Diagnostics milestones and progress update

M. Marchevsky

LBNL

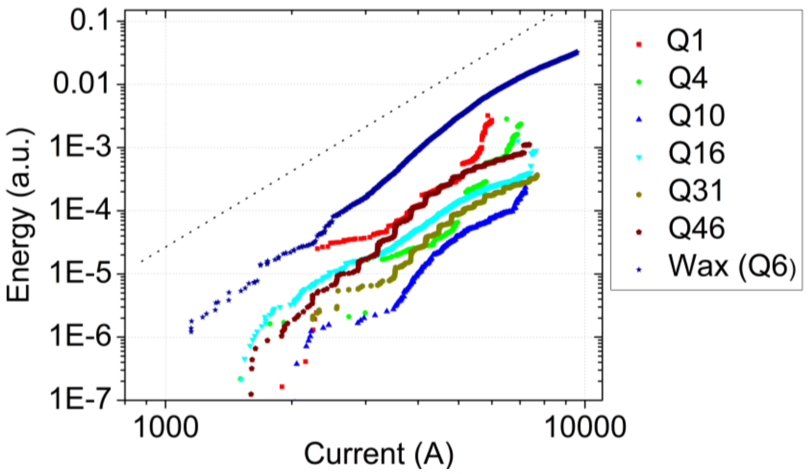
MDP General Meeting – 01/31/24

Milestone table

Milestone #	Description	Target	Status *	Updated Target	Requestor	Comments
AIIId-M1	Development of a new generation of self-calibrating acoustic emission diagnostics hardware	Dec-20	Completed		M. Marchevsky	
AIIId-M2	Finalizing software algorithms for acoustic data analysis, completing analysis for the CCTs and 15T dipole	Dec-20	Completed		M. Marchevsky	
AIIId-M3ab	Development and implementation of non-optical distributed sensing for cables and magnets. RF TDR-based techniques. Ultrasonic waveguide-based techniques	Mar-23	In progress		M. Marchevsky / G.S. Lee	*Geon Seok's talk*
AIIId-M4	Test of a large-scale Hall array and imaging current distribution in HTS tape stacks and coils	May-21	Completed	More work is ongoing		
AIIId-M5	Completing spot heater studies to improve voltage-based diagnostics and address "silent" quenches	Jul-21	Not started	Jul-23	S. Stoynev	No initial agreement on goals (no support); scope changed, agreement reached
AIIId-M5a	Development and commissioning of a dedicated V-I measurement system (multichannel nanovoltmeter) for superconducting magnets	Jan-00	In progress	Mar-23	S. Stoynev	AIIId-M7 *Stoyan's talk*
AIIId-M6a	Demonstration of acoustics-based probing of coil interfaces	Sep-21	In progress	Dec-23	M. Marchevsky	
AIIId-M7	Development of multi-element and flexible quench antennas and localization of quenches using flexible quench antenna arrays	30-Sep-21	Completed		S. Stoynev/J. DiMarco	
AIIId-M7a	Characterization of different quench antenna designs for use in superconducting devices		In progress	Jan-23	S. Stoynev/J. DiMarco	extended studies *Diego's talk*
AIIId-M7b	Development of a flexible 'sinusoid-shaped' quench antenna, which would have loops everywhere parallel to the CCT conductor.		Not started	Sep-23	J. DiMarco/R. Teyber	extended goals *Joe's talk*
AIIId-M8	Characterization of training-like behavior in different impregnation materials under load using a Transverse Pressure Insert (TPI) measurement system	Dec-21	In progress	n/a	E. Barzi	
AIIId-M9	Development and test of a standalone acoustic quench detection and localization FPGA-based system	Dec-21				
AIIId-M10	Development and test of a non-rotating new magnetic probe prototype	Dec-21	In progress	Dec-23	M. Marchevsky / J. DiMarco	
AIIId-M11a	Demonstration of a programmable fully-cryogenic FPGA "smart" sensor core with digital readout	Dec-21	In progress	Jan-23	M. Turqueti	
AIIId-M12a	Calibration of FBG fibers in a small cryostat (2021) Installation of fibers on an MDP magnet and strain measurement during a quench. Modification of magnet test facility top plate to accommodate fiber line (2021) Design a proof of principle experiment for quench detection: Small coil fabrication and tests (March 2023) Energy spectrum analysis (Dec 2023) Coil azimuthal strain mapping: Experiment on coil ten stacks sample made with different epoxy (March 2023) Install distributed fiber on a mirror magnet for coil strain map (Dec 2022)	Dec-22	In progress	Dec-23	M. Baldini	*Maria's talk*
AIIId-M13	Develop quality control capabilities to identify defects and performance-limiting regions in REBCO cables and accelerator magnets		In progress	Nov-23	R. Teyber	*Reed's talk*
AIIId-M14	Advance numerical and experimental abilities to monitor and predict current distributions in ReBCO cables for accelerator magnets		In progress	Mar-24	R. Teyber	

