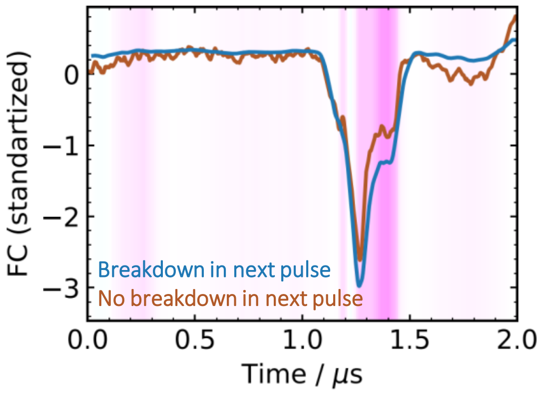
CERN

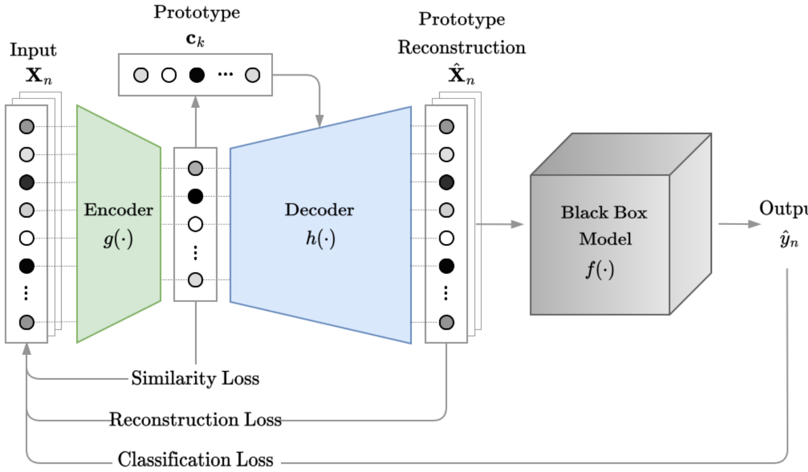
My Ph.D.: Interpretable Fault Prediction

Ph.D. finish line: 19th of January

Main contribution:

- Breakdown prediction in CLIC RF cavities
  - **Field emitted current** following an initial breakdown is related to the **probability of another breakdown** occurring
  - C. Obermair et al., “Explainable Machine Learning for Breakdown Prediction in High Gradient RF Cavities”, PRAB, 2022
- Interpreting ML models for fault prediction
  - **Novel method** for explaining fault predictions with ML, evaluation with **75 people from CERN** and TU Graz
  - C. Obermair et al., “Example or Prototype? Learning Concept-Based Explanations in Time-Series”, PMLR, 2022
- Interpretable Anomaly Detection in the LHC Main Dipole Circuit
  - Understand **normal behavior** and detect **non-normal behavior** in voltage measured at the diode after a FPA
  - C. Obermair et al., “Interpretable Anomaly Detection in the LHC Main Dipole Circuits with Non-negative Matrix Factorization”, to be submitted to IEEE, 2024





Interpretable Anomaly Detection in the LHC Main Dipole Circuit with Non-Negative Matrix Factorization

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Acknowledgement:
Andrea Apollonio, TE-MPE-CB
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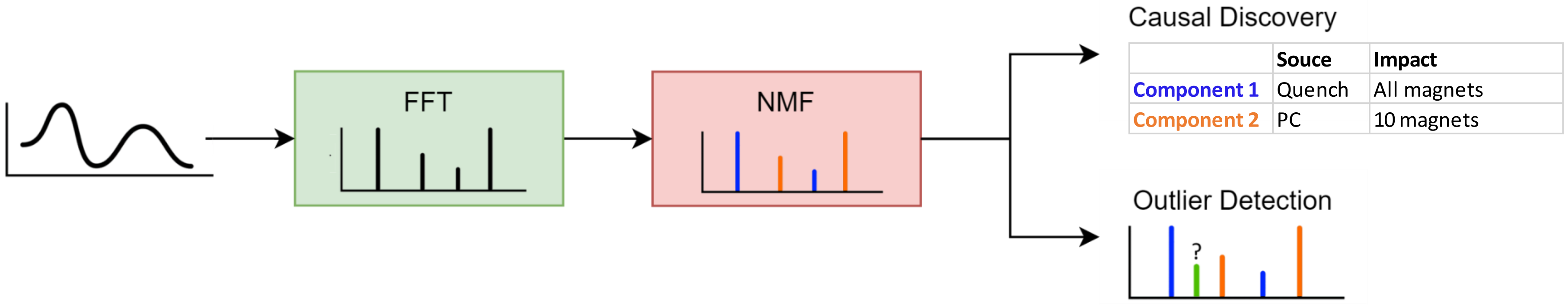
Daniel Wollmann, TE-MPE-CB
Mariusz Wozniak, TE-MPE-PE

Outline

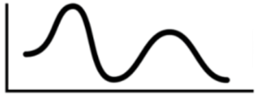
Goal: Define and understand **normal** behavior, detect **abnormal** behavior of the main dipole (RB) circuit

Approach:

1. Extract **frequencies** in data → **Fast Fourier transform (FFT)**
2. Group expected frequencies that occur together into **components** → **Non-Negative Matrix Factorization (NMF)**
    a) **Components** help to understand **normal** behavior → **Causal Discovery**
    b) Deviations help to detect **abnormal** behavior → **Outlier detection**



Select data



Signal:

- U_diode from nQPS in PM

Region:

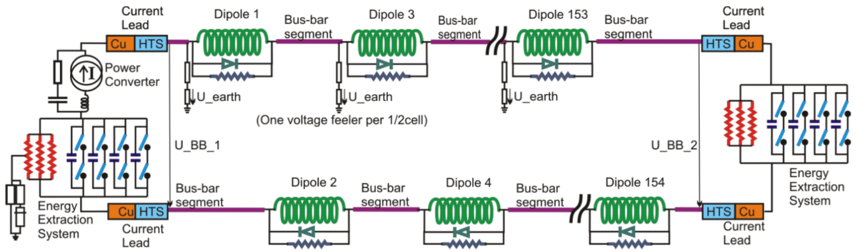
- Plateaus after energy extraction
  → Similar to transient measurement

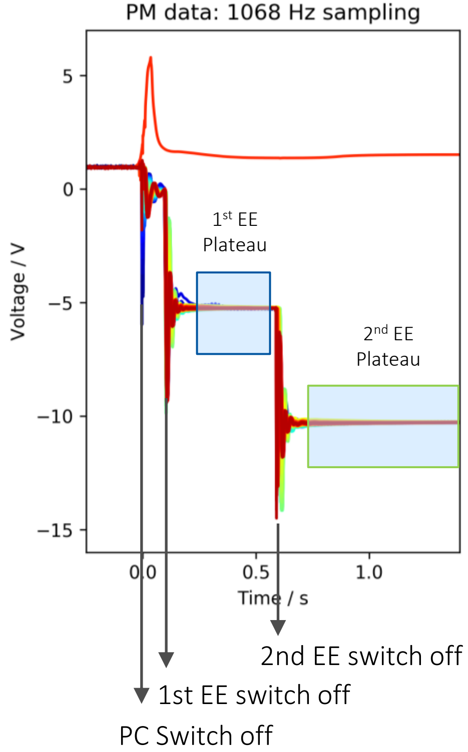
Period:

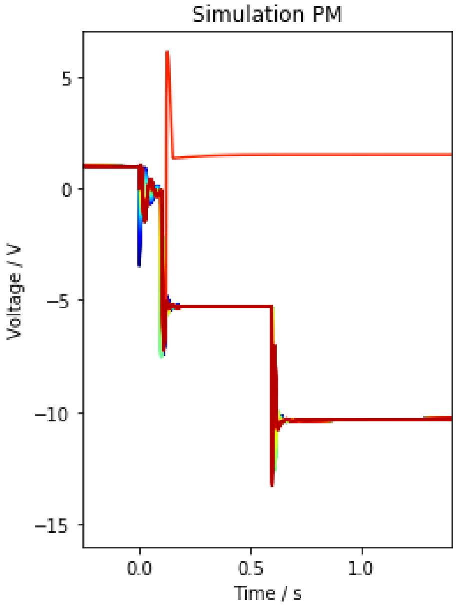
- 2018, Quench + Snapshot data

Data size:

- **731** events x **154** magnets x **400** samples (0.375s)



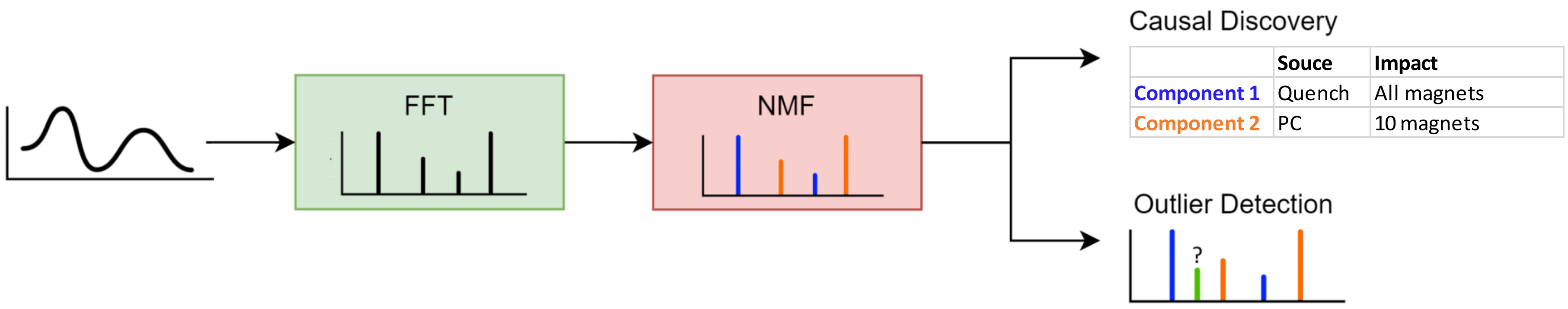




*simulations done by Marvin Janitschke with STEAM framework

Fast Fourier transform

Extract **frequencies** in data

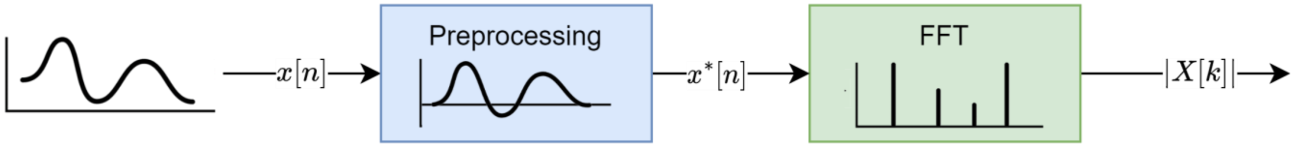


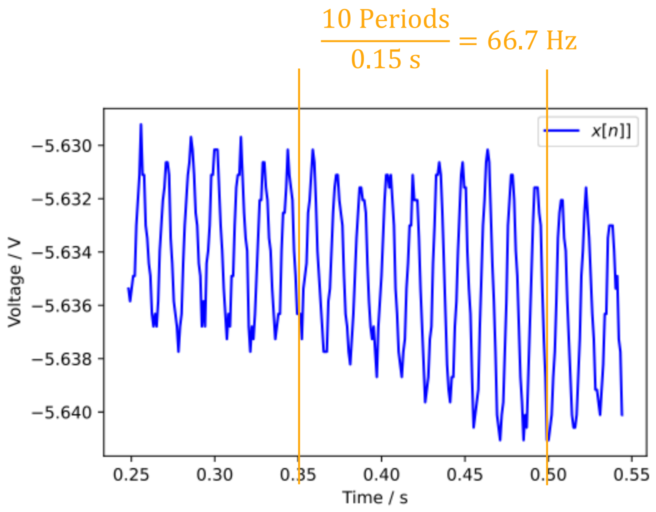
Fast Fourier transform

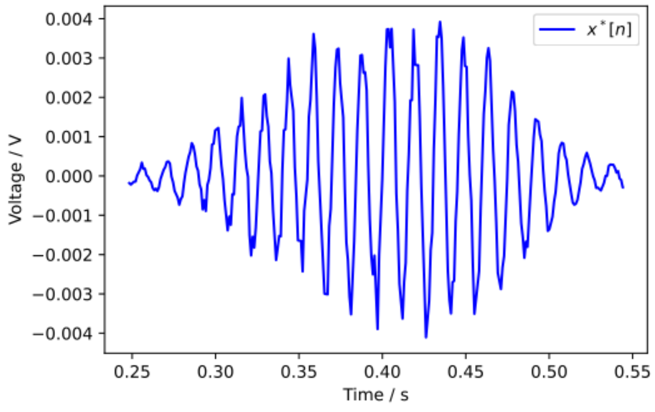
Example signal: B21R3 on 2021-04-18 08:44:17

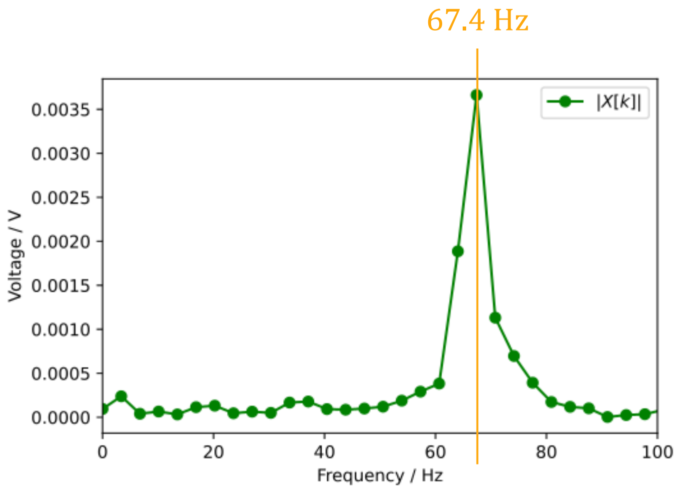
Preprocessing necessary to minimize spectral leakage:

- Subtract offset
- Multiplication with window

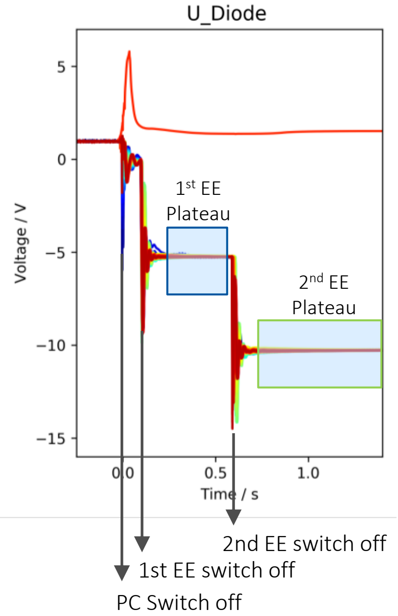


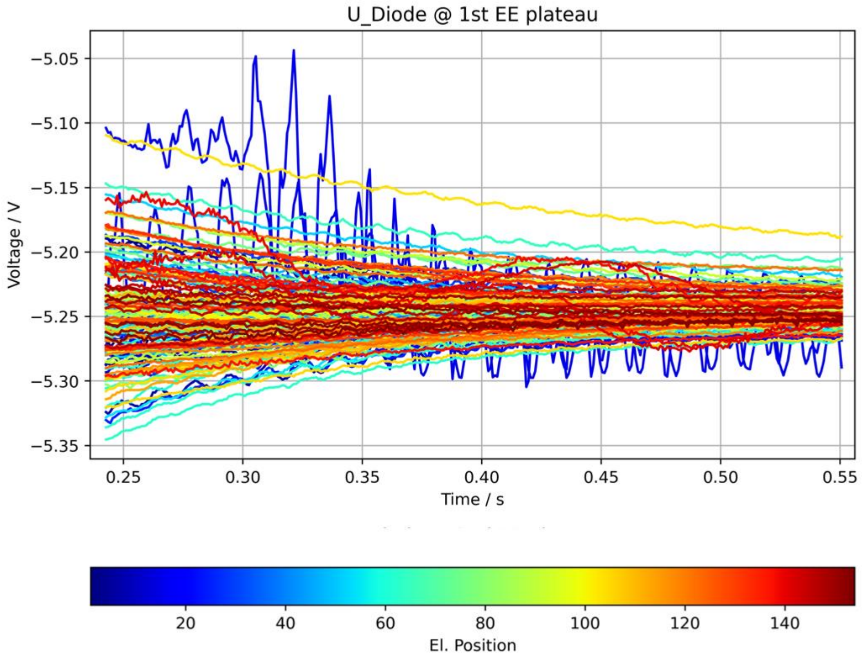






Frequency Position Maps (FPM)

