Detecting mechanical vibrations in superconducting magnets for quench detection and diagnostics

M. Marchevsky,
Lawrence Berkeley National Laboratory

Credits: P. Roy, X. Wang, G. Sabbi, S. Prestemon,
LBNL

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Outline

- Motivation for mechanical vibration (acoustic) sensing and earlier developments in the field
- Magnets as mechanical resonators
- Instrumentation for acoustic sensing
- Case study: correlation of acoustic and voltage imbalance signals in the recent HQ magnet test (HQ01e3)
- Inductive sensing of mechanical vibrations and conductor motion
- Future plans

Why acoustic sensing?

- Voltage taps: this approach is not optimal for longer magnets and may be not viable in newer complex magnet geometries (multi-layers, etc.)

- Magnetic quench antennas: data requires significant post-processing; permanent access to the bore or adaptation to the magnet geometry is needed

Advantages of sensing sounds for magnet diagnostics:

- Propagation velocity is large (several km/s), so that detection can be accomplished on a time scale that is comparable (or faster) to other techniques
- Using sensor arrays, sound sources can be localized with a few cm accuracy through triangulation
- Selectivity for different kinds of events, through frequency and phase analysis
- Outer surfaces sensor mounting for non-intrusive detection
- Immunity to magnetic fields
- Sensors and acquisition hardware are relatively inexpensive, portable and easily adaptable to various magnet configurations

Earlier developments

Dislocation motion and micro-plasticity –> technical superconductors stability –> superconducting magnets training –> active acoustic monitoring of SC magnets

- P. P. Gillis, “Dislocation motion and acoustic emission”, ASTM STP 505, 20-29, 1972
- “Dynamic stress effects in technical superconductors and the "training" problem of superconducting magnets”, G. Pasztor and C. Schmidt, J. Appl. Phys. 49, 886 (1978)
- H. Brechna and P. Turowski, “Training and degradation phenomena in superconducting magnets,” Proc. 6th Intl. Conf. Magnet Tech. (MT6) (ALFA, Bratislava, Czechoslovakia) 597, (1978).
- “Acoustic emission from NbTi superconductors during flux jump”, G. Pasztor and C. Schmidt, Cryogenics 19, 608 (1979).
- “Sources of acoustic emission in superconducting magnets”**,** O. Tsukamoto and Y. Iwasa, J. Appl. Phys. 54, 997 (1983).
- “Discussion on acoustic emission of a superconducting solenoid”, M. Pappe, IEEE Trans. on Magn., 19, 1086 (1983)
- “Acoustic emission monitoring results from a Fermi dipole”, O.O. Ige, A,D. McInturf and Y. Iwasa, Cryogenics 26, 131, (1986)
- “Mechanical Disturbances in Superconducting Magnets-A Review”, Y. Iwasa, IEEE Trans on Magn, 28 113 (1992)

Sound generation in superconducting magnets

Singular events

- Sudden mechanical motion of a cable portion or coil part
- Cracking / fracture of epoxy, de-laminations, etc...

Potentially, also:

- flux jump, as current re-distribution in the cable leads to the local variation of the electromagnetic force
- quench development, as formation of a hot spot leads to the local thermal expansion. It that leads to the change in local stress that propagates away with a speed of sound

"Singular events" are mostly associated with well-localized sources. They generate longitudinal (pressure) waves that propagate radially from the source with a speed of sound. Wave fronts then gets partially reflected by the boundaries, converted into resonant vibrational modes of the structure and into heat.

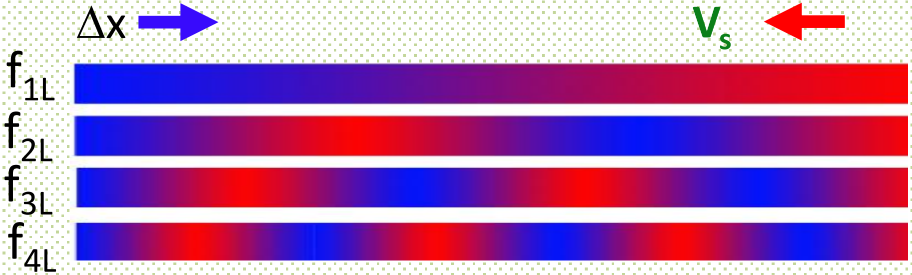
Continuous perturbations

- Mechanical vibrations (various flexural, hoop, "breathing" and other deformation modes of coils, shell and support structures)
- Background noise (helium boiling, cryostat vibrations, etc.)

Coils as mechanical resonators

Long coils can be thought of as solid “bars” or “rods”

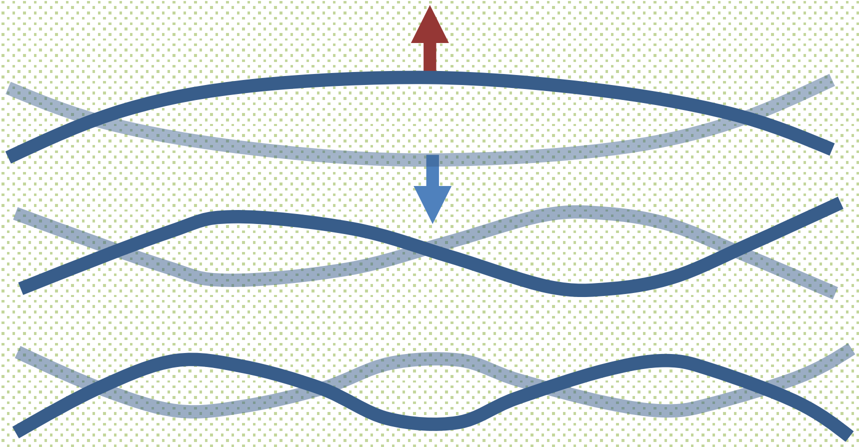
Longitudinal (pressure wave) modes:



$$V_s = \sqrt{\frac{Y}{\rho}}$$ where *Y* is Young modulus and ρ is the density

$$f_{nL} = nV_s/2L$$

Transverse (flexural) modes of “free” rods:



$f_{2T}=2.76\ f_{1T}$

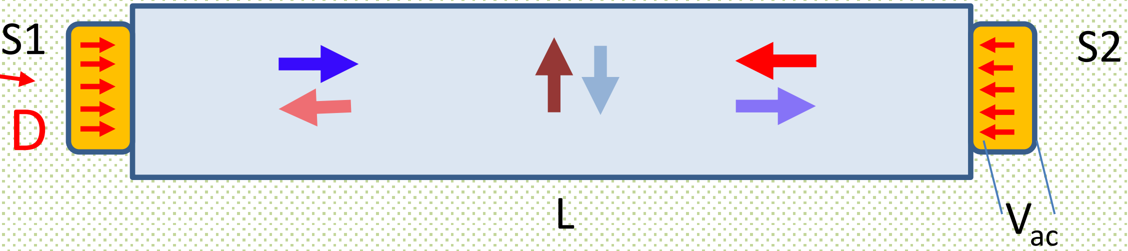
$f_{3T}=5.40\ f_{1T}$

$$f_{1T} \approx 1.028\frac{a}{L^2}\sqrt{\frac{Y}{\rho}}$$

where L is the length and *a* is the cross-sectional area

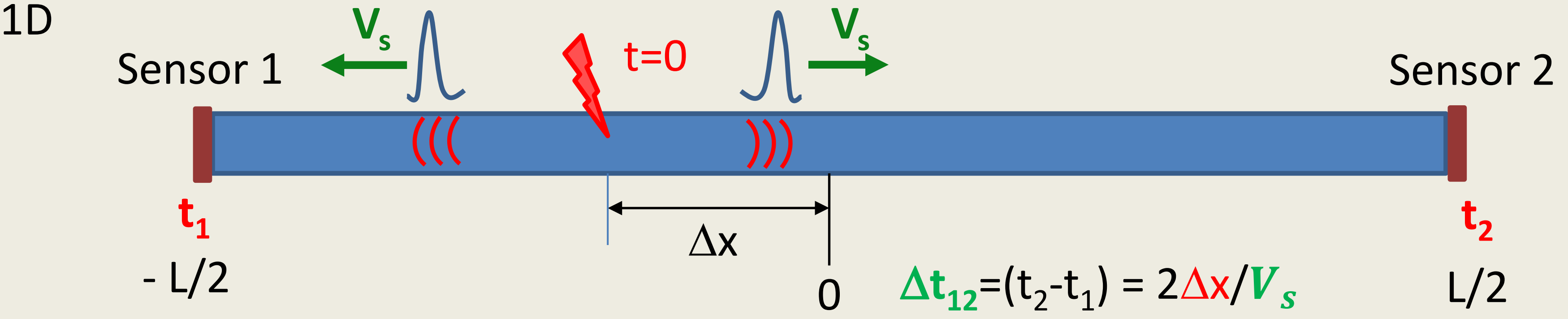
$$f_{nL} \approx 0.441\left[n+\frac{1}{2}\right]^2 f_{1T}$$

