Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

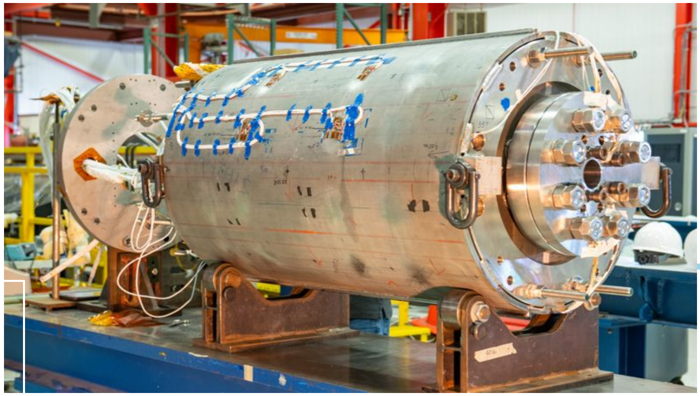
Real Time Magnet Quench Detection

Speaker: Maira Khan

Working Group: Finlay Campbell, Steve Krave, Vittorio Marinozzi, Joseph DiMarco, Jennifer Ngadiuba, Danming Peng, Nhan Tran, Stoyan Stonyev

Previous Investigation by Duc Hoang

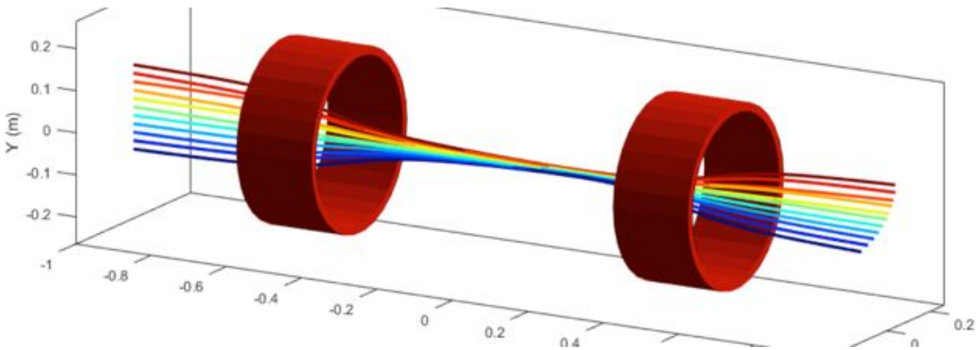
Fast ML Conference 2023



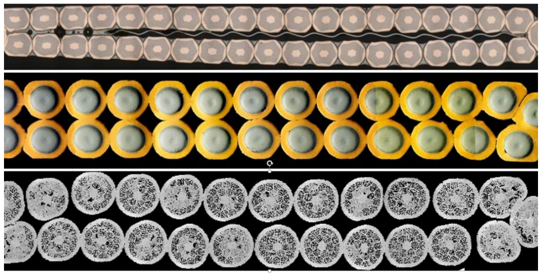
15-Tesla Steering Magnet

Courtesy: FNAL Media Services (2020)

Superconducting Magnets in Particle Accelerators



Simulation of particle trajectories in a solenoid
Source: APS-TD Fermilab



Nb_3 Superconducting cables
Source: APS-TD
Fermilab

- Superconducting (SC) Magnets are critical to controlling particle trajectory
- Due to electron phonon coupling, these magnets have no resistance, allowing them to conduct high currents and induce strong magnetic fields

