# Cryogenic Tests of Electronic Components and Sensors for Superconducting Magnet Instrumentation

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10/10/2024

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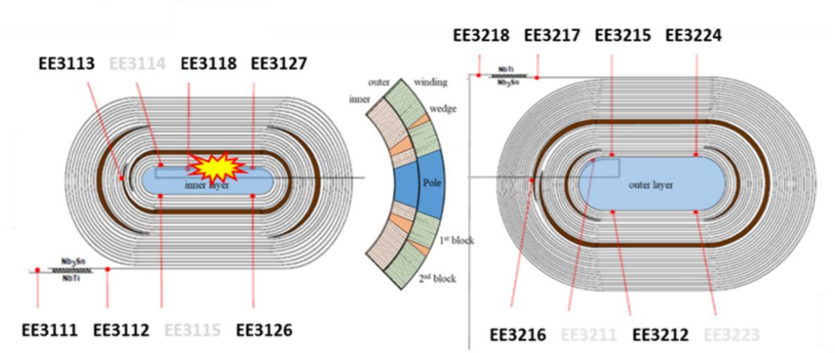
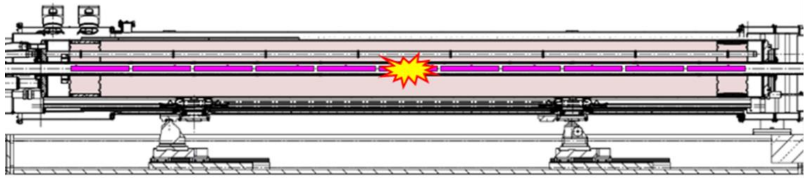
**Motivation** (Quench localization – Current limitations)

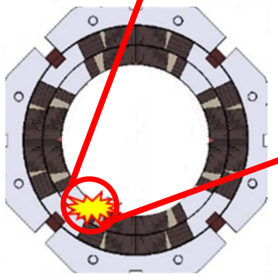
**Proposal** (Embedded detection and controlling electronics – Conclusions)

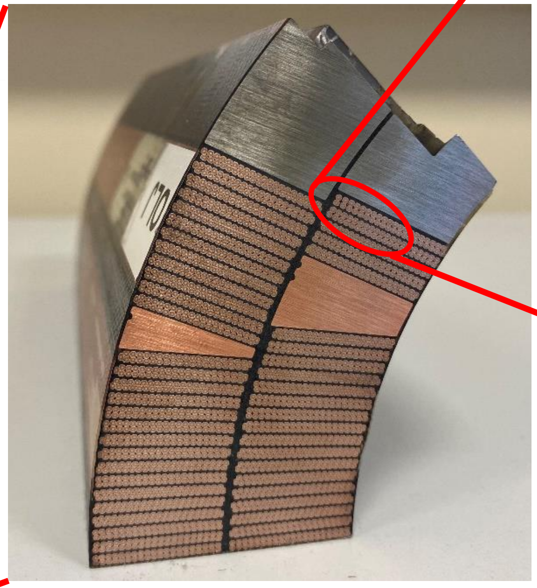
# Quench localization

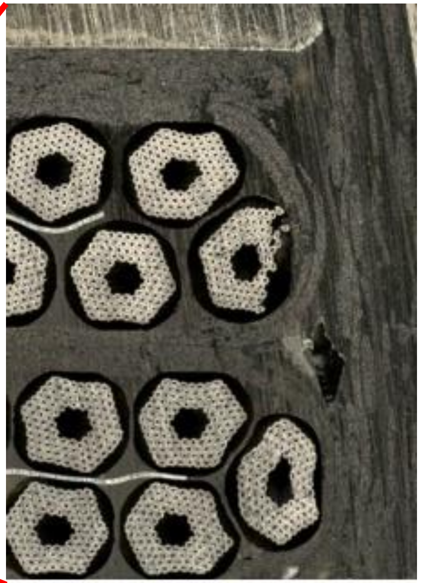
- **Identifying** the starting **location** of a **quench** during superconducting magnets **training** is **critical**:
  - To identify **defects.**
  - To drive the **design** and the **manufacturing**.
  - For **protection** systems.