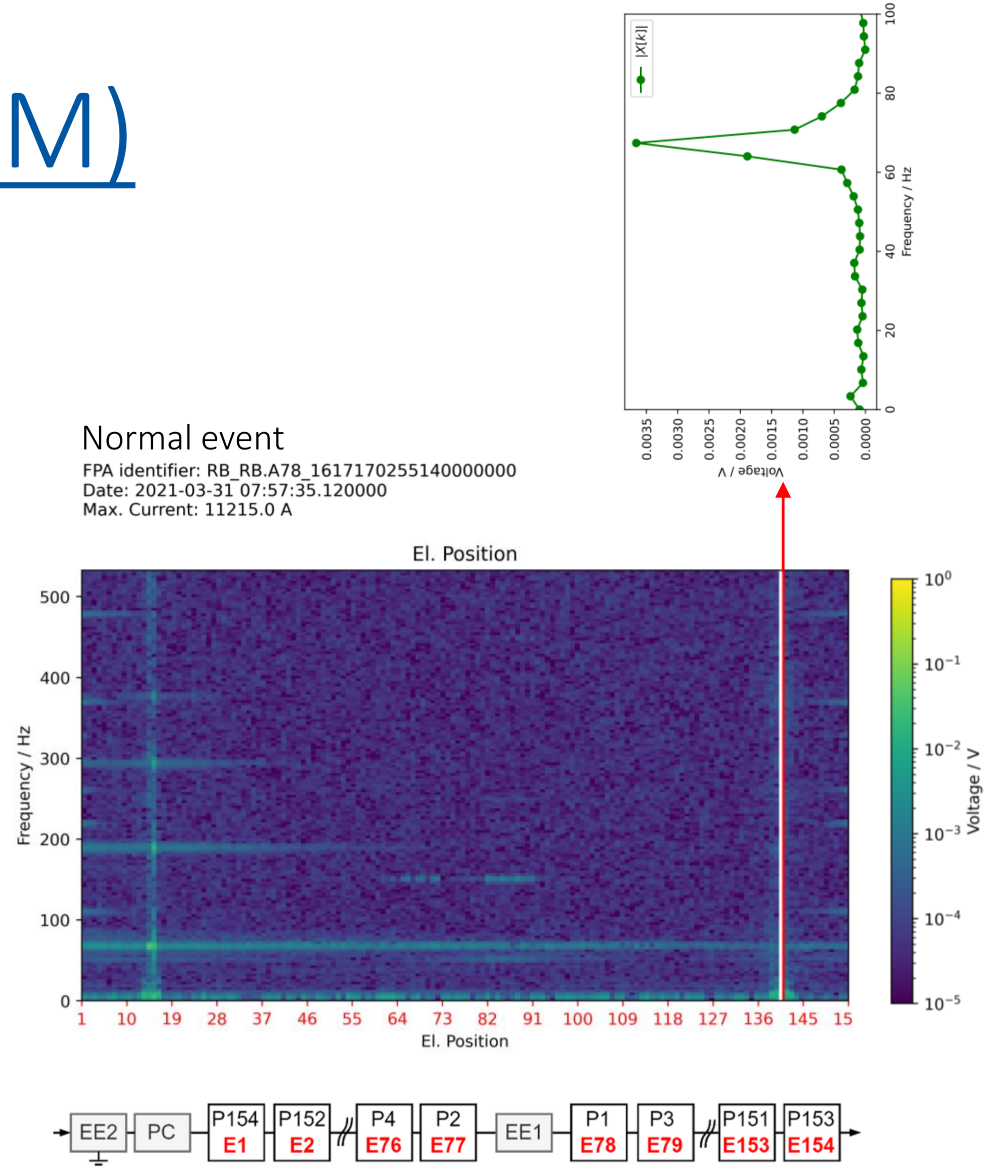




fft

Normal event

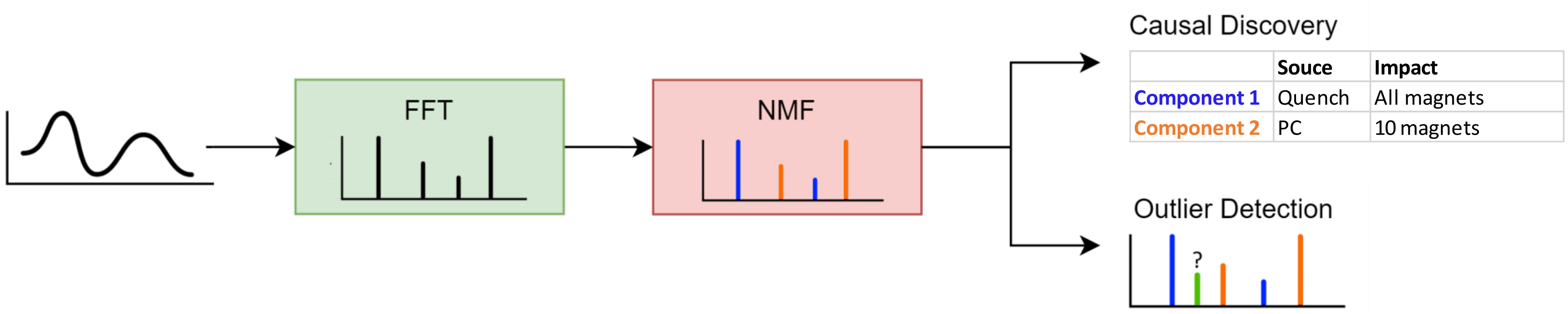
FPA identifier: RB_RB.A78_1617170255140000000
Date: 2021-03-31 07:57:35.120000
Max. Current: 11215.0 A



Non-Negative Matrix Factorization (NMF)

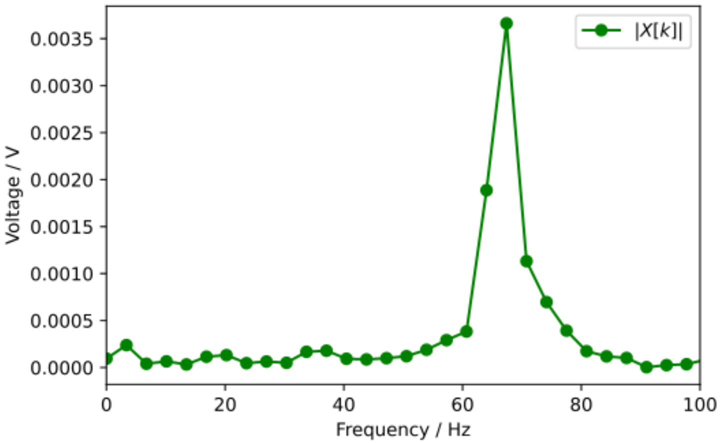
Group expected frequencies that occur together into **components**

a) **Components** help to understand **normal** behavior → **Causal Discovery**
b) Deviations help to detect **abnormal** behavior → **Outlier detection**

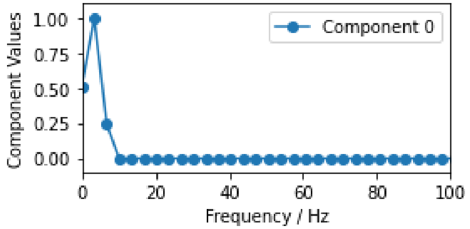


Method

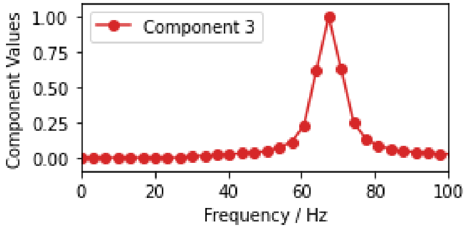
Input $|X[k]|$ $\approx$ $\sum_{k=1}^{r}$ Components W_k $\cdot$ Weights h_k $=$ Reconstruction $|\hat{X}[k]|$



$\approx$

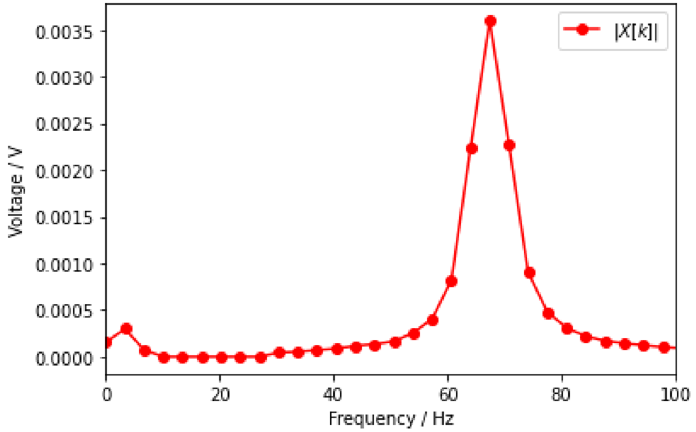


$\cdot$ 0.0003



$\cdot$ 0.0036

$=$

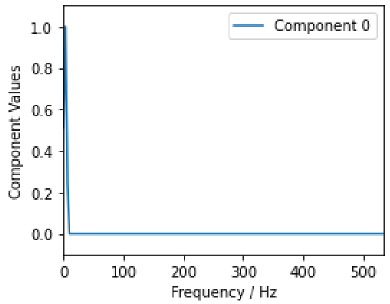
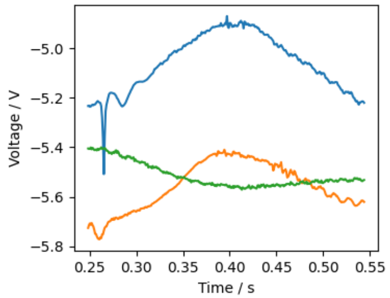
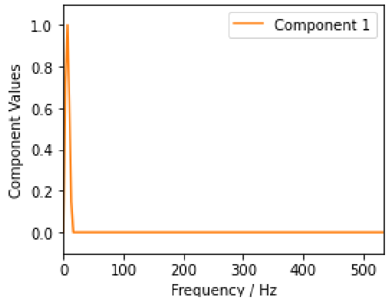
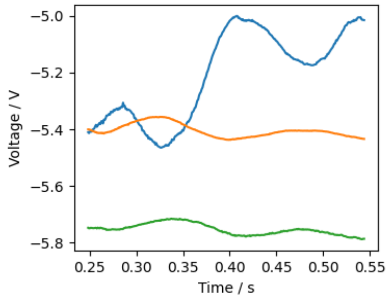
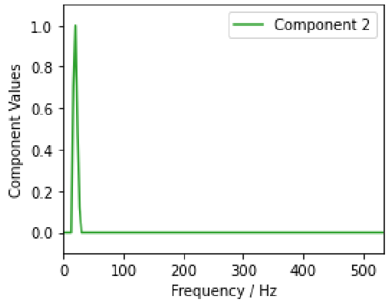
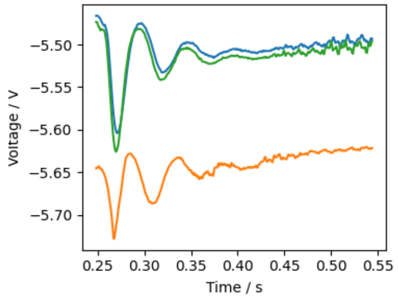


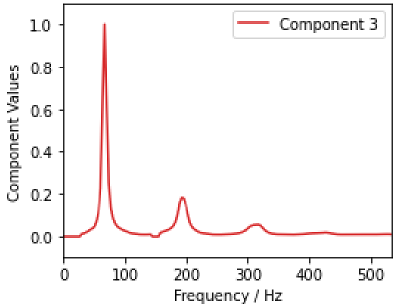
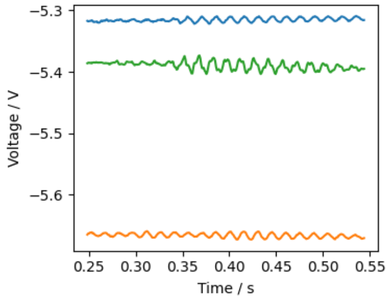
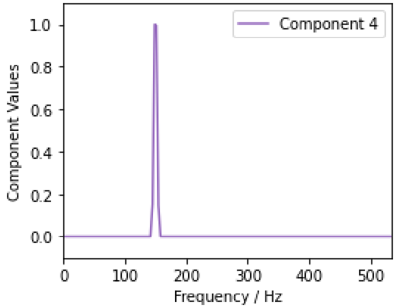
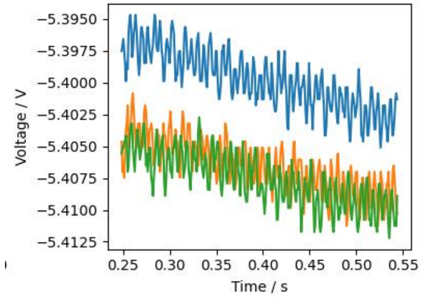
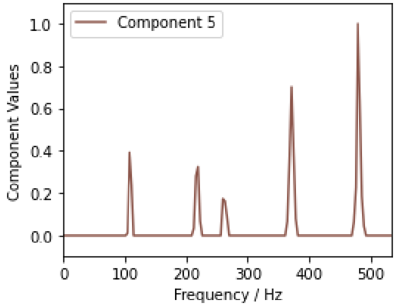
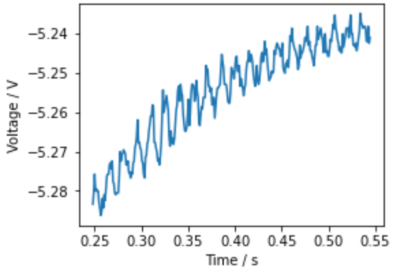
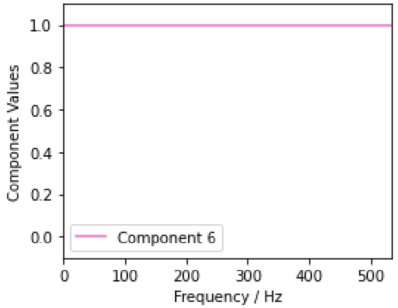
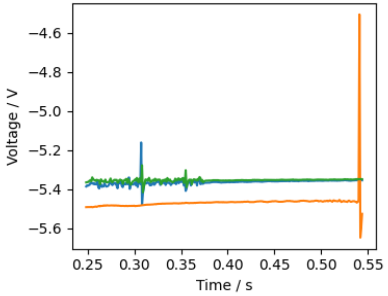
Loss: $\sum_k \left(|X[k]| - |\hat{X}[k]|\right)^2$

How to define W_k & h_k?

1. Manually define r
2. Initialize W_k & h_k randomly
3. Adjust W_k & h_k iterativly until loss over all signals (763 * 154 * 2= 235 004) is minimal

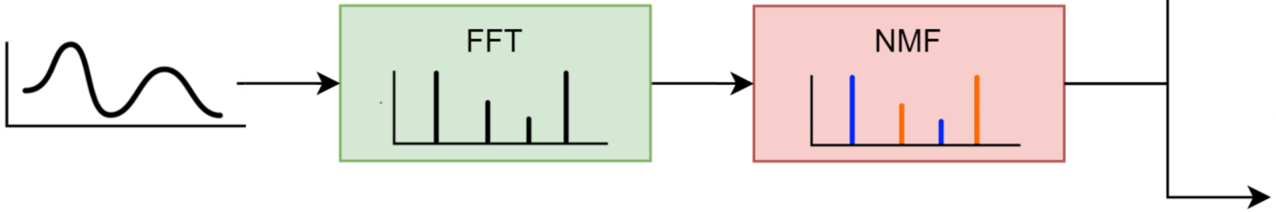
NMF Components

Component Index	Component	3 Event Examples	Dominant Frequencies	Order of magnitude
0*			3 Hz	100mV
1			6 Hz	100mV
2			20 Hz	10mV

<table>
<tr><th>Component Index</th><th>Component</th><th>3 Event Examples</th><th>Dominant Frequencies [Hz]</th><th>Order of magnitude</th></tr>
<tr><td>3</td><td>
</td><td>
</td><td>67 Hz
184 Hz
302 Hz</td><td>100mV</td></tr>
<tr><td>4</td><td>
</td><td>
</td><td>148 Hz</td><td>1mV</td></tr>
<tr><td>5</td><td>
</td><td>
</td><td>107 Hz
220 Hz
260 Hz
370 Hz
478 Hz</td><td>0.1mV</td></tr>
<tr><td>6</td><td>
</td><td>
</td><td>Any</td><td>100mV</td></tr>
</table>

Causal Discovery

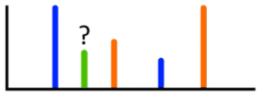
Understand **normal** behavior



Causal Discovery

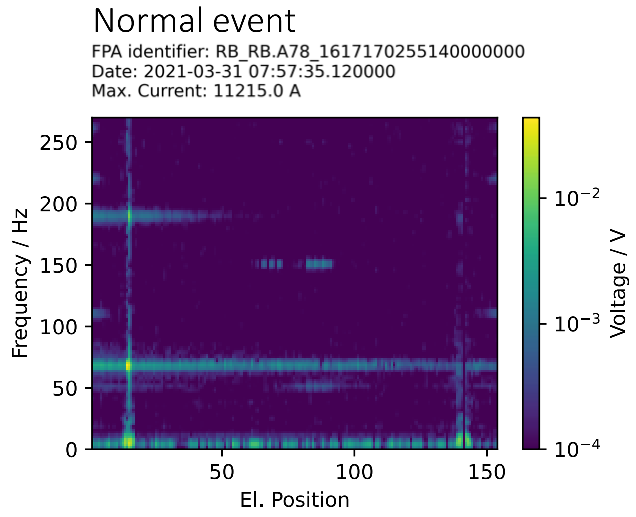
	Souce	Impact
Component 1	Quench	All magnets
Component 2	PC	10 magnets

Outlier Detection



Causal Discovery

Frequency **components** along all magnets in event



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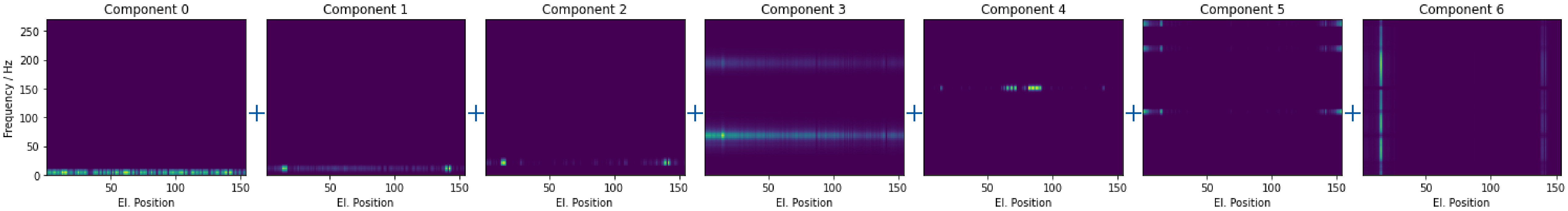


3Hz

Electromagnetic perturbation + FFT smiring

Source Direction: Quench

Propagation: Physical

6Hz

Electromagnetic perturbation

Source Direction: Quench

Propagation: Physical

20Hz

Left over of voltage wave traveling along the chain of magnets by magnet inductance

Source Direction: Quench

Propagation: Physical

65Hz

Oscillations caused by quench

Source Direction: Quench

Propagation: Electrical

143Hz

Repetitive pattern within QPS crate, aliasing?

Source Direction: Quench

Propagation: QPS crate position

478Hz

Oscillations from the direction of Power converter in RB.A78, aliasing?

