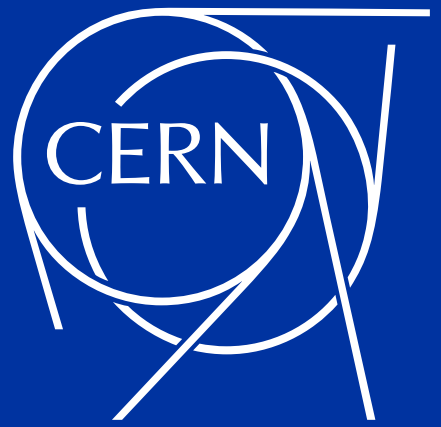


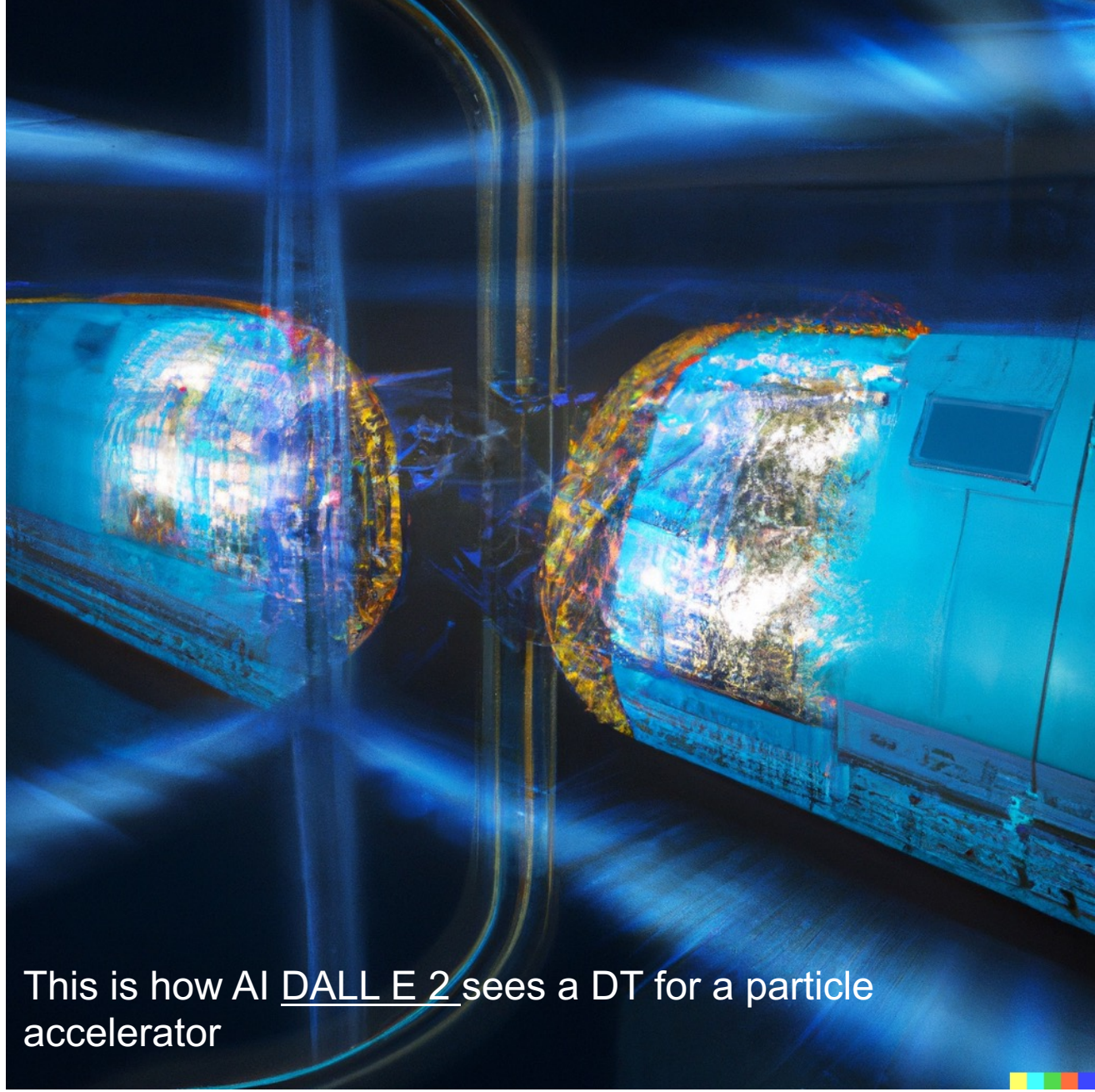
Digital Twin Application in Accelerators

Accelerator Reliability Workshop ’22 – **D. SMAKULSKA**, S. ATIEH on behalf of MME DT WG

2022-10-16/21

What is a Digital Twin?

