Machine Learning methods for superconducting magnet applications

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Contents

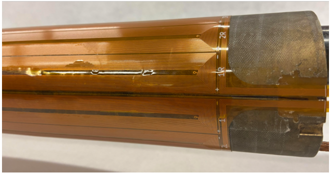
Superconducting materials

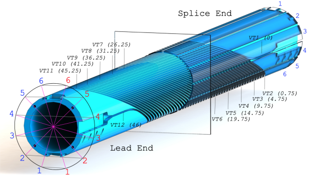
Superconductor:

- Material which achieves superconductivity, a state of matter that has no electrical resistance
- Extremely important for accelerators, because they can generate strong magnetic fields which provide strong bending and focusing of the beam
- Requires very low temperatures: Fermilab best magnets need 1.9 K to provide 14.6 T

Quench antennas

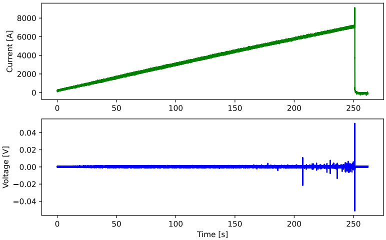
- Quench: sudden and irreversible transition of the superconductor into the normal-conducting state
  - After the quench, the energy stored in the magnet must be dissipated in order to protect the magnet
- Quench antennas: pick-up coil arrays sensitive to changes in the magnetic flux ⇒ provides quench identification and localization





Voltage changes

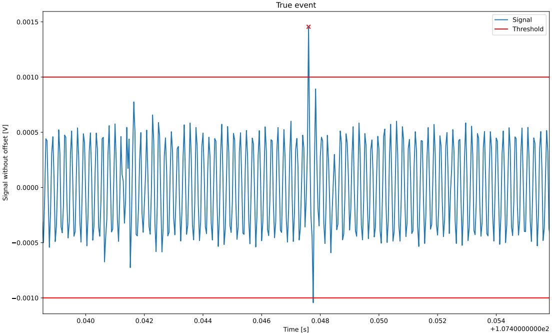
- Quench antennas measure activity along the ramp, all the way to quench, at which point current is extracted from the magnet
    - Once the quench happens, a dump resistor is switched on to convert magnetic energy into thermal energy in the dump resistor



- Voltage spikes along the ramp caused by many possible reasons, some of which are:
    - Current redistribution within the cable
    - Frictional slipping of the cable
    - Vibration of the magnets
    - Epoxy cracks

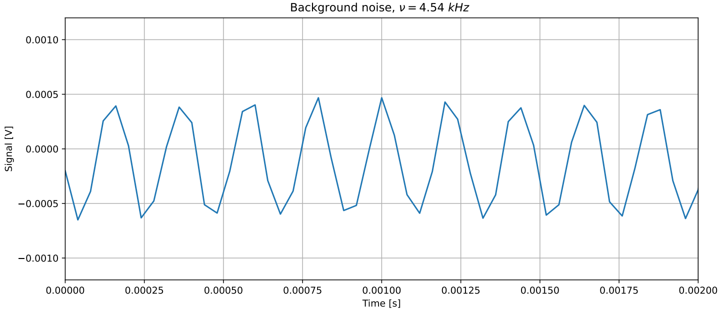
Aim of my work

- My job is to analyse the data provided by the quench antennas, finding the events prior to the quench, in order to find some specific features
- These features will then be fed to an unsupervised ML clustering algorithm in order to classify the events



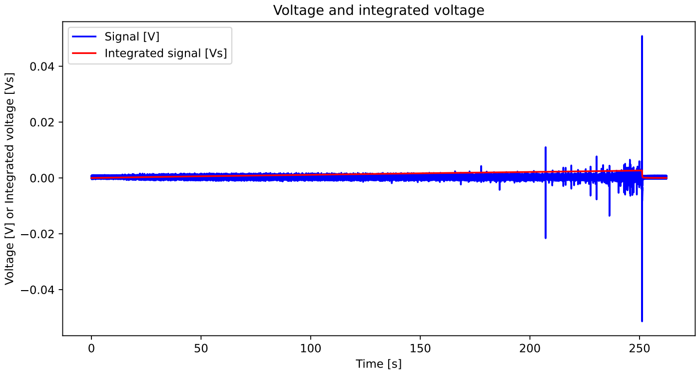
Filter

- To eliminate the background noise ($\nu = 4.54$ kHz), a third-order Butterworth bandstop filter was implemented, allowing only frequencies lower than 4 kHz and higher than 5 kHz



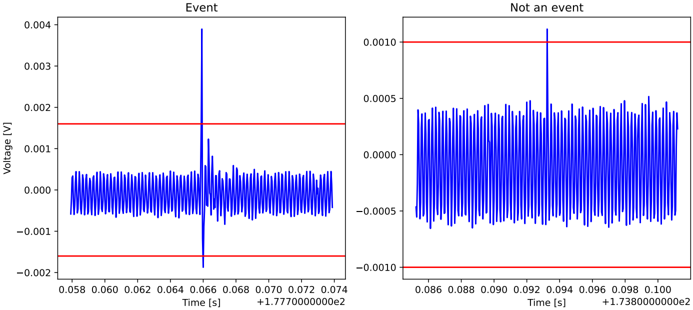
Integral

- To evaluate the magnetic flux received by the quench antennas, I evaluated the integral of the voltage
- The integral was performed using the trapezoid method on the voltage signal



