Fault diagnosis for the LLRF system at the European XFEL

5th Round Table on Deep Learning at DESY

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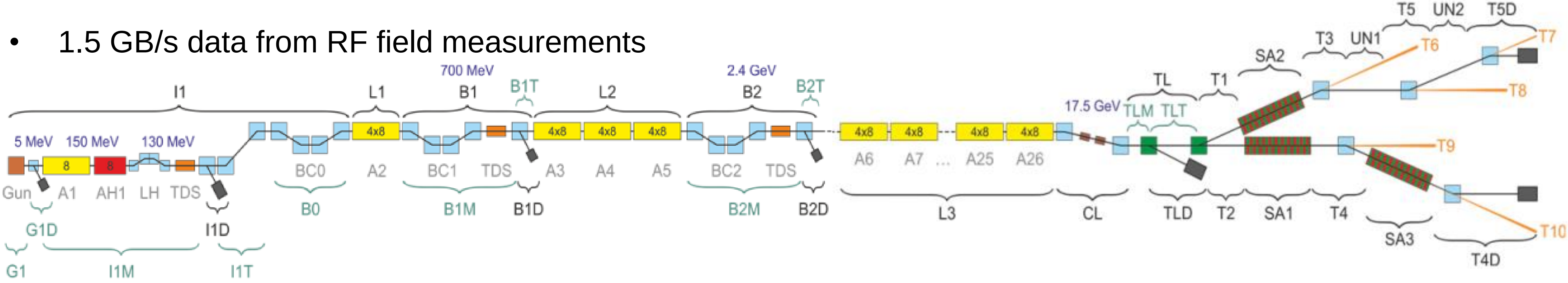
The low-level RF system

For acceleration and energization

- Tesla type cavity (1.3GHz)
- 25 LLRF station with ~ 4 cryomodules per station
  - 8 cavities per cryomodule
  - 32 cavities per station (controlled via one vector sum)
  - 808 superconducting cavities
- 10 pulses per second of 1.8 ms length
  - ~ 700 Million pulses a day
- 9 MHz sampling frequency → 16384 samples per pulse
- 1.5 GB/s data from RF field measurements