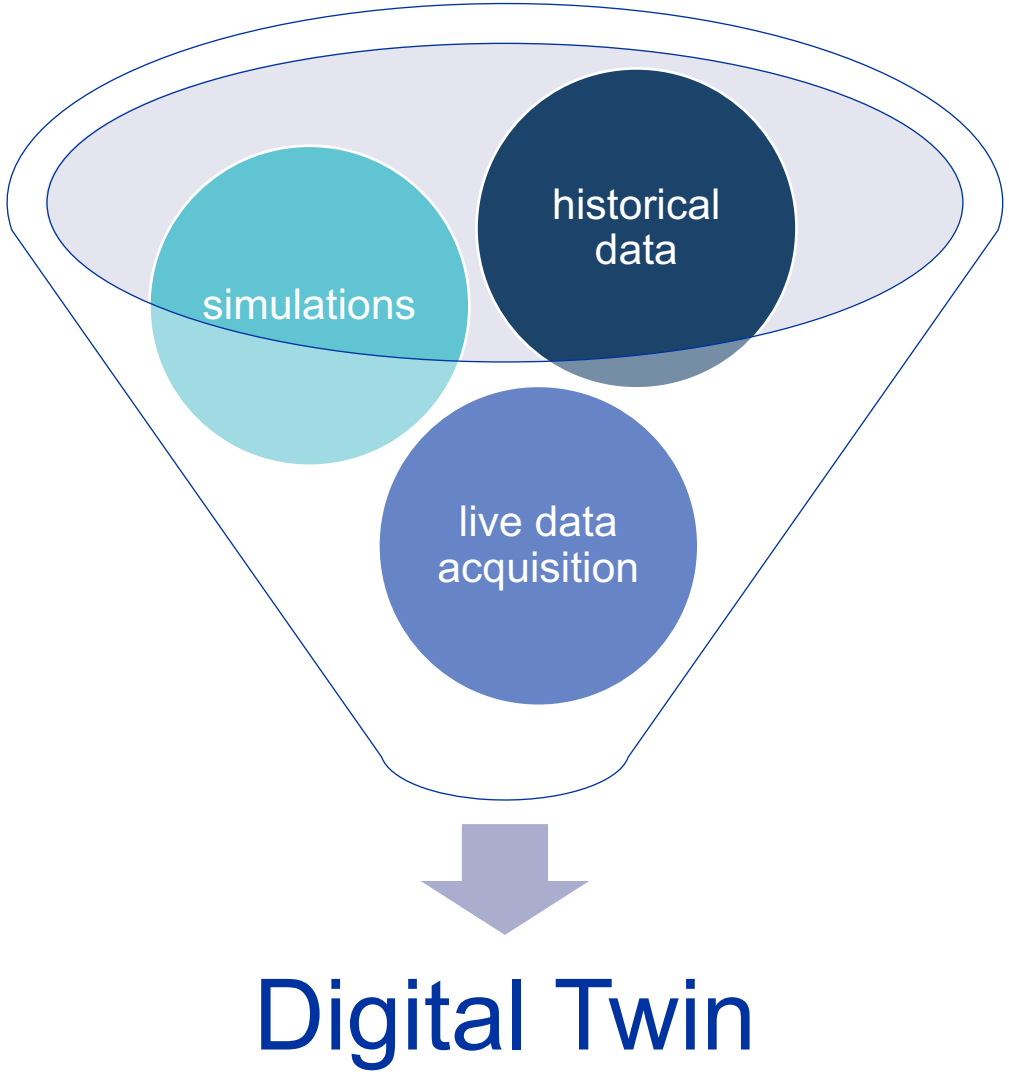
- **virtual representation/model** of an actual **physical asset in operation** (any physical asset: a machine, a building, a cat...)
- simulates the **physical behavior** in a **digital context**
- **mimicking** the behavior of a Physical Twin (PT)
- expected to respond to input variables in the same way as it's PT does



