Enhanced Quench Detection at the EuXFEL

through a machine learning-powered approach

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

European XFEL

MSK

DESY.

The European X-ray Free Electron Laser (XFEL)

Some facts

- The EuXFEL is the largest accelerator for X-ray free electron laser generation in the world
  - In Hamburg, Germany
  - Total length of **3.4 kilometres**
  - Electron acceleration to high energies of up to **17.5 GeV**
  - **Several hundred** users benefit from extremely **intense laser** every year
  - The Linac uses **808** 1.3 GHz **SRFCs**

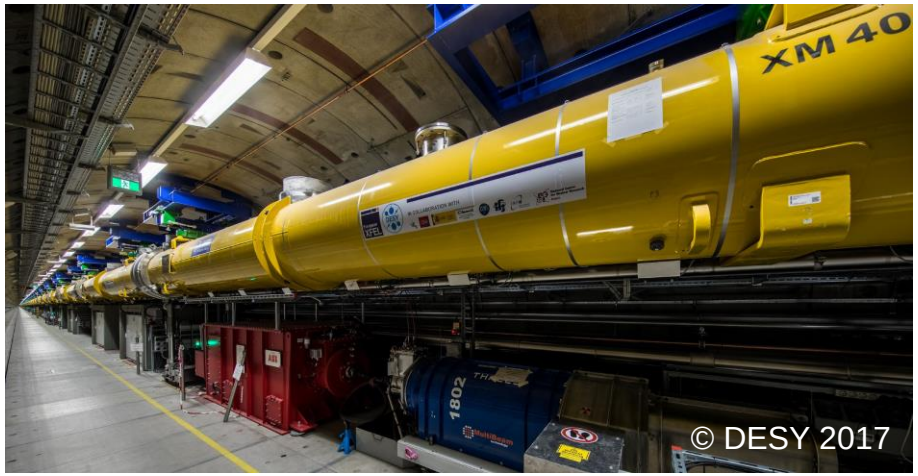
The course of the European XFEL

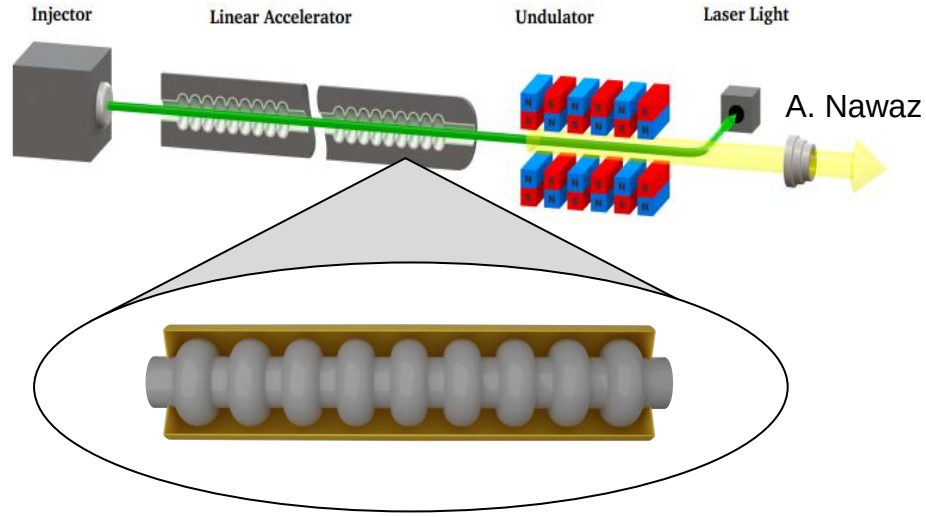
The European X-ray Free Electron Laser (XFEL)

Linac - SRF cavities

- 25 stations, each comprising 4 cryomodules with 8 SRFCs, total of **32 SRFCs** per station
- Cavities controlled and monitored with the LLRF system
- Operated in a **PM**
- At **10 Hz**, duration 1.8 ms, 2700 bunches/pulse

- **Safe** and optimal operation is **crucial**
  - Fault detection and isolation
  - **Quenches** are a priority
    - Significant **down-time (11 hours in 2022)**
    - Facility degradation
    - Energy and financial losses





