U.S. MAGNET DEVELOPMENT PROGRAM

Novel Diagnostics: Current Activities and Milestones

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12/18/24

U.S. DEPARTMENT OF ENERGY | Office of Science

AIIIb – Diagnostics and quench protection

Diagnostics and instrumentation are the basis for all magnet performance information obtained during magnet fabrication and testing and are central to the MDP mission. Multi-sensor diagnostics data obtained in the R&D magnet tests, coupled with AI/ML processing and advanced models, inform our understanding of magnet performance and guide technology improvements.

Quench protection is vital for safe and reliable magnet operation, and it fully relies on the early warning signals produced by the diagnostic and quench detection systems and instrumentation.

AIIIb: Main goals

LTS magnets

- Uncovering physical mechanisms responsible for premature quenching and training. Developing new diagnostics and analysis techniques to probe mechanical energy conversion into heat.
- Performing well-controlled small-scale experiments to better understand the transient thermo-mechanical phenomena and inform the search for new impregnation materials and techniques for future high-field LTS magnets.

HTS and hybrid magnets

- Developing techniques for real-time detection and localization of hot spots is of major importance. Different non-voltage sensing modalities (ultrasonic, RF-based, Hall sensors, fiber-optics) recently explored by the MDP need to be scaled up and integrated into prototype magnet coils to compare their efficiency.
- Techniques for in-situ localization of HTS conductor defects and quantifying current sharing in cables need to be developed
- Various novel quench protection techniques (CLIQ, active current control, smart insulation, etc.) must be explored further for use with hybrid high-field magnets of very large stored energy. Specifically, the interaction between LTS and HTS protection systems is a critical R&D topic for the hybrids. A robust, reliable, and self-consistent quench detection/protection solution for HTS and hybrid magnets is the ultimate goal.

AIIIb: Near-term challenges

- Addressing analysis of big diagnostic data from recent magnet tests with AI/ML. Identifying relevant data connected to magnet behavior and anomalies
- Understanding fundamental mechanisms of transient mechanics and associated heat deposition in LTS conductors and various magnet impregnation materials via small-scale experiments. Providing essential feedback to the MDP design and modeling effort
- Understanding under what conditions can we detect hot spots and safely protect HTS magnets? Developing hardware and software to address this challenge
- Pursuing integration of diagnostic instrumentation into magnets at the early stage of magnet design and construction. Improving communication and joint planning with other MDP groups.

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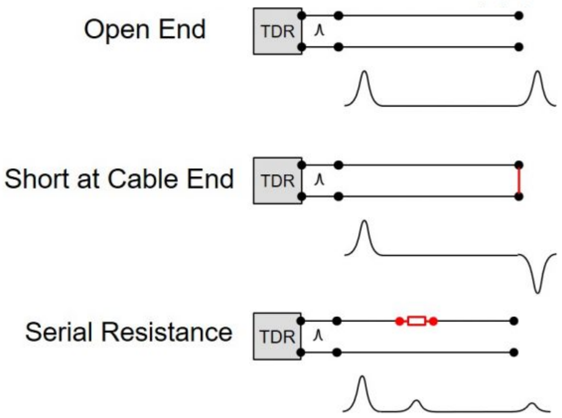
Diagnostics milestone table (2025-2027)

Milestone #	Description	Status	Updated Target	Requestor	Comments
AIIIb-M1	a) Development of RF-based distributed thermal sensing b) Integration of the non-optical and distributed sensing (ultrasonic and RF) into prototype magnets c) Quench antenna development	In progress	Dec-25 Dec-26 ongoing – Dec 26	M. Marchevsky, S. Krave, J. Di Marco, R. Teyber	
AIIIb-M2	a) Large-scale Hall array-based imaging and quenching studies for HTS tapes and cables. b) Quench-tolerant HTS conductor studies.	In progress	Dec-25 Dec-26	M. Marchevsky	In collaboration with Polytechnique Montreal
AIIIb-M3	Diagnostics magnet test / magnet test beds for diagnostics	Started	Jun-27	S. Stoynev	
AIIIb-M4	a) Development and test of MOSFET cryogenic current controls b) Development of novel quench protection methods	Started	Sep-25 ongoing – Dec 27	M. Marchevsky	+SBIRs
AIIIb-M5	Development and test of a non-rotating new magnetic probe prototype	In progress	Dec-25	J. DiMarco, M. Marchevsky	
AIIIb-M6	a) Demonstration of a programmable fully-cryogenic FPGA "smart" sensor core with digital readout. b) Cryo-electronic data acquisition package development	In progress	Aug-25 Jun-27	M. Turqueti, P. Joshi	
AIIIb-M7	a) Energy spectrum analysis b) Coil azimuthal strain mapping c) Strain mapping using distributed fiber d) Temperature sensing / quench propagation tests with HTS	In progress	Dec-25	M. Baldini, S. Krave	
AIIIb-M8	a) Develop quality control capabilities to identify defects and performance limiting regions in REBCO cables and accelerator magnets. b) Advance numerical and experimental abilities to monitor and predict current distributions in ReBCO cables for accelerator magnets	In progress	May-25 Dec-26	R. Teyber	Direct feedback to HTS/CORC magnet development. Seek to exploit recent FES research progress in HEP magnets. +SBIRs
AIIIb-M9	a) Small scale transient thermal energy deposition experiments. b) Development of thermal transient diagnostics instrumentation and data processing.	In progress	Dec-25 Dec- 26	M. Marchevsky, A. Saravanan	

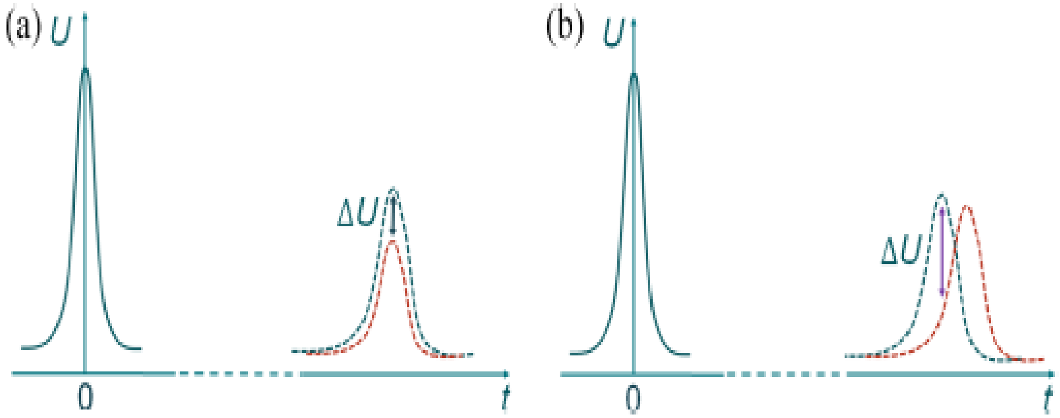
Development of RF-based distributed thermal sensing



$$S_{11}(\omega) = X(\omega) + jY(\omega)$$

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

$$w_i = \sum_{k=0}^{m-1} (-1)^k \cos\left(\frac{2\pi i k}{N}\right)$$



- **Focus on identifying best suitable insulation materials that exhibit substantial temperature dependence of the dielectric constant ore resistance in the entire RT - 4.2 K temperature range.**

