Cryogenic electronics for superconducting magnet instrumentation

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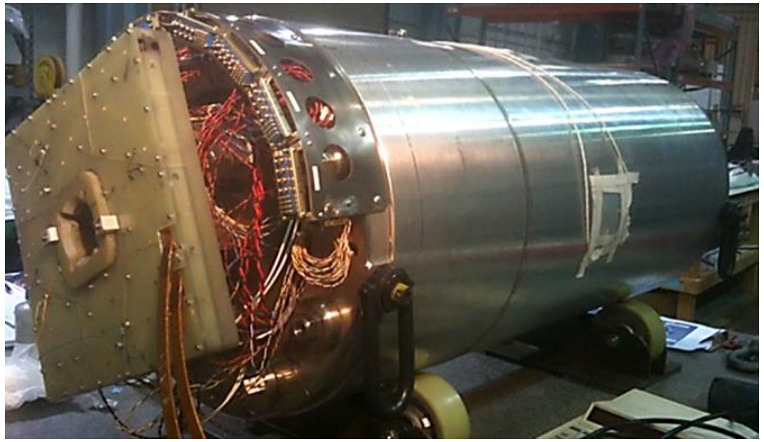
Instrumentation for superconducting magnets

Performance monitoring

Temperature

Strain

Field quality



Magnetic field disturbances

Coil voltage

Acoustic emission

Quench detection and localization

Fast datastream (~ 1Ms/s /ch)

(AE, field disturbances)

Medium datastream (~ 10-100 kS/s /ch)

(Voltage, field quality probes)

Slow datastream (~ 1 – 1000 s/s /ch)

(Strain, temperature)

Benefits of using cryo-electronics for magnet instrumentation

- Long interface cables with multiple interconnects
- High impedance sources
- Significant EM noise injected with the power supply
- Large number of channels

Cryogenic amplification

Cryogenic multiplexing

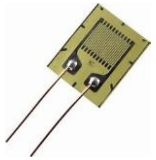
Cryogenic ADC and RT data pre-processing

Sensors and components at cryogenic temperatures

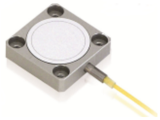
Sensors

- Wire loops (quench antennas)

- Resistive strain gauges



- Capacitive sensors
- (affected by the cryogenic liquid)



Temperature is not a significant factor

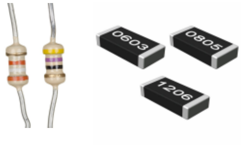
- Hall effect sensors (GaAs)

Sensitivity improves

- Acoustic emission sensors made with piezoelectric ceramics

Sensitivity decreases, quality factor increases

Passive components



- Resistors (metal film)

Temperature is not a significant factor

- Capacitors (X0R, tantalum)

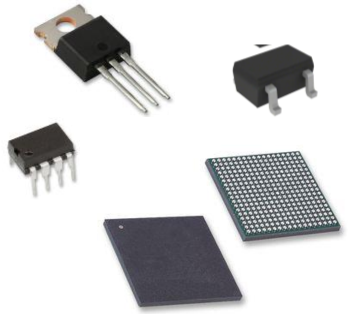
Capacitance decreases

- Diodes

Forward voltage drop increases

Active components

- MOSFETs and MOSFET-based ICs
- Op-amps (CMOS, SiGe)
- Digital electronics, FPGA

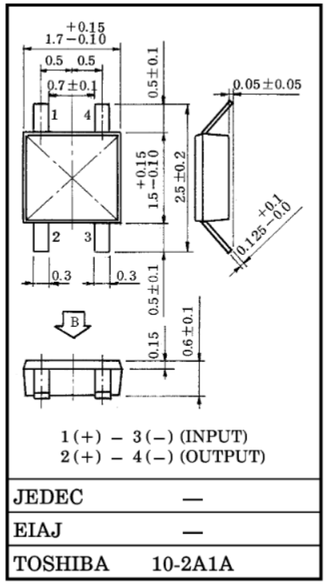


Many work cryogenically, but require some adjustment of operational conditions

Hall effect sensors

THS121

Unit in mm



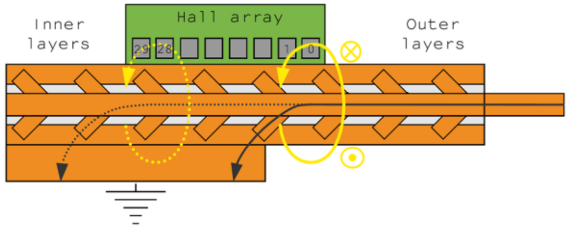
Weight : 0.0047g

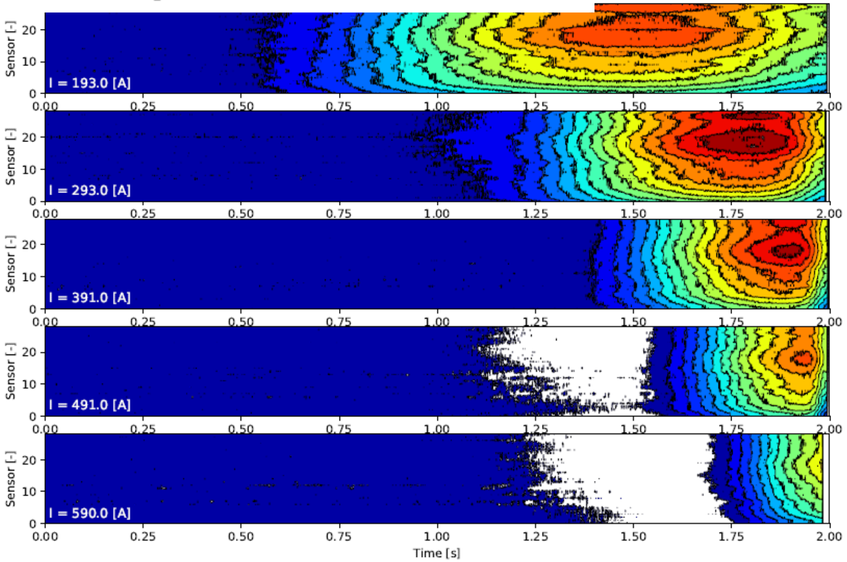
A linear array of 60 Hall sensors for quench detection / quench propagation studies

ELECTRICAL CHARACTERISTICS (Ta = 25°C)

CHARACTERISTIC	SYMBOL	TEST CONDITION	MIN.	TYP.	MAX.	UNIT
Internal Resistance (Input)	R_d	I_C=5mA	450	—	900	Ω
Residual Voltage Ratio	V_{HO}/V_H	I_C=5mA, B=0 / B=0.1T	—	—	±10	%
Hall Voltage (Note 1)	V_H	I_C=5mA, B=0.1T	55	—	140	mV
Temperature Coefficient (Note 2)	V_{HT}	I_C=5mA, B=0.1T T1=25°C, Ta=125°C	—	—	−0.06	% / °C
Linearity (Note 3)	ΔK_H	I_C=5mA, B1=0.1T, B2=0.5T	—	—	2	%
Specific Sensitivity (Note 4)	K*	I_C=5mA, B=0.1T	—	27	—	$\times 10^{-2}$/T
Internal Resistance (Output)	R_{OUT}	I_C=5mA	580	—	1350	Ω

GaAs planar ion-implanted Hall effect sensors (made for automotive applications) are excellent performers at cryogenic temperature.