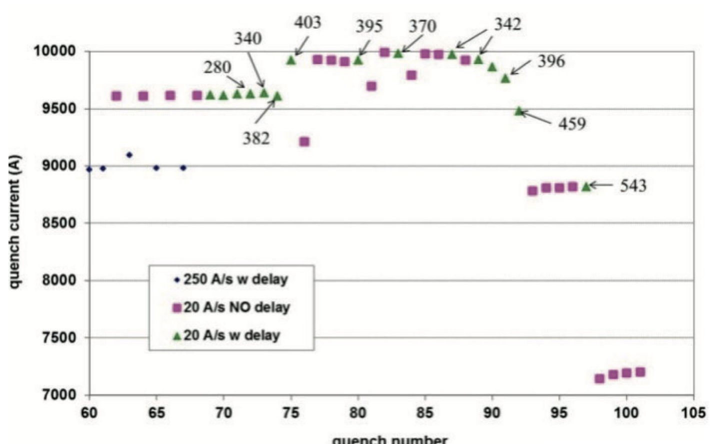
magnetic flux density

magnetic field strength

$$B = \mu_0 \frac{NI}{l} \propto \mathcal{H}$$

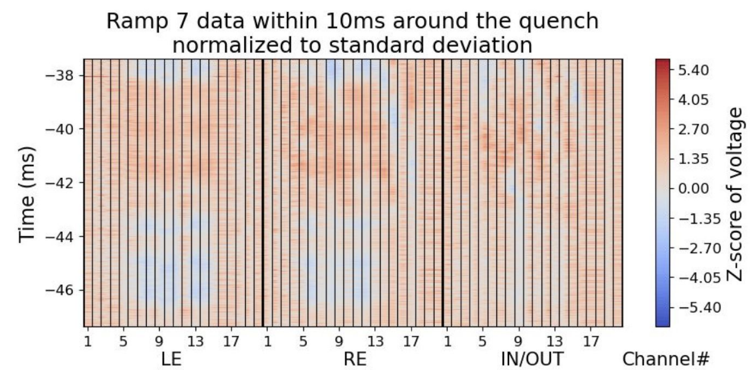
Magnet Quench Event

- A magnet ***quench*** occurs when the SC magnet goes from its superconducting state to a resistive state.
- In data, this is seen as the existence of voltage, due to increase in temperature at the site of quench.
- This is a highly energetic event that causes electromagnetic disturbances which can manifest as mechanical disturbance, heat, or sound.
- Quenching can cause physical damage to the magnet, resulting in high replacement and repair costs
- For example, MQXF magnets undergo ~20 quenches, each costing $15k. With two trainings per day for two weeks, the total cost can be up to $300k per training. For 2000 magnets at an accelerator complex this is $600M

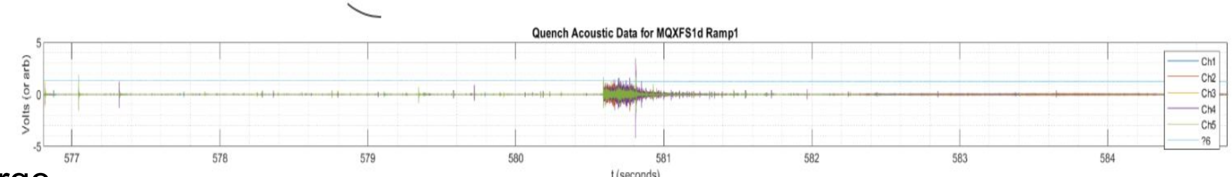


TQS01c High Temperature Quench Curve. Arrows point to temperature (K)

Source: APS-TD



Voltages within 10ms of the quench in QA (above) and acoustic sensors (below)

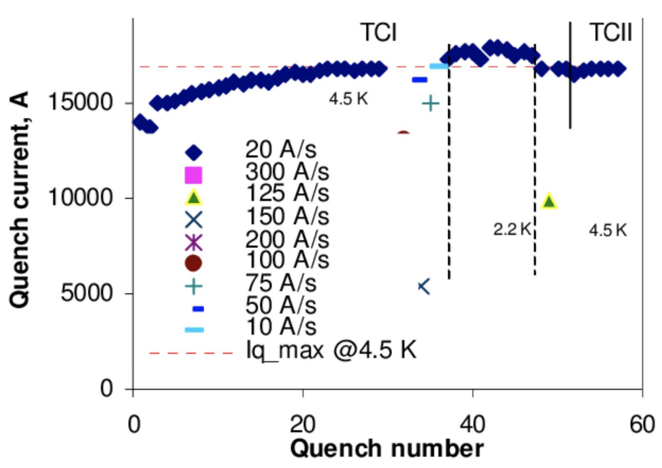


$$E = \frac{I^2}{2}$$

Potential to store large energy!

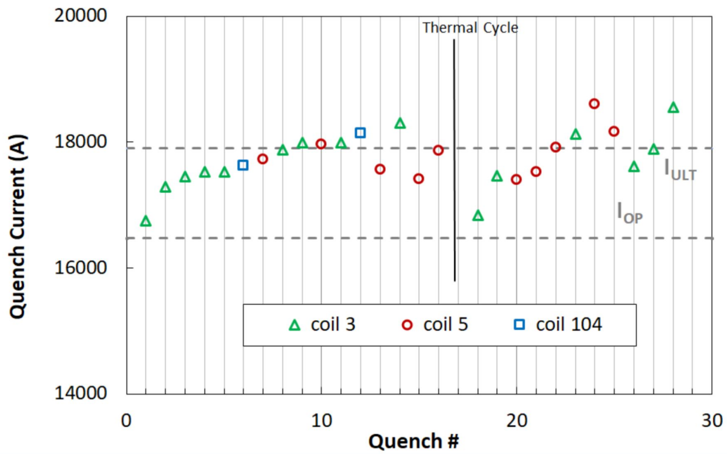
Quench Training

- When testing the magnet, we find that SC magnets show a progressive increase in the quenching current, every time they are subjected to a quench.
  - Cause: Electromagnetic forces causing small movements in magnet
- Magnets then must be “trained” by ramping up the current until the magnet reaches the desired current



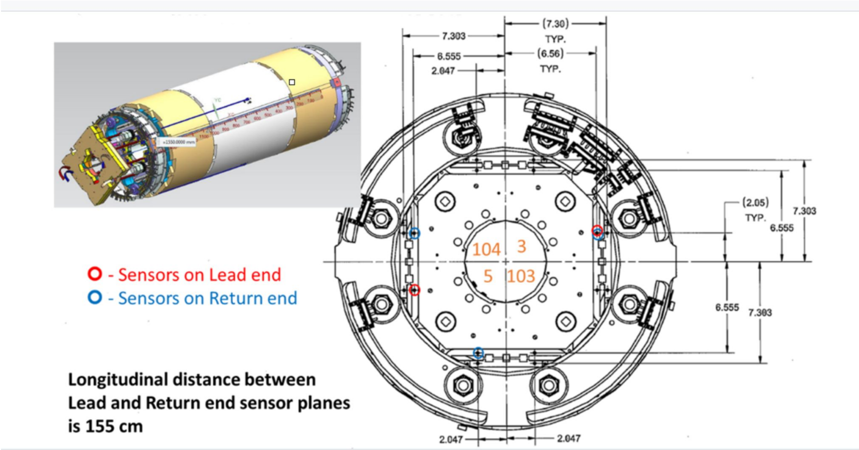
Dipole model HFDM05 quench history.

