U.S. MAGNET DEVELOPMENT PROGRAM

Novel Diagnostics

Milestone status and recent developments at LBNL

Maxim Marchevsky
LBNL

10/27/2021

Technology roadmap

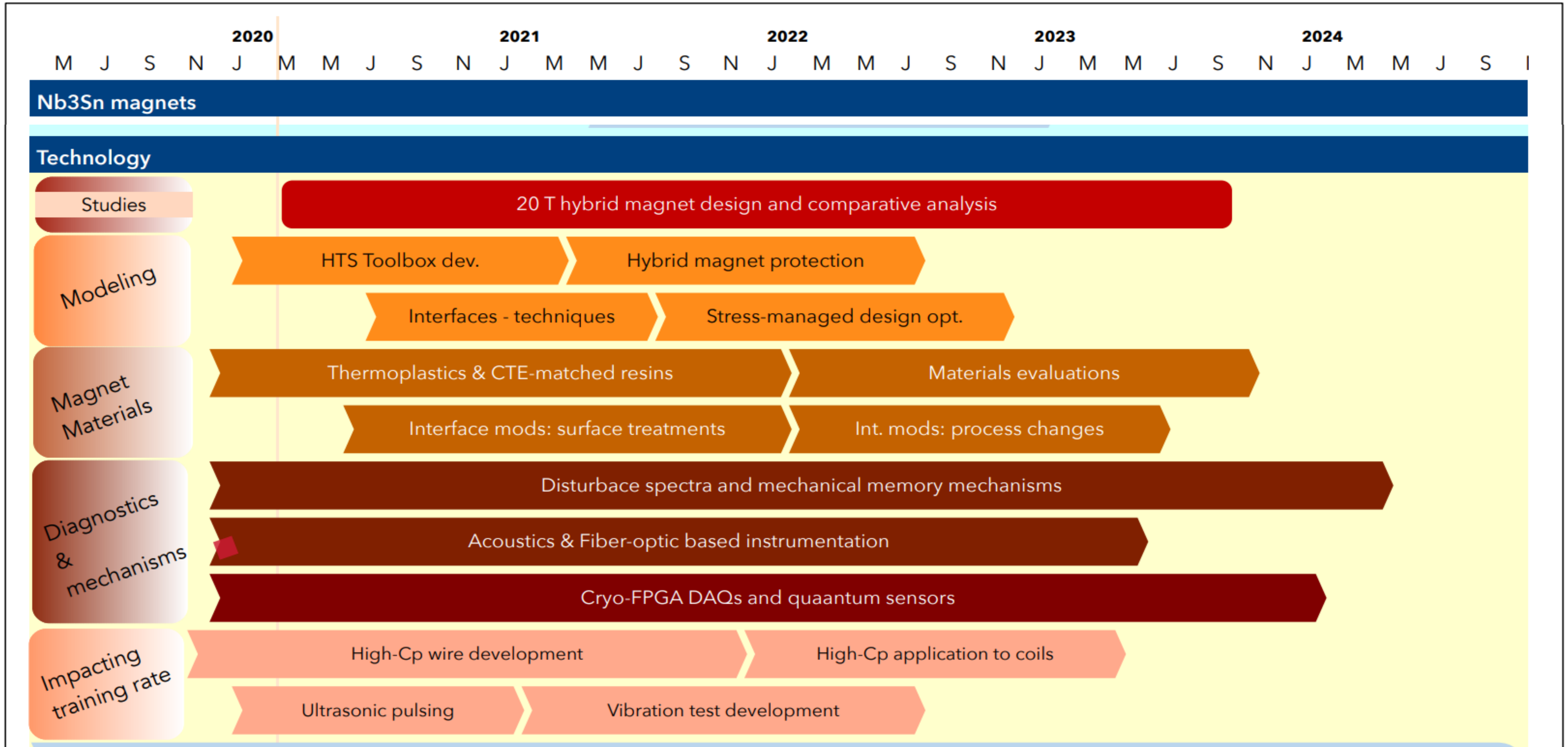


Figure 9. The updated roadmaps for the major elements of the program, including Nb_3Sn Magnets, HTS (Bi-2212 and REBCO) Magnets, and the various Technology areas. The $N_{b3}Sn$ magnet designs will focus on stress-managed structures, motivated by the need to intercept forces in magnets at high field and with large bores compatible with hybrid (HTS/LTS) configurations.

Diagnostics milestone status on 6/9/21

Milestone #	Description	Target
AIIId-M1	Development of a new generation of self-calibrating acoustic emission diagnostics hardware	December 2020
AIIId-M2	Finalizing software algorithms for acoustic data analysis, completing analysis for the CCTs and 15T dipole	December 2020
AIIId-M3	Development and test of a linear quench localization sensor on a Bi-2212 subscale and/or ReBCO CCT series	March 2021
AIIId-M4	Test of a large-scale Hall array and imaging current distribution in HTS tape stacks and coils	May 2021
AIIId-M5	Completing spot heater studies to improve voltage-based diagnostics and address "silent" quenches	July 2021
AIIId-M6	Demonstration of inverse acoustics-based probing of interfaces in a dedicated small-scale coil	September 2021
AIIId-M7	Development of multi-element and flexible quench antennas and localization of quenches in using flexible quench antenna arrays	September 2021
AIIId-M8	Characterization of training-like behavior in different impregnation materials under load using a Transverse Pressure Insert (TPI) measurement system	December 2021
AIIId-M9	Development and test of a standalone acoustic quench detection and localization FPGA-based system	December 2021
AIIId-M10	Development and test of a non-rotating new magnetic probe prototype	December 2021
AIIId-M11	Demonstration of a programmable fully-cryogenic FPGA "smart" sensor core with digital readout and analog front-end (SQUID) amplifiers	December 2021
AIIId-M12	Calibration of FBG fibers in a small cryostat. Installation on an MDP magnet and strain measurement during a quench. Design a proof of principle experiment for quench 3D spatial detection and coil azimuthal strain mapping and install fiber on MDP magnet. Use fibers for energy spectrum analysis and HTS quench detection.	December 2022

- **Next generation acoustic hardware (LBNL)**
- **Acoustic data analysis completed for 15 T (FNAL), CCT4 and subscale 2 – in progress (LBNL). New ML algorithms for quench precursors (FNAL)**
- **In progress, new developments (LBNL)**
- **Hall array hardware built, tested on CORC (LBNL)**
- Talks in progress at FNAL for implementing these studies
- TBD (LBNL)
- **MQXFA QA built and delivered, warm bore tube QA structures are ready as well (FNAL). CCT subscale antennas (LBNL)**
- New tests with matrimid and organic resins mixed with high-Cp ceramics are planned at FNAL
- **Non-FPGA portion was built and tested (LBNL, BNL). Upgrade to FPGA TBD towards the target date**
- TBD (LBNL, FNAL) – likely early 2022
- **New DAQ boards, performance characterized for various cryo-parts. One channel cryo-system to be tested by the end of 2021 (LBNL)**
- **Progress with early tests. Modifications to vertical test facility to integrate fibers. (FNAL, BNL)**

Diagnostics group activity distribution across labs and todays' agenda

Milestone #	Description	Target	
AIId-M1	Development of a new generation of self-calibrating acoustic emission diagnostics hardware	December 2020	Maxim
AIId-M2	Finalizing software algorithms for acoustic data analysis, completing analysis for the CCTs and 15T dipole	December 2020	Maxim, Stoyan
AIId-M3	Development and test of a linear quench localization sensor on a Bi-2212 subscale and/or ReBCO CCT series	March 2021	Maxim, Geon Seok
AIId-M4	Test of a large-scale Hall array and imaging current distribution in HTS tape stacks and coils	May 2021	Maxim, Reed
AIId-M5	Completing spot heater studies to improve voltage-based diagnostics and address "silent" quenches	July 2021	Stoyan
AIId-M6	Demonstration of inverse acoustics-based probing of interfaces in a dedicated small-scale coil	September 2021	Maxim
AIId-M7	Development of multi-element and flexible quench antennas and localization of quenches in using flexible quench antenna arrays	September 2021	Stoyan, Joe, Reed
AIId-M8	Characterization of training-like behavior in different impregnation materials under load using a Transverse Pressure Insert (TPI) measurement system	December 2021	Emanuela
AIId-M9	Development and test of a standalone acoustic quench detection and localization FPGA-based system	December 2021	Maxim, Reed
AIId-M10	Development and test of a non-rotating new magnetic probe prototype	December 2021	Maxim, Joe
AIId-M11	Demonstration of a programmable fully-cryogenic FPGA "smart" sensor core with digital readout and analog front-end (SQUID) amplifiers	December 2021	Marcos, Stoyan, Piyush
AIId-M12	Calibration of FBG fibers in a small cryostat. Installation on an MDP magnet and strain measurement during a quench. Design a proof of principle experiment for quench 3D spatial detection and coil azimuthal strain mapping and install fiber on MDP magnet. Use fibers for energy spectrum analysis and HTS quench detection.	December 2022	Maria, Piyush