Energy release and multiplet AEs analysis for wax-impregnated magnets

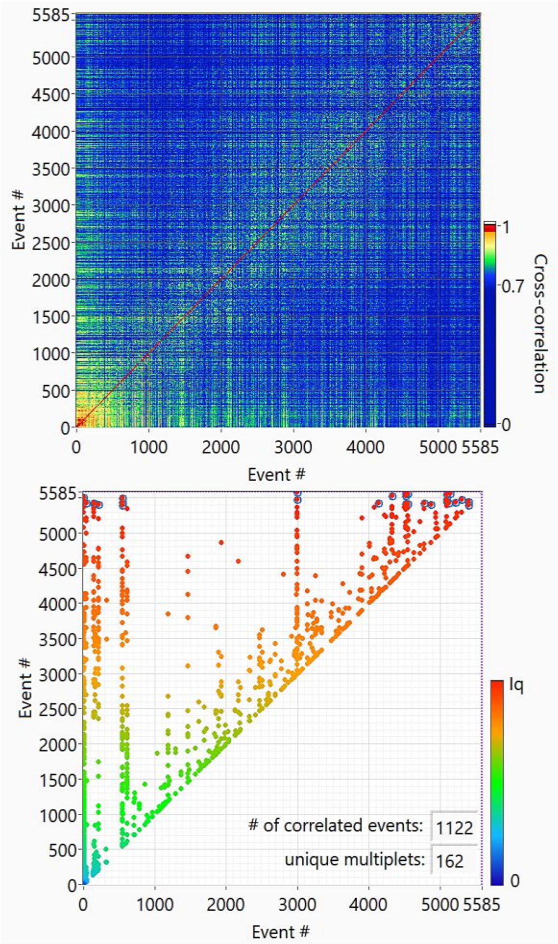
Presented at MT-28



Elastic energy accumulates in the magnet proportionally to I^4. Cumulative AE energy release deviates from this dependence at high currents.

However, the wax-impregnated magnet releases nearly an order of magnitude more energy in AE per event than the epoxy-impregnated magnet!

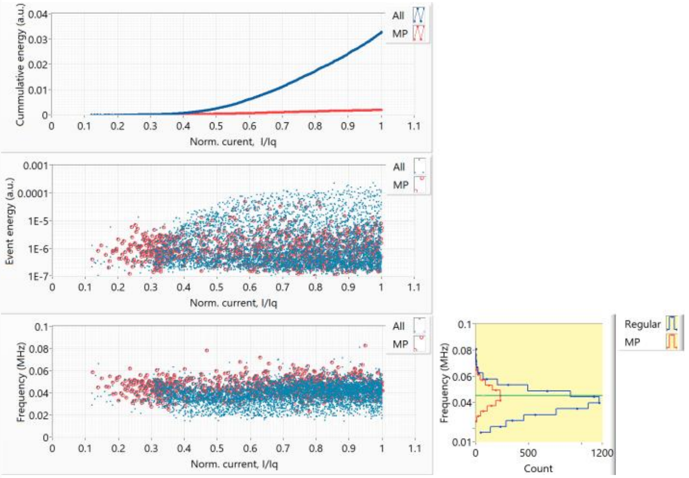
- ➢ Dedicated small-scale experiment measuring heat release in wax and filled wax impregnation materials



# of correlated events: 1122

unique multiplets: 162

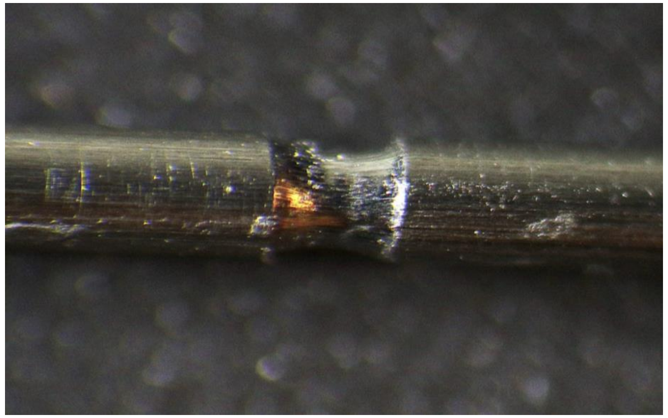
- 20 % of AE events were in multiplets with A_{ij}>0.9
- 6% of the AE energy was released in multiplets
- The frequency distribution peak is higher for multiplet events than for singular events