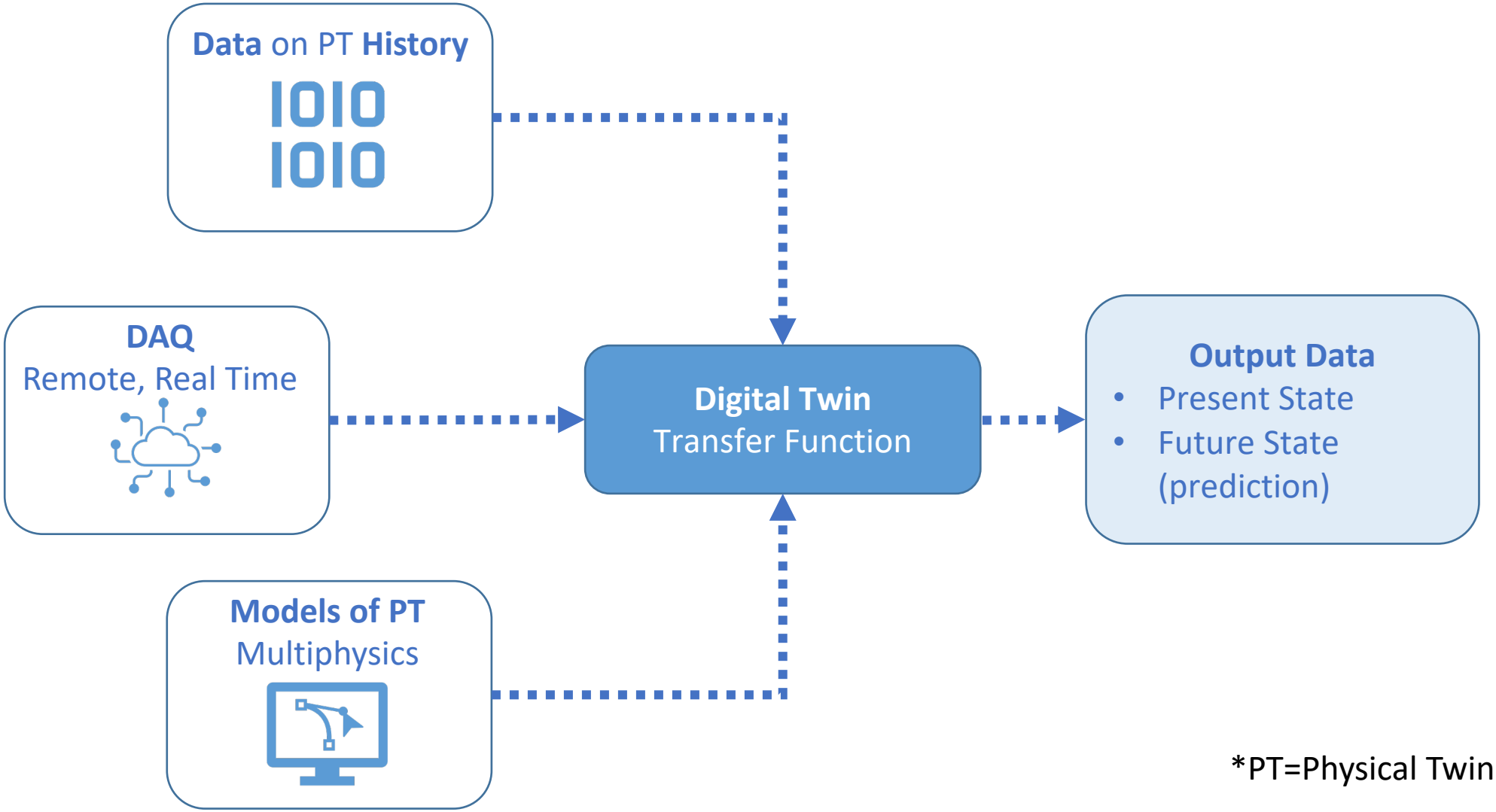
This is how AI DALL E 2 sees a DT for a particle accelerator

What is a Digital Twin?

- **Synergy of :**
  - models, simulations and empirical formulas
  - historical data
  - live data acquisition and interpretation
- **Industry 4.0**
- **DT can be “twining” the behavior of a component, a system of components or a system of systems**



Digital Twin for Mechanical Components



*PT=Physical Twin

Digital Twin for Mechanical Components - INPUTS

Data on PT **History**

DAQ
Remote, Real Time

Models of PT
Multiphysics

Results from Tests	Sensors	Simulation Results
Data Collected until “Now”	Device Telemetry	Empirical Formulas

Input and output features of the Digital Twin are always reflecting the characteristics of a specific asset, reflecting the needs of operator/end-user/critical scenarios

–

there is no “golden rule” of how many inputs and outputs are necessary

Digital Twin– a core

Based on the type and amount of data for a Digital Twin „core”, different approaches can be taken:

Machine Learning

- Clear definition of features
- **Small** dataset – when dataset is too big, there is a **risk of overfitting** the algorithm during the learning process which results in noise in the output data
- **Training time** is relatively **short**
- Eg. **ScikitLearn** library for Python

