AI-driven optimization of operation and maintenance of future accelerators

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Acknowledgements: T. Cartier-Michaud, L. Felsberger, C. Obermair, colleagues from CERN EPC, MPE, RF groups

20/04/2023

Why should we use AI for design, operation and maintenance of particle accelerators?

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1. **Enhanced Performance and Efficiency**: Particle accelerators are complex and require precise tuning for optimal performance. AI can analyze large amounts of data, such as accelerator performance data, sensor readings, and experimental results, in real-time, and identify patterns and anomalies that may be difficult for humans to detect. This can lead to **improved accelerator performance, higher efficiency, and reduced downtime**, resulting in cost savings and increased productivity.
2. **Faster Design and Optimization**: Designing and optimizing particle accelerators can be time-consuming and labor-intensive. AI can assist in automating and accelerating the design process by using algorithms that can generate, simulate, and optimize accelerator configurations. This can result in **faster development cycles, reduced trial and error, and improved performance** of the accelerator.
3. **Predictive Maintenance**: Particle accelerators require regular maintenance to ensure smooth operation and prevent breakdowns. AI can analyze data from sensors, monitors, and other sources to predict potential equipment failures or performance degradation, allowing for proactive maintenance and minimizing unplanned downtime. This can **save time and resources**, as maintenance can be planned more efficiently, and costly equipment failures can be prevented.
4. **Enhanced Safety**: Particle accelerators can involve hazardous materials, high voltages, and other safety risks. AI can be used to monitor and analyze safety parameters in real-time, identifying potential safety hazards and triggering appropriate responses, such as shutting down the accelerator or activating safety protocols. This can **improve safety and reduce the risk of accidents** or incidents.
5. **Optimization of Experimental Parameters**: Particle accelerators are used in various scientific experiments, and the performance of the accelerator can impact the outcome of these experiments. AI can analyze experimental data, optimize experimental parameters, and recommend adjustments to achieve desired results. This can **save time and resources** in experimental trials, and potentially lead to faster scientific discoveries.
6. **Adaptive Control**: Particle accelerators often require precise control of various parameters to maintain desired performance. AI can provide adaptive control strategies that can continuously optimize accelerator parameters in real-time based on changing conditions, such as beam intensity, energy, and stability requirements. This can result in **improved accelerator performance and stability**, leading to better experimental results.

Why should we use AI…explained by AI

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Generated with ChatGPT

Possibilities for AI application are almost unlimited nowadays

Advantages vs disadvantages of AI

Advantages

- Unique capabilities to find patterns in data
- Flexibility (from data exploration to predictions)
- Easy scaling with complexity
- Alternative viewpoint on known problems
- Under continuous development

Disadvantages

- Data quality is key
- Steep learning curve
- Model results are intransparent
- Resource intensive
- Under continuous development

The AI Workflow

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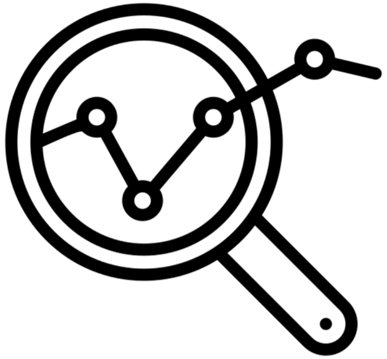
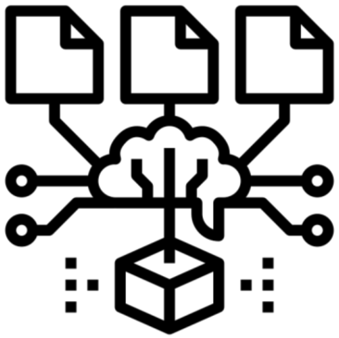
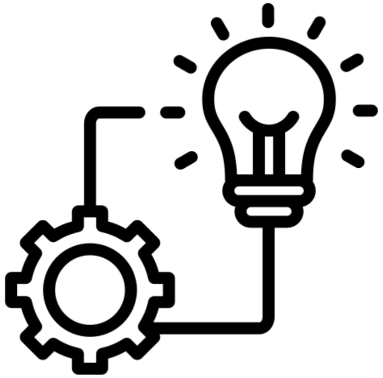
Data Cleaning
Prepare dataset for analysis