HFDM05 Quench Curve
Source: APS-TD



MQFSX1D Quench Curve
Source: APS-TD

How can we detect a quench with data?

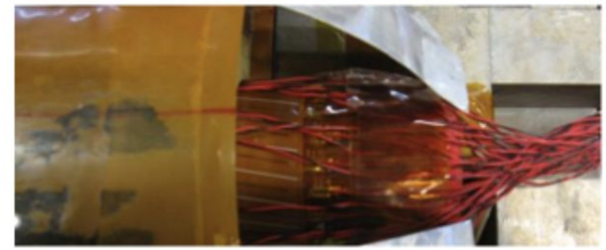


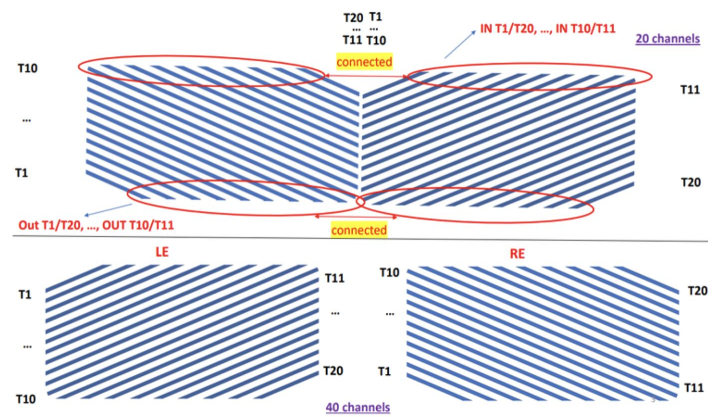
Acoustic data from microphonic sensors gives us information about the release of energy, cracking of the epoxy in impregnated magnets, or other possible mechanical disturbances.

These sensors run along the length of the magnets (155cm)

Recall v_{sound}= 343m/s

Sampling rate from 100kHz to 1MHz depending on magnet



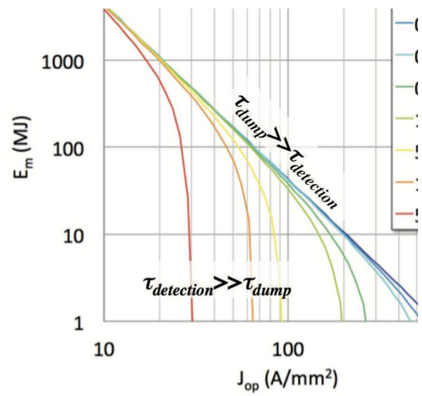


Quench antenna detect magnetic field perturbations caused by current redistribution

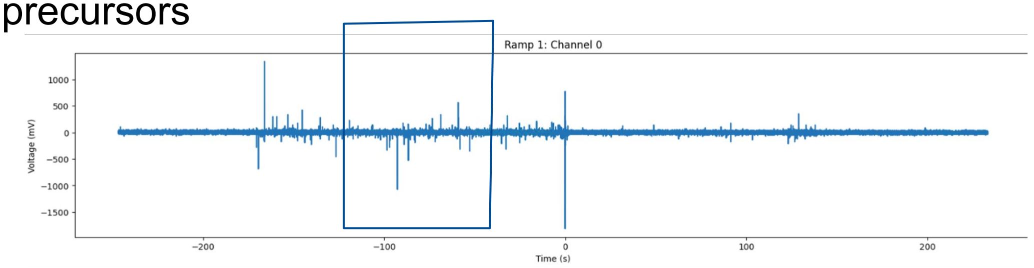
Antenna run the length of the magnet and have a unique geometry that may localize the quench. We have lead and return end channels that measure similar voltages

Energetic Picture of the Magnet

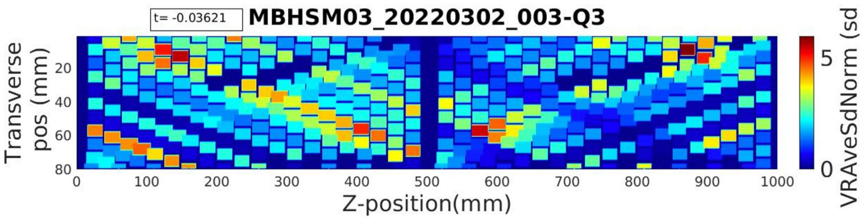
- A quench event is an extreme energetic release, which can be seen most explicitly as mechanical, thermal, acoustic disturbances. We can do our best to extract energy in time and space
- If we would like to detect these energetic changes, the best way to do so is by identifying the features of our data most directly associated with energy (J)
- The direct causes of the quench in most cases is largely unknown and there might be known energetic disturbances that show up as precursors