LBNL FNAL BNL

Today's agenda

1. "Milestones status and recent developments at LBNL" - **Maxim**
2. "Diagnostics Update Time-Frequency Domain Reflectometry for Quench Detection" - **Geon Seok Lee**
3. "Quench antennas, CORC network model and Scanner developments" - **Reed Teyber**
4. "Instrumentation/Diagnostics topics - status" - **Stoyan Stoynev**
5. Update on cryo-FPGA development - **Marco Turqueti**
6. Update on FBG development **Maria Baldini**

Key tasks and standing questions

1. Resolving mechanical and electromagnetic disturbances in Nb3Sn magnets and understanding physics of magnet training
2. Achieving a reliable and minimally invasive quench detection and localization capability for HTS and hybrid HTS/LTS magnets
3. Resolving and understanding impact of current sharing in HTS cables and coils

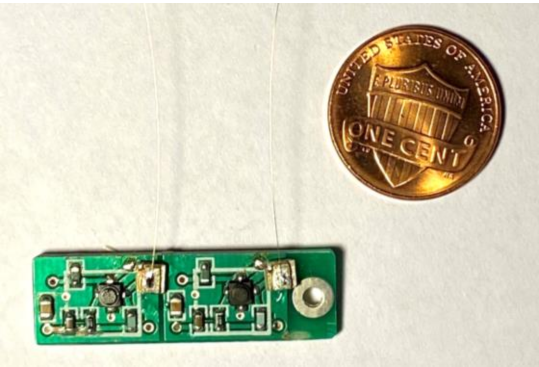
- Can we non-invasively localize weak points and interfaces where mechanical disturbances causing premature quenching take place? Can we manipulate those interfaces *in situ* to improve magnet performance?
- Can we advance magnetic field measurements to the next level using arrays of miniature magnetic sensors and novel magnetic probes?
- Can we drastically simplify/improve diagnostics instrumentation using cryogenic electronics and FPGAs?

New acoustic hardware with improved signal/noise and compatible with the use of waveguides

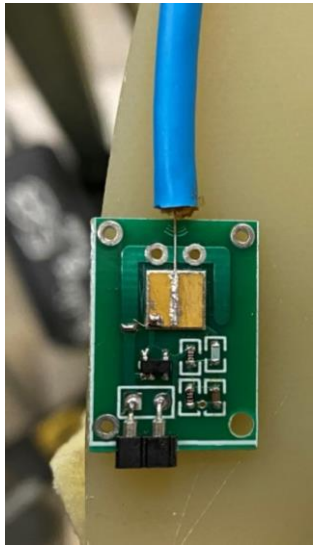
M1

June 2021

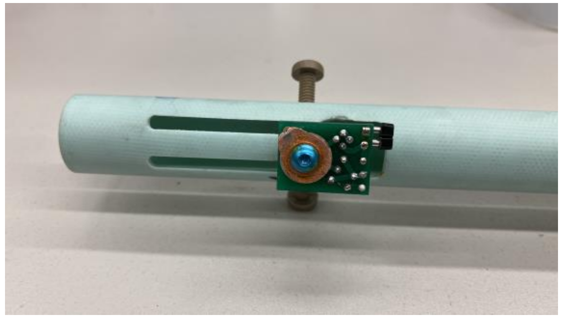
“2/3 original” amp.



GaAs UHF MOSFET amp.

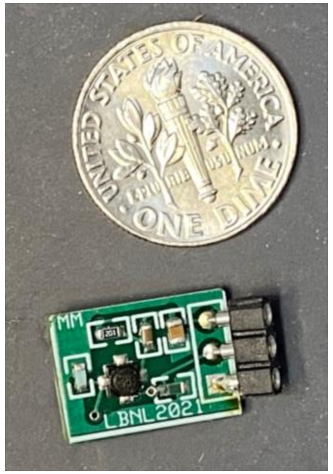


Waveguide amp.



Acoustic mounts

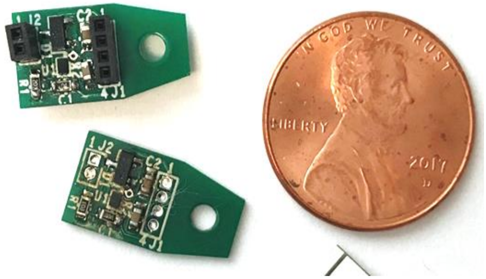
Gain x 5-7



Latest WG GaAs amp (Oct 2021)

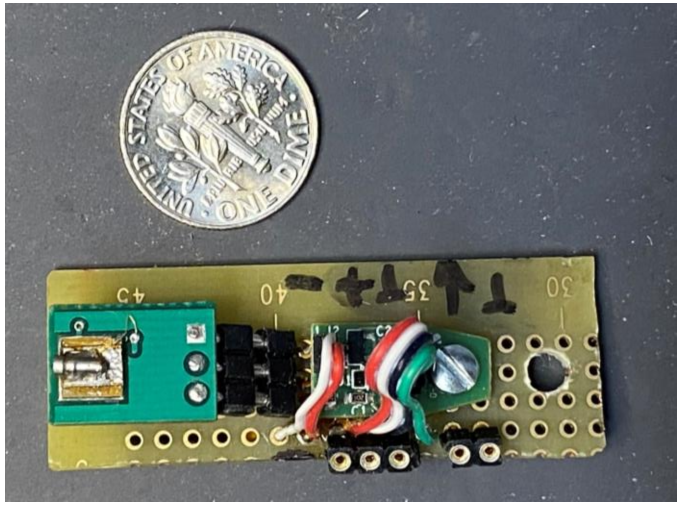
\+

Gain x20



General purpose cryo-amp (2018)

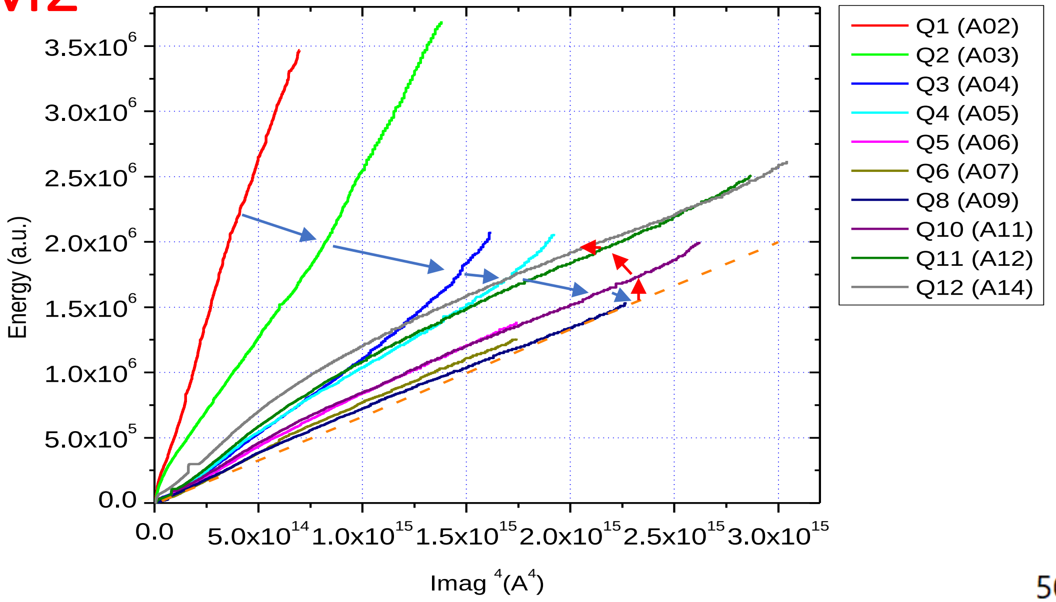
Now testing a two-stage amplifier for ultimate gain of up to x 150 and lowest S/N ratio (r.m.s. noise under 1 mV)

