U.S. MAGNET
DEVELOPMENT
PROGRAM

Diagnostics milestone and goals update

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U.S. DEPARTMENT OF ENERGY | Office of Science

IDSM’02 Workshop and lectures

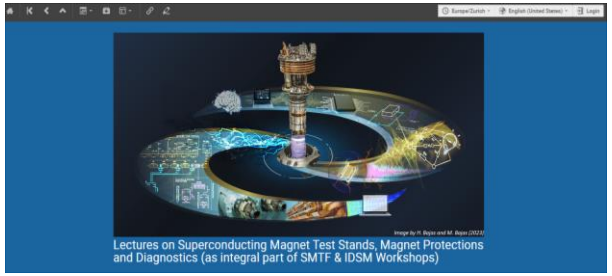
26-28 April, 2023, Paestum, Italy

A follow-up from IDSM’01 organized at Berkeley in 2019

Joint with the Test Stands Workshop
Co-sponsored by CERN and INFN
- 50 participants
- 27 presentations

https://agenda.infn.it/event/32061/

A very useful set of educational lectures was organized by M. Bajko and H. Bajas on various aspects of magnet instrumentation and diagnostics, as a follow-up to SMTF/IDSM workshops



[Lectures on Superconducting Magnet Test Stands, Magnet Protections and Diagnostics (as integral part of SMTF & IDSM Workshops) (May 30, 2023 - June 12, 2023): Overview · Indico (cern.ch)](https://indico.cern.ch/event/1281454/)

https://indico.cern.ch/event/1281454/

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	*Maxim's talk* *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
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
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
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* *Steve'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	

A hybrid challenge

- **Hybrid magnets** are considered the most likely candidate for future colliders. They are also an anticipated “pinnacle” of our MDP program. Diagnostics should be oriented to enable a robust and predictable operation of LTS/HTS hybrids, aiming not just at issues and limitations of LTS and HTS magnets individually but also exploring new issues that may arise from operating them together in a hybrid. Quench protection is undoubtedly one of the most challenging problems among such issues.

➢ HTS magnets: a new paradigm – rely on diagnostics to prevent quenching. There is one clear quench precursor in HTS: resistive flux flow. We can potentially target it using a combination of existing and newly developed QD methods.

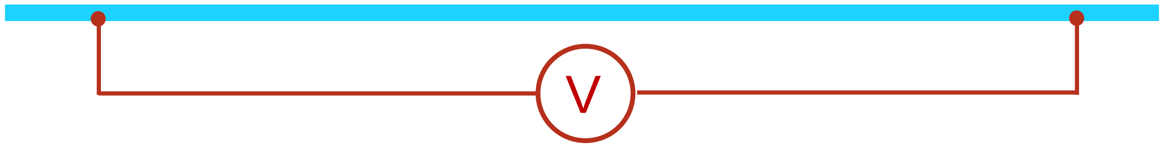
➢ LTS magnets: they train… and may also lose the training memory. No reliable precursors (?).
If an LTS outsert quenches, it will likely quench an HTS insert as well…

So, **can the no-quenching paradigm even be considered for a hybrid magnet?**

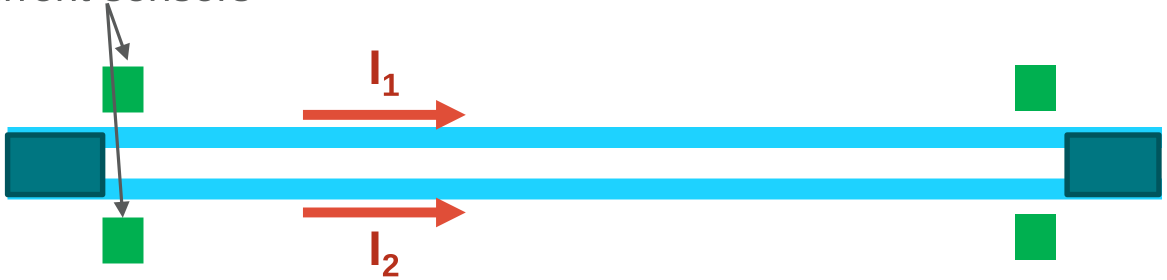
  ➢ If yes, we need to search for true physical quench precursors in LTS and new ways of eliminating premature quenching and training
  ➢ If no, we have to develop an effective way of de-energizing/protecting the HTS insert to prevent it from damage