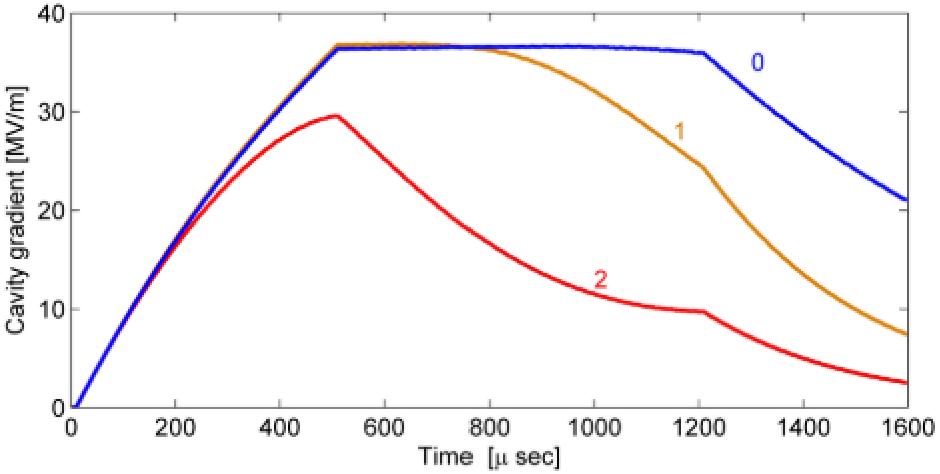


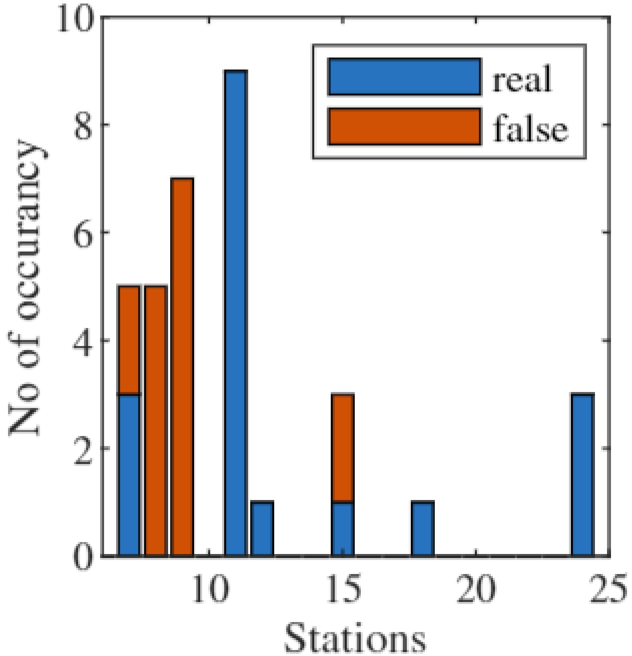
Failures and data in the LLRF system

In operation at European XFEL

- **Quench**
  - Severe cavity fault
  - Loss of superconductivity of the cavity walls
- **Database of failures**
  - A lot of nominal healthy data
  - ~1700 datasets failures saved since autumn 2019
  - Nearly the same format
  - Known that they are failures, but no labels to trust for 100%
  - Soft quenches are not so easy to detect
  - False positive
    - 07/08/2020 till 11/18/2020, 34 snap shots were saved triggered by the quench detection (thanks to Nicholas Walker)
    - 18/34 were real quenches
    - Glitches, detuning or QL changes, field emitters…
  - No idea on false negatives

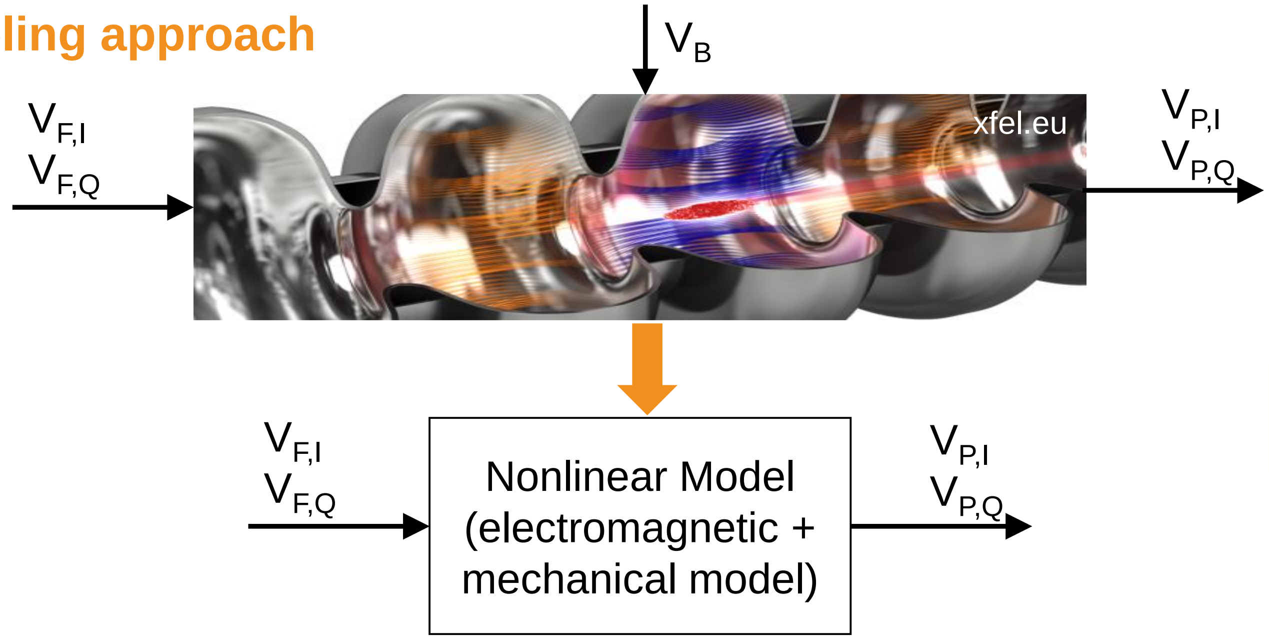
J. Branlard et. al., “Superconducting cavity quench detection and prevention for the European XFEL,” 16th International Conference on RF Superconductivity, 2013.





Hybrid model/data-based fault diagnosis

Modeling approach



V_B

$V_{F,I}$
$V_{F,Q}$

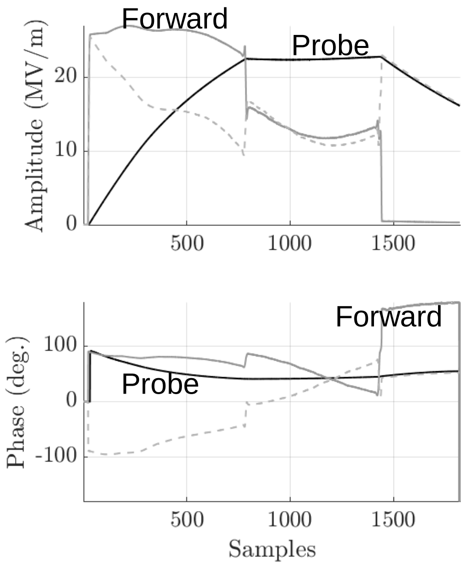
xfel.eu

$V_{P,I}$
$V_{P,Q}$

$V_{F,I}$
$V_{F,Q}$

Nonlinear Model
(electromagnetic +
mechanical model)