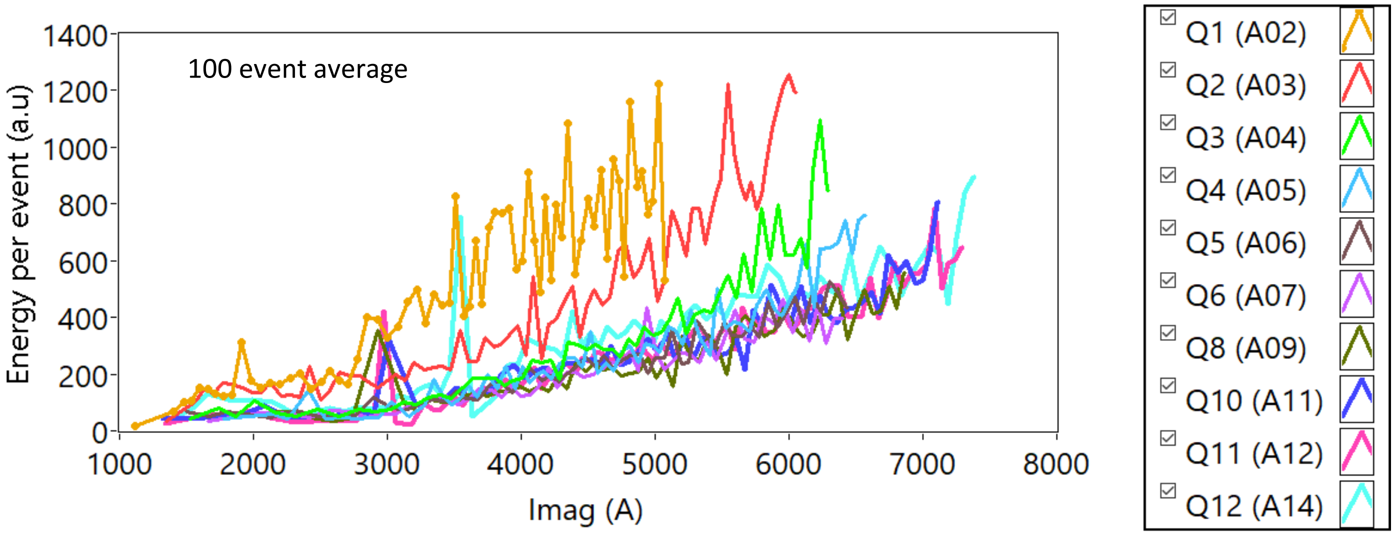


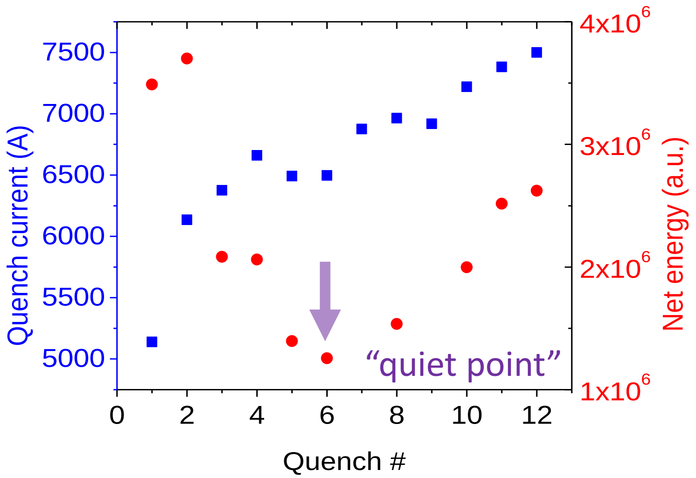
Enable better AE measurements for LTS magnets and more sensitive quench detection for HTS

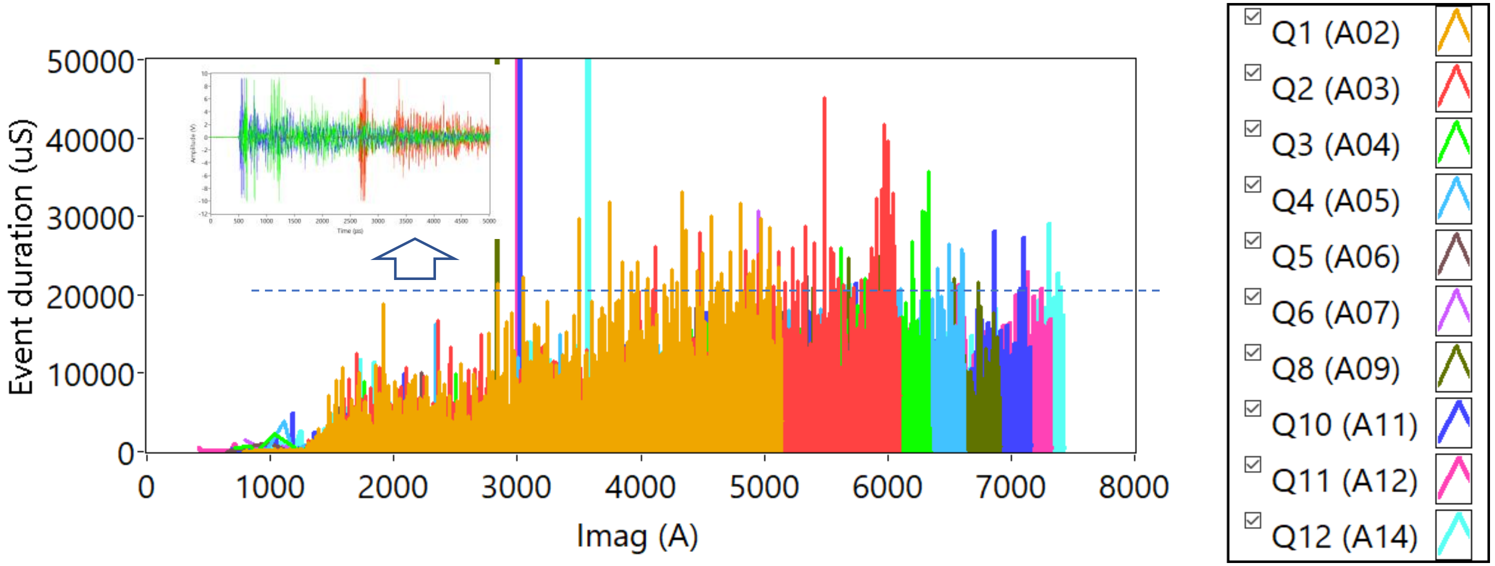
Latest example: energy release and AE event statistics in CCT sub4 training

M2





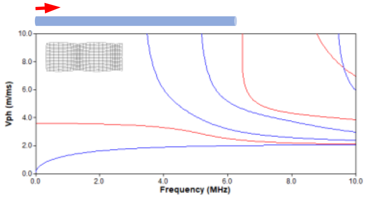




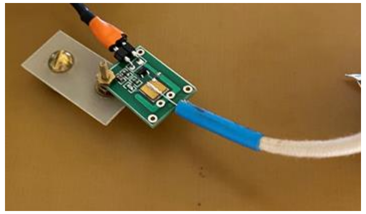
Linear waveguide-based sensor for quench detection in HTS magnets