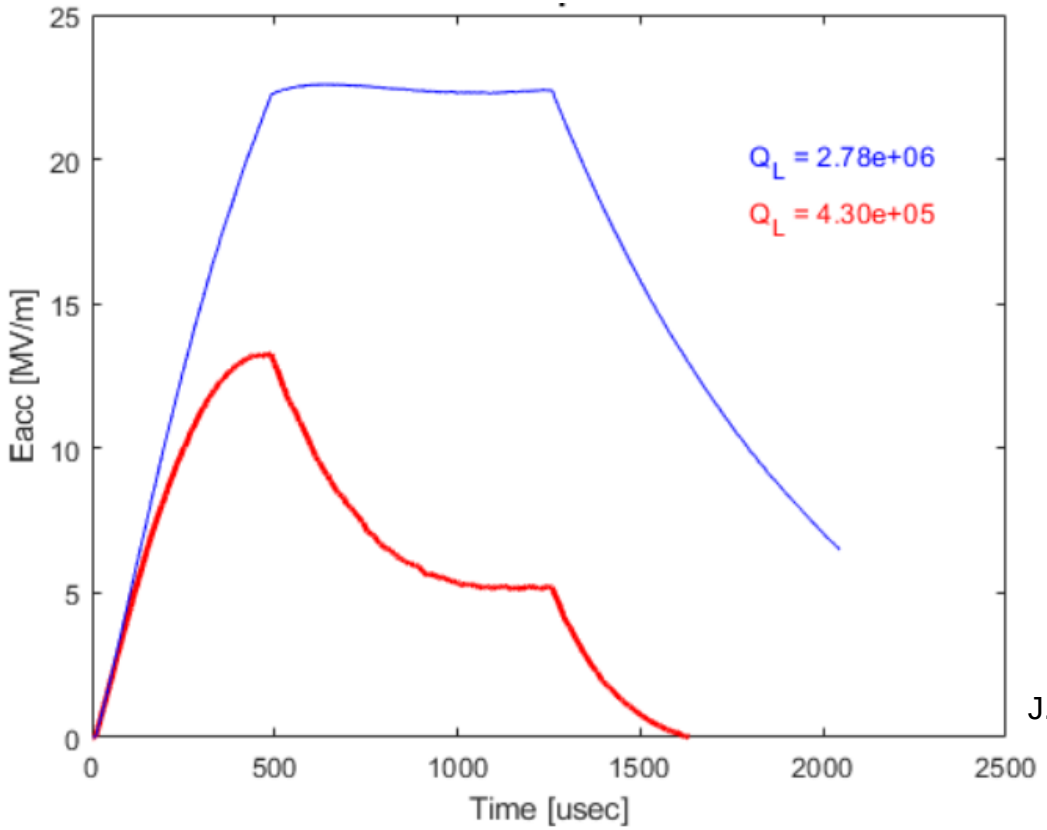
LLRF : Quench Detection

Q_L-based

- Currently, diagnosis through the **QDS**
  - **Q_L-based**, thresholding over the average of previous 100 pulses.
  - **Robustness** issues