$V_{P,I}$
$V_{P,Q}$



Courtesy: Ayla Nawaz

Eletromagnetic oscillation

$$\begin{bmatrix} \dot{V}_{P,I}(t) \\ \dot{V}_{P,Q}(t) \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_{P,I}(t) \\ V_{P,Q}(t) \end{bmatrix}$$

$$+ 2\omega_{1/2} \begin{bmatrix} V_{F,I}(t) \\ V_{F,Q}(t) \end{bmatrix} - V_B(t) \begin{bmatrix} cos(\phi_P) \\ cos(\phi_P + \frac{\pi}{2}) \end{bmatrix}$$

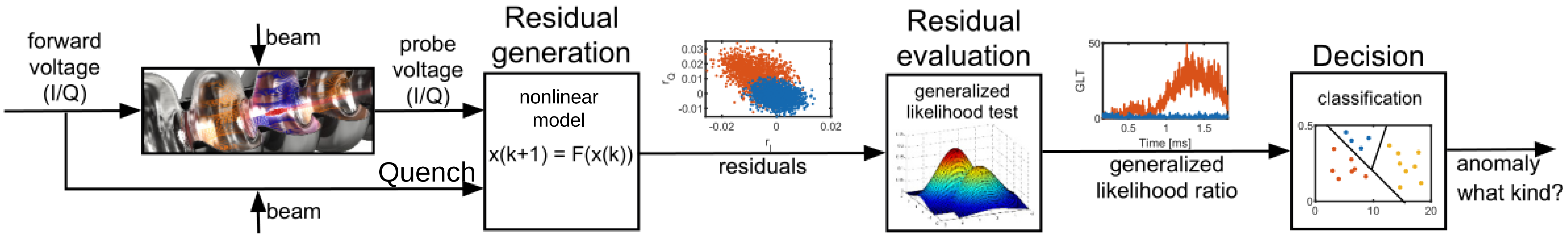
Mechanical deformation

$$\Delta\dot{\omega}_n(t) = -\frac{1}{\tau_n}\Delta\omega_n(t) + K_n\left(V_{P,I}^2(t) + V_{P,Q}^2(t)\right)$$

$$\Delta\omega(t) = \sum_{n=1}^{N} \Delta\omega_n(t) \ , \forall n = 1, \ldots, N \ .$$

Hybrid model/data-based fault diagnosis

Anomaly detection for the SRF cavities



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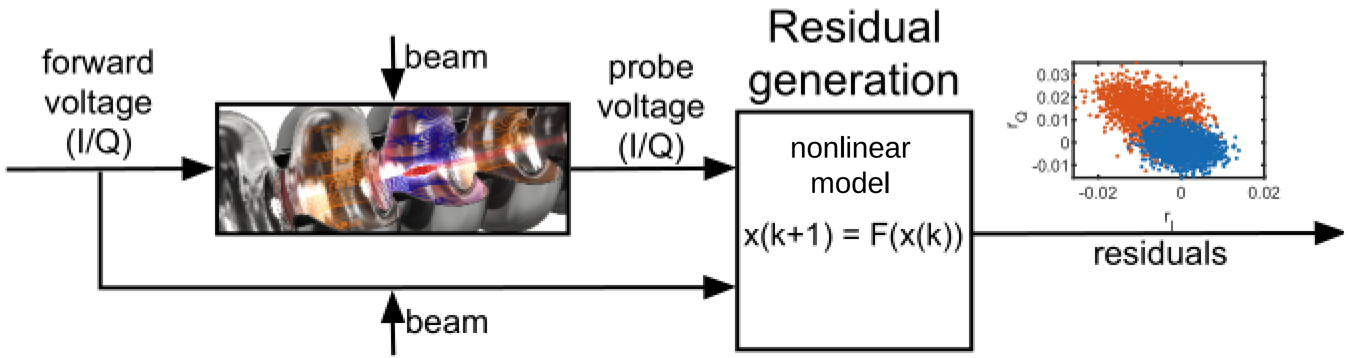

Parity space [1)]

- Solve both electromagnetic equations for detuning Δω
- Residual is the difference (small if model fits well, large otherwise)

\+ Little calculation effort

\- Sensitive to noise

Unscented Kalman filter [2)]

- Kalman filter for nonlinear systems
- Predict and update steps (weighting model and new measurements)

\- Calculation intensive

\+ Optimal filtering (if Gaussian noise)

Parameter estimation [3)]

- Calculate detuning Δω and half bandwidth ω1/2 from forward and probe signals

\+ Little calculation effort

\- Very sensitive to noise

\+ Good physical interpretability

[1)] A. Nawaz, et. al., Anomaly Detection for the European XFEL using a Non-linear Parity Space Method, *Proceedings of SafeProcess*, 51, 1379 (2018)

[2)] A. Nawaz, et. al., Probabilistic Model-Based Fault Diagnosis for the Cavities of the European XFEL, *at – Automatisierungstechnik* (2021).