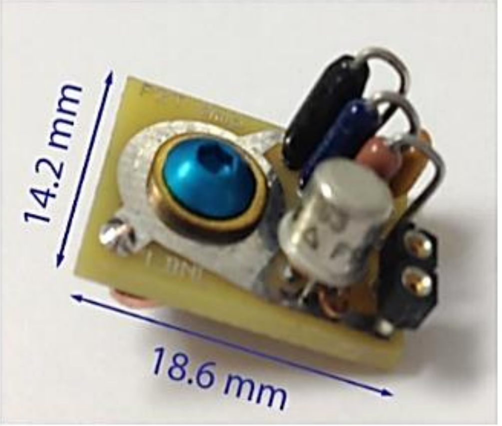


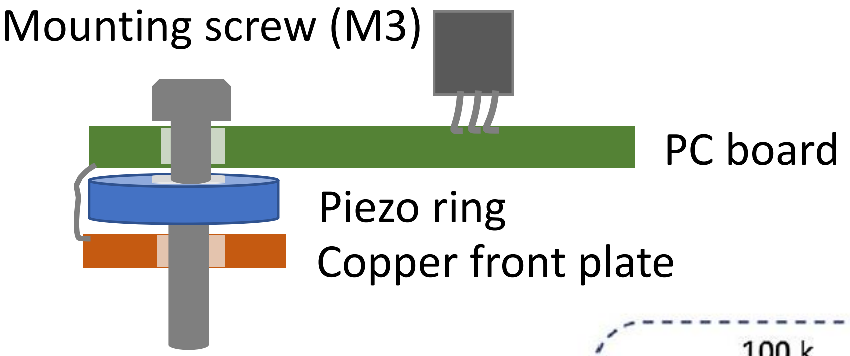


Current re-distribution along HTS CORC® cable terminals as function of time during quench development measured with the Hall array

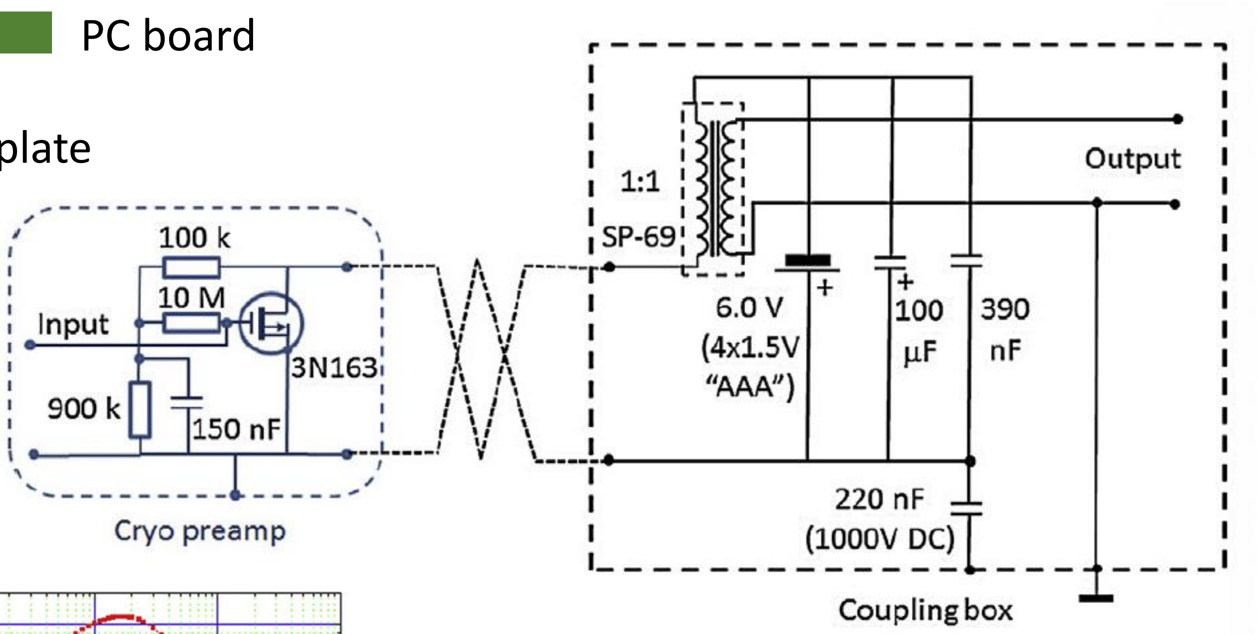
CORC® cable terminations with integrated Hall arrays for quench detection", R. Teyber et al., Supercond. Sci.Technol., 33, (2020)

Acoustic emission sensor

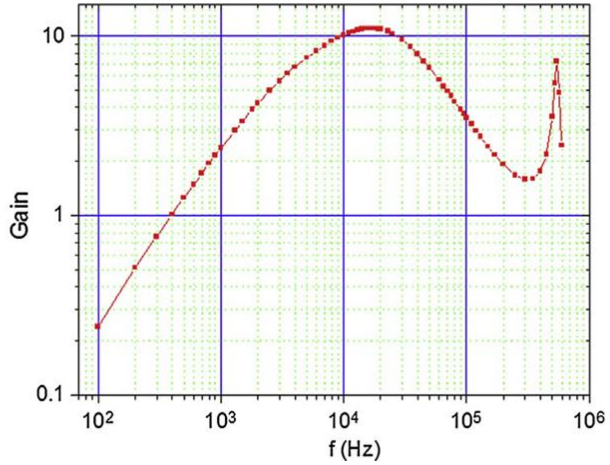




A robust “workhorse” sensor developed and used at LBL on most of our magnets. It is now also used by other labs (FNAL BNL, CERN) and various projects.