Energy dissipation vs. current density for time of quench protection mechanism
Magnet Quench 101, Bottura



The square of the amplitude of a given window gives us the energy

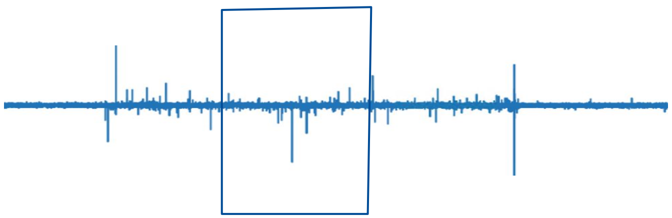


The integral of the quench antenna data with adjusted pedestals gives us changes in flux

Fermilab

Developing a Dynamic Learning Algorithm

Since we don't explicitly know the cause of the quench beforehand, we can do our best to input our features that correspond to energetic disturbances into a full connected autoencoder.

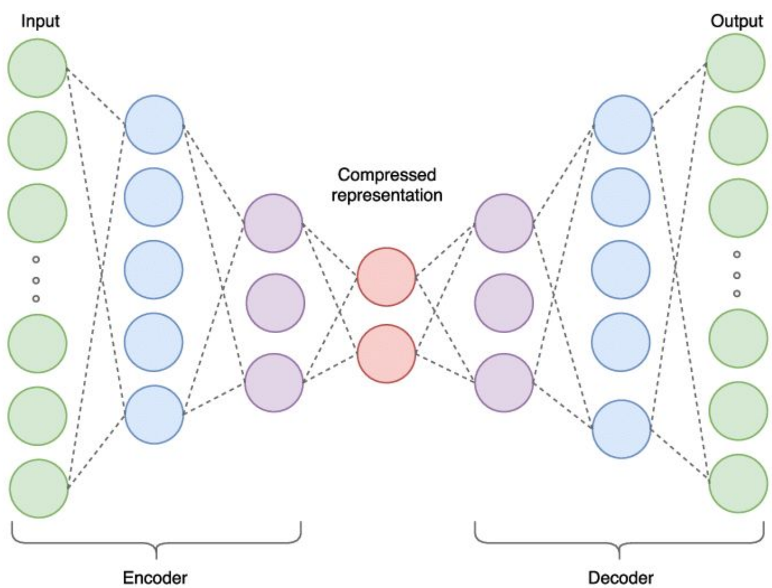


10ms

To simulate real time inference along a ramp of 10 minutes, we update the weights every 10s, with a window size of 10ms, and a step size of 10us. Then we calculate reconstruction loss on each sample. The trigger threshold is updated based on the median of the log reconstruction loss

$$E, \Phi$$

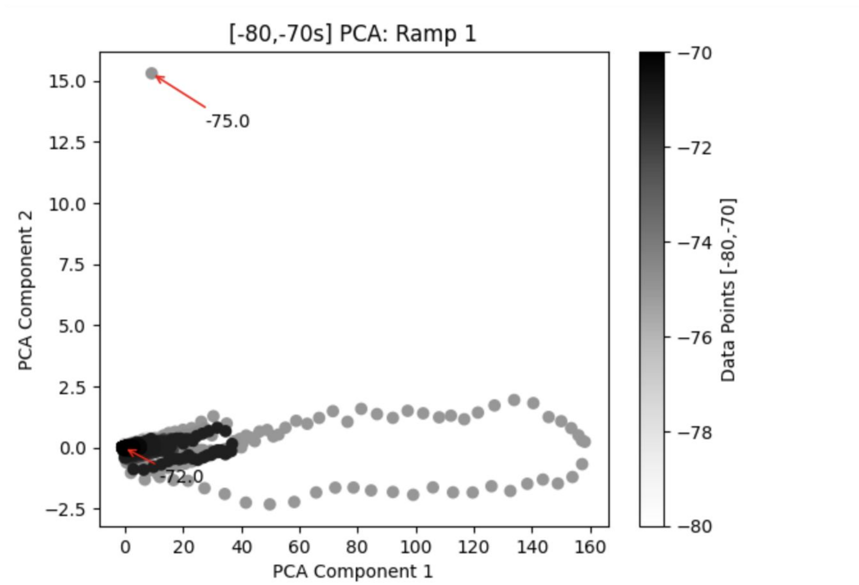
$$\Pi_{i=0}^{i=3}\mu_i \ \Pi_{i=0}^{i=3}\sigma_i$$