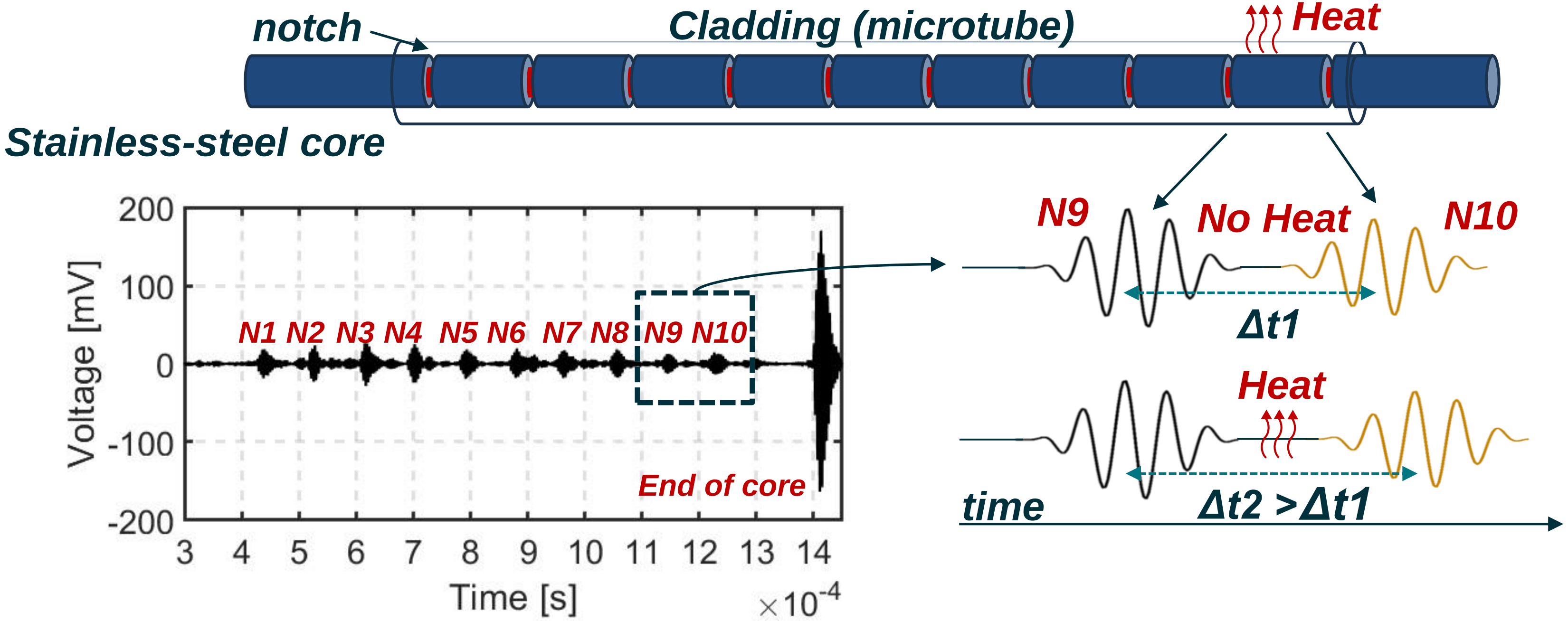
- ➢ Geon Seok: reviving ML effort on the acoustic data analysis

A long ultrasonic waveguide with a periodic array of reflectors

(ETEGENT TECHNOLOGIES, LTD.)

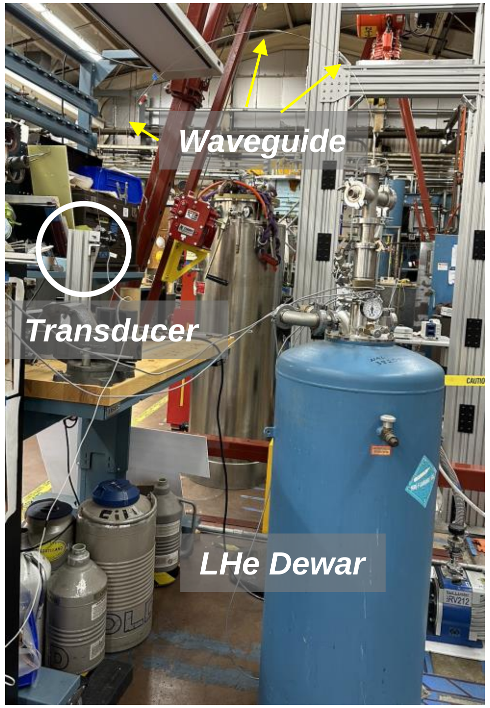


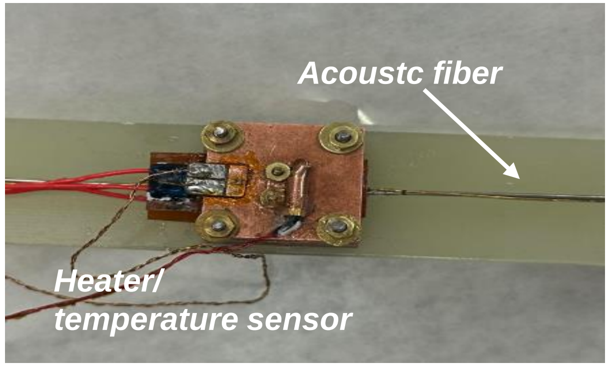
A 3.3 m long sensor made of 304 stainless steel, ~0.7 mm wire diameter, ~1 mm outer diameter



