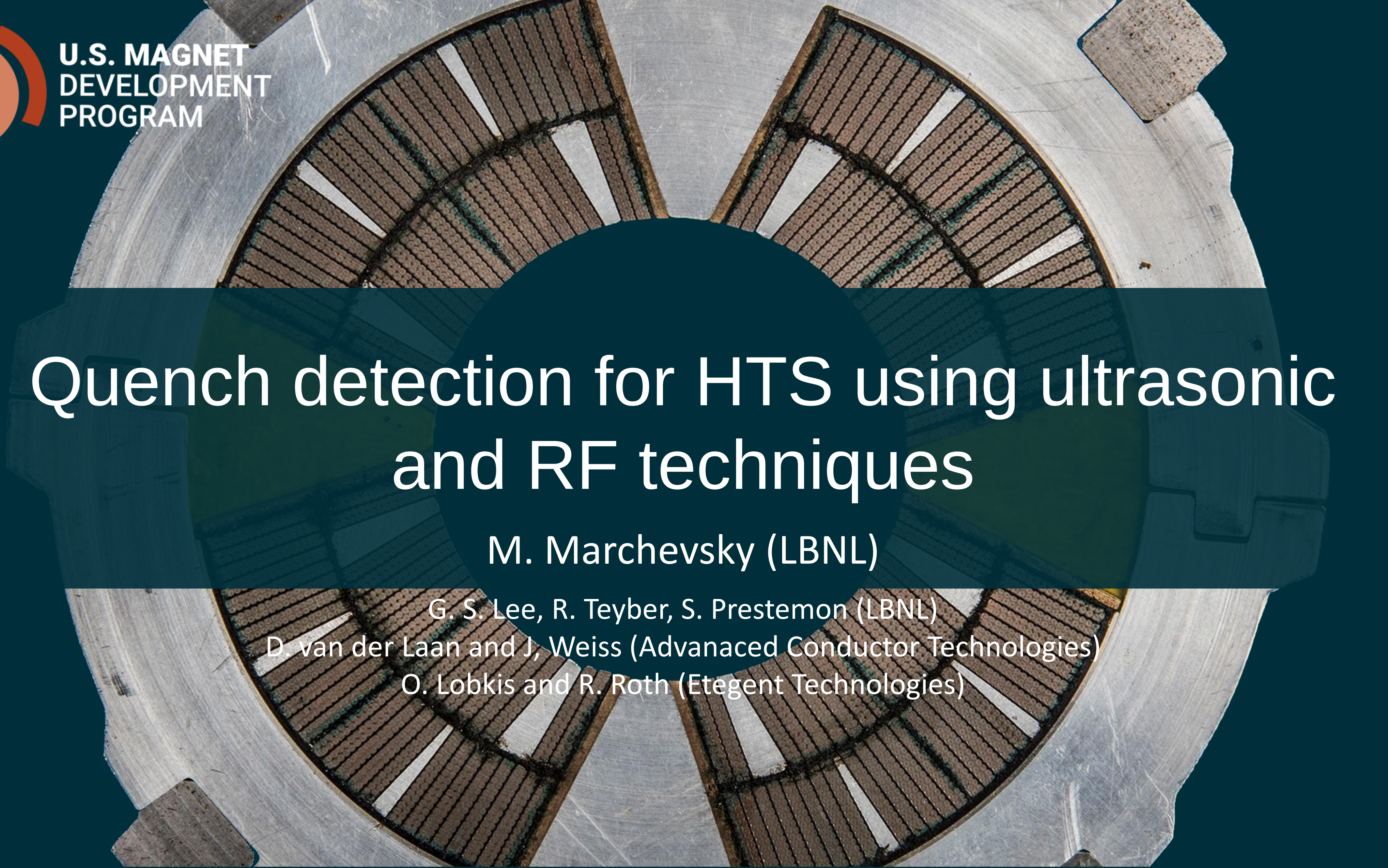


Quench detection for HTS using ultrasonic and RF techniques

M. Marchevsky (LBNL)

G. S. Lee, R. Teyber, S. Prestemon (LBNL)
D. van der Laan and J, Weiss (Advanaced Conductor Technologies)
O. Lobkis and R. Roth (Etegent Technologies)

Quench detection problem

Quench detection in HTS YBCO wire is a serious engineering problem. It is due to a very slow (0.1 – 1 cm/s) normal phase propagation velocity (10^3-10^4 times less than in LTS wires!), resulting in the formation of the localized hotspots.

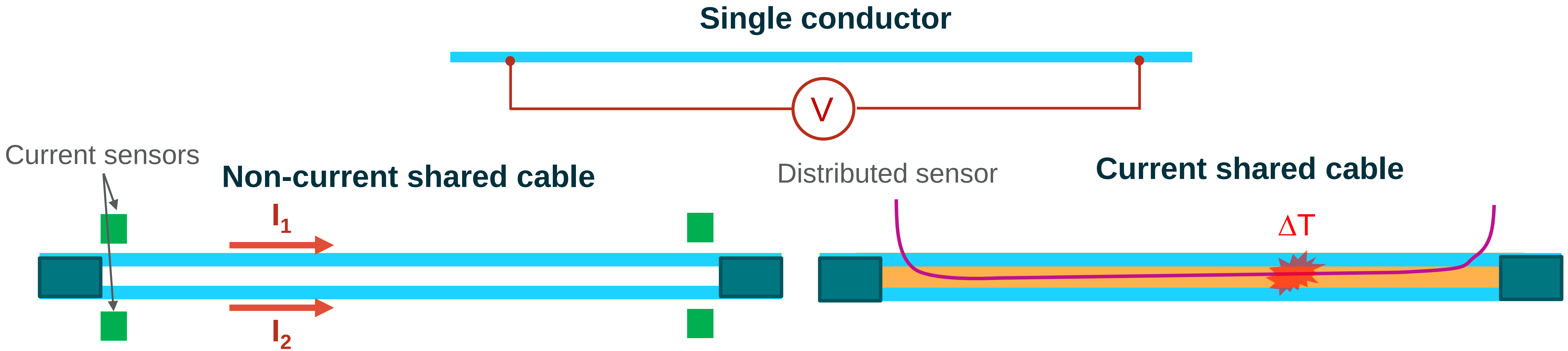
These hotspots are hard to detect, as significant local heating occurs there before the surrounding region transition to the normal state and onset of measurable resistance.

- Non-voltage, **non-invasive methods** are sought to replace the traditional voltage-based detection and improve redundancy

- Once quench starts, it is hard, if not impossible, to be “fast enough” to protect an HTS magnet with large stored energy. Therefore the best protection strategy appears to be **avoiding quenching altogether.**

But what criteria can be used to determine that quench is coming?

Realizing the HTS magnet early quench detection paradigm



Local current sensing at terminations

POINT MEASUREMENT(s)

Distributed temperature sensing along the conductor

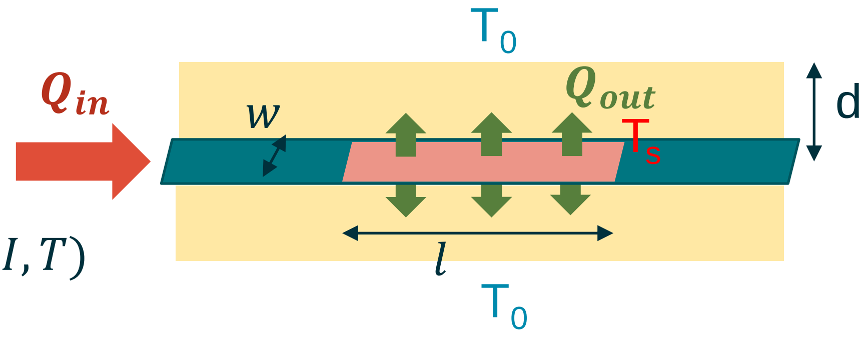
DISTRIBUTED MEASUREMENT

Local temperature rise as a quench precursor

$$U = E_0 l \left(\frac{I}{I_c(T)}\right)^n$$

$$R_s = \frac{U_o}{l}\frac{I^{n-1}}{I_c(T)^n}$$

$$Q_{in} = I^2 R(I,T)$$



$$Q_{out} = \lambda(T)\frac{2lw}{d}(T - T_0)$$

$$Q_{in}(I,T) = \ Q_{out}(T)$$

Copper stabilizer:

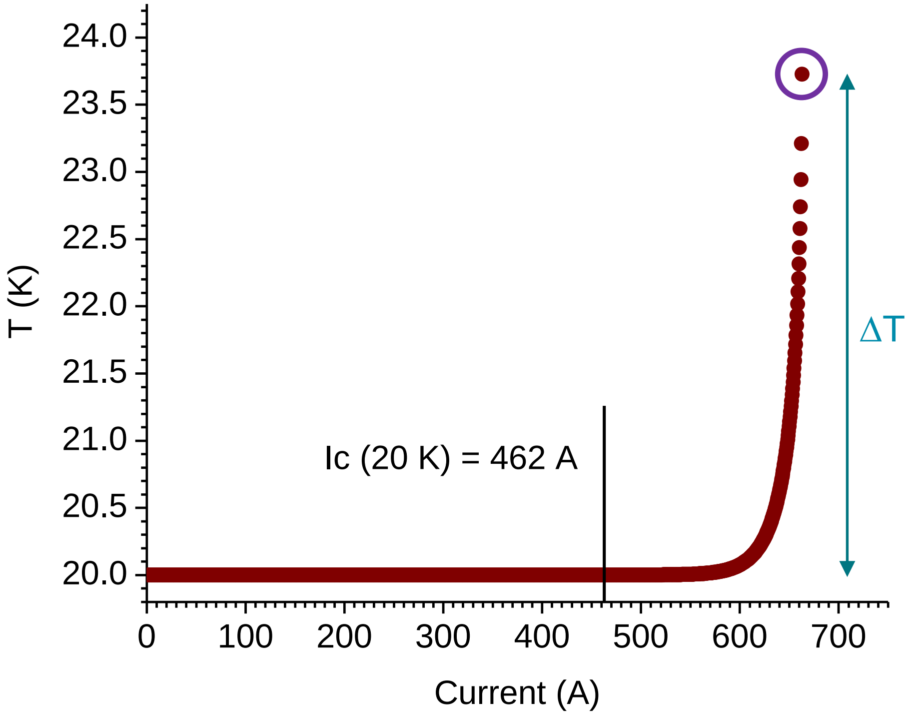
$$R(T) = \frac{R_s(I,T)\,R_{st}(T)}{R_s(I,T) + R_{st}(T)}$$