Source Direction: Power converter in RB.A78

Propagation: Physical

Offset

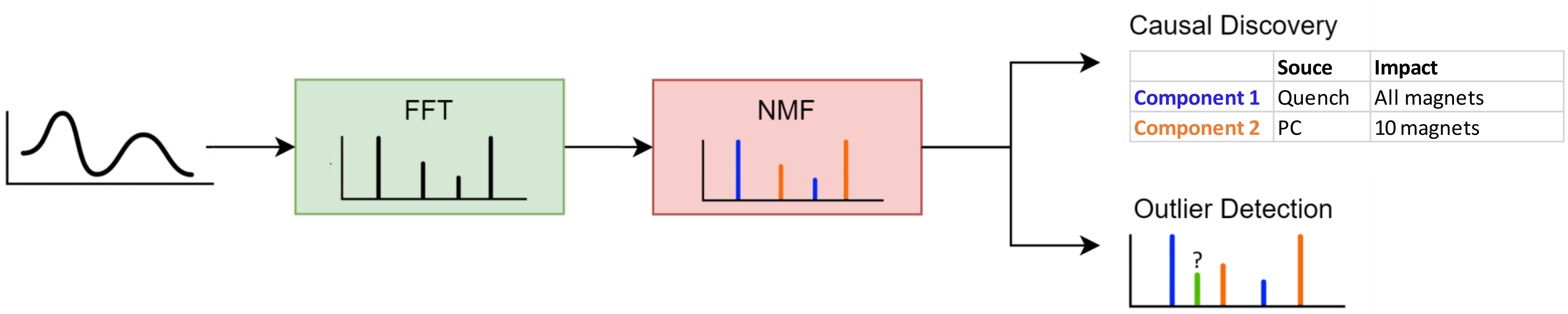
Oscillations caused by quench

Source Direction: Quench

Propagation: Physical

Outlier Detection

Detect **abnormal** behavior



Outlier Detection

Components state frequencies, **expected** to occur

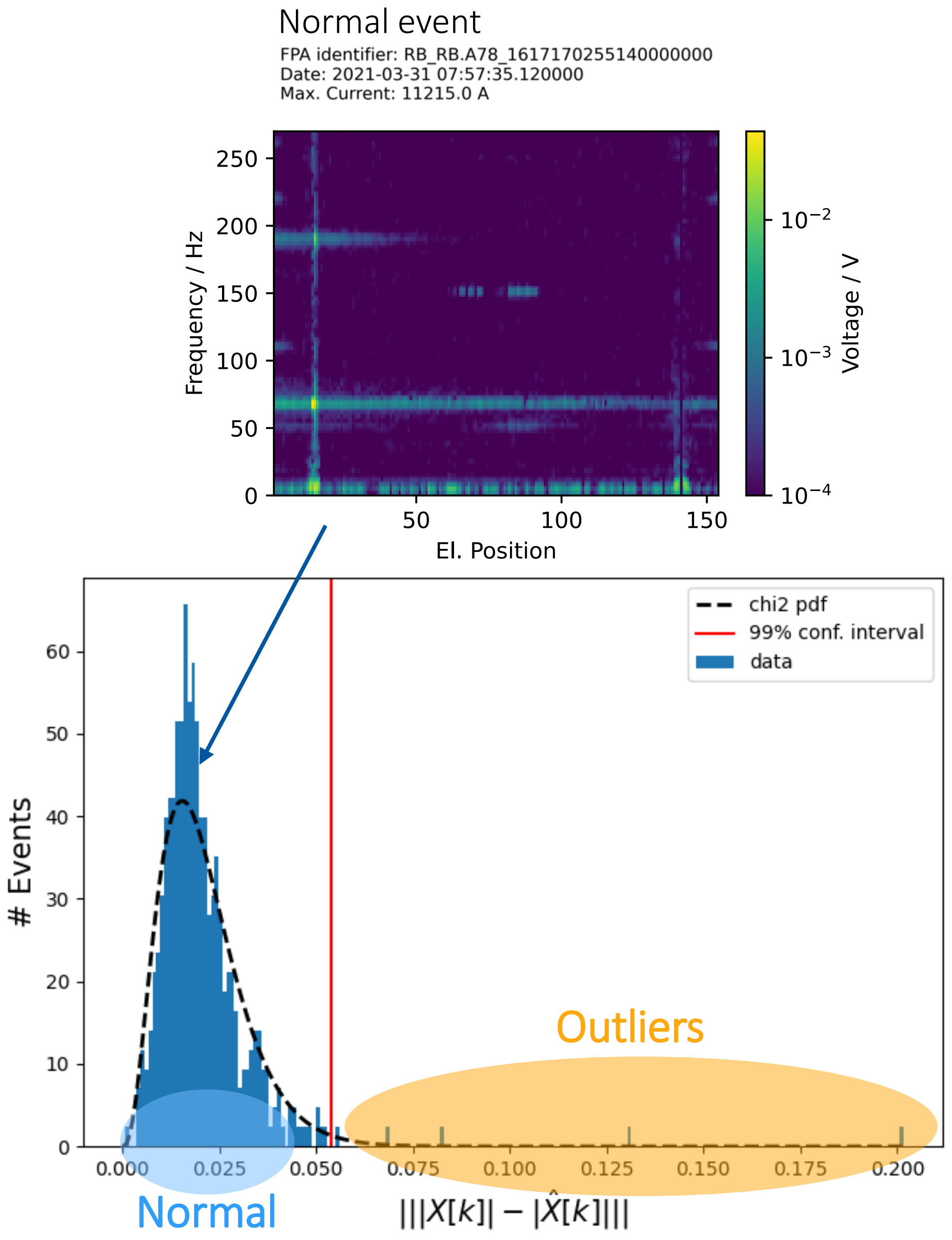
Normal event: Reconstruction with components possible (low loss)

Outlier event: **Unexpected** frequencies occur (high loss)

How to find an outlier:

1. Calculate NMF loss for each event (763)
2. Fit gamma distribution to loss
3. Calculate p value for each event (763)

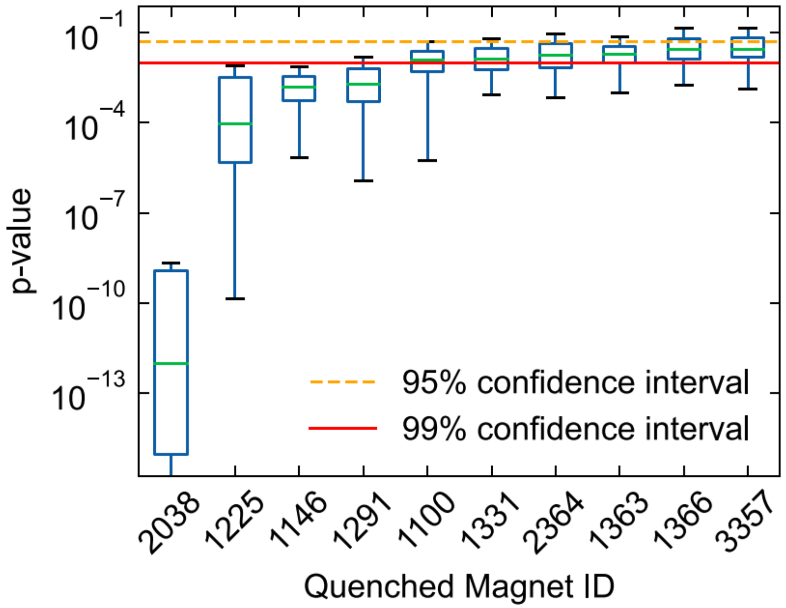
   → probability of obtaining results at least as extreme as the observed



Outliers

Goal: Find outliers robust to assumptions

- Result shows boxplot of 280 different combinations of assumptions
- All outliers occur during 1st EE Plateau → closer in time to quench



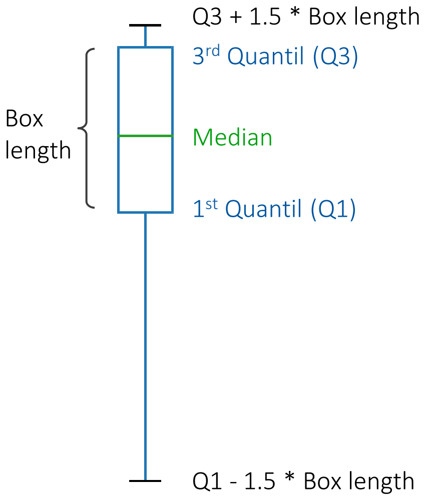


TABLE II
LIST OF DETECTED ANOMALIES WITH DERIVED MAINTENANCE ACTIONS.

Anomaly #	QM ID	Median p-value	Comp. 7 at QM	Maintenance Actions
1	2038 Sector 78 25.04.2021	8e-11	2.4e-1 V	Exchanged 25.04.2021 (Intermittent Short Circuit)
2	1225 Sector 45 12.05.2021	7e-5	8.0e-2 V	Add. Measurements Repl. Measurement Unit Ev. Repl. Magnet
3	1146 Sector 34 06.05.2021	1e-3	8.2e-4 V	Add. Measurements
4	1291 Sector 12 14.05.2021	2e-3	2.1e-1 V	Add. Measurements Repl. Measurement Unit Ev. Repl. Magnet
5	2421 Sector 34 20.04.2021	-	1.2e0 V	Add. Measurements Repl. Measurement Unit Ev. Repl. Magnet

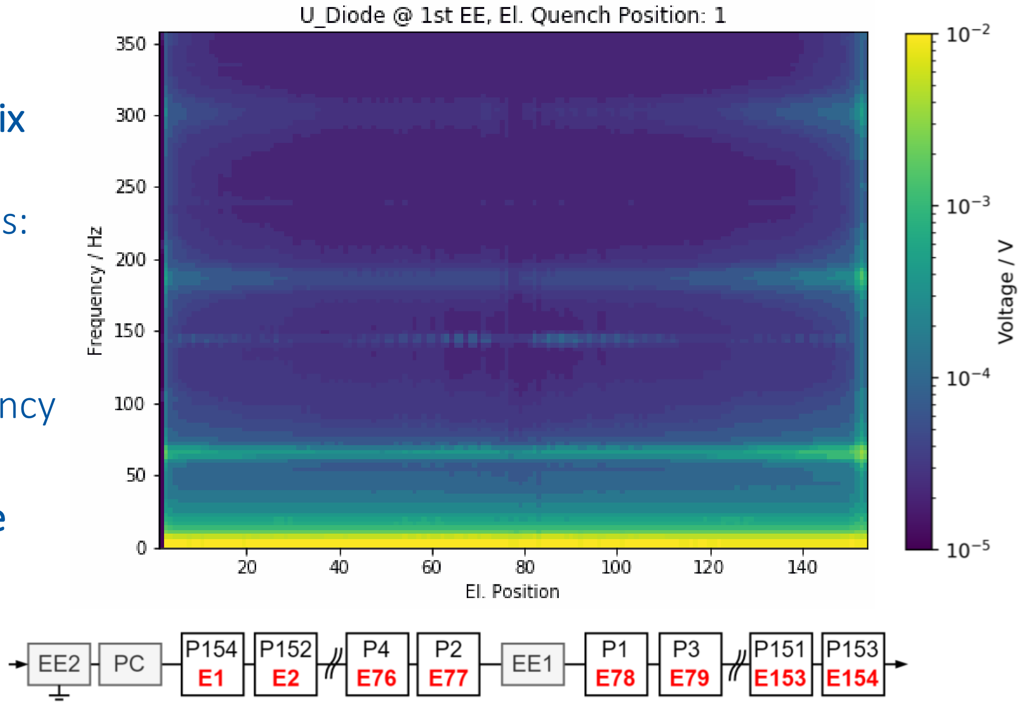
Conclusion

Causal Discovery:

- Detection of "normal" frequency components with **Non-Negative Matrix Factorization**
  → Depending on the quench position, a typical FPM would look like this:

Outlier Detection:

- Outliers are **events** which cannot be composed out of "normal" frequency components
- Ongoing additional **measurements, additional safety measures, possible replacement**

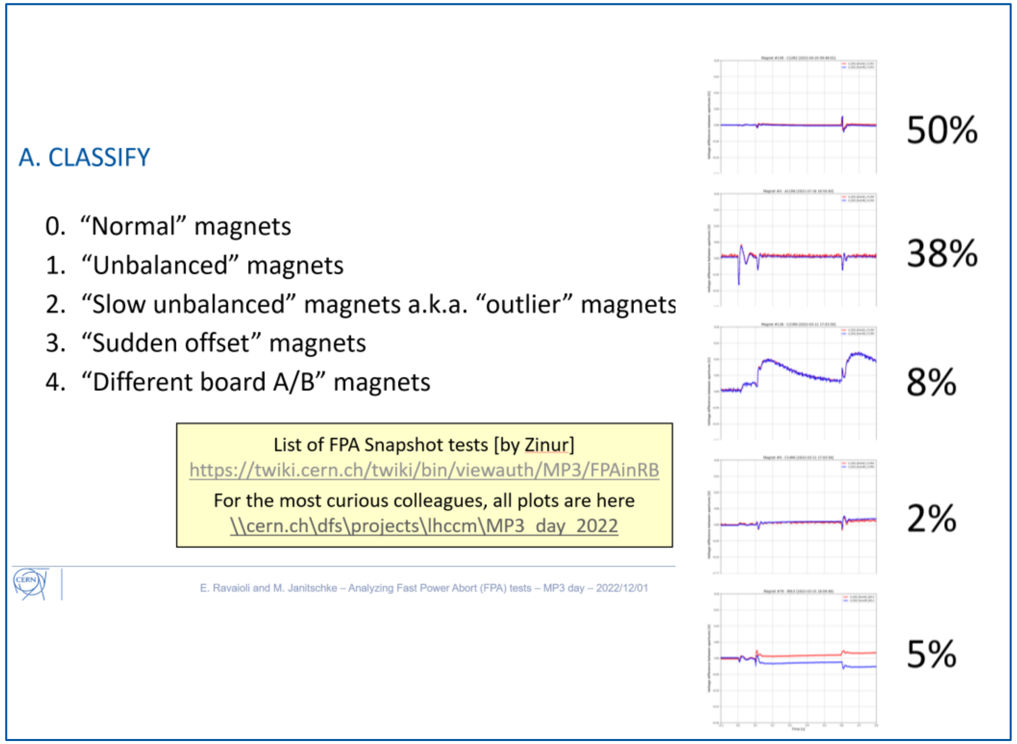


Next Steps

Understand where **experts** can profit from data analysis!

Ongoing ML projects:

- U_diode NXCALS data
  - Investigation of secondary quenches
- mb-feature-classification
  - Make decisions: Gather RB machine parameters and analysis results
  - Find correlations with ML
- UQS0 signal classification
  - Classify ~35000 UQS0 signals from snapshot FPAs similar as experts
  - 80% of signals are classified similarly
  - In the remaining 20%, ML was right in 90%
- SOH prediction in capacitor banks
  - Assisting Timm Baumann SY/EPC



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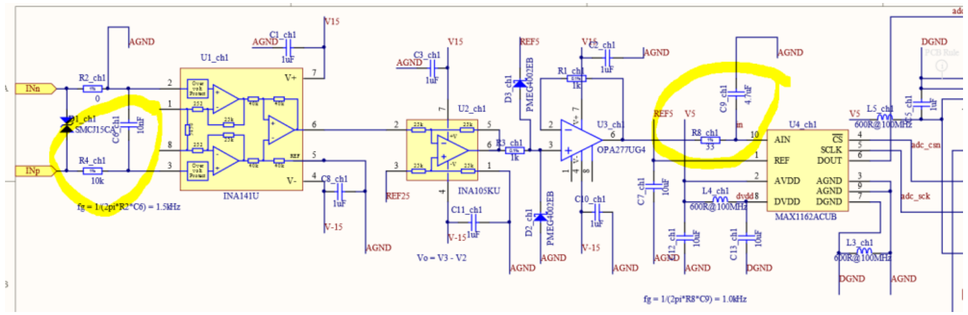
Backup Slides

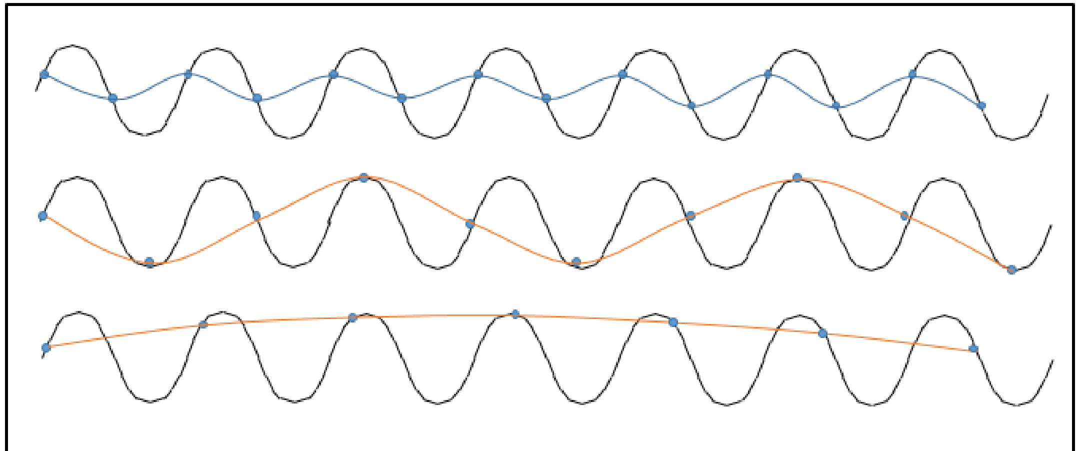
Aliasing

High frequency components could potentially cause **aliasing in results**.