Polarized piezo-ceramics



Localization of the sound source

1D

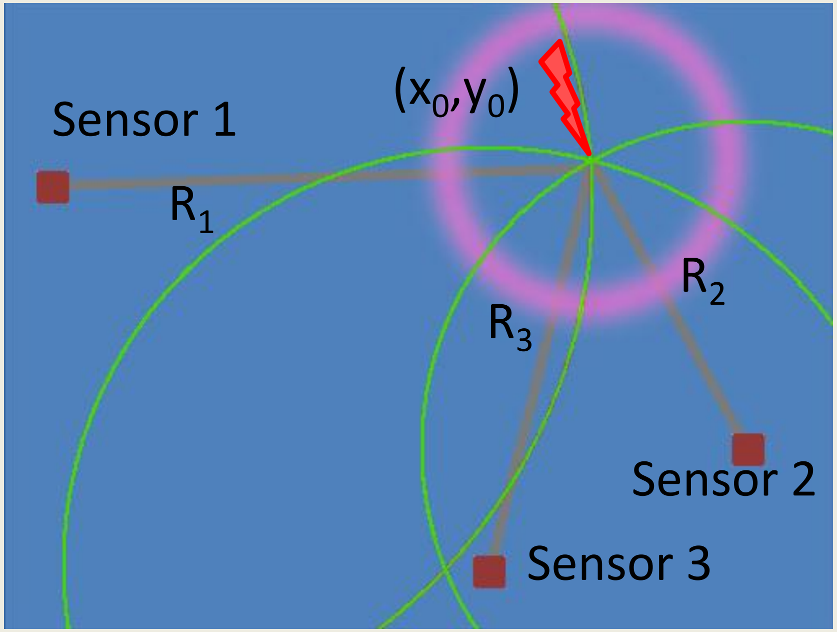


$\Delta t_{12} = (t_2 - t_1) = 2\Delta x / V_s$

2D

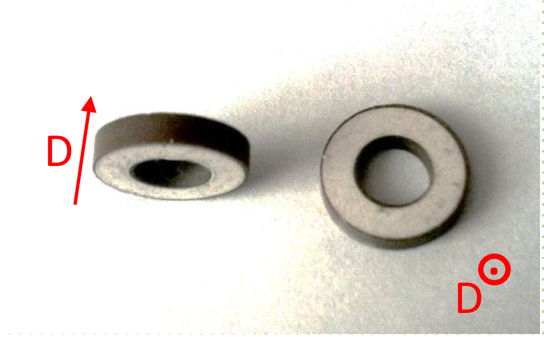
$$\begin{cases} (x_0 - x_1)^2 + (y_0 - y_1)^2 = R_1^2 \\ (x_0 - x_2)^2 + (y_0 - y_2)^2 = R_2^2 \\ (x_0 - x_3)^2 + (y_0 - y_3)^2 = R_3^2 \\ |R_1 - R_2| = V_S \Delta t_{12} \\ |R_1 - R_3| = V_S \Delta t_{13} \end{cases}$$

Think GPS !



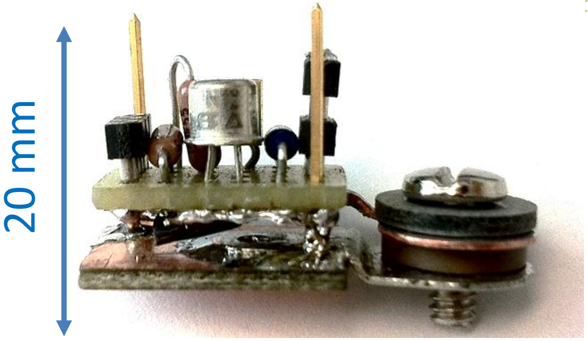
Instrumentation

Piezosensor



- SM118 type piezoelectric ceramics, polarized across thickness
- OD 10 mm x ID 5 mm x Thickness 2 mm,
- **f_r = (154 ± 4) kHz**

Cryogenic preamplifier



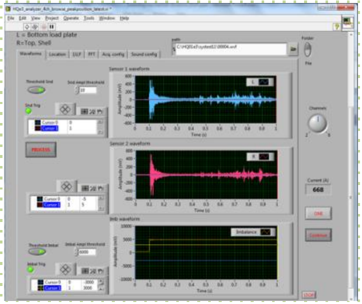
- GaAs MOSFET-based amplifier
- Linear bandwidth of 0-100 kHz
- 300 -1.9 K operation temperature range

Converts impedance down to ~1 kΩ, significantly improves S/N ratio, allows use of regular "twisted pair" connections in the cryostat instead of the coaxes

DAQ

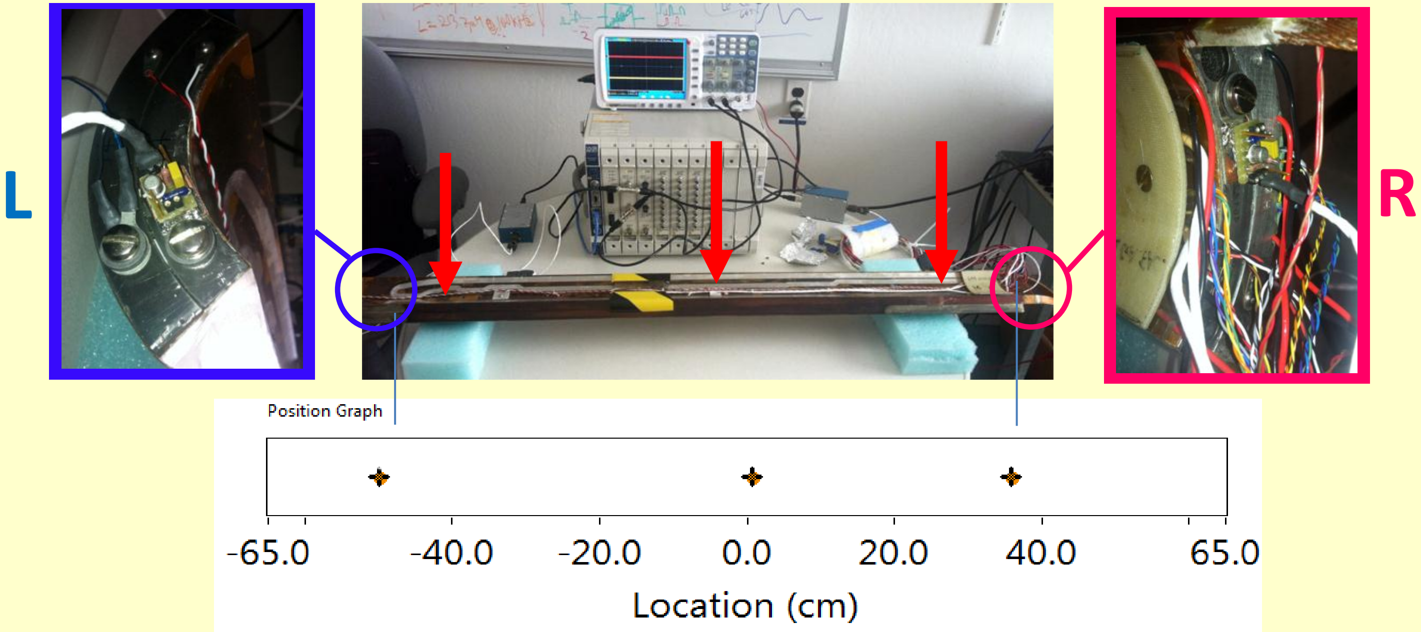
- Yokogawa WE7000 simultaneous multi-channel DAQ system
- 100 mV-100 V range
- up to 1 MHz speed

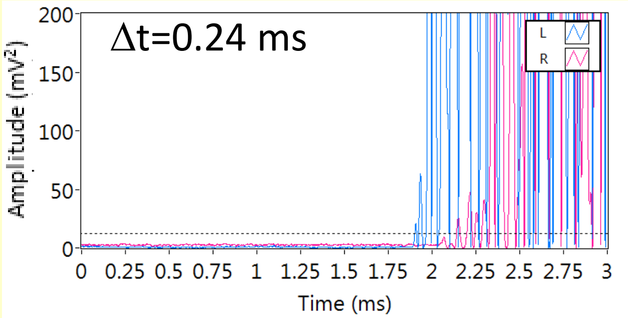
Software

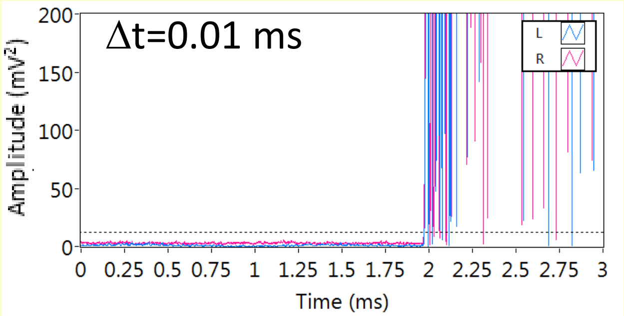


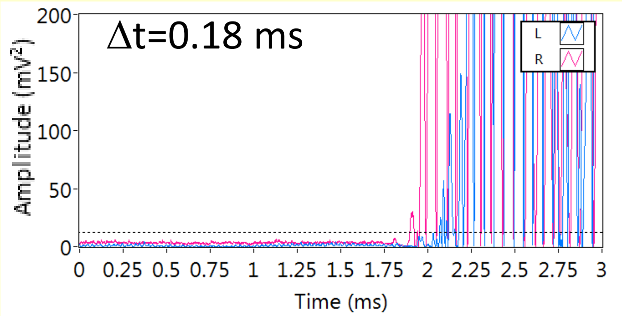
LabView-based software for waveform analysis, re-sampling and location triangulation of the sound source