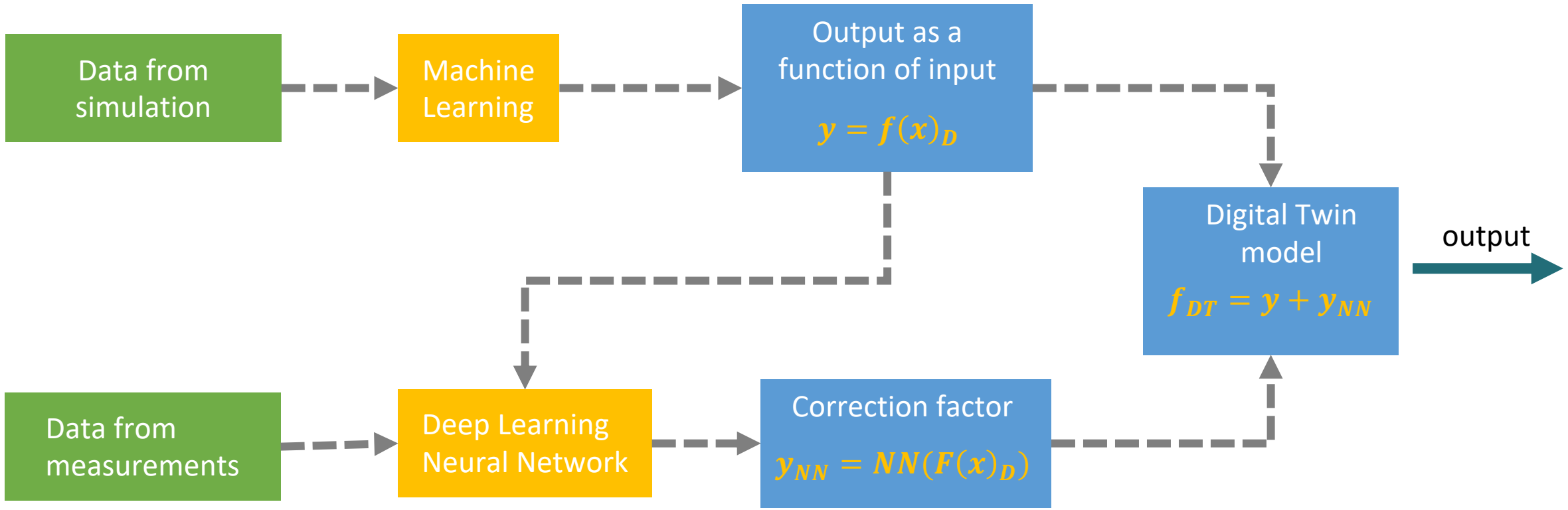
Deep Lerning

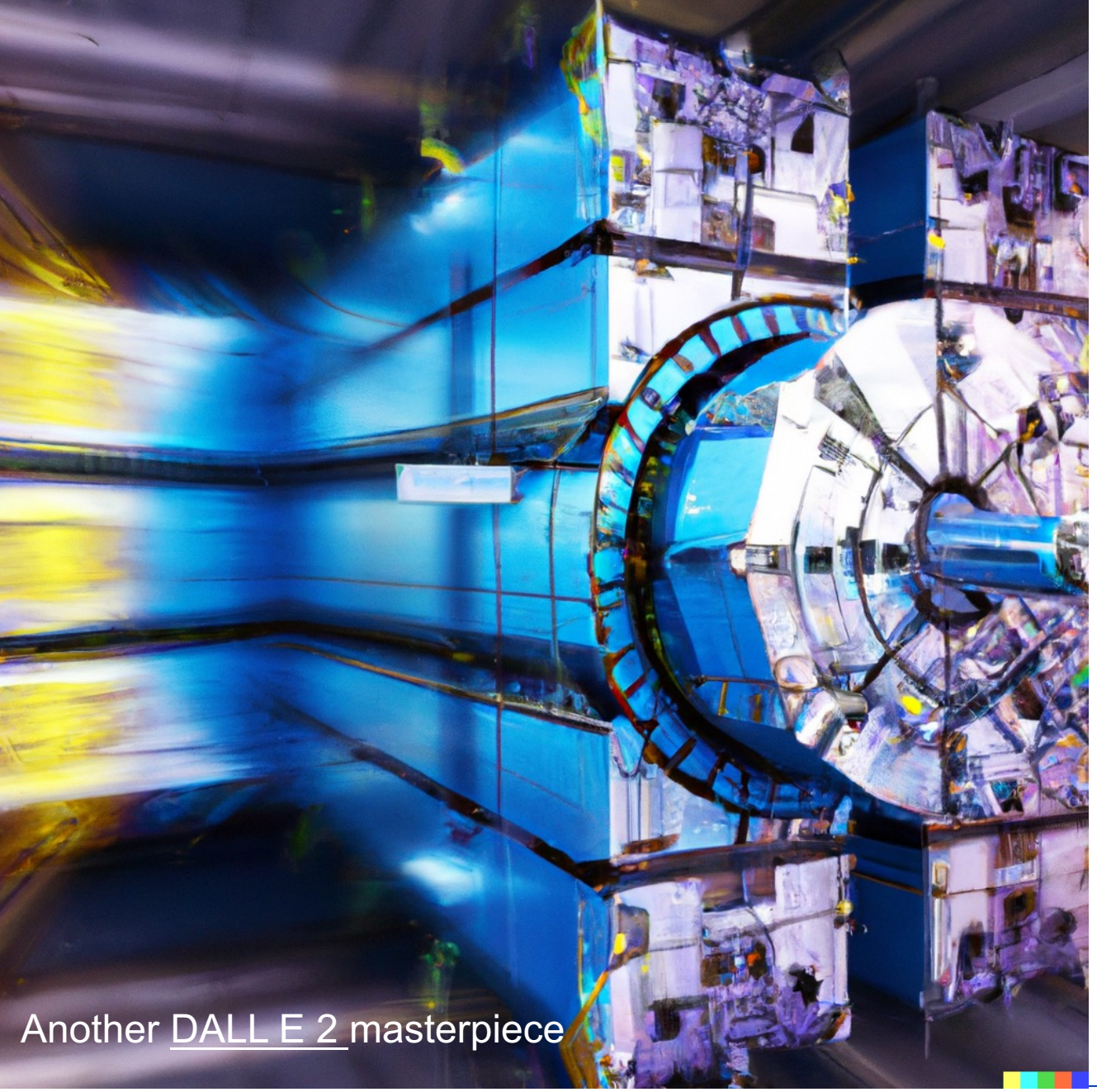
- No need of features definition
- **Big** dataset – when dataset is small, deep learning algorithms do not perform well
- **Training time** is relatively **long**
- Eg. **Keras** library for Python

