XFEL Accelerator R&D Status
Fault Diagnosis for the LLRF control system

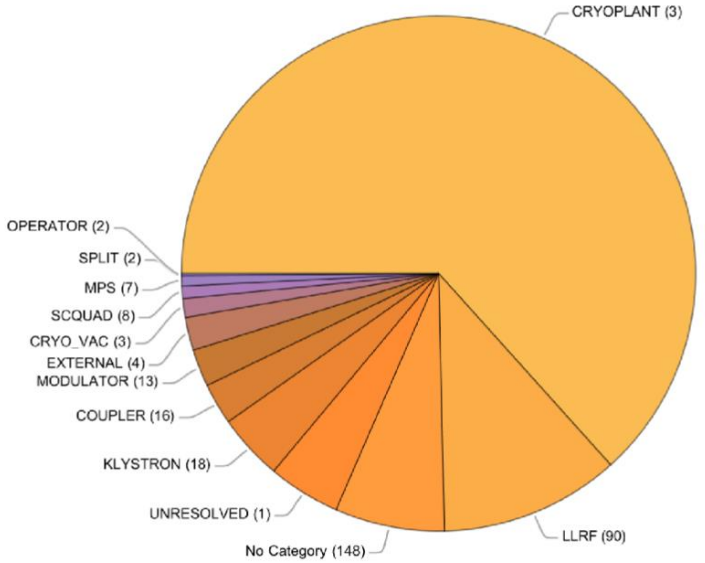
Annika Eichler, Julien Branlard

12.09.2025

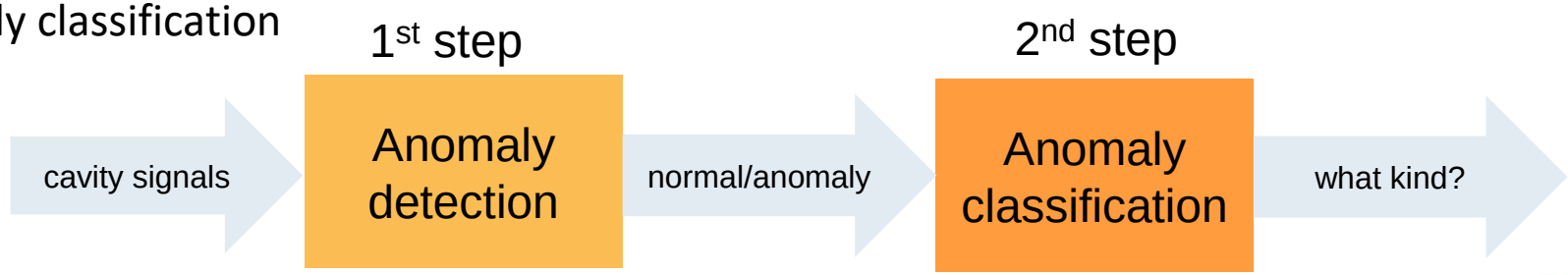
HELMHOLTZ

Scope of the R&D activity (extension 2024-2027)

- **Summary**
  - Detect and mitigate anomalies and failures in the LLRF system for **increased availability** of the European XFEL
- **Interface**
  - **MSK** LLRF (Julien Branlard), Software (Nadeem Shehzad) and Firmware (Burak Dursun)
  - Other XFEL proposals: CW LLRF development
- Deliverables
  - Concept: **Two-step** anomaly classification
  - Prototype(s): **Online** anomaly classification

