Digital Twins for Accelerators and Detectors

Óscar Sacristán

ENGINEERING DEPARTMENT

MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS

Outline

- Intro to Digital Twins
- Mechanical Digital Twins at CERN
- Other Digital Twin Initiatives in Particle Accelerators

Intro to Digital Twins

Digital Twin Definition

A virtual representation of a physical entity that uses real-time and historical data to simulate and describe the behaviour, characteristics, and performance of its physical counterpart

Real-Time Monitoring and Visualization

- Data Integration
- Live Visualization

Simulation and Modelling

- Behavioral Simulations
- What-If Scenarios

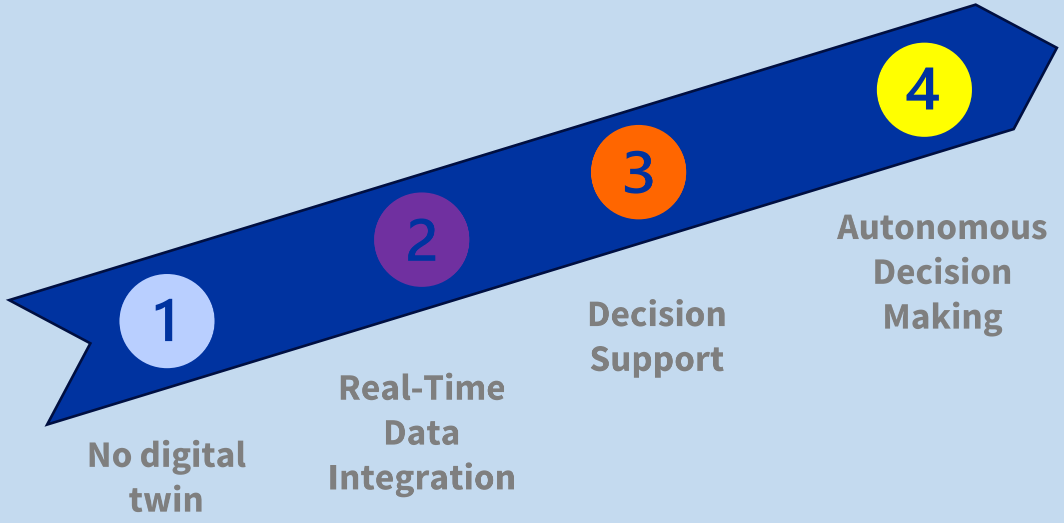
Enhanced Decision-Making

- Data-Driven Insights
- Predictive maintenance

Training and Education

- Virtual Training
- Knowledge Retention

Complexity Level



Not all digital twins need to reach the highest levels of complexity

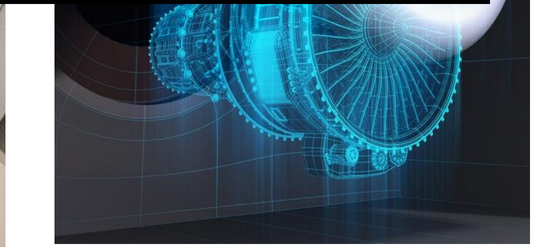
DT History and evolution

First written mention in David Gelertner's Digital Worlds:

"You will look into a computer screen and see reality. Some part of your world … will hang there in a sharp color image, abstract but recognizable, moving subtly in a thousand places." - David Gelernter

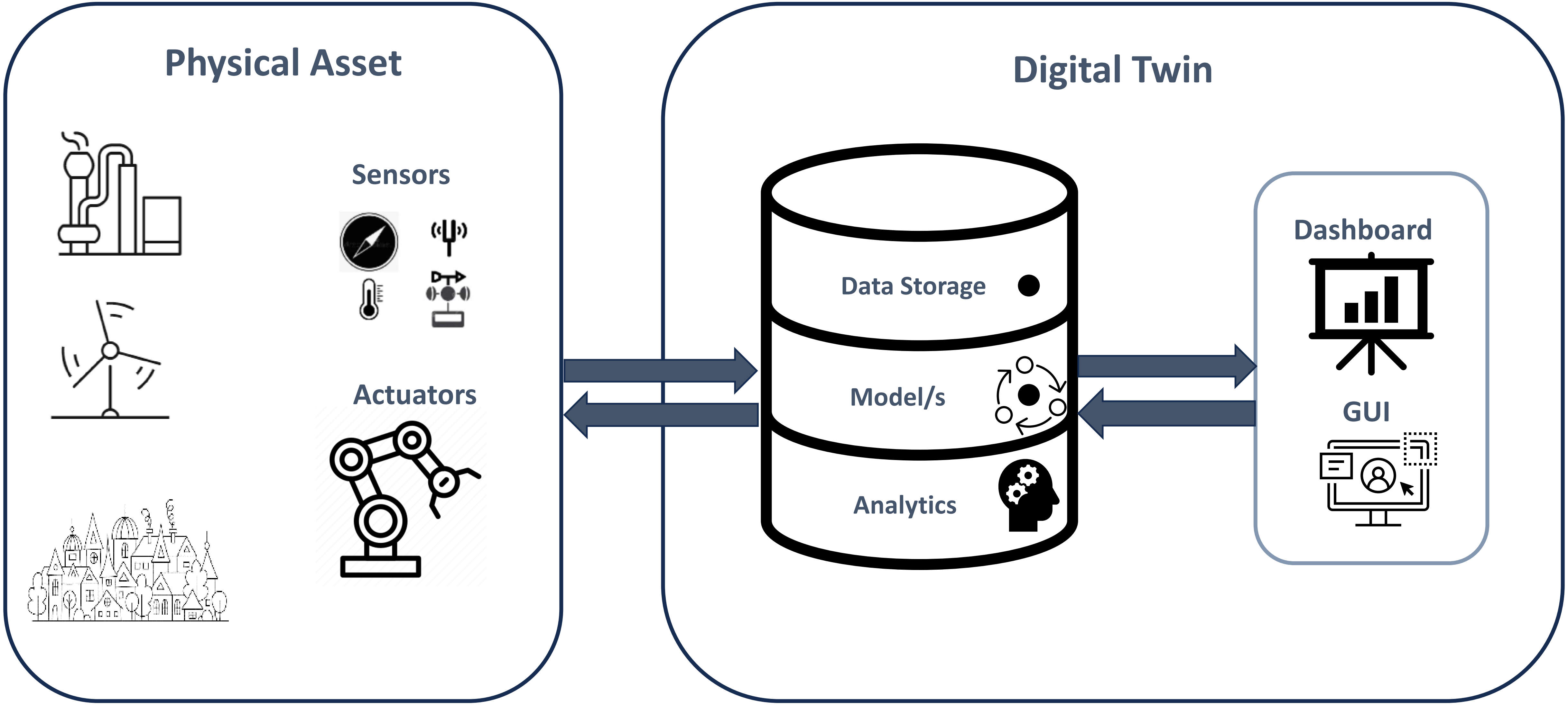
Since then, enormous progress in DT enabling technolo