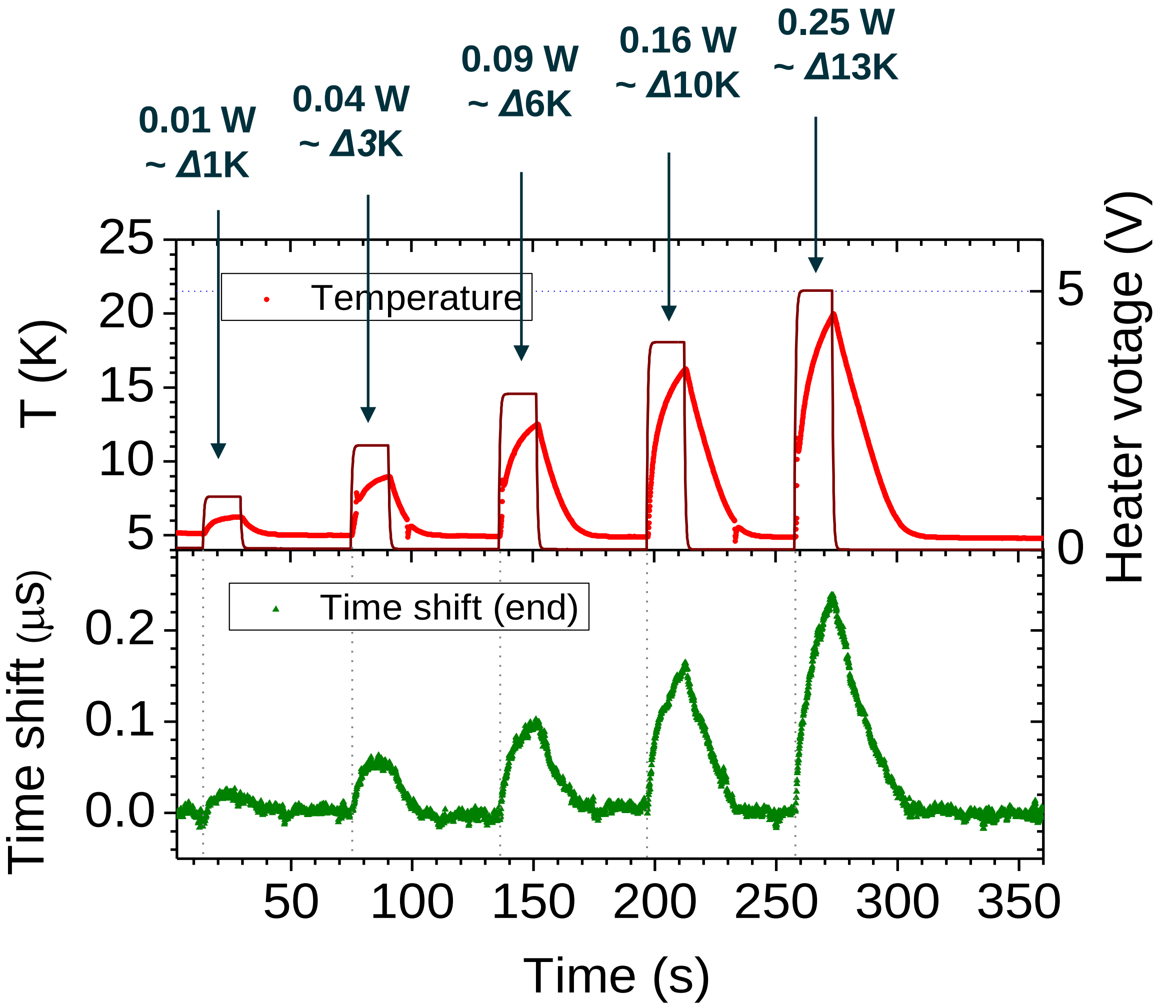
- Each of the 10 reflected signals from notches is correlated with the initially measured signals.
- **Differential time shift** calculated for the neighboring notches is used to monitor each segment individually, fully compensating thermal and stress-related variations outside of the monitored segment.

Cryogenic test of the long acoustic fiber





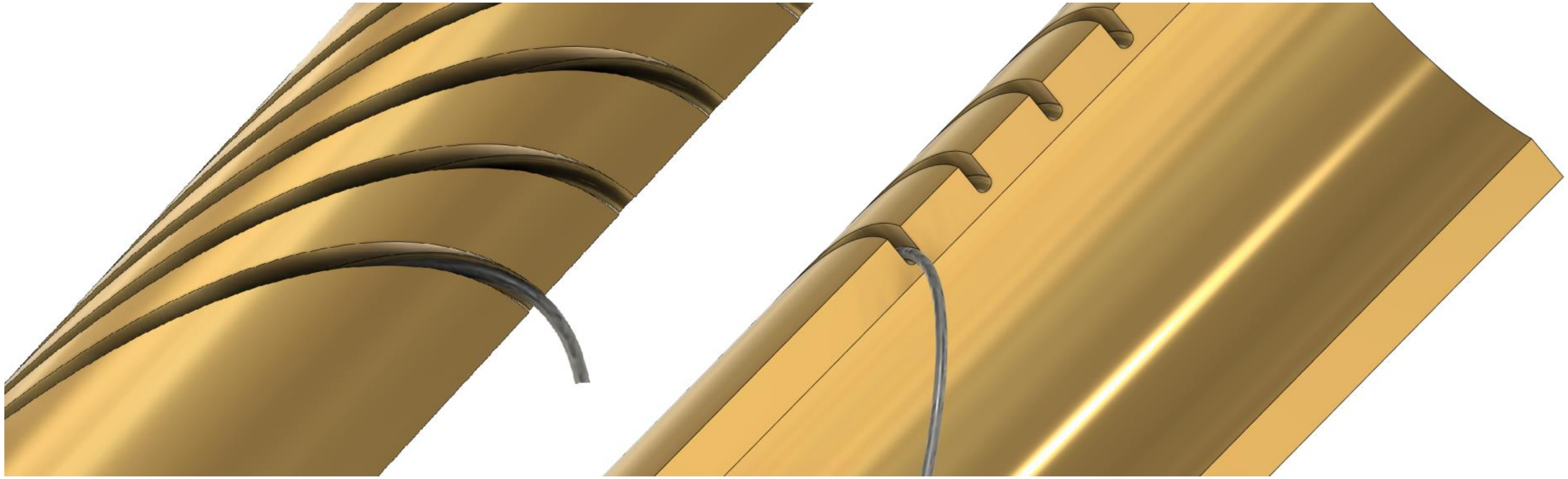
Time shift at the segment containing the heater is detectable down to **1 K temperature difference and less than 0.01 W of heater power**



