ML methods for superconducting magnets

Elisa Stabilini

Supervisor: Emanuela Barzi (FNAL)
Cosupervisor: Reed Teyber (LBNL)

Fermilab

UNIVERSITÀ DEGLI STUDI DI MILANO

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Table of Contents

Superconducting materials

- Super-conducting materials: materials that can achieve a zero-resistance state for particular values of temperature, magnetic field, and current density
- Quench: sudden and irreversible transition of a portion of conductor to resistive state in a superconducting magnet [SZ19]
- Due to large stored energy magnets can be damaged by quench (e.g. localized heating, high voltage).

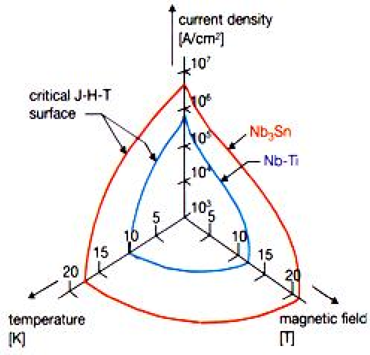


Figure 1: Superconducting region for different alloys magnets

Magnet training

- Spontaneous quenches happen below the expected magnet performance
- Magnets training: it takes several quenches before reaching nominal performance
- Current is increased until quench happen (current ramp)
- More current ramps constitute a thermal cycle
- Magnets mentioned here are Canted-Cosine-Theta (CCT) subscale magnets
- Sub-scale magnets present lot of diagnostics, including quench antenna (QAs)

Figure 2: Example of QA on a subscale magnet

Quench antenna

- Quench antennas provide information on events location and time
- QAs measure $V = \sum_{i=1}^{n} \frac{\mathrm{d}}{\mathrm{d}t}(\int B \mathrm{d}A_i)$
- A change in the voltage can occur for different reasons:
  - mechanical (epoxy cracks, friction, slipping)
  - electromagnetic (current redistribution, flux jumps)

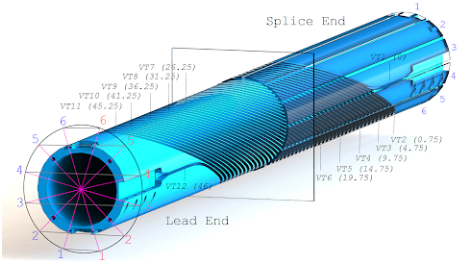


Figure 3: Model of QA on the CCT magnet at LBL

Table of Contents

Global signal analysis

Dataset Data from two different CCT subscale magnets from LBNL:

- **sub2**: NHMFL mix-61 - baseline (standard) epoxy impregnated magnet
- **sub4**: CTD 701X - ultra tough (epoxy-non-epoxy) impregnated magnet

Parameters tuning

- different threshold depending on the sampling frequency
- different filters for the different magnets

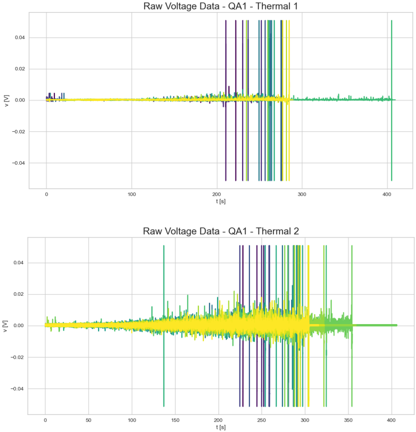


Figure 4: Raw data registered from QA1 for ramps in different thermal cycle

Event detection - different antenna

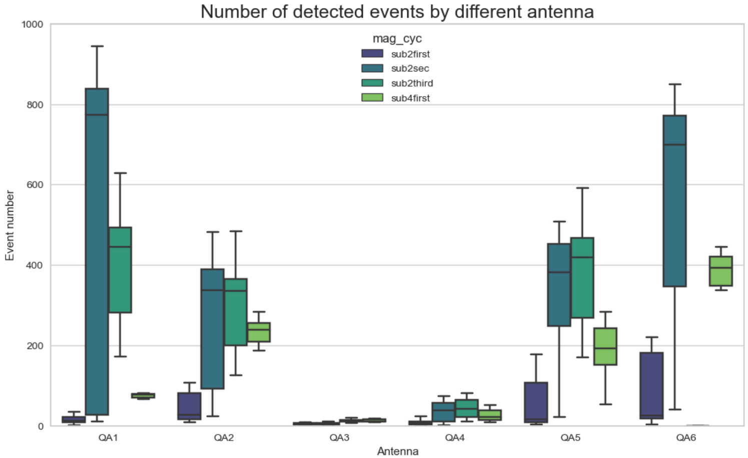


Figure 5: Number of events comprehensively detected by different antennas along the first, second and third thermal cycle for magnet `sub_2` and first thermal cycle for magnet `sub_4`