$$\frac{1}{Q_L} = \frac{1}{Q_{\text{ext}}} + \frac{1}{Q_0}$$

Loaded — External — Unloaded

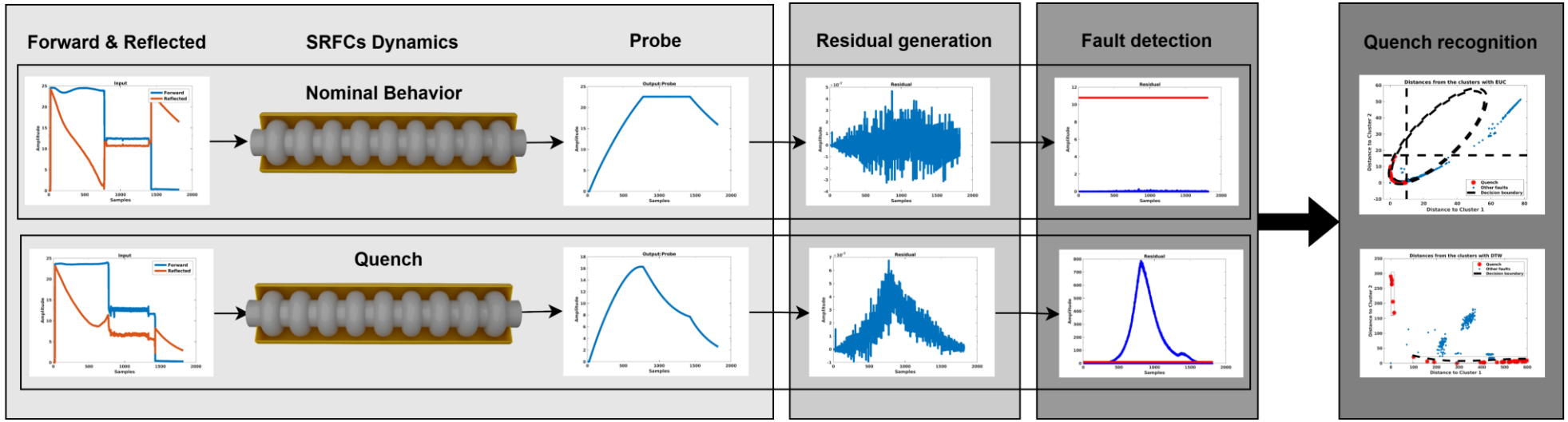


J. Branlard

LLRF : Quench Detection

ML-powered approach

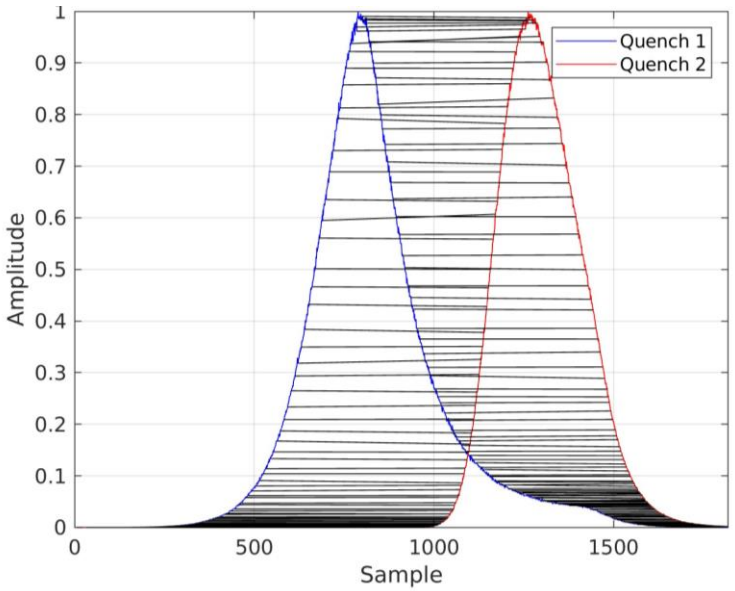
- New AI-powered diagnosis
  - Well-established **model, residuals** for consistency assessment, statistical test for **residual evaluation, m**achine learning for **fault isolation**