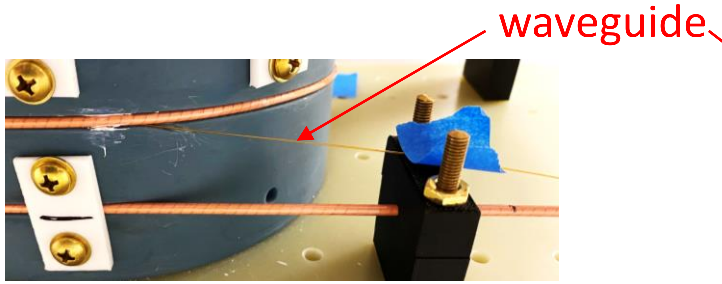
M3

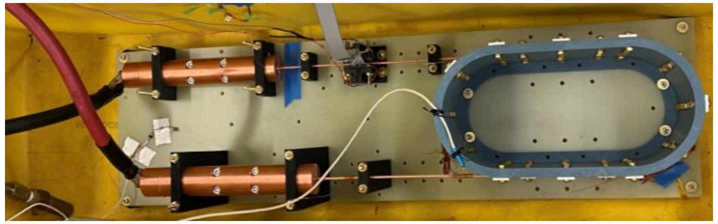
Acoustic WGs, if successful can serve as robust and inexpensive replacement for fiber-optic instrumentation based on as FBGs or Rayleigh scattering

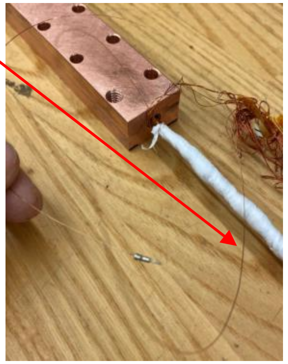


L(0,1) mode









- Needs more research into "acoustic insulation" material that would conduct heat but prevent acoustic wave "leakage" from the waveguide

- Presently being tested with short (30-50 cm) and medium (4.2 m) length free CORC cable samples, as well as with the impregnated U-bent CORC samples
- Next potential use in the MDP CORC magnet built by BNL and ACT, to be tested in the BNL common coil test facility in the spring of 2021
- Results to be presented at MT-27

➢ **More on quench detection and localization using TFDR in Geon Seok Lee's presentation**

Understanding current distribution and current sharing in HTS cables with tape defects

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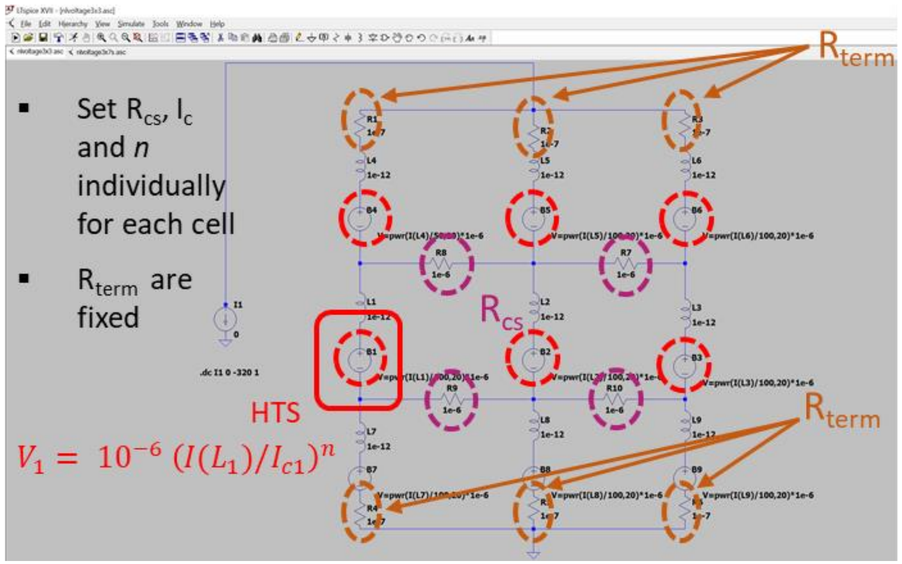
M4 Modelling current sharing using various network modelling tools + experimental validation with large-scale Hall arrays

Example of a 3x3 network model in LTSpice

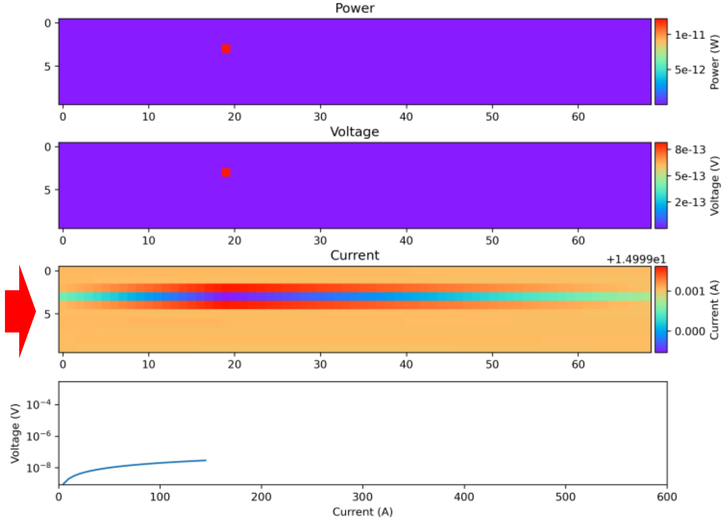


Simulations were done for 10 x 70 matrix (10 tapes in a stack of "70 cm" length)

Similar work done in our group:

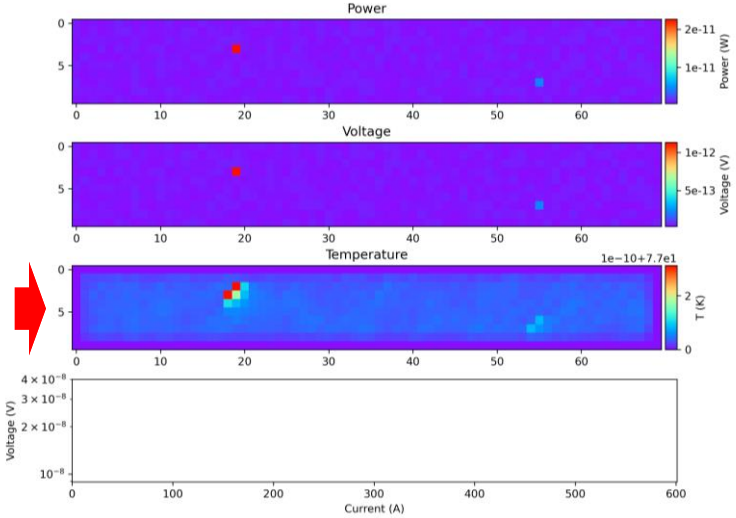
- A. Martinez et al., https://doi.org/10.1109/TASC.2020.2972215
- Zoe Webb- Mack et al., presentation to the MDP modelling WG

Example 1 (non-thermal)



I_c = 50 A; 5% random variation
R_{cs} = 20 nΩ; 5% random variation
R_{term} = 1 nΩ
n = 20
Two pre-defined "bad spots":
$I_c(3,19)$ = 30 A and $I_c(7,55)$ = 40 A
Ramping from 150 A to 600 A, step 5 A

Example 2 ($I_c(T)$)



I_{c0} = 180 A; 1% random variation
R_{cs} = 20 nΩ; 5% random variation
R_{term} = 1 nΩ
n = 20
Two pre-defined "bad spots":
$I_{c0}(3,19) = 0.85\, I_{c0}$ and $I_{c0}(7,55) = 0.9\, I_{c0}$
Ramping from 200 to 600 A, step 1 A; boundary elements are kept at 77 K

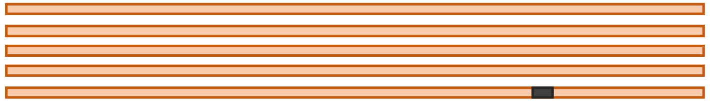
➢ **More on network modelling for CORC conductors in Reed Teyber's presentation**