[3)] A. Bellandi, et. al., Online Detuning Computation and Quench Detection for Superconducting Resonators, IEEE Trans. Nucl. Sci. 68, 385 (2021)

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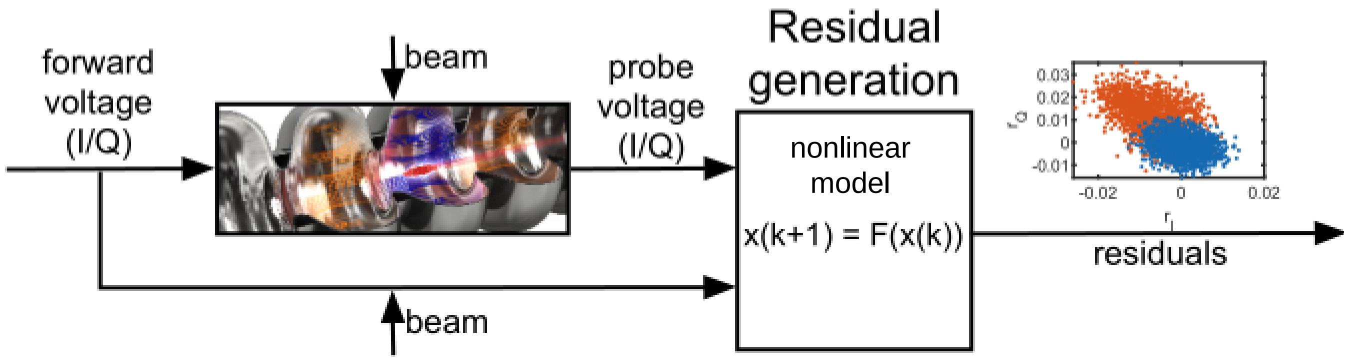

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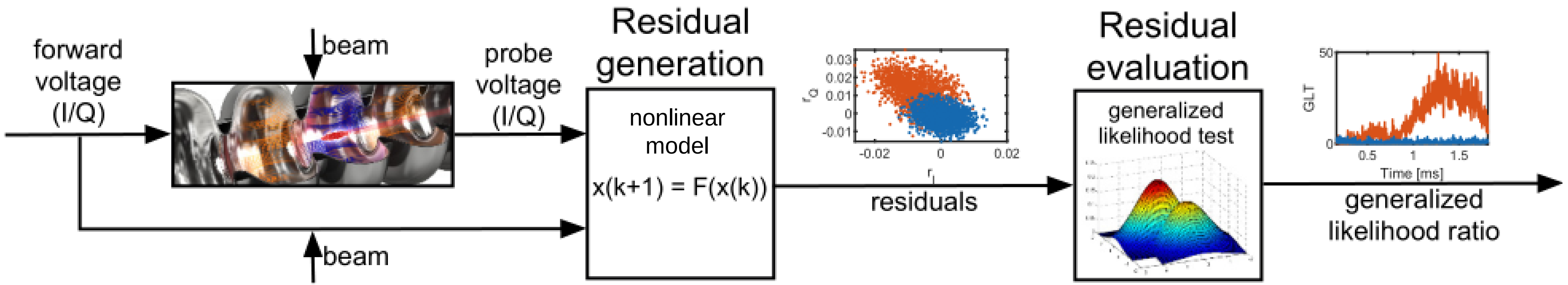
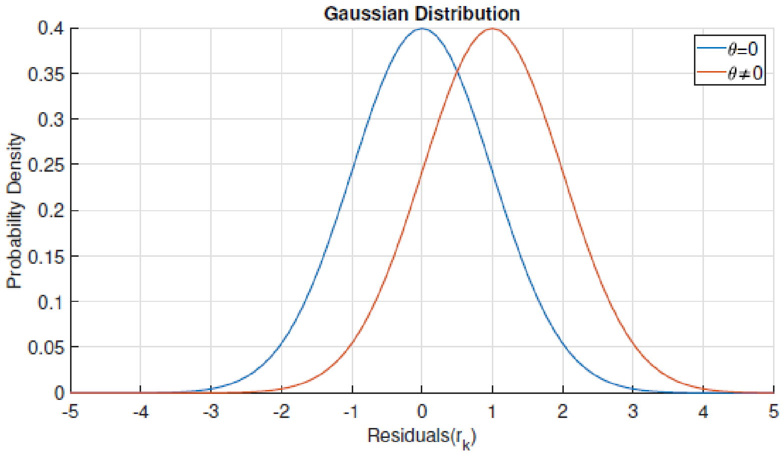