Localization tests at RT using HQ Coil 14



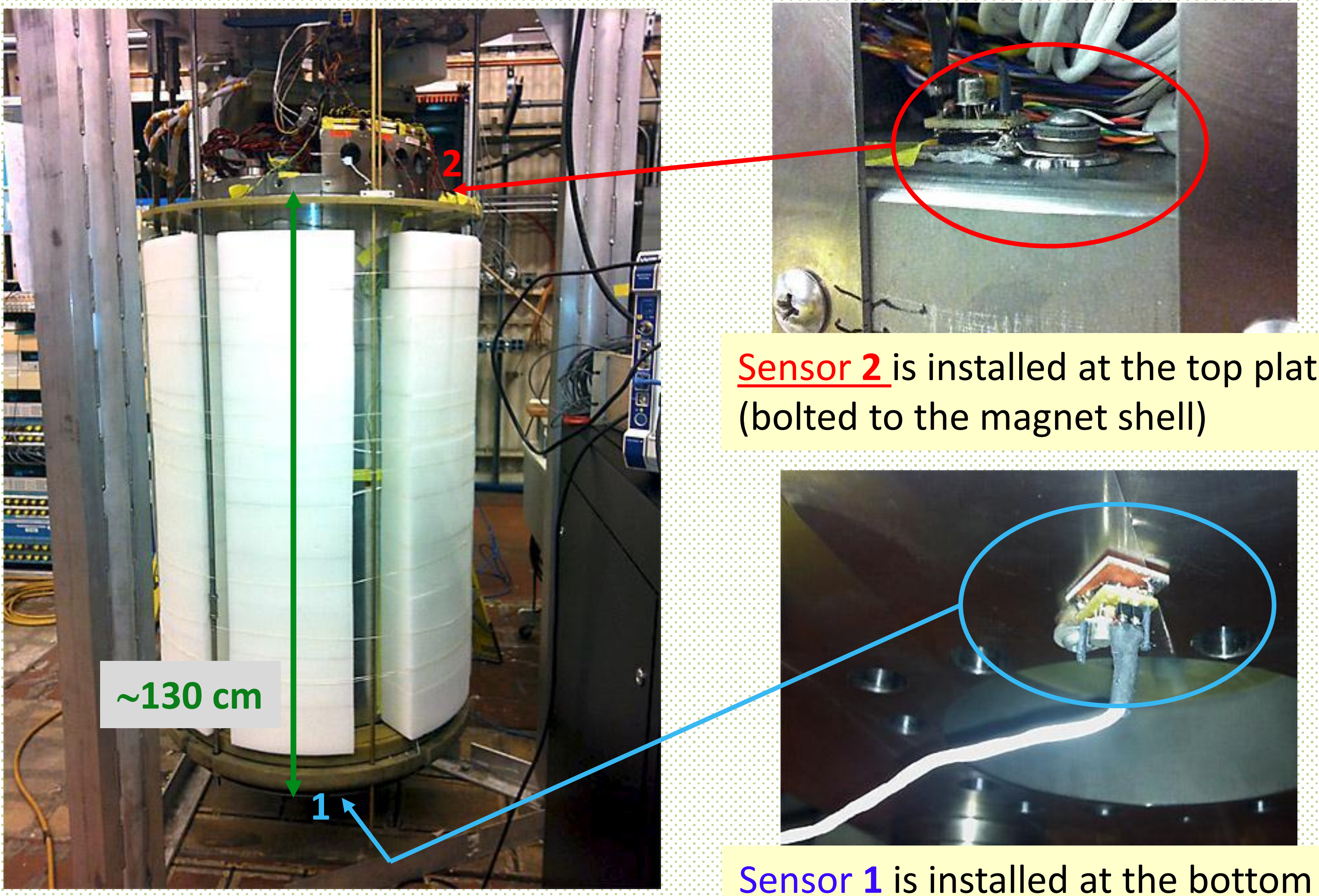






Sound speed: V_s~ 4.1-4.3 km/s

Installation on the HQ magnet



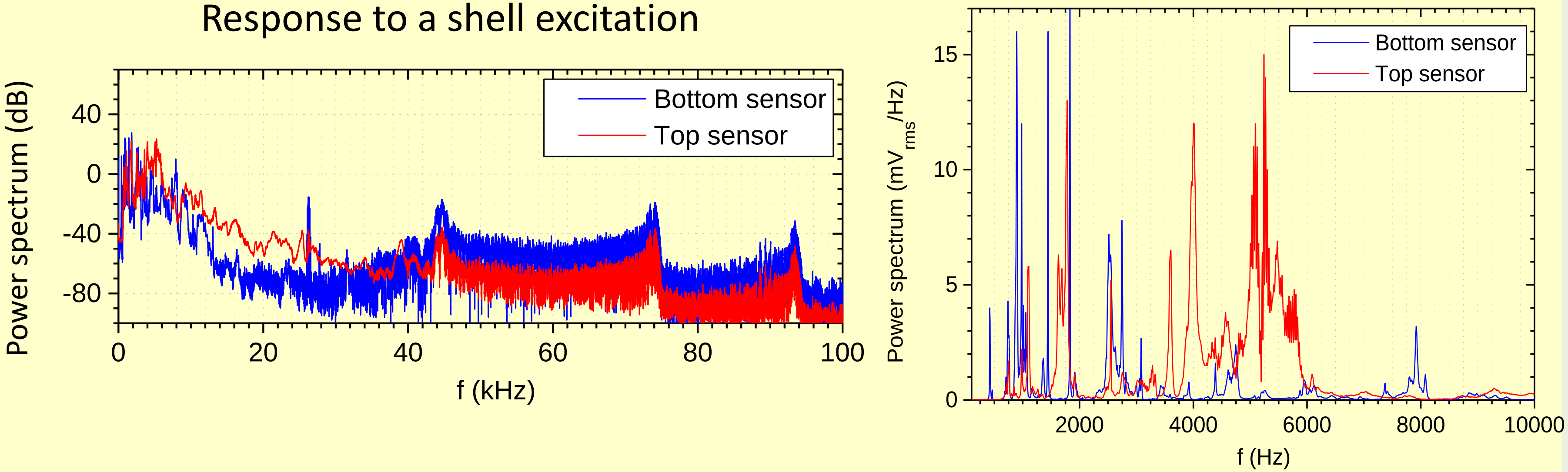
Sensor **2** is installed at the top plate (bolted to the magnet shell)

Sensor **1** is installed at the bottom load plate (bolted to the axial rods)

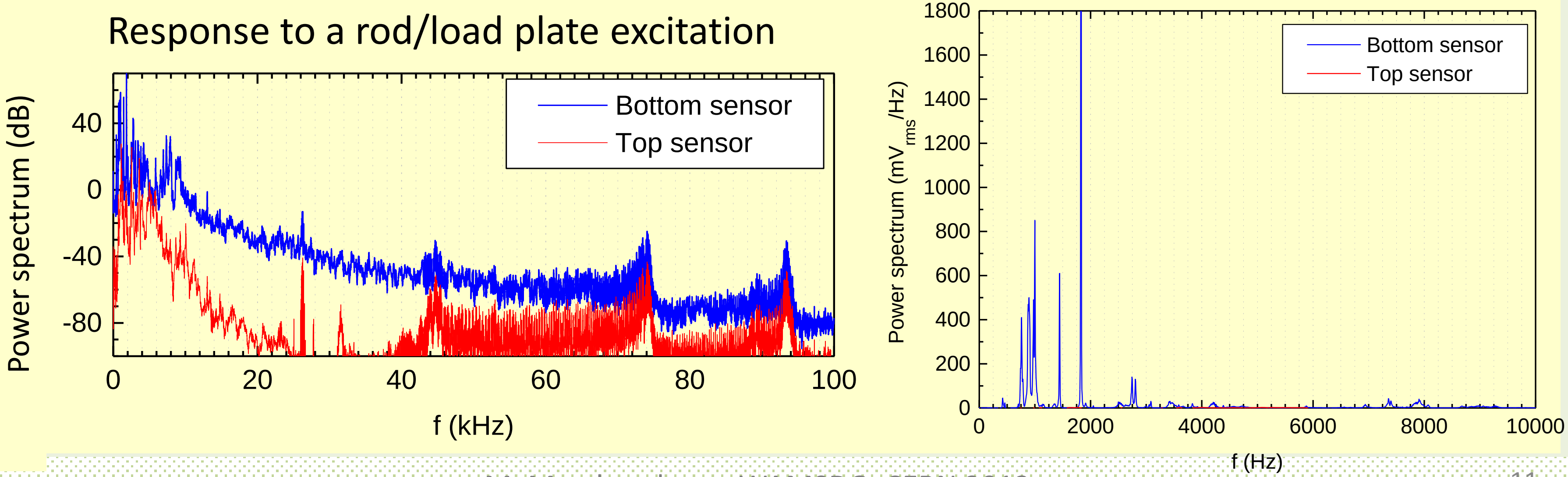
“Available” (not optimized) locations were used

HQ vibrations resonant spectrum (room temp.)