Various commercial and home-made coaxes using non-standard dielectric materials were tested and possible candidates for future developments identified

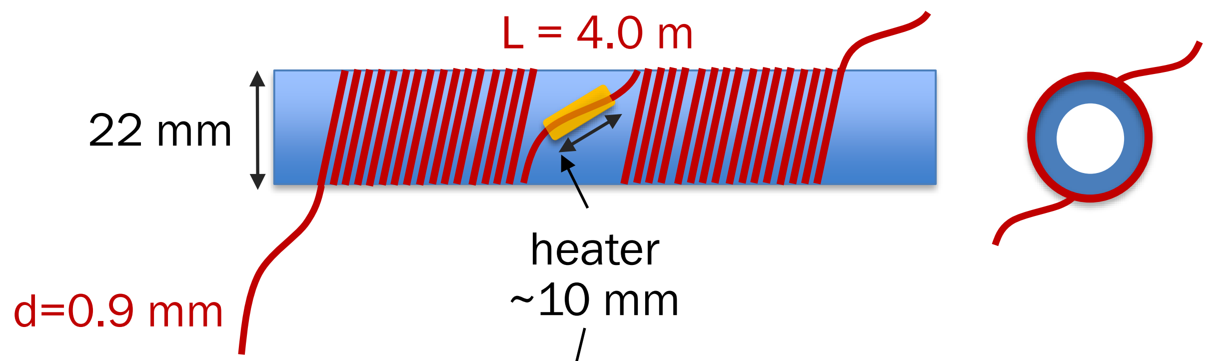
There are dielectrics that exhibit substantial ε(T) variations

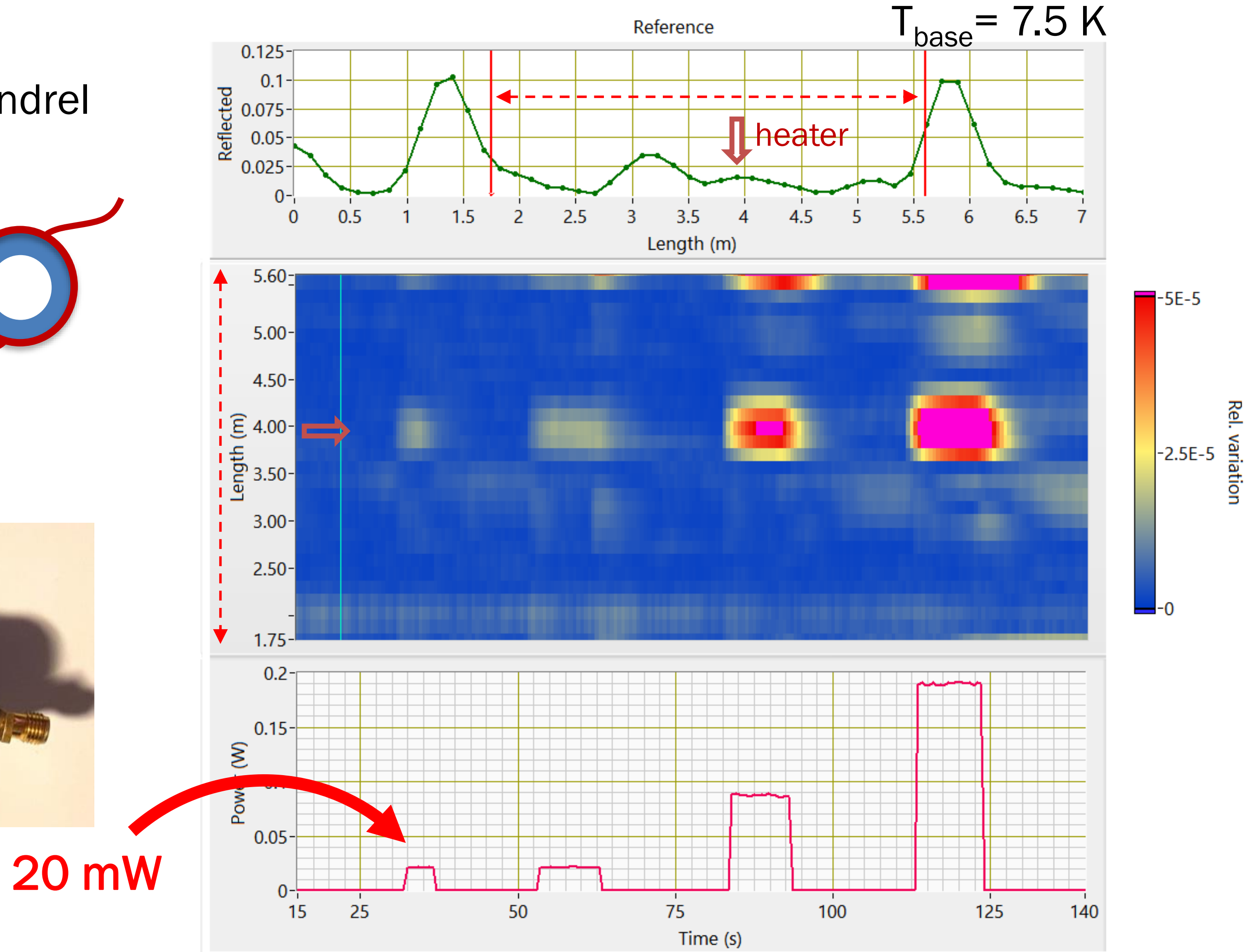
Same dielectrics that exhibit substantial e(T) are usually also exhibit high losses at frequencies above 1 GHz, limiting spatial resolution of the potential sensor