- Based on a single P-channel enhancement mode MOSFET
- Uses only 2 wires (twisted pair or coax)
- Bandwidth is ~300 kHz
- Power consumption is ~ 25 mW
- 2-3 mV rms of noise

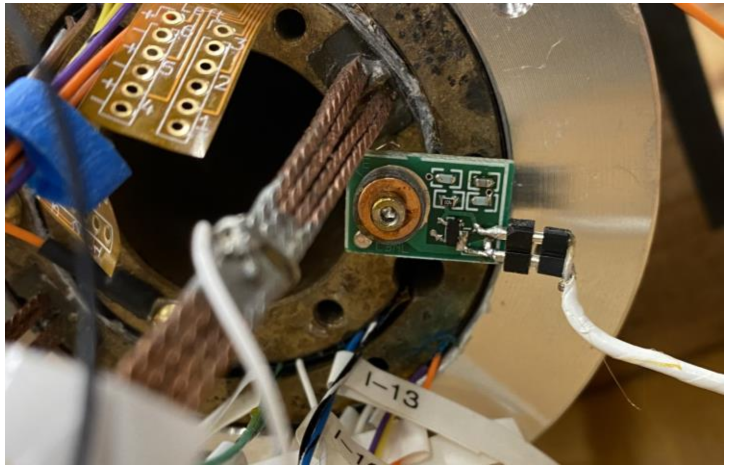


“*Acoustic emission during quench training of superconducting accelerator magnets*”, M. Marchevsky, G. Sabbi, H. Bajas, S. Gourlay, Cryogenics 69, 50–57 (2015)

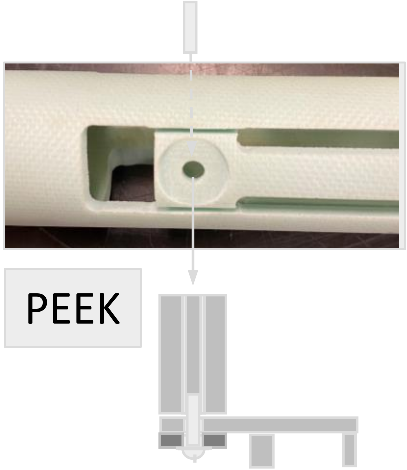
Latest 2-wire sensor re-design

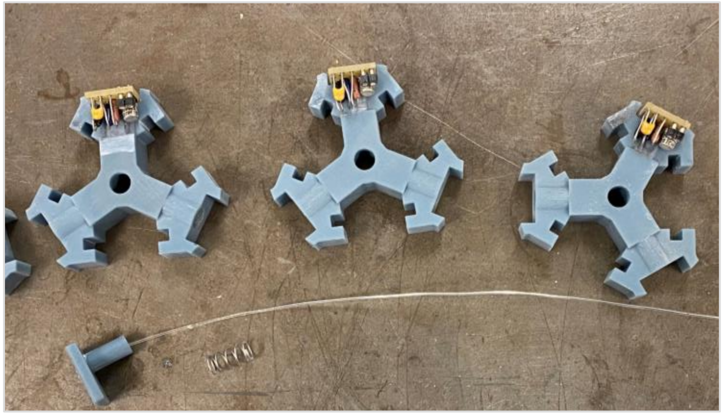
- 2/3 the size of the original sensor
- M2 mounting screw
- < 5 mm thickness (including the piezo-element)
- Better high-frequency response

Same 2-wire interfacing, fully compatible with old interface and powering hardware



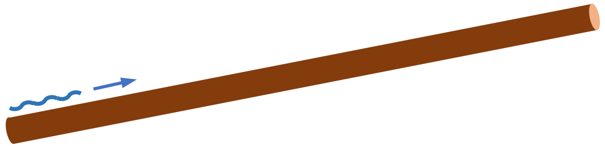
Various supporting structures for AE sensors