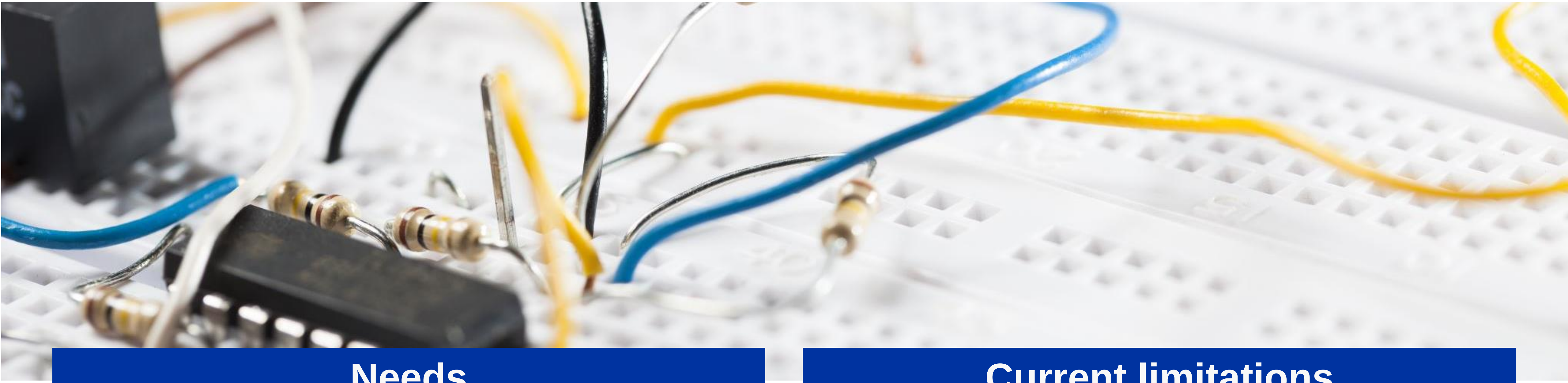


# Quench localization methods

- **Electrical**
  - **Passive**: voltage taps to monitor the resistance.
  - **Active**: AC signals to measure impedance, reflectometry, or stray capacitances.
- **Magnetic**
  - Array of **induction coils.**
  - Array of **Hall sensors.**
- **Mechanical**
  - **Acoustic emission** sensors.
- **Thermal**
  - **Fiber-optic** sensors.

> - **Voltage taps and induction coils are widely used for LTS magnets.**
> - **All others are considered promising for HTS magnets.**

# Electronics for quench localization



## Needs

- Acquire a large number (>40)  of signals.
- Signal conditioning (mV range).
- High sample rate (>50 kHz).

## Current limitations

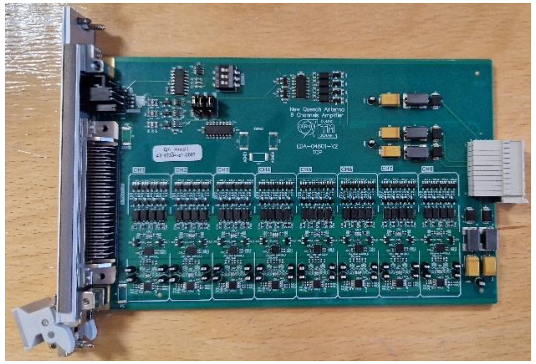
- The number of signals.
- Signal integrity.
- Environmental noise.

# Needs

- **Acquire a large number** (>40) **of signals**.
  - **Internal:** V taps, induction coils, Hall probes.
  - **External:** Quench antenna, Hall probes.

- **Signal conditioning** (mV range).
  - Multi-stage **amplifiers** to increase the **SNR.**
  - Antialiasing **filtering.**

- **High sample rate** (>50 kHz).
  - To capture the full **dynamic** of the acquired signals.

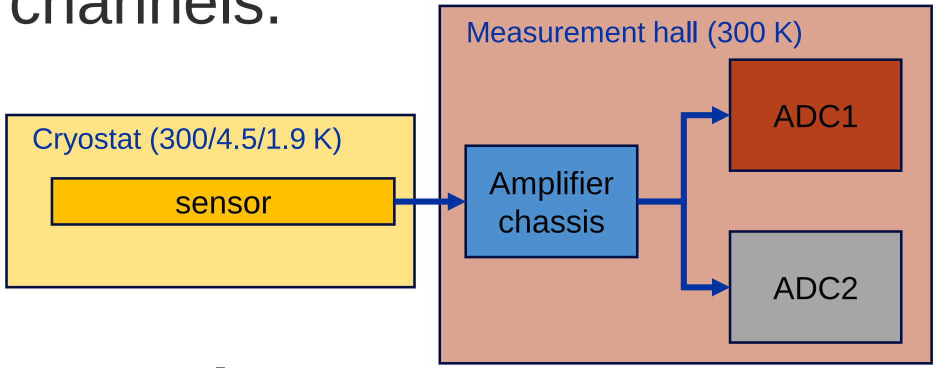


Custom design of amplifier cards and crates for Quench Antenna.