Event Samples

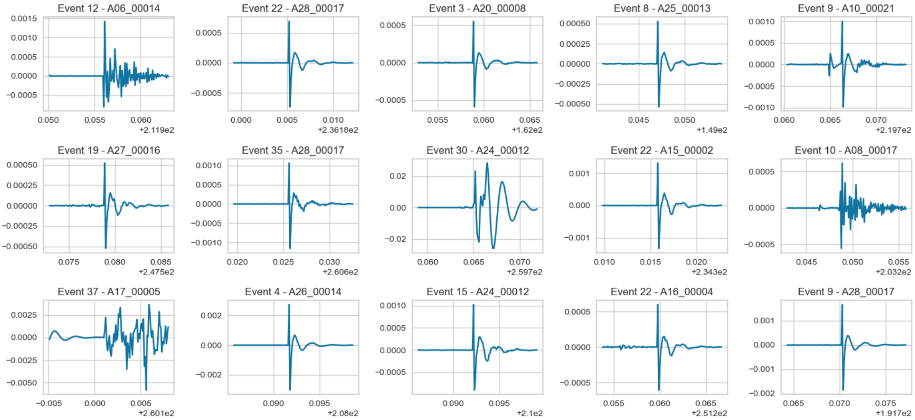


Figure 6: Samples of events from different ramp from the first thermal cycle - magnet `sub_2`

First Features Study

- The results presented here refers to data from QA1 antenna for the 23 current ramps of the 1st thermal cycle
- Considered three groups of features: **voltage** features, **signal** features and **frequency** features.
  - Voltage: `max_volt`, `min_volt`, `norm`, `abs_max`, `diff_t_Mm`, `full_integral`, `arclen`
  - Signal: `time_80`, `time_50`, `time_20`
  - Frequency: `occ_1000`, `cwt_lead`, `num_peaks`

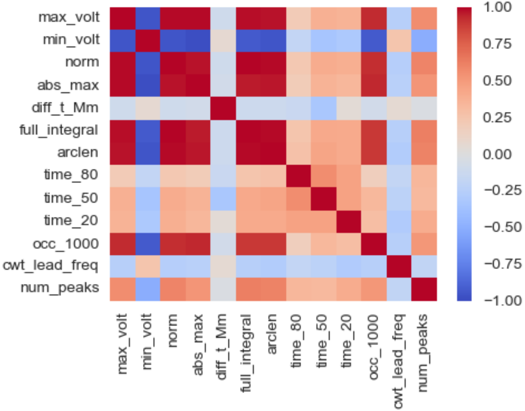


Figure 7: Heat-map of the correlation matrix for the mentioned features. We are looking for non-correlated features.

Principal Component Analysis

- Principal Component Analysis (PCA) for dimensional reduction: all features are taken into consideration
- particularly important due to the data set size
- PCA retaining at least 90% of the information
- Explained Variance Ratio (EVR):
  - Comp_1 : 0.650817
  - Comp_2 : 0.140681
  - Comp_3 : 0.094779
  - Comp_4 : 0.046818