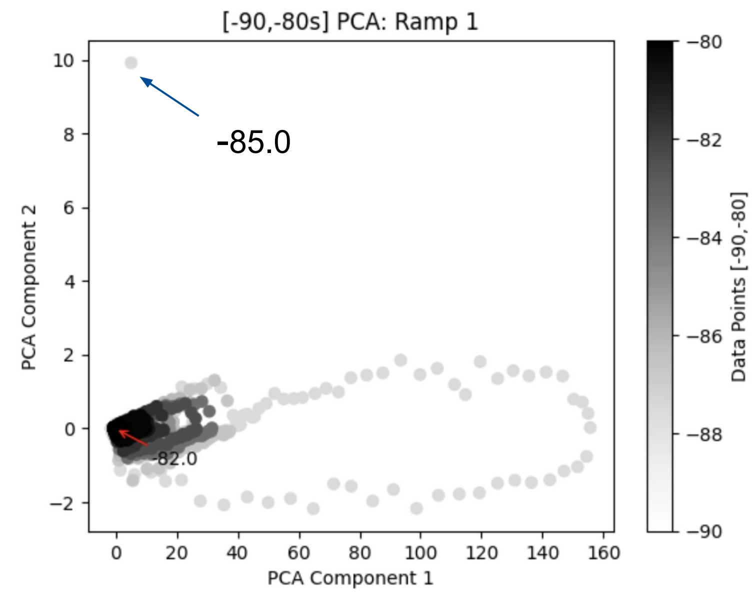


3 Dense Layers

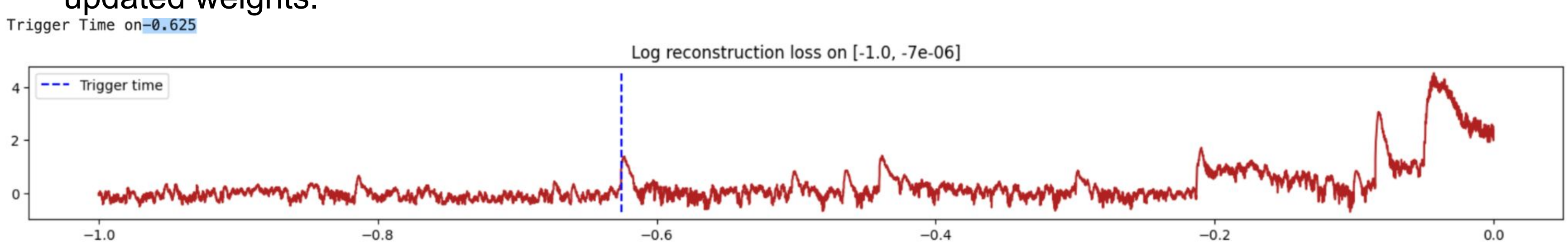
A uniform activation function (ELU) is used at every layer of the encoded network to capture these energetic features

Searching for Anomalies in Acoustic Data





We see that there are indeed precursors in the latent space of the autoencoder that might contribute to a quench downstream. These are captured in the dynamically updated weights.



Example of reconstruction loss trigger

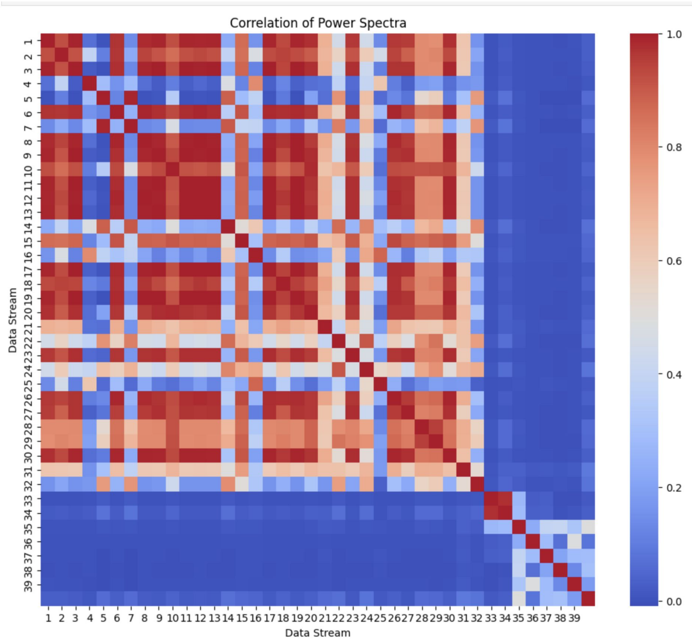
Fermilab

Searching for Anomalies in QA Data

In our quench antenna data, anomaly detection must take into account the instrumentation.

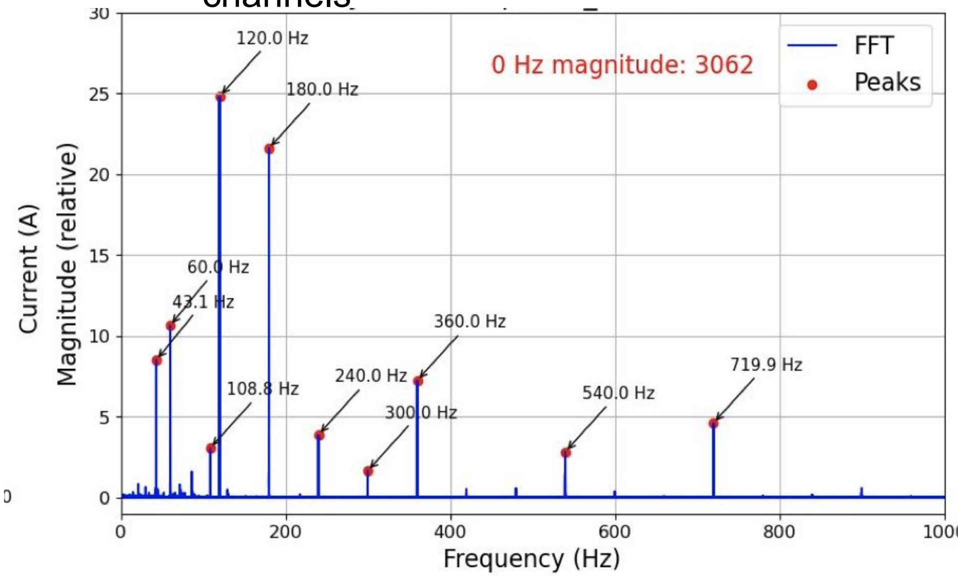
There are hum frequencies caused by the power supply that must be filtered out. There is also correlated electrical noise that may be associated with anomaly, but also might be ambient around the coil.