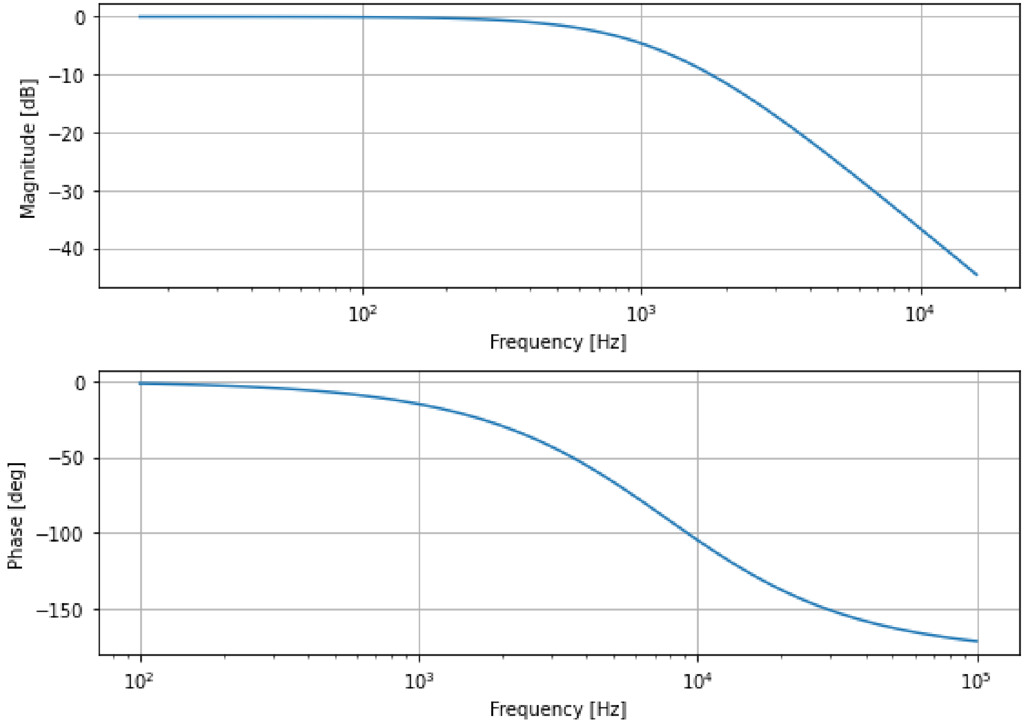
Anti-aliasing filters in the nQPS crates:

- Two 1st order lowpass filters with 1.5 kHz and 1 kHz cutoff frequency*
- Sampling frequency of nQPS crates: 1068 Hz





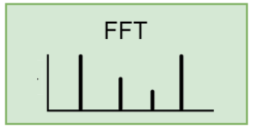
Aliasing Examples



*provided by Jens Steckert

Fast Fourier transform

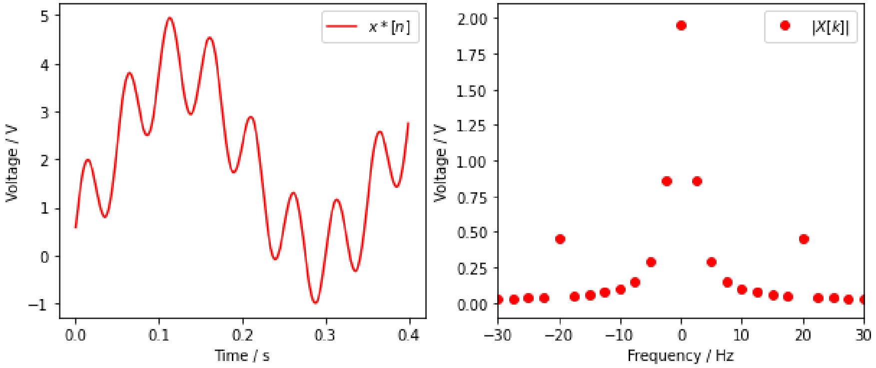
Fast Fourier transform



→ The FFT is an algorithm to calculate the discrete Fourier transform (DFT). The DFT is defined as:

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-i2\pi\frac{nk}{N}}$$

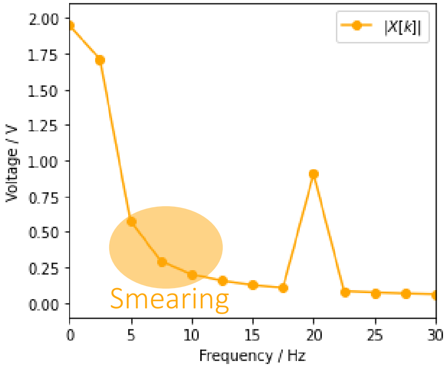
$x[n] = 2\text{V} + 2V * \sin(2\pi\ 3\text{Hz} * n\ - 90°)\ + \sin(2\pi\ 20\text{Hz} * n)$



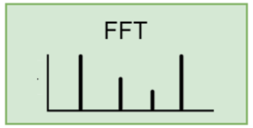
Apply Hilbert transform:
Multiply all but first sample of FFT amplitude with 2

$$z = x + i\text{H}(x)$$

$$\text{where } \text{H}(x) = \begin{cases} -ix, & f > 0 \\ 0, & f = 0 \\ ix, & f < 0 \end{cases}$$

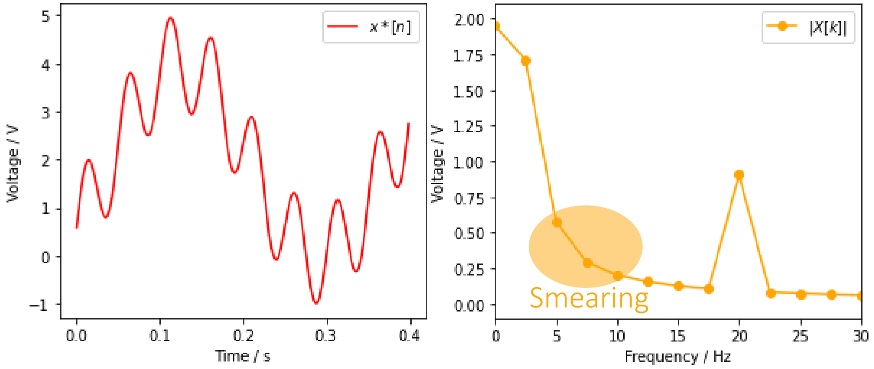


Window data

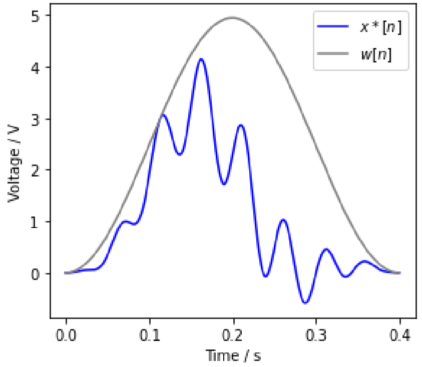


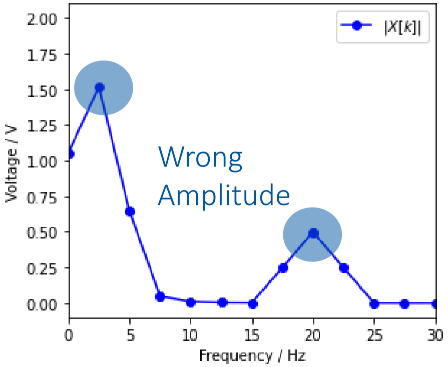
→ Avoid smearing

$$x[n] = 2\text{V} + 2V * \sin(2\pi\ 3\text{Hz} * n\ - 90°)\ + \sin(2\pi\ 20\text{Hz} * n)$$

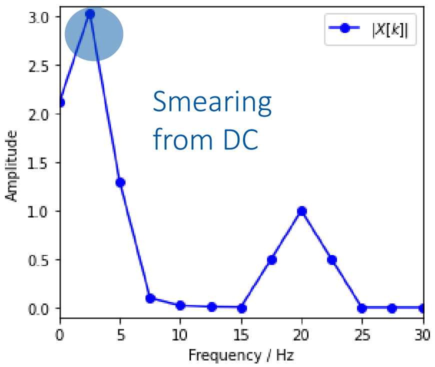


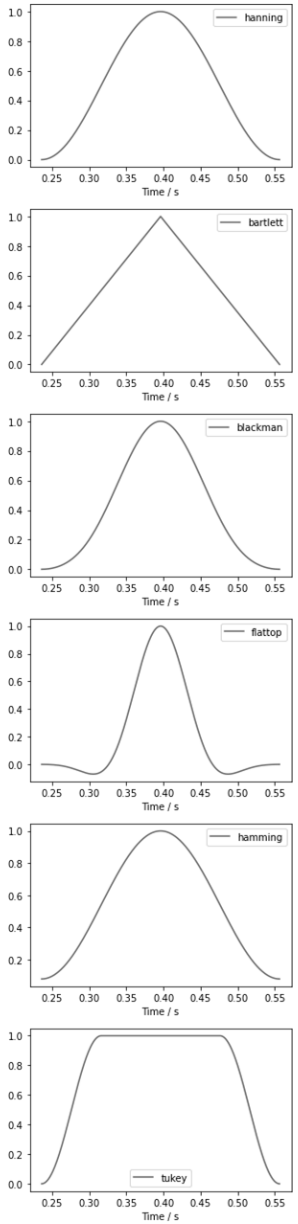
Use Window:
$x^*[n] = x[n] * w[n]$



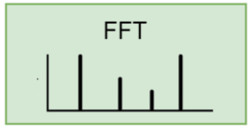


Add Window gain:
Divide $|X[k]|$ with $\frac{1}{\text{N}}\sum_n^N w[n]$



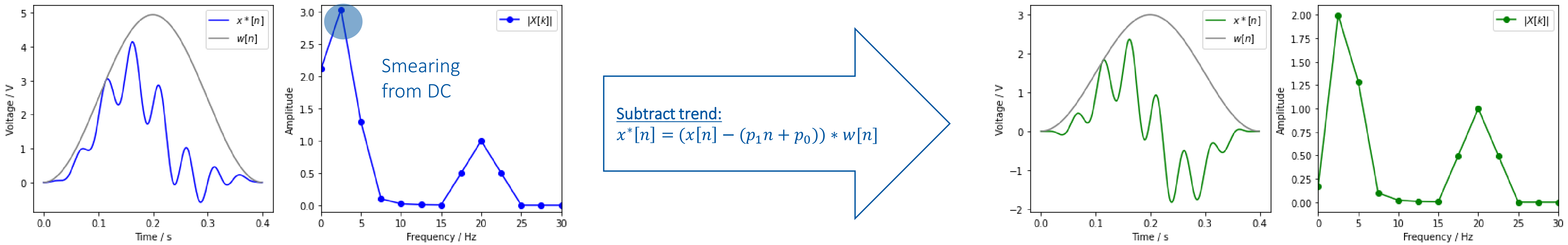


Detrend data



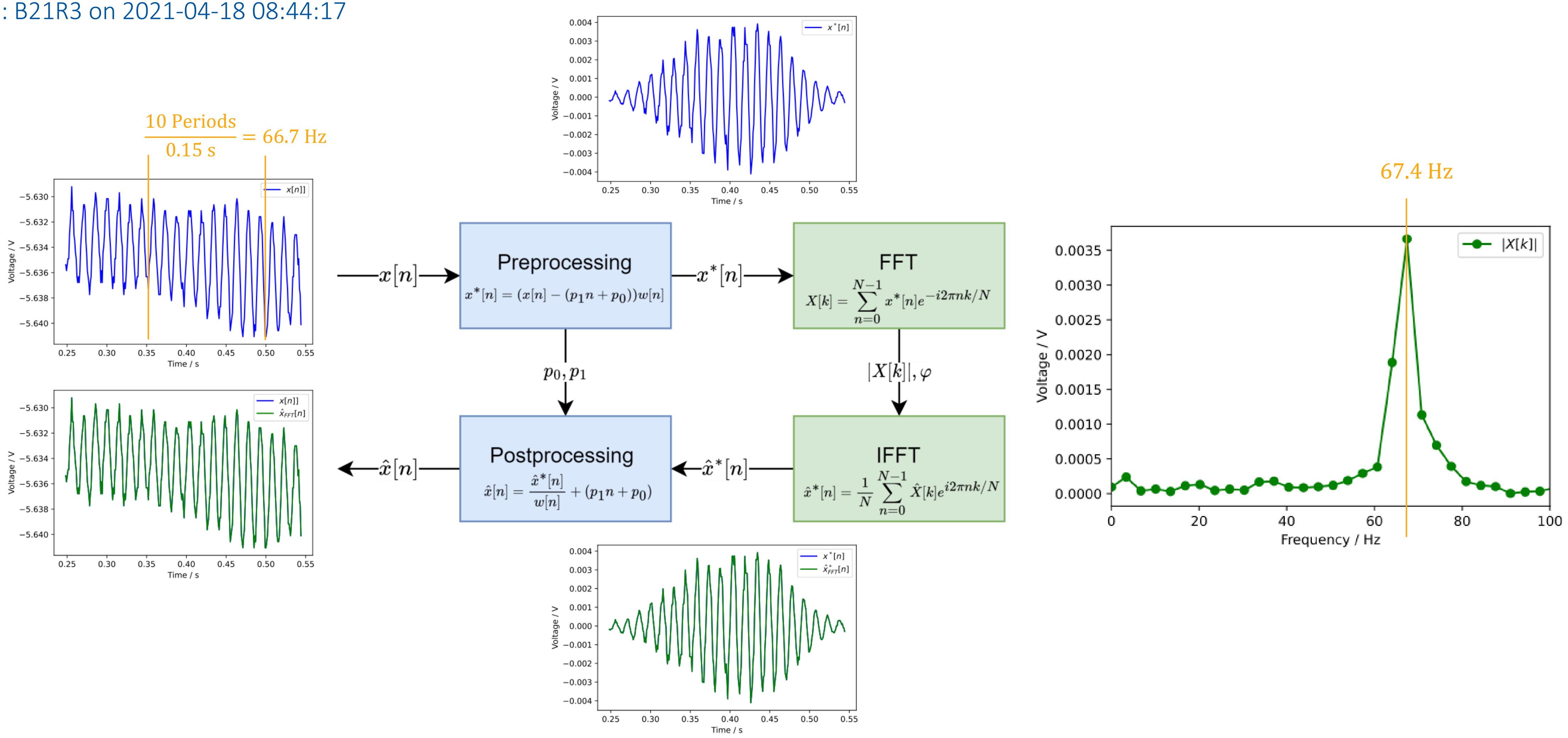
→ Smearing of DC component interferes with low frequency component

$x[n] = 2\text{V} + 2V * \sin(2\pi\ 3\text{Hz} * n\ - 90°)\ + \sin(2\pi\ 20\text{Hz} * n)$



Backwards Path

Signal: B21R3 on 2021-04-18 08:44:17



Non-Negative Matrix Factorization (NMF)

https://www.nature.com/articles/44565
https://proceedings.neurips.cc/paper/2000/file/f9d1152547c0bde01830b7e8bd60024c-Paper.pdf

Objective Function

$V \approx WH$

m ... number of i **events * positions** (560 x 154)

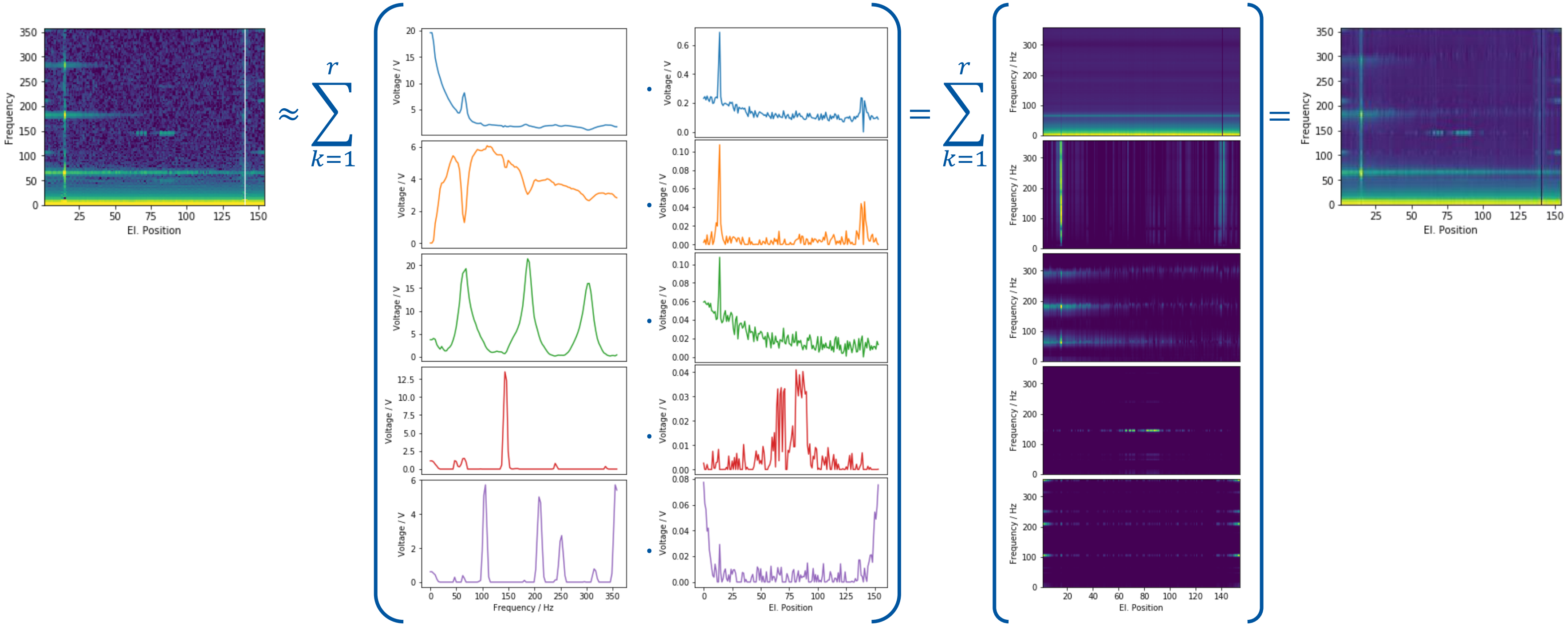
n ... number of **frequencies** (0-360Hz)

r ... number of components (1-5)

$V \in \mathbb{R}_{+}^{n \times m}$ ... reconstructed event at position

$W \in \mathbb{R}_{+}^{n \times r}$ ... components

$H \in \mathbb{R}_{+}^{r \times m}$... presence of components

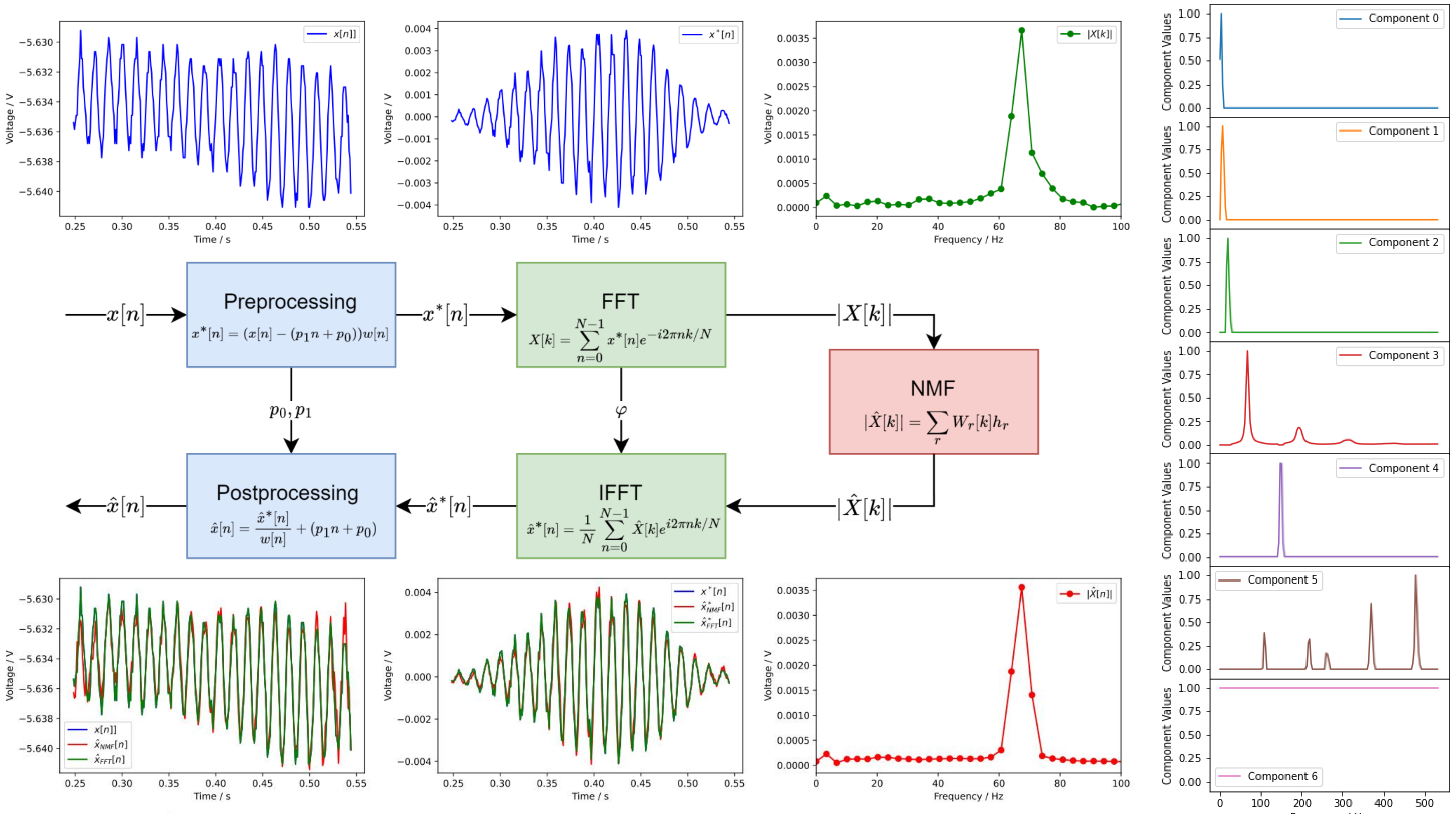


NMF Objective Function:

$$\min_{W,H} f(W,H) \equiv \frac{1}{2}\|V - WH\|_F^2, \text{ s.t. } W,H \geq 0$$

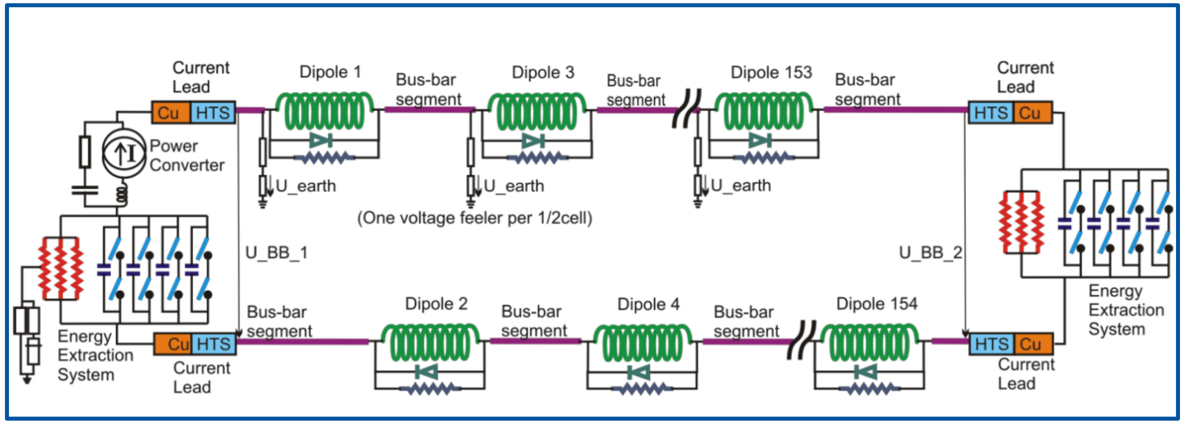
Backwards Path

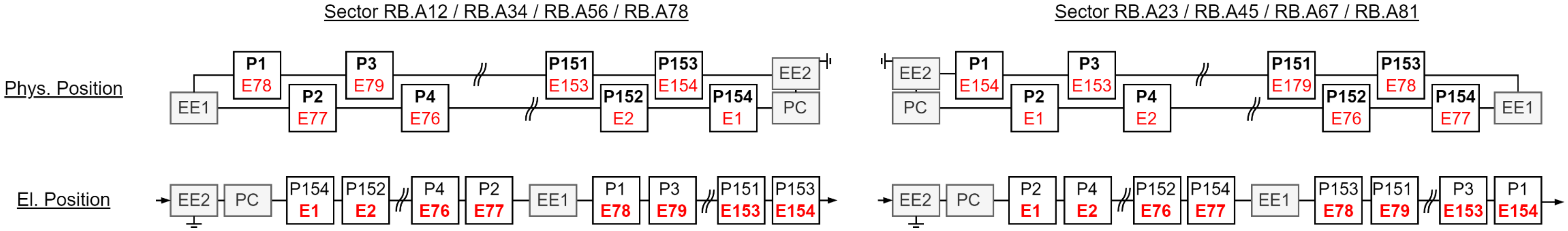
Signal: B21R3 on 2021-04-18 08:44:17



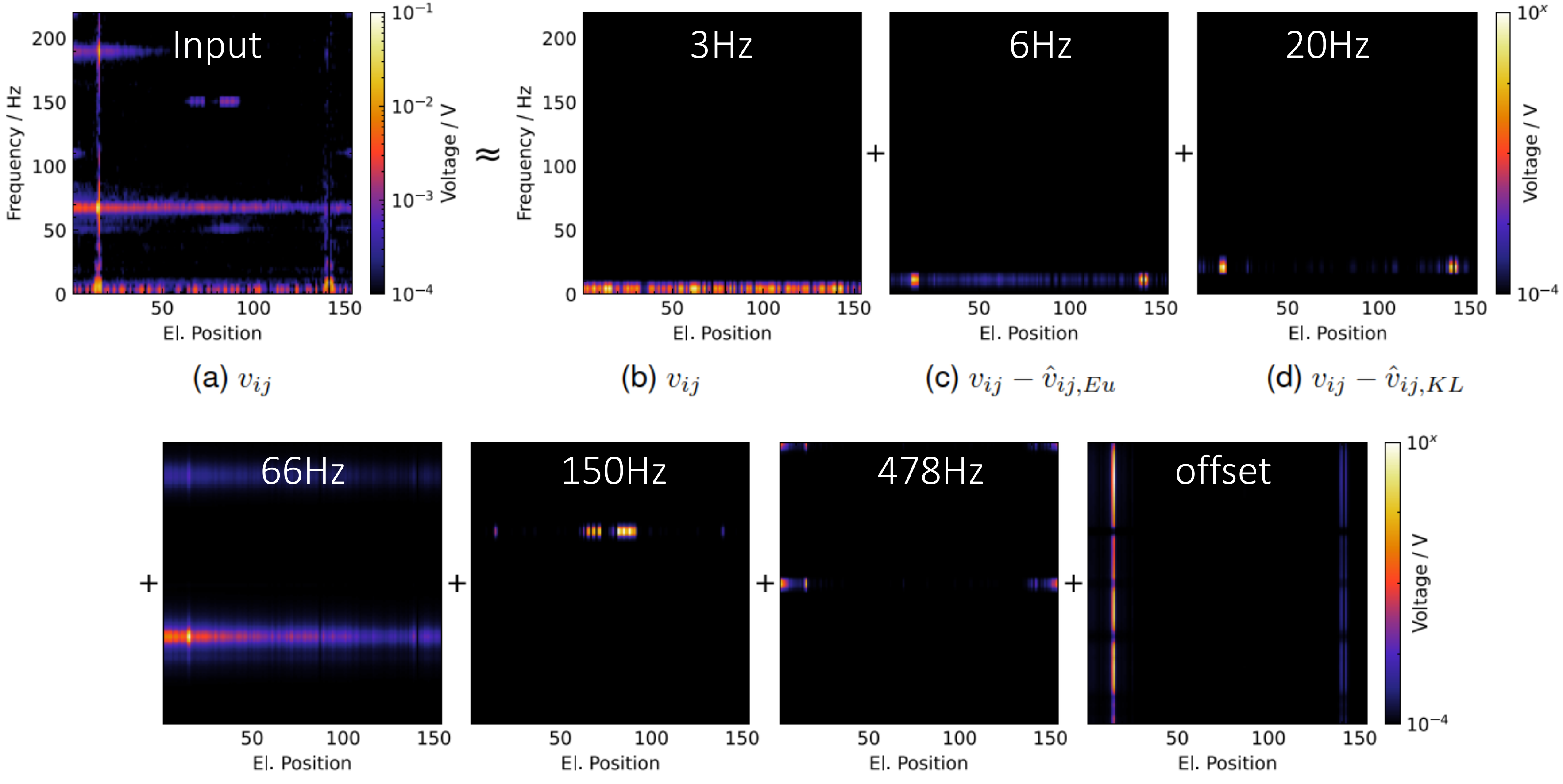
Causal Discovery

El. Vs Phys. Position





U-diode frequencies



(a) v_{ij} (b) v_{ij} (c) $v_{ij} - \hat{v}_{ij,Eu}$ (d) $v_{ij} - \hat{v}_{ij,KL}$

(e) $v_{ij} - \hat{v}_{ij,IS}$ (f) $v_{ij} - \hat{v}_{ij,IS}$ (g) $v_{ij} - \hat{v}_{ij,IS}$ (h) $v_{ij} - \hat{v}_{ij,IS}$

Overview

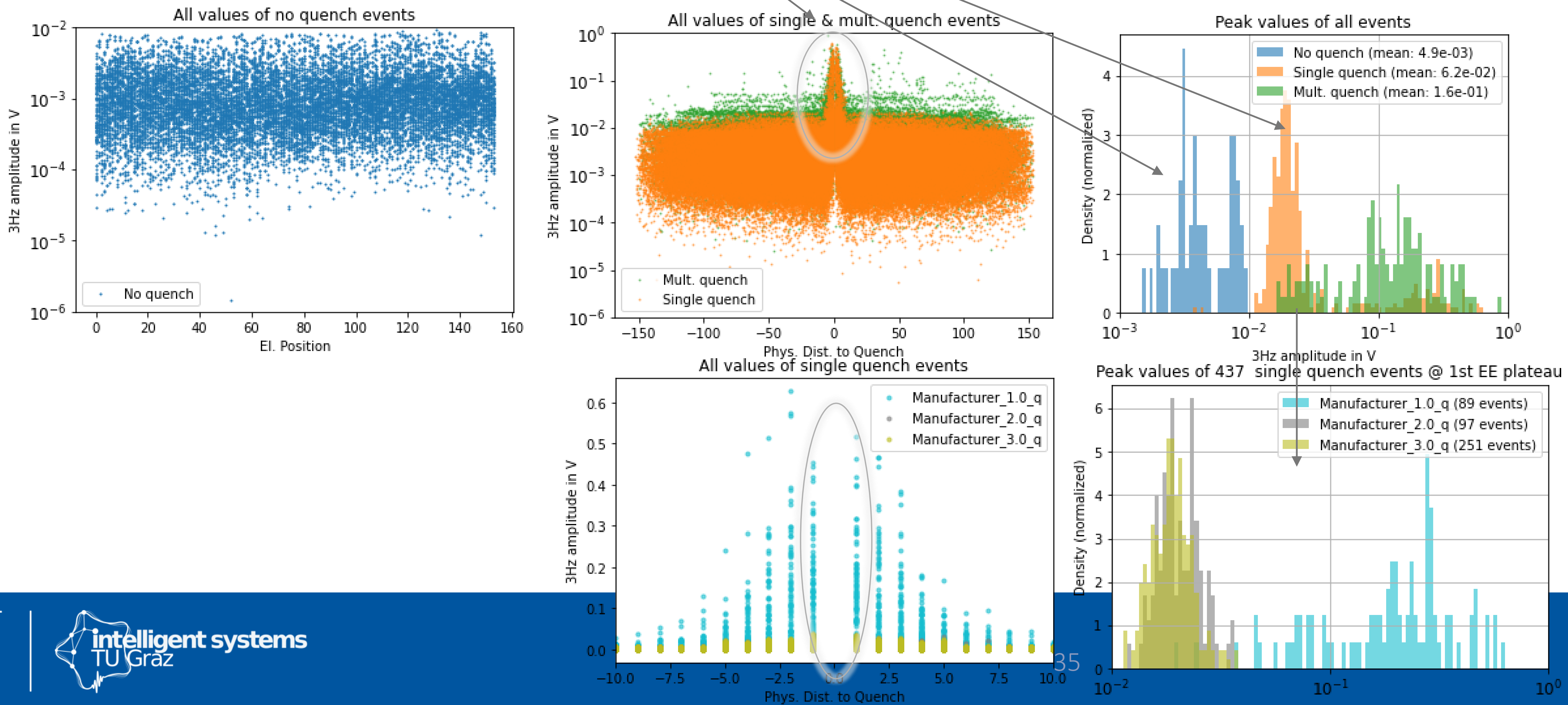
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
1 Fig. 7b	3 Hz	Phys. & el. neighbors of quenched magnet	6.2e-2 V	Phys. & el. position	Electromagnetic perturbation
		-	4.9e-3 V	-	Preprocessing
2 Fig. 7c	6 Hz	Phys. & el. neighbors of quenched magnet	3.6e-2 V	Phys. & el. position	Electromagnetic perturbation
3 Fig. 7d	20 Hz	Constant across all magnets	1.4e-2 V	Constant across all magnets	Diode induced oscillation
		Phys. & el. neighbors of quenched magnet	3.7e-3 V	Phys. & el. position	Electromagnetic perturbation
		Phys. & el. neighbors of power converter	1.2e-3 V	Phys. & el. position	Leftover voltage waves traveling along the chain of magnets by magnet impedance
4 Fig. 7e	66 Hz 184 Hz 302 Hz	Phys. neighbors of quenched magnet	7.3e-2 V	El. position	Oscillations caused by quench
5 Fig. 7f	150 Hz	El. neighbors of EE systems	1.0e-3 V	Position in QDS measurement unit	Artifact of the QDS measurement unit
6 Fig. 7g	107 Hz 220 Hz 260 Hz 370 Hz 478 Hz	Phys. & el. neighbors of PC	6.9e-4 V	El. position	Passive hardware elements of PC
7 Fig. 7h	Offset	Phys. & el. neighbors of quenched magnet	3.9e-3 V	Phys. & el. position	Quench heater induced oscillation
		Phys. & el. neighbors of quenched magnet	9.9e-4 V	Phys. position	Quench dependent oscillations

3Hz

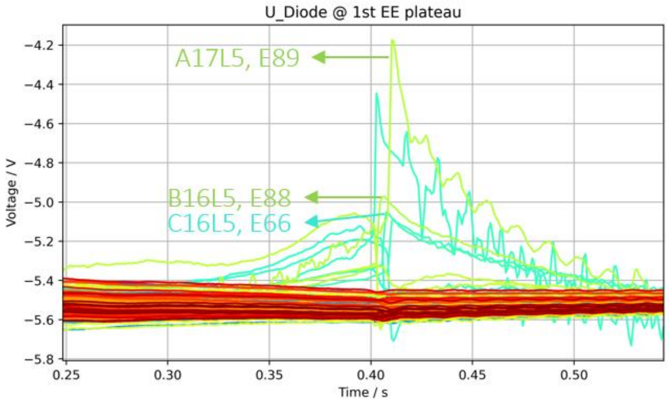
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
1 Fig. 7b	3 Hz	Phys. & el. neighbors of quenched magnet	6.2e-2 V	Phys. & el. position	Electromagnetic perturbation
		-	4.9e-3 V	-	Preprocessing

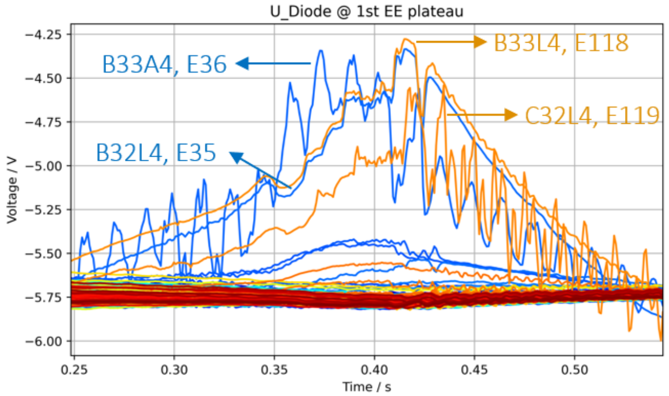


3Hz Examples

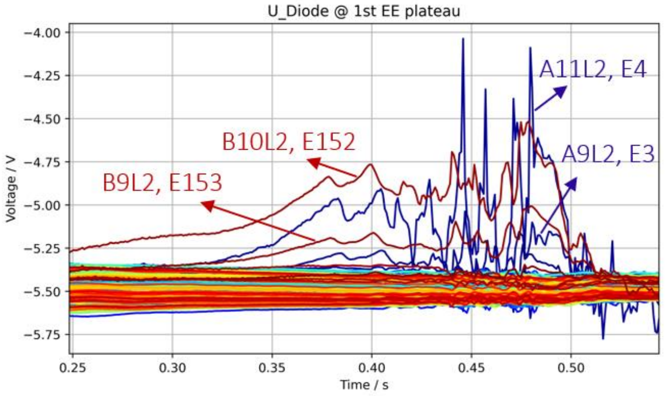
Quenched Magnet: C17L5 (Manufacturer 1)



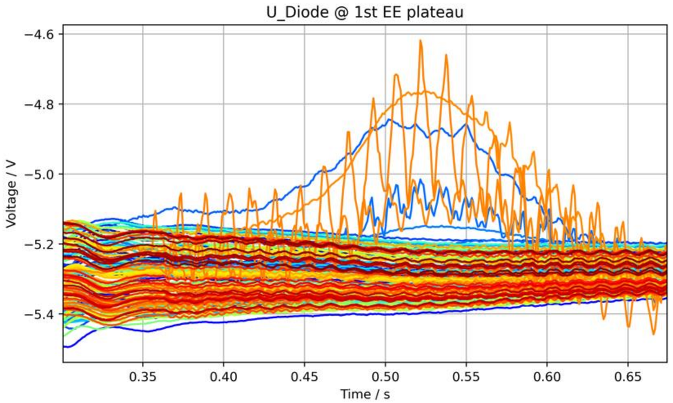
Quenched Magnet: A32L4 (Manufacturer 1)



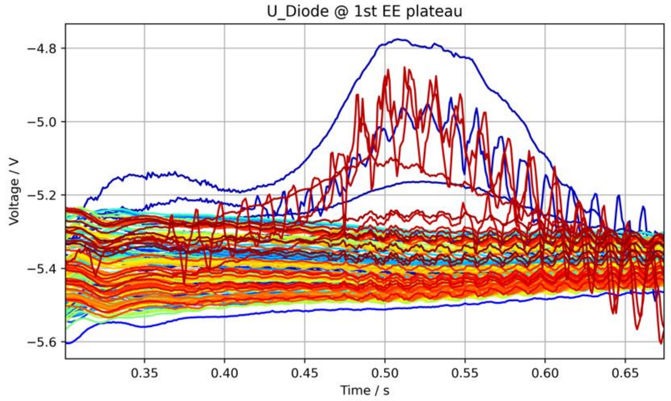
Quenched Magnet: B11L2 (Manufacturer 1)



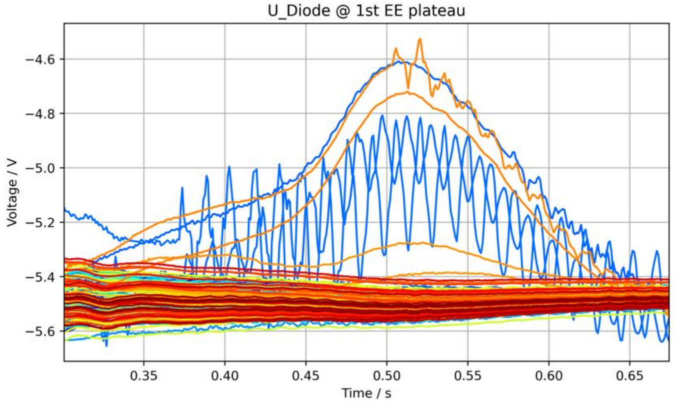
Quenched Magnet: C32L2 (Manufacturer 1)
RB_RB.A12_1619462088820000000_2021-04-26