- **Generalized likelihood test**
  - Anomaly is significant change in otherwise white Gaussian process
  - GLR = Generalized likelihood ratio
  - GLR follows chi-square distribution
  - Choose a desired false positive rate



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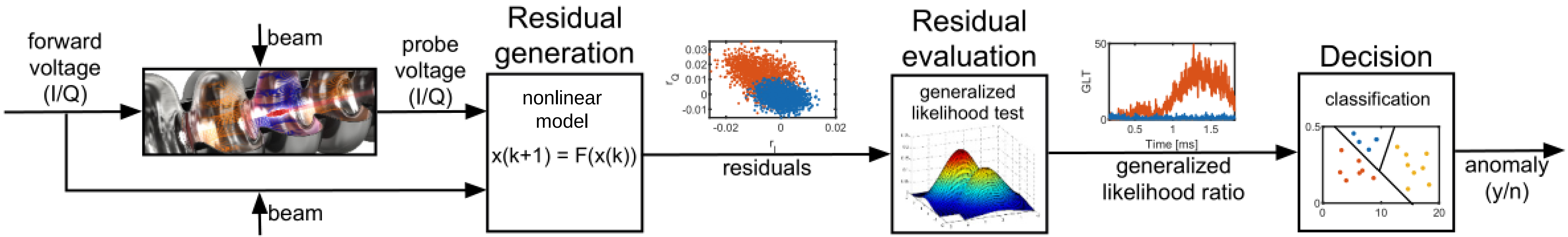
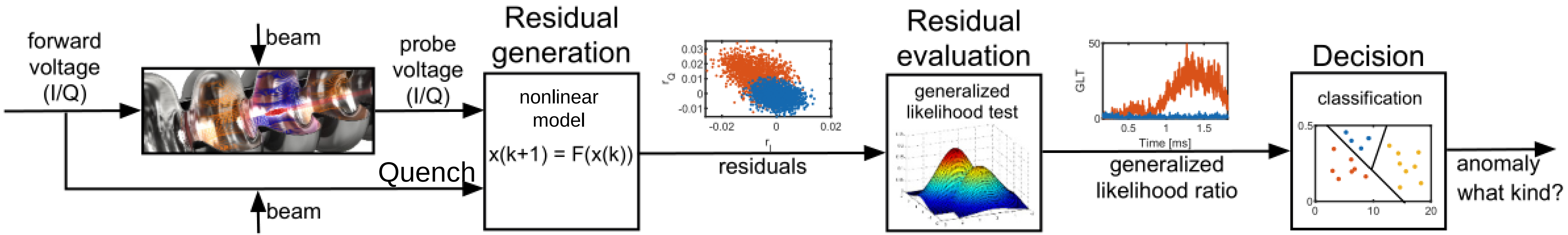


- **Decision**
  - Threshold test → anomaly (yes/no)

A. Eichler, J. Branlard, J.H.K. Timm., Anomaly Detection at the European XFEL using a Parity Space based Method, *arXiv preprint arXiv:2202.02051*

Hybrid model/data-based fault diagnosis

Anomaly detection for the SRF cavities


forward voltage (I/Q)

beam

probe voltage (I/Q)

Quench

beam

Residual generation

nonlinear model

x(k+1) = F(x(k))