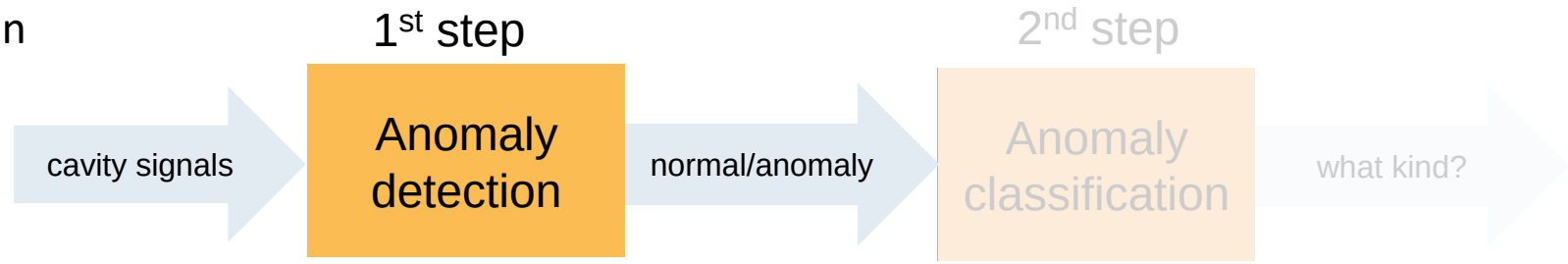


Courtesy: Nick Walker

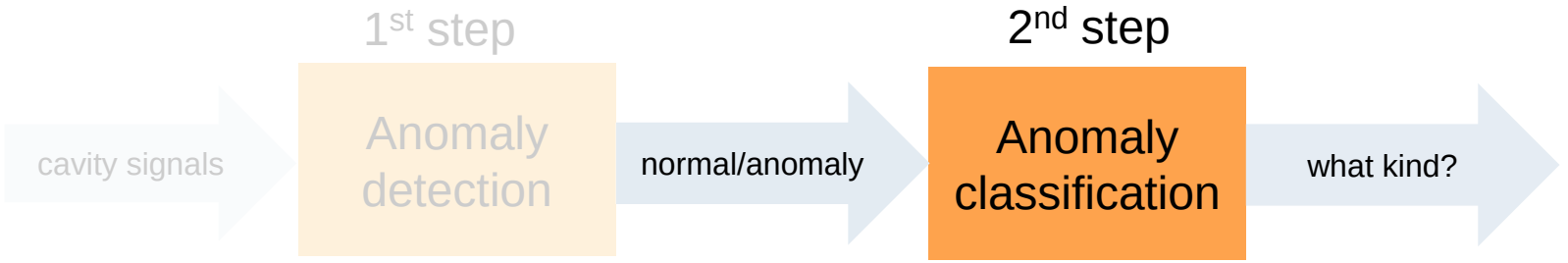


Achievements in the past year

- Prototype: Online anomaly detection
  - Software implementation
  - Firmware implementation



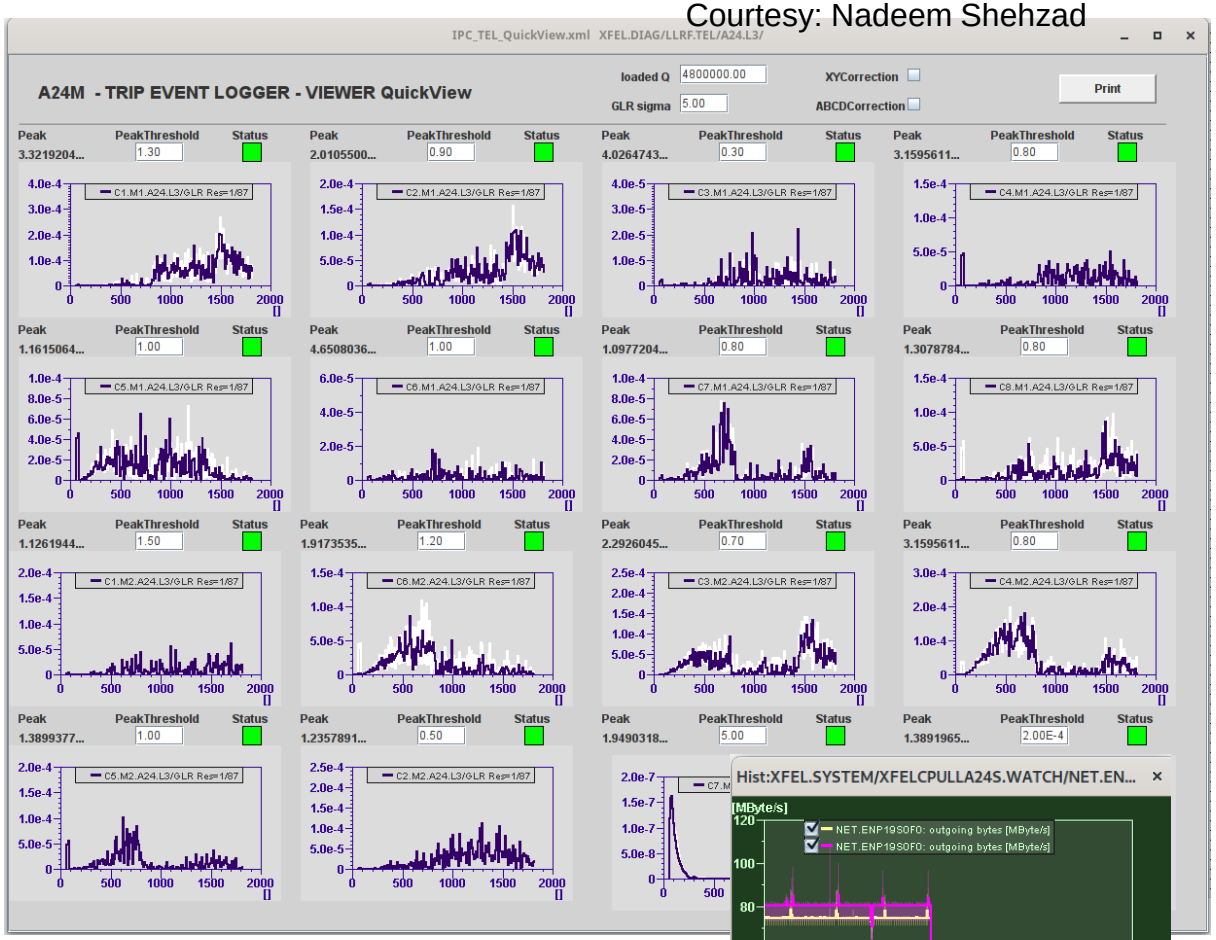
- Improvement on the classifier training
  - Efficient classifier (with respect to computation effort/ board resources and delays)
    - Neural architecture search
  - Multi-class classification (instead of binary classifier Quench/no Quench before)
    - Labelling as prerequisite