Quenched Magnet: C14L2 (Manufacturer 1)
RB_RB.A12_1619935955860000000_2021-05-02



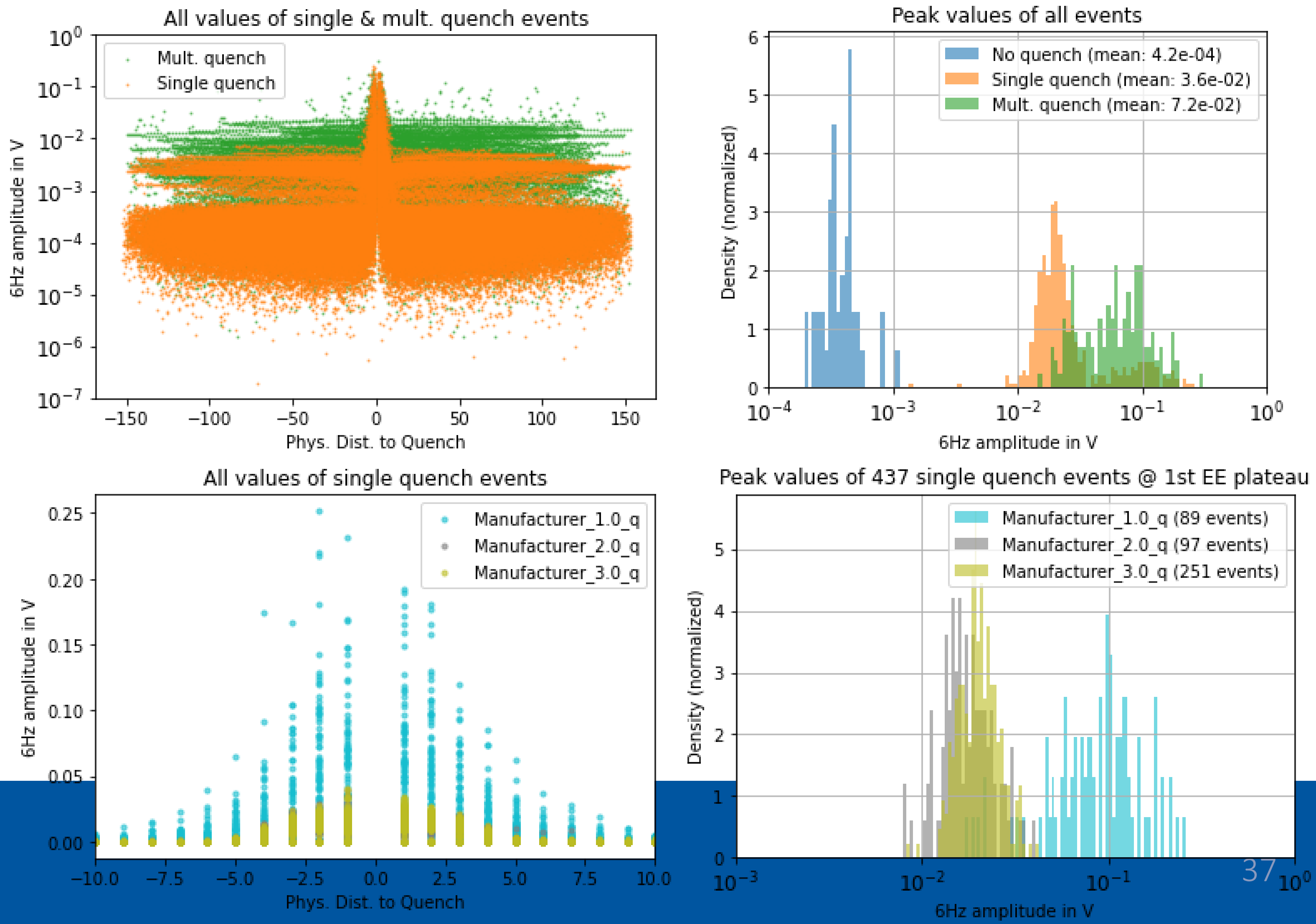
Quenched Magnet: B33R4 (Manufacturer 1)
RB_RB.A45_1620232873800000000_2021-05-05



6Hz

TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
2 Fig. 7c	6 Hz	Phys. & el. neighbors of quenched magnet	3.6e-2 V	Phys. & el. position	Electromagnetic perturbation

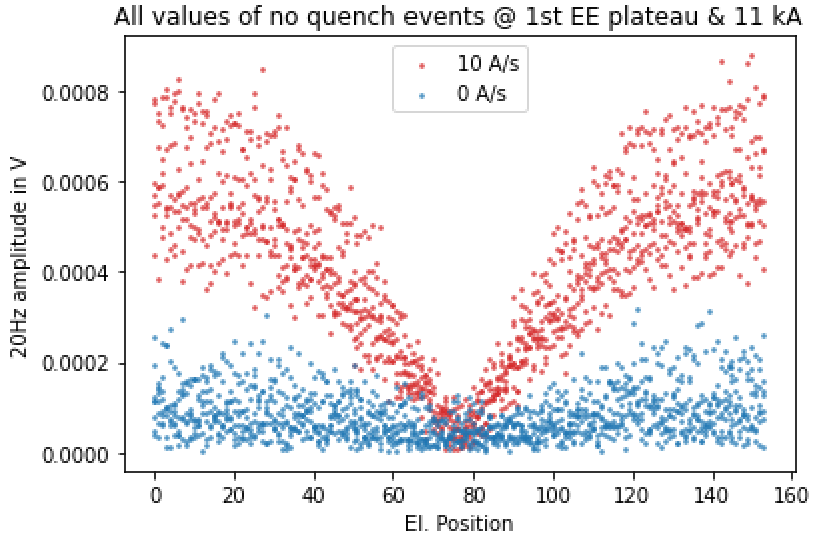


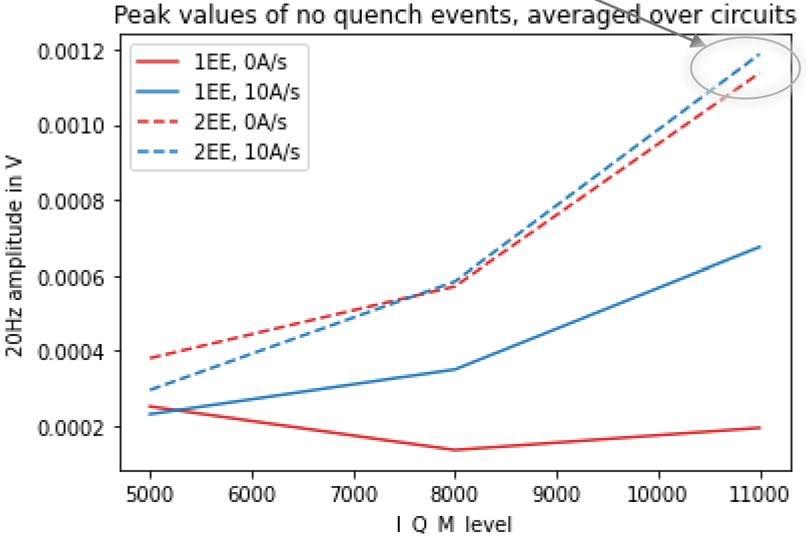
CERN intelligent systems TU Graz

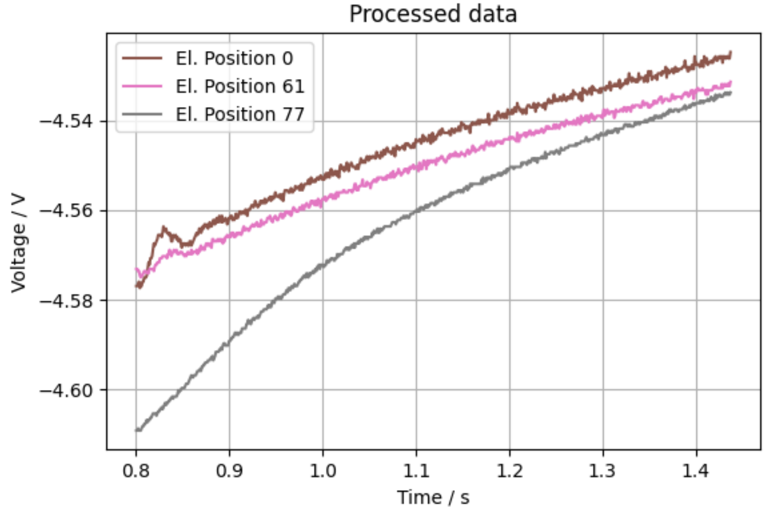
20Hz

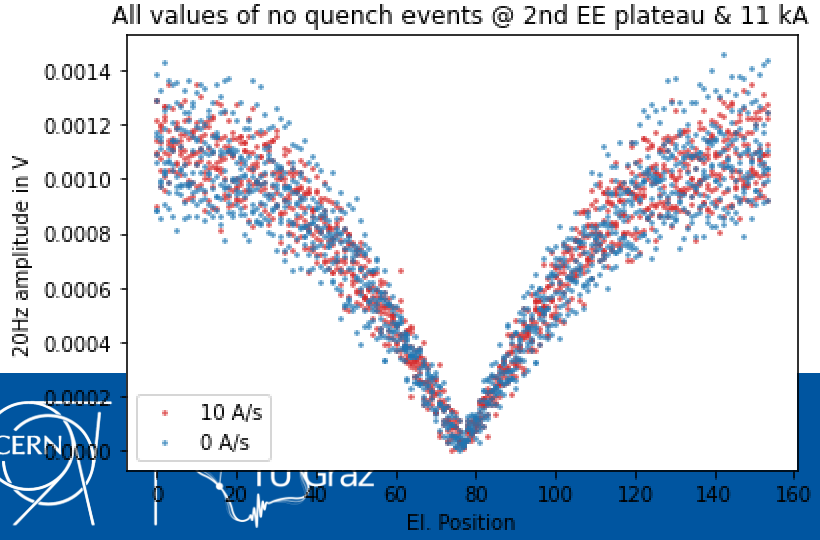
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

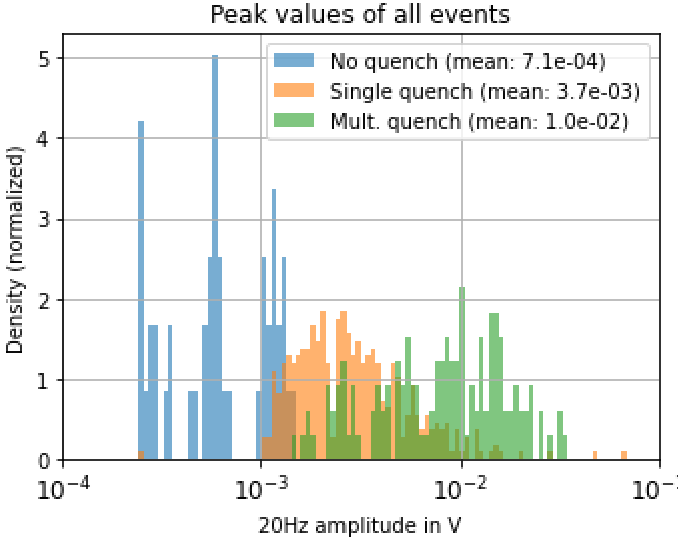
Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
		Phys. & el. neighbors of power converter	1.2e-3 V	Phys. & el. position	Leftover voltage waves traveling along the chain of magnets by magnet impedance

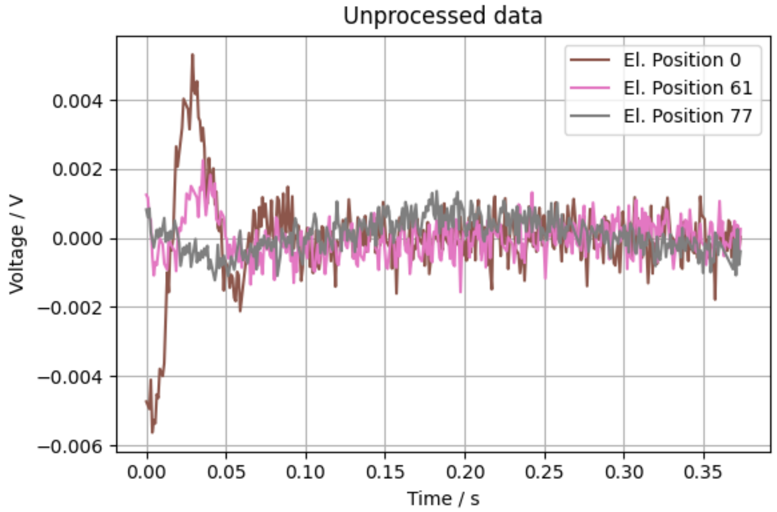








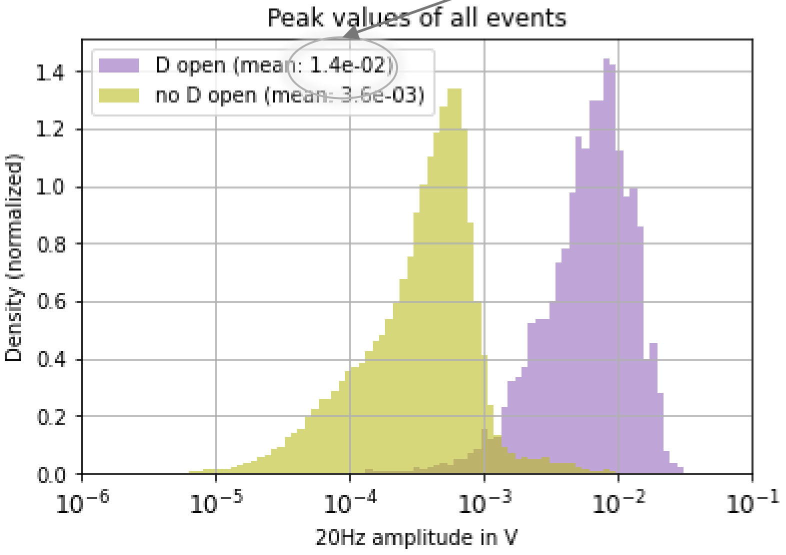


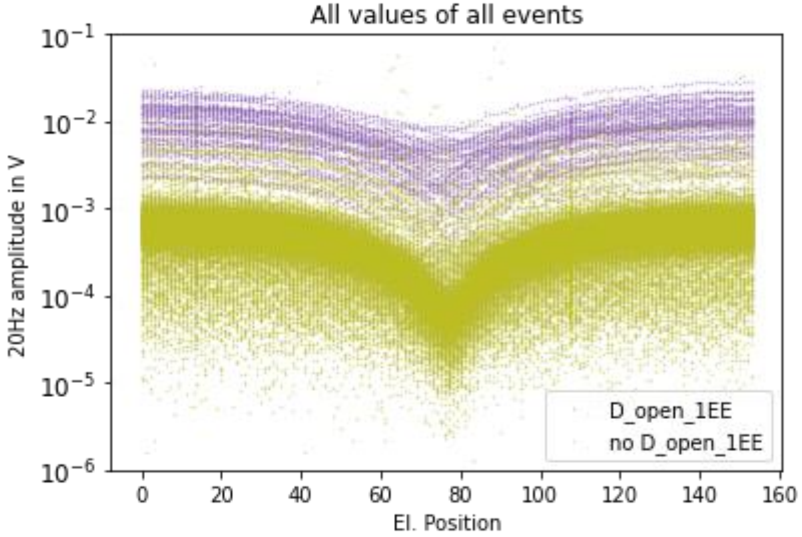


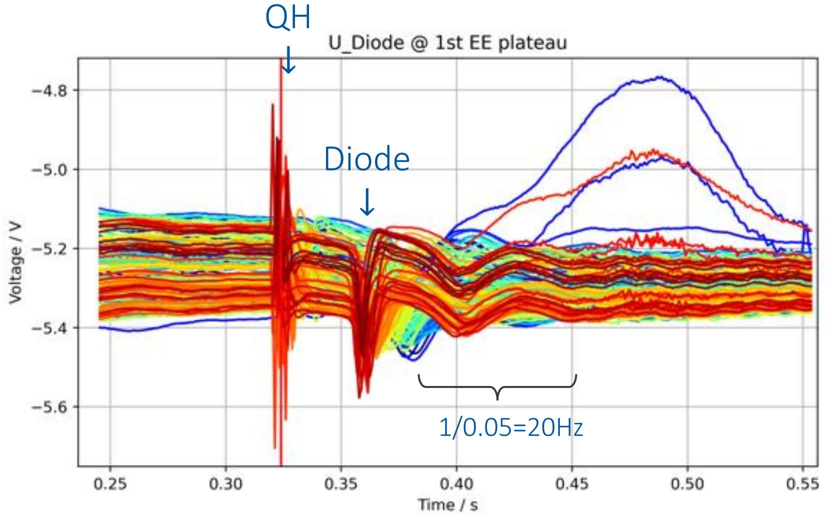
20Hz

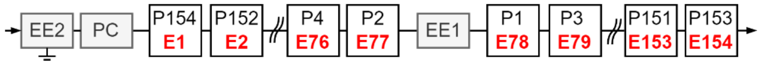
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
3	20 Hz	Constant across all magnets	1.4e-2 V	Constant across all magnets	Diode induced oscillation