residuals

Residual evaluation

generalized likelihood test

generalized likelihood ratio

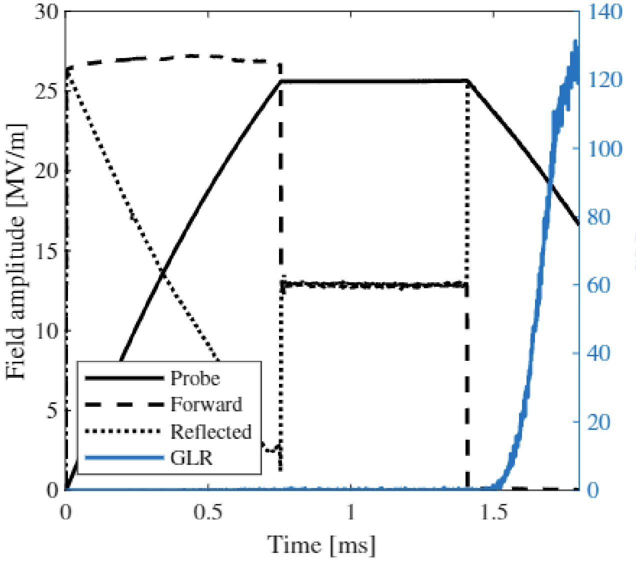
Decision

classification

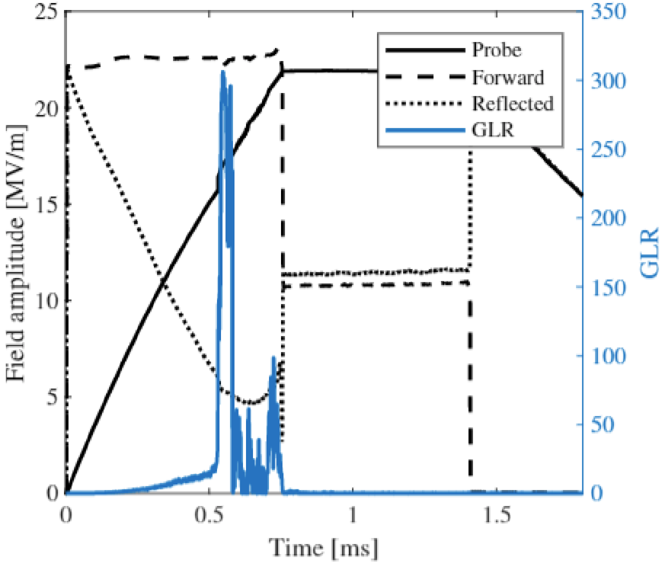
anomaly what kind?

- **Decision**
  - Threshold test → anomaly (yes/no)
  - Classify the different kinds of faults?
    - Clear distinction between different kind of faults
    - Amplification of small anomalies

Quench



Field emitter?



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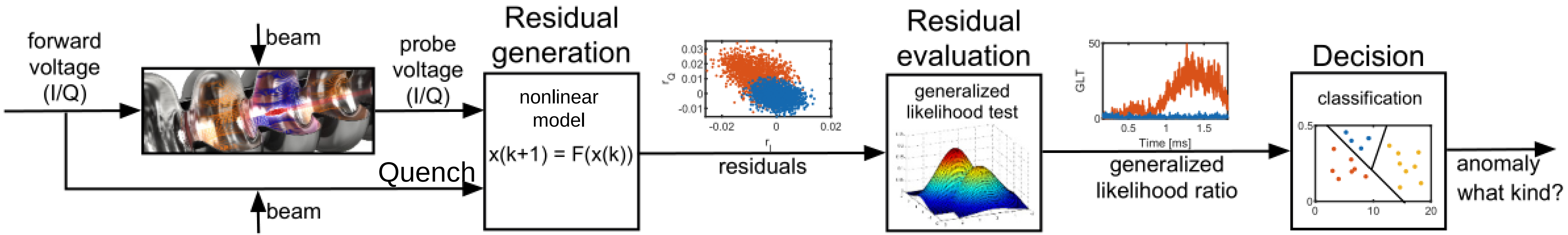
Anomaly detection for the SRF cavities



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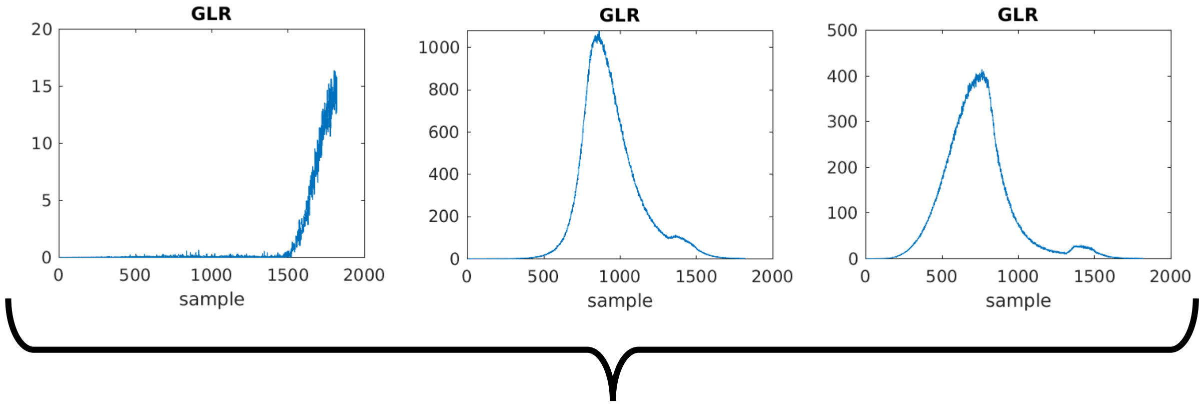
→ **Unsupervised classification**



All these signals are quenches?

