Training and Detection of Anomalies at European XFEL

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Antonin Sulc

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CDCS
CENTER FOR DATA AND COMPUTING
IN NATURAL SCIENCES

DESY.

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What's an Anomaly

- a person or thing that is different from what is usual, or not in agreement with something else and therefore not satisfactory [Cambridge Dictionary]
- a thing, situation, etc. that is different from what is normal or expected [Oxford Dictionary]
- something different, abnormal, peculiar, or not easily classified [Merram-Webster]

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Overview

- What’s European XFEL.
- Diagnosis and predictive maintenance tasks on accelerator controls.
- **Example:** Quench detection with a purely data-driven model.
- **Example:** Anomaly detection on beam position monitors.

European XFEL - Overview

The European XFEL:

- Consists of a superconducting cavities that boosts electrons.
- The electrons are then directed through specially arranged magnets (undulators).
- Then they emit extremely short and intense X-ray flashes.
- These X-ray flashes are then distributed to three beamlines (SASE).

Data-Driven Predictive Maintenance on European XFEL

- Thousands of devices are involved in EuXFEL.
- Many components are operating in **extreme conditions** (radiation, heat...).
- At any moment, any component can **fail**.
- When a component fails, it can lead to undesired **downtime**.

Examples

(1) LLRF Cavities

- Monitoring signals from cavities.
- Detecting quenches and other faults.

(2) Orbit Monitoring

- Analyzing electron orbits in SASEs.
- Various types of problems are indicated by variations on orbits.

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(1) Superconducting Low-Level Radio Freq. Cavities

Cavities

- The superconducting LLRF cavities accelerate electron bunches.
- The electrons are accelerated by alternating electric fields.
- Trajectory is manipulated via a magnetic field.
- Superconductivity is important to maintain the efficiency.
- Very low temperatures (near absolute zero) are needed for superconductivity.

[Wikipedia contributors(2022)]

(1) Monitoring Superconducting LLRF Cavities

- We record an envelope (phase, amplitude) of three signals - probe, forward and reflected signals.
- Each signal consists of a pair of 1820 values (amplitude, phase) per pulse.
- Quench (right) means a loss of superconductivity in a cavity, which has a significant effect on the quality factor.

(1) Data-Driven Monitoring of Superconducting LLRF Cavities

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- Semi-supervised anomaly loss [Ruff(2019)]

$$L(\theta) = \|f_\theta(\mathbf{x}) - \mathbf{c}\|_2^y + \|f_\theta(\mathbf{x}) - \mathbf{c}\|_2 \text{ where } y \in \{-1, 1\}.$$

(1) Semi-Supervised Anomaly Loss

Semi-supervised anomaly loss [Ruff(2019)]

$$L(\theta) = \|f_\theta(\mathbf{x}) - \mathbf{c}\|_2^y + \|f_\theta(\mathbf{x}) - \mathbf{c}\|_2 \text{ where } y \in \{-1, 1\}.$$

(1) Results - Quenches

(1) Feature Space - TSNE of $f_\theta(\mathbf{x})$

Healthy / Faulty

Healthy / Healthy

(2) Orbit Monitoring

Assumption

There is a systematic pattern shown in orbits given by the physical construction of EuXFEL.

Orbit Monitoring - FODO Lattice

[Wendt(2011)]

[Holzer(2006)]

(2) Orbit Monitoring

(2) Orbit Monitoring

(2) Data-Driven Orbit Monitoring

Model-Based Orbit Monitoring

- Credits to **R. Kammering**.
- Fit a sine and measure residual.
- **Pros** It is **fast** and **intuitive**.
- **Cons** No intra-bunching instabilities.

Model-Free Orbit Monitoring

- Series of BPM read-outs.
- Train a model with the anomaly loss.
- **Pros** Takes into consideration intra-bunching instabilities.

(2) Model-Free Data-Driven Orbit Monitoring

- Stacked transformers that are scoring series of BPM read-outs
- Each input are stacked horizontal and vertical positions from all beamlines.
- We **do not** have any **faulty labels**.
- **Unsupervised one-class anomaly** loss [Ruff(2018)]:

$$L(\theta) = \|f(\mathbf{x};\theta) - \mathbf{c}\|_2$$

Beam is O.K.

Anomaly score s

TSNE Embedding of $f(\mathbf{x})$

Lowest score orbits

Highest scores orbits

PSM Board Failture

Anomaly score s

TSNE Embedding of $f(\mathbf{x})$

Lowest score orbits

Highest scores orbits

Undulator Crash

Anomaly score s

TSNE Embedding of $f(\mathbf{x})$

Lowest score orbits

Highest scores orbits

Phase Shifter Crash

Anomaly score s

TSNE Embedding of $f(\mathbf{x})$

Lowest score orbits

Highest scores orbits

Thank you for your attention!

This is the joint work of A. Eichler, R. Kammering and T. Wilksen!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Antonin Sulc
0000-0001-7767-778X
MCS DESY
antonin.sulc@desy.de

Bibliography I

BJ Holzer.
Lattice design in high-energy particle accelerators.
2006.

L Ruff.
Deep one-class classification.
In International conference on machine learning, pages 4393–4402. PMLR, 2018.

L Ruff.
Deep semi-supervised anomaly detection.
arXiv preprint arXiv:1906.02694, 2019.

Bibliography II

Manfred Wendt.
Overview of recent trends and developments for bpm systems.
Technical report, Fermi National Accelerator Lab.(FNAL), Batavia, IL (United States), 2011.

Wikipedia contributors.
Superconducting radio frequency — Wikipedia, the free encyclopedia, 2022.
URL https://en.wikipedia.org/w/index.php?title=Superconducting_radio_frequency&oldid=1102288054.
[Online; accessed 12-September-2022].