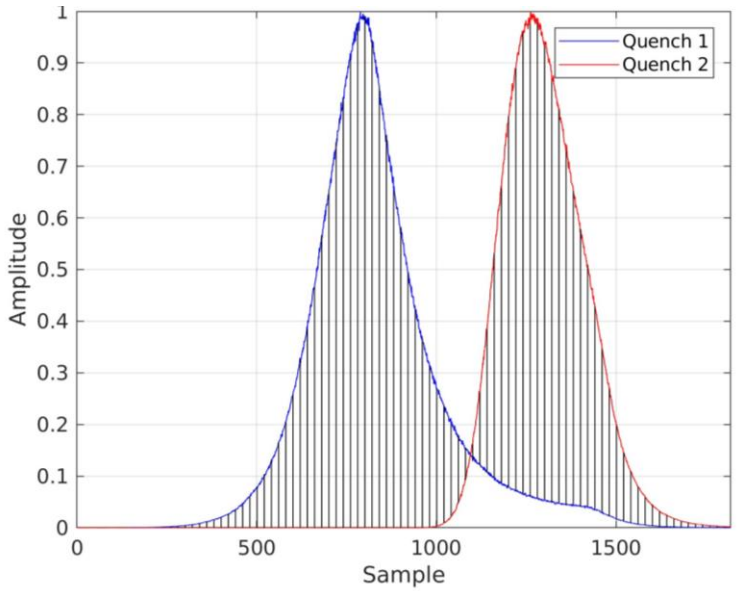


LLRF : Quench Detection

ML-powered approach

- K-medoids for **clustering**, **two** models





$$\mathrm{DTW}(x_1, x_2) = \arg\min_{i,j} \sum \mathrm{dist}(x_1^i, x_2^j)$$

$$\mathrm{EUC}(x_1, x_2) = \sqrt{\sum_{i=1}^{n} (x_1^i - x_2^i)^2}$$

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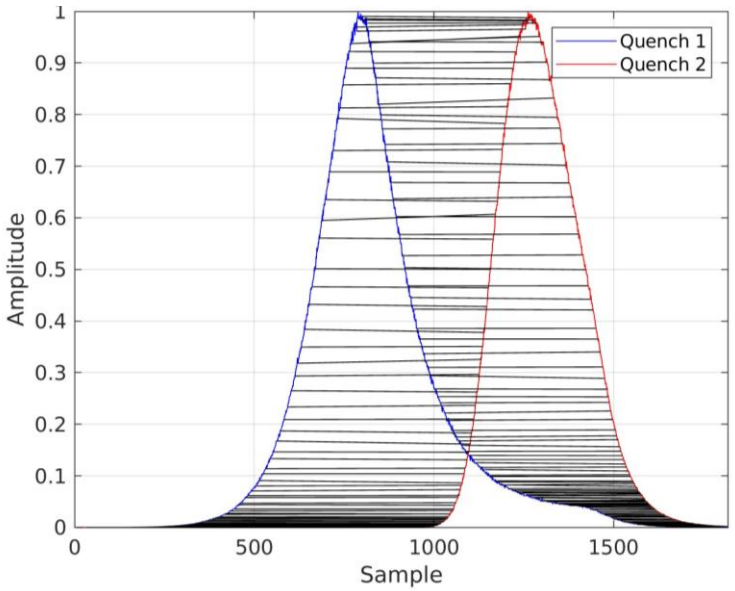

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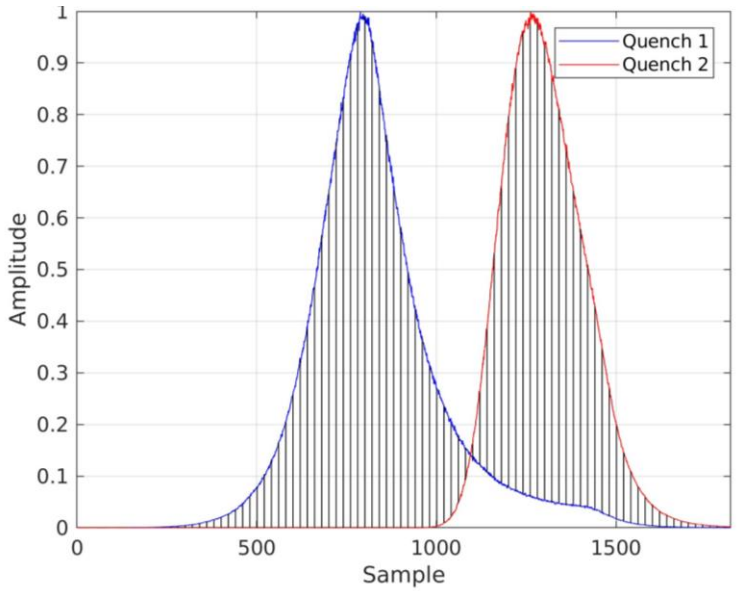