Hybrid

- **Improving an empirical or semi-empirical models** with gathered experimental data
- Obtaining a correction factor for **empirical formula** based on collected data
- **Empirical formulas corrected with Machine Learning or Deep Learning**

Digital Twin– Transfer Function – hybrid example





Another DALL E 2 masterpiece

Digital Twin - OUTPUT

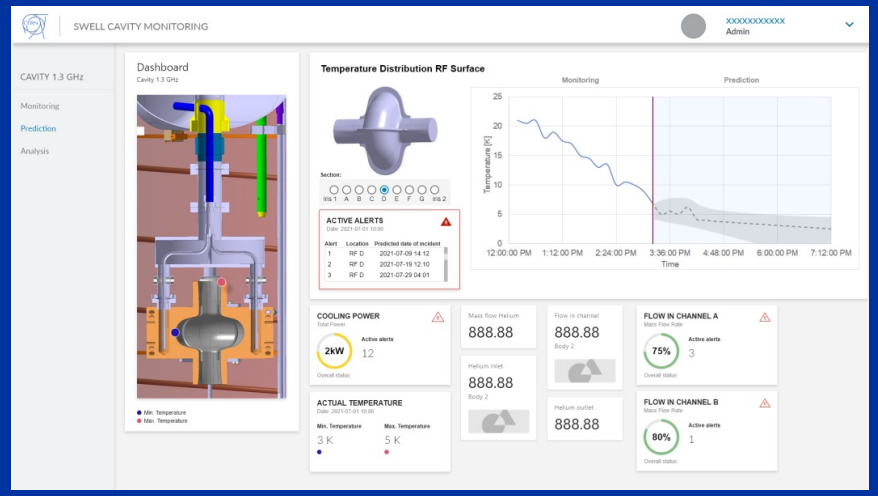
Output Data

- Fast (quasi real-time) Feedback on the Systems State
- Aquisition from ‚Virtual Sensors'
- What-if Simulations
- Fatigue Cycles Counter - evolution
- Decision Support

Digital Twin - OUTPUT

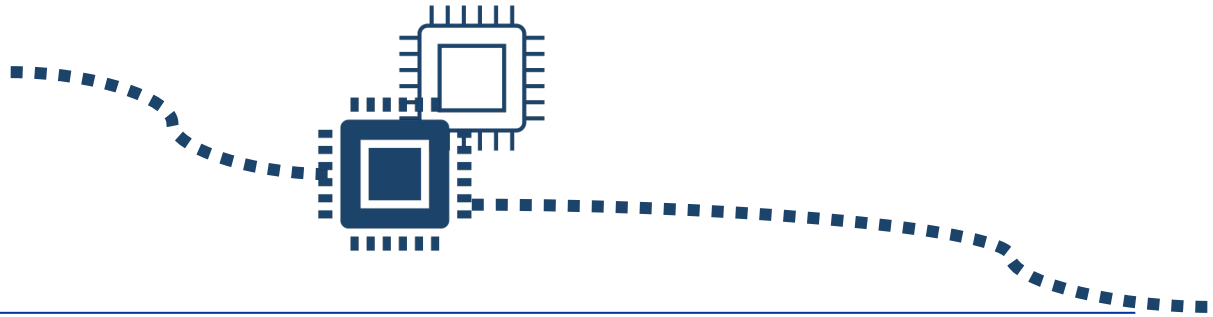
Fast (quasi real-time) feedback on the systems state

- A Digital Twin interpretates the output on-line and displays the sytstem/component status
  - Normal Operation
  - Critical State
  - Failure
- Prediction of the near-future parameters values



Aquisition from ‚Virtual Sensors'

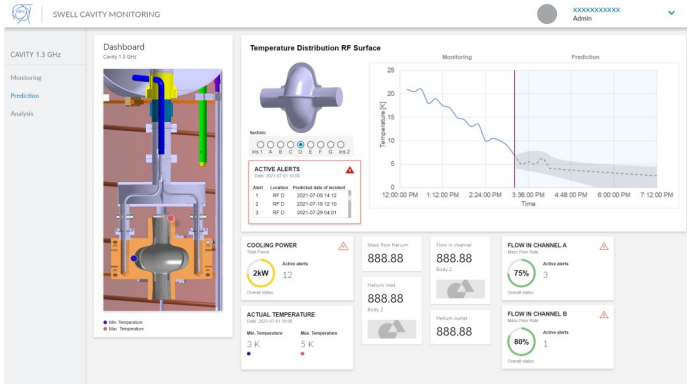
- Monitoring of parameters without physical sensors installed
- Displaying the parameters difficult to measure ina a conventional way (e.g. temperature distribution of RF Cavity innternal surface)
- Real-time calculation of the non-measurable properties
- Less sensors can be installed in the final application compared to the propotype
- In case of physical sensor failure, the virtual one can replace it



Digital Twin - OUTPUT

What-if simulations

- All what-if scenarios might be checked at any time, with the **actual** asset initial condition
- New fetures of the system can be implemented and tested before applying them physically in the asset
- Support for the operators in trainng sessions
- **Decision support** in case of emergency or system's malfunction