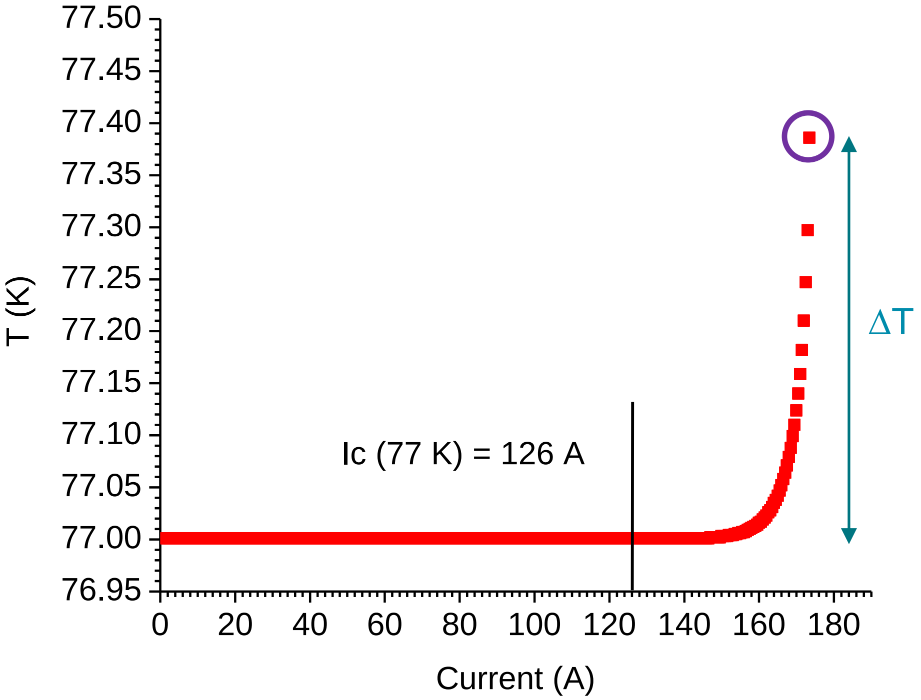
As long as the condition $Q_{in}(I,T) = \ Q_{out}(T)$ can be satisfied for current I < I* (and the corresponding T*< T$_c$) the hot spot is **stable indefinitely, and there is no thermal runaway**.

There is no equilibrium solution for currents I > I*, and thermal runaway would take place (in which case MIITs approach becomes appropriate for calculating the conductor temperature vs time, and “classic” quench protection principles can be applied.

Current-Temperature curves

λ =65 W / K m I_c (T=0) = 500 A $n = 30$





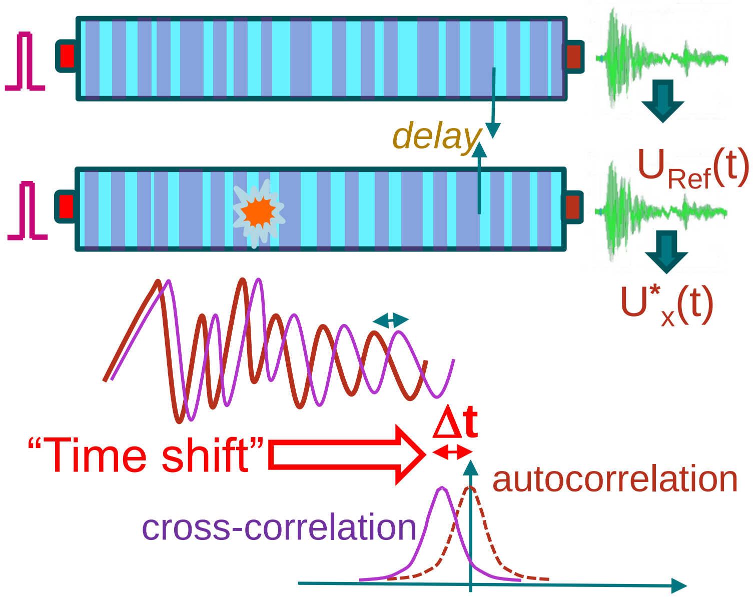
Current-temperature curves can be generated, where each point represents a dynamic equilibrium. The last point of each graph (encircled) defines the critical surface above which a thermal runaway will occur.

Some preliminary conclusions

- The temperature difference between the conductor and the environment is a relevant physical quantity for estimating the proximity to a quench. Temperature monitoring along the conductor should be a reliable way of estimating its proximity to the quench and measuring I_c distribution along the conductor path.
- In-situ determination of the practical heat transfer coefficient λ can be performed using a local heater/thermometer integrated with the conductor.
- Distributed temperature measurements along the conductor can then be used for early quench diagnostics, estimating ΔT and its variation along the conductor path and comparing with the calculated critical surface $\Delta T(I/I_c, n, T_0)$.

Ultrasonic techniques for distributed temperature sensing

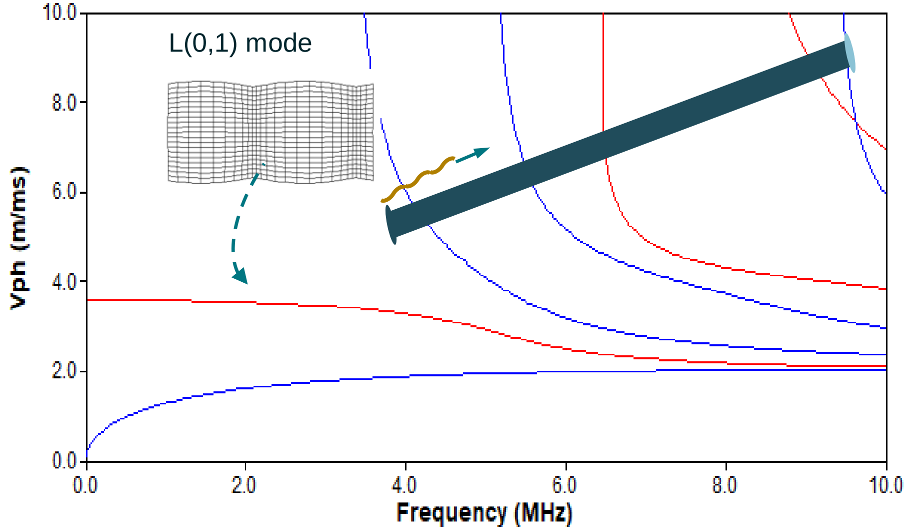
Acoustic waveguide sensors for quench detection



$$E(T) = E_0 - s/\left[e^{t/T} - 1\right]$$

(s, t – adjustable parameters)