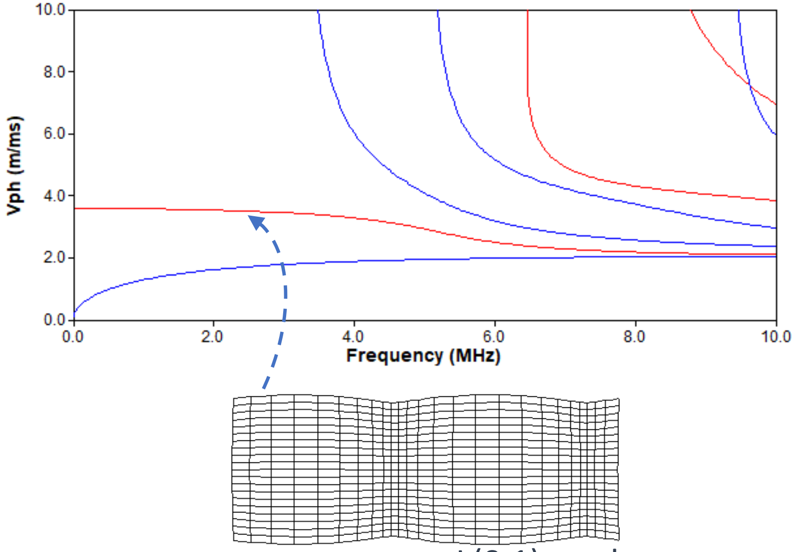


R. Teyber, M. Maruszewski

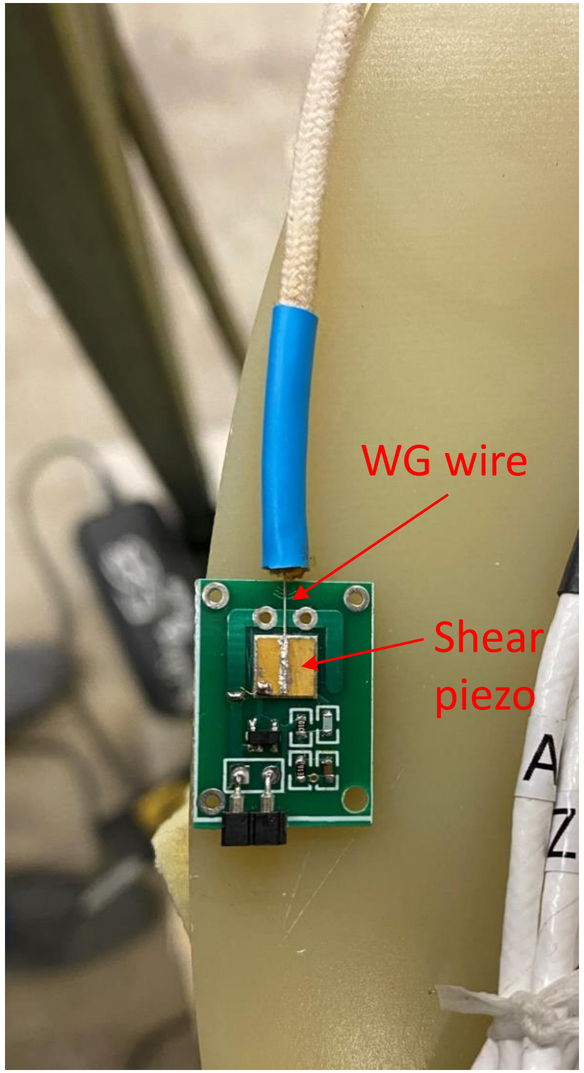
Waveguide acoustic sensors



Dispersion plot for traveling acoustic waves in a 0.4 mm diam. brass rod

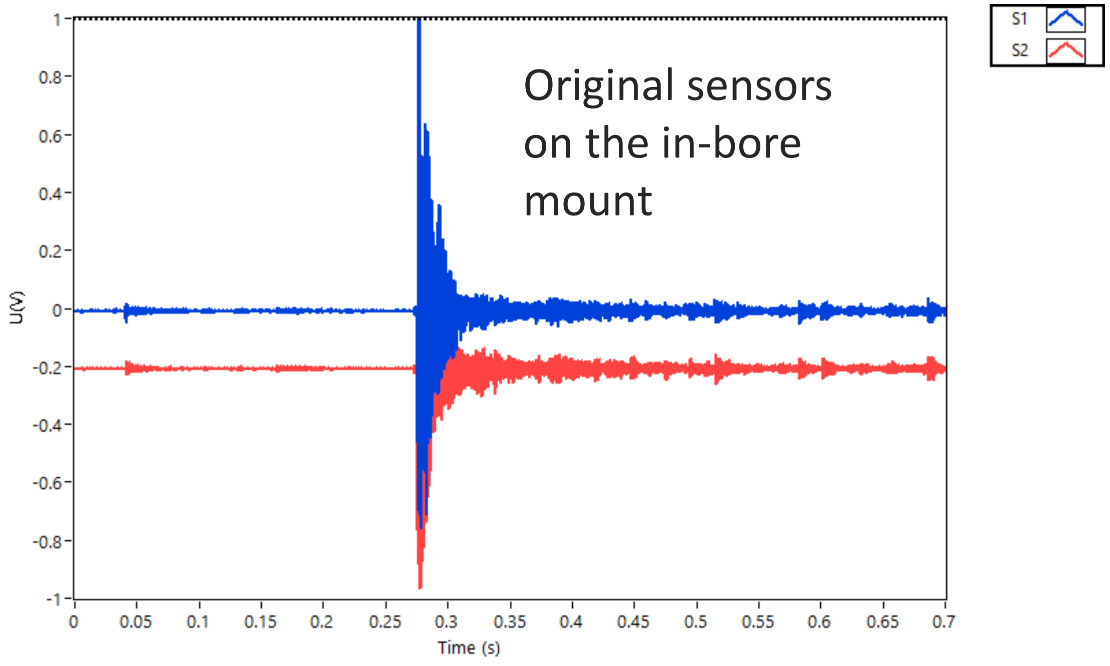


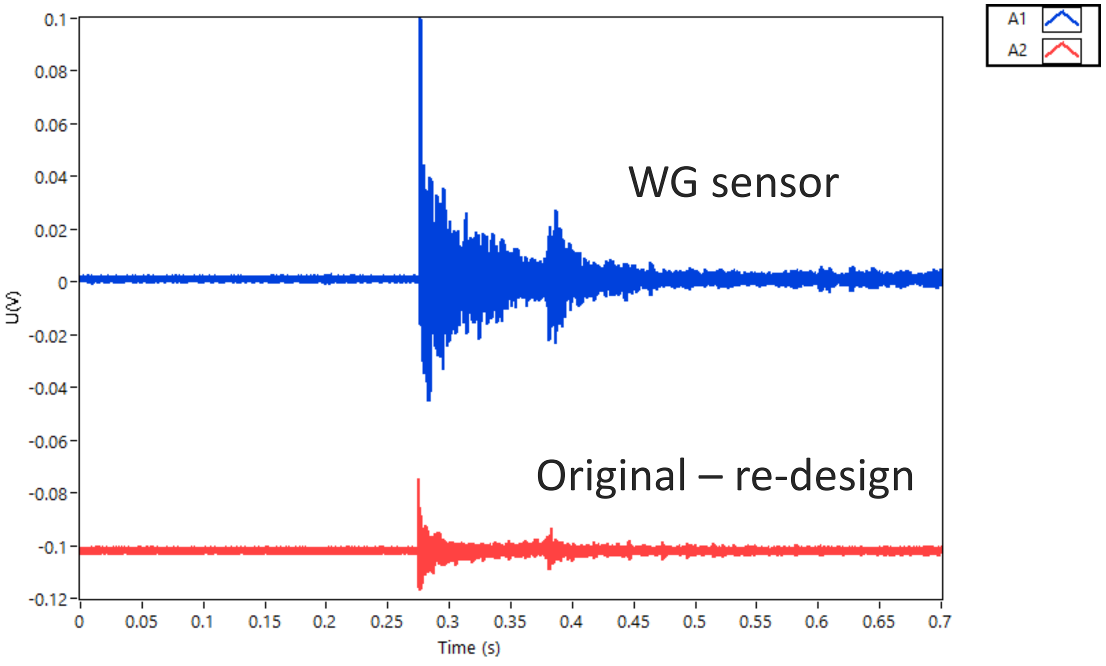
L(0,1) mode



- The entire sensor is one low-profile soldered board, including the piezo.
- It can be installed away from the magnet; acoustic signal is fed from the magnet by a waveguide wire
- Enables multiple sensors being integrated in a single board, probing specific locations inside the magnet that otherwise are impossible to reach with standard diagnostics