Validating current sharing model: Hall array studies on HTS tape stacks

U.S. MAGNET DEVELOPMENT PROGRAM

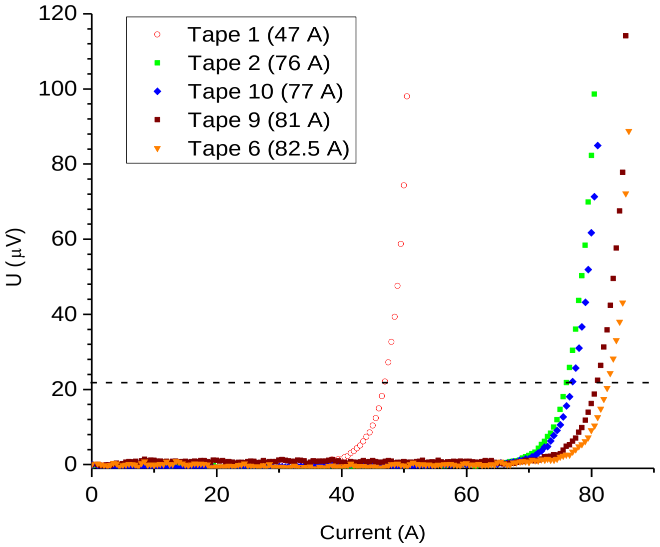
M4

1. *2mm wide ReBCO tapes*

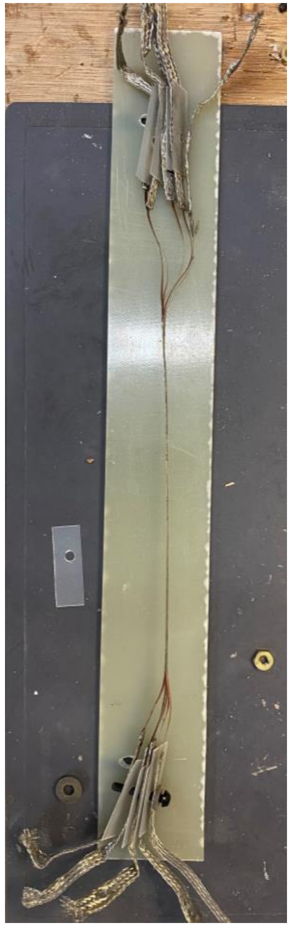


defect

2.

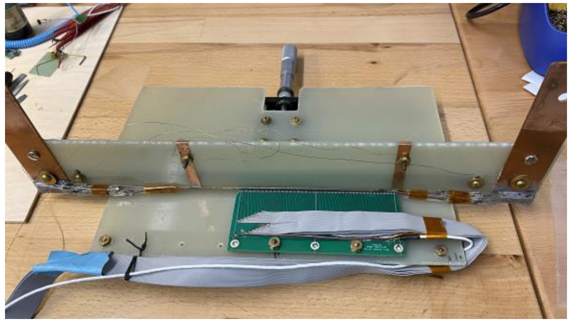


3.

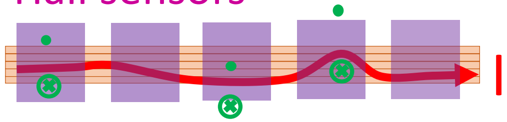


4. Inter-tape contact resistances measured at 77 K

5.

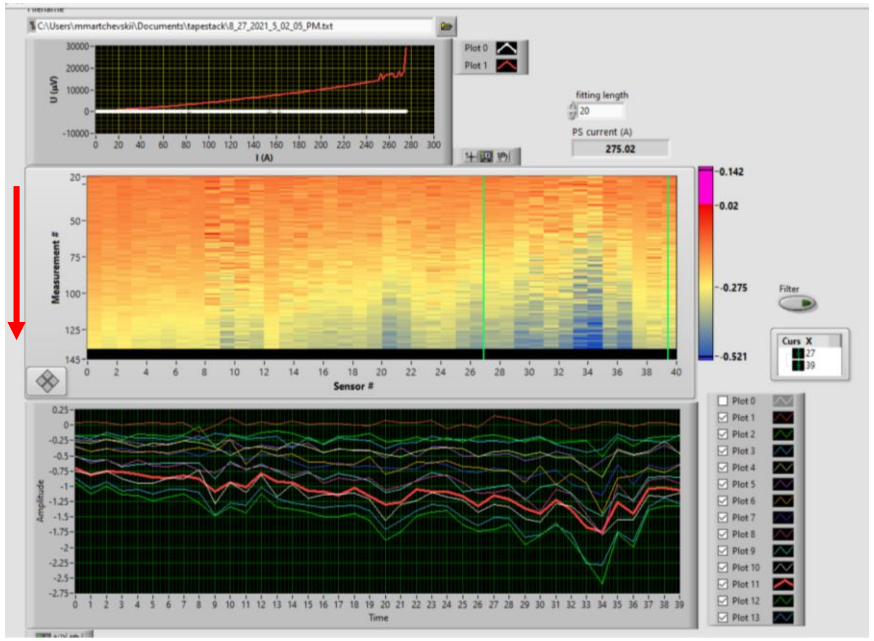


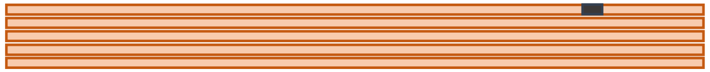
Hall sensors



6.

Current increases



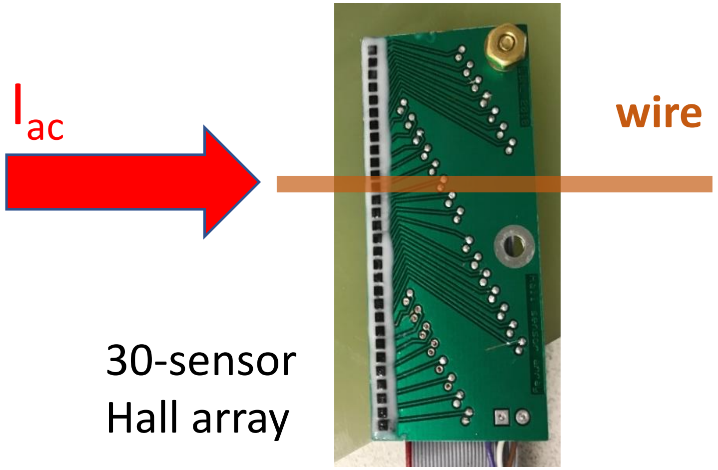


Work in progress to connect experimental and modelling results

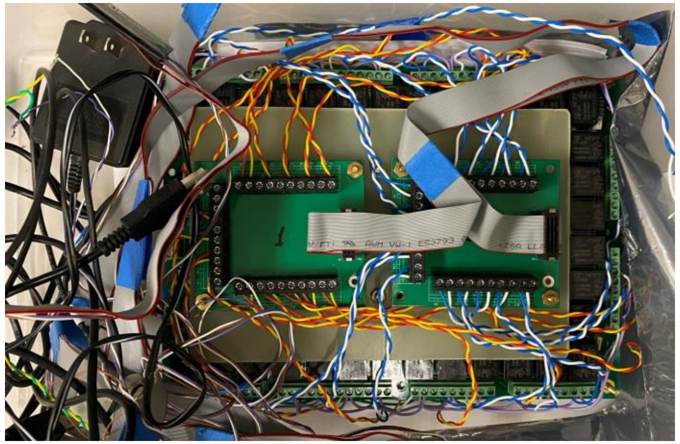
➢ **More on 3D Hall scanner in Reed Teyber's presentation**

Ac Hall array probe: a better tool to measure current sharing (in development)

