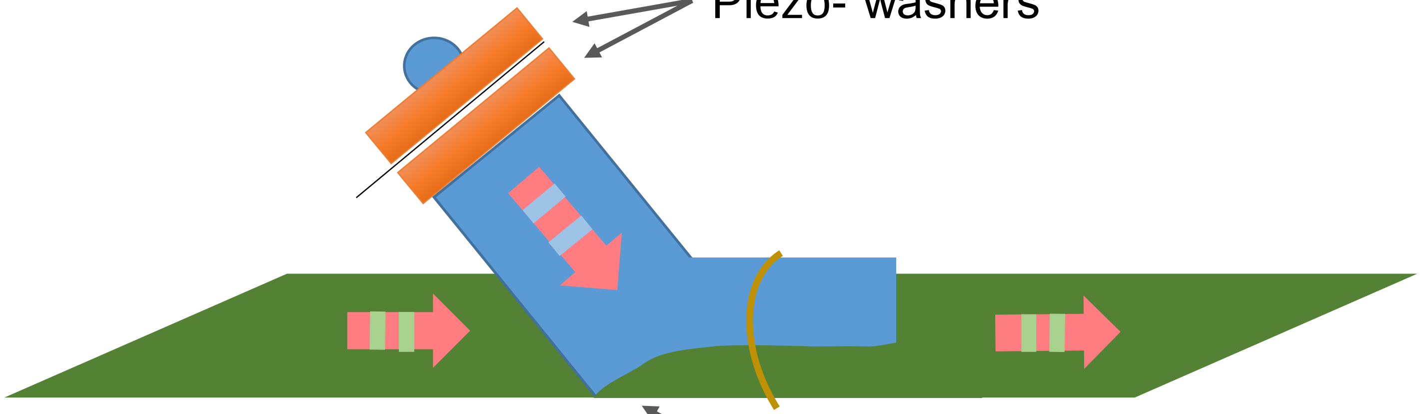
  29 REBCO tapes distributed around a 2.56 mm diameter copper core wire.
  - Tapes are 2 mm wide, and have 30 mm-thick substrate.
  - Cable diameter is 3.63 mm, length is 2.25 m, including out-of-mandrel portions



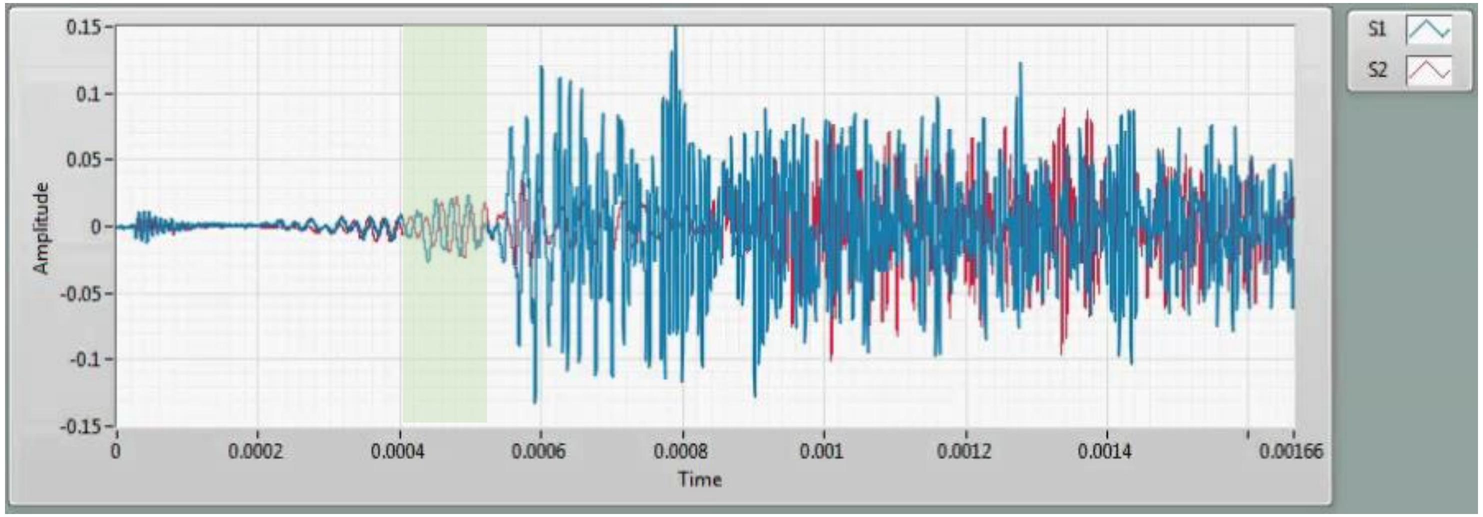
# Angled transducers and transients in the CORC