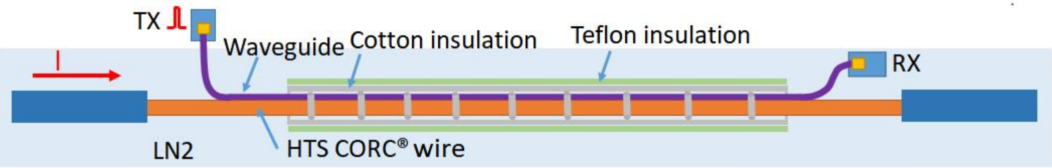
Diffuse ultrasound => guided ultrasound

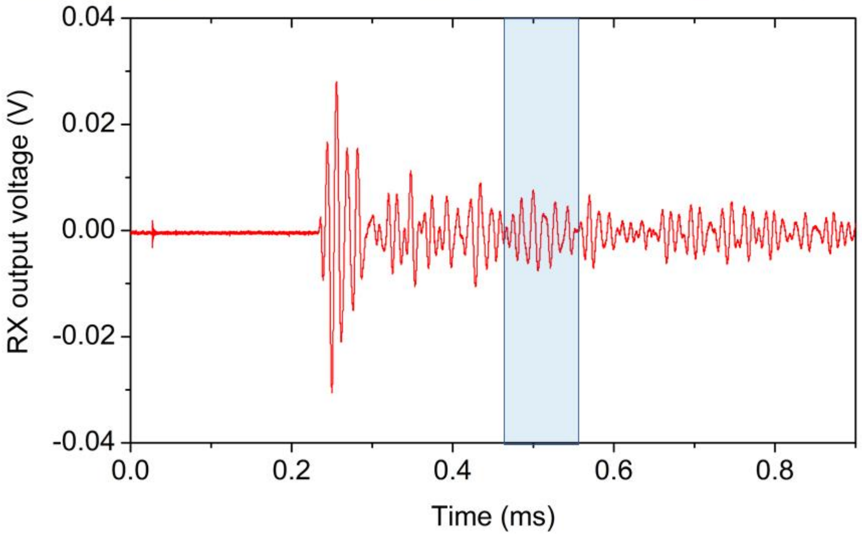


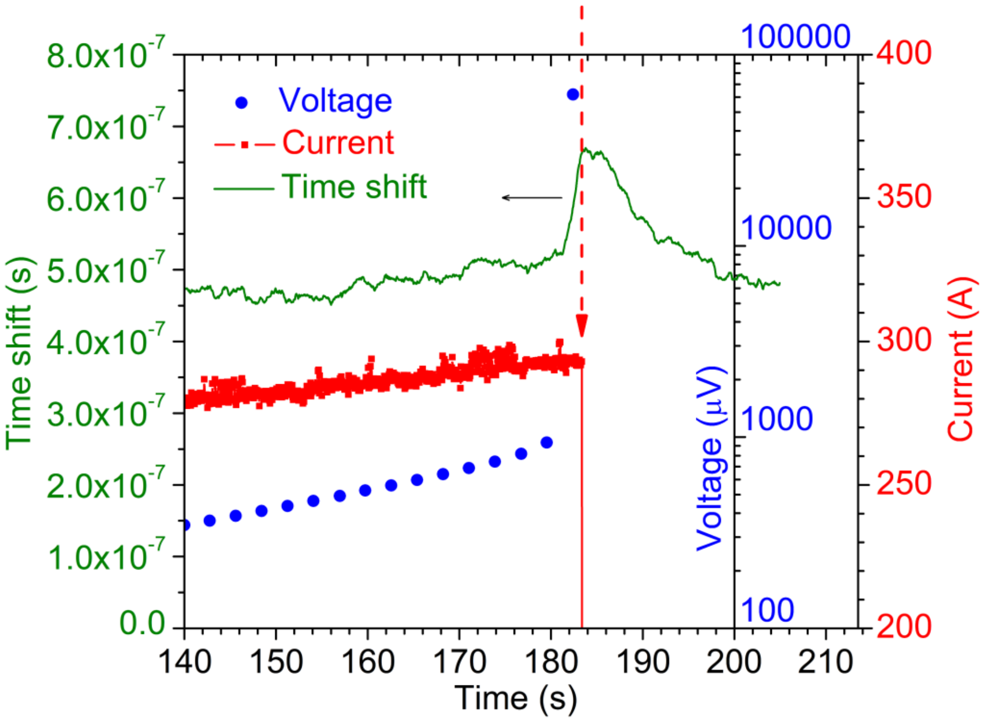
Longitudinal mode in thin cylinder (wire) is very weakly dispersive and allows for the high fidelity transmission of ultrasonic signals.

- Longer probing distance
- Ability to localize hot spots

Quench detection with acoustic fibers

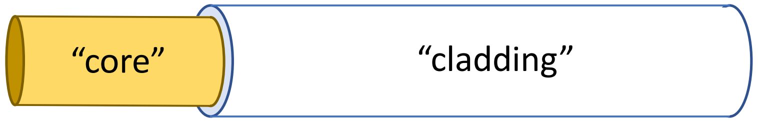


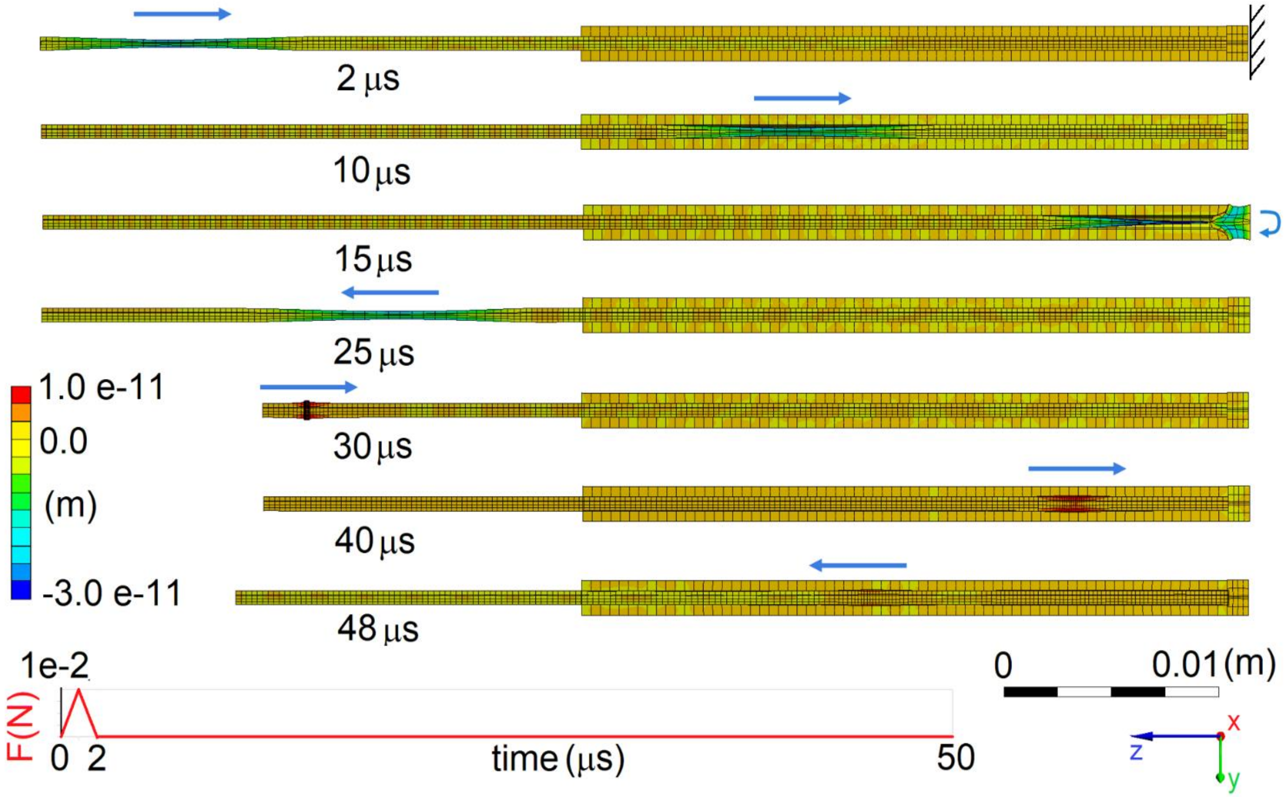


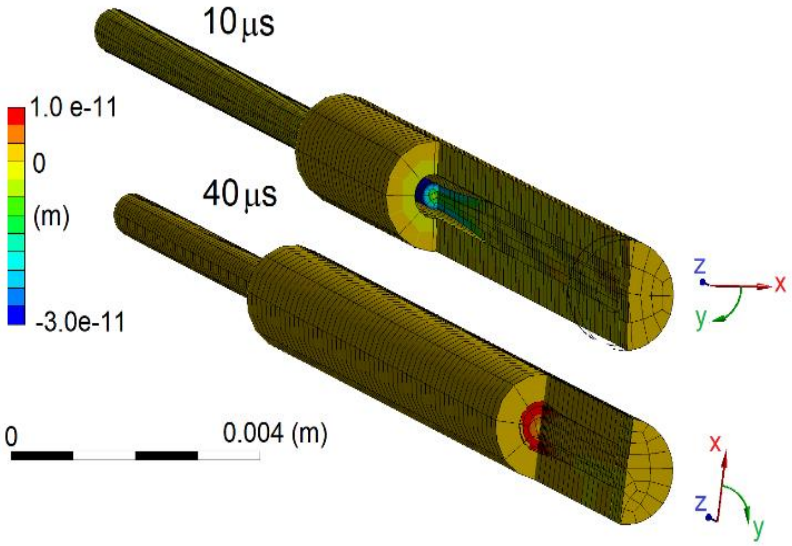


“Ultrasonic Waveguides for Quench Detection in HTS Magnets.” M. Marchevsky, S. Prestemon, O. Lobkis, R. Roth, D. C. van der Laan, and J. D. Weiss, IEEE Trans. Appl. Supercond., 32, 4701705, (2022)

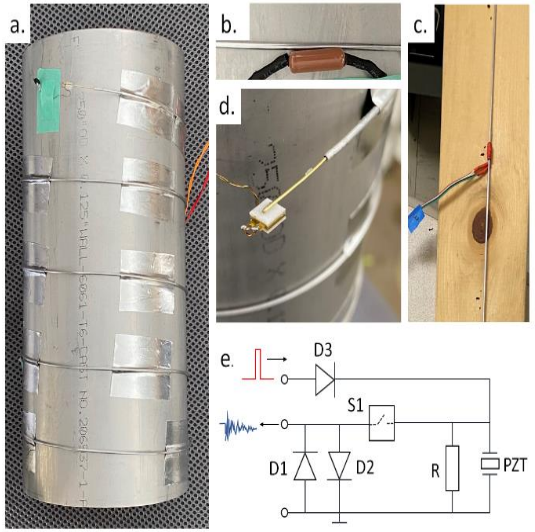
Longitudinal pulse propagation in a cladded waveguide