Realizing the HTS magnet early quench detection paradigm

Single conductor



Non-current shared cable



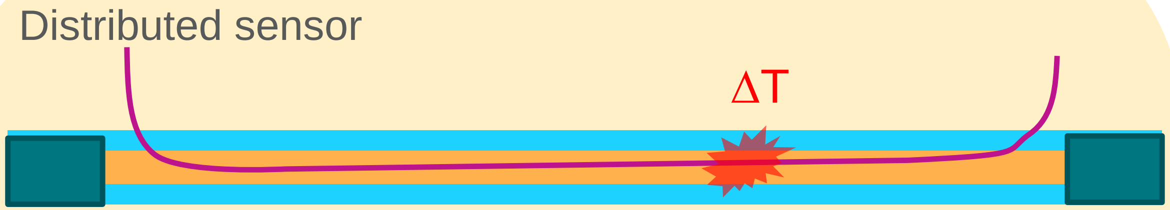
Local current sensing at terminations

POINT MEASUREMENT(s)

Hall arrays

+ network modeling of current distribution

Current shared cable



Distributed temperature sensing along the conductor

DISTRIBUTED MEASUREMENT

Distributed temperature sensors

+ modeling of thermal runaway conditions

Understanding transient heat dissipation in LTS magnets

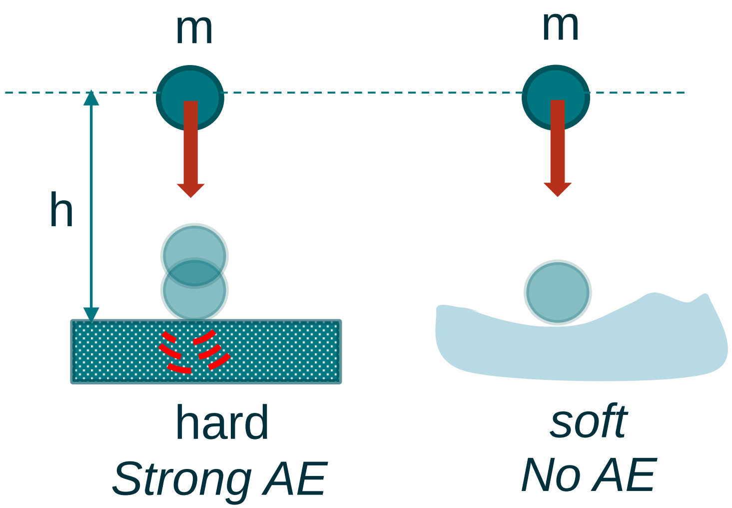
- We are improving in classifying types of mechanical disturbances and transient events by analyzing AE data and combining it with the quench antenna data… But we still do not know which of those disturbances are quench "precursors" and which are not.

- Quantitative aspect of energy release in those events is still poorly developed

➢ One crucial question is **what fraction** of the released mechanical energy is converted into the local heating of the conductor

➢ Another important question is **over what effective volume** this heat dissipation is actually taking place

A simple analogy: a metal ball dropped either over a hard floor or a soft cushion