AIIIb-M1

An experiment on a 4 m-long RF sensor at 7.5 K

Coaxial cable sensor wound around a Garolite mandrel





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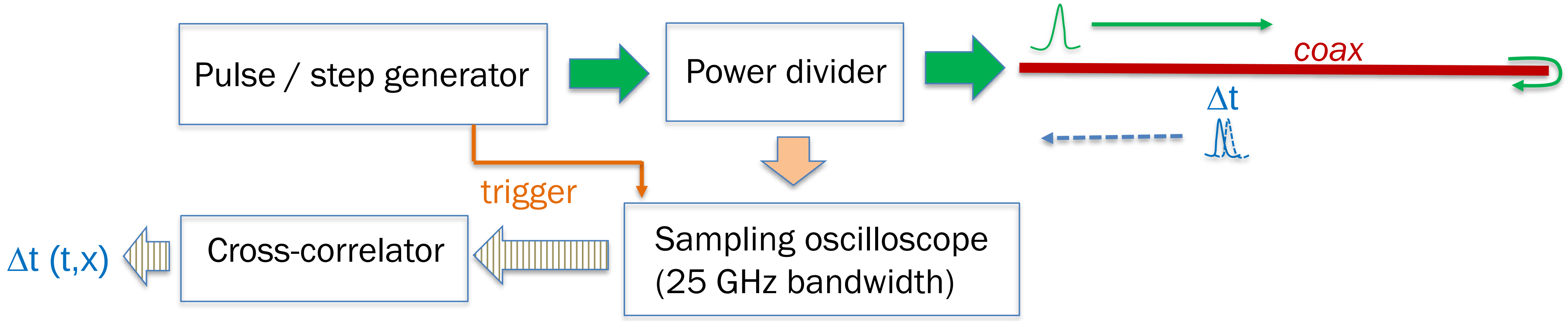
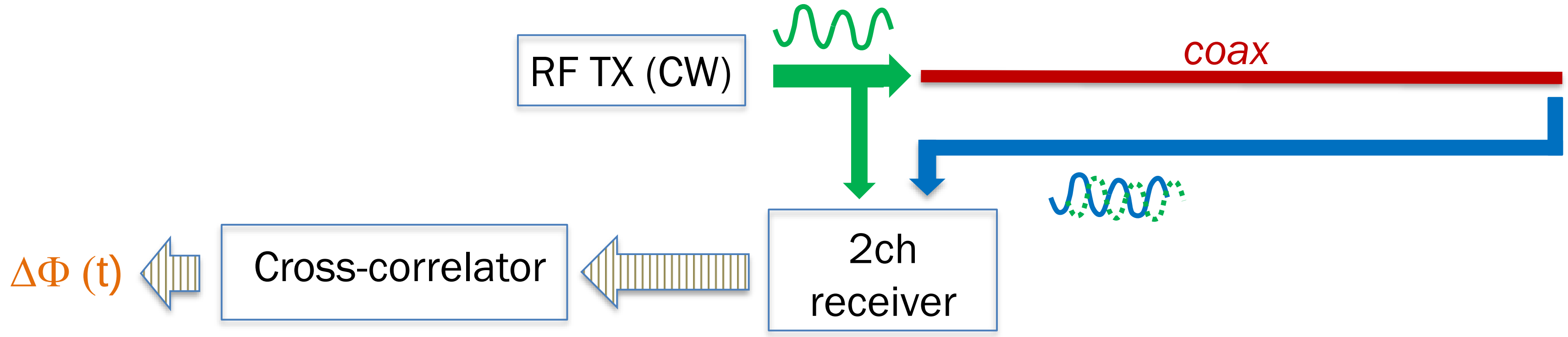
New RF developments

1. TDR with ps-level time resolution. Measuring *time shift* instead of amplitude.
   Advantage: much higher spatial resolution, Immunity to parasitic capacitances, losses.

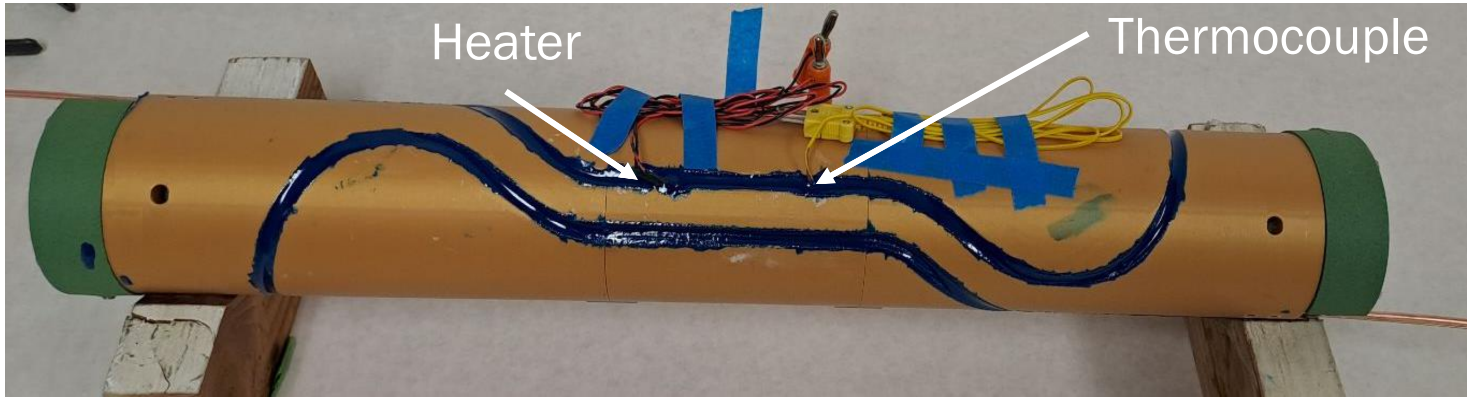


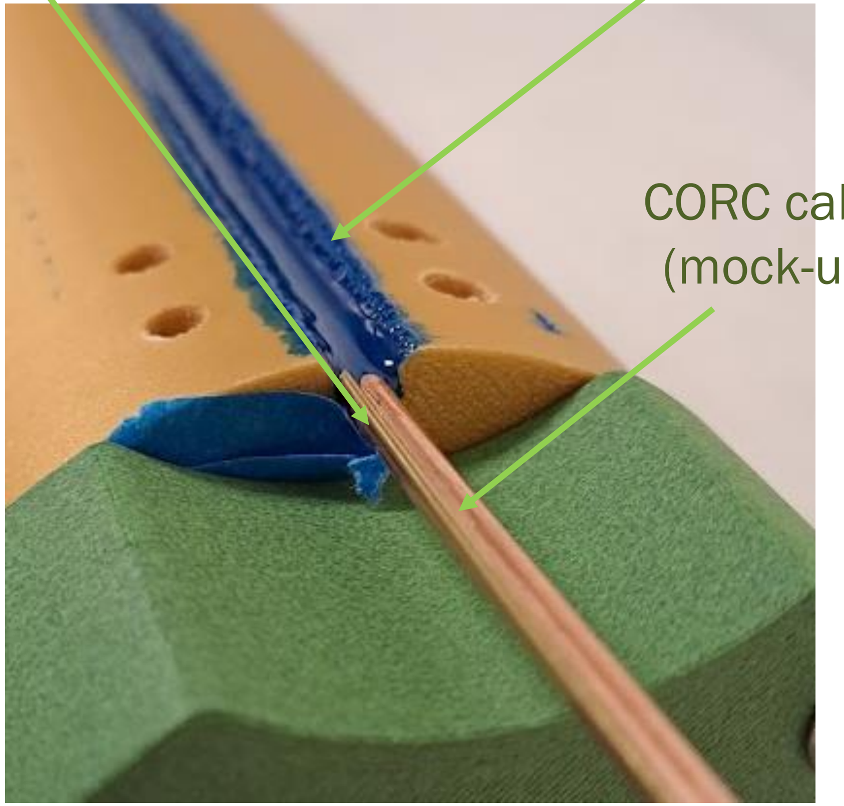
2. RF interferometer: a simple standalone hardware solution. High sensitivity and speed, inexpensive, but no localization.