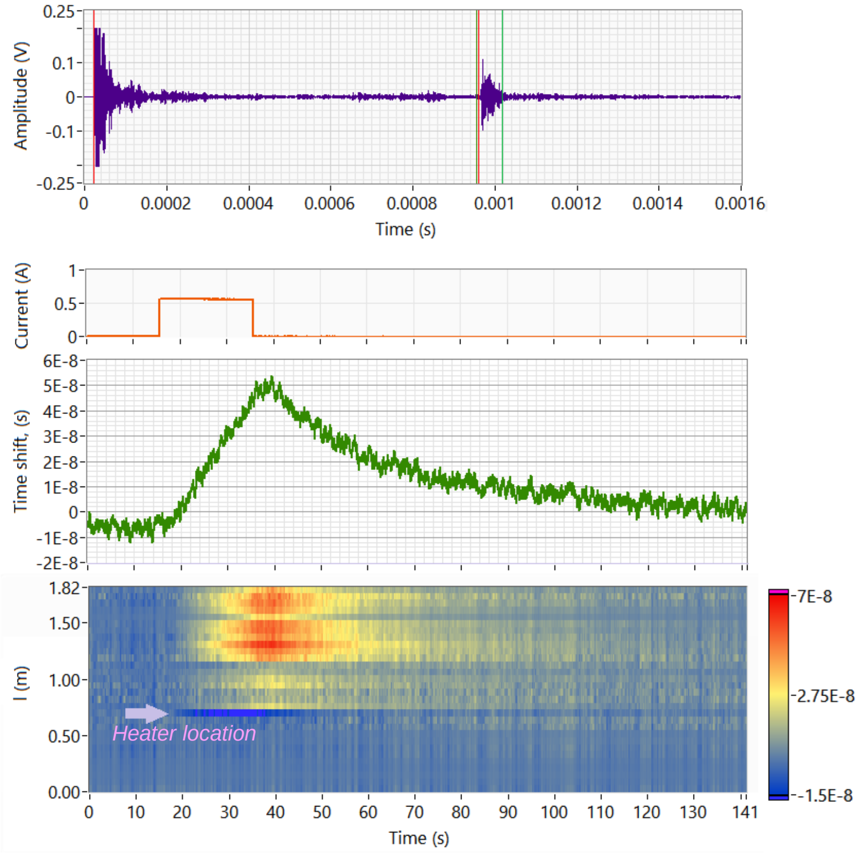


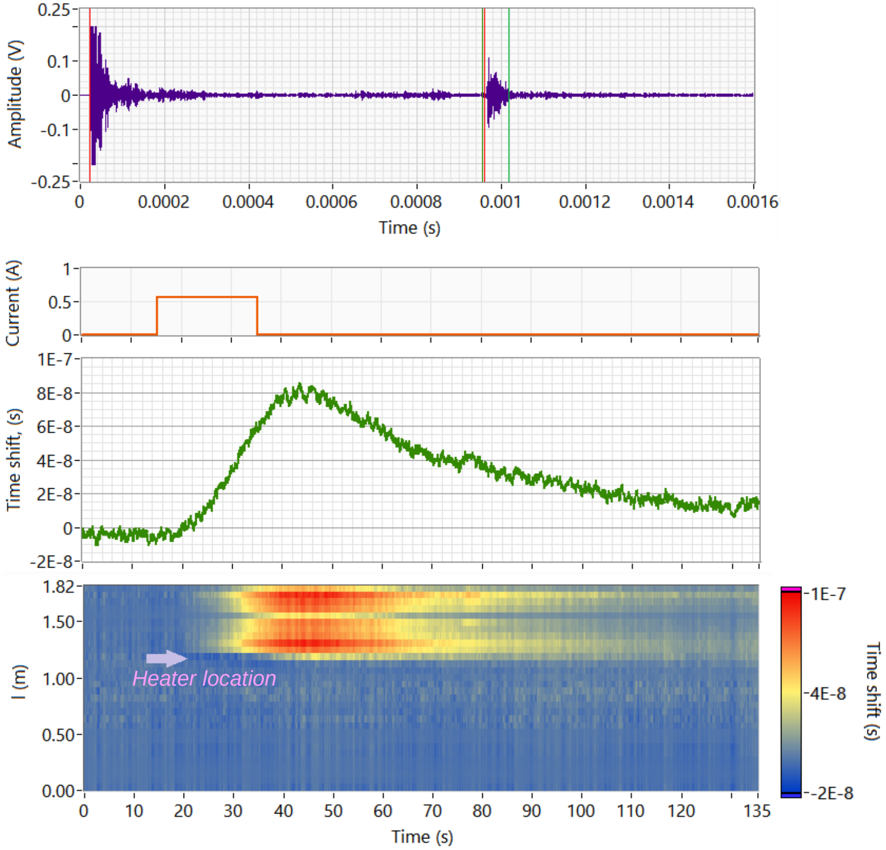




A "non-leaky" acoustic waveguide is suitable for the practical integration of distributed thermometry into HTS magnets



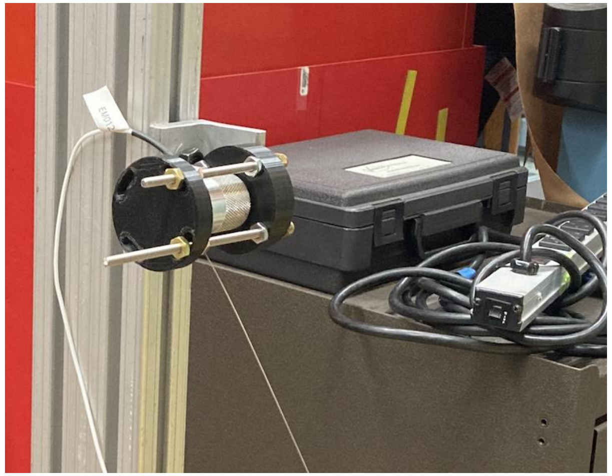


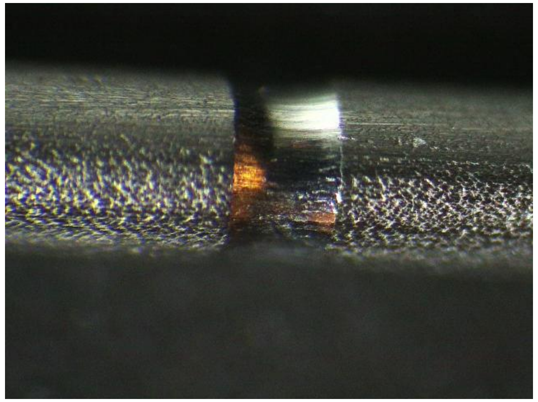


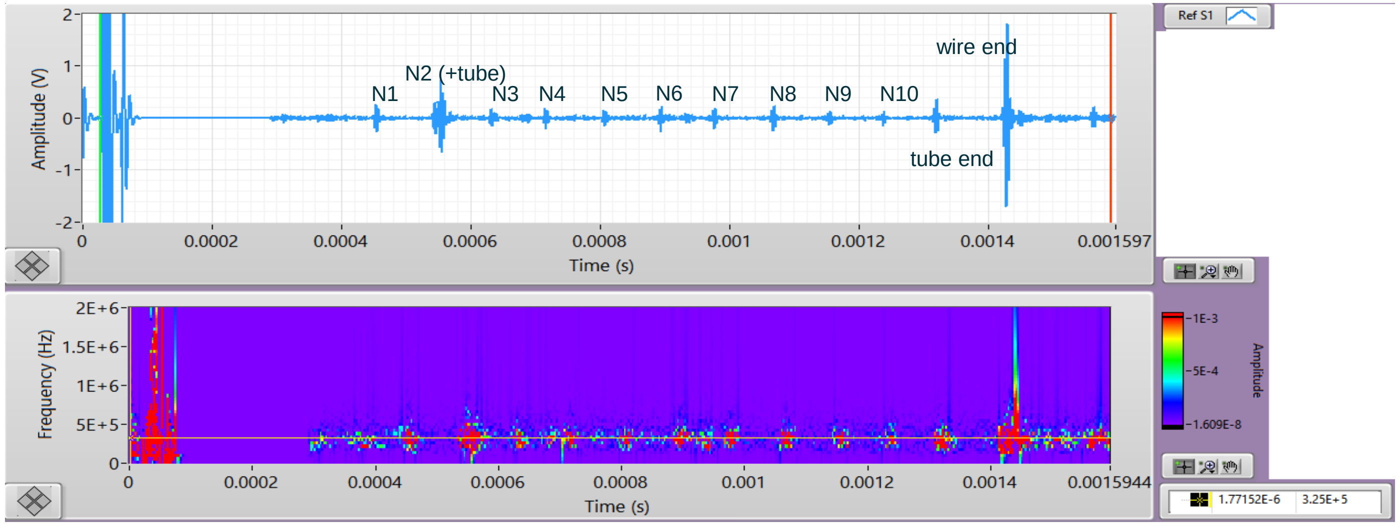
"Distributed thermometry for superconducting magnets using non-leaky acoustic waveguides",
M. Marchevsky and S. Prestemon, Supercond. Sci. Technol. 36 045005, doi:10.1088/1361-6668/acb23a

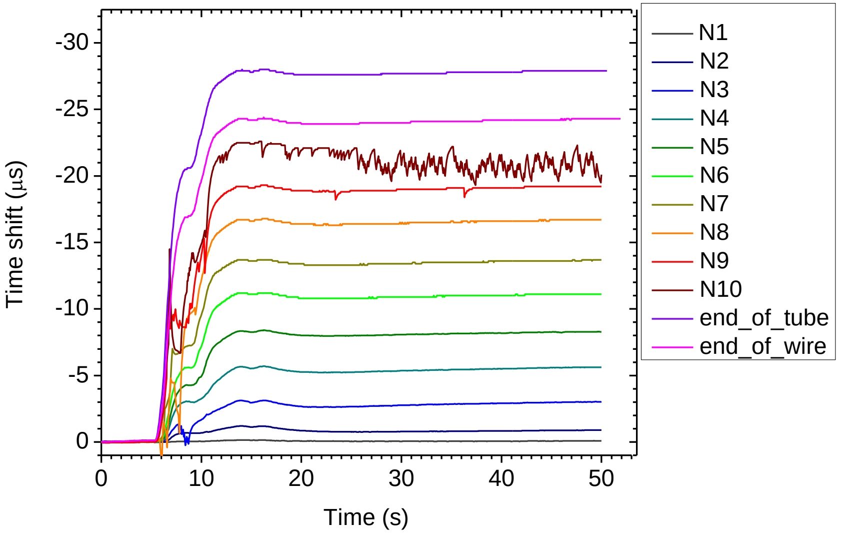
Tests of a 3.4 m-long acoustic fiber sensor