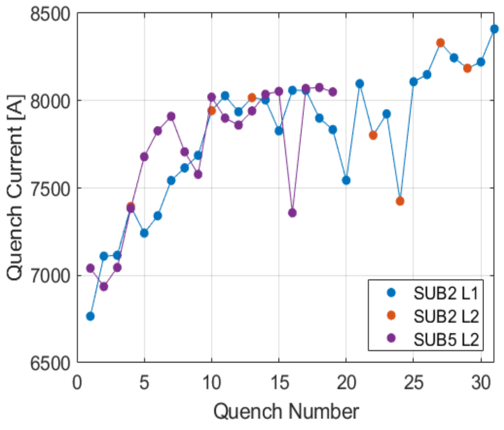


Same energy dissipated

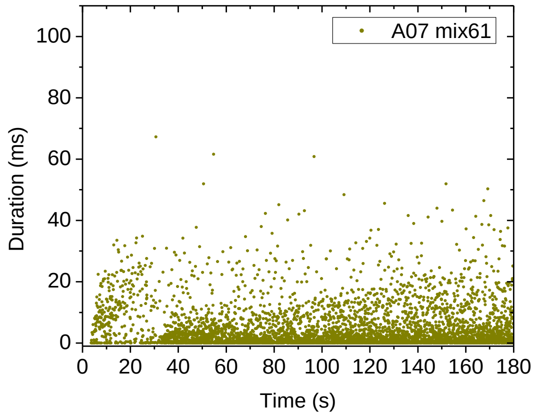
The properties of the impregnation medium define the energy fraction that will be **locally** converted to heat.

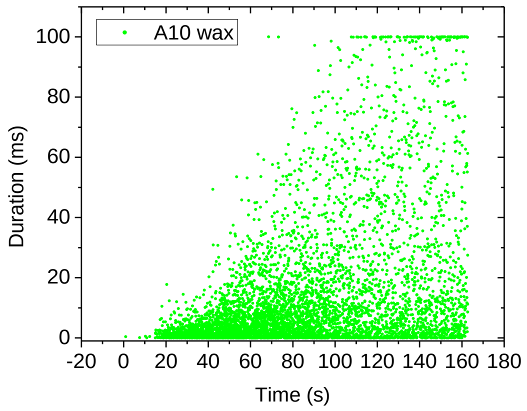
Some impregnation materials effectively reduce or eliminate training… but what is the physical mechanism?

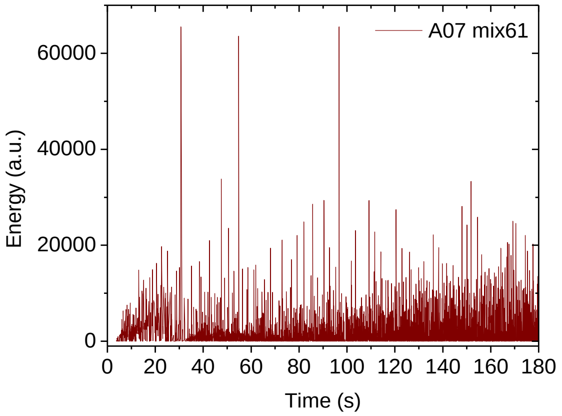
Wax impregnated layer does not train, but surprisingly the magnet emits more AE energy than the epoxy-impregnated one

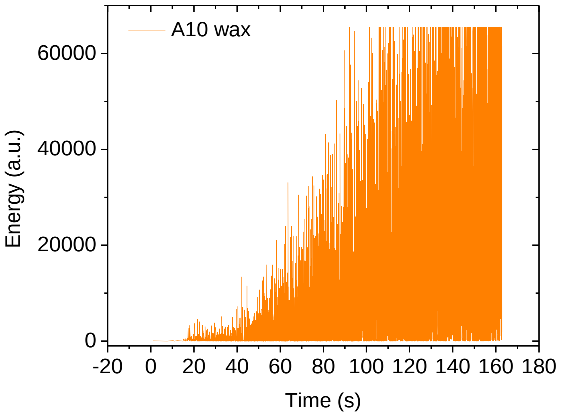


Comparison Between SUB 5 and SUB 2C (D. Arbelaez)









Mix 61 (sub2)