- CAD (Computer Aided Design)
- Simulation and Modelling
- SCADA (Supervisory Control and Data Acquisition) Systems
- PLM (Product Lifecycle Management) S
- Cloud computing
- **IoT (Internet of Things)**



1960 **1991** **2003** **Present**

Basic Structure



Physical assets of interest

Complex and high added value systems

Multiple interacting components and complex behaviors
High precision and reliability

Data rich environments

Systems naturally integrating large amounts of sensors
Diverse data sources

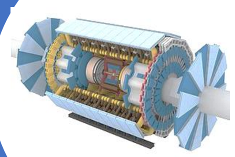
Dynamic changing conditions

Systems operating under varying conditions
Frequent changes and updates

High maintenance and operation costs

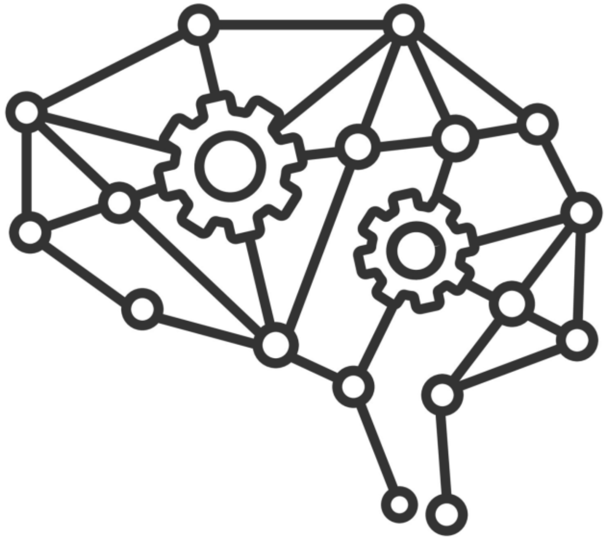
Maintenance intensive systems
Costly down time

Digital twins modelling strategies

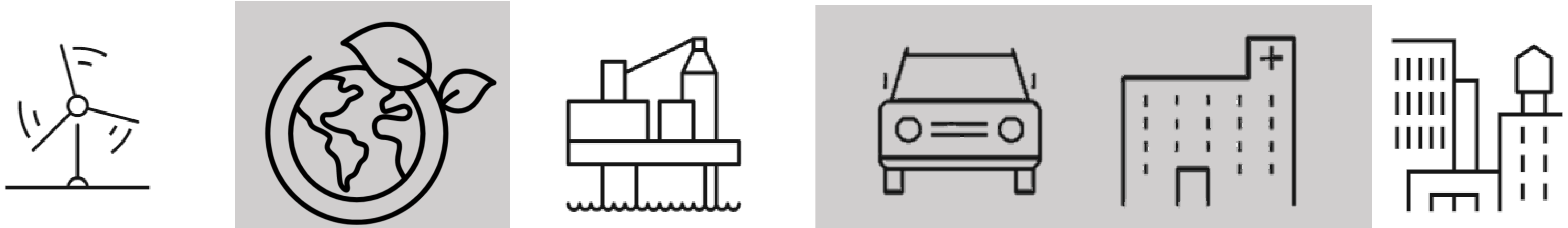


Geometric Models

- Detailed geometric representations of physical objects
- Visualization of complex structures and components



Applications



European Commission Initiative under Horizon Europe Programme

Highly accurate digital model of planet Earth at global scale

Monitor, simulate and predict the interaction between natural phenomena and human activities