Event Selection

- Looking for events prior to the quench, $\nu_{\text{samp}} = 25$ kHz
  - From a continuous waveform, trying to build windows around the selected events
  - Event selected when there are values above the positive threshold and below the negative threshold close to the positive peak



Threshold analysis

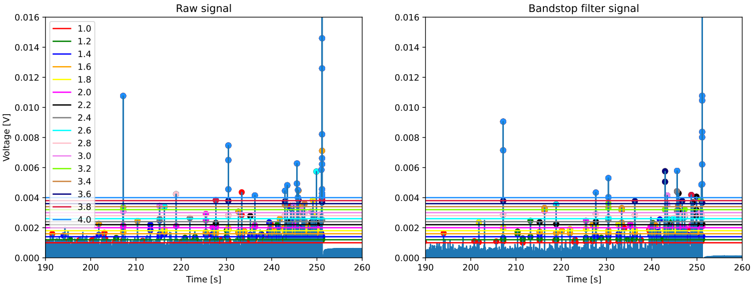


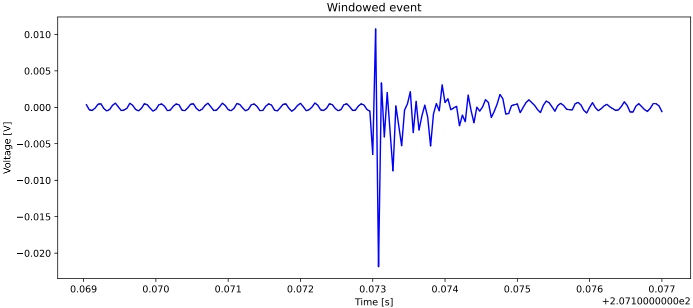
Figure: Plot representing the events found using different thresholds, for both the raw signal and the filtered signal. The thresholds were selected between 1 mV and 4 mV

Threshold analysis: number of events found

Threshold (mV)	Raw data	Bandstop Filter data
1	147	95
1.2	90	66
1.4	67	51
1.6	51	45
1.8	36	35
2	31	32
2.2	27	25
2.4	24	18
2.6	22	17
2.8	20	14
3	17	14
3.2	13	13
3.4	13	11
3.6	12	10
3.8	11	7
4	10	6

Features matrix

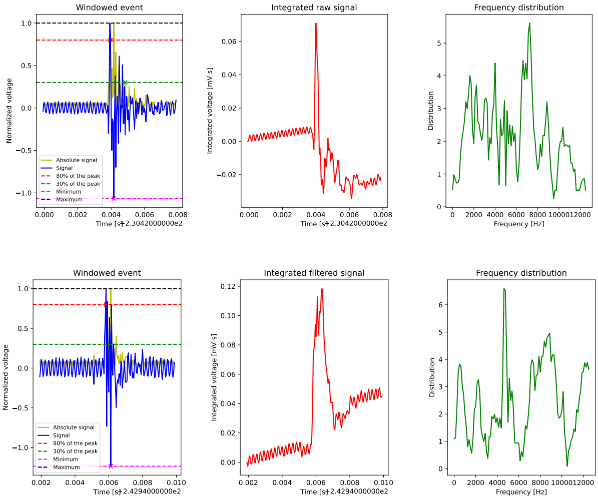
- Prior to performing ML techniques, I first need to identify some features which will be used for the clustering
- Features extracted from each event, both for raw and filtered signal
- The features will then be added to a matrix, which will then be fed to an unsupervised clustering algorithm to identify the representative events



Description of features

- I divided the features in four main categories:
  1. Voltage signal features
     - Maximum and minimum value of the voltage
     - Norm of the voltage array
  2. Integrated signal (magnetic flux) features :
     - Maximum and minimum value of the integrated voltage
     - Norm of the integrated voltage array
     - Definite integral of the voltage
  3. Signal shape:
     - Width and tail of the signal
     - Signal length
  4. Fast Fourier Transform (FFT) features:
     - Peak frequency
     - Distribution of frequencies obtained with FFT analysis

Plots displaying some features, both raw and filtered



Summary and next steps

- Goal: use Machine Learning to identify and learn about the disturbances in high field superconducting accelerator magnets
- Achieved so far:
  1. Build a routine to automatically extract windowed events from continuous data
  2. Analysis of windowed events for signal characteristics, signal shape and frequency distribution
- Next steps:
  1. Finalize FFT analysis on the signal
  2. Perform unsupervised k-means clustering on feature matrix
  3. Implement a Neural Network to identify the events and check prediction power on more data

Thank you for the attention