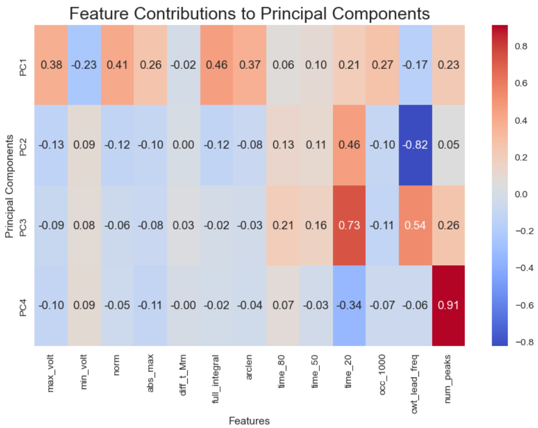


Figure 8: Heatmap representing features contributions to each PCA component

K-means clustering

- Clustering performed over all events identified along 1 complete thermal cycle (`sub2`, thermal 1 - 23 ramps)
- Final choice for number of clusters determined using:
  - Silhouette Score: 4 clusters (0.748)
  - Number of negative silhouette score: 4 clusters (5 points)
  - K-Elbow: 4 clusters
  - WSS cross validation: 4 clusters (WSS score of 18.16)

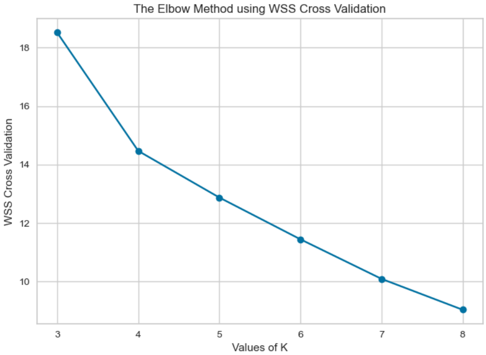
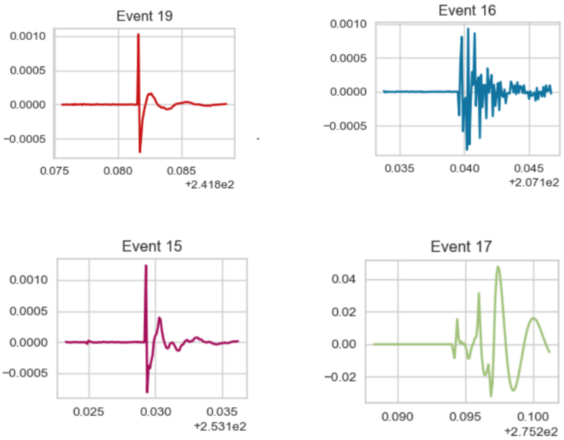


Figure 9: K-Elbow plot

Clustering results



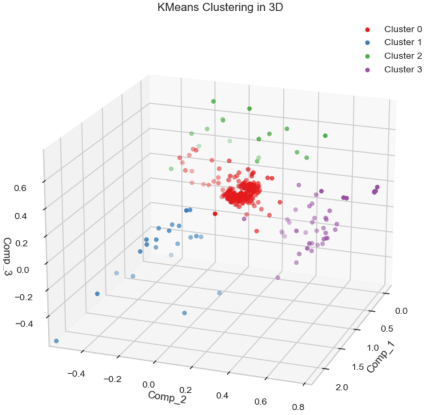


Figure 10: 3D cluster representation in PC space

Event Samples from clustering

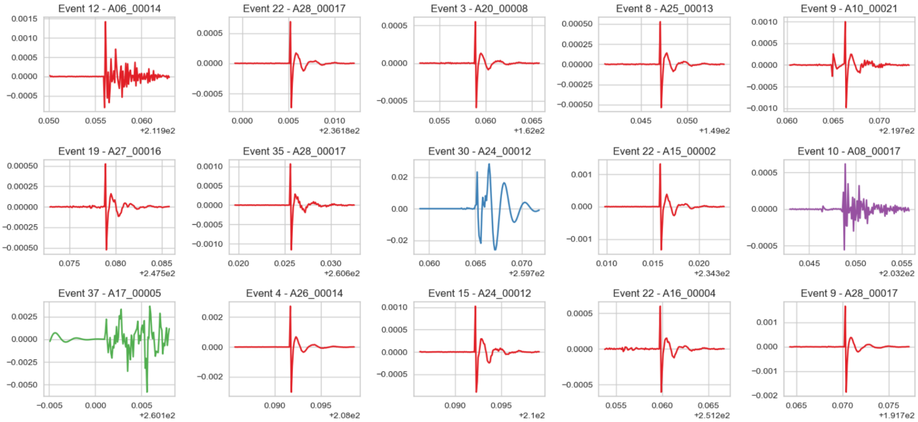


Figure 11: Samples of events from different ramp from the first thermal cycle - magnet sub 2 after clustering