Built on top of Copernicus earth observation initiative

Full digital replica of the earth by 2030

Mechanical Digital Twins at CERN

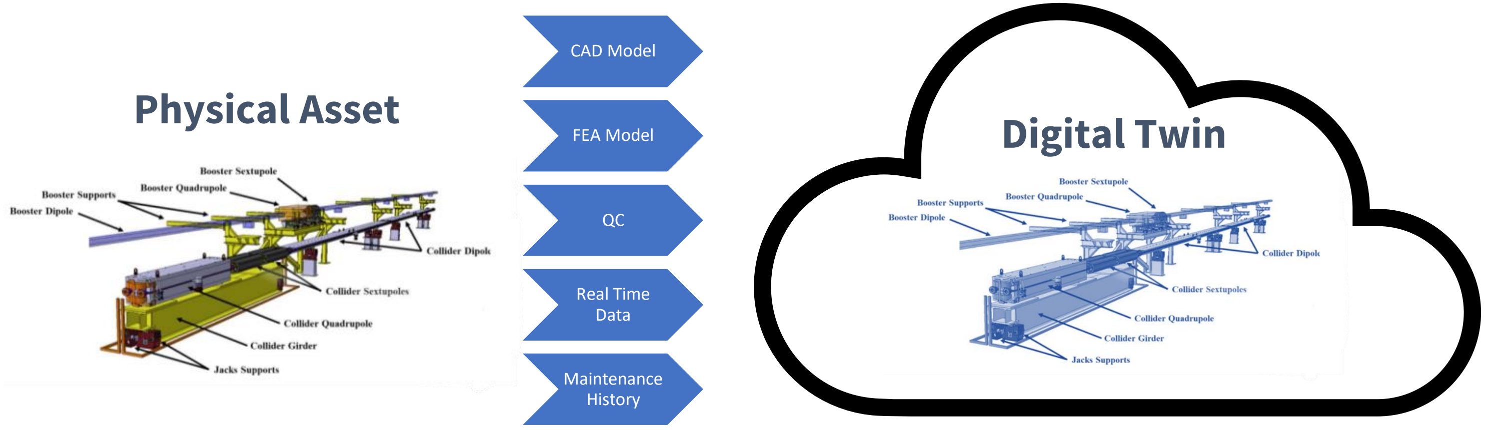
Operational Benefits of a Mechanical DT

Automatic structural integrity and vibrational stability monitoring in real time

Unique dashboard for all available measurements

Predictive maintenance

Virtual Sensors



DT Precursors within our Group Competences

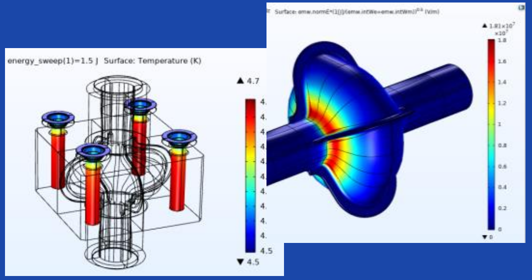
CERN-wide Technology Service

Engineering and Design

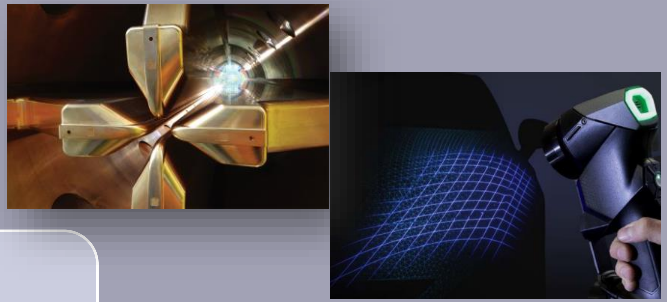
Manufacturing

Materials Science

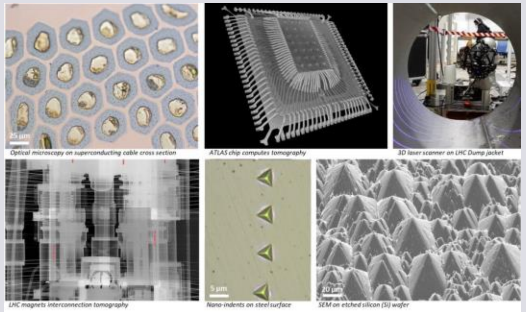
Advanced Modelling and Simulation



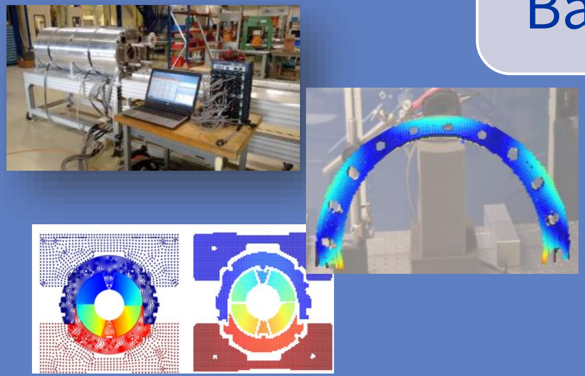
Design, Manufacturing and QC



DT Backbone



Measurement

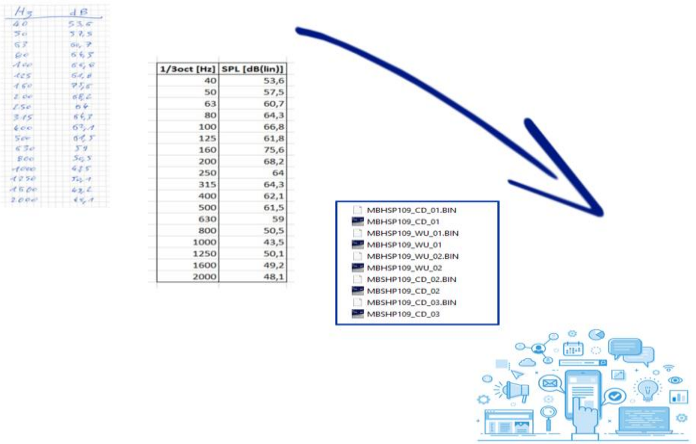


Materials Science and NDT

Modelling and Interacting with the Physical Asset

Creating and Maintaining the Digital Thread

Digital Transformation of the Mechanical Measurement Laboratory



Increasing complexity of the measurement devices ecosystem	In order to keep up with state-of-the-art measurement technology
Fast paced iterative development cycles	Increasing need of concurrent real time data availability for swift decision making
Increased international collaboration	Development team does not forcibly in the same place where assembly and test happen
Technologies available to push forward digital transformation in the laboratory	Not only from measurements industry, but the Internet of Things, cloud computing, etc.

Mechanical Measurements ~ IOT?