Upgraded ultrasonic waveguide sensors for magnet integration

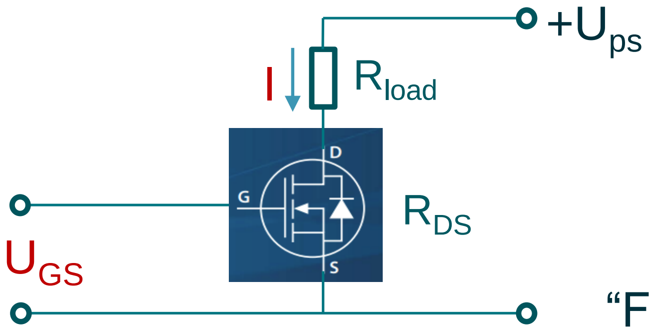
Placing acoustic waveguide on the (rounded) bottom of the cable groove in the CCT, prior to cable winding/impregnation would be the best integration option

- Stainless /stainless sensor: 1 mm diameter. Brass/brass sensors of 0.7 mm diameter are also available. Experiments with 0.23 mm diameter sensors are in progress.

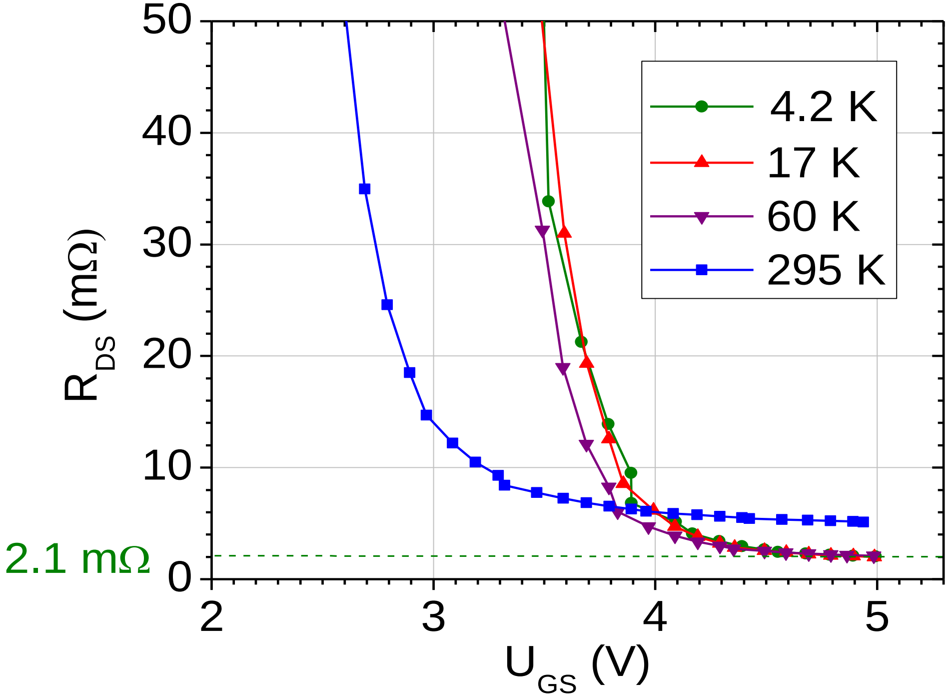


- Potentially we can also monitor temperature distribution during Nb_3Sn reaction with the stainless sensor.