Integration of an ultrasonic waveguide sensor into a prototype unilayer CORC® coil

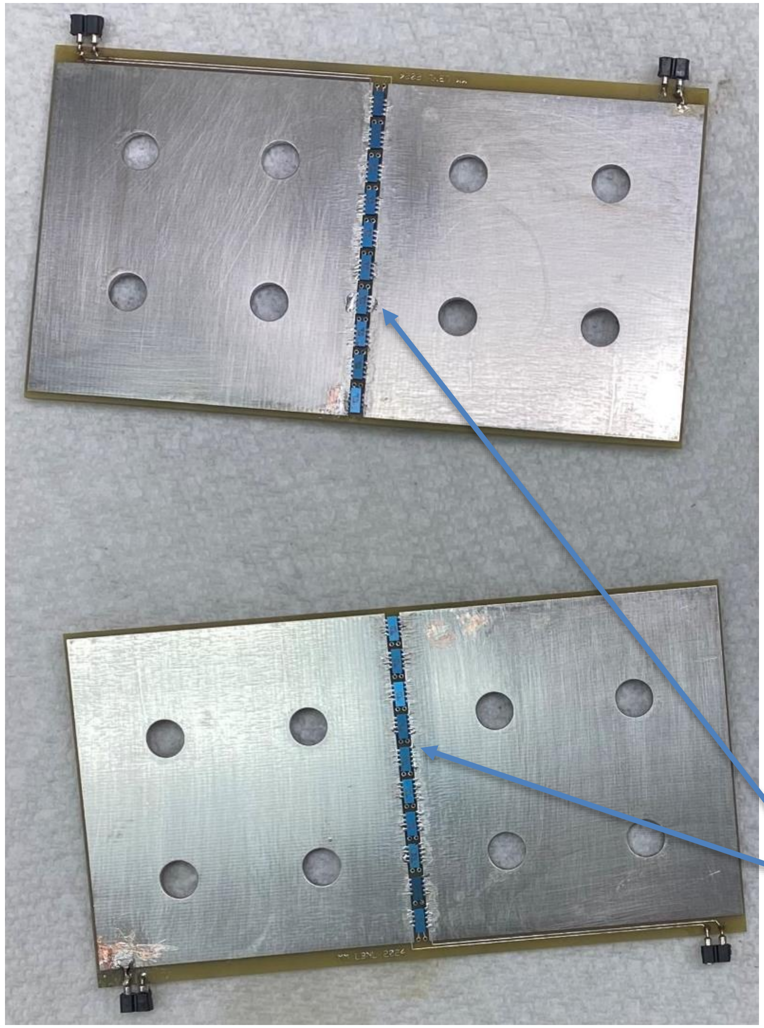
Davide Cuneo (INFN), J.L. Rudeiros-Fernadez (LBNL)



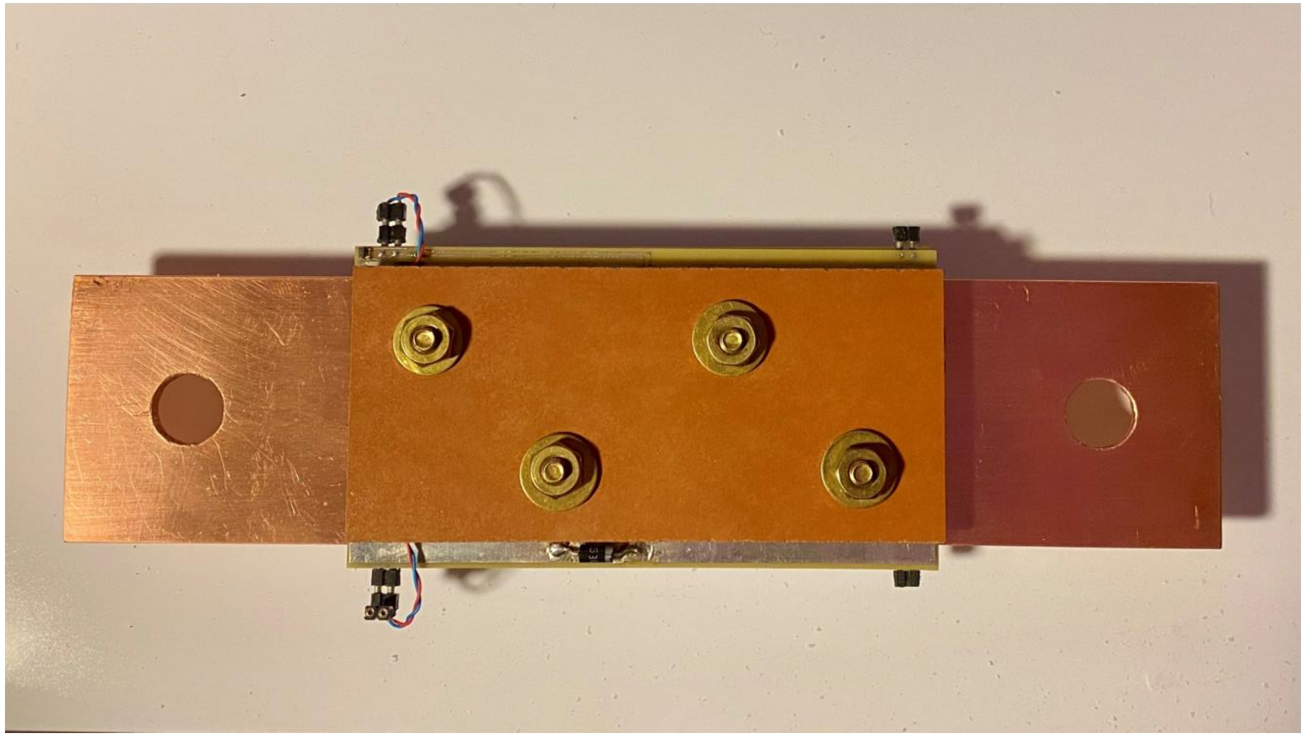


- **Due for the beginning of March**
- Test of the CORC cable (straight) to assess I_c at different field levels
- Winding of the CORC on the Uni-Layer mandrel (aluminum)
- Test of the degradation of the I_c due to the bending after winding
- Implementation of the acoustic waveguide on top of the conductor
- Test of the acoustic waveguide
- **Future Development**
- Development of a full mandrel with a secondary channel
- Implementation of the sensor on a secondary channel under the conductor (45 degrees channel)
- Test of the sensor in this last configuration