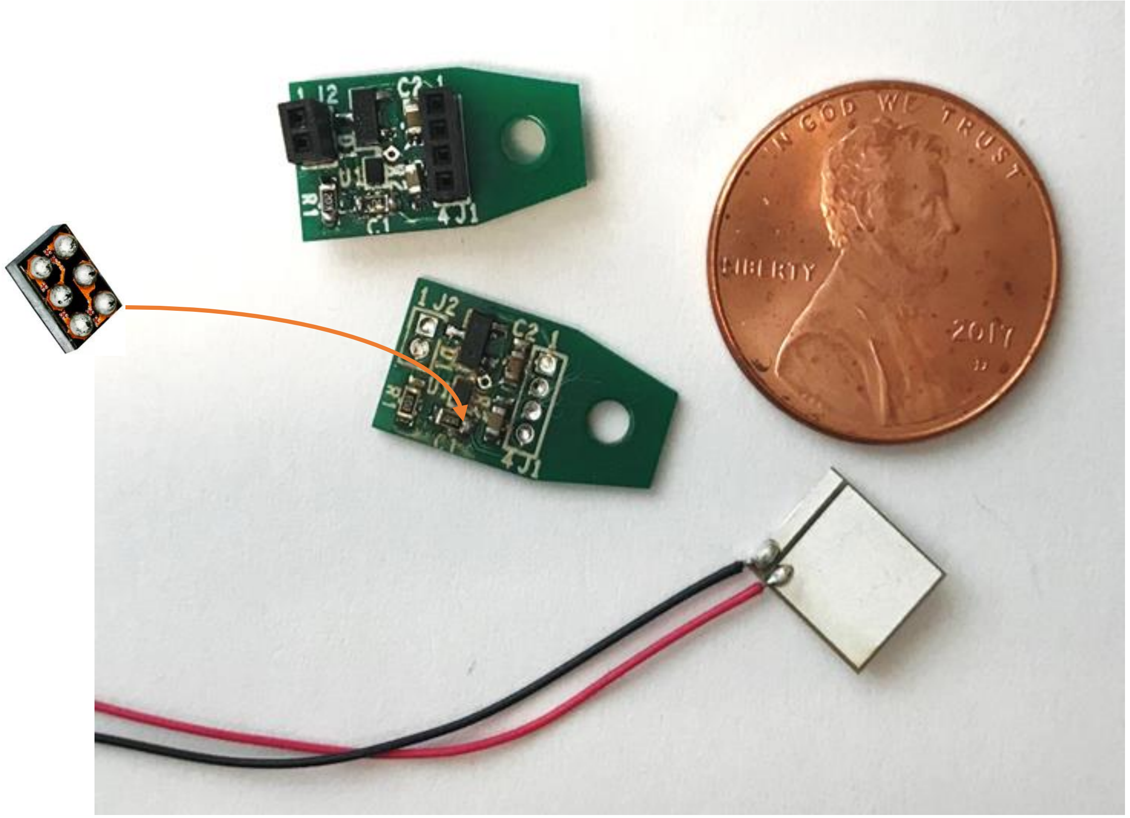
Comparative AE sensor test

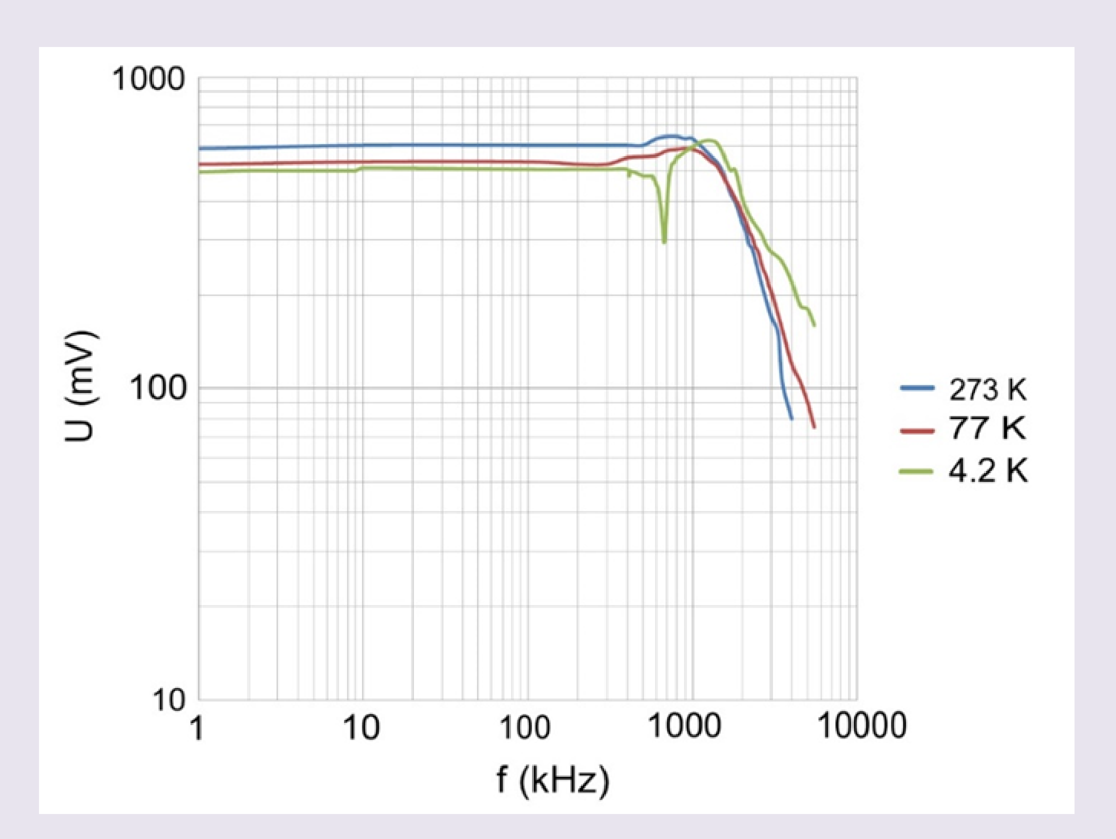




Quench in Nb3Sn CCT Subscale 3 dipole monitored with the old and new style acoustic sensors

Cryogenic general purpose (or acoustic) amplifier





- Based on ultra-low-power Maxim Integrated MAX44290 chip
- Power consumption at 4.2 K is ~15 mW with +/- 3V rail to rail output
- High impedance (> 1 MΩ), diode-protected input
- Excellent noise performance
- Flat frequency response in 0-1 MHz range