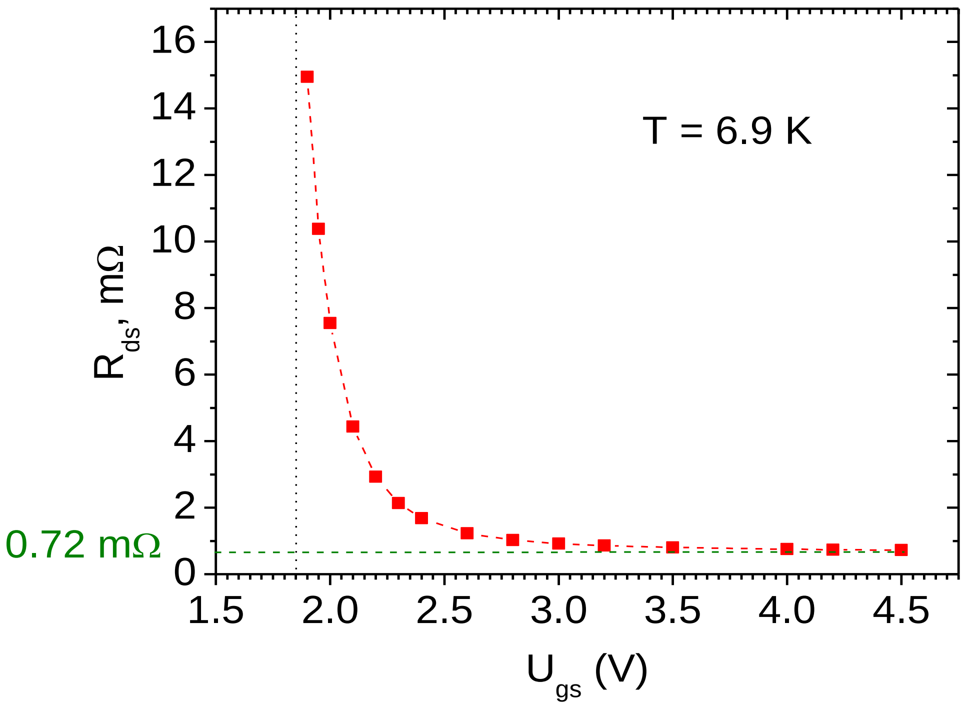
MOSFETs at cryogenic temperatures



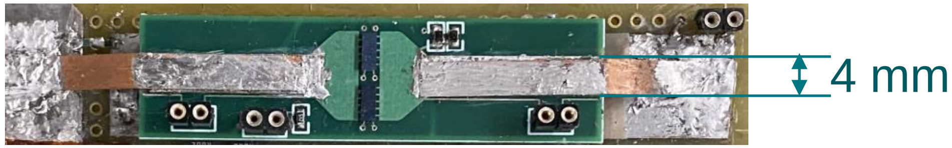
“FET 2” I_d = 60 A (r.t.)



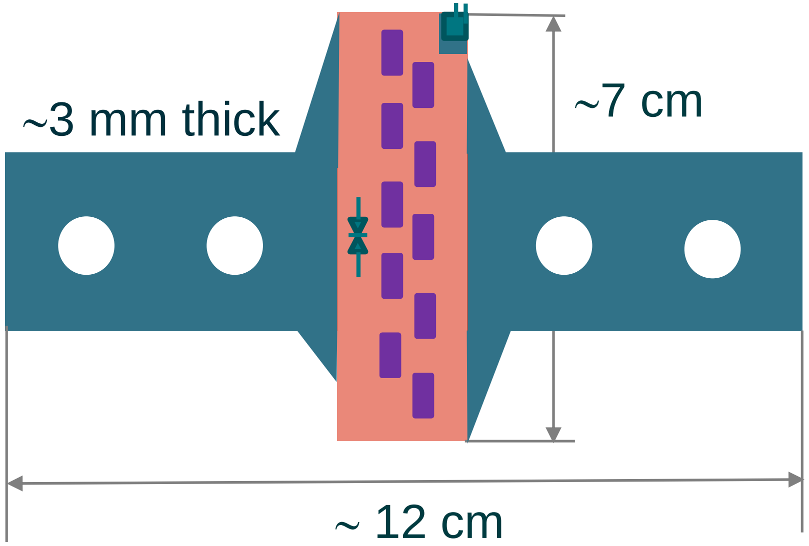
“FET 3” I_d = 90 A (r.t.)