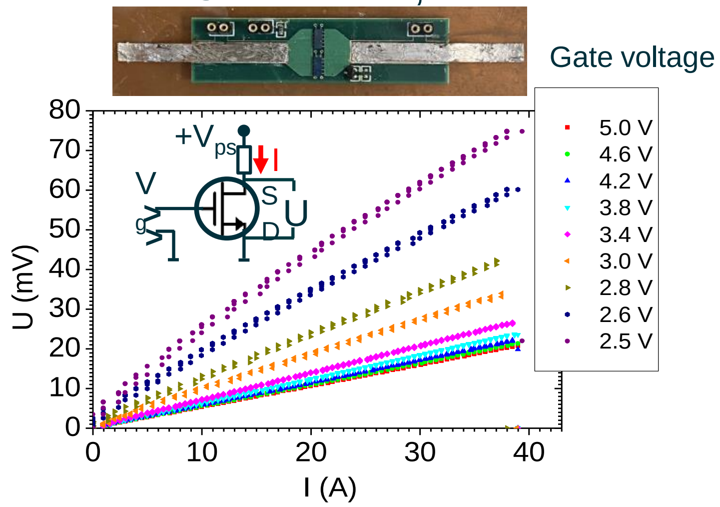
Wax (sub5)

- AE events are much longer in duration and stronger in amplitude for the wax-impregnated magnet compared to the epoxy-impregnated one. AE amplitude is strongly dependent on the magnet current.

What is the heat dissipation mechanism here?

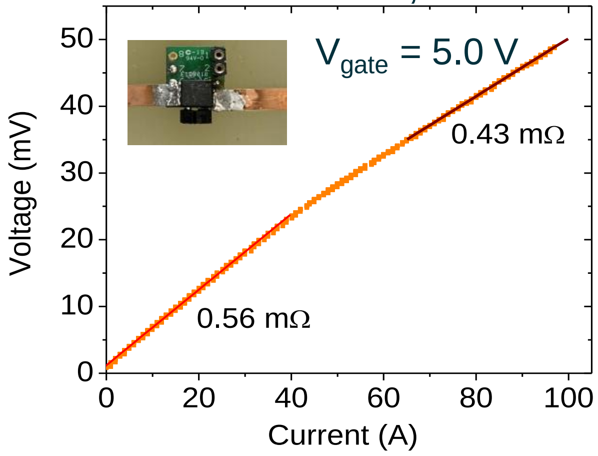
Cryogenic current control for effective protection