If we integrate the voltage, we must take into account pedestal subtraction to avoid false scaling of the weights



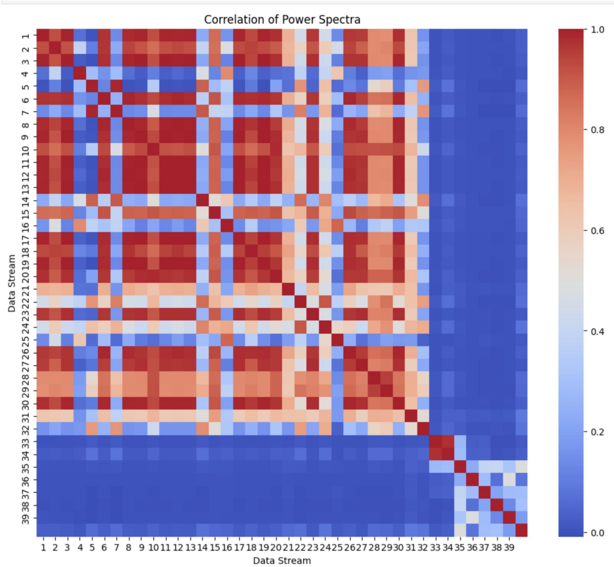
Correlation of power spectra for channels on a quench antenna (QA) sensor

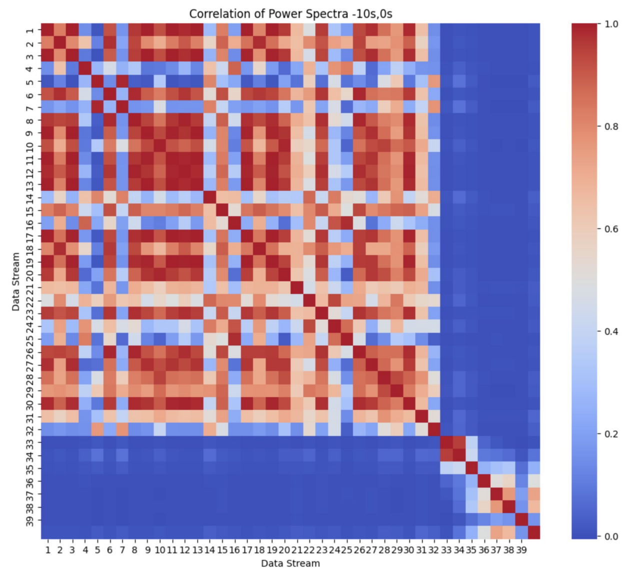
FFT for a particular channel (done for all channels



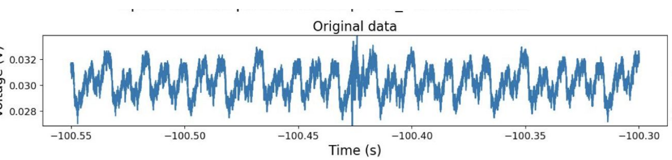
Multiple 60Hz Hum frequencies that can be removed prior to implementing to machine leanrig model

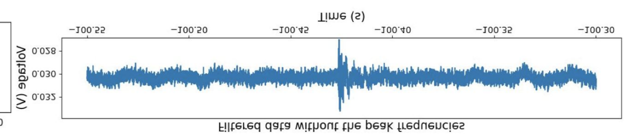
Correlated Noise and Background Removal



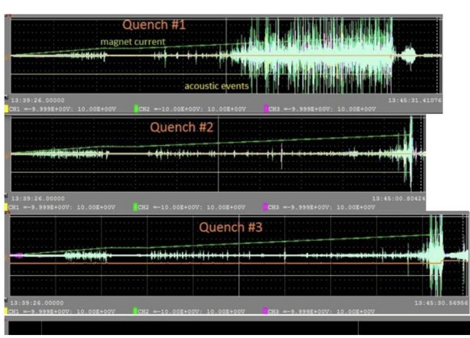


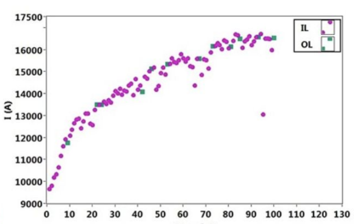
Correlation plot of power spectra for QA channels 90s before the quench (left) and 10s before the quench (right). Correlations are decreases between lead and return channels (light pink) which indicates disturbance in the magnetic field.