Development of a high-current cryogenic MOSFET driver

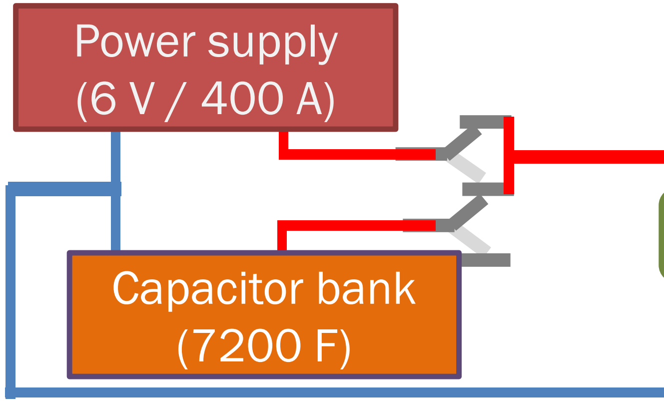


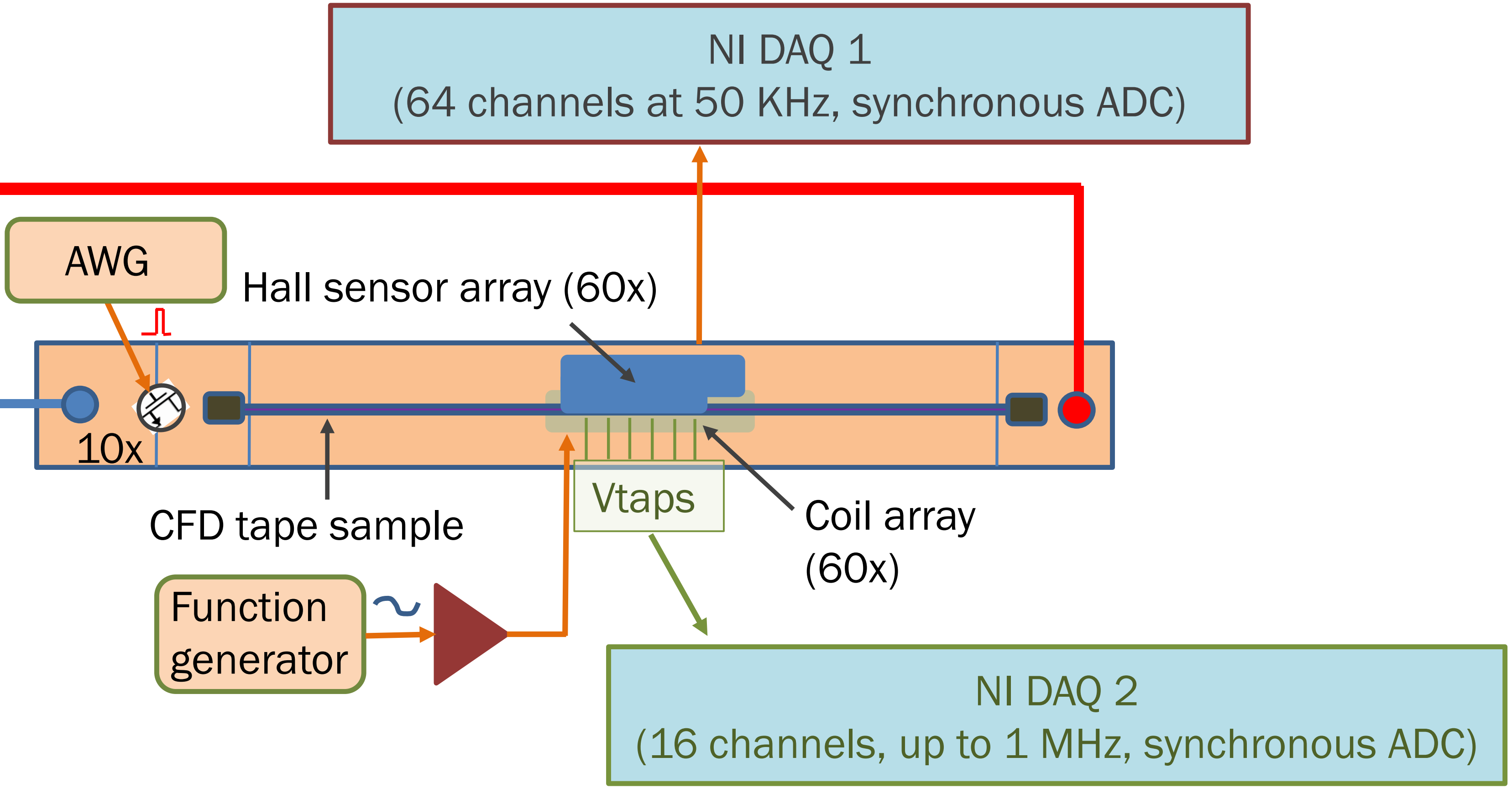
An assembled prototype board for 500+ A cryogenic use

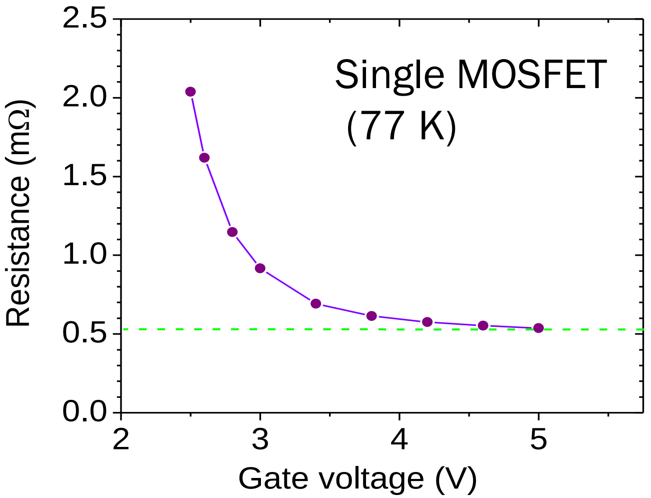


20x GaN MOSFETs
(30 A per, 2.5 mΩ at 77 K per device)