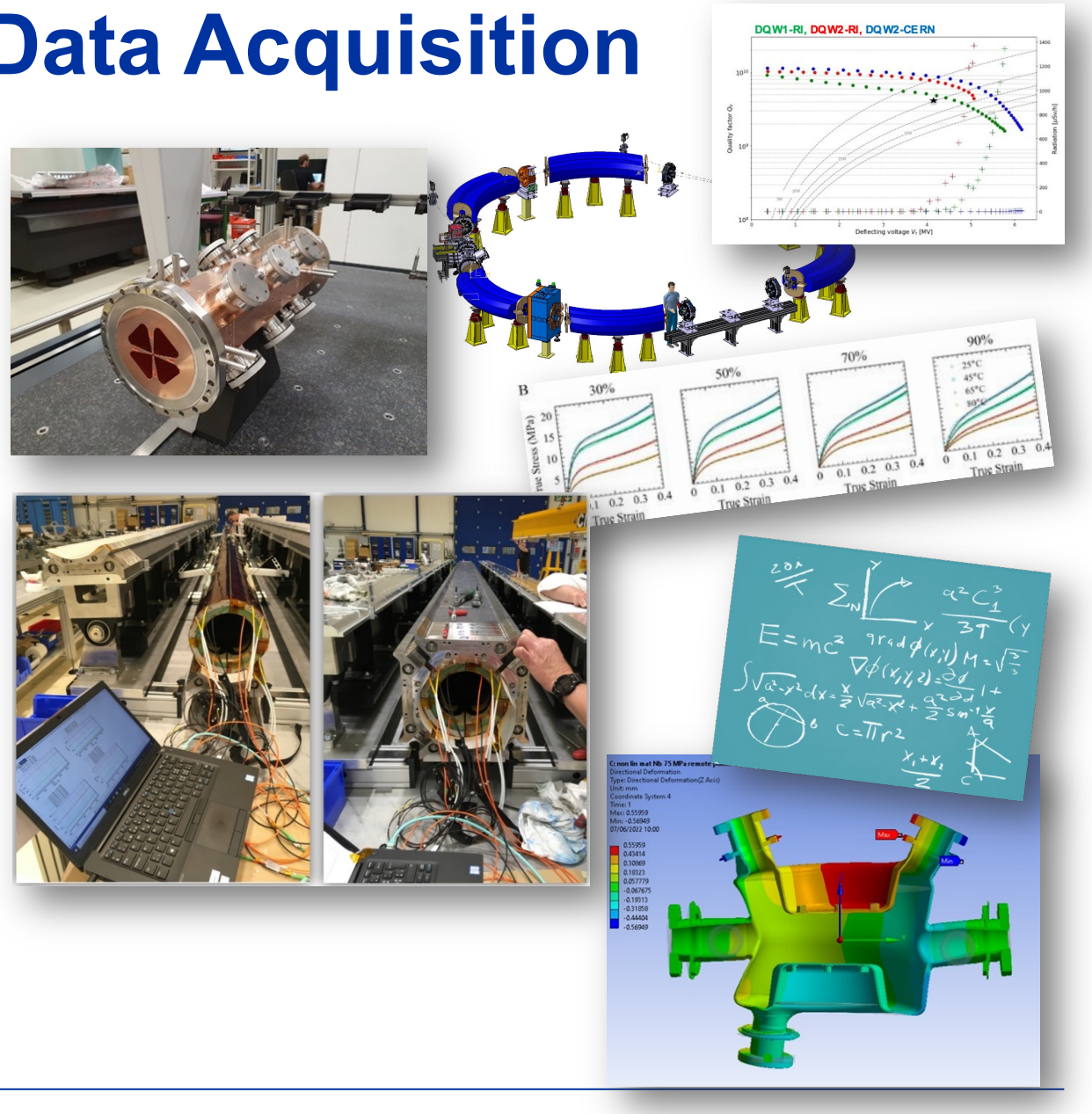
Fatigue cycles counter

- Predictive maintenance input
- Adjusting cycles in case of abnormalities
- Real-time wearness of the component (eg. Bellows)
- Correction of the component specification if dependent from loading cycles (eg. Batteries)

Digital Twin is more than Data Acquisition

Digital Twin IS MORE than:

- **data acquisition & monitoring**
- **set of simulations**
- **experience from historical records**



Digital Twin is **DYNAMIC** – it mirrors the exact state of the system is quasi real-time, gives feedback on system current status and predicts the future behavior. It can evolve with asset.

Digital Twin in an Accelerator

- **Expensive & bespoke components**
- **High complexity**
- **Hardly accessible for the maintenance**
- **Failure of a single component is highly critical**

A Digital Twin is an answer!

- Tailor-made solution for each component
- Complexity of the system reduced to key physical sensors
- Improvement of predictive maintenance inputs
- Operators can be warned and gain time for decision on the actions to be taken

EN-MME Group at CERN

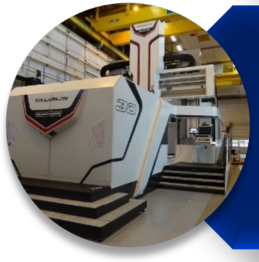
MME
Mechanical & Materials Engineering
GL: S. Atieh
DGL: A. Bertarelli

- **EDM** — Engineering Design & Measurements — *O. Capatina*
- **EDS** — Engineering Design & Simulation — *A. Bertarelli*
- **FS** — Fabrication Methods & Subcontracting — *A. Dallocchio*
- **FW** — Forming & Welding — *G. Favre*
- **MA** — Machining & Maintenance — *M. Garlaschè*
- **MM** — Materials, Metrology & Ndt — *S. Sgobba*

The mandate of the MME group is to provide to the CERN community specific **engineering solutions combining mechanical design, fabrication and material sciences**, using in-house and industry facilities, for accelerator components and physics detectors.