Filtering these frequencies allows us to isolate anomalies in reconstruction loss





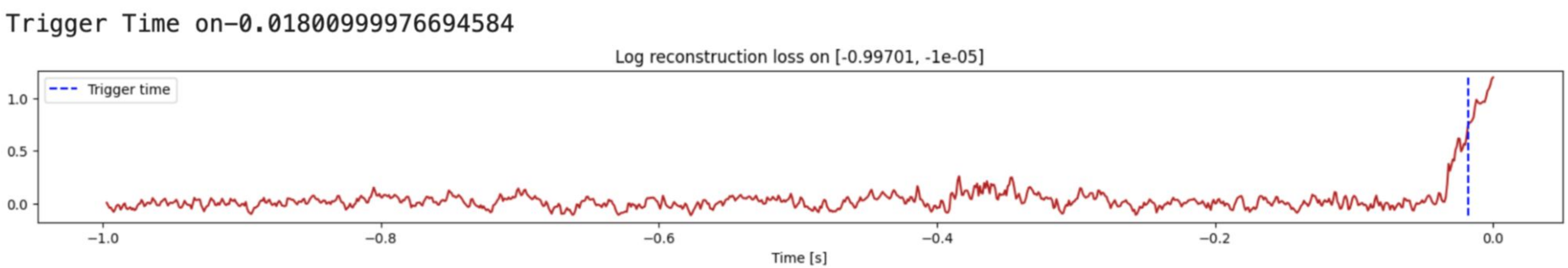
Indication of a Kaiser effect - anomalies and precursors scale I^4 for epoxy impregnated data

Fermilab

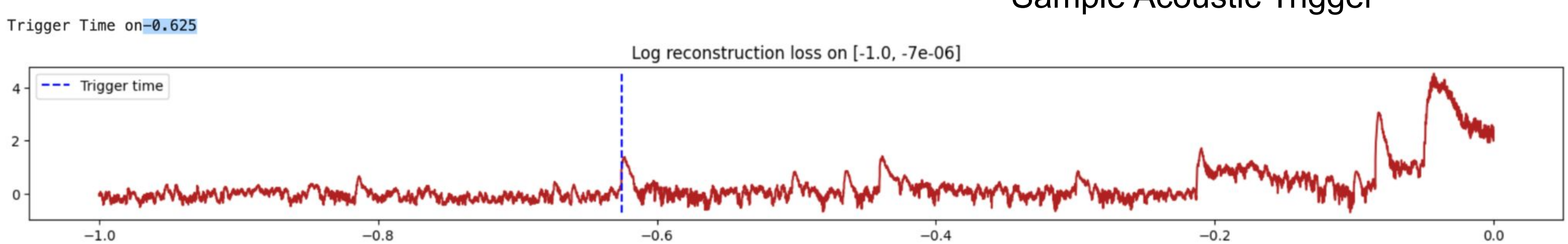
Viewing QA and Acoustic Triggers Together

We compute reconstruction loss in inference on every incoming data point. If the reconstruction loss is greater than the updated weights trigger threshold, we quench (blue dotted line). The QA channels are quieter in the time up to the quench event.

Sample QA Trigger



Sample Acoustic Trigger



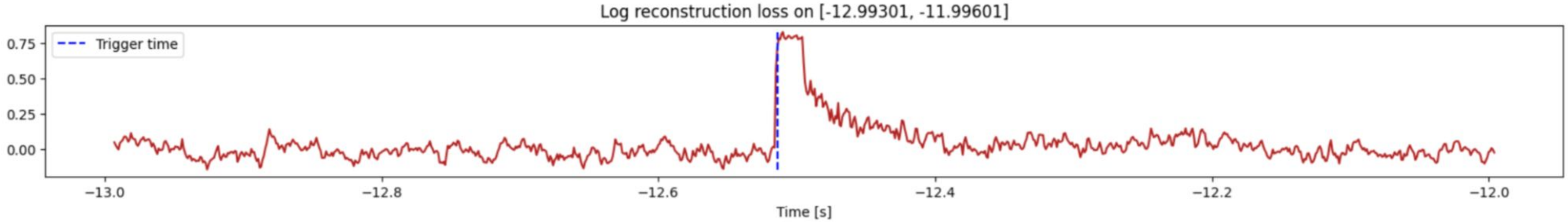
Fermilab

Viewing QA and Acoustic Together

However, QA data may pick up precursors to the quench that acoustic data does not due to geometry along the sensor, and larger deviations in voltage that indicate changes in flux. Note there is a difference in longitudinal and transverse quench propagation

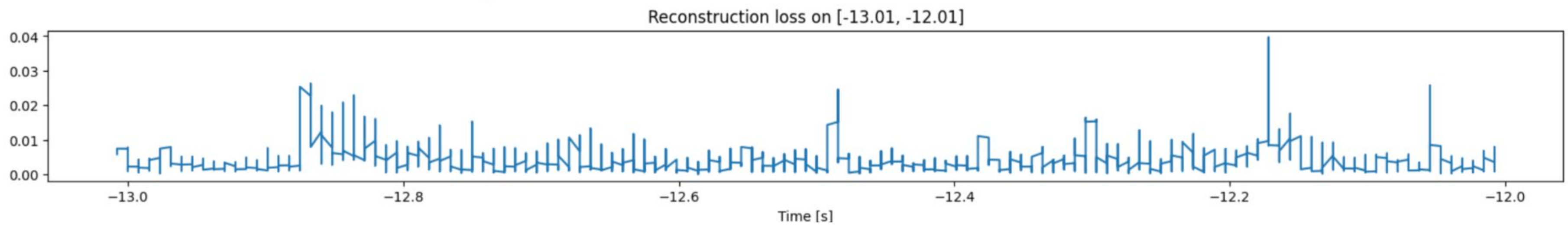
Sample QA Trigger at t=-12.4s

```
Trigger Time on-12.514009475708008
32/32 [==============================] - 0s 995us/step
32/32 [==============================] - 0s 782us/step
```