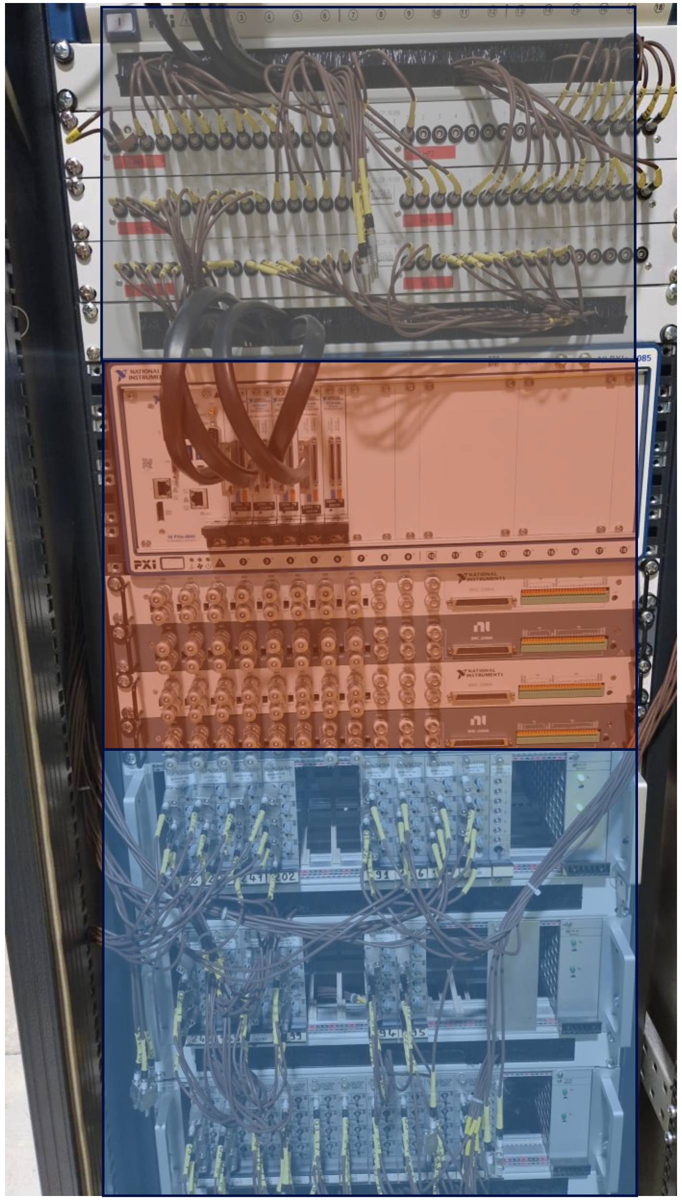

Commercial acquisition system with real-time processing.

# Current limitations

- **The number of signals.**
  - **Internal**: Number of signals that are possible to extract from the cryostat.
  - **External**: Acquisition channels.




- **Signal integrity.**
  - Due to several **interconnections.**
- **Environmental noise.**
  - **Captured** by sensors and cables.



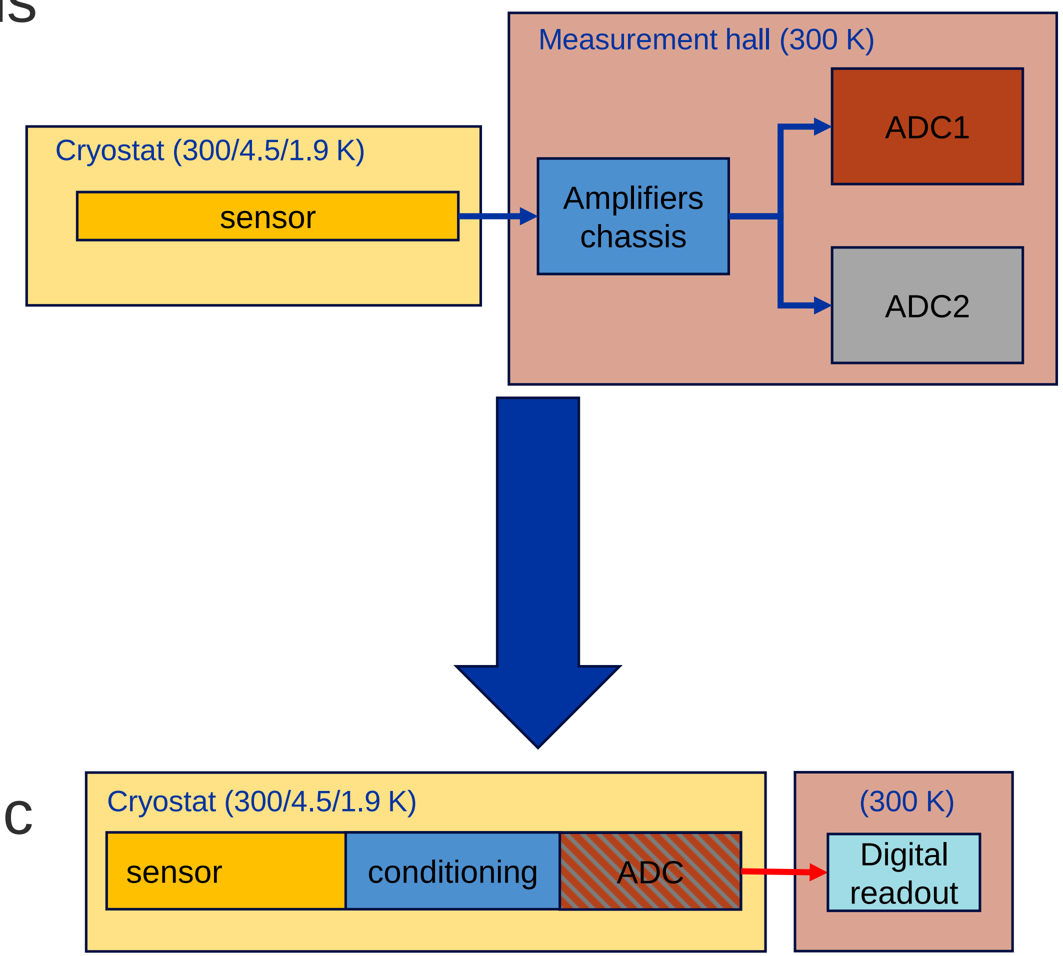
Quench Antenna conditioning and acquisition rack.

# Embedded detection and conditioning electronics

- One Approach to mitigate most of these limitations would be to **embed the whole chain** into the sensors and/or into the cryostat:

  - **Signal conditioning:**
    - Shorter distances.
    - Fewer interconnections.