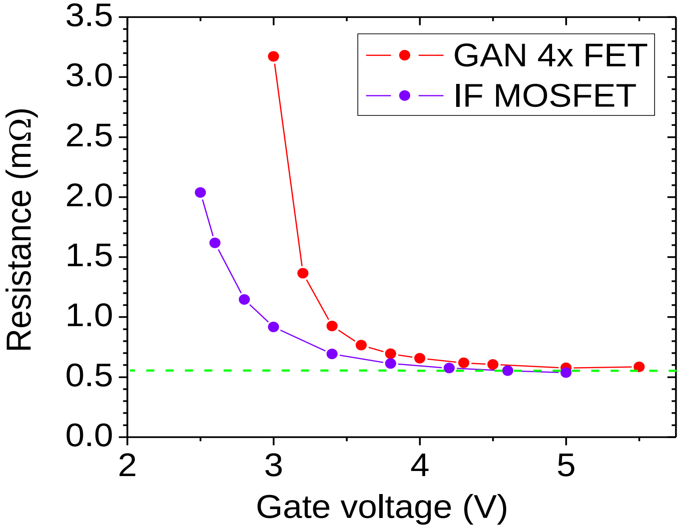
GAN 4xFET, 77K



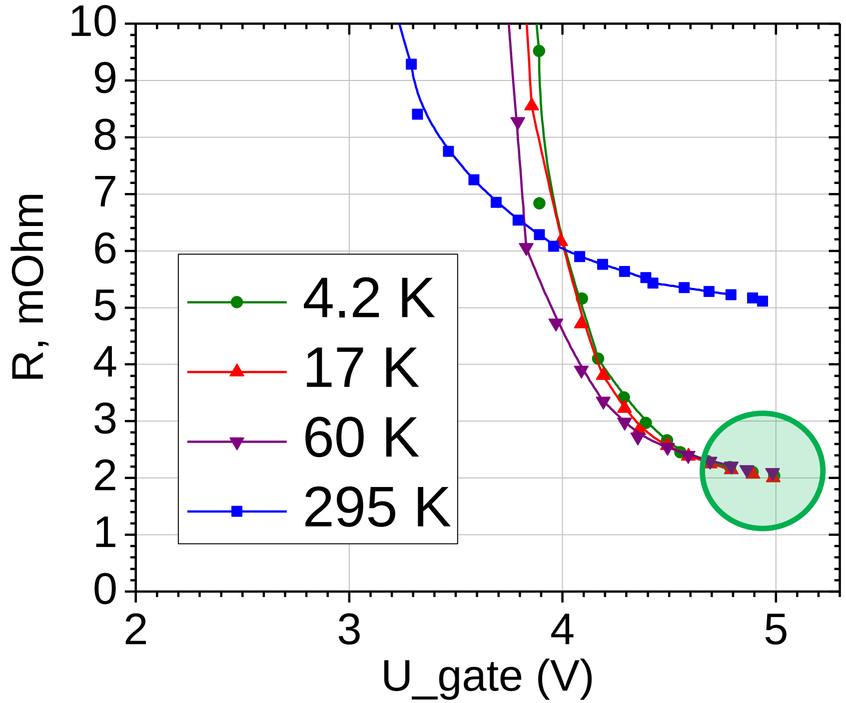
- MOSFET assemblies can be used as efficient cryogenic current regulators with closed-state resistance in tens of micro-Ohms. A pathway to "active" cable terminations to enable new protection methodologies

IF MOSFET, 77 K





New results



Can be potentially used down to 4.2 K for HTS and hybrid magnet protection

Three key learning pathways

Need more of these!

Diagnostics data acquisition and analysis for large magnet tests

- *CCT subscales*
- *15 T dipole*
- *MQXF test*
- *ReBCO magnets*
- *Bi-2212 CCT*
- *….*

- ***Hybrid tests***

Modeling to improve diagnostics or bring it up to a new level

- *Current re-distribution in Rutherford cables and quench antenna signal simulations*
- *Network models for cables and stacks*
- *Hall-array-bases current reconstruction*
- *Ultrasonic wave propagation modeling*
- *Thermal runaways modeling*

Small-scale dedicated experiments to reproduce and understand the phenomena that define or limit magnet performance

- What are the disturbance-caused heat release mechanisms and their dimensional and temporal scales?
- True measurable precursors of quenching?
- Why do some impregnation materials (like wax) eliminate training? Mechanisms?

- Current flow and sharing in HTS at different dimensional length scales
- Overcurrent regimes in HTS: flux flow and heat transfer

- Radiation effects
- Etc…

Key goals and development trends for diagnostics

- Developing reliable, sensitive, long-length distributed temperature monitoring is a crucial goal for **HTS and LTS** diagnostics. Distributed sensing of temperature and strain (optical fibers, ultrasonic, RF) should become a more robust and widely accepted technology.
- Conduct small-scale experiments should provide a next-level understanding of disturbances in LTS magnets and the associated heat dissipation, helping identify the true quench precursors
- Demonstrate new approaches to detecting and preventing quenches in HTS magnets relying on “digital twin”- based simulation and active real-time control of current distributions.
- Advanced ML models should become increasingly popular choices for analyzing large arrays of diagnostic data
- Develop cryogenic data acquisition and power electronics in order to amend or change the way how we diagnose, power, and protect magnets