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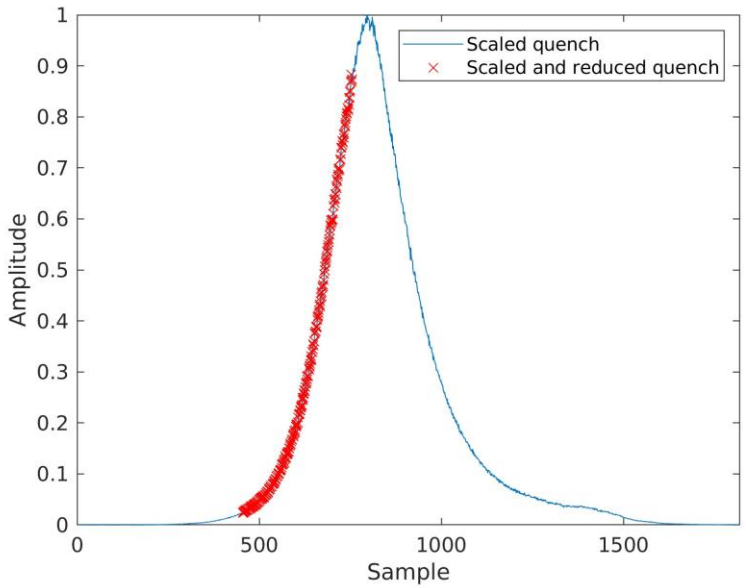
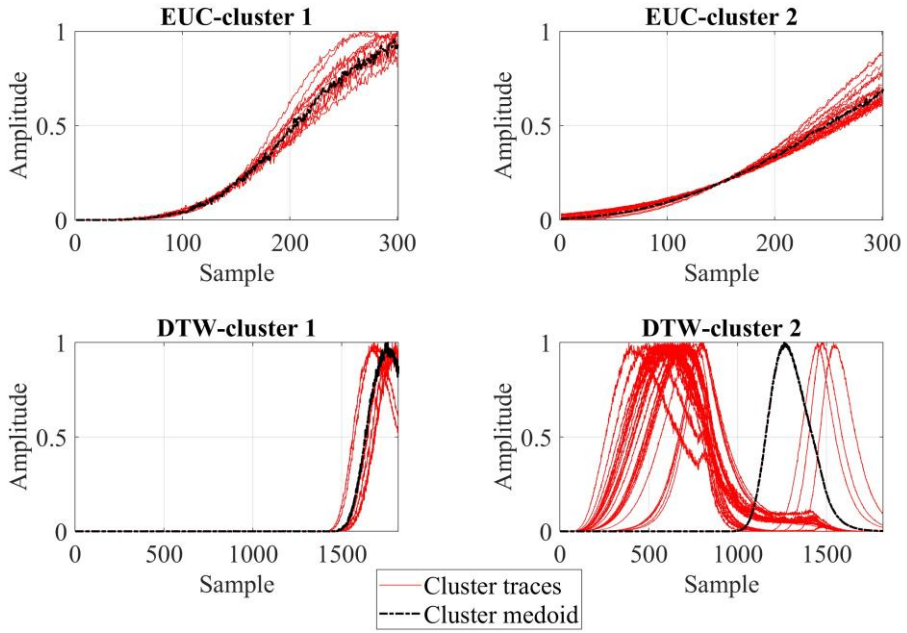


$$\mathrm{Norm}(x_i) = \frac{x_i}{\max(x_i)}$$

LLRF : Quench Detection

ML-powered approach

- Data from 2021 is used
- With both models, **two patterns** and medoids
- Assignment mainly related to **time of occurrence**