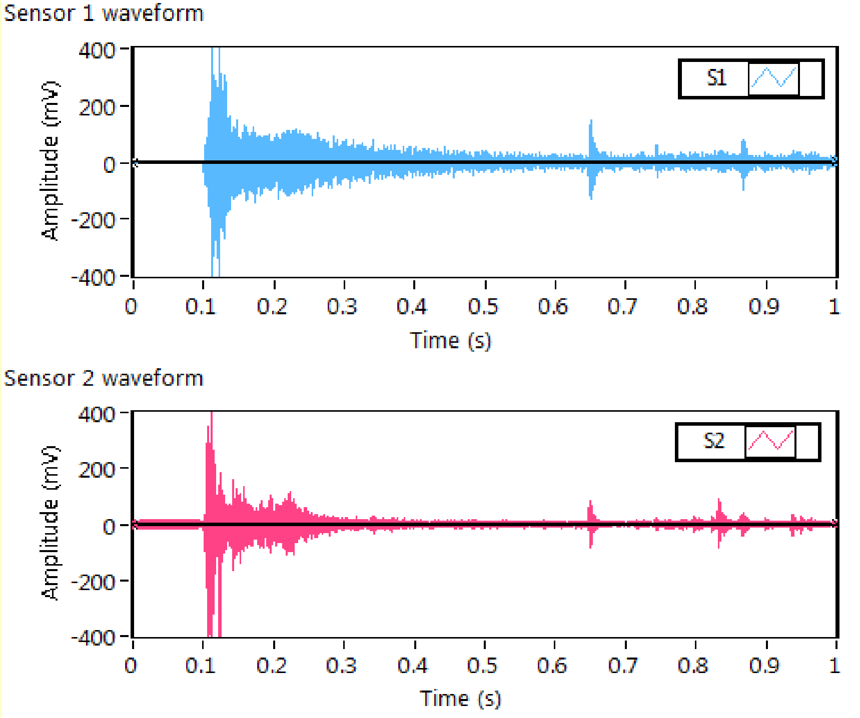
Response to a shell excitation

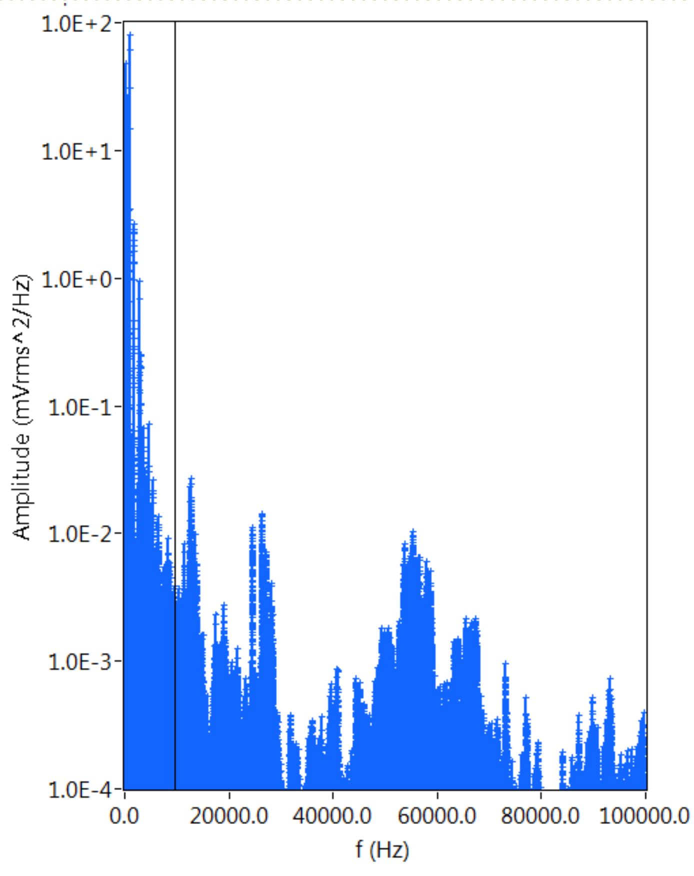


Response to a rod/load plate excitation



Extraction at 5.5 kA





Original sound

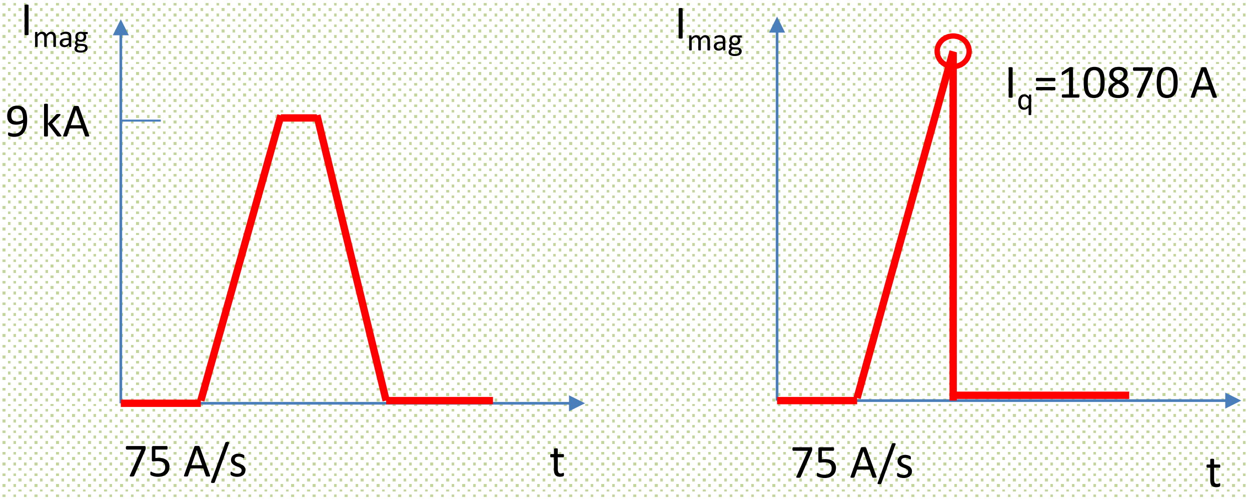
slowed down 10 times

When current is extracted from the magnet, sounds are recorded (*step-like change of elastic strain?*), followed by a prolonged (0.5-1 s) "ringing" of the structure at its resonance modes, with occasional "bursts" of mechanical activity (*thermal relaxation?)*

Magnet is a good mechanical resonator with Q~100!

HQ experimental setup

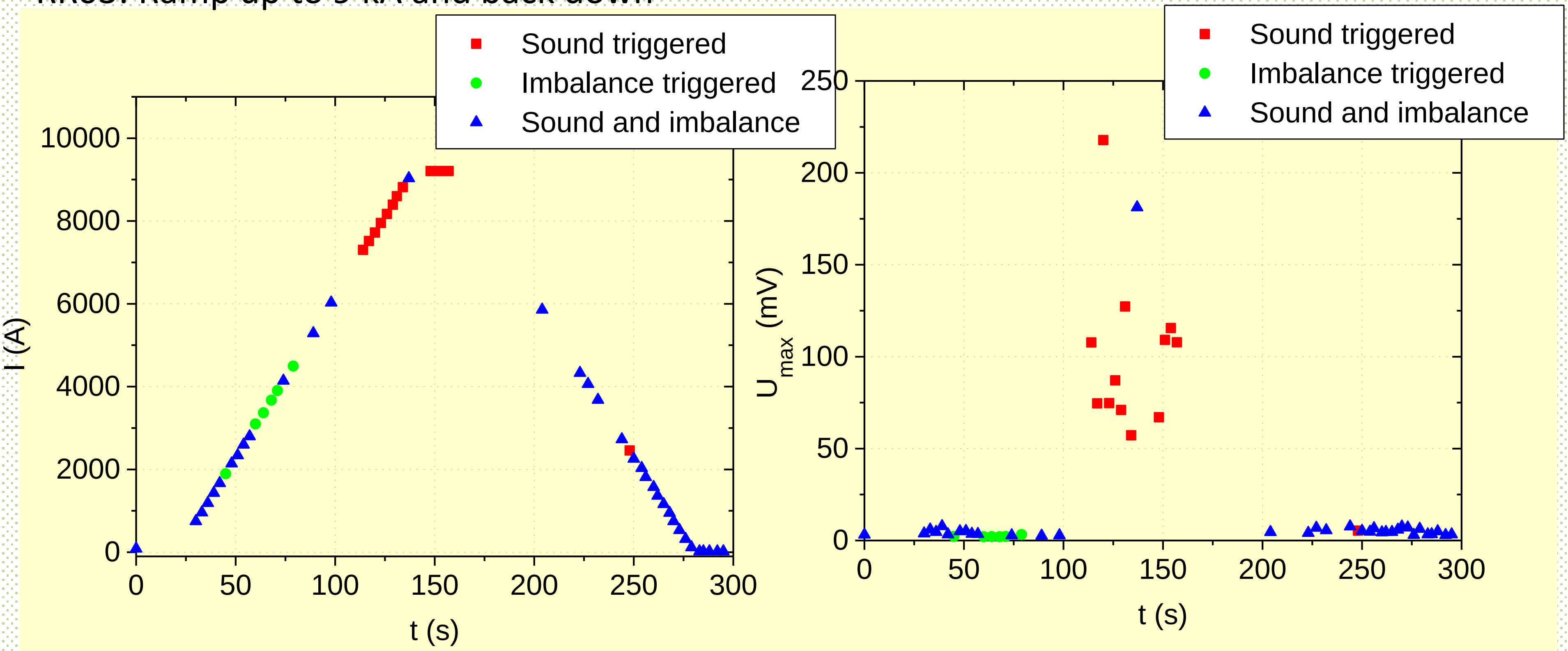
- Magnet imbalance signal is formed by subtracting negative half (Coils 5,7) from the negative (Coils 8,9) of the magnet, then amplified x40.
- Sound signals from both sensors, magnet imbalance and magnet current are recorded at 1 Ms/s; the time window is 0.2 s.
- Acquisition is triggered when **either** imbalance or sound is above the threshold level.