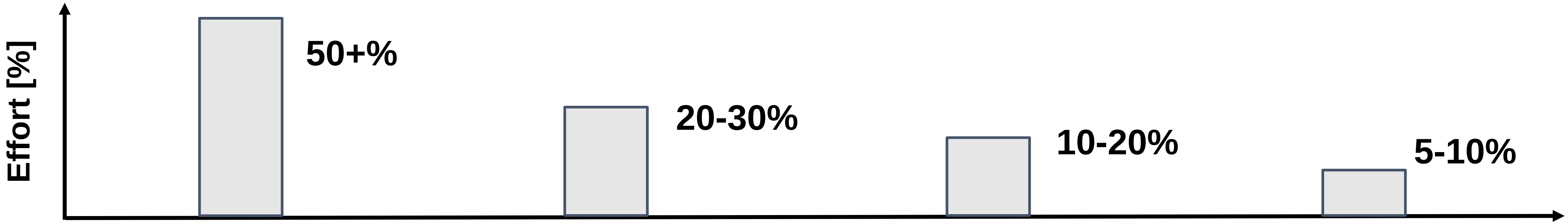
Exploration
Understand data, relevant features



Modelling
Classification, prediction,...

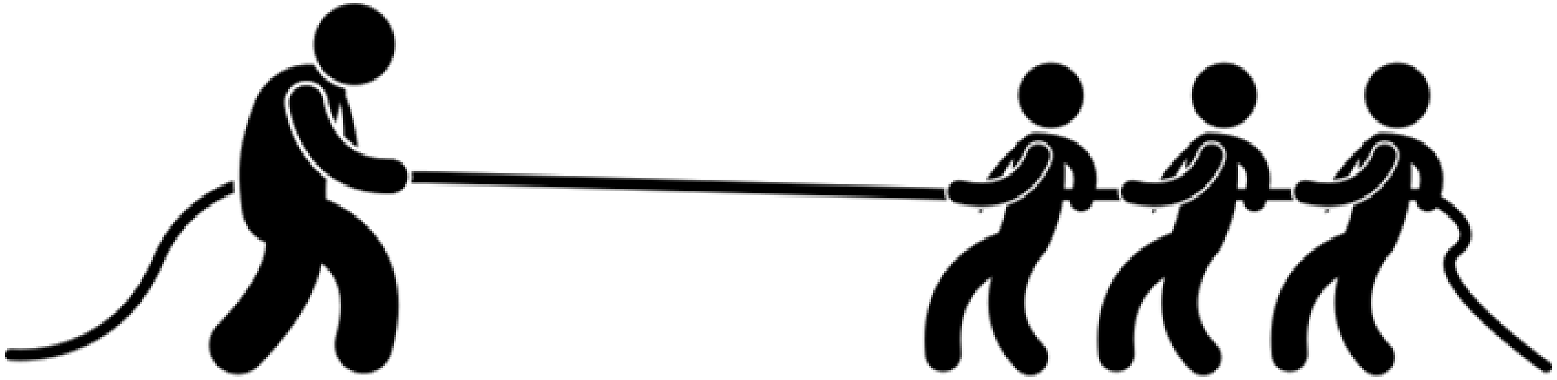


Implementation
Deploy model in operation setting



Challenges of next generation particle accelerators

Innovation
New technologies vs reliability



Enhanced safety
Asset protection
Personnel protection

Increased performance
Physics output
Number of patients treated
Neutron fluence
…

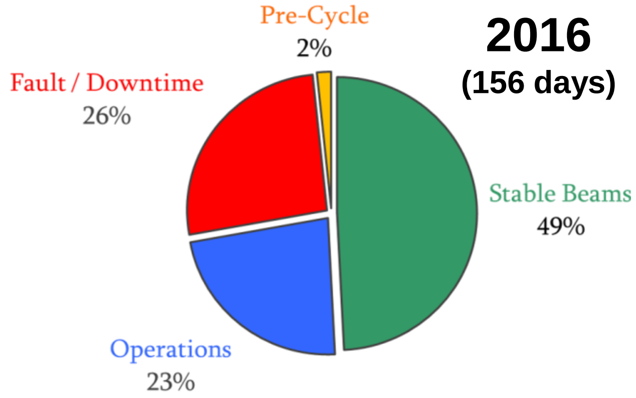
Sustainability/Reduced costs
Energy efficiency
Availability
Operational efficiency