Combining MOSFETs in parallel enables higher operational I_D and lower R_{DS}

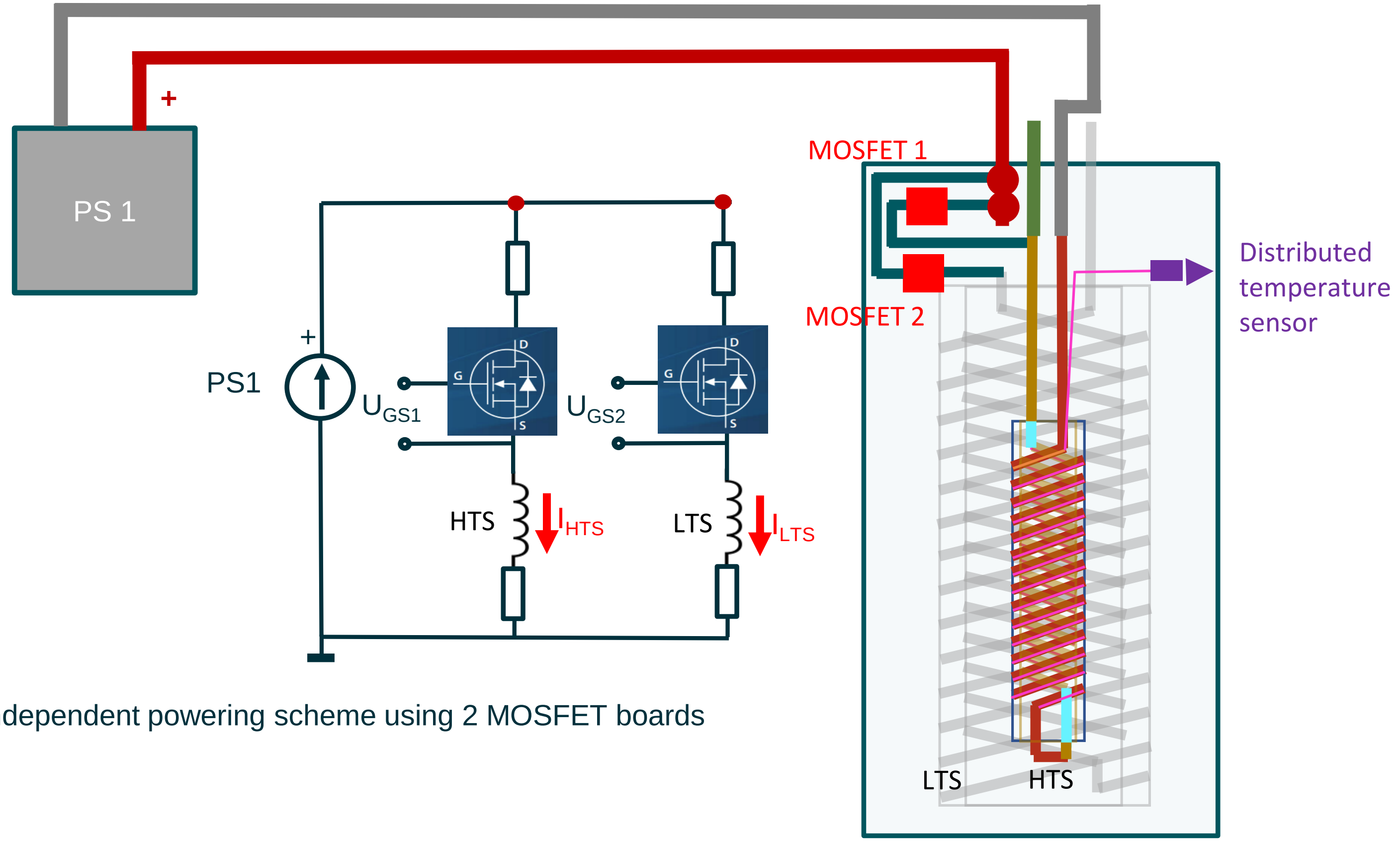


Prototype “FET 2” board with 4 devices (~120 A and 0.5 mΩ at 4.2 K)



A prospective 10x “FET 3” card, with I_D = 500 A and R_{DS} = 50 μΩ.

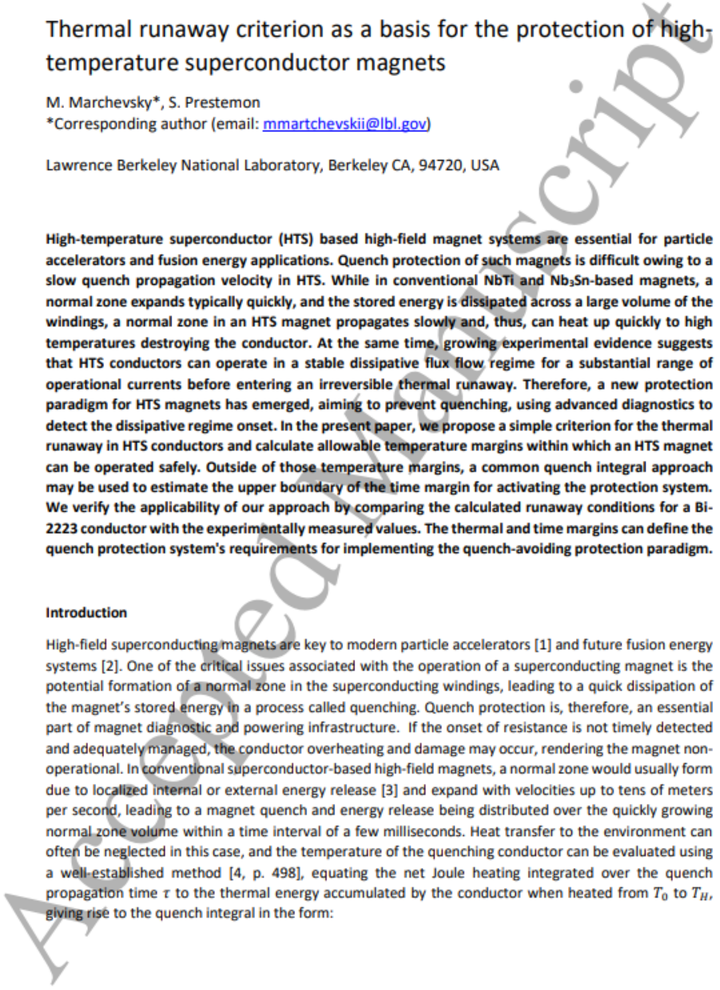
Cards will be further stacked to achieve the necessary current capacity.