Data Acquisition

HBM

LUNA

SAFIBRA

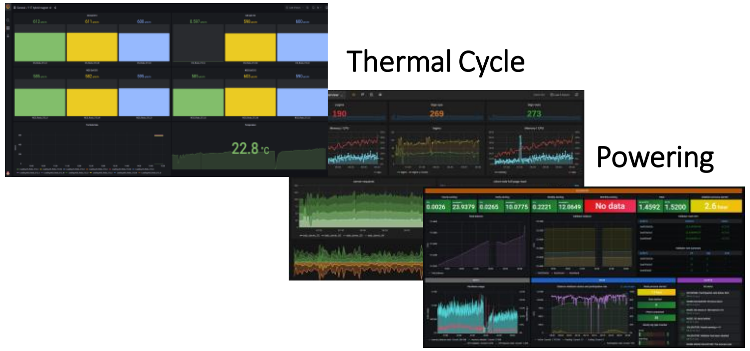
NATIONAL INSTRUMENTS

NTP/PTP Synchro

NTP

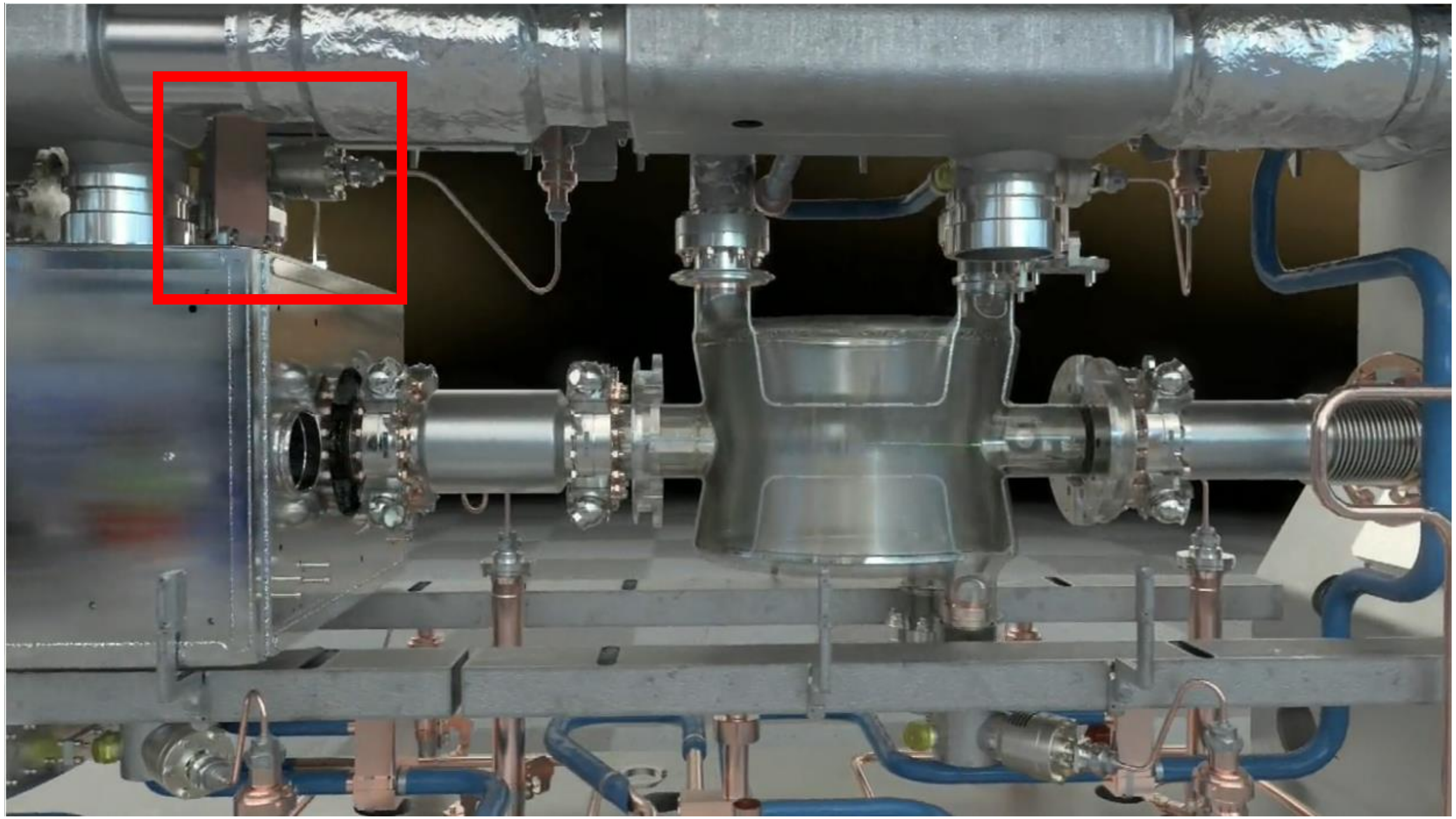
InfluxDB Database

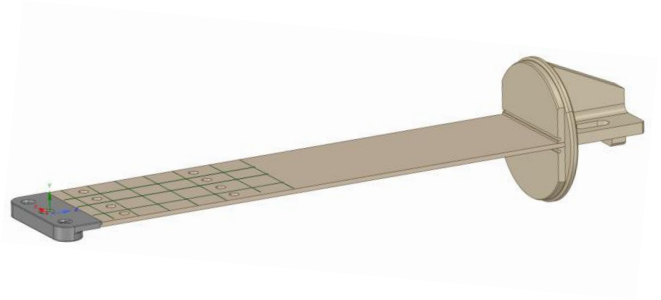
Dedicated Real Time Data Visualization



Online Monitoring and Alerting

Proof of Principle: HL-LHC CRAB – Supporting Structure

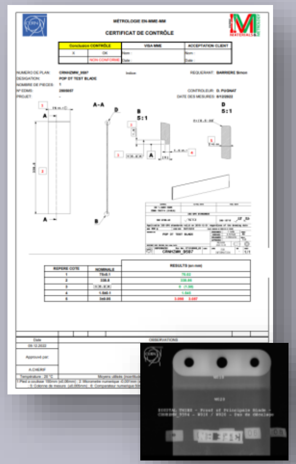




- First organized effort within MME Group
- An actual component of HL-LHC beam line
- Equivalent instrumentation to the final component
- A testbench for the integration of the different techniques involved