Block diagram of the setup







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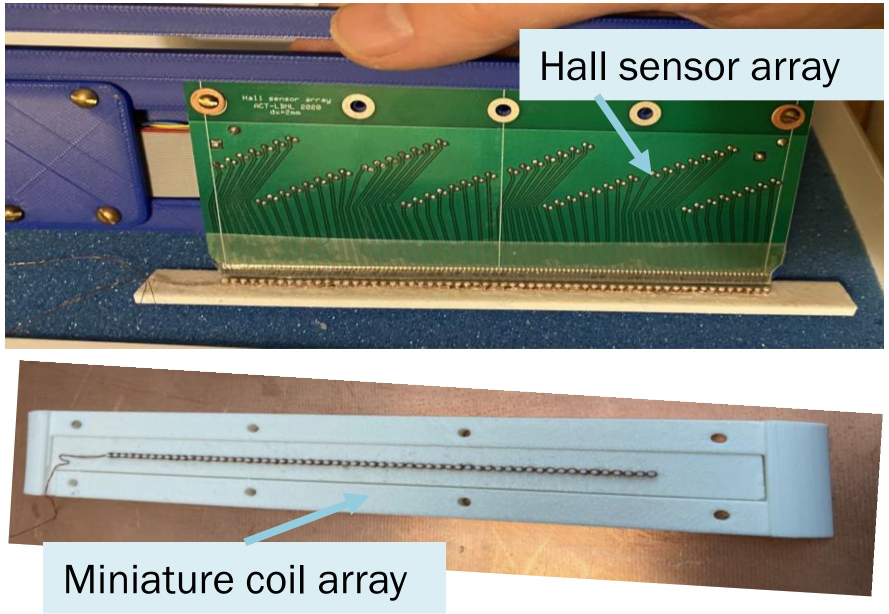
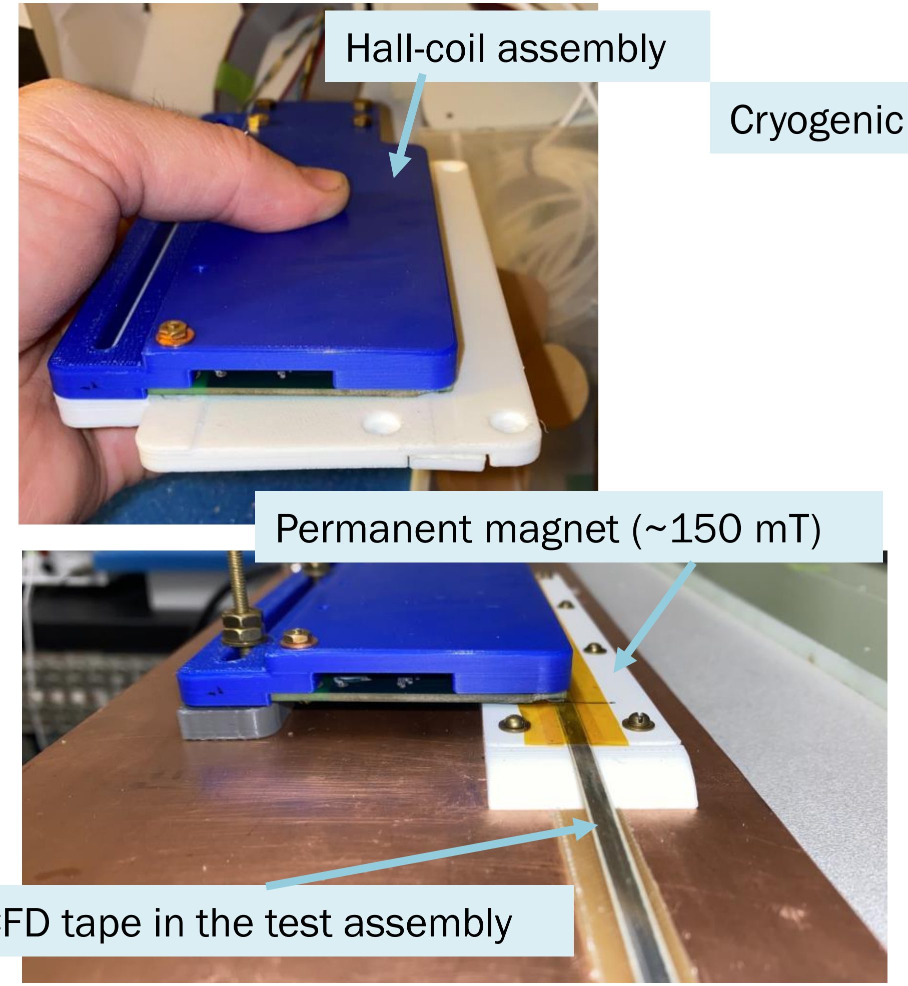
- Ability to detect a normal zone and measure propagation velocities in a large interval (mm/s – m/s)
- Fast current control and quench detector

AIIIb-M2

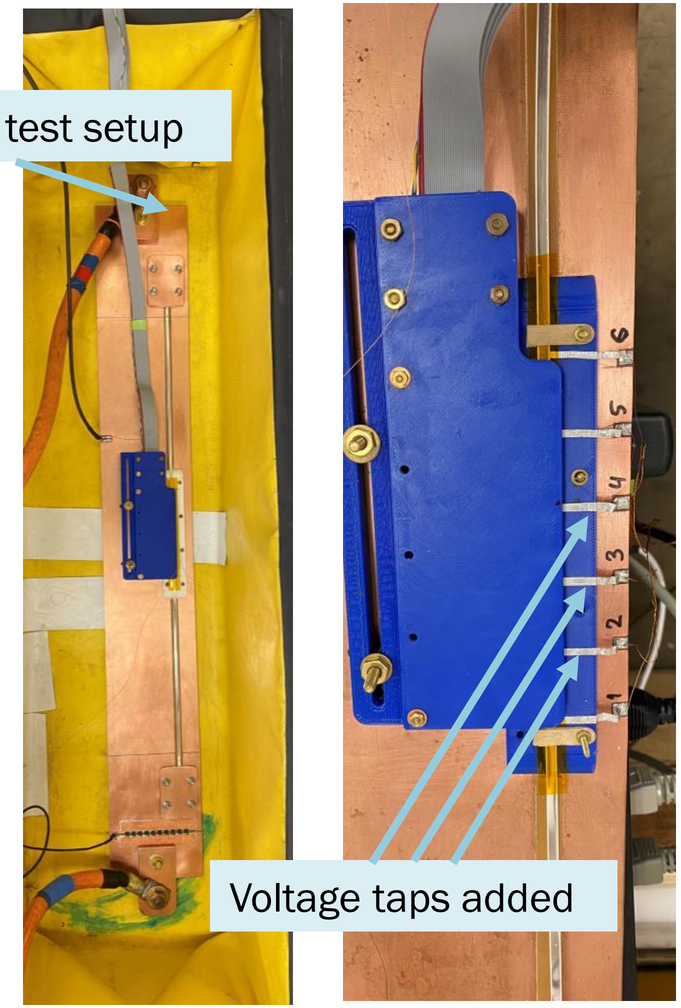
Components of the experimental setup



The 60-element Hall sensor array, and an array of miniature coils with matching 2 mm period