Hybrid model/data-based fault diagnosis

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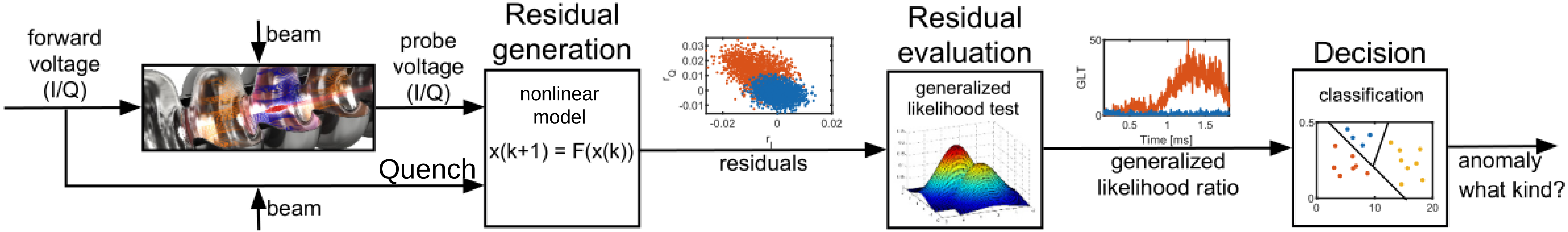
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- **Decision**
  - Threshold test → anomaly (yes/no)
  - Classify the different kinds of faults?
    - Clear distinction between different kind of faults
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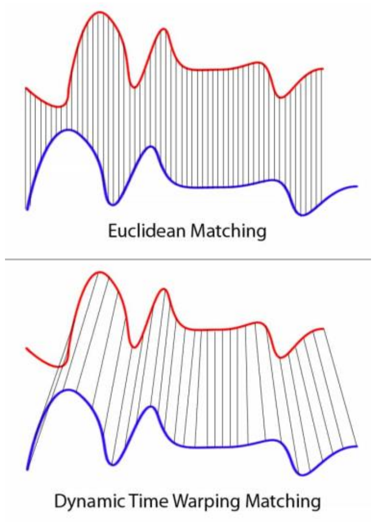
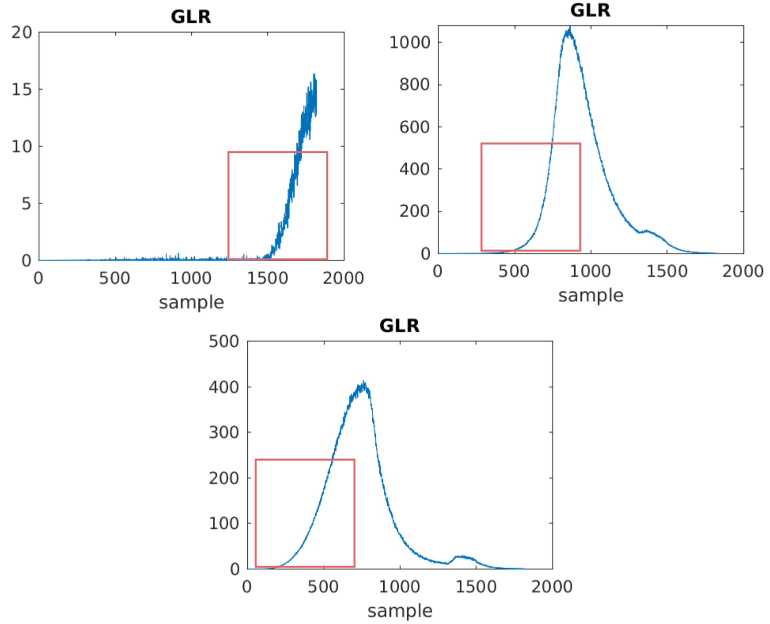
  - → **Unsupervised classification**
    - K-means clustering
    - Dynamic time warping / limited window



or



Results

Post mortem analysis

SUMMARY

602/1408 = 42.7557% pulses evaluated
446/453 = 98.4547% events evaluated

False negative

False positive

DTW	Quench (expert)	No quench (expert)
Quench	6.04%	4.19%
No quench	1.07%	88.71%

Limited window	Quench (expert)	No quench (expert)
Quench	5.61%	0.43%
No quench	1.49%	92.47%