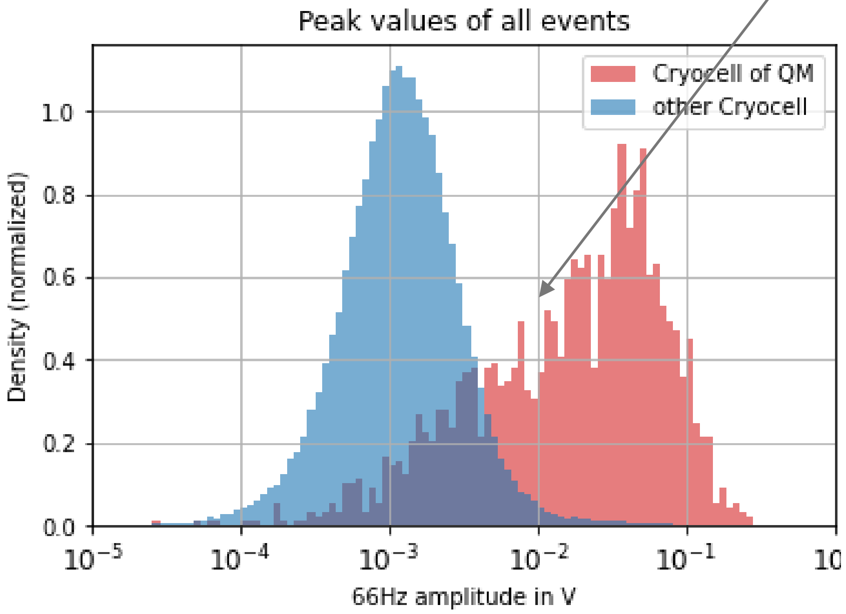




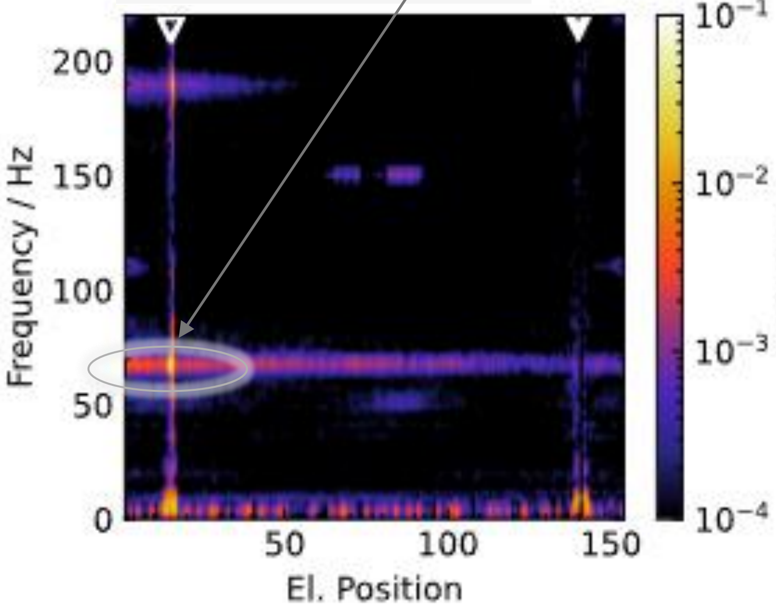
66Hz

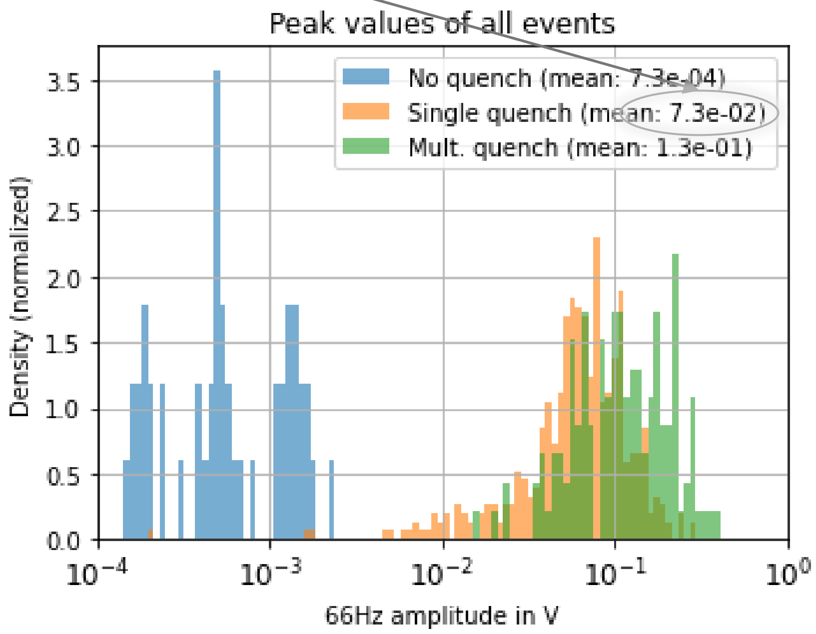
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
4 Fig. 7e	66 Hz 184 Hz 302 Hz	Phys. neighbors of quenched magnet	7.3e-2 V	El. position	Oscillations caused by quench



Circuit	Magnet	#Electric_circuit	Cryostat
RB.A78	MB.A18L8	14	LBBRD.18L8
RB.A78	MB.C18L8	15	LBBRA.18L8
RB.A78	MB.B18L8	141	LBARA.18L8

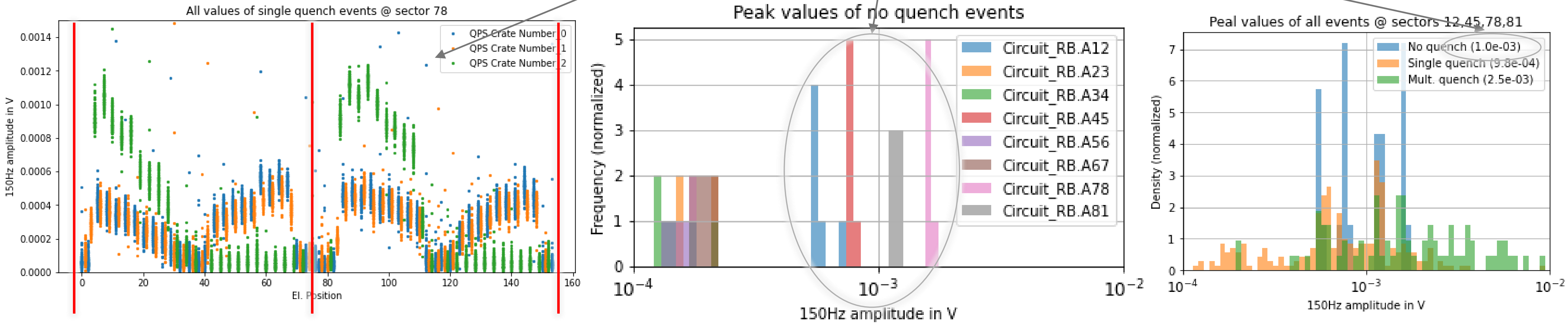




150Hz

TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
5 Fig. 7f	150 Hz	El. neighbors of EE systems	1.0e-3 V	Position in QDS measurement unit	Artifact of the QDS measurement unit



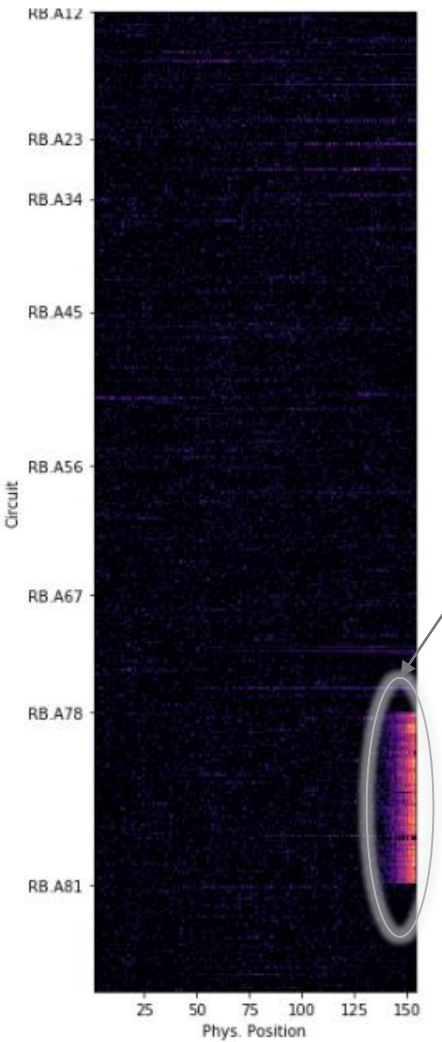
EE switch EE switch EE switch

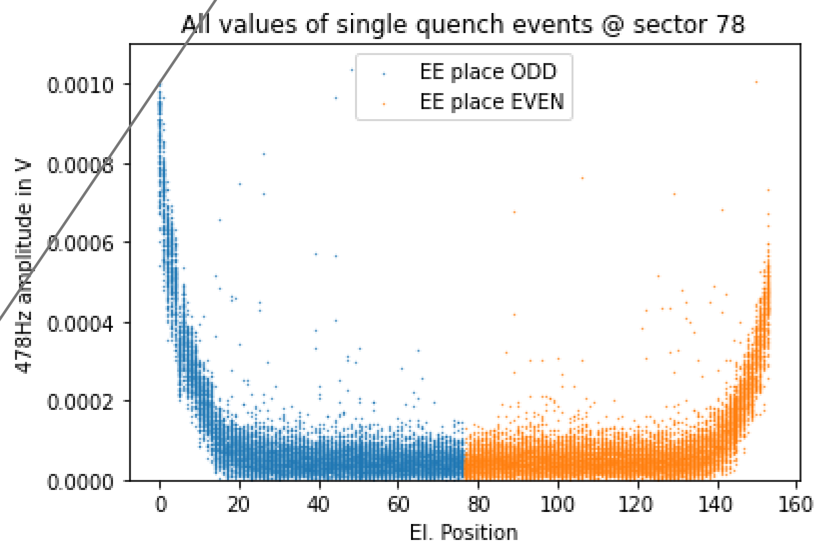
It actually starts 1 QPS crate after the EE switches

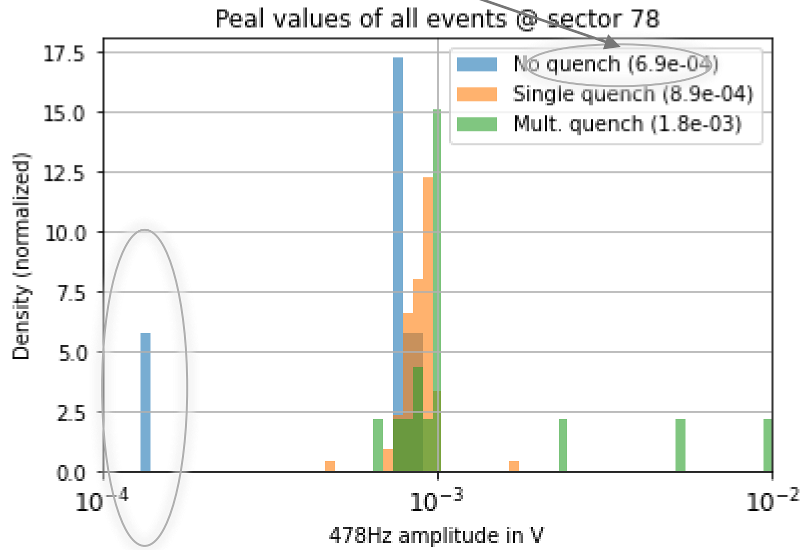
478Hz

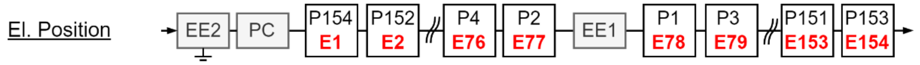
TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
6 Fig. 7g	107 Hz 220 Hz 260 Hz 370 Hz 478 Hz	Phys. & el. neighbors of PC	6.9e-4 V	El. position	Passive hardware elements of PC









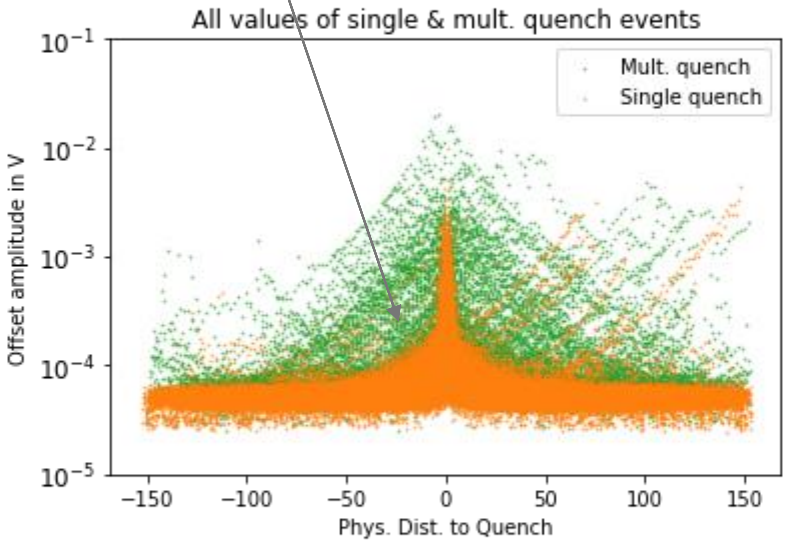
No Oscillations
@ Snapshots 11 kA, 10A/s

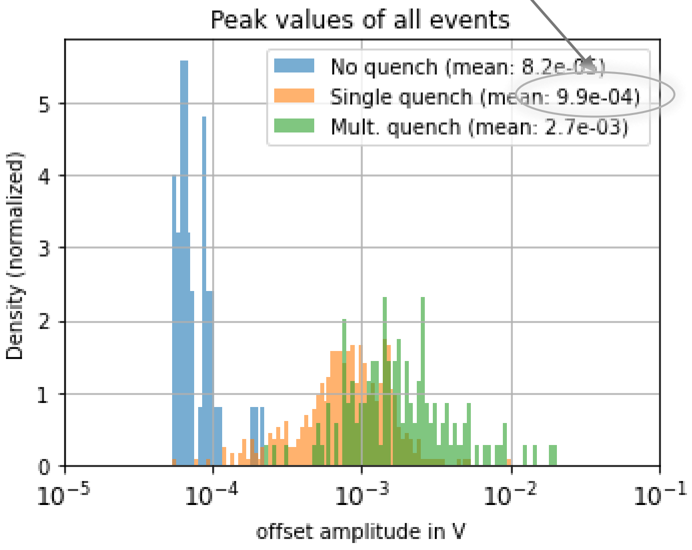
nt systems

Offset

TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
Fig. 7h	Offset	Phys. & el. neighbors of quenched magnet	9.9e-4 V	Phys. position	Quench dependent oscillations

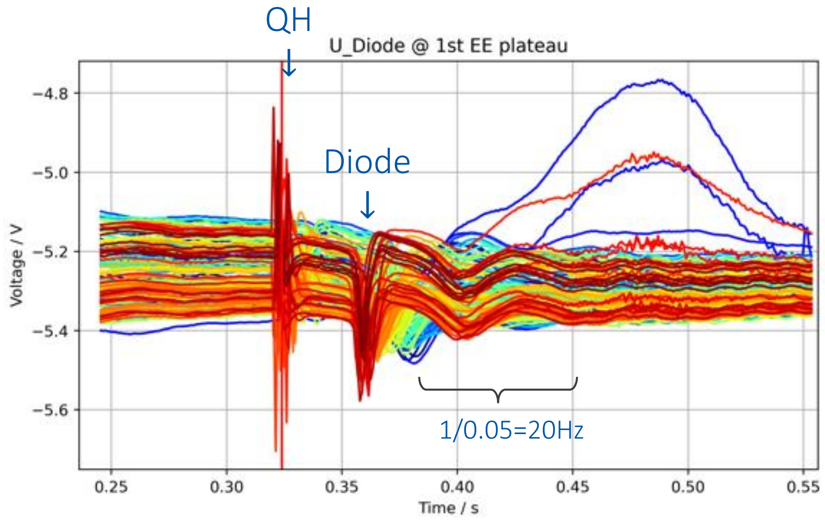


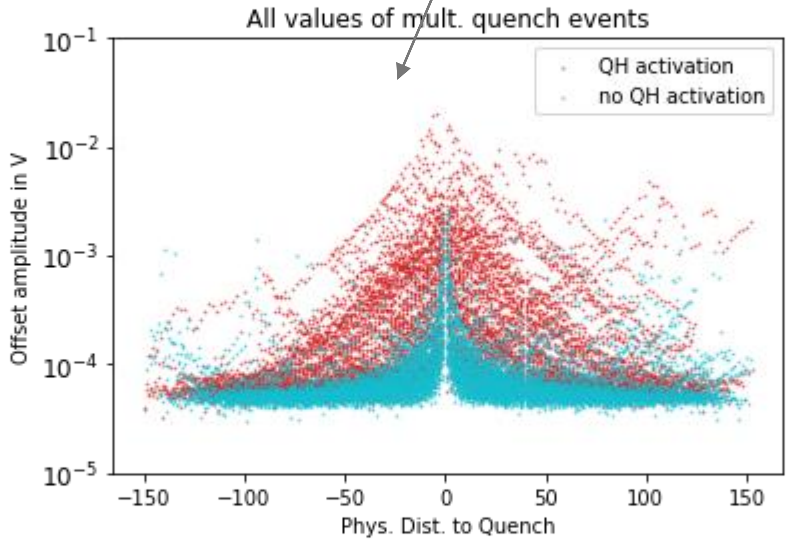


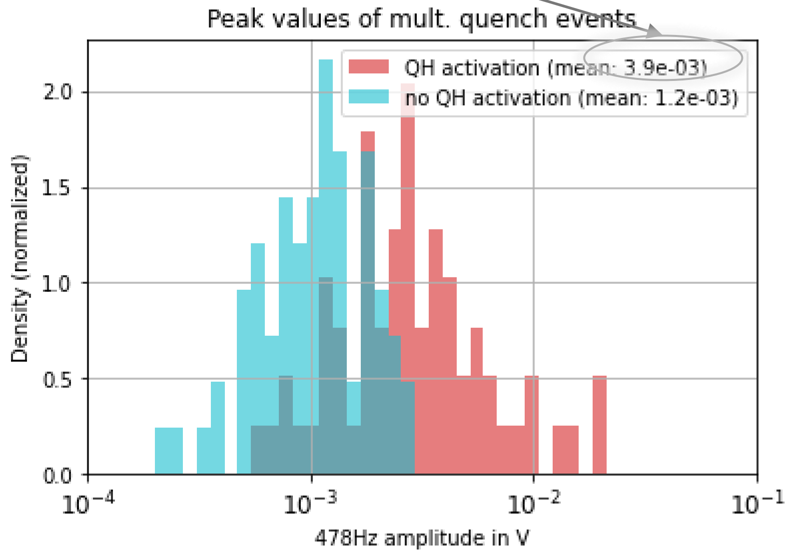
Offset

TABLE I
CHARACTERISTICS OF FREQUENCY COMPONENTS.