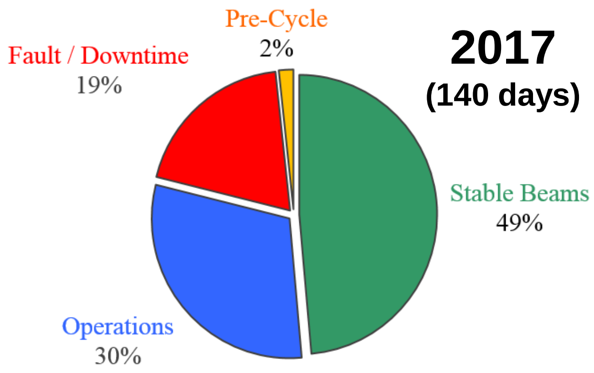
Can AI help to tackle these challenges?

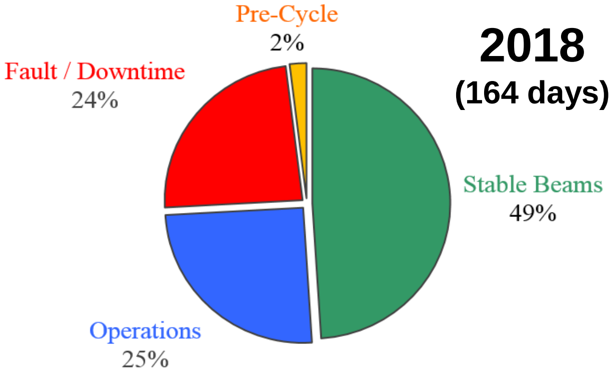
Accelerator availability

*References – Availability Working Group reports (2016, 2017, 2018)

LHC example (Run2)*:







Availability (A) is a measure of the useful time of accelerator operation

- A(reliability, maintainability)

Reliability (R) is a measure of the failure frequency

- R(number of systems, operating conditions)

Maintainability (M) is a measure of how fast we can recover from failures

- M(diagnostics time, logistics time, repair time)

Unfavorable scaling with increasing complexity

We need new ways to address this challenge in the future!

Can AI help for operation and maintenance of particle accelerators?

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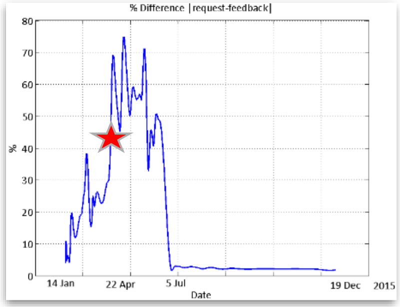
Failure