- SBIR Phase I project with Etegent Technologies



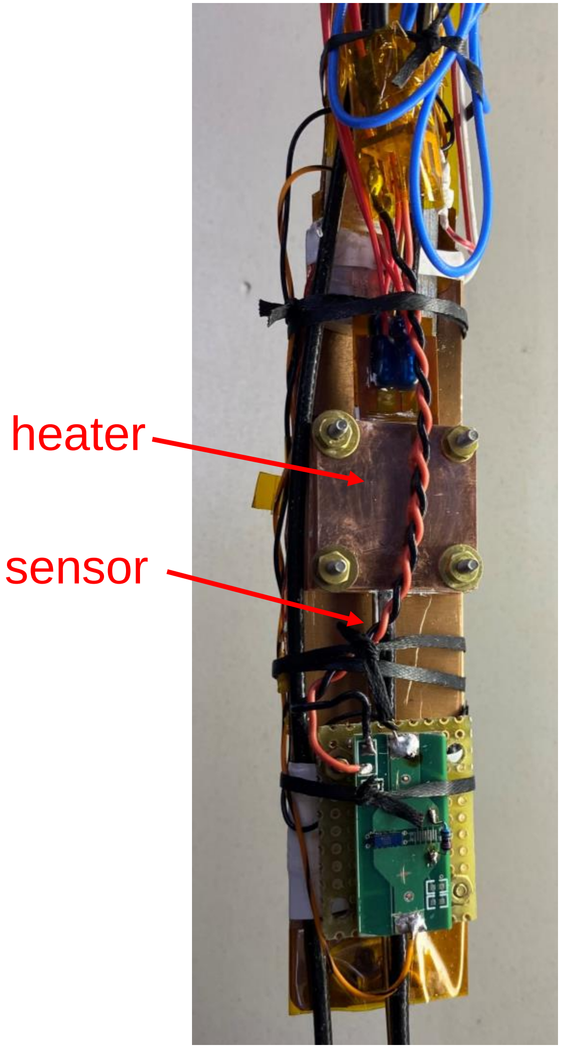




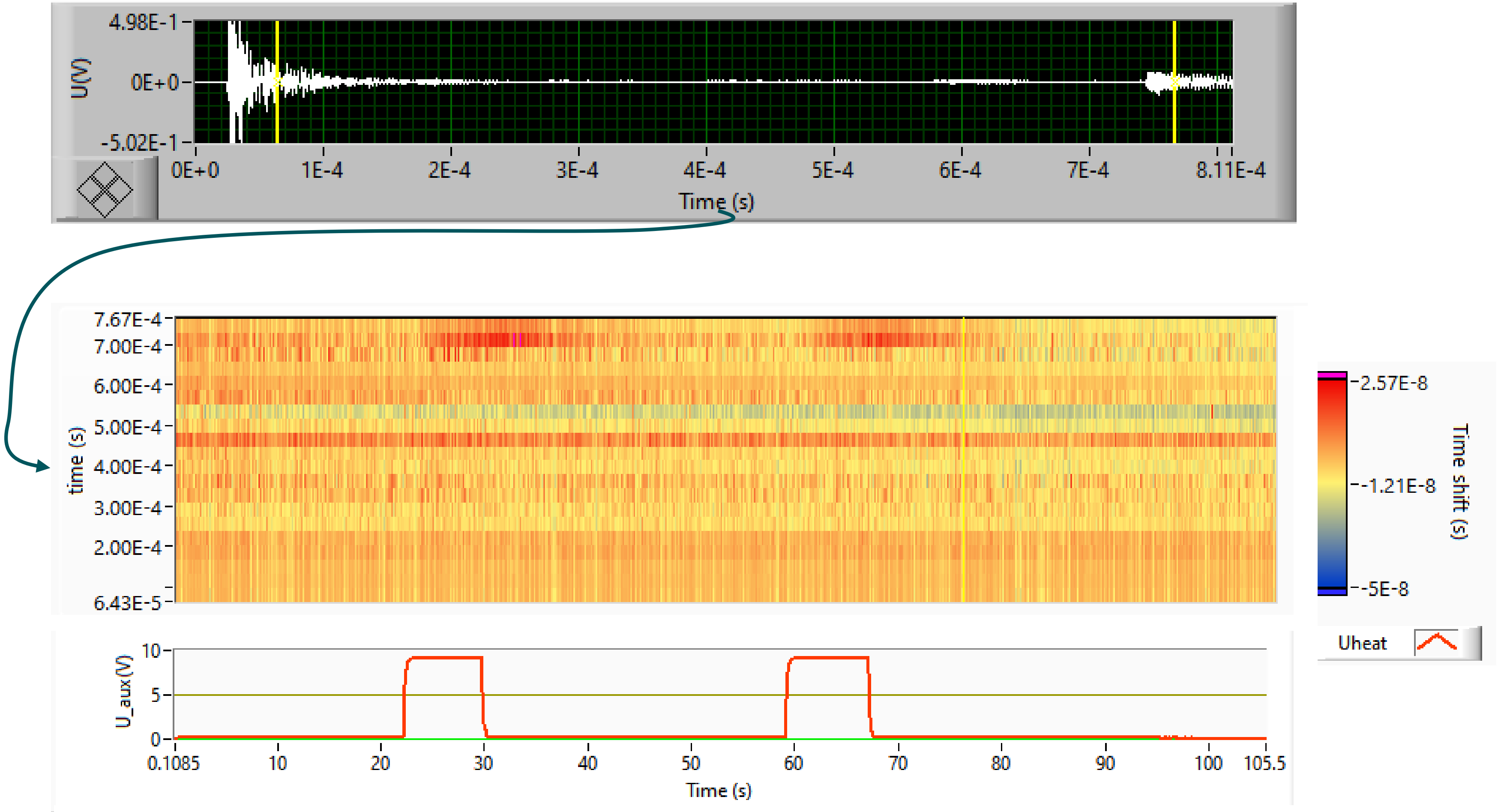


Time shift over cooldown to 77 K

Test at 6 K



ΔT ~ 4 K (from 6 K to 10 K)



RF-based techniques

Principles and realization of TDR

In most TDR systems, a train of suitably generated fast-rising pulses is applied to a transmission line, and the waveform in the line is observed at some point by a voltage probe connected to a sampling oscilloscope or other data acquisition system.

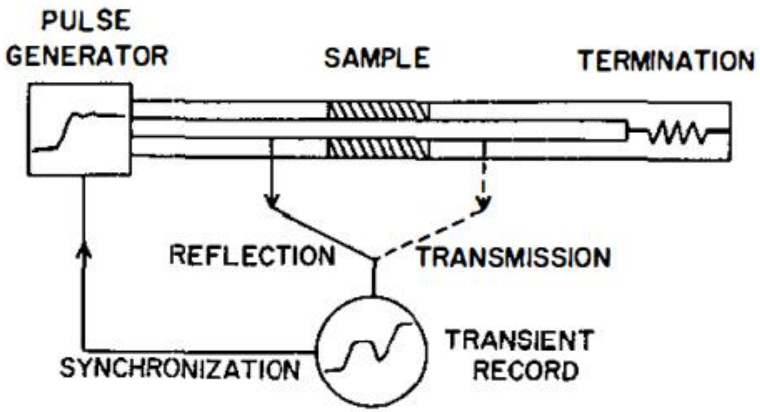
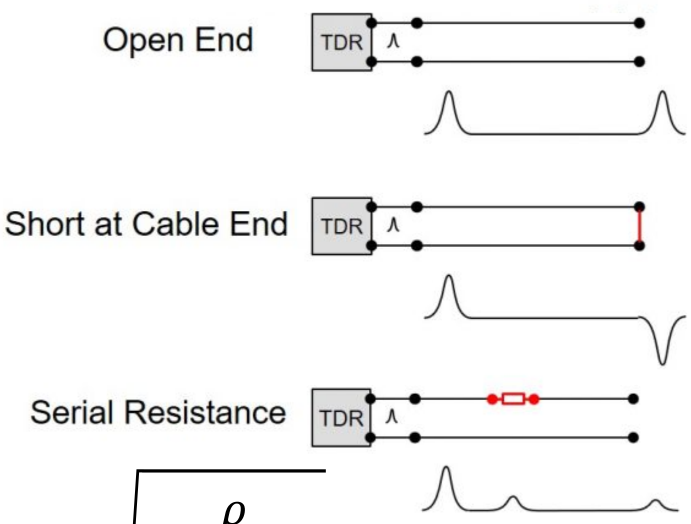


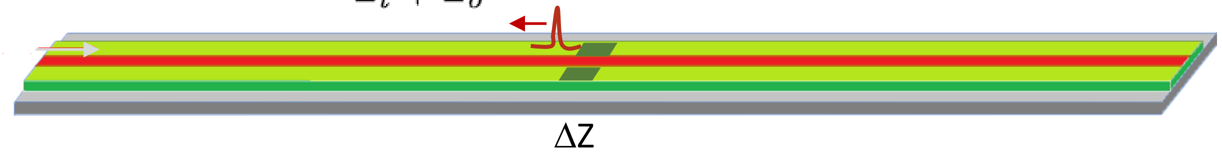
Figure 1 Schematic diagram of instrumentation for time domain measurements.

Pulse width defines the spatial resolution: 0.1 ns => 3 cm in vacuum, ~ 2.5-2.7 cm in the transmission line

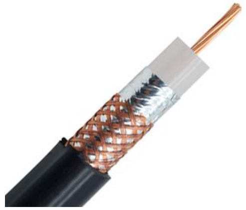
Radio-frequency TDR sensors



$$\rho = \frac{Z_t - Z_o}{Z_t + Z_o}$$



Coaxial cable



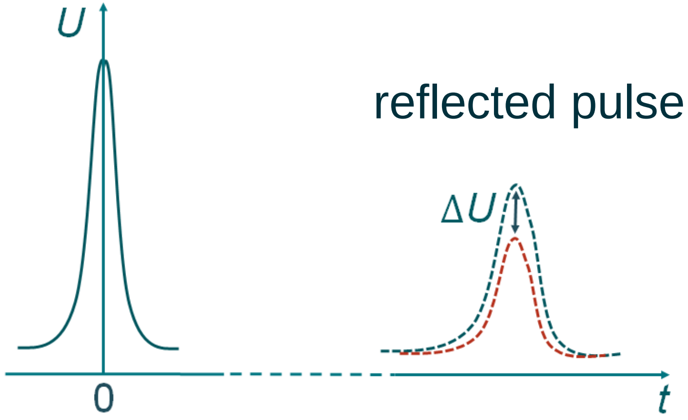
The typical characteristic impedance is 50 Ω

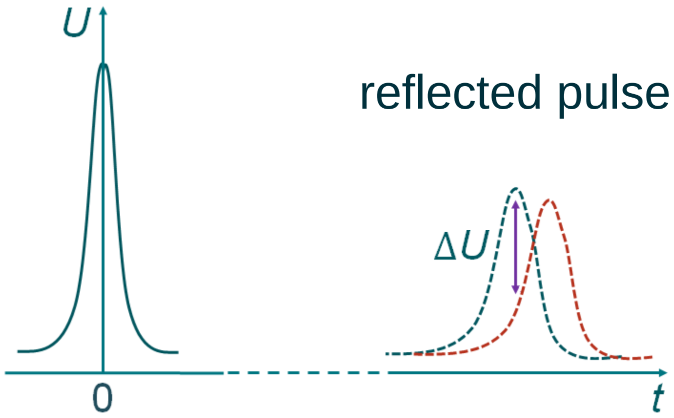
$$Z = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}}\ln\left(\frac{b}{a}\right)$$

$$\delta = \sqrt{\frac{\rho}{2\pi f \mu_R \mu_0}}$$ - skin depth

Change in amplitude

(variation of impedance)





Change in position

(variation of length)

Time domain vs frequency domain measurements

Classical TDR

A short (sub-ns) pulse is sent into the line and its reflection is acquired.