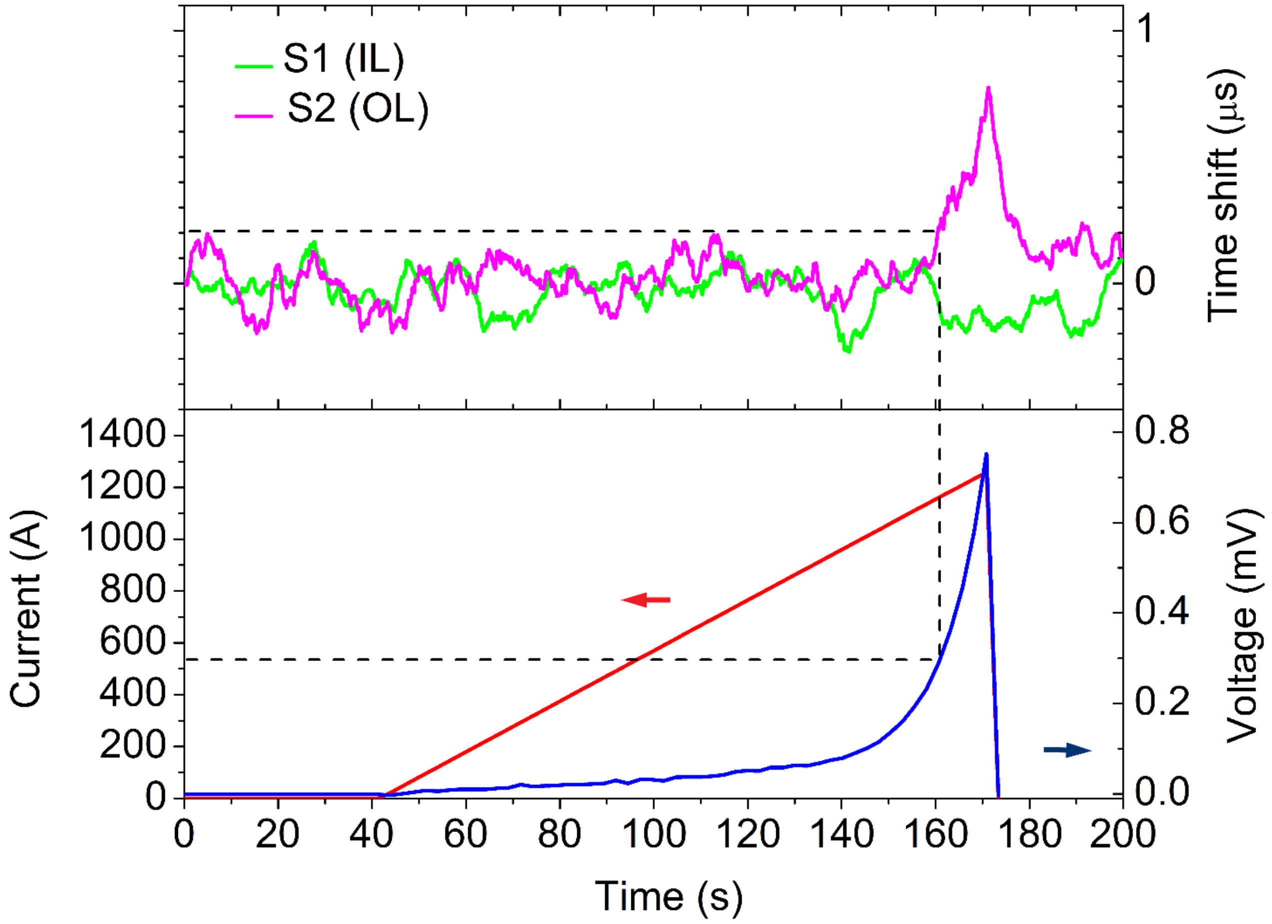

Acoustic pulse is injected from the surface, then propagates linearly along the cable length.

- Transient waveform is unstable after multiple reflections. May be a result of intermittent mechanical interaction between individual tapes.
- The stable fraction is likely passing through the copper core



# Quench detection in the CORC coil






The acoustic time shift signal rises above background noise level at I=537 A which corresponds to the coil voltage of 0.3 mV and power dissipation of 0.16 W in the cable.

We are looking to improve mechanical coupling between transducers and the central core of the cable to rely on its transverse travelling wave mode.

# Conclusions and future plans



- We developed a novel technique for detecting hot spots based on acoustic transient response
- Technique is non-invasive, it uses conductor itself as distributed thermometer
- It is applicable to cryo-stable conductors; sensitivity is significantly enhanced for impregnated / quasi-adiabatic conditions
- Better than 1 K thermal resolution for local hot spots in a 1.2 m long bare HTS tape and a coil of 2.25 m-long CORC has been demonstrated

Further testing of the technique with ReBCO CORC and also Bi-2212 subscale coils (talk 4L02-04 by T. Shen at al.) is presently underway.