Attempted current ramps

Events during an up-down current ramp

RR03: Ramp up to 9 kA and back down



Current of the triggered events

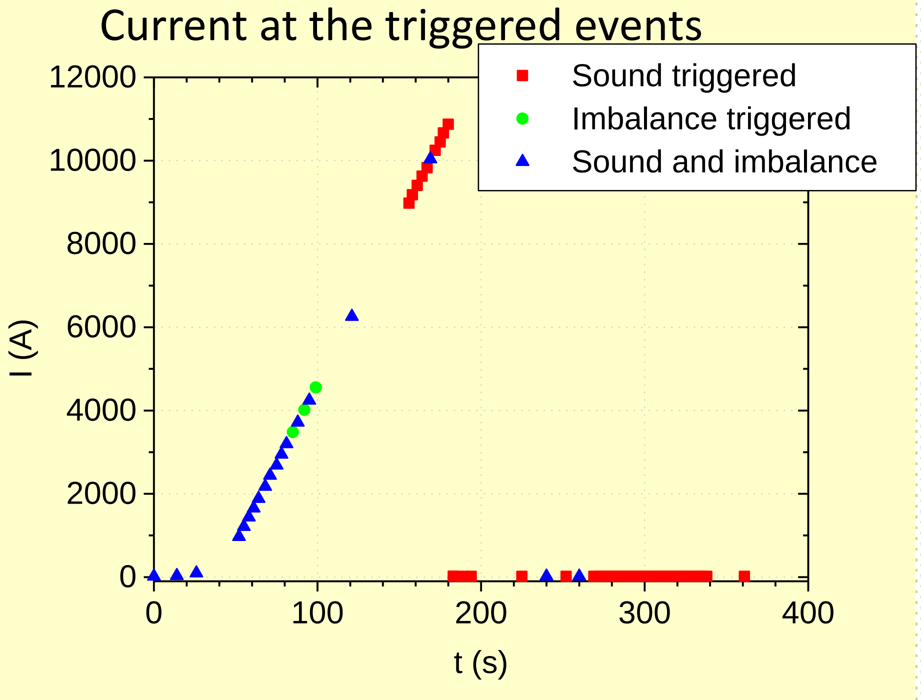
Sound amplitude of the triggered events

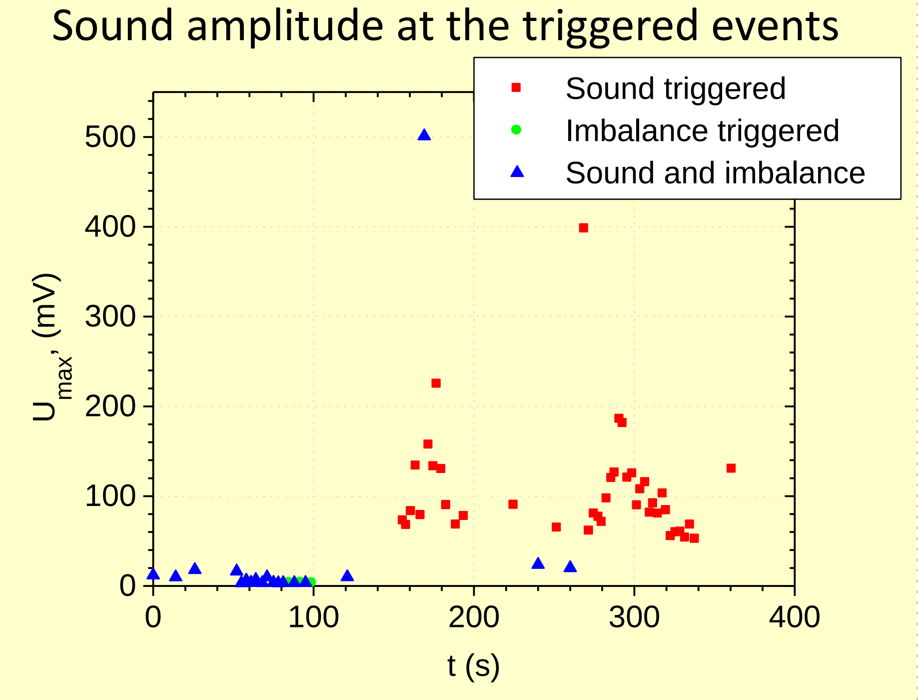
Threshold settings:

- Sound: 5 mV
- Imbalance: 3 V (amplified; true imbalance threshold is ~75 mV)

Events during a current ramp into quench

RR04: Ramp to quench at 75 A/s I_q=10870 A

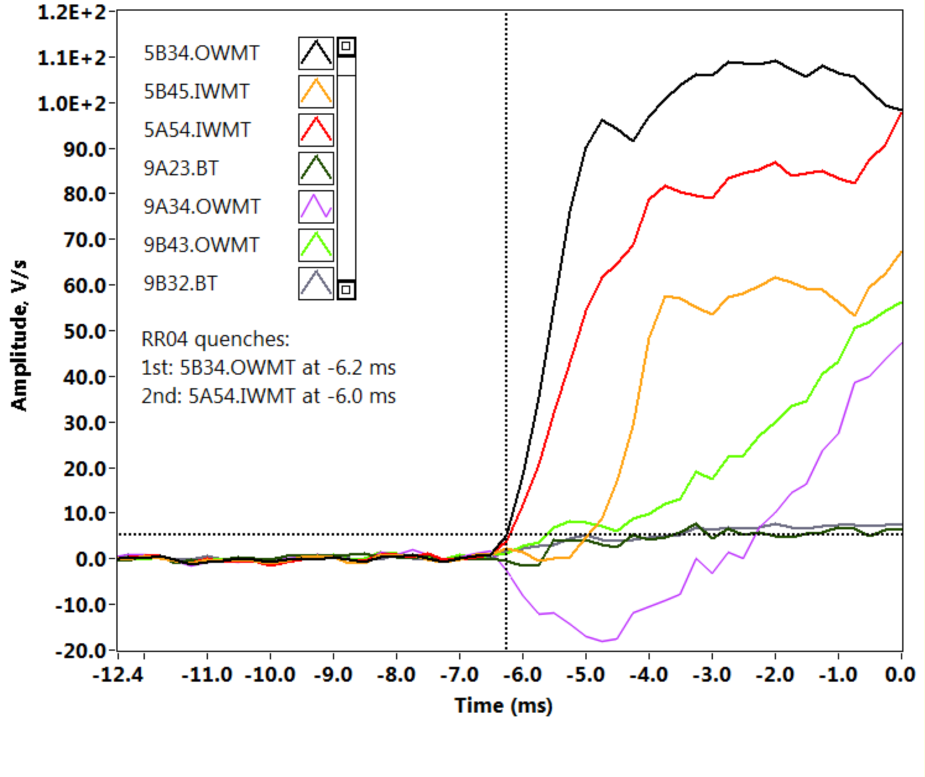




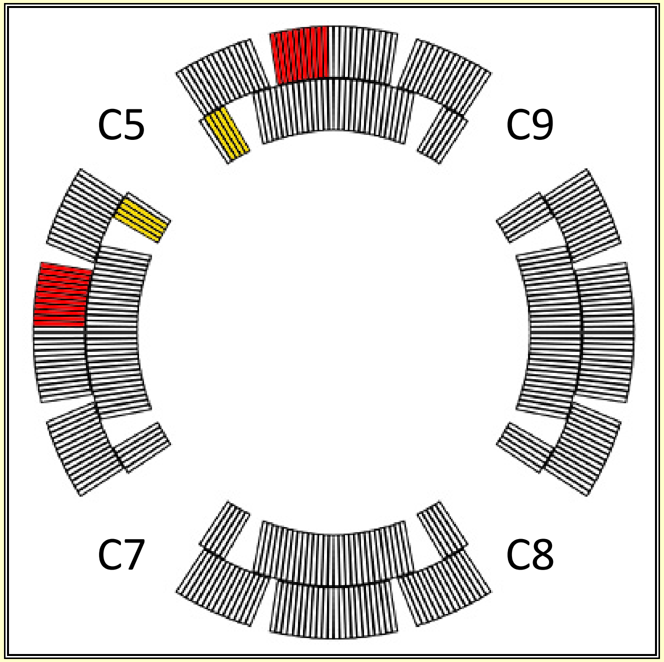
Four possible scenarios are observed:

1. Imbalance variation without any associated sound (below 5 kA)
2. Imbalance variation associated with weak sound signals (below 5 kA)
3. Stronger sounds without association with imbalance variations (above 8.5 kA)
4. Stronger sounds associated with imbalance “spikes” (around 10-10.5 kA)

The 75A/s quench



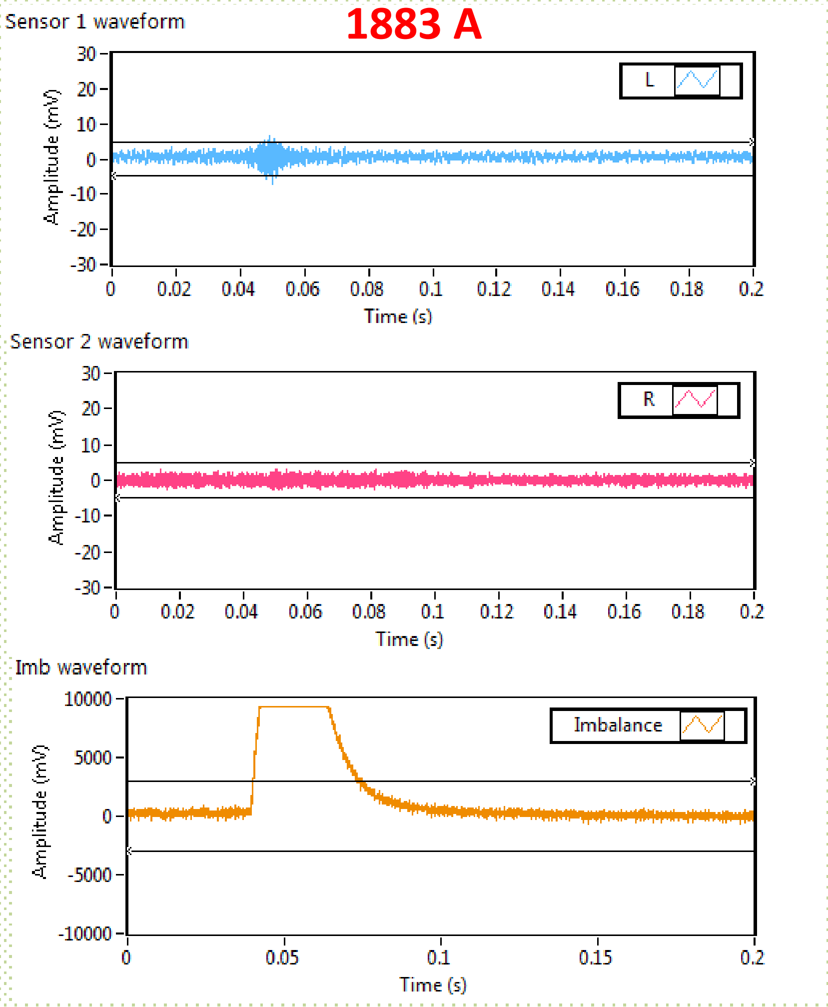
RR04 quenches:
1st: 5B34.OWMT at -6.2 ms
2nd: 5A54.IWMT at -6.0 ms