Identification



Diagnostics

Logistics

Repair

AI for anomaly detection and failure prediction

Switch from reactive to proactive approach

Remote/robotics maintenance

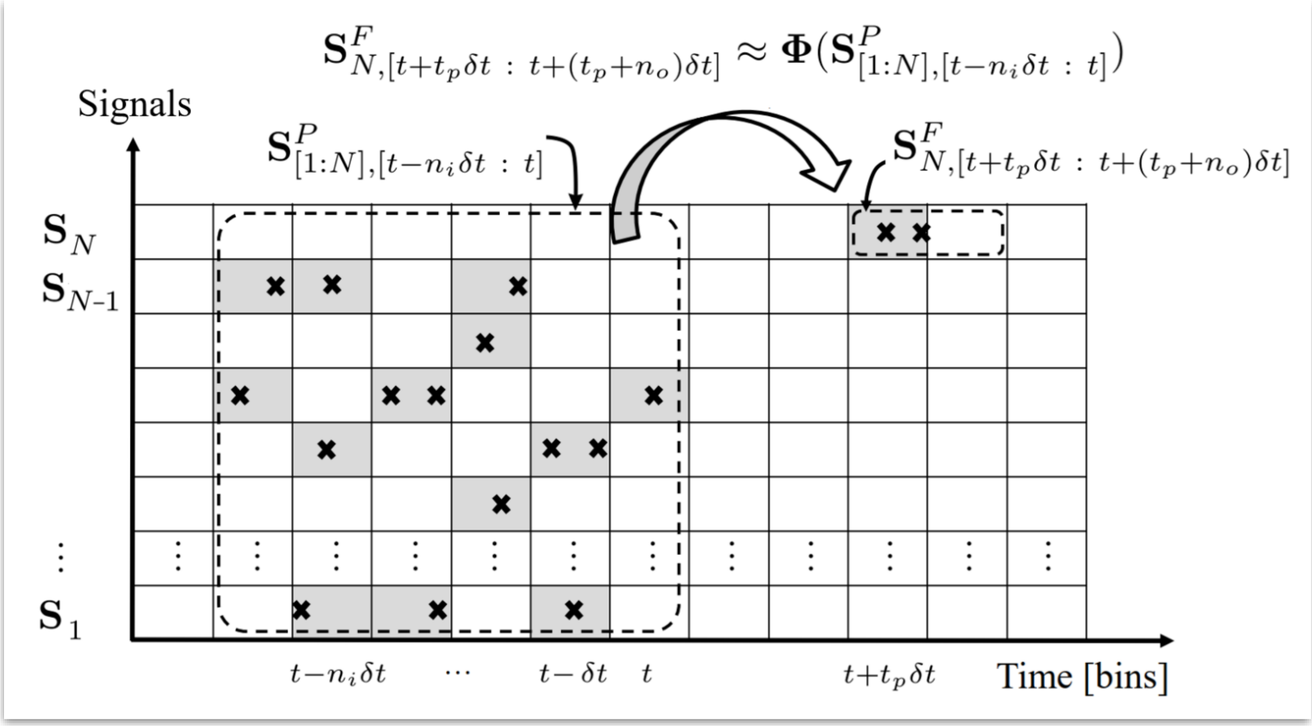
Switch from manual to automated

Failure identification example: PSB alarm system

Idea: use historical data from CERN PSB alarm system for failure prediction

Goal: identify failure precursors and hidden system dependencies in alarm system

Data sources: *alarm system*, fault tracker, operations logbook, system logbooks, AMMSs



Problems: synchronization of different data-sources, modification of alarm definitions, high class imbalance

Findings: failure precursors can be identified among N=100 signals with as low as 10 failure events in the training set

"Explainable Deep Learning for Fault Prognostics in Complex Systems: A Particle Accelerator Use-Case", L. Felsberger et al.

Failure identification example: CLIC RF breakdown prediction

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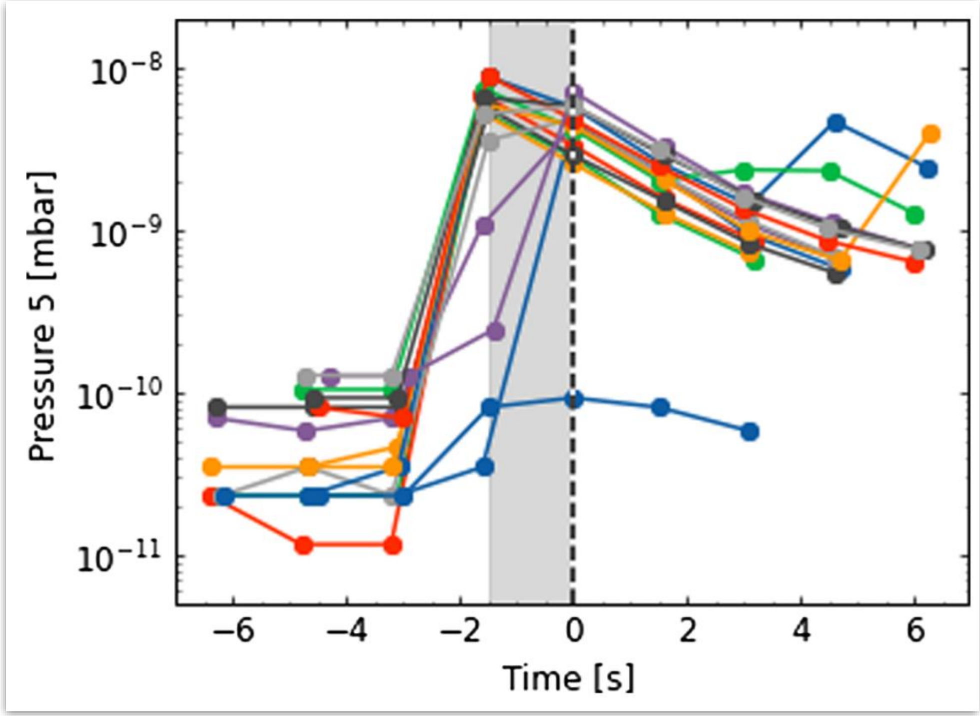
Idea: analyze data from CLIC RF test stand (XBOX) to predict the occurrence of breakdowns