  - **Digitalization:**
    - **Reduced impact** of external electromagnetic **disturbances**.
    - We need to **extract** only a **few digital signals.**

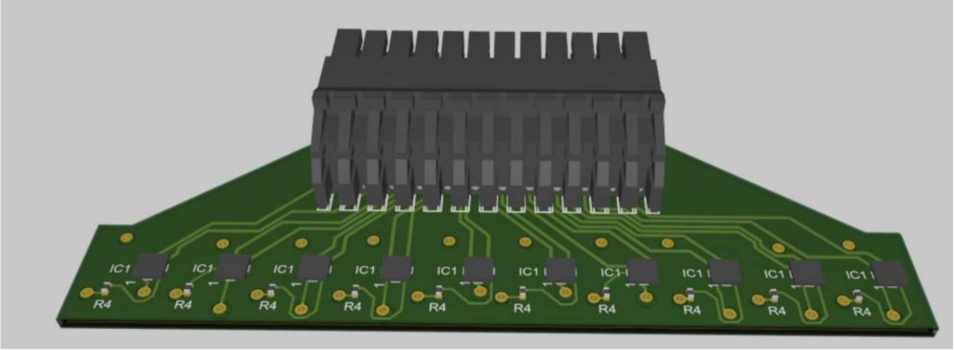


# Cryogenic electronics

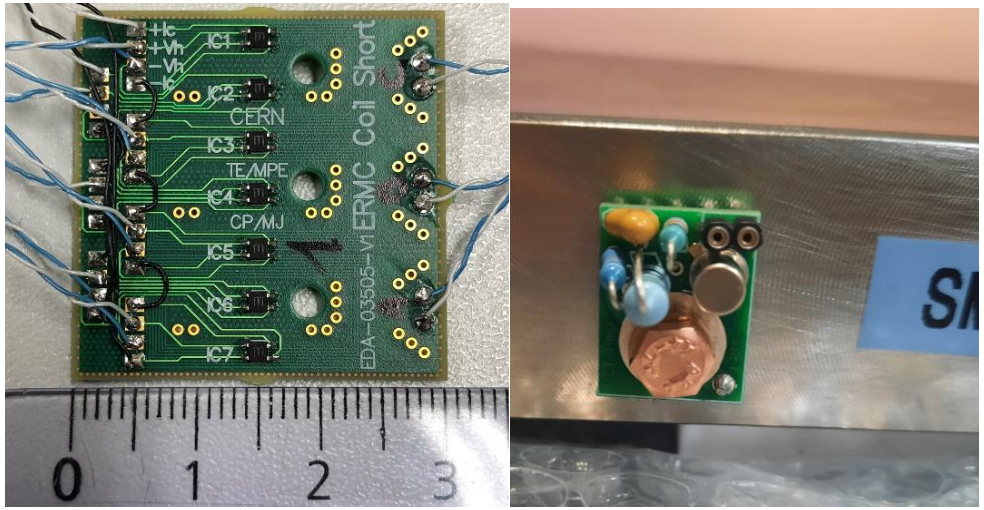
- A crucial aspect to be investigated is **to embed sensors and electronics** in the superconducting **magnets' cryostats.**

- A **vast literature** on using commercial microphones, Hall probes, and conditioning **electronics at cryogenic temperatures** (4.5 and 1.9 Keven if only in dry conditions)[1,2,3,4]

- Each component family and each manufacturer **must be evaluated individually.**



Hall probe array for cryogenic environments.



Hall probe sensors already in use on racetrack magnets (left) (credits: Carlo Petrone). Piezoelectric cryogenic sensor with embedded amplifier (right).

[1] Marchevsky, M. (2022). Understanding training in superconducting accelerator magnets using acoustic emission diagnostics. *arXiv preprint arXiv:2203.08871*.
[2] D. Conway Lamb, et All; An FPGA-based instrumentation platform for use at deep cryogenic temperatures. *Rev. Sci. Instrum.* 1 January 2016; 87 (1): 014701.
[3] Song, M., et All,(2018, March). Evaluation of commercial-off-the-shelf (COTS) electronics for extreme cold environments. In *2018 IEEE Aerospace Conference* (pp. 1-12). IEEE.
[4] Valiente-Blanco, et All (2013). Characterization of commercial-off-the-shelf electronic components at cryogenic temperatures. *Instruments and Experimental Techniques*, *56*, 665-671.