Prototype: Online anomaly detection in software

- Implementation in **C++** utilizing the **ChimeraTK software framework** to communicate with other servers
- **A24** as test station (**dedicated hardware** had to be installed: 2 servers + dedicated Ethernet communication links)
- Challenges and mitigations
  - Computing load on in-crate CPU → new dedicated server
  - Bandwidth limitations, DAQ packet loss → dedicated Ethernet connection
  - Getting the IQ components → data correction
  - Reliable beam information source (different station with a different timing) → synchronization with PIDs

Courtesy: Nadeem Shehzad



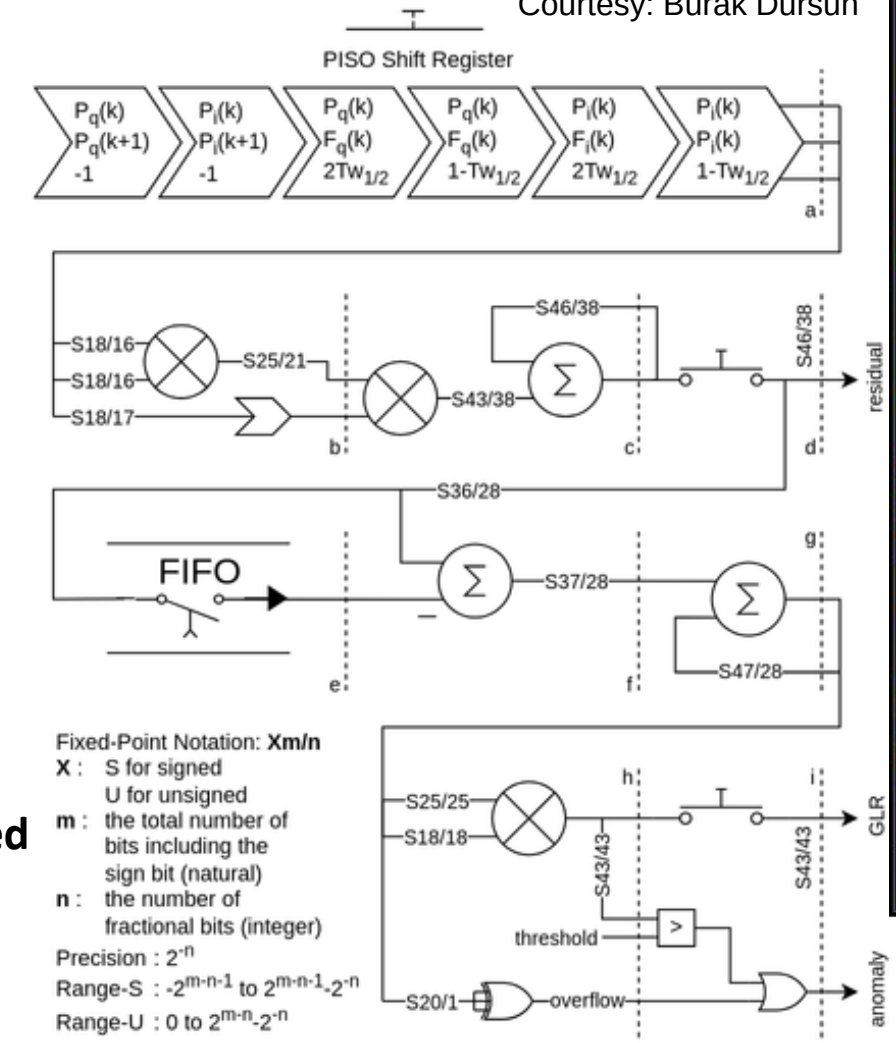
Outgoing traffic rises from 20 MB/s to 80 MB/s when anomaly detection is active (before new connection)