The Hall sensor array / coil array assembly



The cryogenic test setup

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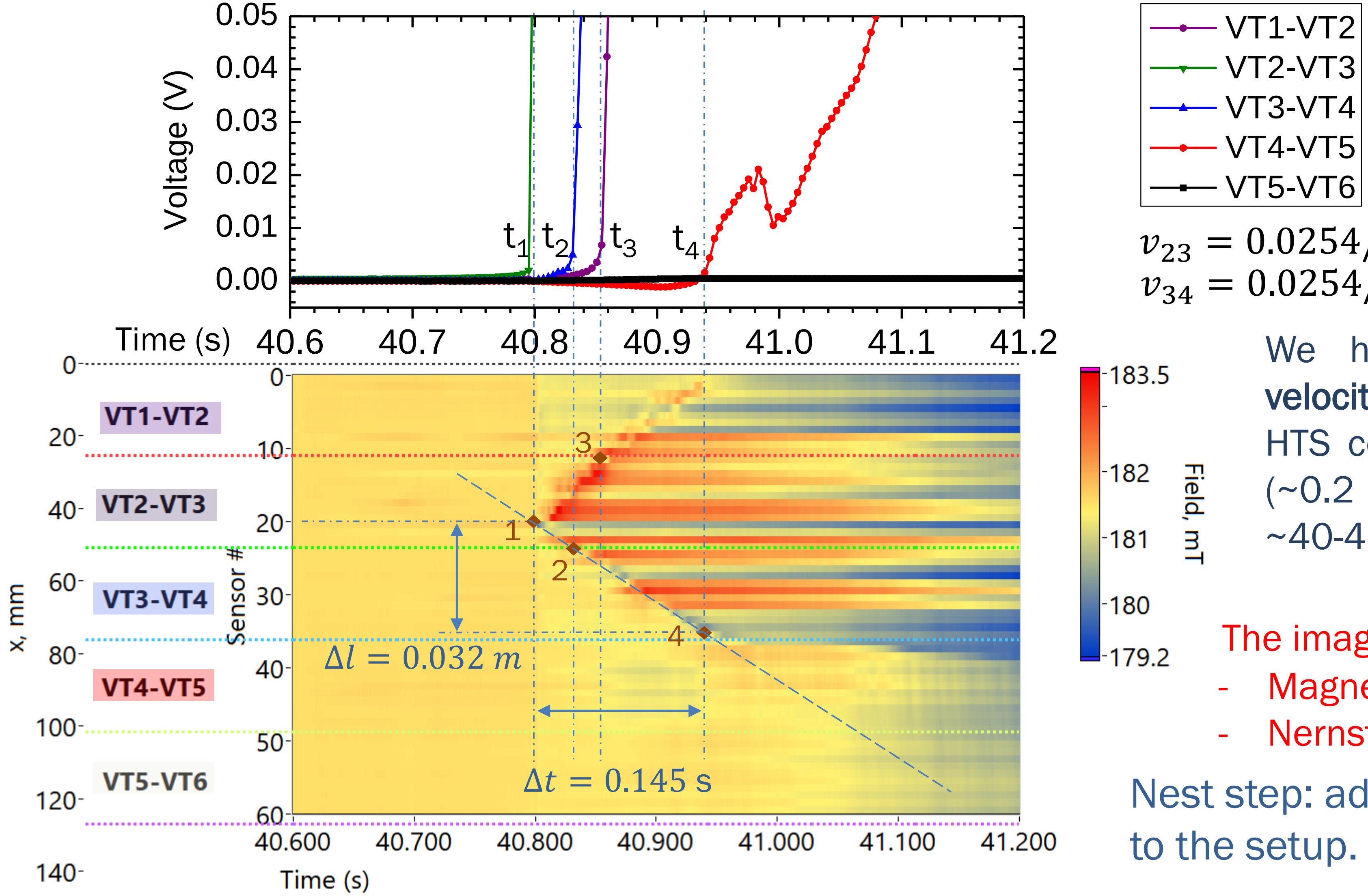
AIIIb-M2

Quench propagation imaging validated

POLYTECHNIQUE MONTRÉAL



t_1=39.693 s
t_2=39.7288 s
t_3=39.7529 s
t_4=39.8414 s

$v = \frac{\Delta l}{\Delta t}$ = **0.22 m/s**

$v_{23} = 0.0254/((t_2 - t_1) + (t_3 - t_1))$ = 0.265 m/s
$v_{34} = 0.0254/(t_4 - t_2)$ = **0.225 m/s**

We have **measured quench propagation velocity** in Current Flow Diverter – modified HTS conductors, and confirmed high NZPVs (~0.2 m/s) at moderate quench currents of ~40-45 A, in concert with the simulations.

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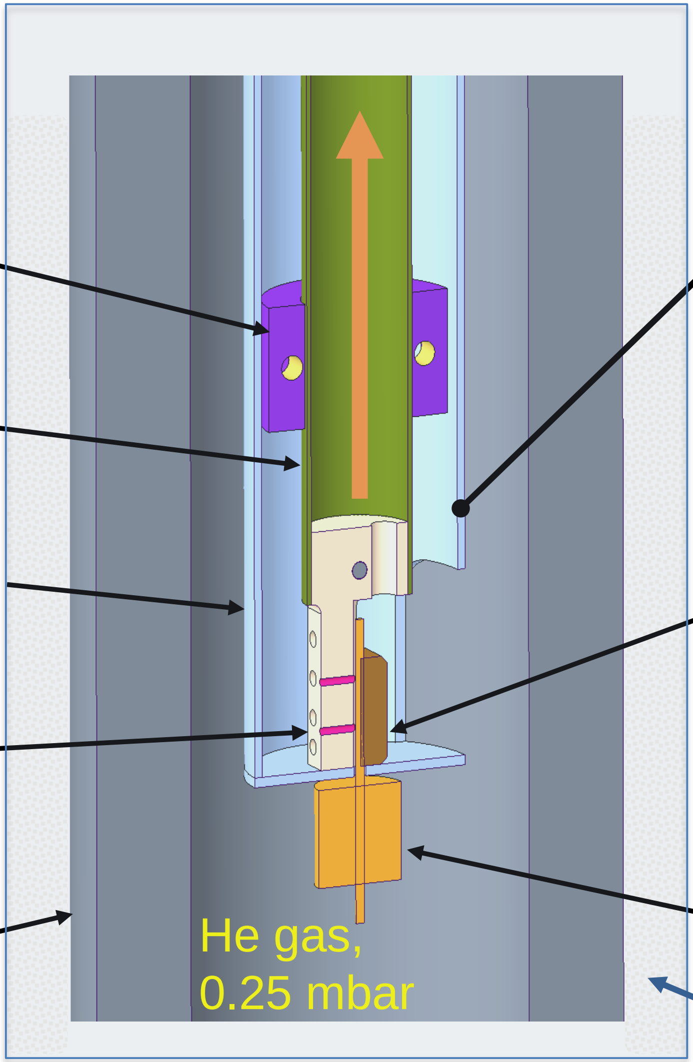
The imaging mechanism still needs to be clarified
- Magnetization clearing?
- Nernst effect?

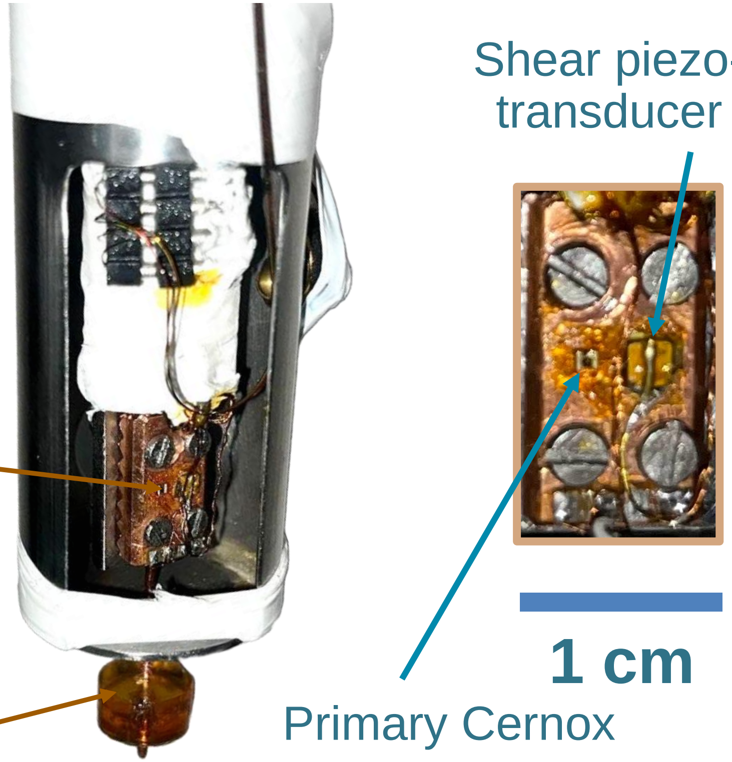
Nest step: adding array of thermometers/heaters to the setup. Test more CFD samples