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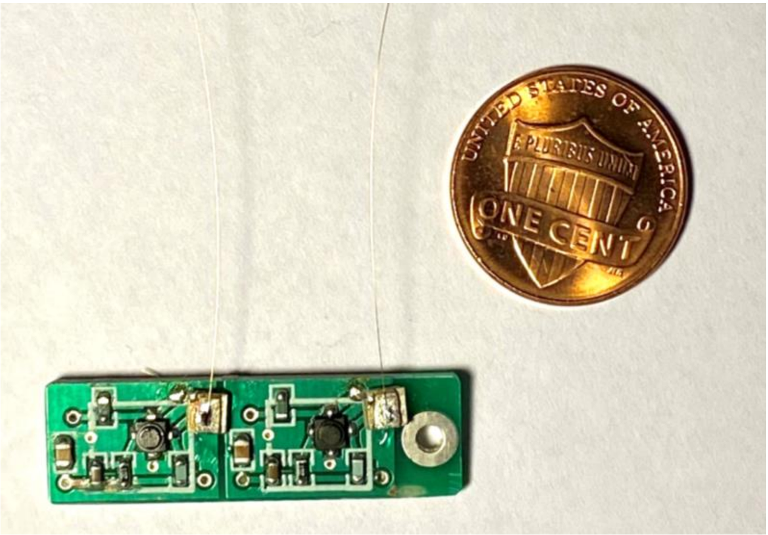
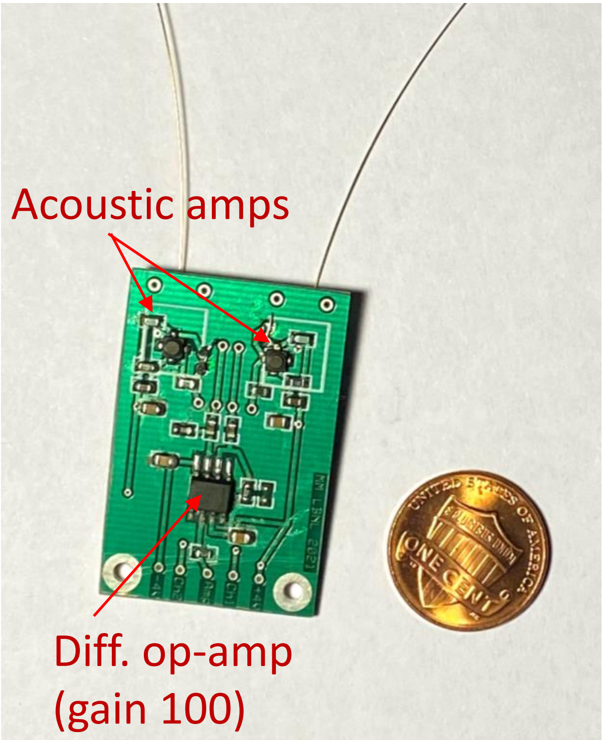
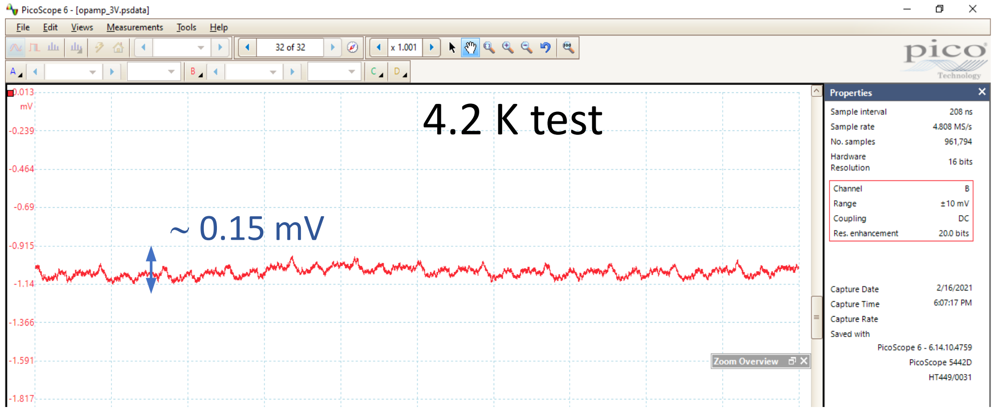
“Acoustic tap” boards



Waveguide
acoustic sensors based on GaAs FETs



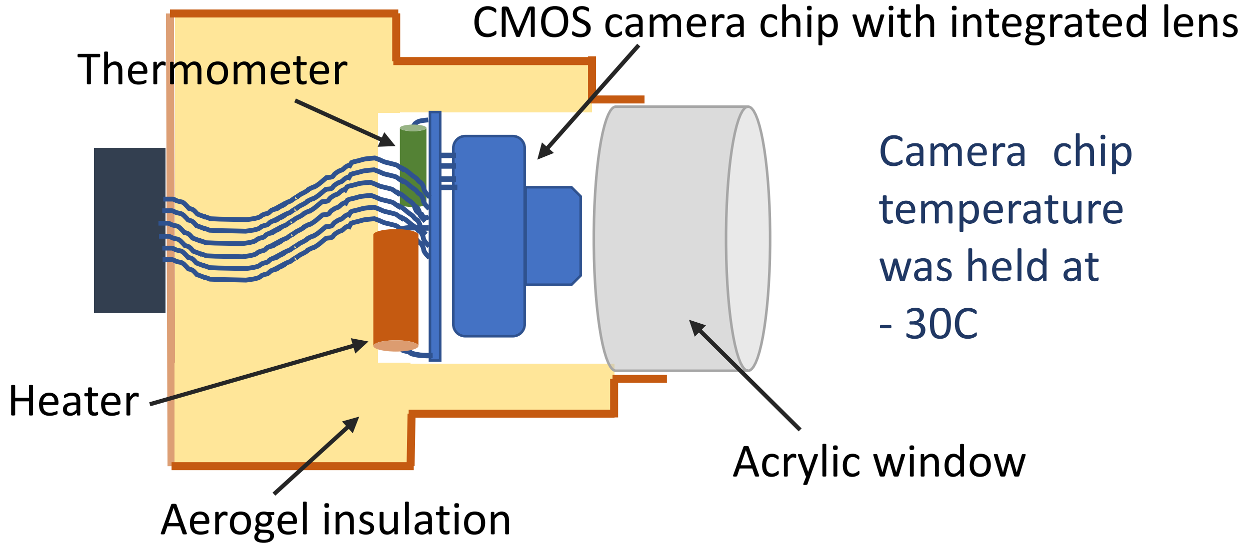
“Universal tap” board: two acoustic amplifiers combined with a differential amplifier based on SiGe technology