Component	Dominant Frequencies	Location of Maximum	Average Maximum Amplitude	Propagation	Possible Physical Process
7	Offset	Phys. & el. neighbors of quenched magnet	3.9e-3 V	Phys. & el. position	Quench heater induced oscillation







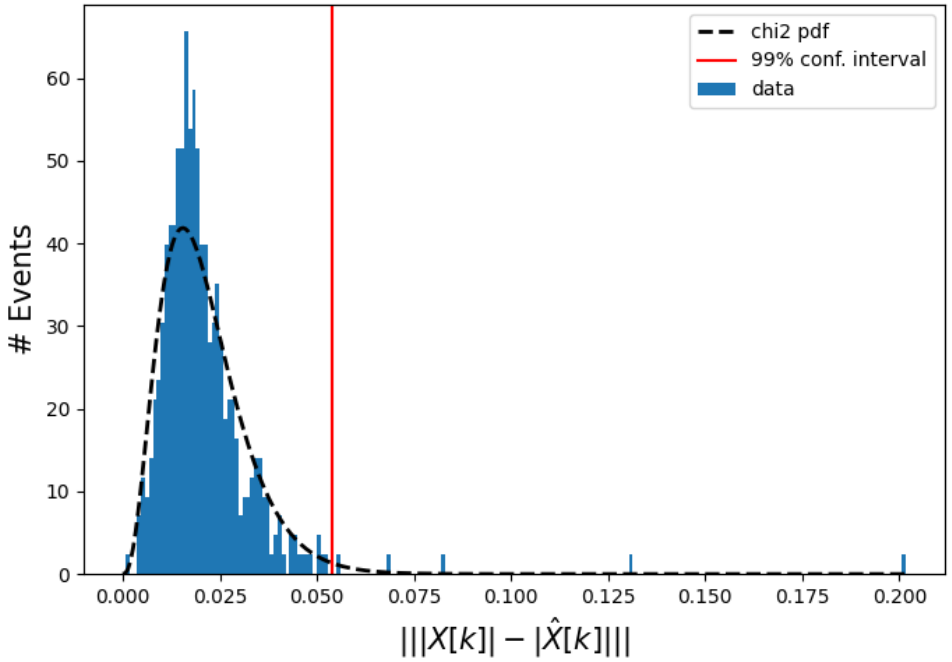
Outlier Detection

Assumptions

1. **Preprocessing**:
    1. Degree of detrend:
        1. 0 - Offset
        2. 1 - Linear Trend
    2. Window multiplication:
        1. none (best reconstruction, high smearing)
        2. hanning (lowest smearing, no reconstruction)
        3. hamming (low smearing , good reconstruction)
        4. barlett
        5. blackman
        6. flattop (high smearing, accurate amplitude)
        7. tukey
2. **NMF**:
    1. n_components (2-12)
    2. Distance measure*:
        1. Frobenius (Eu)
        2. Kullback-Leibler (KL)

280 x

Assumptions for this plot:
- Linear detrend
- Hamming window
- 4 components
- Frobenius distance

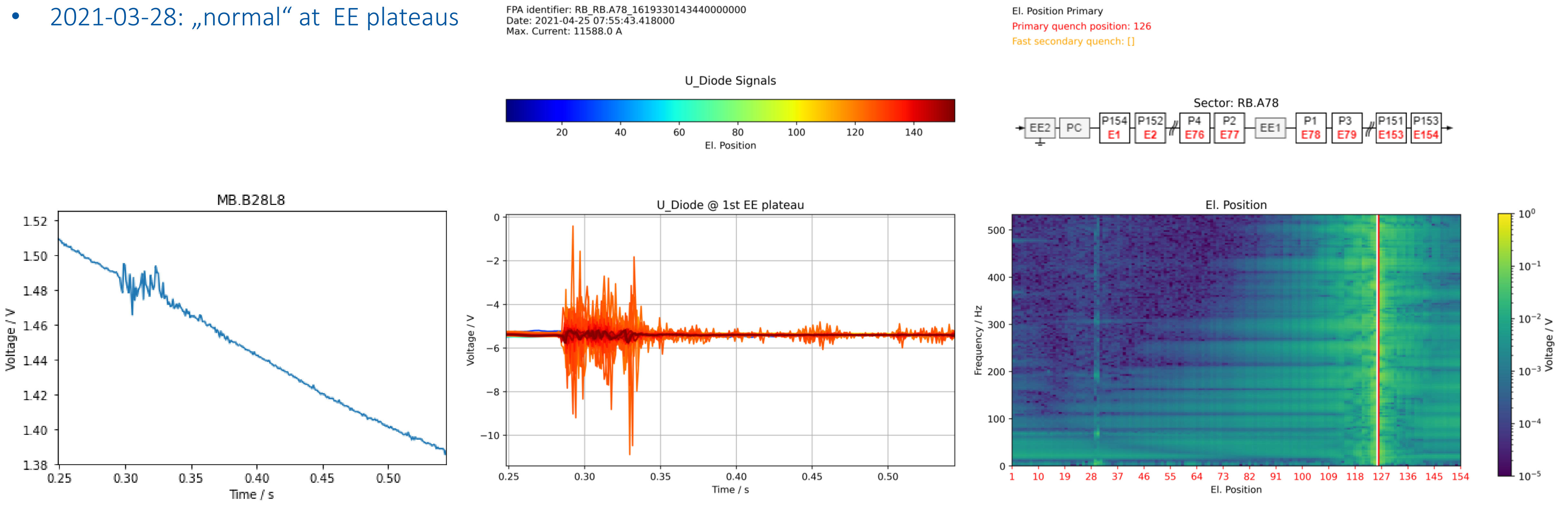


* https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6410389

2038 - RB.A78 - B28L8 – Intercoil short

Event with B28L8 quench before:

- 2021-03-28: „normal“ at EE plateaus



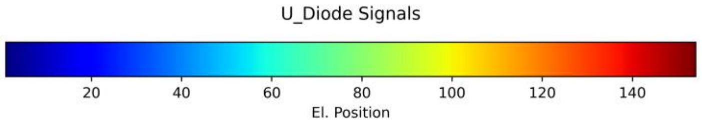
1225 - RB.A45 - C17L5

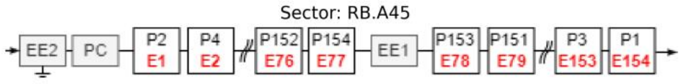
Events with C17L5 quench before:

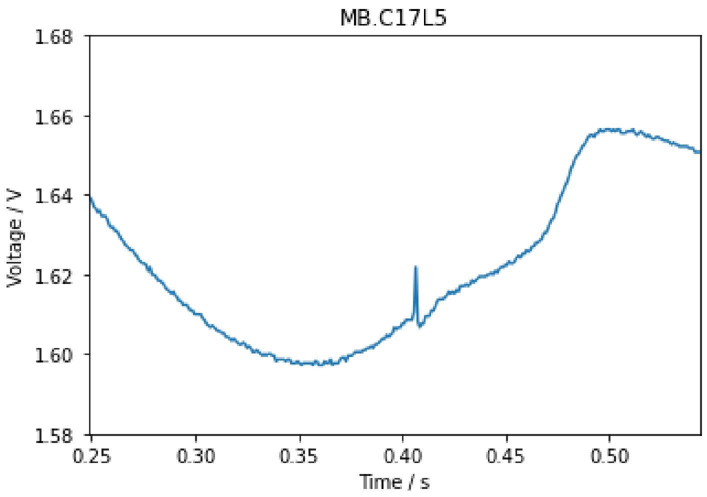
- 2021-05-07: „normal“ at EE plateaus
- 2021-05-07: „normal“ at EE plateaus

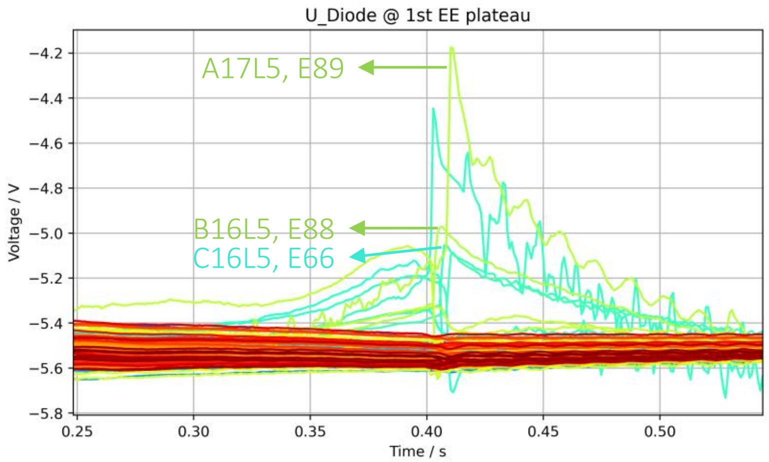
FPA identifier: RB_RB.A45_1620797547820000000
Date: 2021-05-12 07:32:27.799000
Max. Current: 11701.0 A

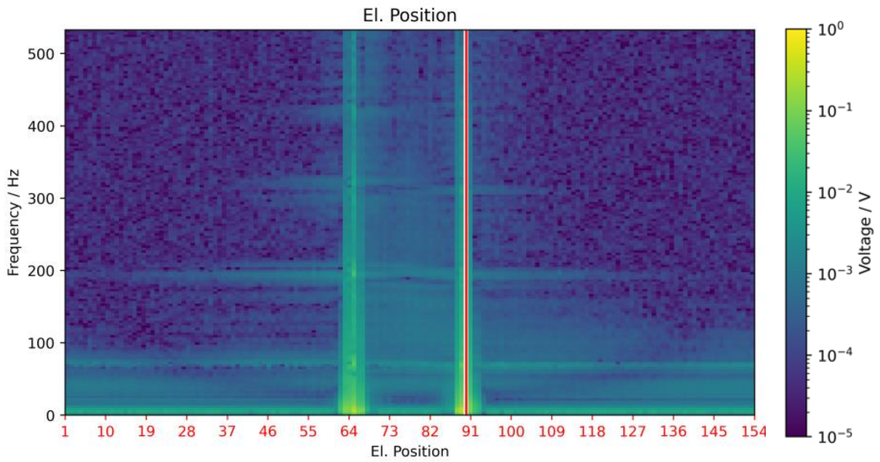
El. Position Primary
Primary quench position: 90
Fast secondary quench: []











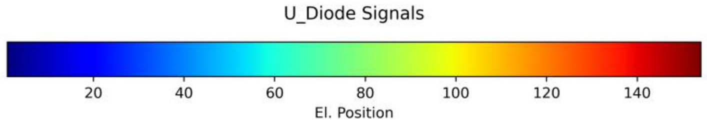
1146 - RB.A34 - A32L4

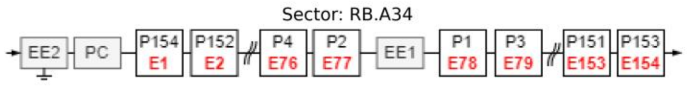
Events with A32L4 quench before:

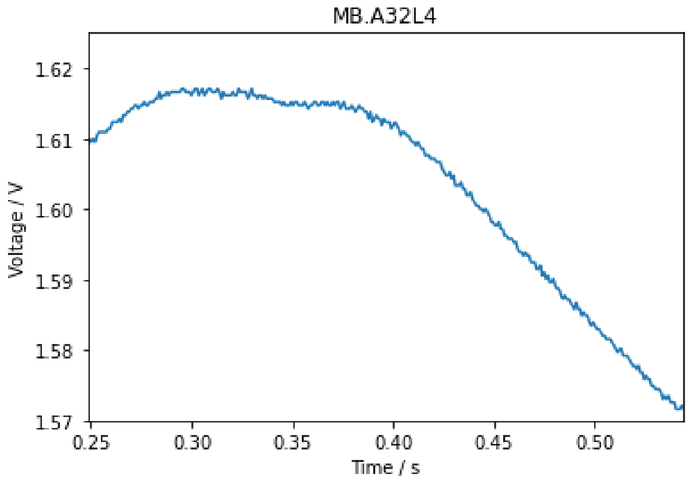
- 2021-04-04: „normal“ at EE plateaus
- 2021-04-14: 3 fast sec. quenches

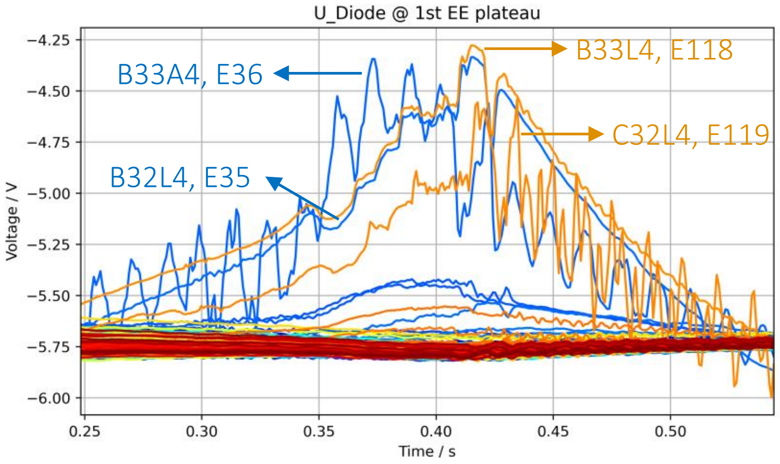
FPA identifier: RB_RB.A34_1620323722320000000
Date: 2021-05-06 19:55:22.295000
Max. Current: 11950.0 A

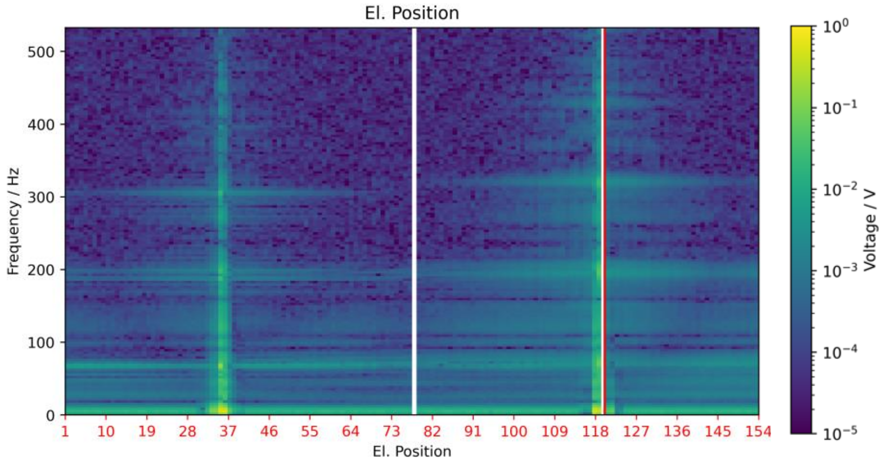
El. Position Primary
Primary quench position: 120
Fast secondary quench: []









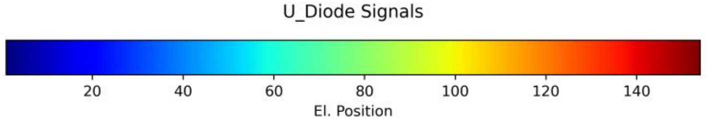


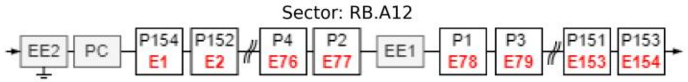
1291 - RB.A12 - B11L2

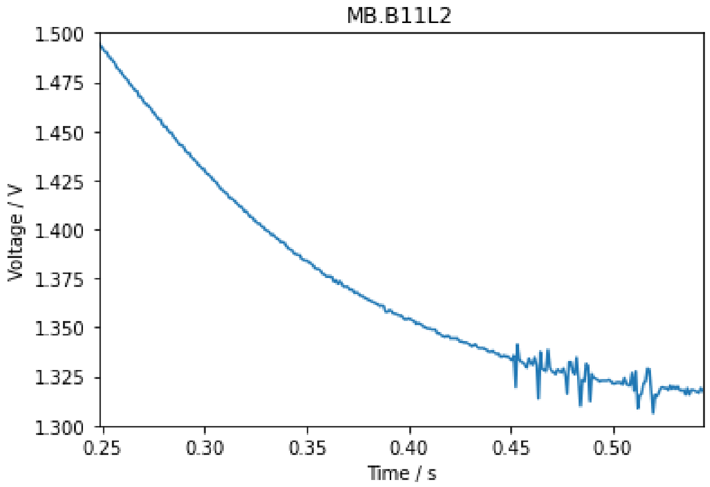
No B11L2 quench before

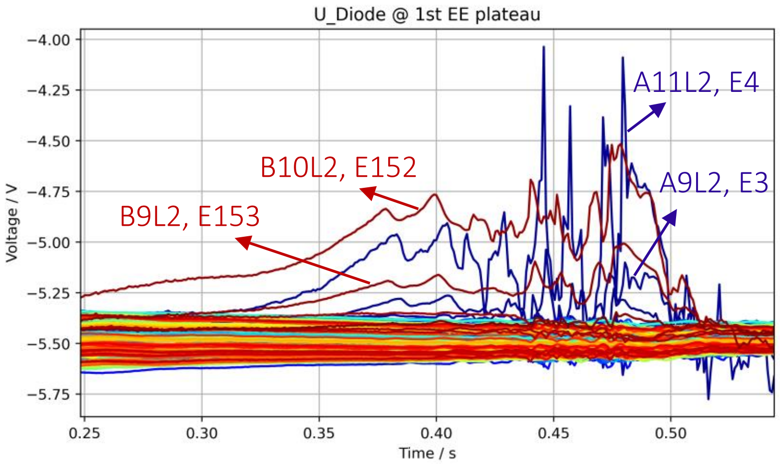
FPA identifier: RB_RB.A12_1621014819920000000
Date: 2021-05-14 19:53:39.901000
Max. Current: 11751.0 A

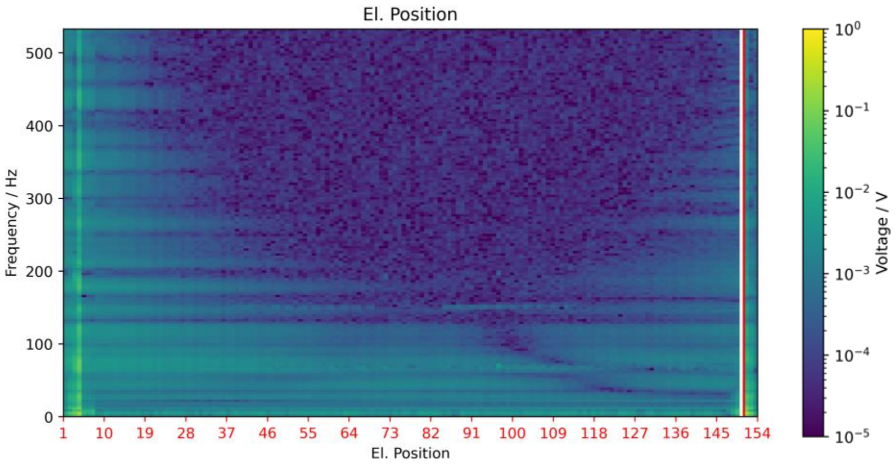
El. Position Primary
Primary quench position: 151
Fast secondary quench: []











2421 - RB.A34 – B28R3

No B28R3 quench before

Most likely scenario of noise from simulations:

- Partially emerging resistor, in parallel to diode
- Degraded diode contact?

FPA identifier: RB_RB.A34_1618896510960000000
Date: 2021-04-20 07:28:30.924000
Max. Current: 11786.3 A

El. Position Primary
Primary quench position: 106
Fast secondary quench: ['49@198ms']