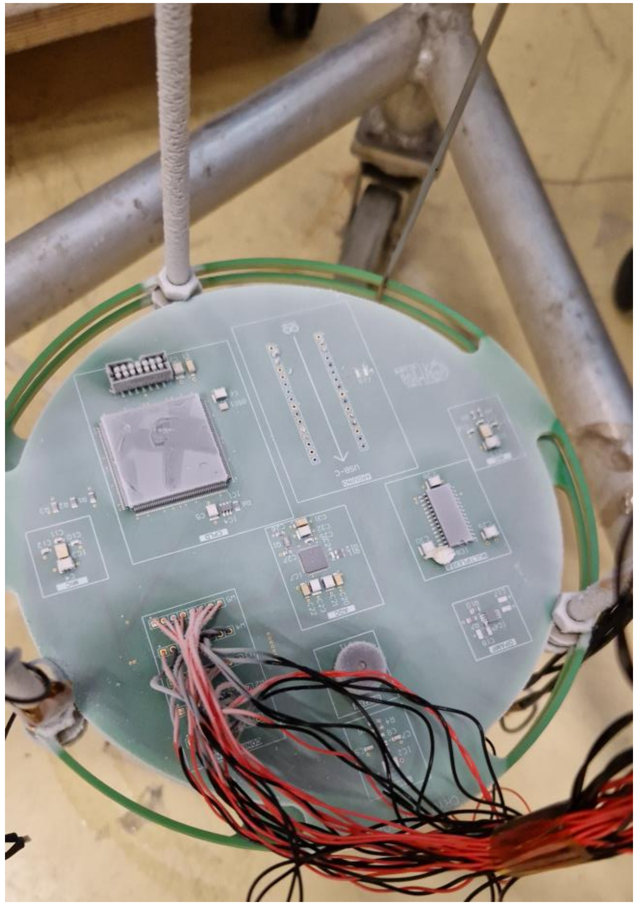
# Selected components

- The components were selected with the final **goal** of building a **complete acquisition chain.**
  - Components have been chosen by taking **inspiration from** the existing **literature.**
  - The test of digital components (**FPGA, MCUs**) has been postponed to the **next test campaign.**

| Device | Description |
|---|---|
| OPA192IDGKT | Operational amplifier |
| IM73A135V01 | MEMS microphone with analog differential output |
| ADG506AKR | CMOS 16-Channel Analog Multiplexers |
| KXG1205C | Piezoelectric transducer |
| SMD Thick Film Resistors | 25 k$\Omega$, 10 k$\Omega$, 5.1 k$\Omega$, 4.7 k$\Omega$, 1.1 k$\Omega$, 50 $\Omega$ |
| SMD PPS Film Capacitors | 100 nF, 2.2 nF, 220 pF, 100 pF, 4.7 pF |
| SMD Tantalum Capacitors | 10 $\mu$F |

# Evaluation board

- **Custom PCB** has been designed to host all the devices under test and provide a suitable **interface for the** signal cable and the 40 available feed-throughs.
- **Test points** have been added to simplify the **debugging** in case of faults.
- Form factor **tailored** to the test head.
- Standard industrial processes, **FR4** dielectric, and **ENIG** surface finish.



PCB for 1st campaign of tests of sensor and electronic components at cryogenic temperature.

# Test plan and setup

- All the selected **components** have been **tested at :**
  - **300 K** (room temperature)
  - **77 K** (liquid nitrogen)
  - **4.5 K** (liquid helium)
  - **1.9 K** (superfluid liquid helium)

- **Each test** has been **repeated twice:**
  - **Immediately** after power on.
  - **Check for performance stability.**

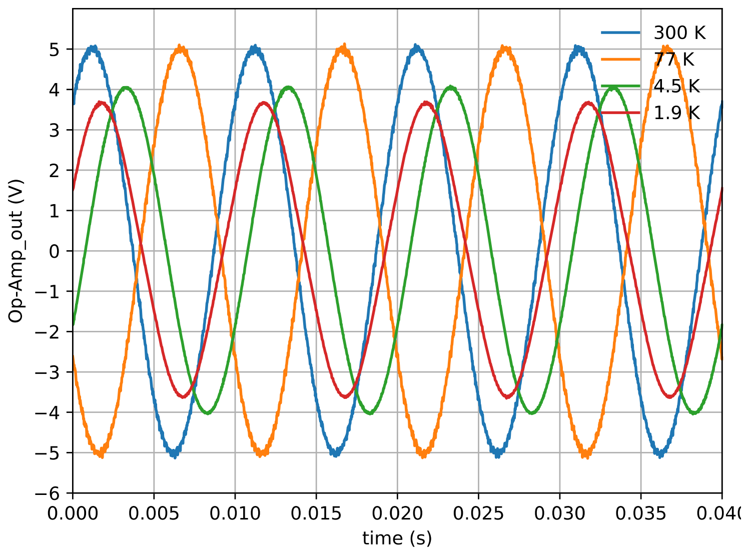
- **After each test**, the PCB has always been brought **back to room temperature.**

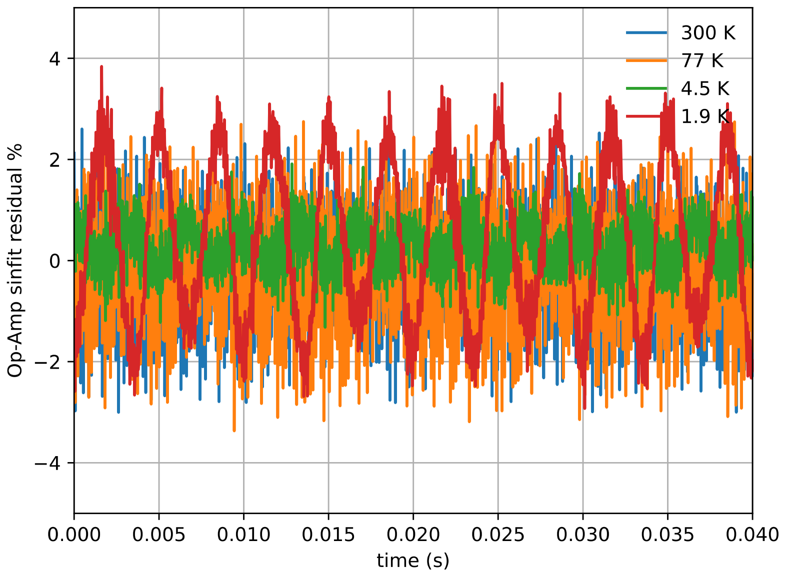
Assembled test head (left), liquid nitrogen tests (right).