Goal: improve conditioning (recovery algorithms) and optimize availability through dynamic failure compensation

Data sources: XBOX control system

Problems: synchronization of data acquisition devices, high class imbalance

t=0 breakdown



Findings:

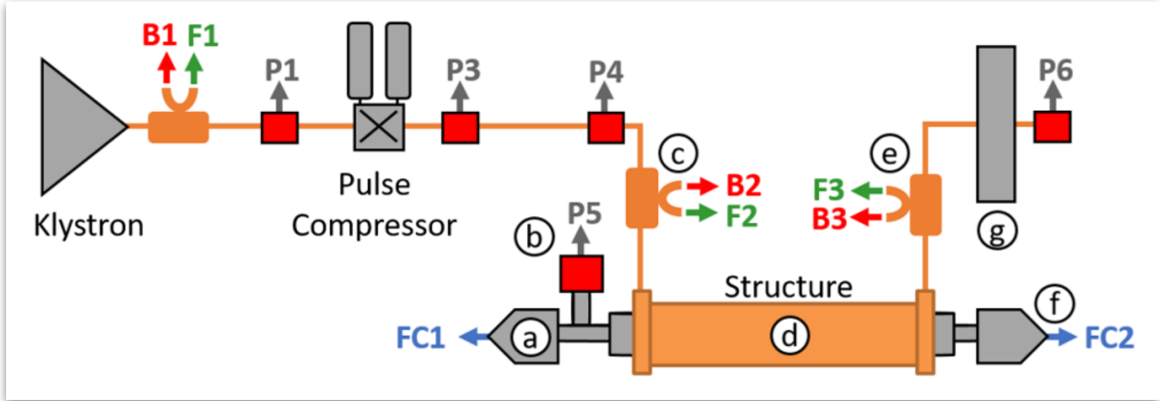
- Trend data (scalar): *possible* precursor of primary RF breakdowns (tbc with further tests)
- Event data (timeseries): 89.7% *accuracy* in the prediction of follow-up breakdowns

“Explainable machine learning for breakdown prediction in high gradient RF cavities”, C. Obermair et al.

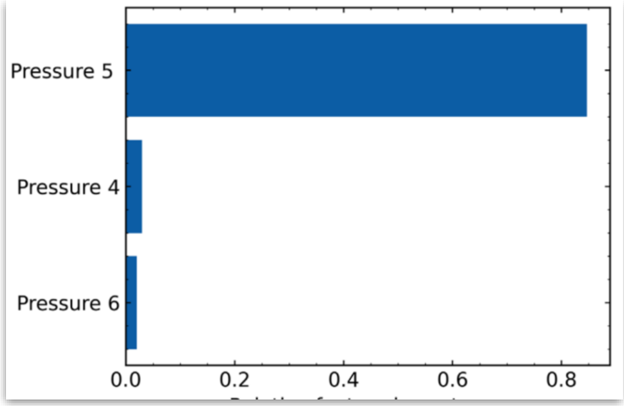
The role of explainable AI

- AI models often feel like “**black boxes**”, where given (large) inputs a result/action is returned
- Having control over model decisions can be an essential ingredient for a successful application of AI models, especially in **safety-critical applications**
- Explainable AI aims at “opening the black box” and providing **insights into model decisions**
- **SHAP values:** assess feature importance for model predictions