Advantages:
- High repetition rate is possible, and minimal processing is required => very fast

Disadvantages:
- signal is broadband and therefore it may be harder to achieve a high S/N ratio
- GHz-range DAQs are required and they are expensive

Frequency domain TDR:

Frequency response is measured over a broad range and inverse FFT is used to convert data into the space domain

Advantages:
- can be achieved using a single Vector Network Analyzer (VNA)
- signal is narrowband, higher S/N ratio can be achieved using selective amplification

Disadvantage: frequency scanning and processing take a longer time

To obtain a TDR measurement, N frequency tones

$$\omega_i = \frac{2\pi i}{N} f_{max} \,, \quad i = 0, 1 \ldots N-1$$

are subsequently emitted by the VNA, and the signal reflected by the transmission line $S_{11}(\omega) = X(\omega) + jY(\omega)$ is acquired.

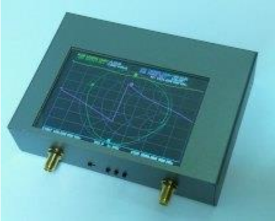
Next, a windowed inverse Fourier transform is calculated to convert the frequency response data into the time domain:

$$U(t) = \frac{1}{N} \sum_{i=0}^{N-1} w_i S_{11}(\omega_i)\, e^{j\omega_i t}$$

using some appropriate window function w_i to enhance spatial resolution

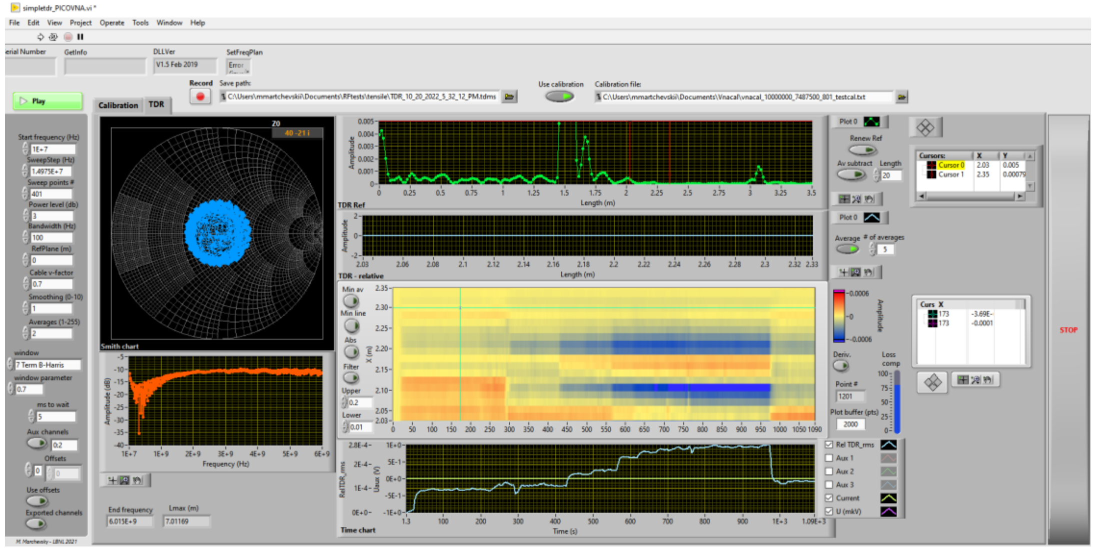
Practical VNA-based TDR

Nano-VNA v2 – a ”toy” VNA with a frequency range of 40 kHz – 4 GHz, 90 dB of dynamic range, and -40 dB noise floor. Can accomplish basic TDR measurement at a minimal cost ($300)



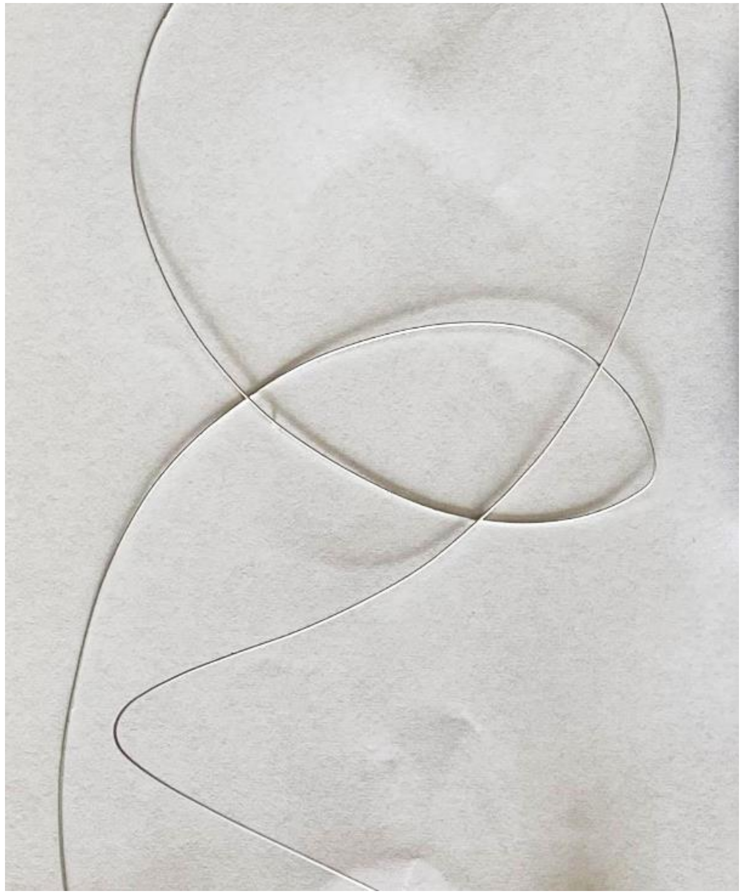
Commercial VNA – “Pico-VNA” from Pico Technologies (0.1 MHZ – 6 GHZ range, 124 dB of dynamic range, - 60 dB noise floor), (~$6000)

Software – in-house written Labview suite interfacing to both devices’ APIs for acquiring S11 data, converting it into the time domain, and providing essential visualization capability



DLLVer: V1.5 Feb 2019
SetFreqPlan: Error
Save path: C:\Users\mmartchevskii\Documents\RFtests\tensile\TDR_10_20_2022_5_32_12_PM.tdms
Calibration file: C:\Users\mmartchevskii\Documents\Vnacal\vnacal_10000000_7487500_801_testcal.txt
Start frequency (Hz): 1E+7
SweepStep (Hz): 1.4975E+7
Sweep points #: 401
Power level (db): 3
Bandwidth (Hz): 100
RefPlane (m): 0
Cable v-factor: 0.7
Smoothing (0-10): 1
Averages (1-255): 2
window: 7 Term B-Harris
window parameter: 0.7
ms to wait: 5
Aux channels: 0:2
Offsets: 0
End frequency: 6.015E+9
Lmax (m): 7.01169
Z0: 40 -21 i
Length: 20

Micro-coax as strain and temperature sensor

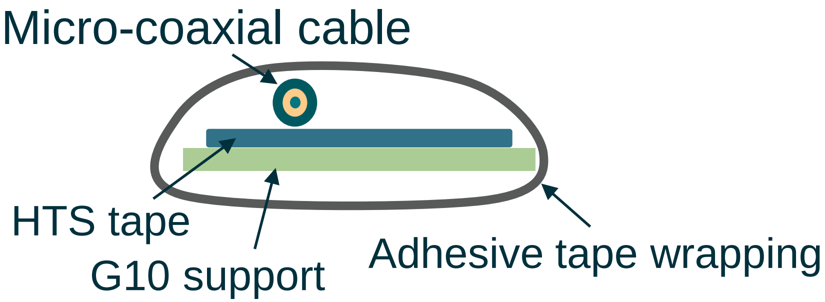


- 32 AWG (0.2 mm central conductor, 1.1 mm diameter) micro-coaxial cable, PFA insulation)
- 40 AWG (0.07 mm central conductor, 0.2 mm diameter, PFA insulation)

The shield is silver platted copper braid

PFA insulator

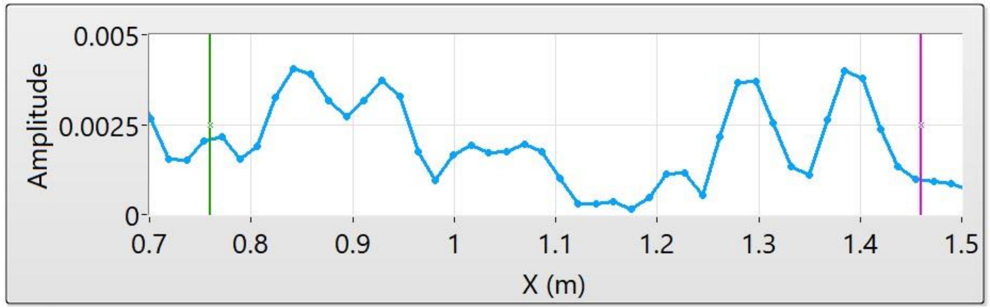
Thermal quench sensing using micro-coaxial cable