AIIIb-M9

The cryogenic measurement probe

A. Saravanan





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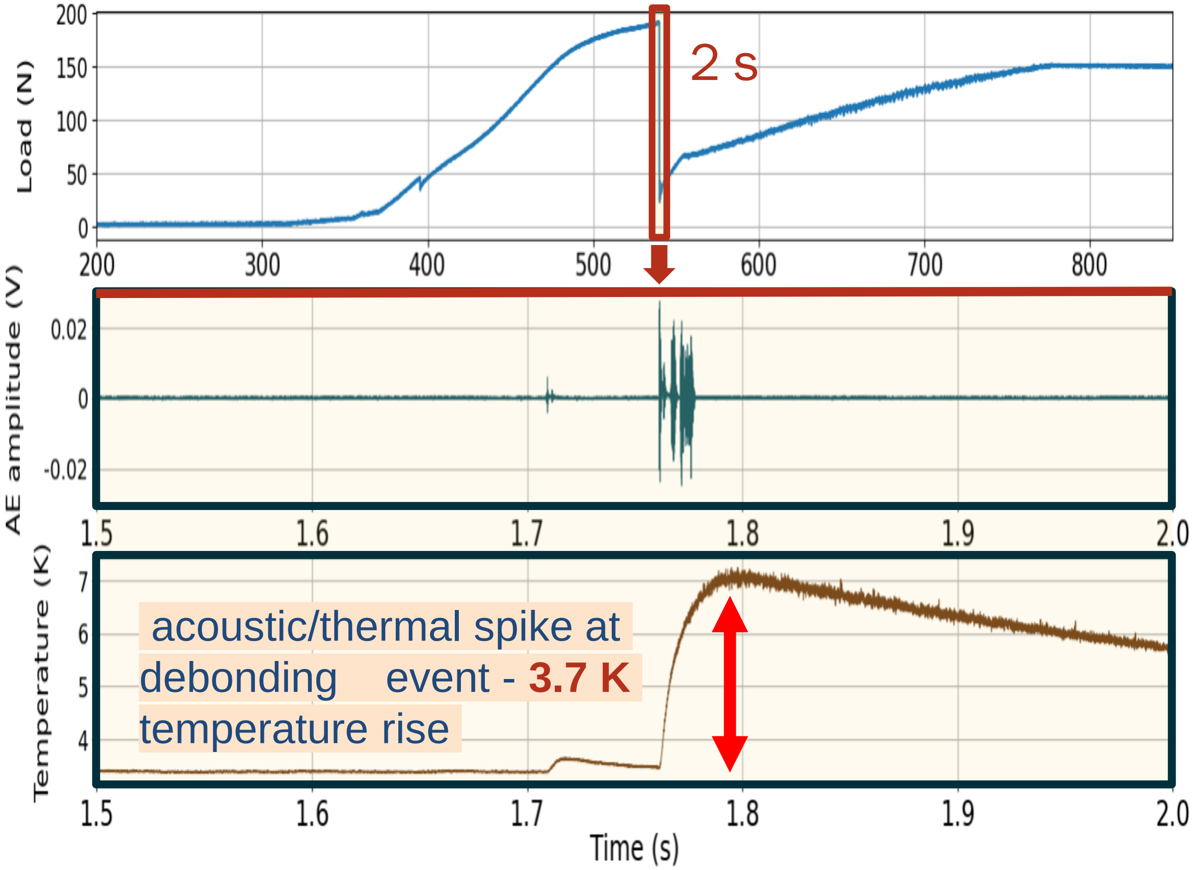
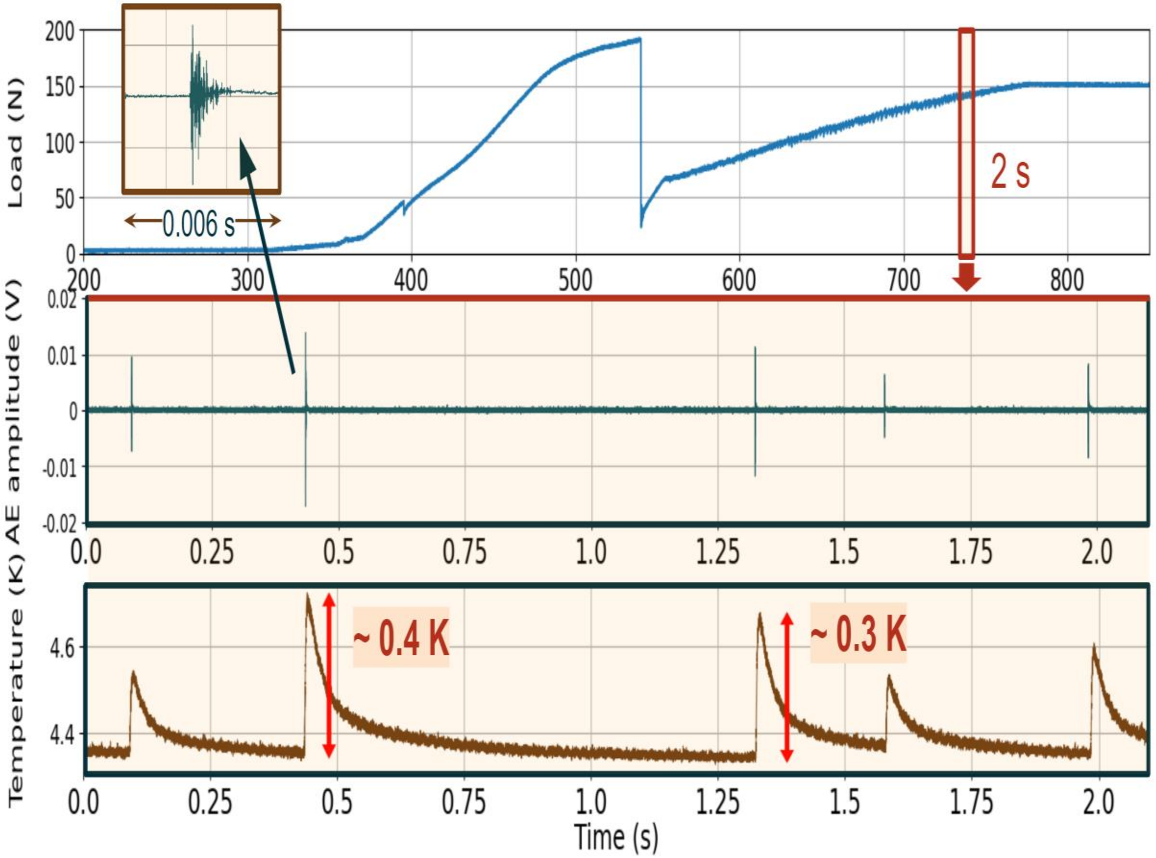
Acoustic emission and temperature rise associated with the de-bonding and slip-stick events

AIIIb-M9





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- Add high-resolution displacement sensor and heater for calorimetry calibration
- Test more samples / other epoxies (Mix61, Stycast, wax, Telene (?)