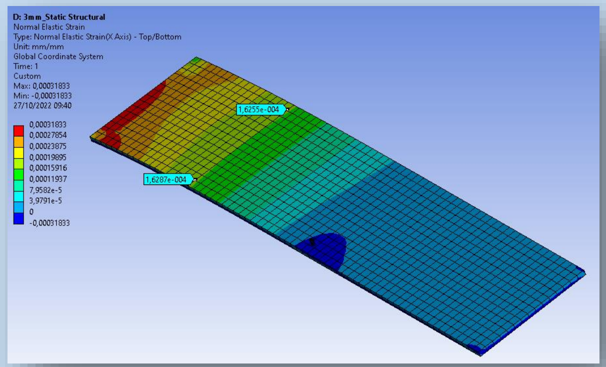
Proof of principle overview

Digital Thread



Training Dataset

FEA



Measurements History

Live Data + Model Outputs Visualization

Virtual Sensors
Anomalies
Untrained Situations

- Physical modelling
- Autoencoder

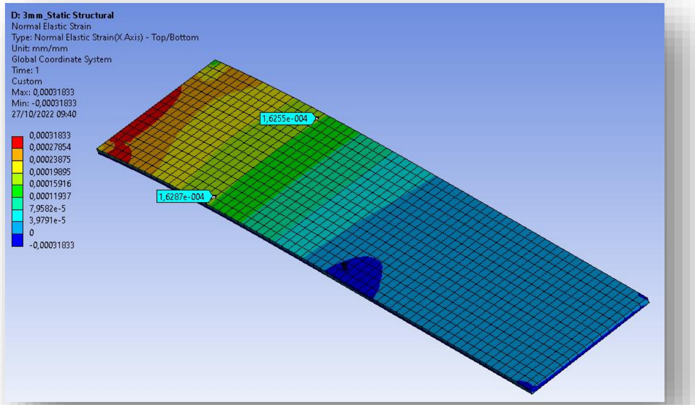
Model Building

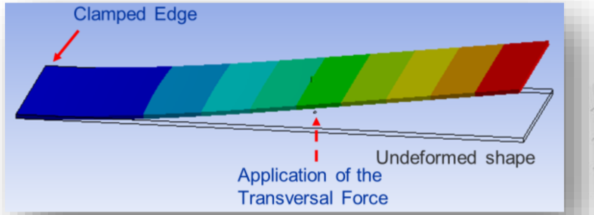
Model Feed

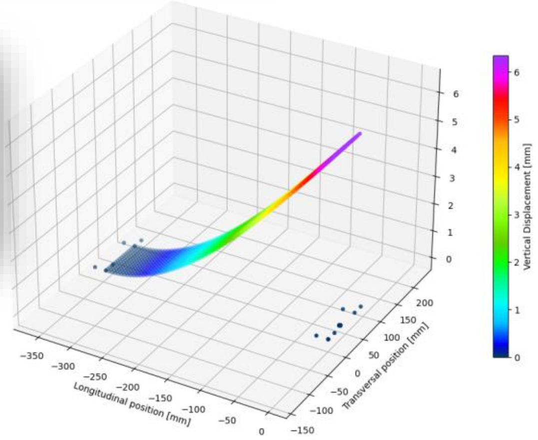
Real Time Data Acquisition

Proof Of Principle : Modelling and Measurements

Parametric simulations based on Finite Element Method

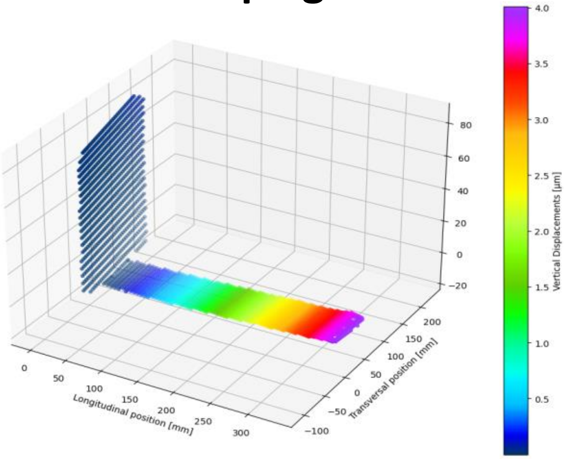




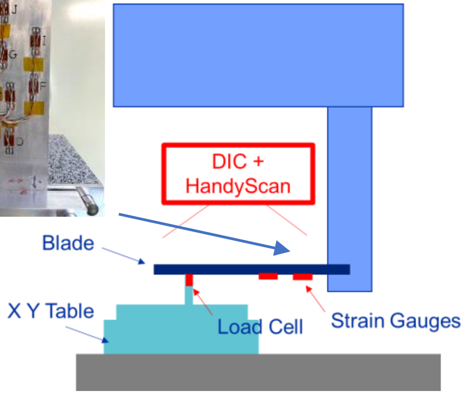


Ansys

Experimental Measurements Campaign



Post-treated data from DIC measurement



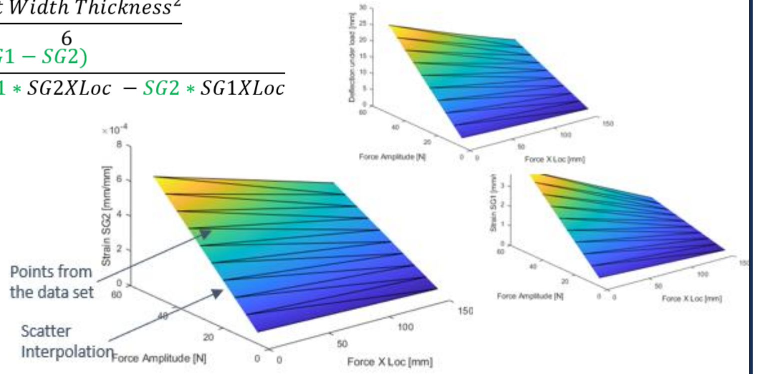
Proof Of Principle: DT deployment

Model

Analytic definition of the transfer functions

$$LoadXLoc = \frac{SG1 * SG2XLoc - SG2 * SG1XLoc}{SG1 - SG2}$$

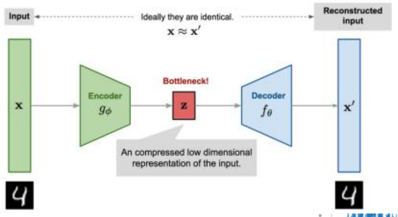
$$LoadAmpl = \frac{\frac{Emat\ Width\ Thickness^2}{6} \; SG1 * (SG1 - SG2)}{(SG1 - SG2) * SG1XLoc - SG1 * SG2XLoc - SG2 * SG1XLoc}$$