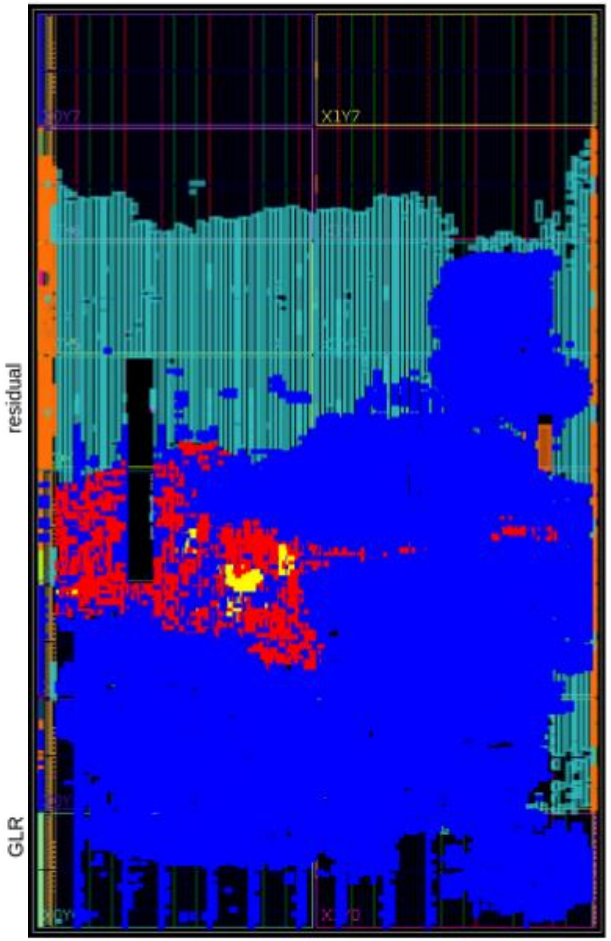
Prototype: Online anomaly detection in firmware

- Specifications
  - Implemented on DAMC-TCK7
  - Application clock: 81.25 MHz
  - Throughput: 1/7 clock cycles
  - Latency: 9 clock cycles for residual, 12 clock cycles for GLR, ~50us for K=450

- Challenges and mitigations
  - Sufficient performance and throughput while minimalizing resources → **optimized VHDL implementation** (future with NAS)
  - **Co-simulation** against software implementation
  - Careful scaling for **fixed-point operation** → co-simulation (python+SW)