Feature boxplots

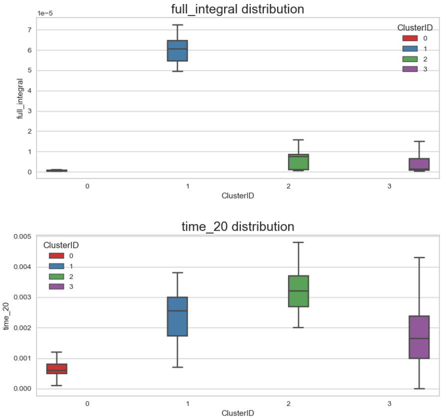


Figure 12: Boxplot of the integral value and of the time at which the 20% of the maximum voltage is reached in each cluster

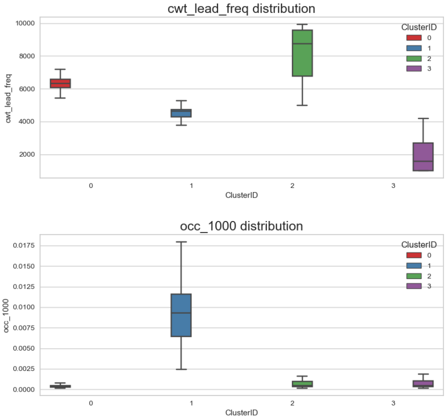


Figure 13: Boxplot of the lead frequency value and of the occurrence of 1kHz frequency in each cluster

Feature distribution across clusters

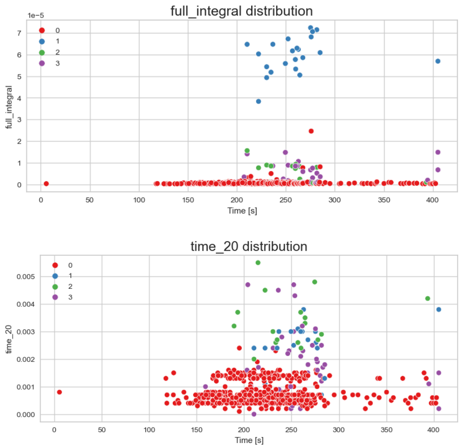


Figure 14: Integral value and reach of 20% of the maximum voltage distribution

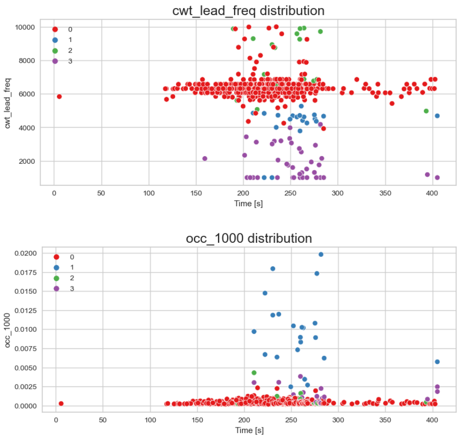


Figure 15: Lead frequency distribution in CWT analysis and occurrence of 1kHz frequency