Independent powering scheme using 2 MOSFET boards

- A synergy with SBIR Phase I (Alphacore) on developing cryo-electronic IC for sensor signal processing and MOSFET gate control

Quench avoidance strategy for HTS based on thermal runaway criterion



Thermal runaway criterion as a basis for the protection of high-temperature superconductor magnets

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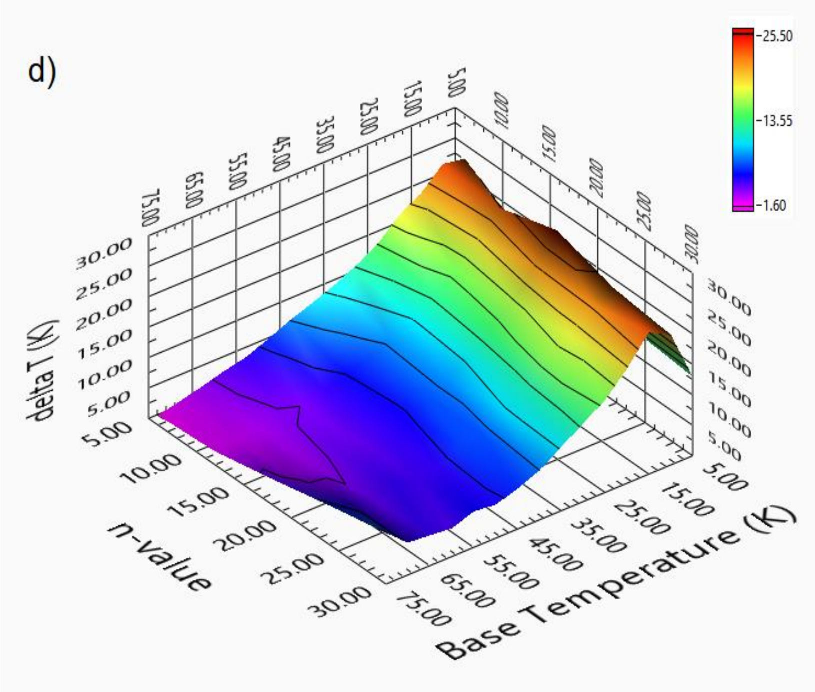
High-temperature superconductor (HTS) based high-field magnet systems are essential for particle accelerators and fusion energy applications. Quench protection of such magnets is difficult owing to a slow quench propagation velocity in HTS. While in conventional NbTi and Nb_3Sn-based magnets, a normal zone expands typically quickly, and the stored energy is dissipated across a large volume of the windings, a normal zone in an HTS magnet propagates slowly and, thus, can heat up quickly to high temperatures destroying the conductor. At the same time, growing experimental evidence suggests that HTS conductors can operate in a stable dissipative flux flow regime for a substantial range of operational currents before entering an irreversible thermal runaway. Therefore, a new protection paradigm for HTS magnets has emerged, aiming to prevent quenching, using advanced diagnostics to detect the dissipative regime onset. In the present paper, we propose a simple criterion for the thermal runaway in HTS conductors and calculate allowable temperature margins within which an HTS magnet can be operated safely. Outside of those temperature margins, a common quench integral approach may be used to estimate the upper boundary of the time margin for activating the protection system. We verify the applicability of our approach by comparing the calculated runaway conditions for a Bi-2223 conductor with the experimentally measured values. The thermal and time margins can define the quench protection system's requirements for implementing the quench-avoiding protection paradigm.

Introduction

High-field superconducting magnets are key to modern particle accelerators [1] and future fusion energy systems [2]. One of the critical issues associated with the operation of a superconducting magnet is the potential formation of a normal zone in the superconducting windings, leading to a quick dissipation of the magnet's stored energy in a process called quenching. Quench protection is, therefore, an essential part of magnet diagnostic and powering infrastructure. If the onset of resistance is not timely detected and adequately managed, the conductor overheating and damage may occur, rendering the magnet non-operational. In conventional superconductor-based high-field magnets, a normal zone would usually form due to localized internal or external energy release [3] and expand with velocities up to tens of meters per second, leading to a magnet quench and energy release being distributed over the quickly growing normal zone volume within a time interval of a few milliseconds. Heat transfer to the environment can often be neglected in this case, and the temperature of the quenching conductor can be evaluated using a well-established method [4, p. 498], equating the net Joule heating integrated over the quench propagation time τ to the thermal energy accumulated by the conductor when heated from T_0 to T_H, giving rise to the quench integral in the form:



Future work

- Distributed sensing of temperature and strain (optical fibers, ultrasonic, RF) should become a more robust and widely accepted technology! Integration of ultrasonic and RF fibers into magnets, evaluation of the available distributed temperature sensing techniques in real magnet operation conditions.

Synergy with sponsored projects / FES

- Build and test current control boards capable of driving HTS /LTS magnet coils and high-current cables (such as multiphase CORC® or other non-current shared conductors). Integrate with the hybrid program at LBL. Demonstrate new approaches to detecting and preventing quenches in HTS magnets using active real-time control of current distributions.
- Conduct small-scale experiments to quantify energy release in different impregnation materials. This should provide a next-level understanding of disturbances in LTS magnets and the associated heat dissipation, helping identify the true quench precursors.
- Imaging of the quench dynamics and overcurrent state in HTS conductors and cables
- Advancing ML models for AE and QA data analysis, future integration into FPGA for real-time analysis