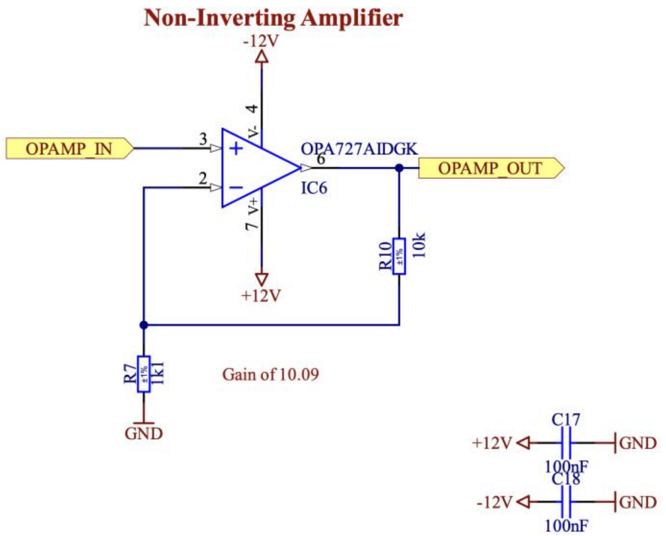
setup for the test in liquid Helium at 1.9 K.

# Operational Amplifier

- configured in **non-inverting** mode.
- DC **gain of 10.**
- Test (**SNR evaluation**):
  - **1.1 V AC input at 100 Hz.**
  - output acquired at **50 kHz.**
  - Four parameters **Sinfit.**