Cluster distribution in time

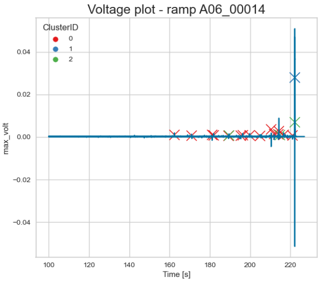


Figure 16: Example of events distribution for ramp A06_00014 - thermal 1

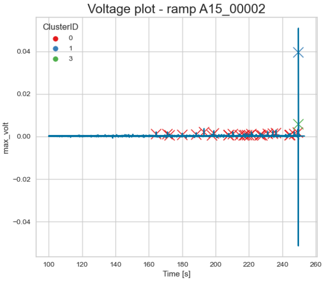


Figure 17: Example of events distribution for ramp A15_00002 - thermal 1

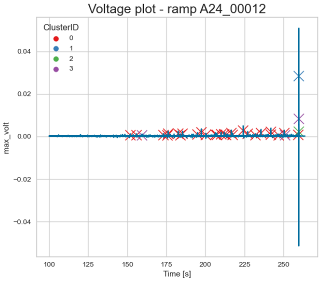


Figure 18: Example of events distribution for ramp A24_00012 - thermal 1

Table of Contents

Results

- Development of a tool that can consistently label events and detect similarity between events
- There is a very large increase in events in `sub2` after the thermal cycle, which needs to be better understood
- Remarkably similar events which has implications on the underlying disturbances better understanding is needed in the future
- The low number of events in QA3 and QA4 are likely due to the orientation of antennas with respect to the field direction
- `sub4` virgin ramp shown to have more events than the baseline magnet, as a result of the impregnation material mechanics

What's next

- Physics:
  - More work is necessary to understand the variation of clusters across the magnet data
  - Try to locate the signal source
  - Compare properties and feature of the two magnets `sub2` and `sub4`
- Algorithm:
  - Using both acoustic and quench antenna data to improve results
  - Test different clustering techniques to improve efficiency and flexibility of the model
  - Improve hyper-parameter tuning depending on different data features
  - Try to implement an adaptive algorithm

Thank You!

References I

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Feature distribution along ramps

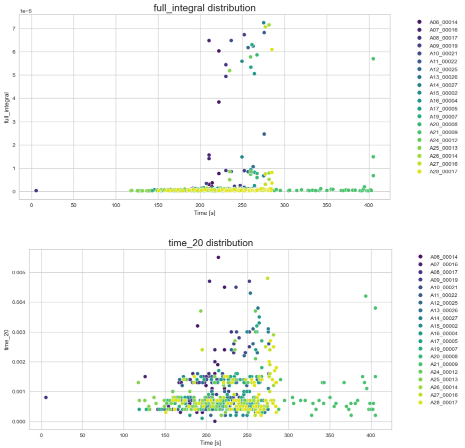

Figure 19: Example of feature distribution along different ramps

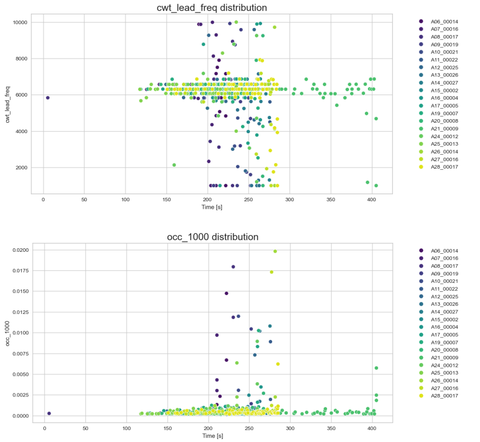

Figure 20: Example of feature distribution along different ramps

Dataset details

Data from two different CCT subscale magnets from LBNL

`sub2`: standard epoxy impregnated magnet

- 3 different thermal cycles
- 3 different sampling frequency: 10 kHz, 20 kHz, 25 kHz respectively for the 1st, 2nd, 3rd thermal cycle
- data from all antennas (QA1 - QA6)

`sub4`: epoxy-non-epoxy impregnated magnet

- 1 thermal cycle
- sampling frequency: 25 kHz
- data coming from antenna QA1 - QA5

Global signal analysis details

- different threshold depending on the sampling frequency
- different filters:
  - **sub2**: high pass filter with 4500 Hz cutoff frequency
  - **sub4**: band stop filter with 4000 - 5000 Hz cutoff frequency
- different thresholds:
  - 0.5 mV for 10 kHz and 20 kHz
  - 1 mV for 25 kHz sampling frequency

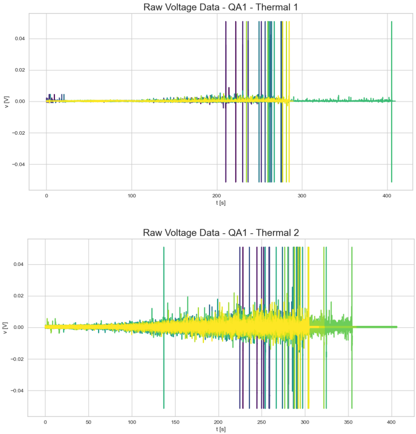

Figure 21: Raw data registered from QA1 for ramps in different thermal cycle