Courtesy: Burak Dursun



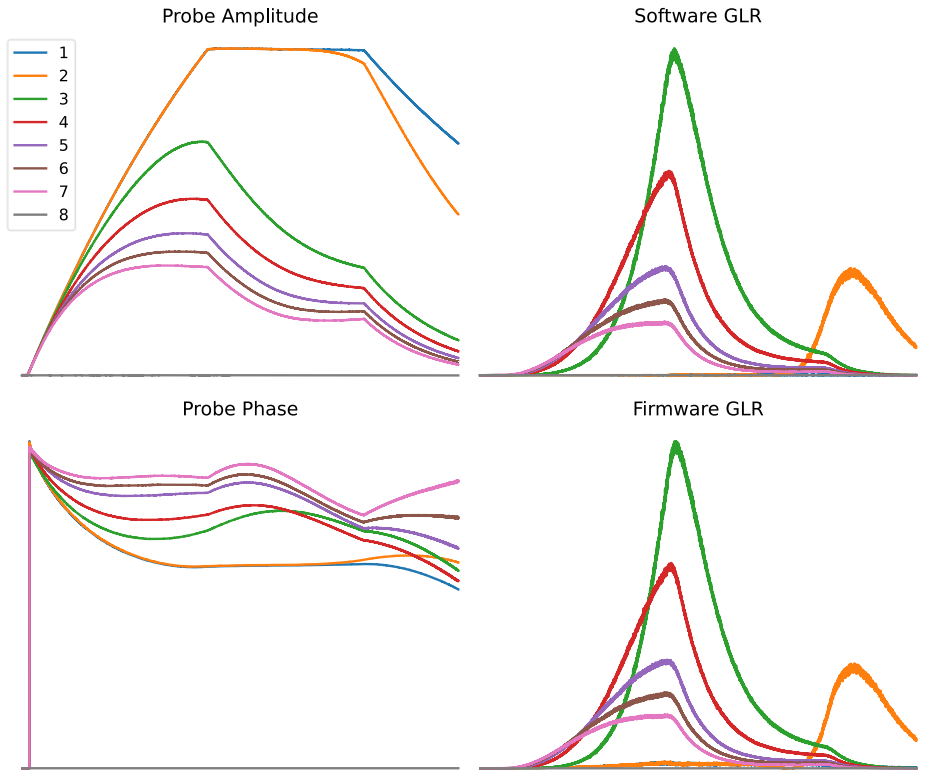


FPGA implementation layout (yellow: single cavity anomaly detection, red: anomaly detection for 15 cavities, blue: LLRF controller for 32 cavities)

Software vs firmware

Courtesy: Burak Dursun

Software	Firmware
Interpulse detection (10Hz) (many faults do not need intrapulse reaction)	**Intrapulse** detection → intrapulse reaction and mitigation (quenches)
Additional hardware → installation with **tunnel access**	**No additional hardware** → rollout **without tunnel access**
Easy prototyping	Very optimized implementation → time consuming and dedicated personnel
Modular	

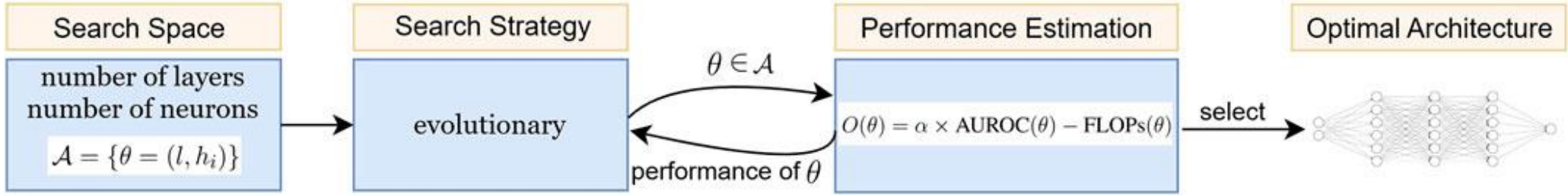


Eichler, A., Shezad, N., et. al. (2025). Enhancing quench detection in SRF cavities at the EuXFEL: Towards machine learning approaches and practical challenges. IPAC25. https://doi.org/ 10.18429/JACoW-IPAC25-THPS134 (to appear)

Courtesy: Lynda Boukela

Neural architecture search (NAS)

- **Goal**: find a **light-weight neural network architecture** for **FPGA deployment**
- Trading of **complexity vs. performance** by optimization