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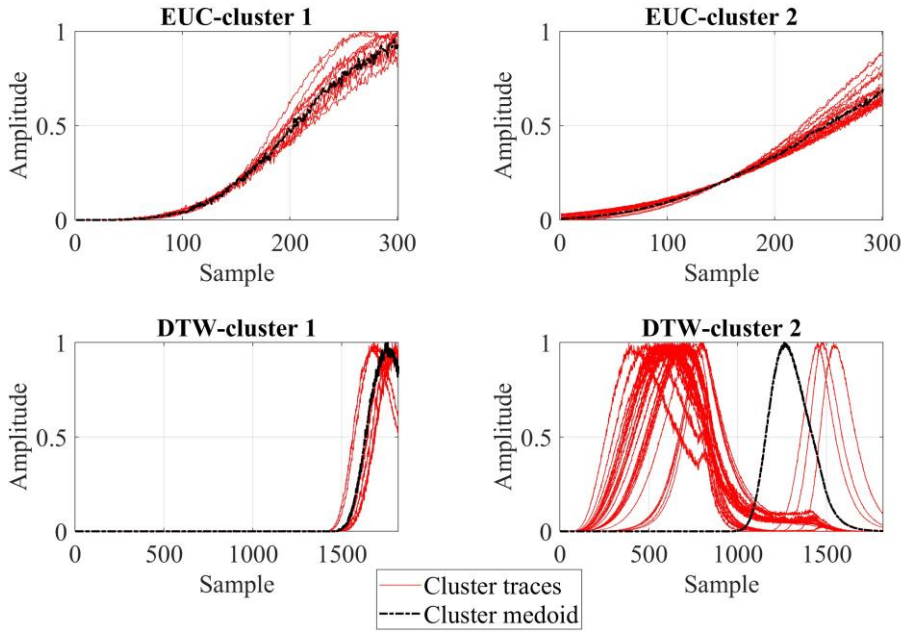
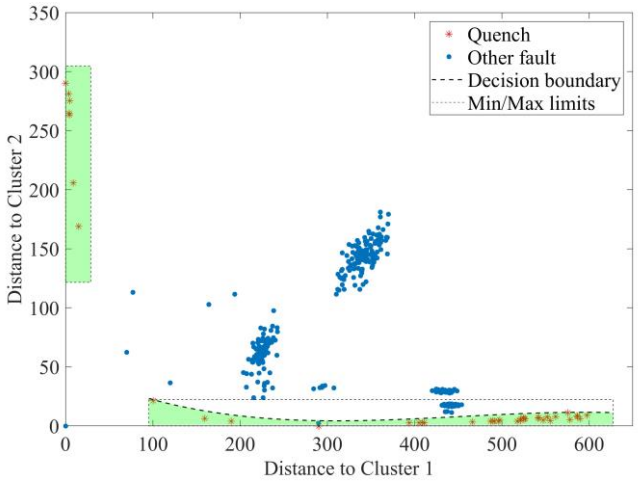
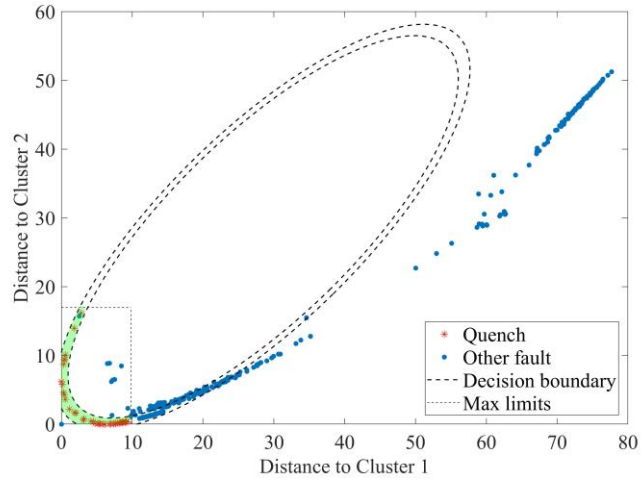
- Decision making
  - In distance space
  - Thresholds & decision boundaries
  - Fitting different based on the measure





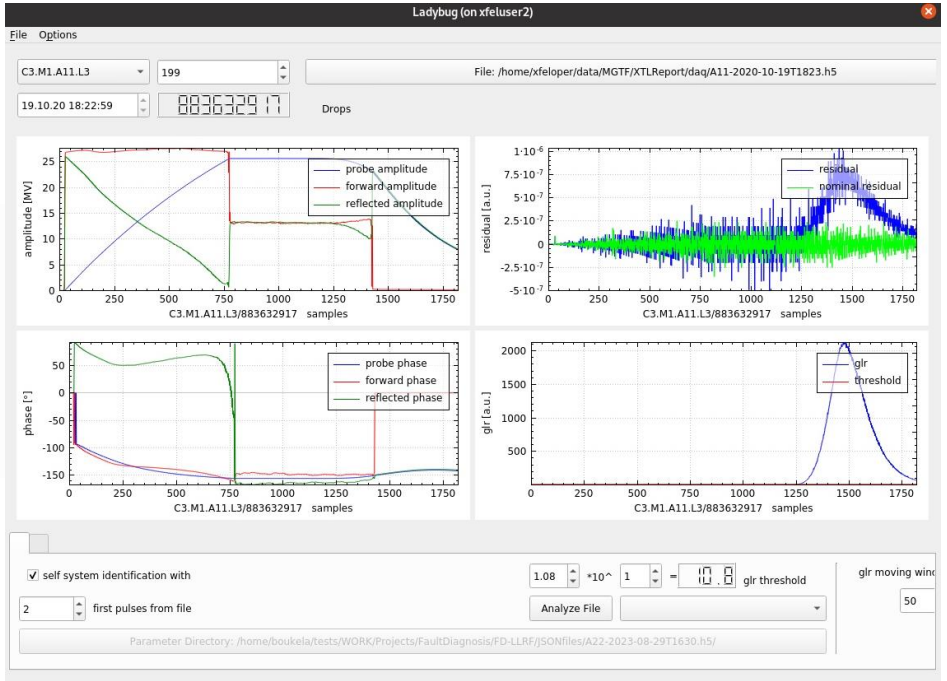


LLRF : Quench Detection

ML-powered approach

- Implementation and evaluation
  - Snap shot files, 250 pulses (50 first nominal)
  - Fault detection to the trip event logger(TEL), including a visualization tool
  - The TEL runs daily along with the ML-based quench identification