Micro-coaxial cable

HTS tape

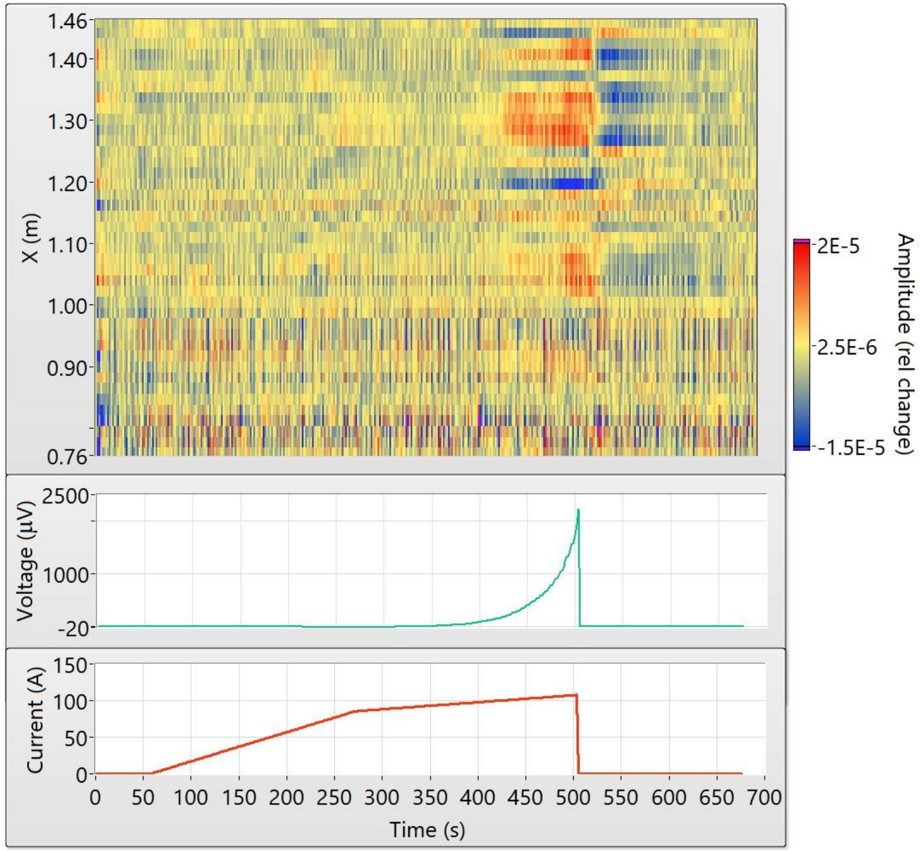
G10 support

Adhesive tape wrapping



Plotting a derivative of the change better separates local variation from the background.

Peak power is 0.24 W



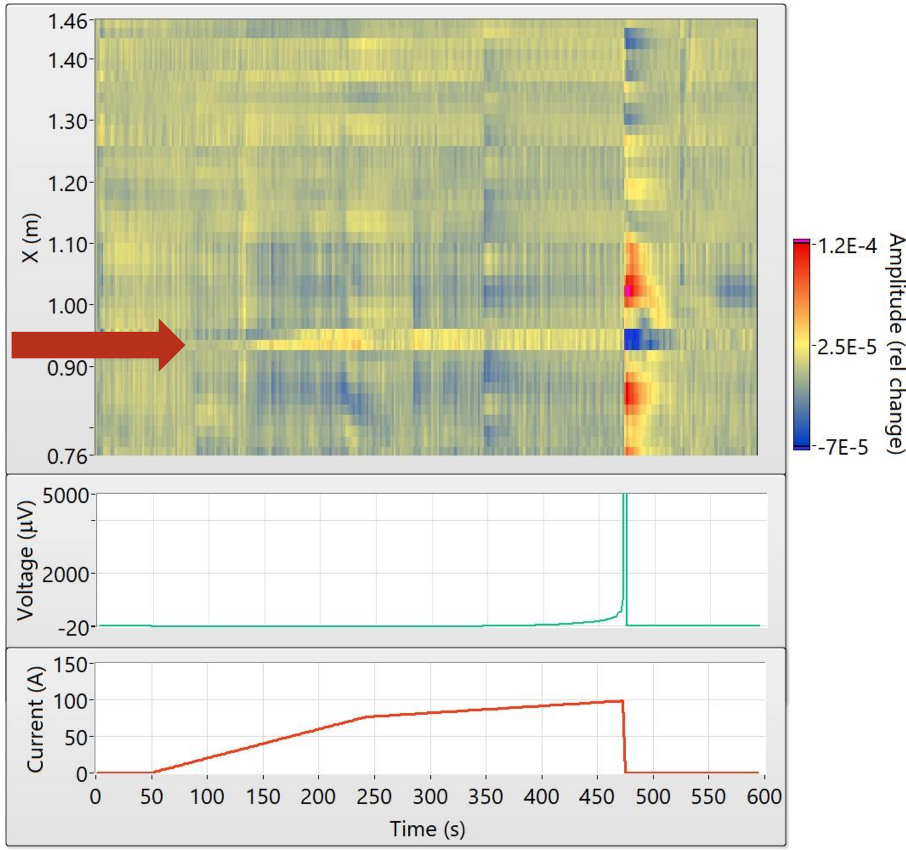
Thermal quench sensing using micro-coaxial cable

Permanent magnet (~ 0.1 T surface field)

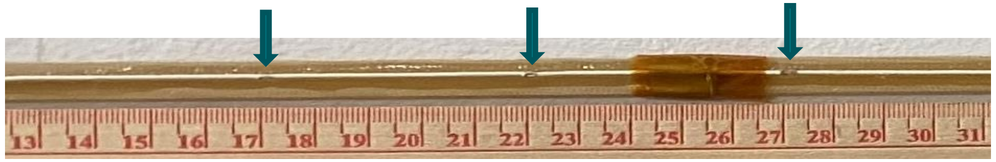
Placing a permanent magnet next to the tape reduced critical current locally, leading to a quench development at ~100 A

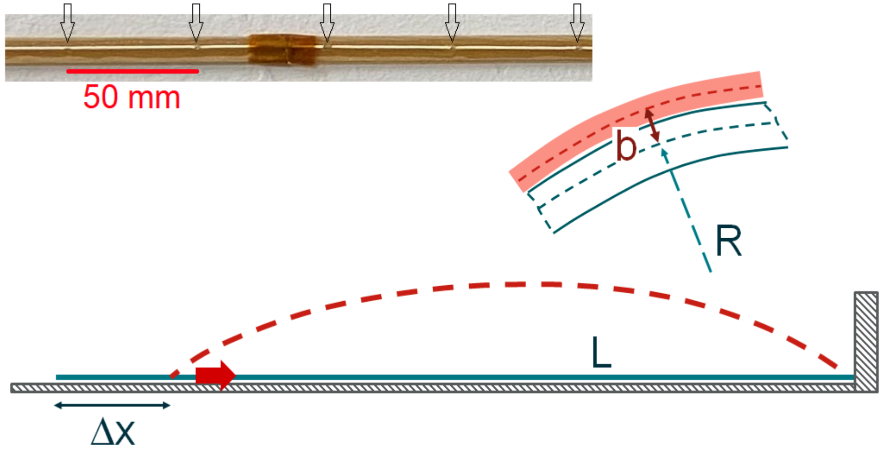
Heat distribution along the tape has changed, and a large heated area centered at the magnet position has been observed.