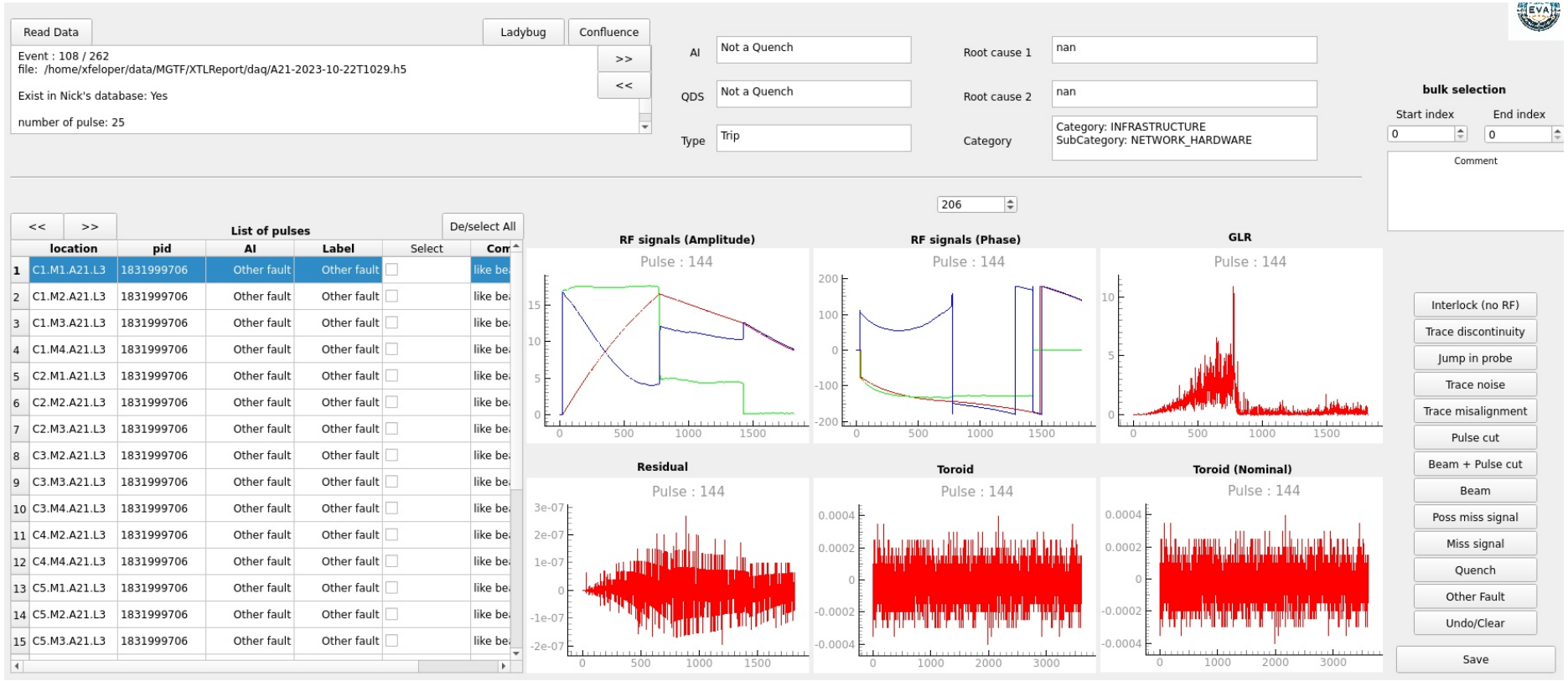
Anomaly measure	Model	AUROC	FLOPS	SIZE
EUC	NAS	0.9950	11367	10847
	Manual	0.9903	38305	37537
DTW	NAS	0.9662	241	193
	Manual	0.9665	551	471

Boukela, L., Branlard, J., & Eichler, A. (2025). Exploring NAS for anomaly detection in superconducting cavities of particle accelerators. Frontiers in Physics, 13. https://doi.org/10.3389/fphy.2025.1553993

Courtesy: Lynda Boukela

Multi-class classification: Expert labeling

- EVA: tool for **eased data labelling**
  - Bringing together **all information from different sources** (QDS, root cause by Nick's data base → note all are event-wise not pulse-wise)



Deviations from plan

- Personal left
  - New personal had to jump in
  - Outsourcing to MSK software and firmware group (schedule of these groups are full → delays)
  - Adaption of content → at the beginning less implementation, more algorithmic development (NAS)
- Installation in tunnel
  - Failed hardware and long delivery times
  - Limited access for tunnel installation → delays

Timeline

Date / Period	Milestone Description	New Date/ Period
Q4/2021	Hire software expert Reason: the person hired left, new hire process	Q2/2022
Q4/2023	Module integration of signal calibration (PostDoc) Reason: delays in unifying the firmware and software implementation	Q4/2025
Q2/2023	Online implementation of the trip event logger (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q4/2024
Q4/2022	In-depth offline analysis Reason: the person in charge left, new PhD student jumped in	Q2/2025
Q3/2023	Online analysis of the cavity module (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q3/2024
Q4/2022	Hire PostDoc	
Q3/2023	Scalable solution of the infrastructure (PostDoc) Reason: Several attempts to get system in tunnel up and running combined with limited opportunity to access tunnel	Q3/2024
Q4/2023	Fault classification and data labeling in one subsystem (PostDoc)	Q4/2025
Q3/2024	Infrastructure updates for feedback to allow system recovery and fault prevention (PostDoc) → good progress, not finished	Q4/2025
Q4/2024	Continuous learning through human in the loop strategy with the active labeling → started, delayed Q4/2025	Q2/2025
Q2/2025	Analysis of the overall system with regard to all modules and capabilities (PostDoc)	