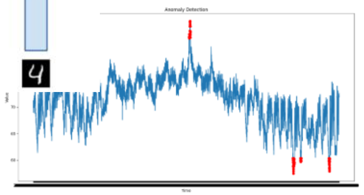


Anomaly Detection with Autoencoder Neural Networks

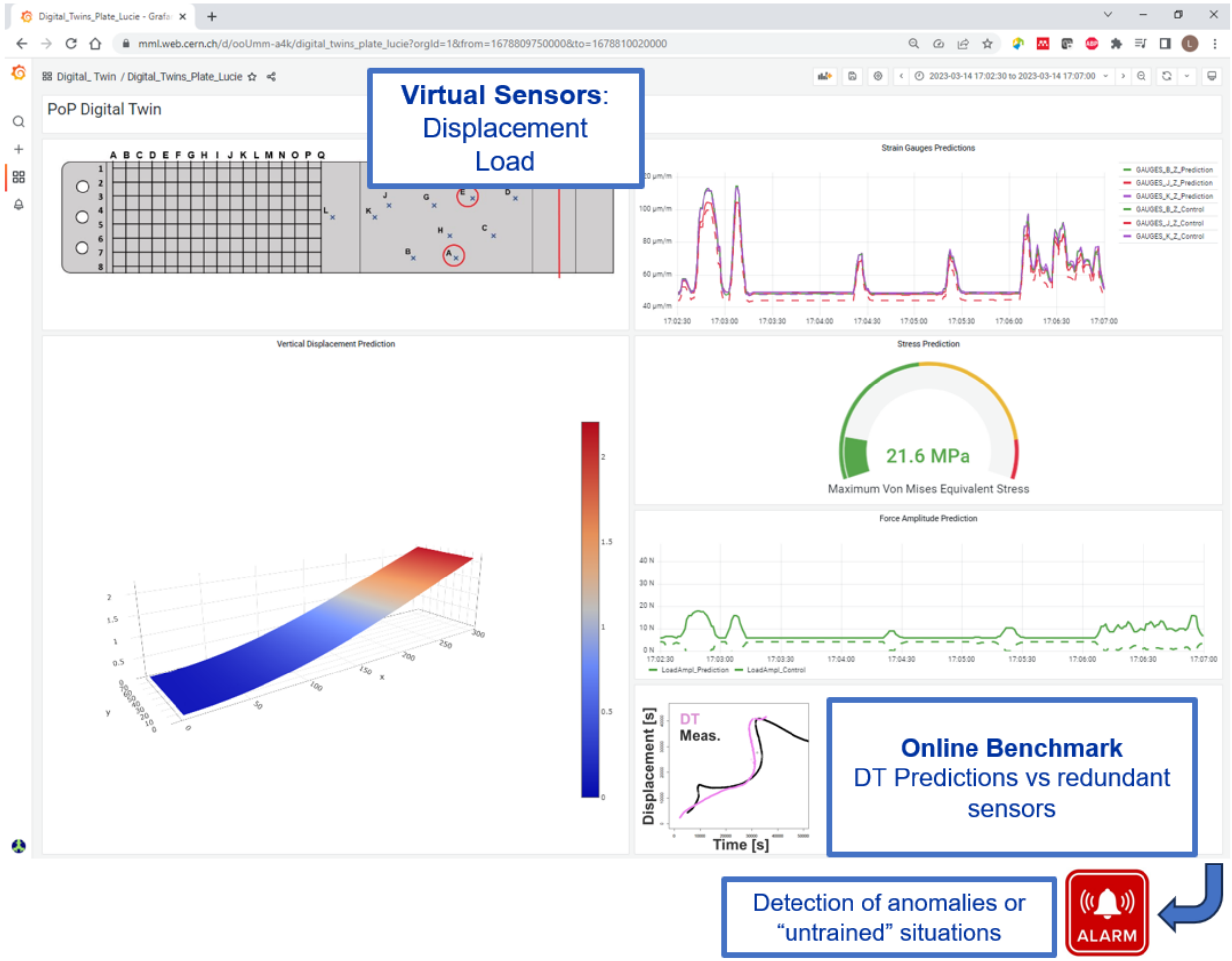
Keras

python™





Visualization Panel



POP Lessons Learnt…

- The completion of the Proof of Principle allowed us to explore the different building blocks of a digital twin, and :
  - Validate potential use cases of interest in practice (virtual sensors and anomalies detection primarily)
  - Identify shortcomings of our approach
    - We are comfortable in our traditional domains of expertise (measurements, modelling, etc.), but…
    - Need help in developing a robust and scalable infrastructure
  - Define a group DT strategy for the next 3 years

…and Perspectives

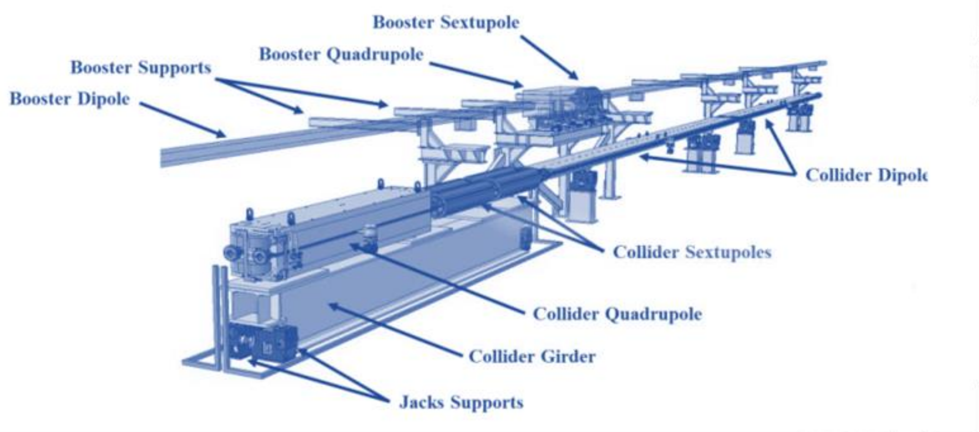
Acquisition of talent:

- Comprehensive training in machine learning, industrial IoT, data bases, etc.
- New recruits with complementary background
- External collaborations with industry and academia

Consolidation of the digital twin infrastructure:

- Collaboration with InterTwin Project

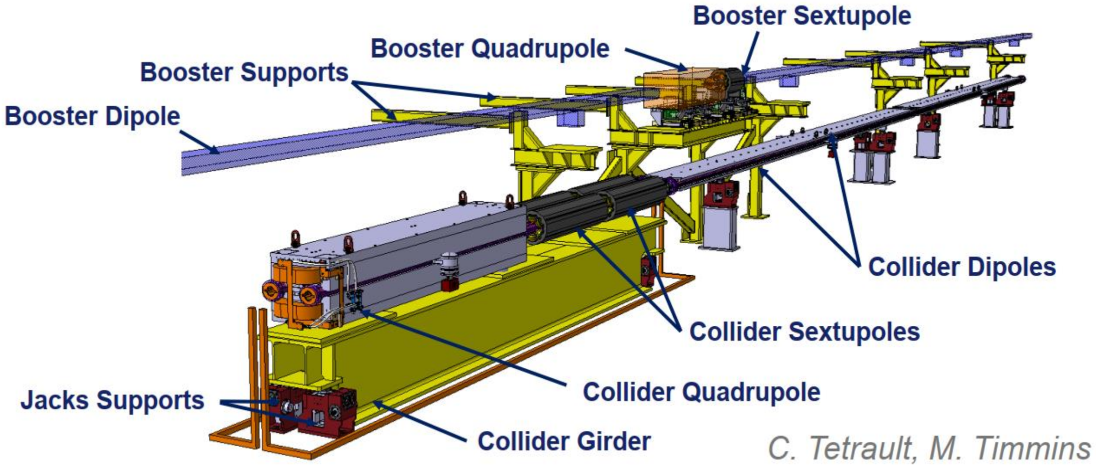
Digital twin of FCC-ee arc half-cell



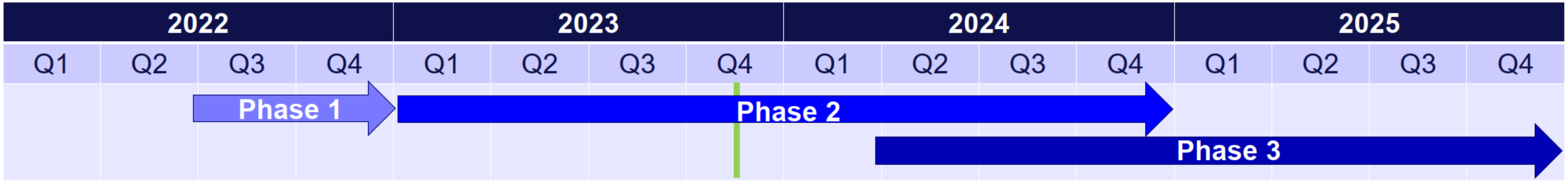
Next Steps: FCC-ee arc half-cell mock-up project Digital Twin Study

Arc half-cell is the most repeated region of mechanical hardware in the tunnel

77 km over 90 km are arc cells



A sub Mock-Up project is ongoing in order to assess the mechanical stability of the Ground-Girder-Magnet system



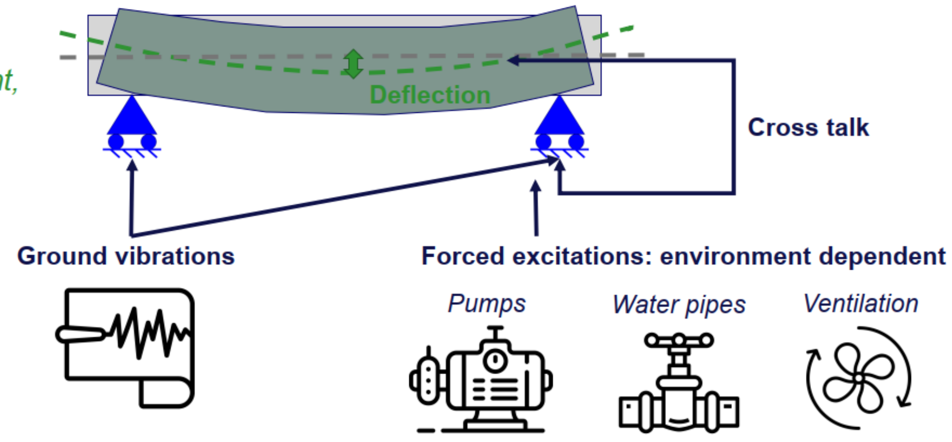
Phase 1: Concept development Phase 2: Engineering design Phase 3: Fabrication

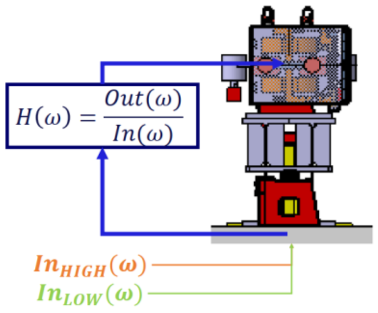
DT and the Challenge of FCC Mechanical Stability

FCC-ee presents extremely stringent demands in terms of stability (sub µm even for very low frequencies)

→**Static stability**
Requires mitigation via alignment, extra supports, wedges, etc.