Magnet position

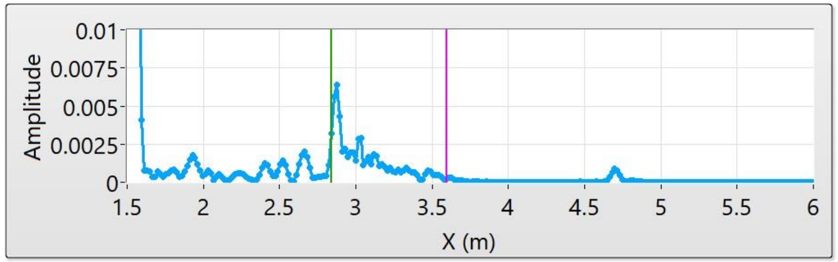


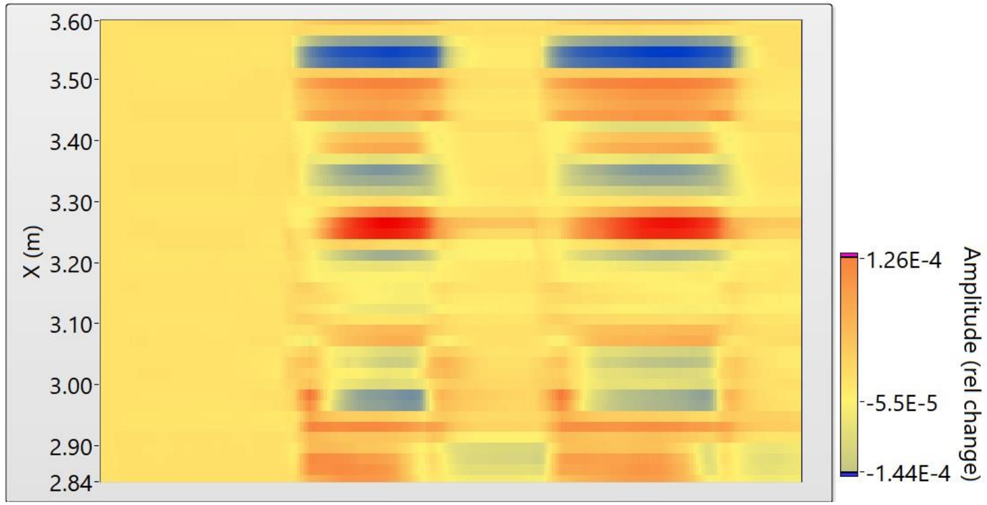
Strain sensing using TDR

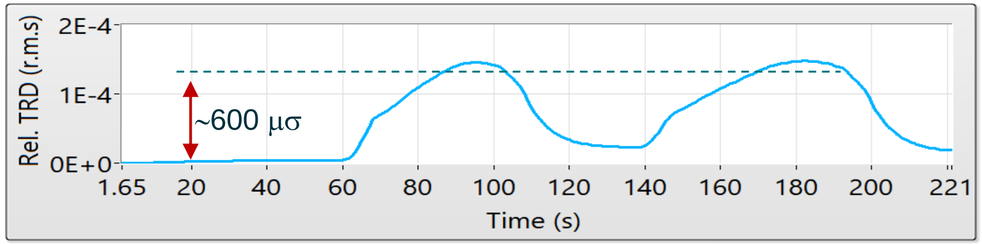




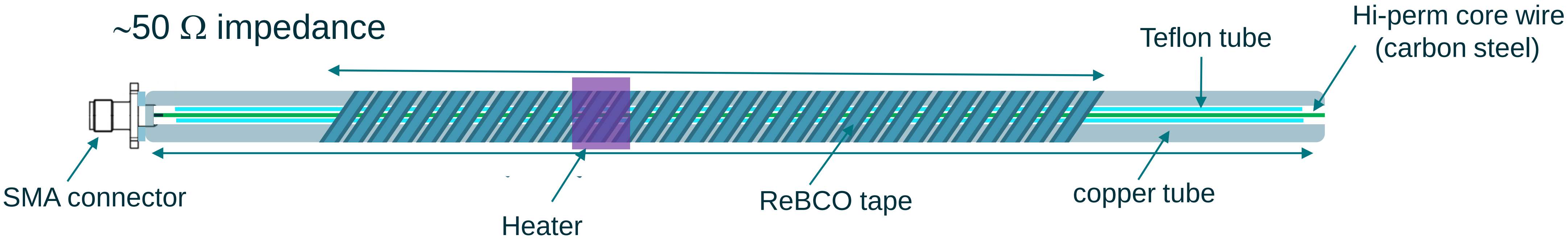
$$\frac{L-\Delta x}{2R}=\sin\left(\frac{L}{2R}\right)$$

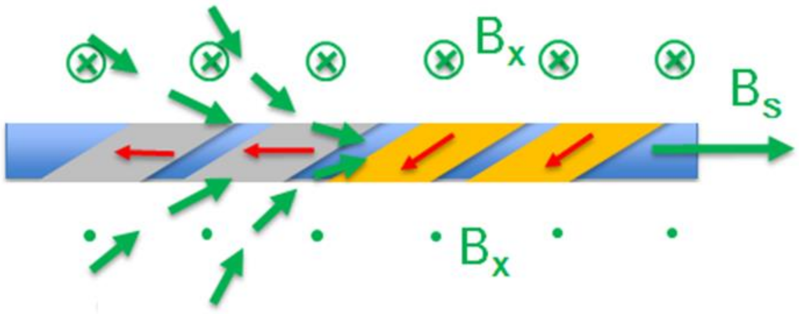






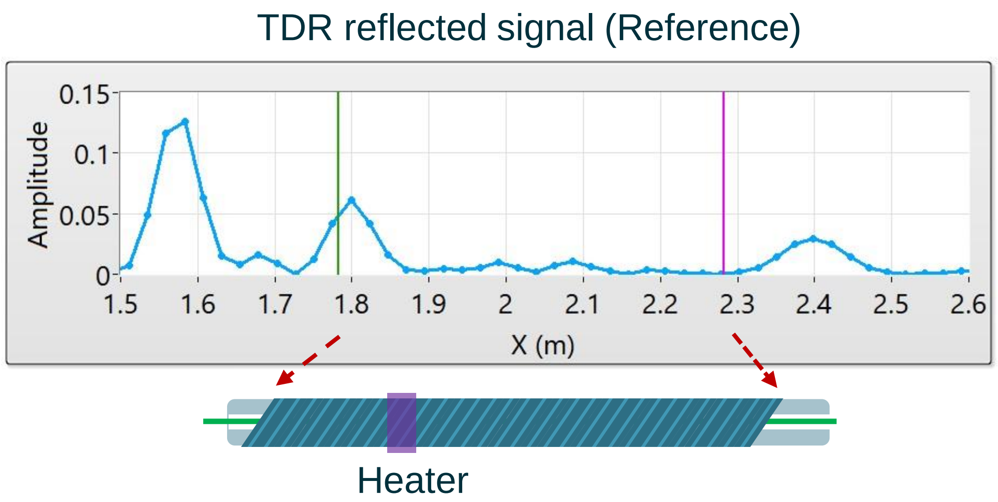
Magnetic TDR sensor

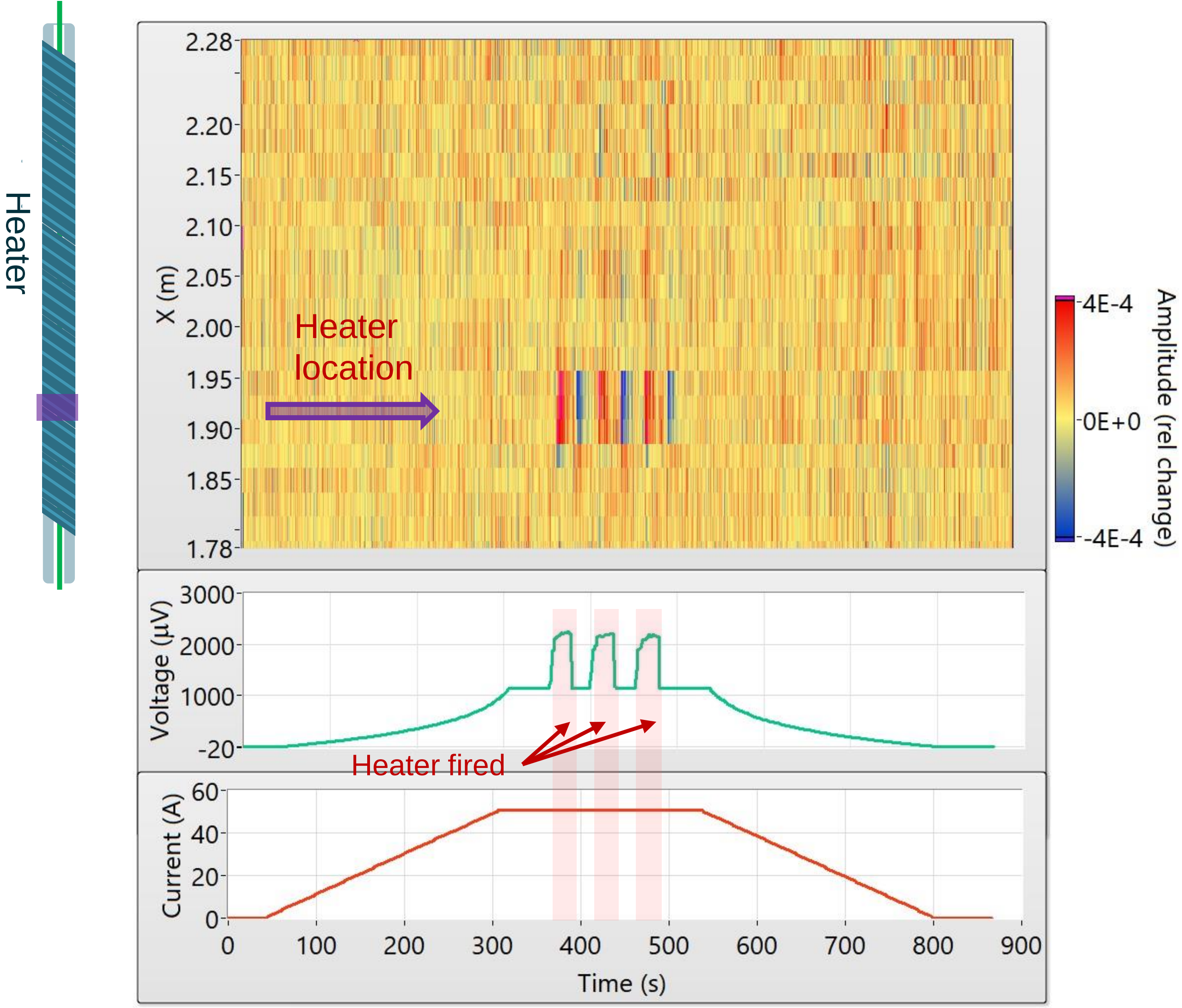




- The solenoidal current path yields an axial magnetic field in the copper tube, along the core magnet wire
- When the solenoidal current path is interrupted due to a hot spot formation, this field “leaks out, thus locally reducing the field in the core

Magnetic TDR sensor for cable diagnostics





- Spot heater locally transitions the tape to the normal state, causing current and magnetic filed re-distribution at that location
- Derivative of the reflected RF signal shows change at the heater location when the heater is energized. No response is seen when no current is flowing in the tape.

"Radio Frequency-Based Diagnostics for Superconducting Magnets",
M. Marchevsky , G. S. Lee , R. Teyber , and S. Prestemon, IEEE, Trans. Appl. Supercond., v. 33, (5), 9000206 (2023), https://doi.org/10.1109/TASC.2023.3236877

Summary

- Distributed temperature monitoring is a valid practical method for early quench detection in HTS superconducting cables and magnets. Thermal sensitivity of the order of 1 K is required at a base temperature < 20 K and sensitivity of the order of 0.1 K is needed at ~ 77 K.

- Time domain reflectometry in acoustic and RF domains is a promising technique for distributed diagnostics of HTS conductors, and detection, and localization of hot spots. It has the potential to be a robust and inexpensive alternative to optical techniques allowing to implement the distributed sensing on a large scale and a relatively small budget.

- Tests of both technologies are presently underway at LBNL in collaboration with commercial partners, aiming at sensor lengths of 10 + meters and integration into practical HTS subscale coils and hybrids developed under US Magnet Development Program and towards future fusion applications.