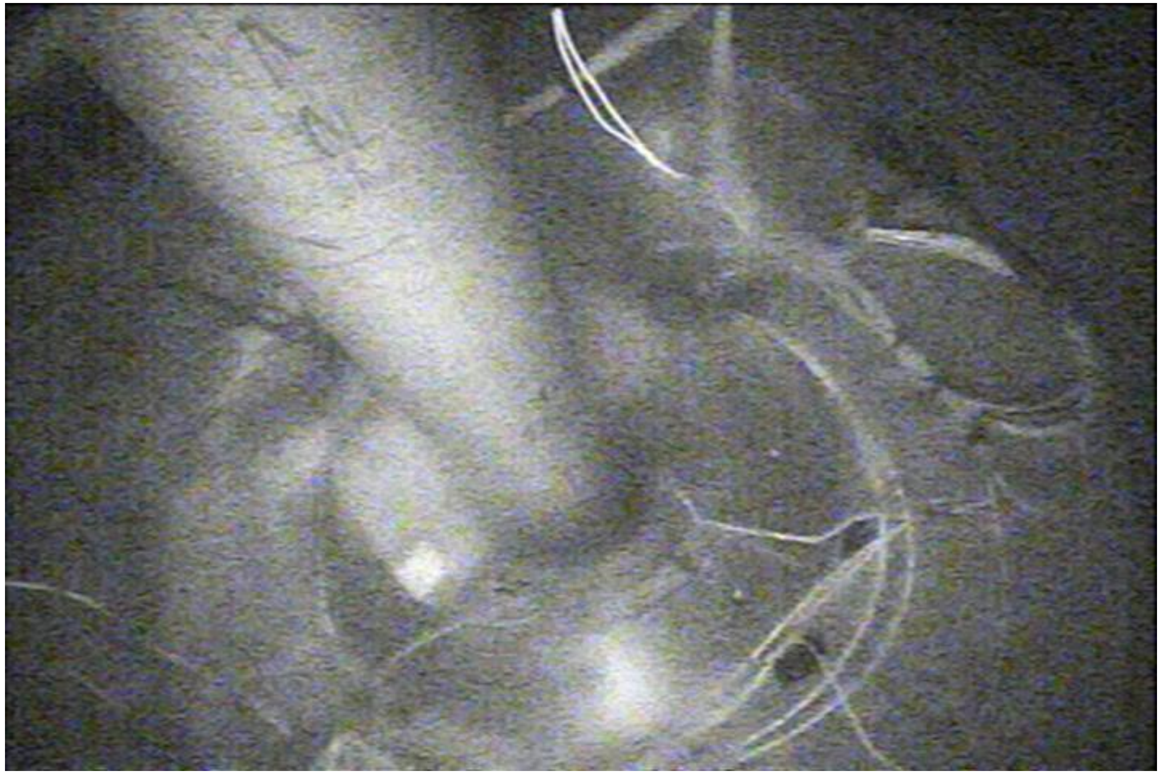
- Extremely low noise (< 1 nV/$\sqrt{Hz}$ at 1 MHz), uniform performance 300 K-> 4.2 K
- Ultra wide bandwidth, limited by the piezo-transducer Single-ended and differential amplification possible
- 50 Ω output

- Simultaneous measurement of differential voltages and acoustic emissions can be achieved with a single pair of taps

"Video calorimetry" enabling quick identification of heat sources in the magnet

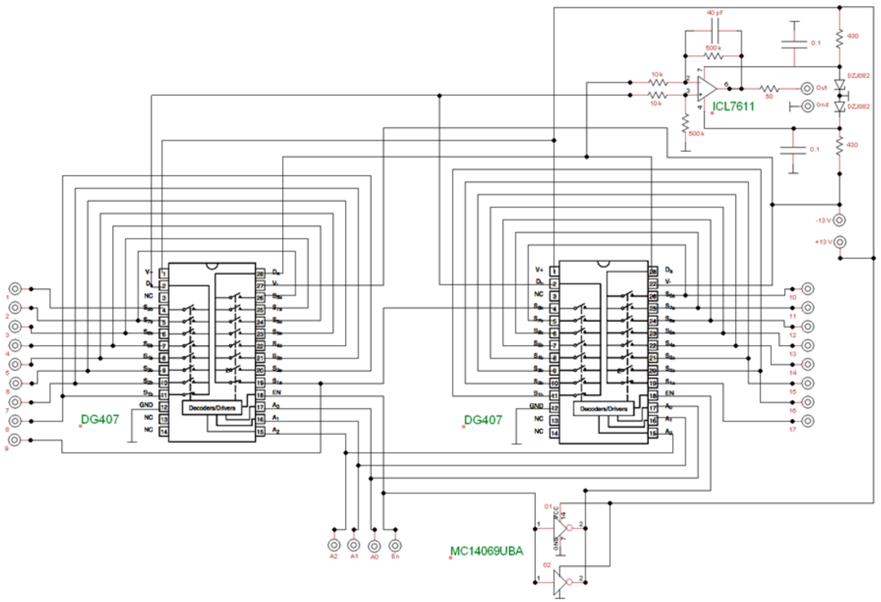


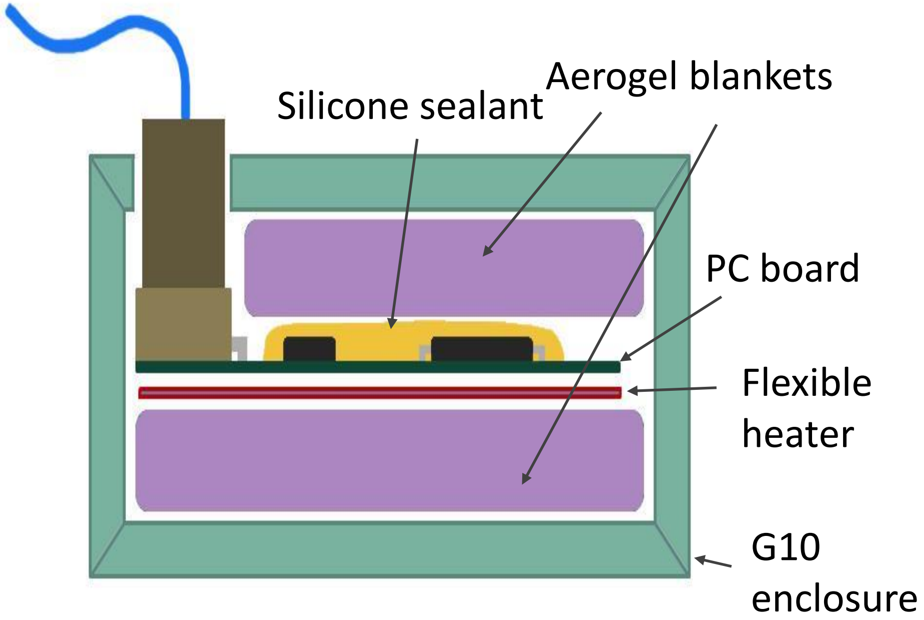
Camera chip temperature was held at - 30C



- CCT3 magnet quenching at ~11 kA
- One can hear the quench occurring in the magnet ("hissing" sound) followed by a slight increase in boiling
- ~2 s later helium bath comes to violent boiling and liquid is propelled upwards along the bore tube.