Sample Acoustic Event (No Trigger)

```
313/313 [==============================] - 0s 1ms/step
```



Conclusions

- SC magnet data presents promising opportunities for quench prediction, and potentially understanding the precursors associated to the event
- We hope to test transformer models, and RL models that can handle multi-modal data streams. However we are aware of the resource scaling issues of this project.
- Current results show that we may trigger within -10s of the event on multiple ramps
- Aligning acoustic and QA data gives us a deeper energetic picture of the magnet, but still much to learn about quench propagation.

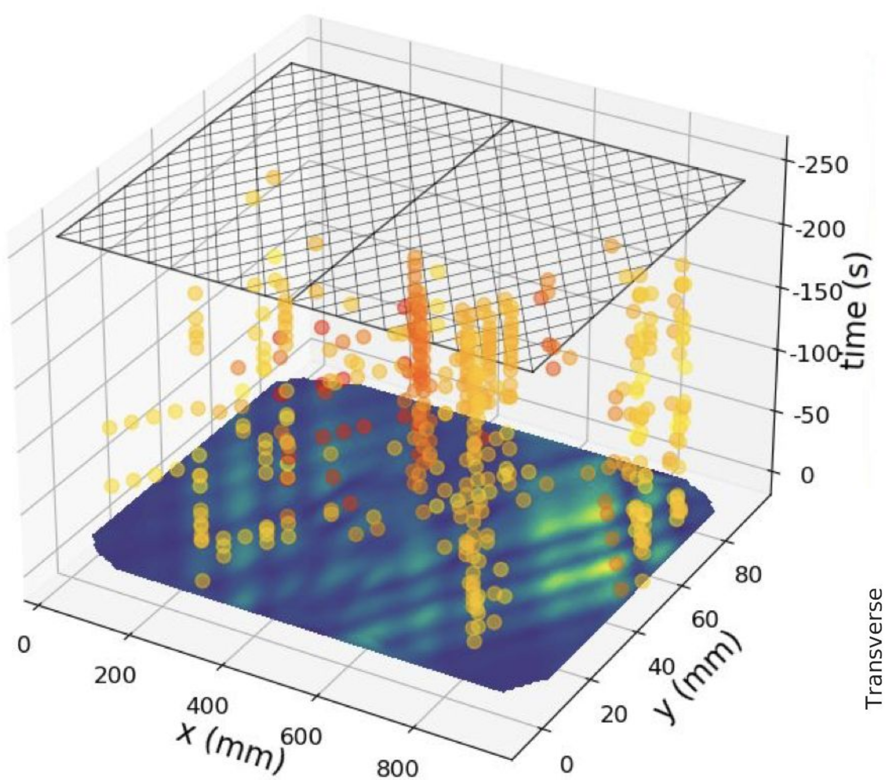
We are looking to integrate our data taking process in a way that is compatible with our new machine learning infrastructure. Codesign is important!

Backup Slides

Localizing The Quench Geometrically

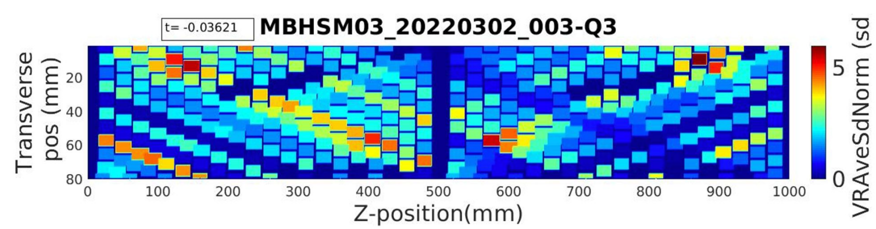
Even with correlated noise removal, and removal of the hum frequencies, we find that certain channels that indicate high voltages that persist throughout the ramp training.

We can investigate the eigenfrequencies associated to a particular channel that might correspond unknown precursors.



(Left) Intensities of normalized voltage along channels aligned geometrically

We find that certain regions correspond to field disturbance which which appears in our reconstruction loss, but ultimately does not affect our anomaly detection significantly



Ramps and Trigger Times

Architecture	Features	Loss Function	Data Streams	Trigger Times
Dense Layers (Uniform Activation)	rolling window stats, abs_max	MSE	Acoustic	Ramp 1: -7.44921875, Ramp (n+1): n = 3: -3.794921875 n= 7 : -2.47265625 n= 11: -0.625
Dense Layers (Uniform Activation)	rolling window stats, abs_max, integral	L^P + w*MSE	QA	Ramp 1: -12.514, Ramp (n+1): n =3: -2.541 n = 7: -0.018 n = 11: -1.982421875