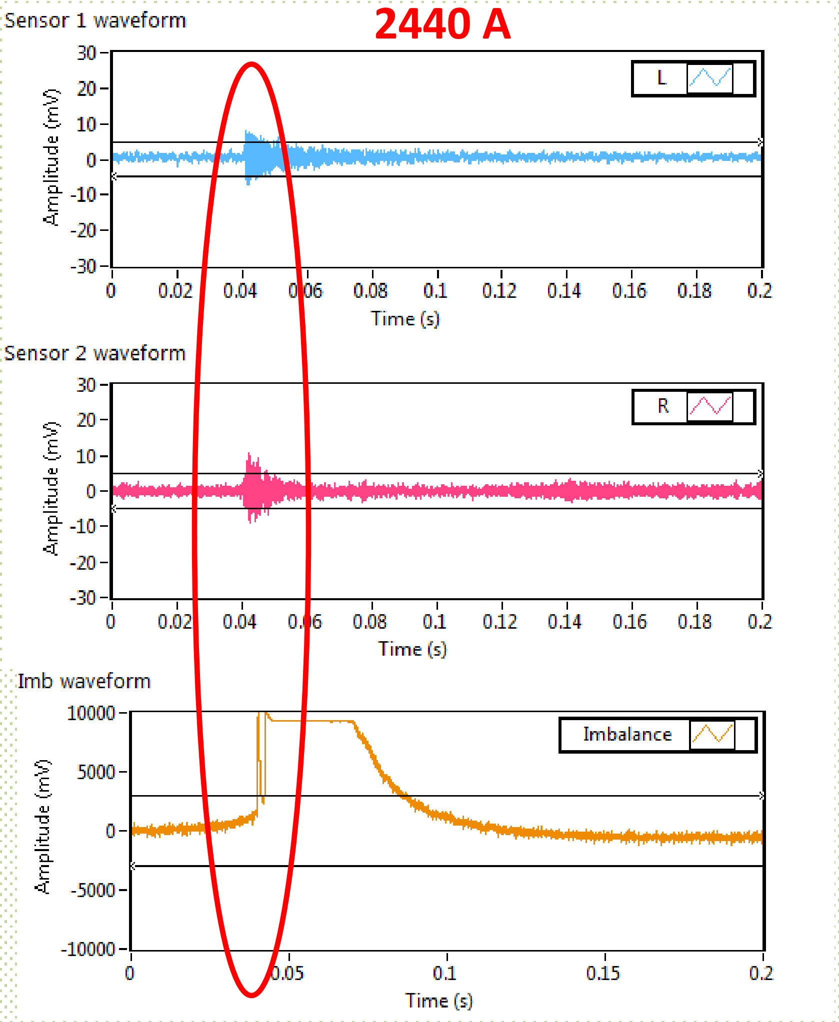


Quench starts in the outer layer multi-turn of C5

Sounds of magnet (low current)

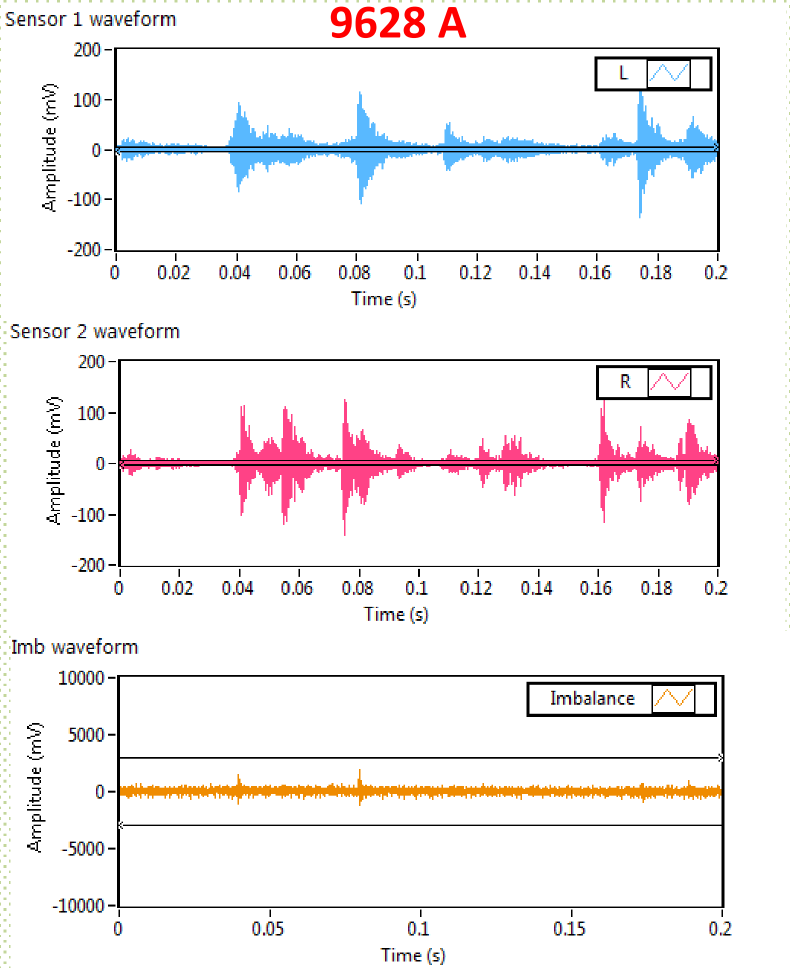
- Some imbalance variations at low currents are associated with (weak) sounds!