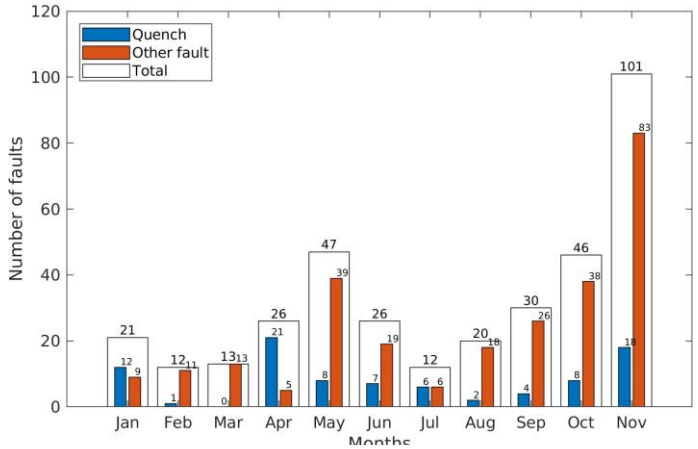
```
In total 105 Events have been detected. 1 of them have been identified as
quenches (0) and 0 and 0 as possible quenches (2) and (3).

location        timeStamp        anomaly        maxGradient
C7.M3.A22.L3        21-Oct-2023 11:46:29        0        26.65
>> 7 events from C5.M1.A5.L2 are ignored.
>> 0 events detected because of missing signals.
```

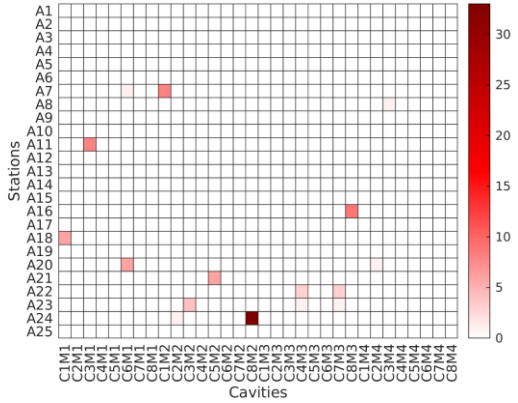


LLRF : Quench Detection

ML-powered approach

- Implementation and evaluation
  - Data from **2022** used for evaluation (**671 events , 354 faults , 87 quenches**)
  - With fault detection, statistics and insights can be obtained