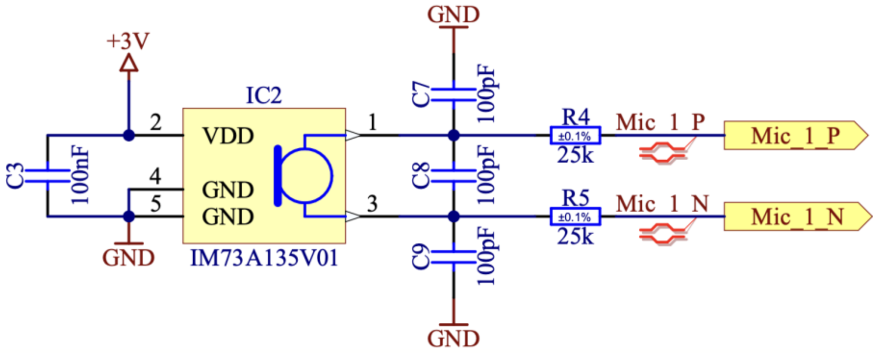



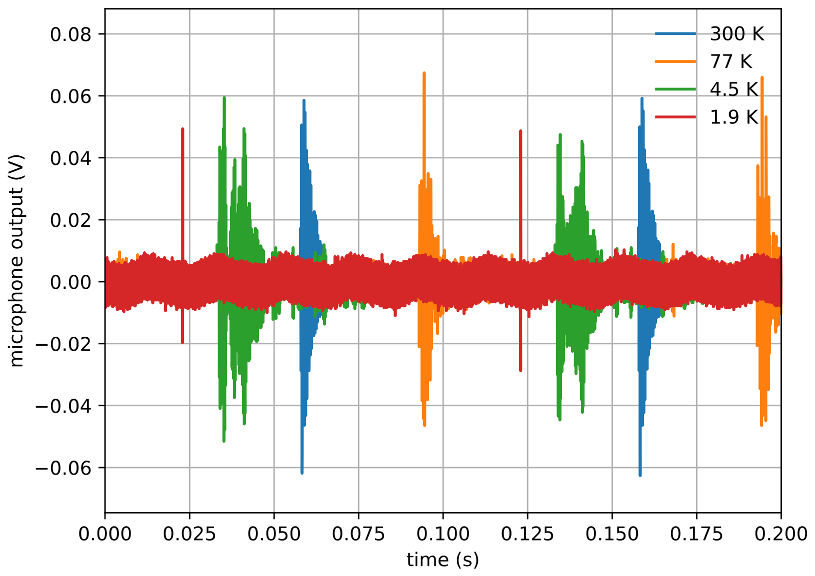




| | 300 K | 77 K | 4.5 K | 1.9 K |
|---|---|---|---|---|
| SNR (dB) | 74.58 | 73.66 | 85.7 | 65.74 |

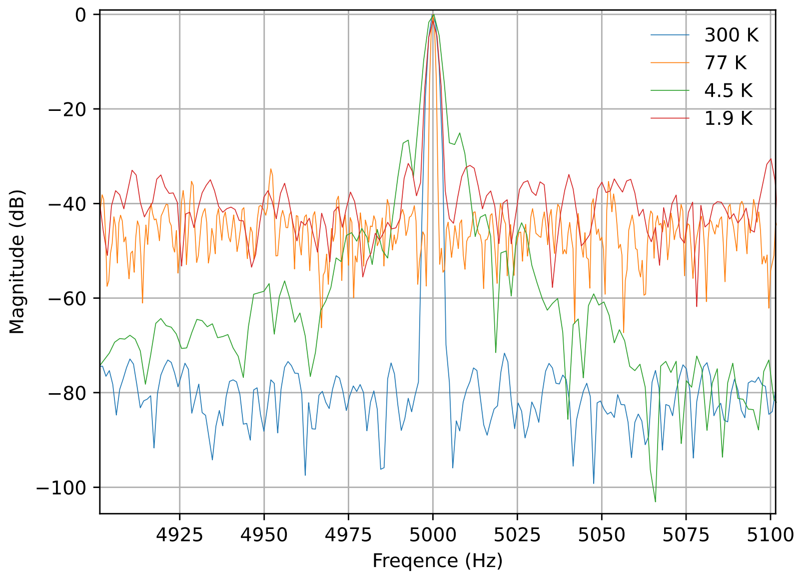
# MEMS microphones

- Acoustic vibrations are provided by a piezoelectric transducer.
- Test the full bandwidth of the sensor.



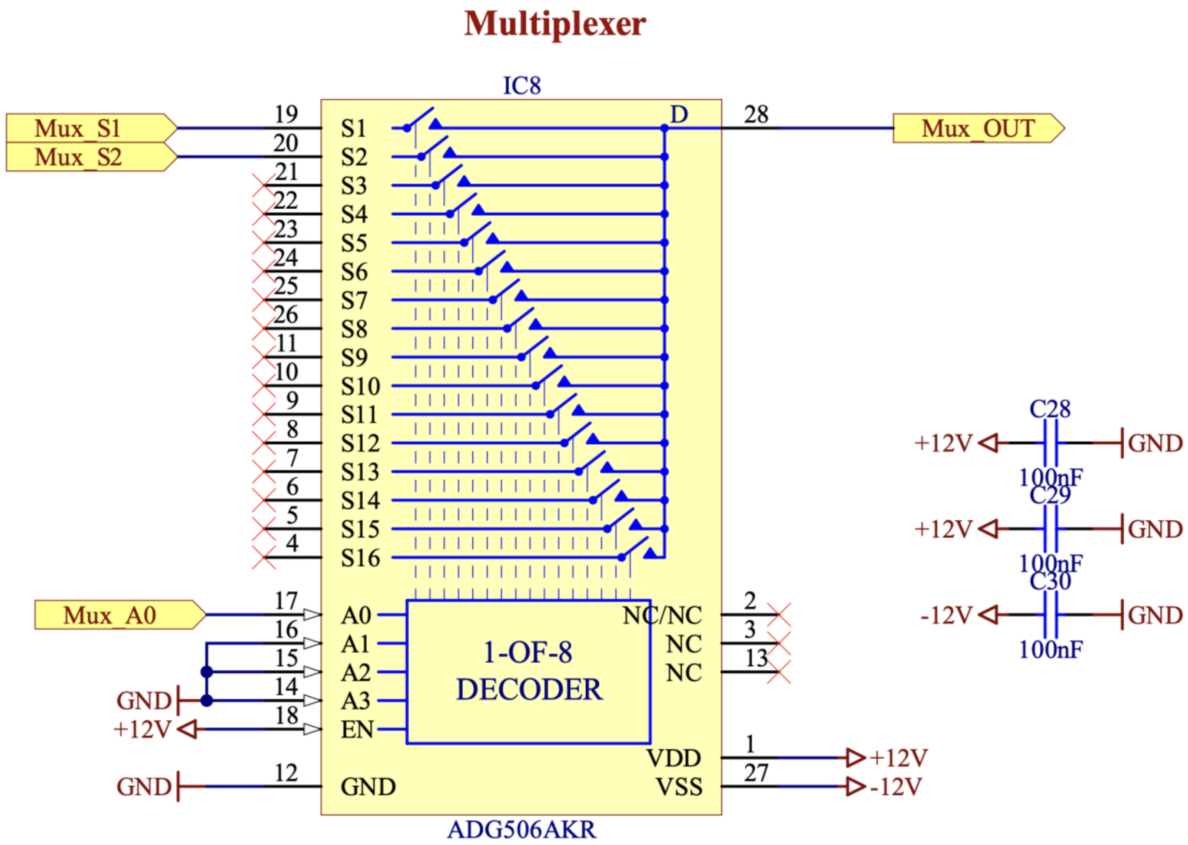




| unit mV/V | 300 K | 77 K | 4.5 K | 1.9 K |
|---|---|---|---|---|
| **Pulse train** | 2.1 | 6.7 | 5.6 | 4.9 |
| **1 kHz** | 3.3 | 0.6 | 0.7 | 0.5 |
| **5 kHz** | 1.5 | 0.5 | 0.4 | 0.5 |
| **10 kHz** | 1.9 | 0.5 | 0.6 | 0.6 |
| **15 kHz** | 2.4 | 0.5 | 1.5 | 0.5 |
| **20 kHz** | 1.5 | 0.5 | 0.5 | 0.5 |



# Multiplexer

- **In-out resistance was** evaluated for two of the inputs of the multiplexer.
  - **Liquid nitrogen** performance comparable with room temperature.
  - **Increase in liquid helium** by a factor of almost 2, with a negligible difference between 4.5 K and 1.9 K.
- Component suitable for multiplexing signals at cryogenic temperatures.