Timeline + Deviations

Date / Period	Milestone Description	New Date/ Period
Q4/2021	Hire software expert Reason: the person hired left, new hire process	Q2/2022
Q4/2023	Module integration of signal calibration (PostDoc) Reason: delays in unifying the firmware and software implementation	Q4/2025
Q2/2023	Online implementation of the trip event logger (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q4/2024
Q4/2022	In-depth offline analysis Reason: the person in charge left, new PhD student jumped in	Q2/2025
Q3/2023	Online analysis of the cavity module (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q3/2024
Q4/2022	Hire PostDoc	
Q3/2023	Scalable solution of the infrastructure (PostDoc) Reason: Several attempts to get system in tunnel up and running combined with limited opportunity to access tunnel	Q3/2024
Q4/2023	Fault classification and data labeling in one subsystem (PostDoc)	Q4/2025
Q3/2024	Infrastructure updates for feedback to allow system recovery and fault prevention (PostDoc) → good progress, not finished	Q4/2025
Q4/2024	Continuous learning through human in the loop strategy with the active labeling → started, delayed Q4/2025	Q2/2025
Q2/2025	Analysis of the overall system with regard to all modules and capabilities (PostDoc)	

- Personal left
  - New personal had to jump in
  - Outsourcing to MSK software and firmware group (schedule of these groups are full → delays)
- Installation in tunnel
  - Failed hardware and long delivery times
  - Limited access for tunnel installation

Timeline + Deviations

Date / Period	Milestone Description	New Date/ Period
Q4/2021	Hire software expert Reason: the person hired left, new hire process	Q2/2022
Q4/2023	Module integration of signal calibration (PostDoc) Reason: delays in unifying the firmware and software implementation	Q4/2025
Q2/2023	Online implementation of the trip event logger (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q4/2024
Q4/2022	In-depth offline analysis Reason: the person in charge left, new PhD student jumped in	Q2/2025
Q3/2023	Online analysis of the cavity module (PostDoc) Reason: the person in charge left, new PhD student jumped in	Q3/2024
Q4/2022	Hire PostDoc	
Q3/2023	Scalable solution of the infrastructure (PostDoc) Reason: Several attempts to get system in tunnel up and running combined with limited opportunity to access tunnel	Q3/2024
Q4/2023	Fault classification and data labeling in one subsystem (PostDoc)	Q4/2025
Q3/2024	Infrastructure updates for feedback to allow system recovery and fault prevention (PostDoc) → good progress, not finished	Q4/2025
Q4/2024	Continuous learning through human in the loop strategy with the active labeling → started, delayed Q4/2025	Q2/2025
Q2/2025	Analysis of the overall system with regard to all modules and capabilities (PostDoc)	

- Content changes
  - Personal left
  - Adapt to skills of personal

Risks to R&D Project

- Helps needed from other groups (software and firmware) → strong involvement
- Personal (difficulties in hiring and keeping personal with the right skill set)

Outlook / Summary

- Outlook
  - Protoype:
    - Software solution: **Improvements** (offline feature, data analysis, etc.) in the LIMP, afterwards **testing**
    - Firmware: **Codesign** and implementation of classifier
  - Classifier
    - Model training and evaluation
    - **Active learning**

- **Publications**

  - Eichler, A., Shezad, N., et. al. (2025). Enhancing quench detection in SRF cavities at the EuXFEL: Towards machine learning approaches and practical challenges. IPAC25.
  - Boukela, L., Branlard, J., & Eichler, A. (2025). Exploring NAS for anomaly detection in superconducting cavities of particle accelerators. Frontiers in Physics, 13.
  - Boukela, L., Eichler, A., Branlard, J., & Jomhari, N. Z. (2024). A Two-Stage Machine Learning- Aided Approach for Quench Identification at the European XFEL. 12th IFAC SafeProcess
  - Eichler, A., Branlard, J., & Timm, J. H. K. (2023). Anomaly detection at the European X-ray Free Electron Laser using a parity-space-based method. Physical Review Accelerators and Beams, 26(1). https://doi.org/10.1103/physrevaccelbeams.26.012801