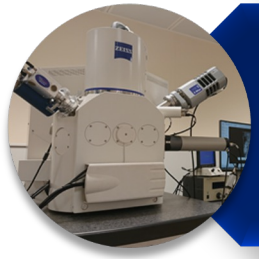
Design

- **Design Office**
- **Engineering Unit**
- **Mechanical Measurements Laboratory**
  - 40+ designers and 15+ engineers



Fabrication

Mechanical Workshop & Technical Subcontracting unit

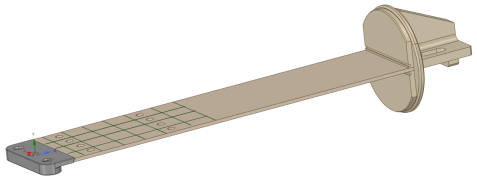


Materials

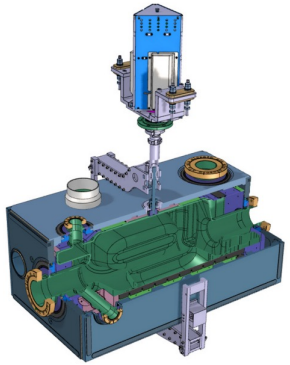
- **Material science consultancy**
  - Metallurgical analyses, microscopy including FIB, Mechanical tests
- **NDT:** UT, radiography, microtomography
- **Metrology:** 350 m² Lab., several CMM

MME Roadmap to DT for Mechanical Components

Proof of Principle Q1 2023



Demonstrator Q4 2024



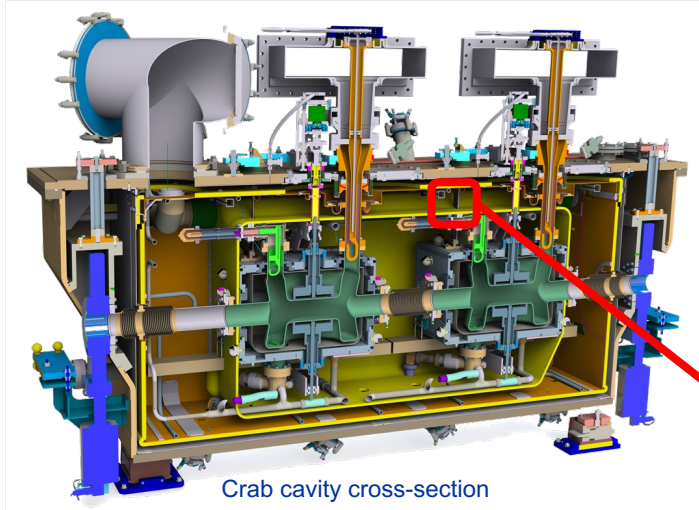
Digital Twin in operation

MME Roadmap to DT for Mechanical Components

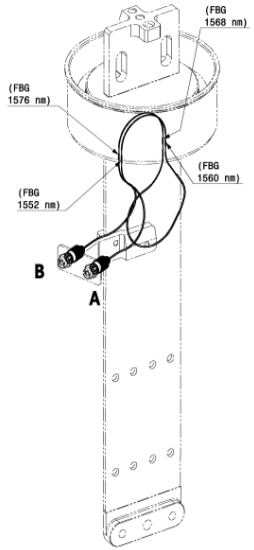
Step-by-Step Approach

1st Step: Proof of Principle (PoP)

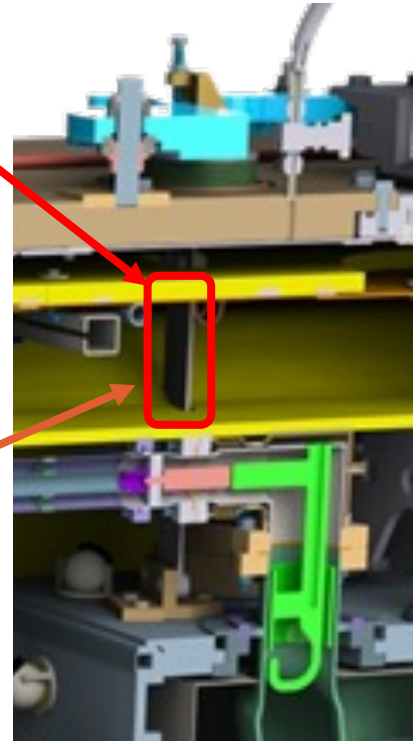
- Selection of a **simple component** – support of the Crab Cavity Cryomodule - mechanical component
- **Real time** BUT **steady state** conditions considered (static thermal/mechanical loading)
- **Testing** the DT data flow system
- **Real time feedback** on component loading based on reduced sensors scenario – no prediction considered