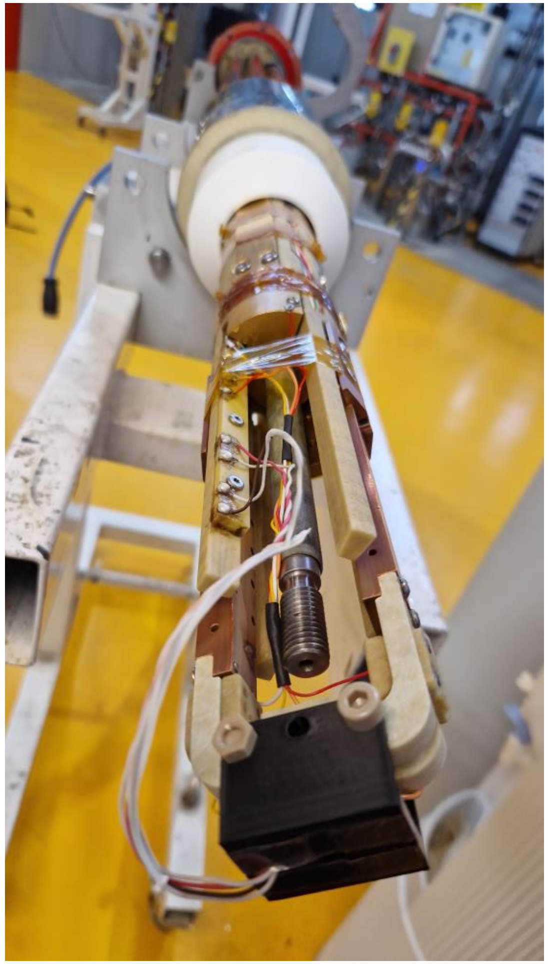

| | 300 K | 77 K | 4.5 K | 1.9 K |
|---|---|---|---|---|
| in1-out (Ω) | 166 ±1 | 109 ±1 | 315 ±1 | 328 ±1 |
| in2-out (Ω) | 167±1 | 57 ±1 | 282 ±1 | 305 ±1 |

# Future perspectives

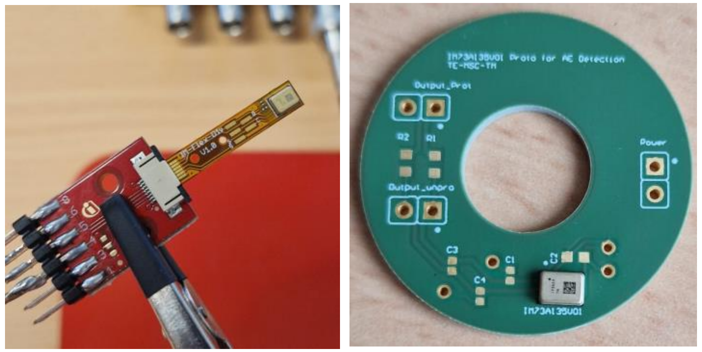
- A **second test campaign** is foreseen.
  - ADC, microcontrollers, and FPGA.

- A small PCB for **integration** of MEMS sensors **on magnet structure** has been developed and characterized.

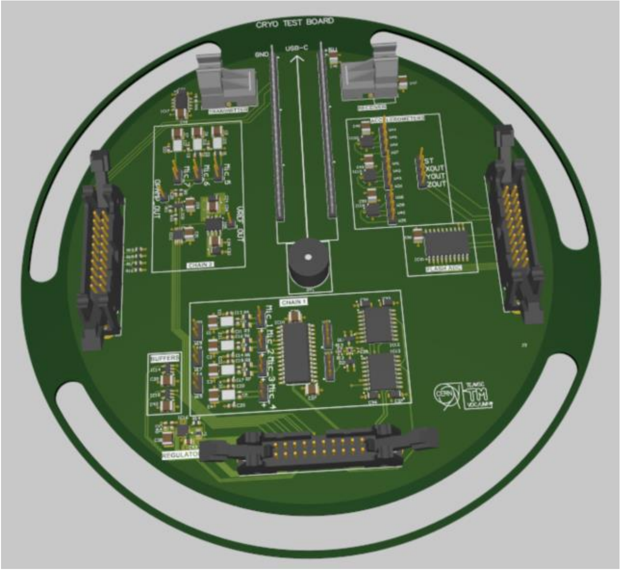
- **Acoustic emission** during critical current tests of **REBCO tapes** is currently under study.
  - Case study with only one **MEMS sensor** up to 15 T.



Test insert for critical current test on REBCO tapes.



Commercial MEMS microphones (left) and PCB board for integration in the magnet structure (right).




PCB for 2nd campaign of tests of sensor and electronic components at cryogenic temperature.

# Conclusions

- **Quench** detection and **localization** are **crucial** for optimizing the design and manufacturing of superconducting magnets.
- Typically, **a large number of small signals** (greater than 40, each a few millivolts) need to be acquired and sometimes extracted from the cryostat.
- Using **cryogenic electronics** for signal conditioning and acquisition can **improve** the signal-to-noise ratio (**SNR**).
- **Individual tests** are necessary to verify the functionality and characterize electronic components beyond the manufacturer’s specifications.
- We **successfully tested the signal conditioning chain's essential components** and established a stable setup and procedure.
- **Future tests** are planned to develop a **complete cryogenic acquisition chain.**
- The **tested MEMS** sensors have already been **deployed with success for cryogenic applications.**

# Thanks for the attention!

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