Cryogenic CMOS Multiplexer



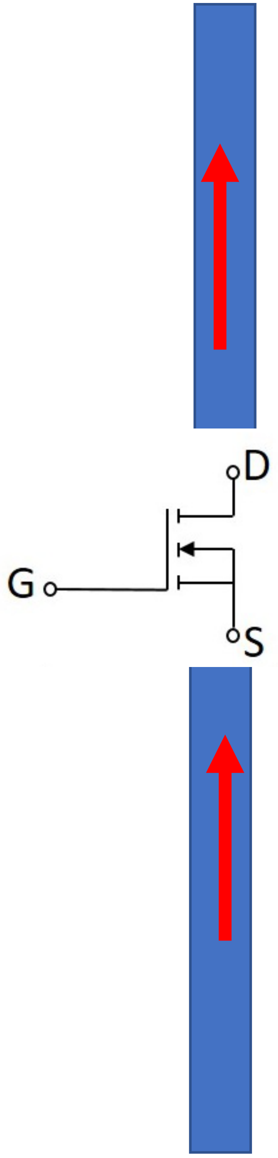


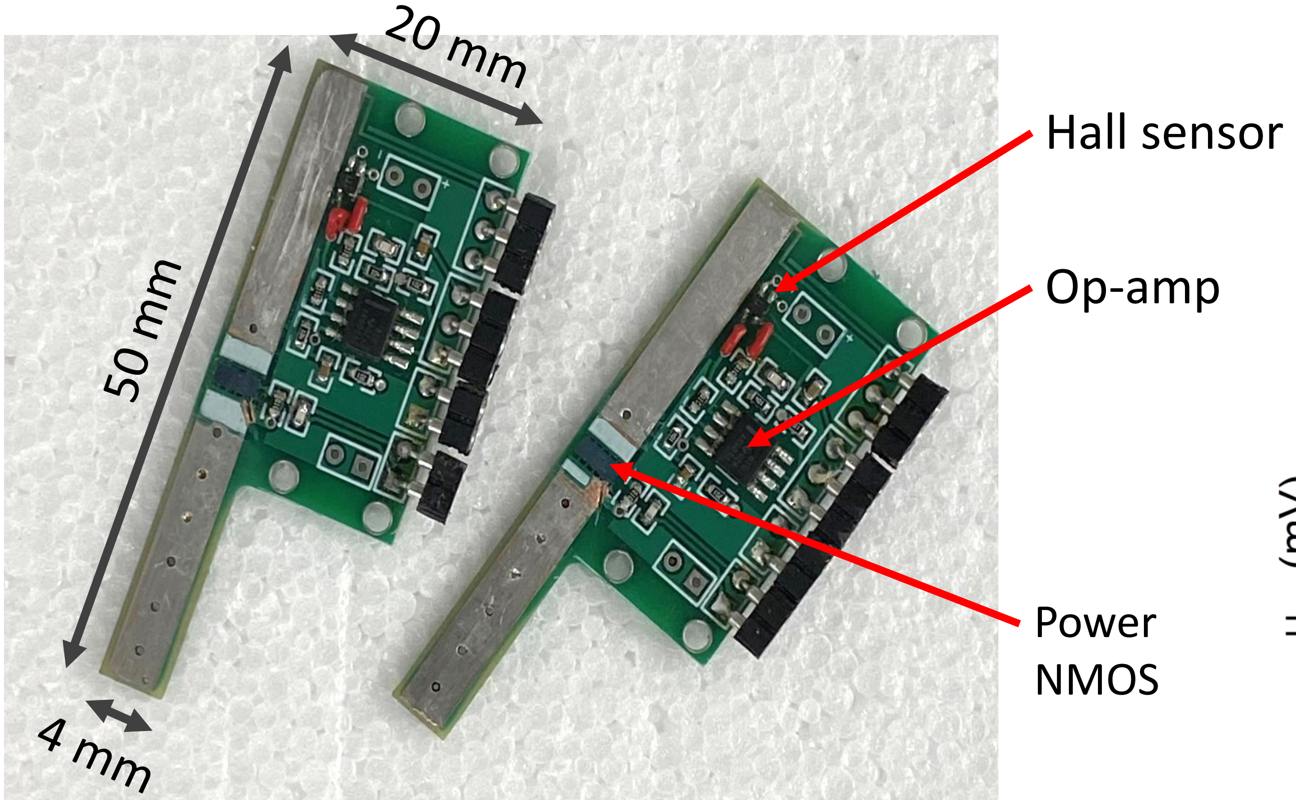
- Two 8-channel DG407 analog multiplexers are commutating 16 differential inputs to a gain x50 amplifier built using ICL7611 op-amp.

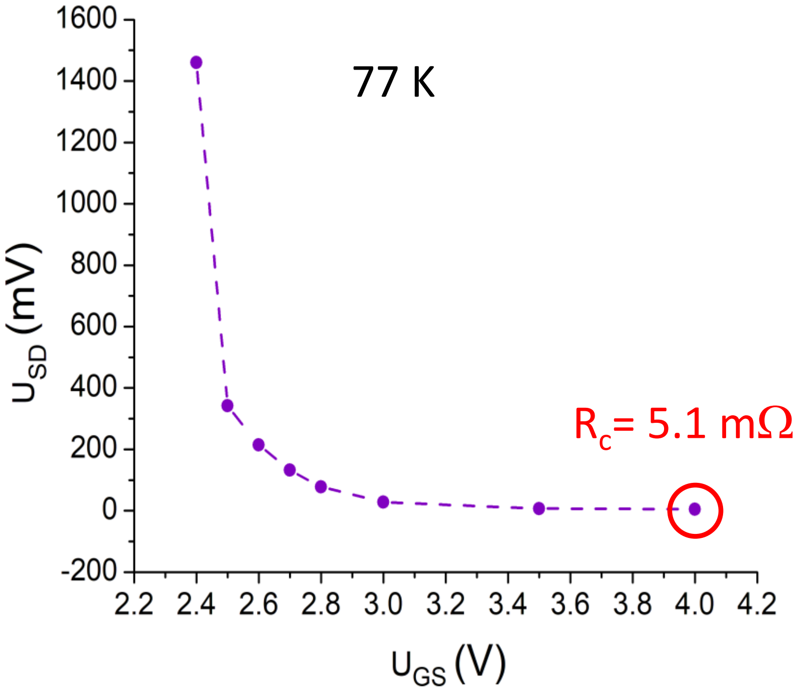
- Reliable operation has been confirmed down to 30 K, with switching rates up to 60 kHz/ch limited by the performance of control software. At lower temperatures the **DG407** ICs were no longer responding to control voltages, but the operation restored back to normal at above 30 K.

- To extend low-temperature functionality, the board was sandwiched with a flexible Kapton sheet incorporating a 50-micon thick stainless heater (R = 9 Ω) and two Aerogel blankets inside a G10 box enclosure. With only 0.3 A dc current in the heater the board temperature can be raised above 30 K without having any notable impact on the helium boil-off rate

Cryogenic current drivers







- Can drive up to 50 A (room temp, over 100 A expected in LN2)
- Used for quench detection and protection, imaging studies with HTS conductors

U.S. MAGNET DEVELOPMENT PROGRAM

BERKELEY LAB

Future trends

- Synergistic approach to data acquisition and pre-processing. Combining various magnet sensors together with real-time digitizer and pre-processors. A cryogenic magnet “neural system”.

- Integration with magnet, structural elements and cryogenic infrastructure. ”Smart” terminals, functional supports, etc.

- Cross-integration with other technologies (optical fibers, RF)

- Cryo-electronics status changes from being a “novelty” in magnet diagnostics to becoming a mainstream approach, essential part of future magnet diagnostic systems.