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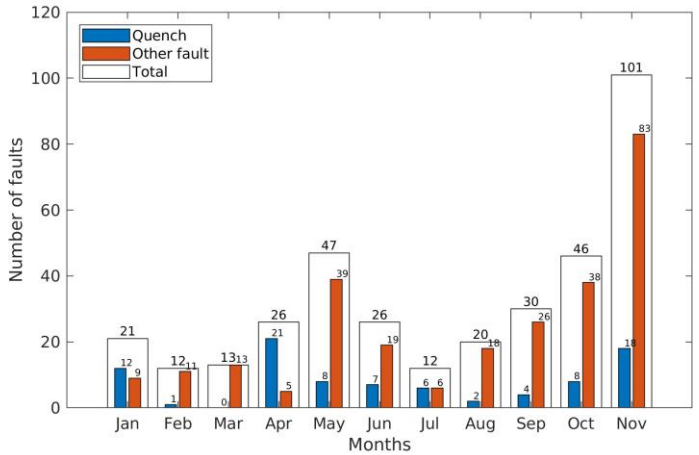
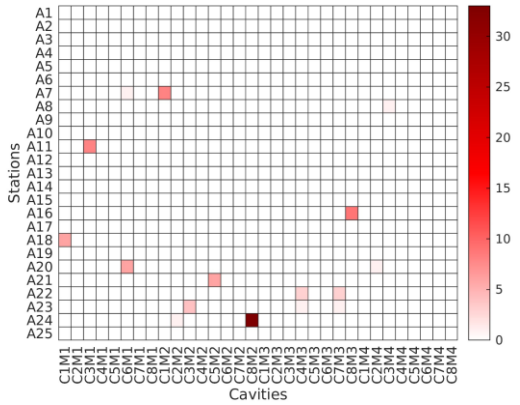
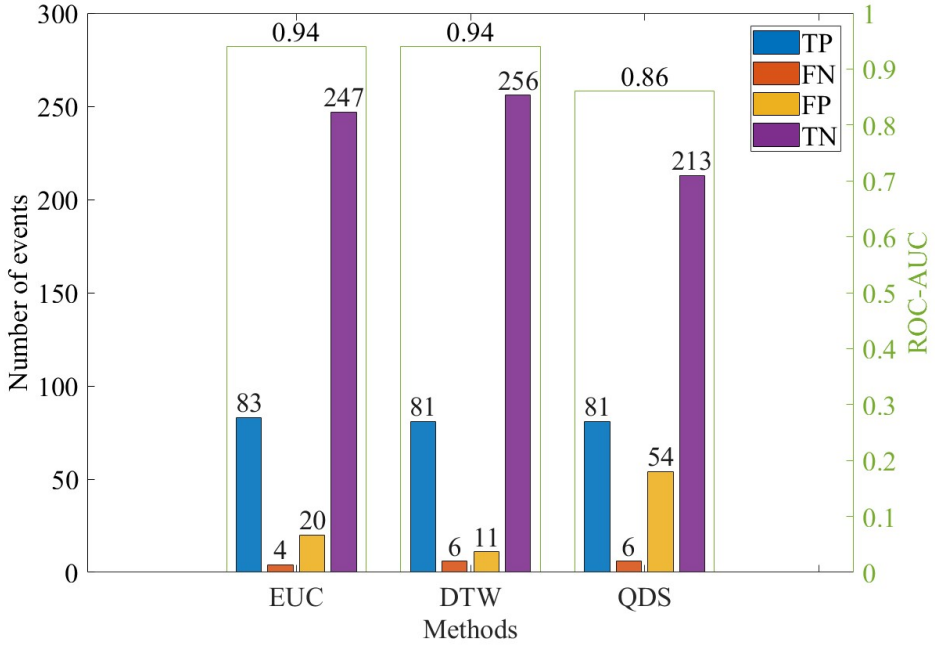






TP : the method accurately identified a quench

TN : the method accurately recognized a fault was not a quench

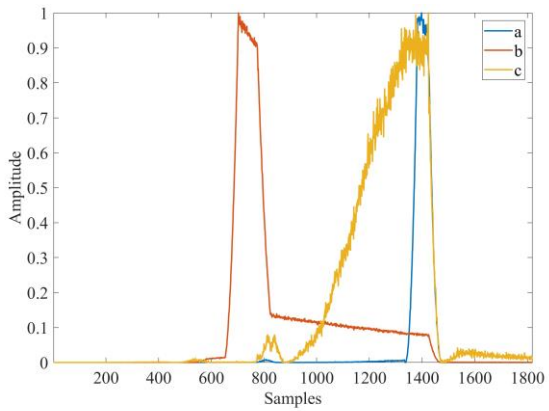
FP : the method identified a quench that's in reality not a quench

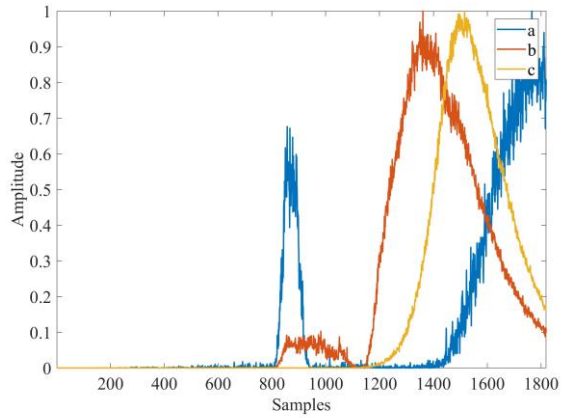
FN : the algorithm failed to identify a real quench

LLRF : Quench Detection

ML-powered approach

- What's next?
- Online deployment
- Beam information inclusion
- Enhance the ML part (expert in the loop)
- Long-term diagnosis
- Further distinction and understanding
- More tools (annotation)





Thank you !

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