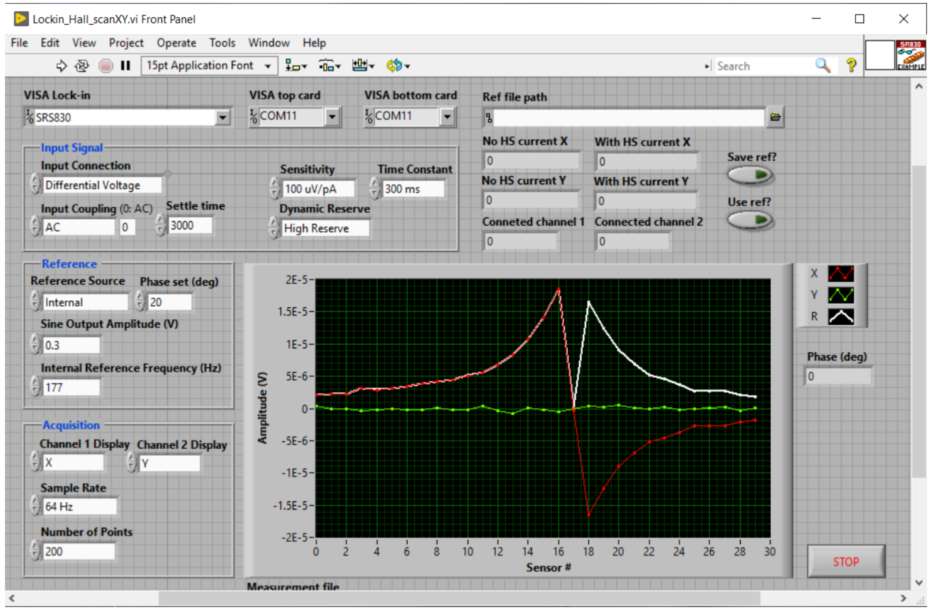
M4



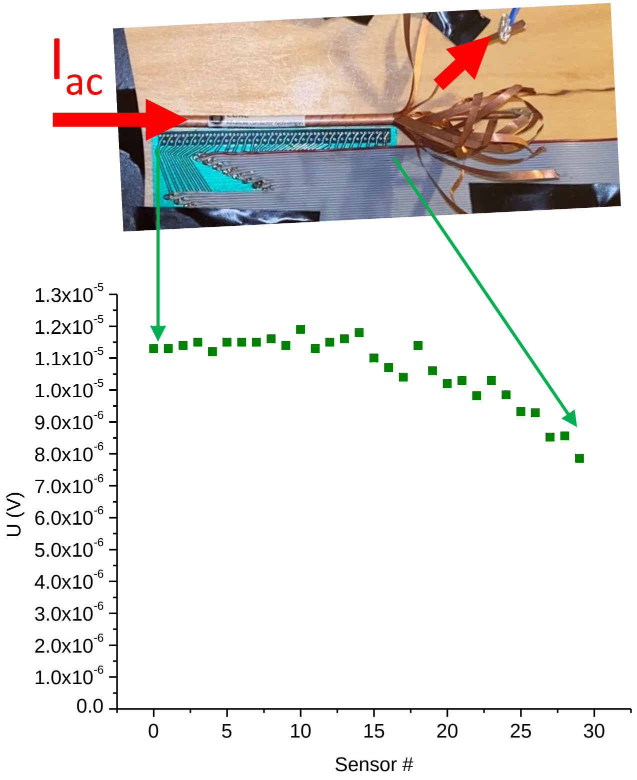
30-sensor Hall array



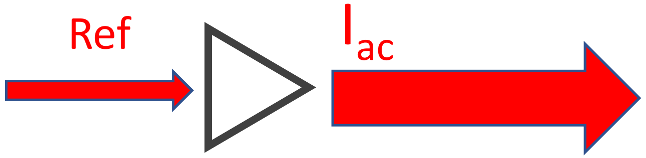
32-position differential scanner (USB control)



Measurement done with ~0.6 A of ac current in the wire (nearly two orders of magnitude improvement in field resolution over dc)

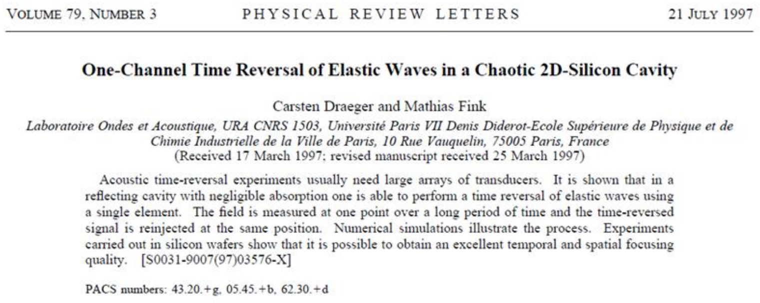


Lock-in amplifier



Current amplifier

Time-reversal acoustics for localized deposition of acoustic energy


VOLUME 79, NUMBER 3 PHYSICAL REVIEW LETTERS 21 JULY 1997

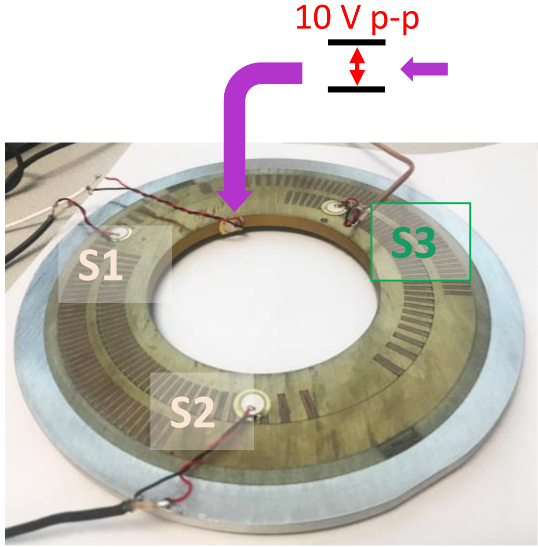
One-Channel Time Reversal of Elastic Waves in a Chaotic 2D-Silicon Cavity

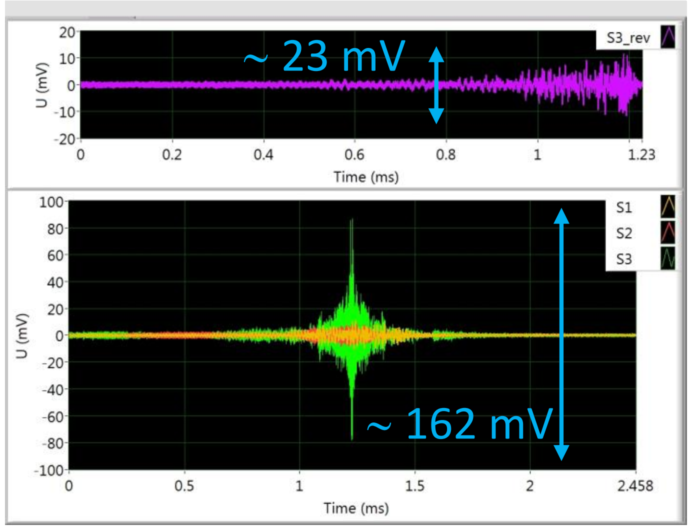
Carsten Draeger and Mathias Fink
Laboratoire Ondes et Acoustique, URA CNRS 1503, Université Paris VII Denis Diderot-Ecole Supérieure de Physique et de Chimie Industrielle de la Ville de Paris, 10 Rue Vauquelin, 75005 Paris, France
(Received 17 March 1997; revised manuscript received 25 March 1997)