Crab cavity cross-section



Available space for the instrumentation

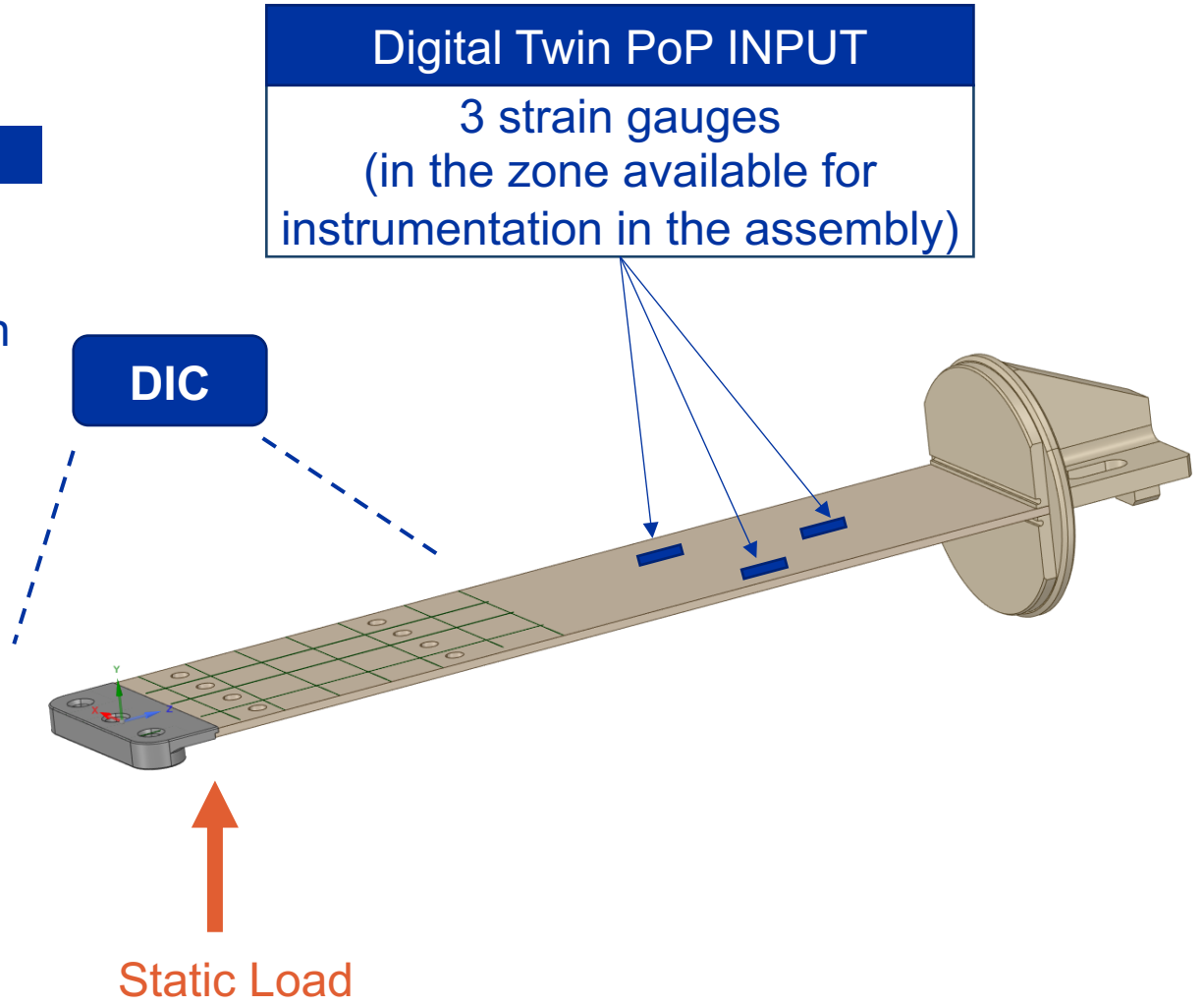


Credits: T. Capelli

MME Roadmap to DT for Mechanical Components

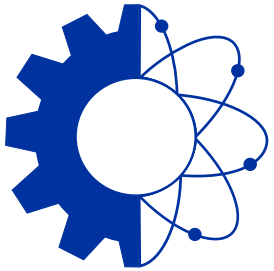
1st Step: Proof of Principle (PoP)

- Definition of Load Cases
- Static Load application in pre-defined location with multiple amplitude values
- Collecting DIC image
- Collecting strain gauges measurements
- Simulation of the same Load Cases with FEM
- Creation of the DT Transfer Function
- Test of the model in real time:
  - Input: strain gauge read
  - Output: information of what was the applied force and position



Summary

- Digital Twin is an **established solution**, within domains with high-end critical equipment
- **Powerful tool** for equipment Design, Operation, Safety
- **Each Digital Twin is unique**, tailored to user's needs and component specification
- **Quasi real-time reaction of the system** thanks to Machine Learning implementation
- Great application potential for **key accelerator components and systems**
- **CERN MME Group** current strategy: **step-by-step approach**, within mastered competencies



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