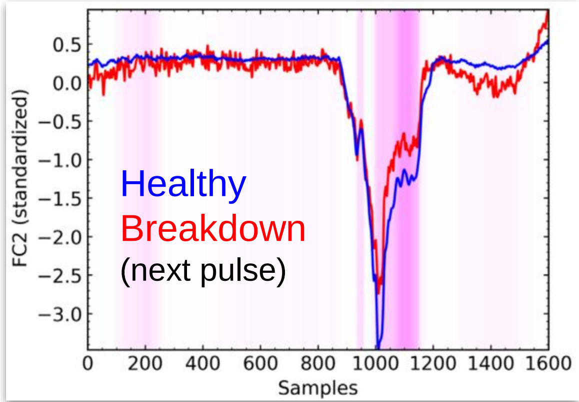
CLIC RF test setup



Feature importance



Trend data



Event data

[“Explainable machine learning for breakdown prediction in high gradient RF cavities”, C. Obermair et al.](#)

Diagnostics: use of Large Language Models

Operation and maintenance of particle accelerators relies on **highly trained staff**

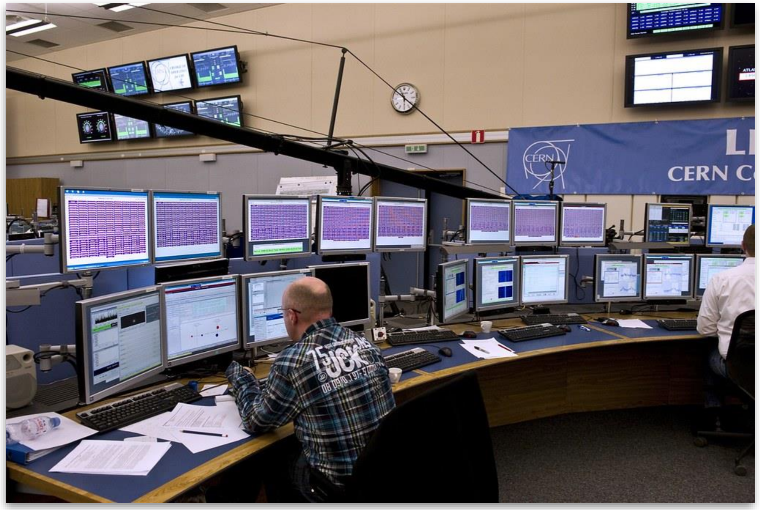
- Operators: problem identification and initial diagnostics
- On-call experts: dedicated support for complex problem resolution

Management of **organizational knowledge** is a great challenge for large research institutions

- Can be problematic in situations of high turnover
- Difficult to ensure continuity in case of key members leaving the organization

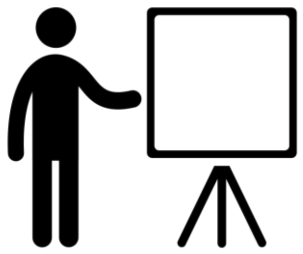
Latest developments in **Large Language Models** (LLMs) could help to develop solutions to increase operational efficiency

- Easy access to historical information
- Faster fault diagnostics and problem resolution

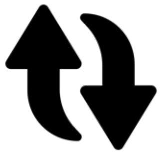


CERN Control Center

Organization of AI activities - my 2 cents



Accelerator expert



ML expert

Within an organization

Definition of case studies
(boundaries, constraints, data sources,...)

Support during data exploration and result interpretation

Data cleaning

Identification of models
suitable for case study

Model implementation

Across organizations

Definition of common case studies

Examples: beam control, failure prediction, dose delivery to patients

Standardization of data sources

Example: fault tracking systems

Identification of common AI solutions

Examples: models, deployment strategies

Conclusions and Outlook

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- AI shows extremely **high potential** for a wide range of applications in particle accelerators
- Close **collaboration** between accelerator experts and AI experts required for successful application
- Systems will have to be conceived to be **AI-friendly** in the future to fully exploit its potential
- Application of advanced methods for **anomaly detection and failure prediction** is a must for next generation particle accelerators
- Latest LLMs could be used to improve management of **organizational knowledge**

The most dangerous sentence in engineering:
“We have always done it this way”

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20/04/2023