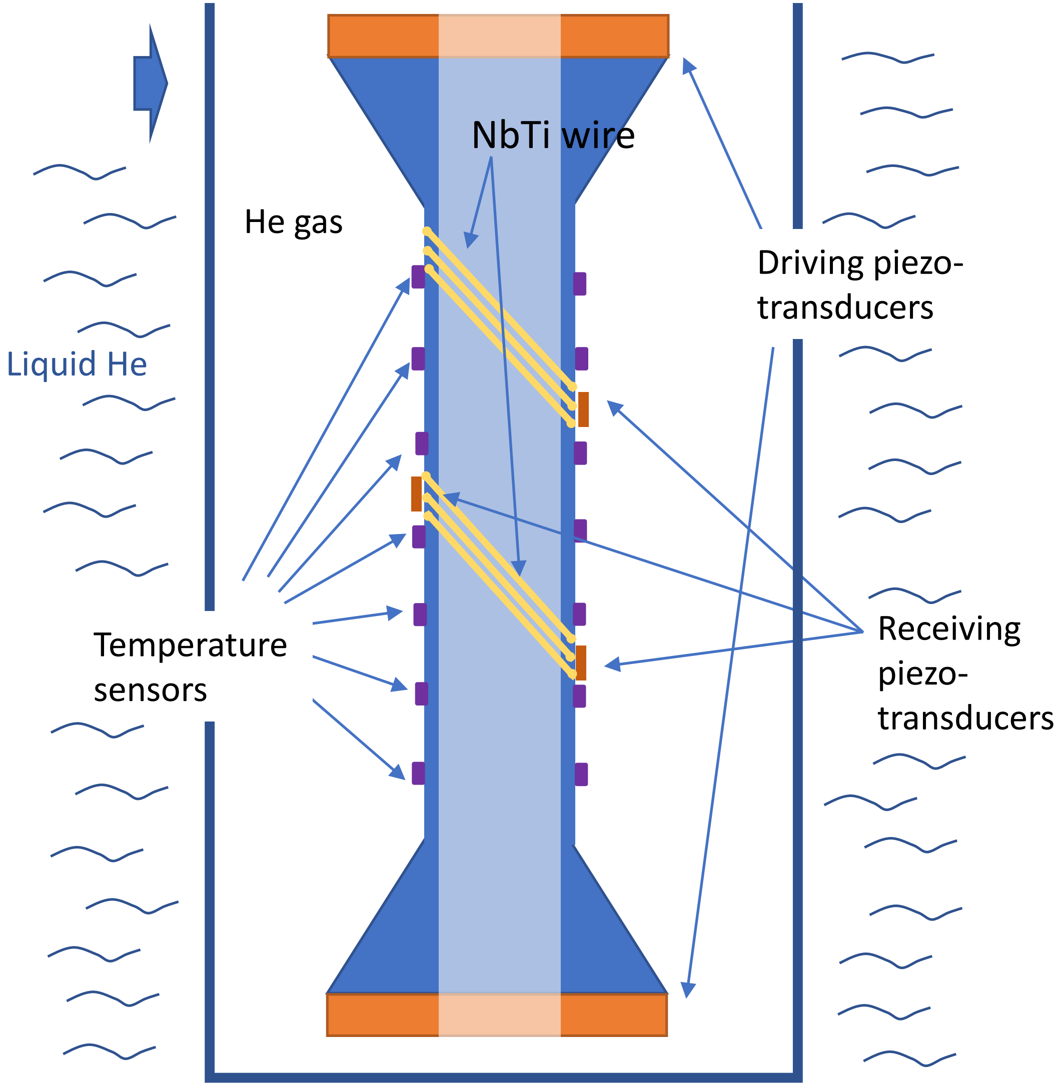
Acoustic time-reversal experiments usually need large arrays of transducers. It is shown that in a reflecting cavity with negligible absorption one is able to perform a time reversal of elastic waves using a single element. The field is measured at one point over a long period of time and the time-reversed signal is reinjected at the same position. Numerical simulations illustrate the process. Experiments carried out in silicon wafers show that it is possible to obtain an excellent temporal and spatial focusing quality. [S0031-9007(97)03576-X]

PACS numbers: 43.20.+g, 05.45.+b, 62.30.+d

A potential experimental setup to explore time-reversal acoustics at cryogenic temperatures







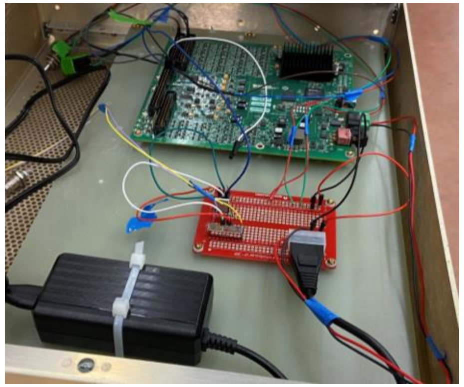
We plan to do those experiments in the next 2-3 months

Standalone acoustic QD/localization: FPGA-based system

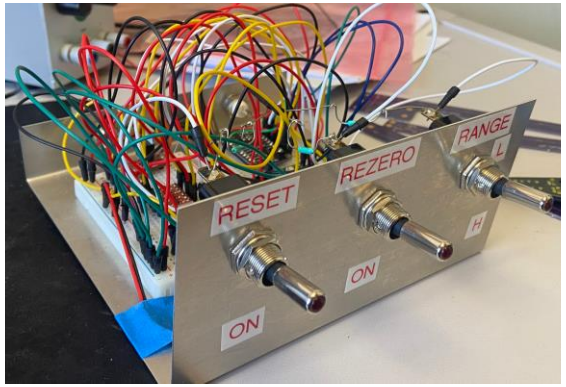
M9

Algorithms for acoustic QD are well developed and presently also deployed at our lab on a dedicated mini-PC. Programming it into FPGA is expected to dramatically boost sampling rate, enabling faster and/or more sensitive detection. It will also convert the technique from being a lab experiment into a robust package that can be deployed quickly anywhere.

- Several FPGA QD systems for voltage detection have been tested and operated so far, both at room temperature and cryogenically (Marcos Turqueti's presentation)
- Also some non-FPGA based autonomous systems we tested recently show promise:



Commercial FPGA board from NI

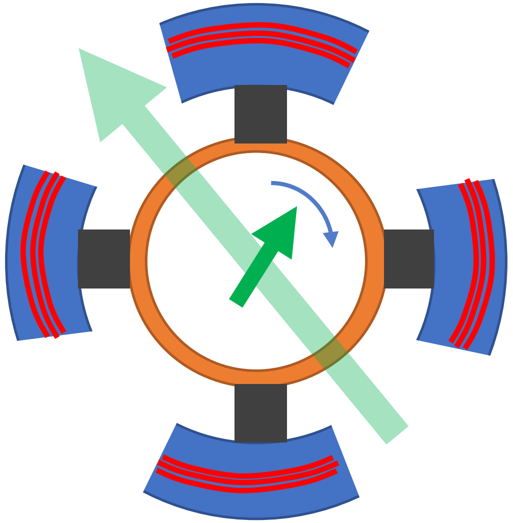


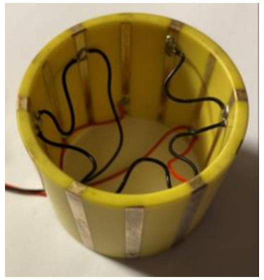
Home-made "Teensy"-based system by R. Teyber

We are planning on completing this task in 2022, potentially in synergy with accomplishing our Milestone on SBIR Ph II with ACT where similar task exists for Hall-based QD and due in Aug 2022. Some dedicated effort from an electronics engineer or an EE student would be very helpful here to accelerate this work.

Non-rotating magnetic probe

M10 Non-rotating magnetic probe should be much more redundant and easier to deploy, also at cryogenic temperatures. Also, measurements can be much faster, allowing to monitor fast fluctuations of harmonic fields caused by instabilities.