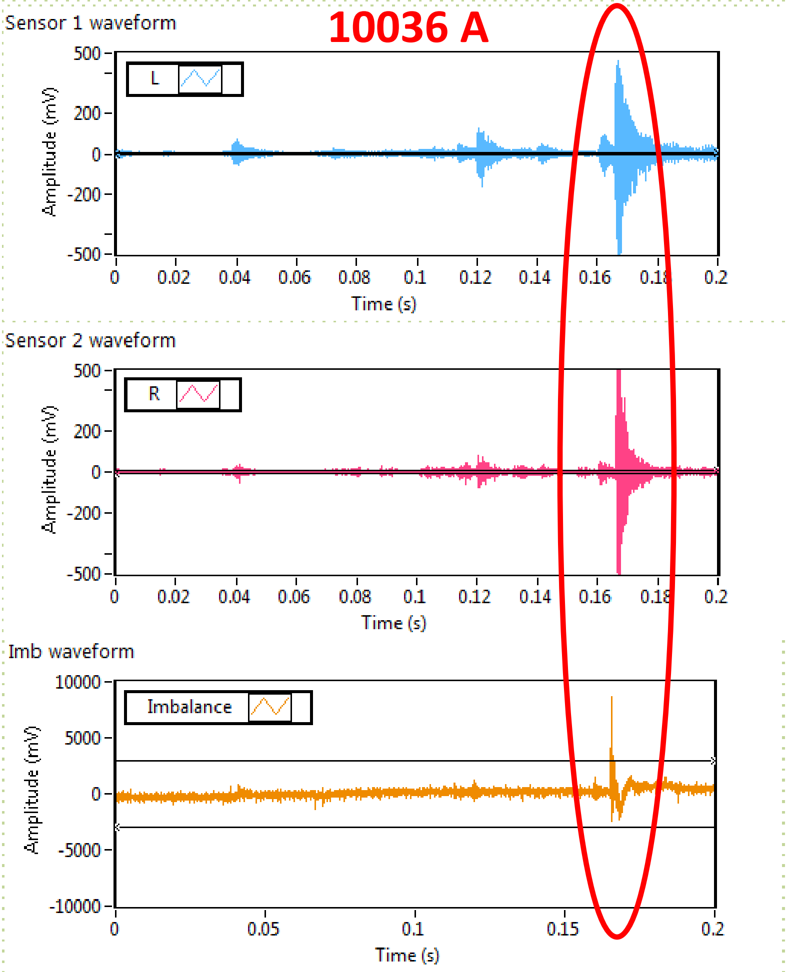


Sounds at higher magnet current

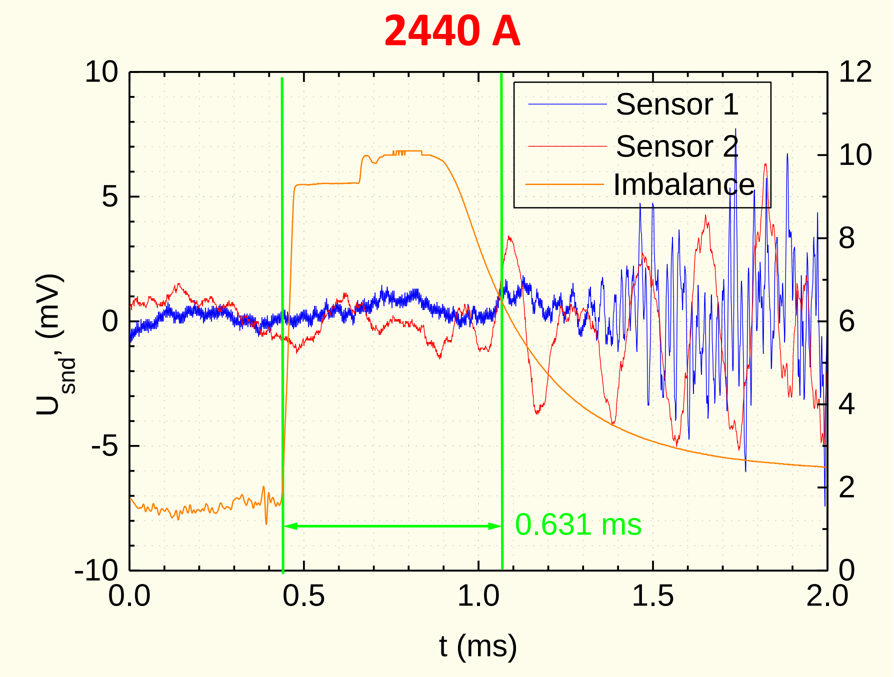
Much stronger sounds are observed, that are either not correlated with any imbalance variations:

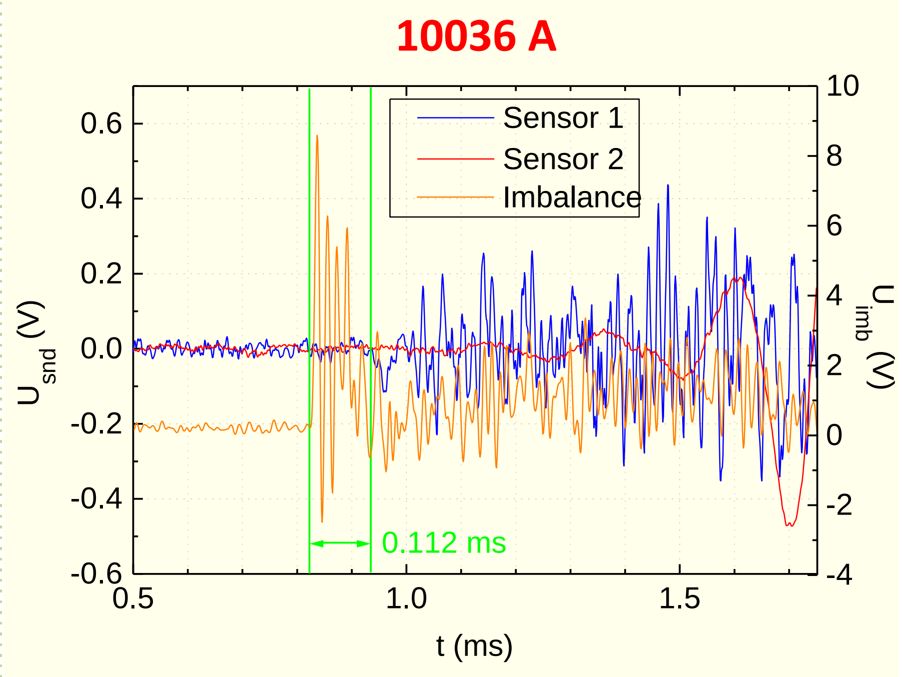

9628 A

or, occasionally, are correlated with a short "spike" in the imbalance signal:


10036 A

Origin of the sounds?


2440 A


10036 A

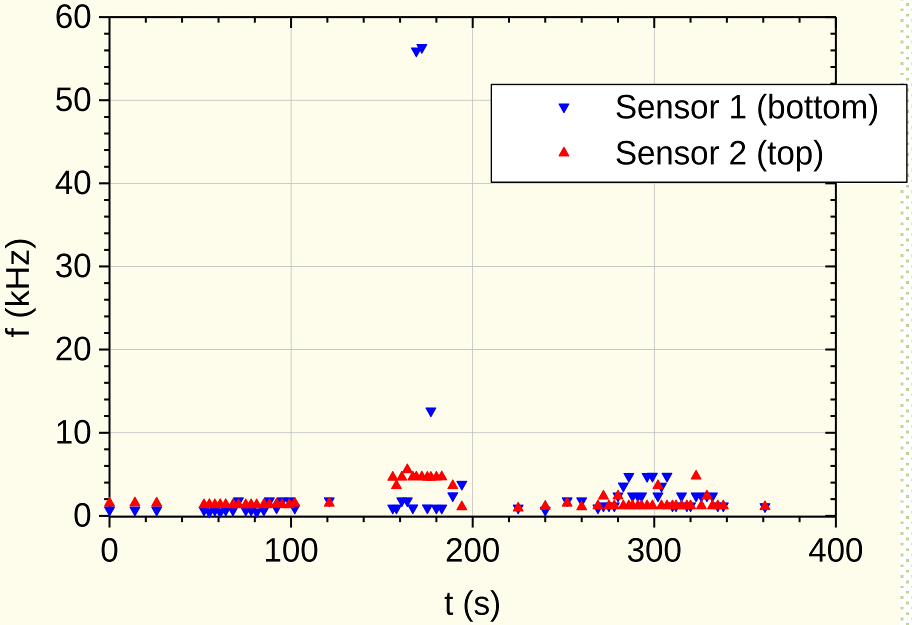
The 0.63 ms delay corresponds to the ~2.6 m distance, which would be outside of the magnet length. The sound is likely produced during the (long) imbalance variation, but not at its onset.

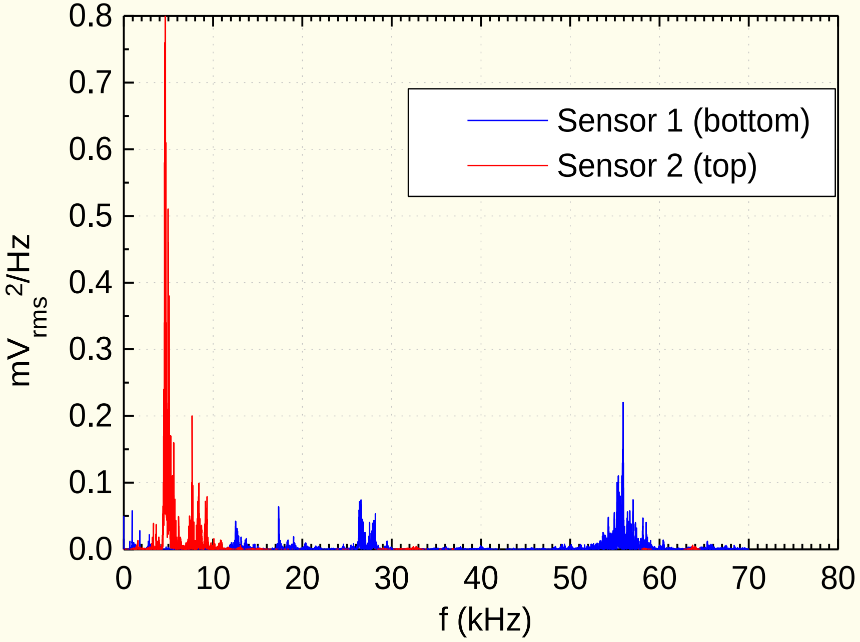
The 0.11 ms delay corresponds to ~0.46 m distance => the sound is produced within the magnet length.

Current re-distribution in the cable triggers sound?

Mechanical motion event is triggering the imbalance?