Thanks to Julien Branlard

Automatic analysis for every day

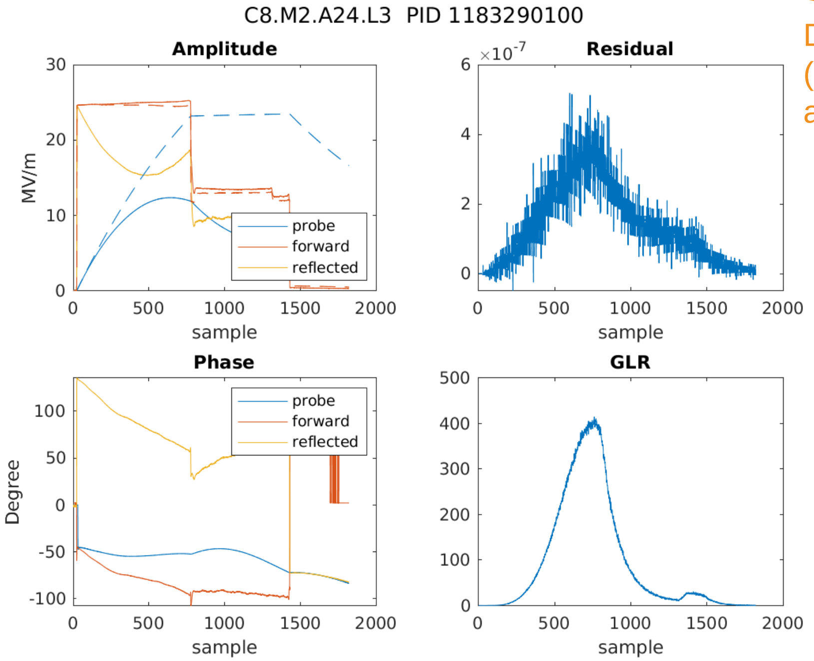
- Daily automatic evaluation of all trips that occurred
- Email is sent to LLRF experts

Quench (both algorithms agree)

In total 4 Events have been detected. 1 of them have been identified as quenches (0) and 3 and 0 as possible quenches (2) and (3).

location	timeStamp	anomaly	maxGradient
C8.M2.A24.L3	01-Oct-2021 14:10:19	2	23.47
C8.M2.A24.L3	01-Oct-2021 14:10:19	2	23.41
C8.M2.A24.L3	01-Oct-2021 14:10:19	0	19.29
C8.M2.A24.L3	01-Oct-2021 14:10:19	2	12.34

Disagreement (one says quench and other not)



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SUMMARY

602/1408 = 42.7557% pulses evaluated
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False negative

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DTW	Quench (expert)	No quench (expert)
Quench	6.25%	0.28%
No quench	0.85%	92.61%

Limited window	Quench (expert)	No quench (expert)
Quench	6.68%	0.43%
No quench	0.43%	92.47%

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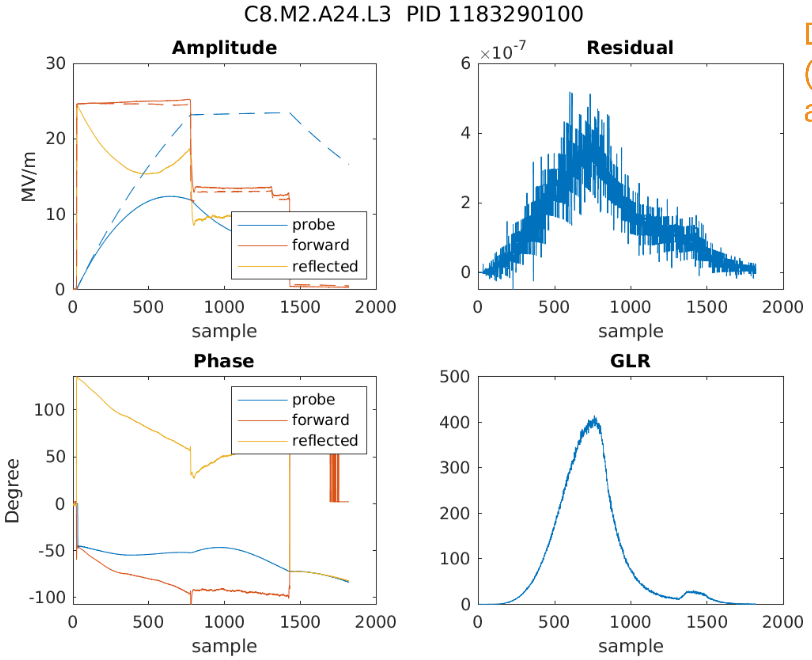

Conclusion

And summary

- Calculation speed is essential
- High-data rates and a lot of data channels
- Synchronization with given system
- Data bandwidth are the limiting factor
- Model is needed for hybrid approach
  - Alternative with purely data-driven approach (see Antonins talk)
- Good understanding of physics and feedback of the experts is essential
  - But here the underlying model helps for understanding

Next steps

- Bring it to online operation
- Software solution
  - C++ direct in our control system
  - Bandwidth limitations
  - Do the calculation in the tunnel
- Hardware solution

Thank you

Contact

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