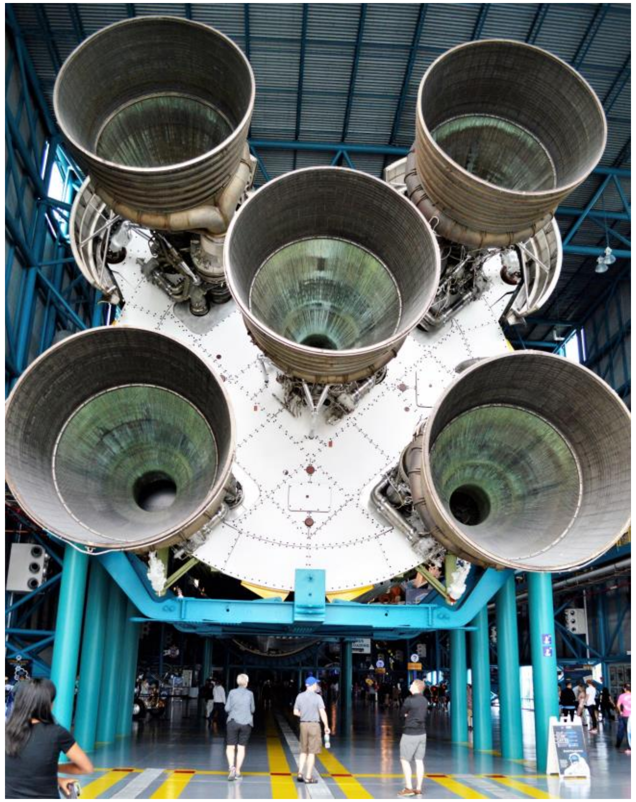


Torsional wave piezo-transducer

- Rotating magnetic dipole is created using a set of orthogonal coil pairs that are powered with 90-deg phase-shifted harmonic drive of same frequency ω
- Interaction between the rotating dipole and main field of the magnet creates an oscillating torque that is mechanically transferred to the torsional piezo-transducer
- Harmonics of the main field will produce harmonics of the oscillating torque of ω, 2ω, 3ω, 4ω etc. respectively for the dipole, quadrupole, sextupole and octupole moments
- By tuning ω electronically, we can match higher harmonics of ω to the mechanical resonance frequency of the torsional piezo-transducer thus enabling independent and sensitive detection of the harmonic amplitudes
- We will then cross-calibrate our experimental non-moving probe with the existing state of the art rotation probe (J. di Marco, FNAL) to see if this idea is feasible for practical use

This could be a good project for an undergraduate student!

New control capabilities enable more redundant and flexible systems at a lower cost

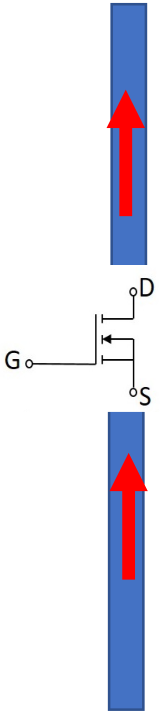


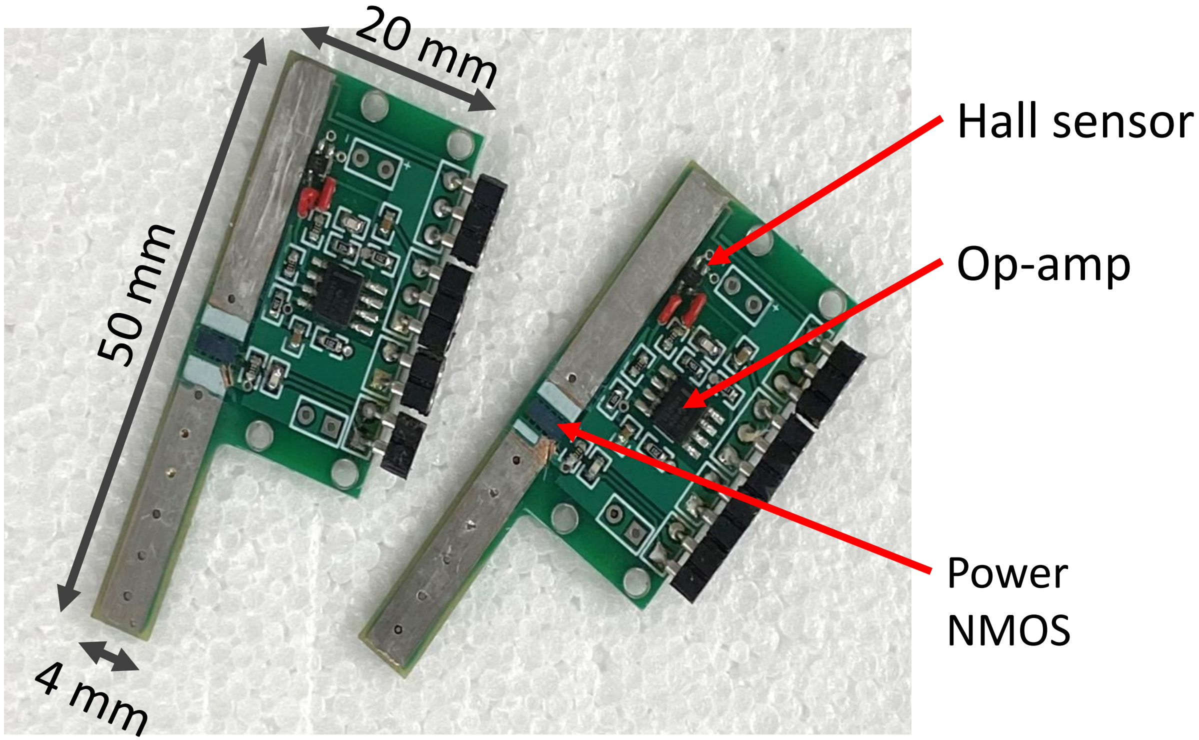
Saturn 5 (1967)

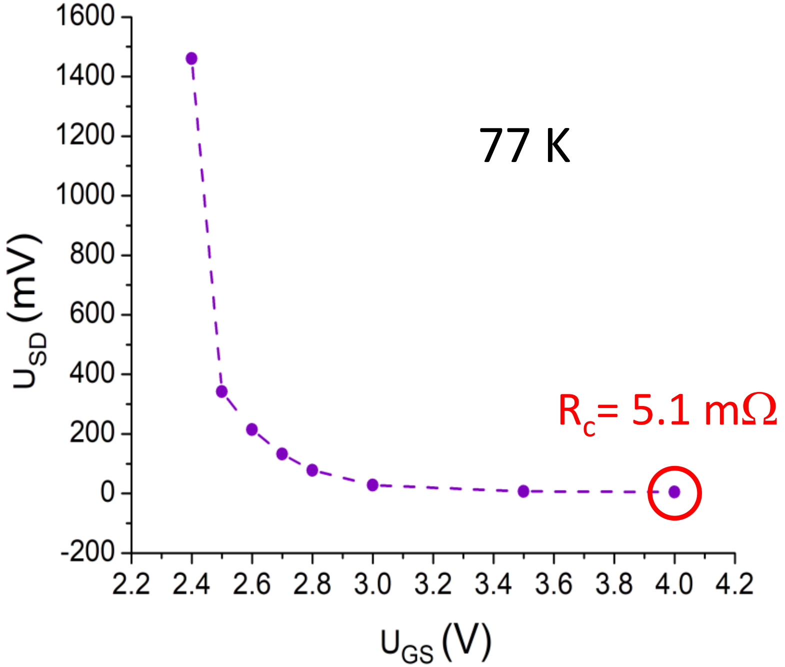
Falcon Heavy (2018)

We typically control our magnets using a single power supply / extraction system, and rely entirely on passive means (normal metal stabilizers, current sharing, dump resistors, etc.) of achieving stability, redundancy, field quality and quench protection. This severely limits our capabilities in all those areas. New means of active control can removing those limitations; they are increasingly available and should be explored.

Cryogenic power MOSFETs for active control of current flow in HTS cables (and magnets?)







- Can drive up to 100 A peak / 35 A continuous – **tested in LN2**
- To be used for current sharing and imaging studies with HTS cable conductors

Dual board – tapes in parallel test

➢ Added as an SBIR topic suggestion for DOE's next year call

U.S. MAGNET DEVELOPMENT PROGRAM

New collaborations

- Collaboration with CERN (Glyn Kirby, Daniel Molnar) on acoustic emission diagnostics in magnets. LBNL provided detailed info on fabricating the published version of the acoustic sensor hardware, and advises the CERN group on a regular basis on deploying these sensors on CERN magnets (FRESCA II, CCT correctors, etc.). We were promised full access to test data of those magnets and inclusion in all resulting publications.

- Proposal submitted to DOE FES call in collaboration with Univ. of Illinois at Urbana, addressing novel detectors for dark matter search. We proposed to build a single photon detector for THz frequency range based on a superconducting nanowire (UIUC group expertise). The plan is to use LBNL-developed cryoelectronic instrumentation, develop novel superconducting amplifiers (also of high relevance to future magnet instrumentation!), and then integrate the detector with an existing CCT magnet for a cryogenic test.