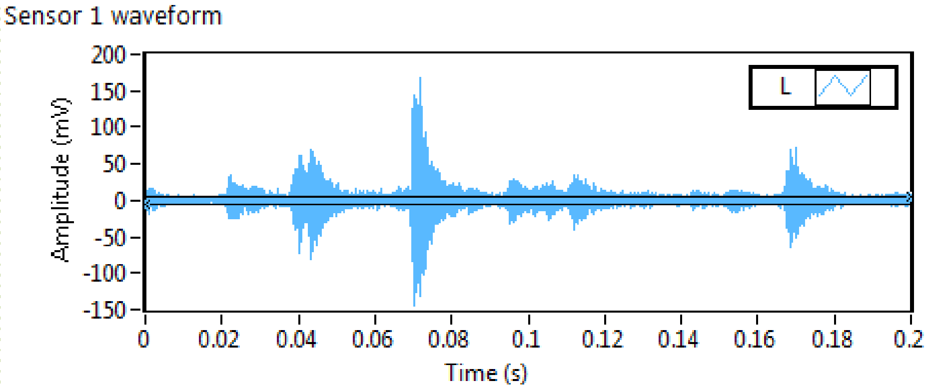
Frequency of the sounds



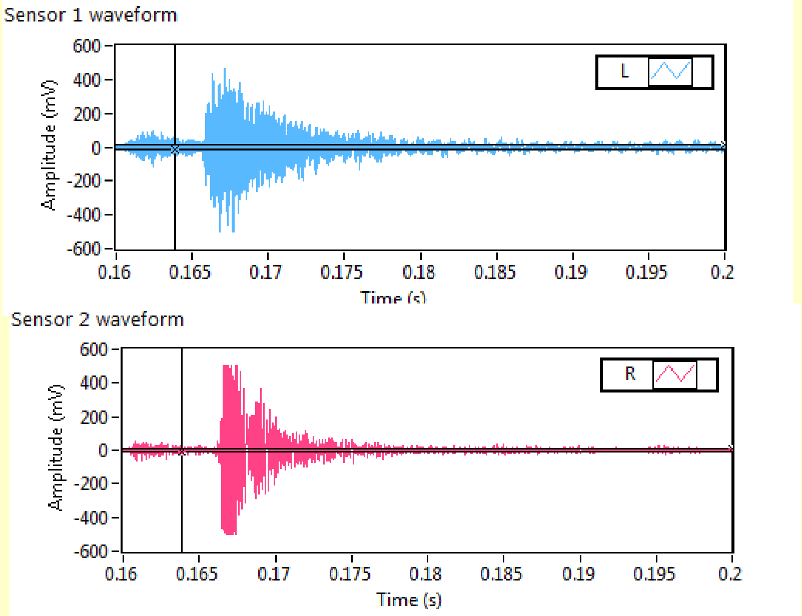


Very high frequency sound is detected at I_{mag}>10 kA

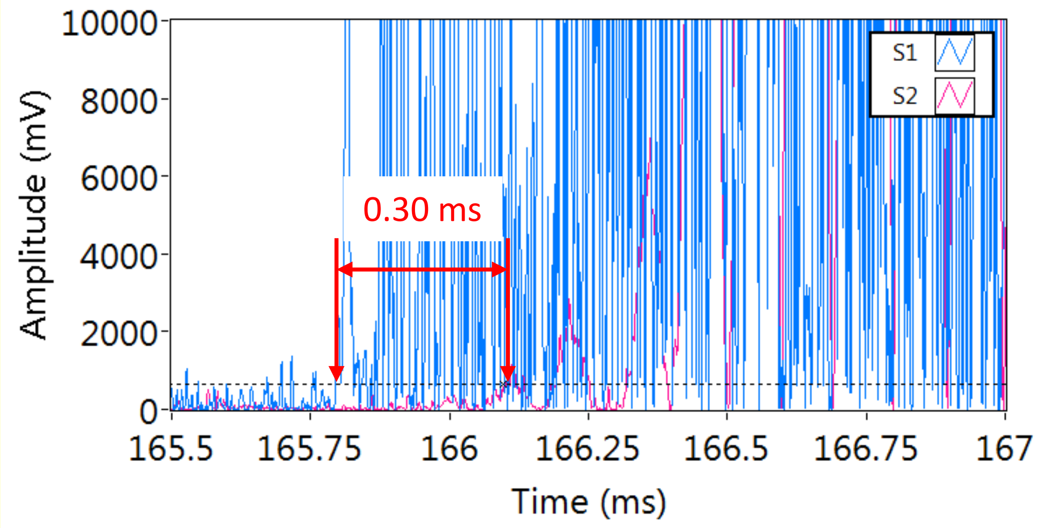
(Sound slowed down 10x)



Location of the sound sources



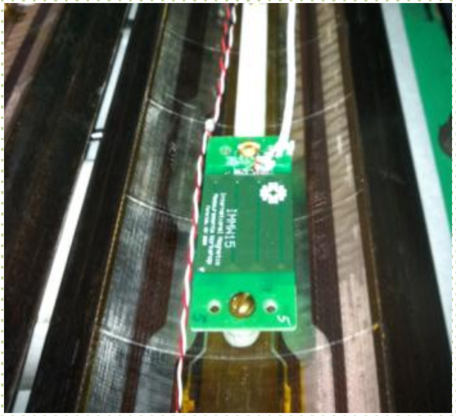
10036 A



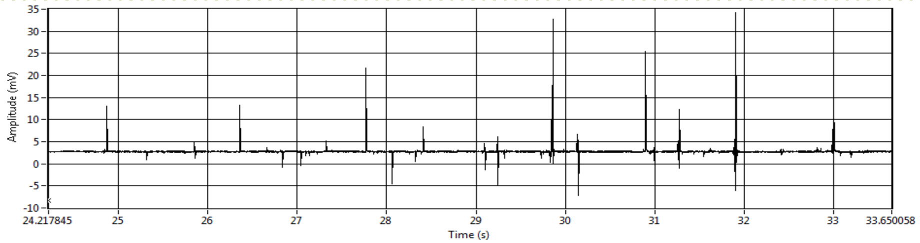
X= - 63 cm (at the bottom end)

It appears that the sources of strong sound generated in HQ01e3 ramps above 9 kA are located near the bottom (return end) of the magnet

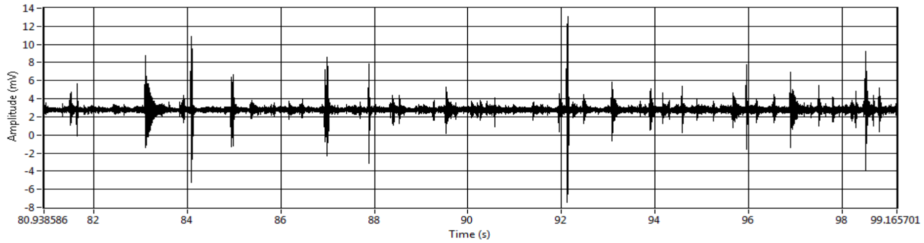
"Sound" from the Quench Antennas



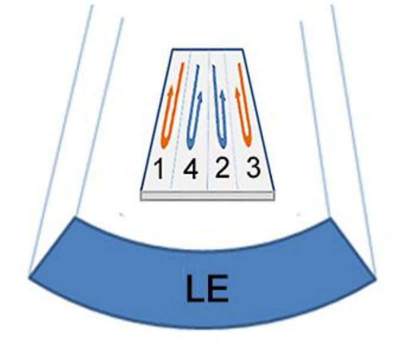
<u>HQ01d magnet, ramping at 100 A/s</u>

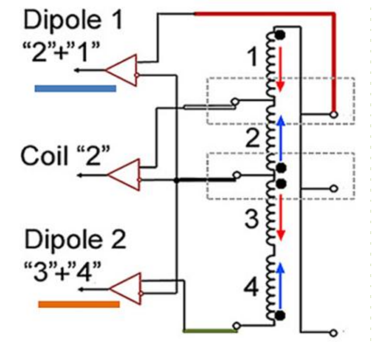


Flux jumps



Mechanical vibrations





M. Marchevsky et al., ASC 2012 presentation

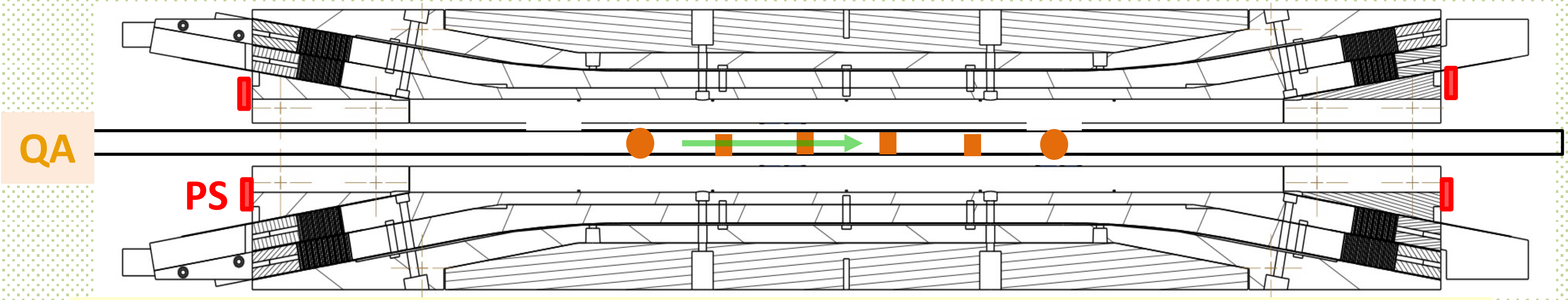
Inductive quench antenna is an electromagnetic microphone! It picks up vibrations of the current-carrying (or magnetized) structures

By correlating EM QA and piezo-sensor signals, one can potentially differentiate between flux jumps, conductor motion and other mechanical motion in magnets

Future testing opportunities

Upcoming test of the high-field dipole magnet HD3 at LBL:

We plan to have both, inductive QA and the piezo-sensors installed.



Proposed positioning of the piezosensors on the magnet: four wedges that are in direct mechanical contact with the windings

Upcoming test of the LARP HQ02 magnet:

At least two acoustic sensors can be installed on the endplates; some kind of inductive pickup QA may also be installed, t.b.d.

Next steps / challenges

- Filtering out the resonant modes and improving selectivity for small signals
- Developing microphone arrays and algorithms for precise localization
- Quantifying mechanical energy release and conductor motion amplitudes observed with piezo and EM sensors
- Acoustic quench detection system?

Conclusions

- Amplified piezosensors, in combination with cryo-electronics, modern data acquisition and processing techniques show good potential for real-time characterization of various mechanical events in superconducting magnets during ramping, quench and recovery

- HQ magnet produces increased acoustic emissions (seemingly unrelated to FJ) and high-frequency (>50 kHz) vibration "bursts" when energized above 9kA. The latter are occasionally correlated with the short imbalance spikes and most likely caused by stick-slip motion of the conductor

- Inductive pickups sensors they provide a unique insight into conductor motion; can be developed and used in conjunction with acoustic devices to improve selectivity for the specific mechanical and electrical events

Listening to magnets sounds like fun!