→ **Dynamic stability**

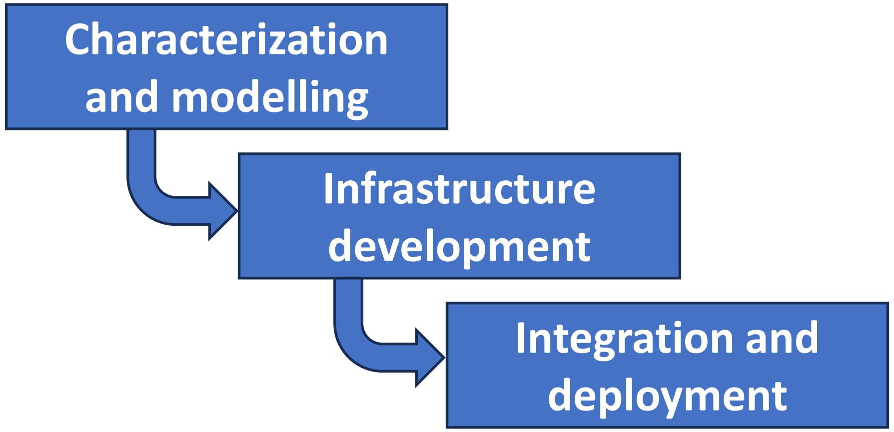




Frequencies	Tolerance at beam level
10 > f > 1 Hz	20 nm
100 > f > 10 Hz	5 nm

Digital Twins Motivation

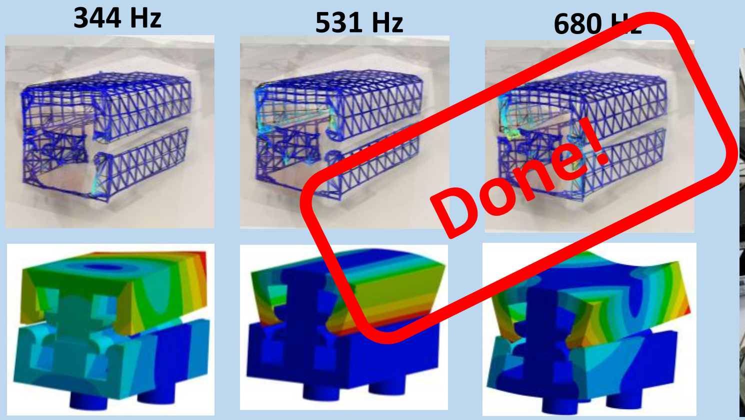
- Real time prediction of the magnetic axis displacement
- Integration of remote seismic sensor data for predictions
- Combination of physical modelling with AI for detection of anomalies



FCC-ee arc half-cell mock-up experimental campaign

1st Step: characterization of the prototype quadrupole

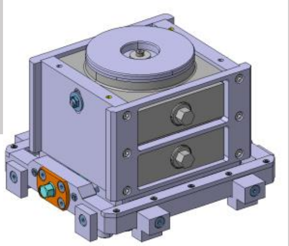
Modal Analysis – Experimental vs Simulations



4th Step: characterization of the girder jacks

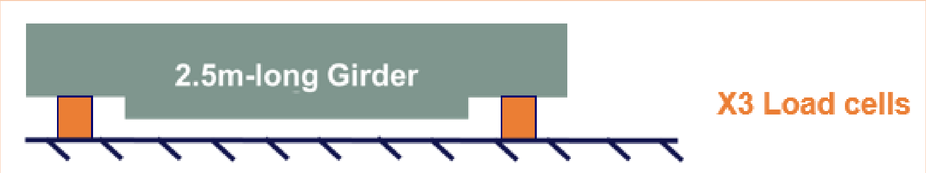
Transfer function from ground to top of the girder / load cells

X3 Load cells on the top of PSI JACKS



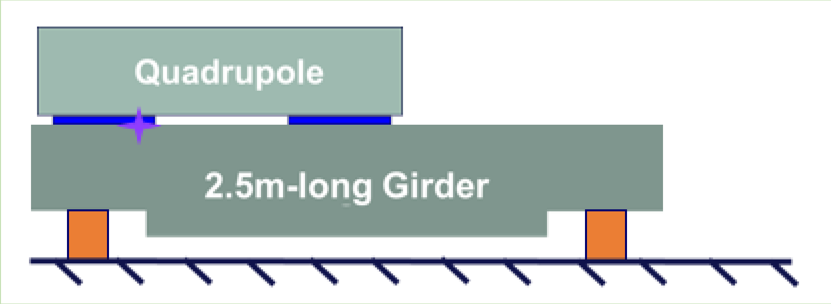
2nd Step: characterization of the supporting girder

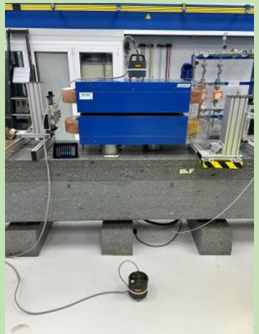
Transfer function from ground to top of the girder / load cells



3rd Step: characterization of the girder + quadrupole

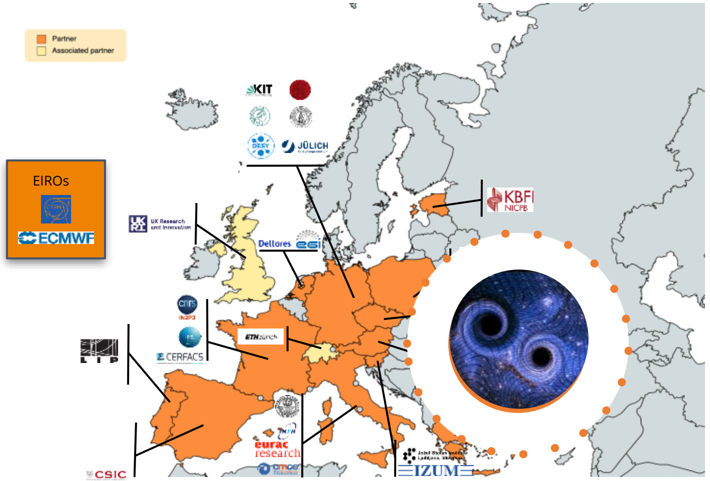
Transfer function from ground to top magnet / load cells





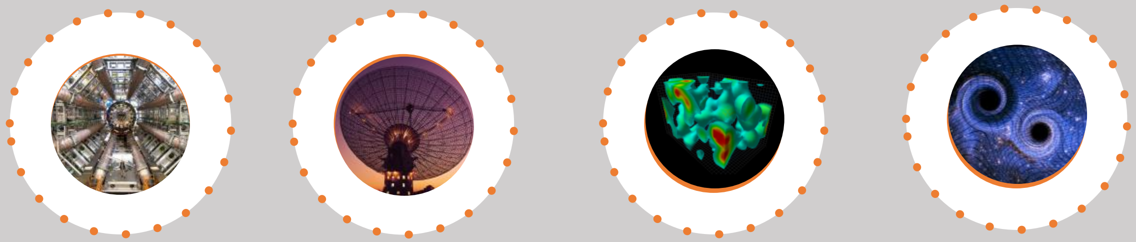
Digital Twin Infrastructure: InterTwin Project

EU funded project aimed at implementing the prototype of an interdisciplinary Digital Twin Engine



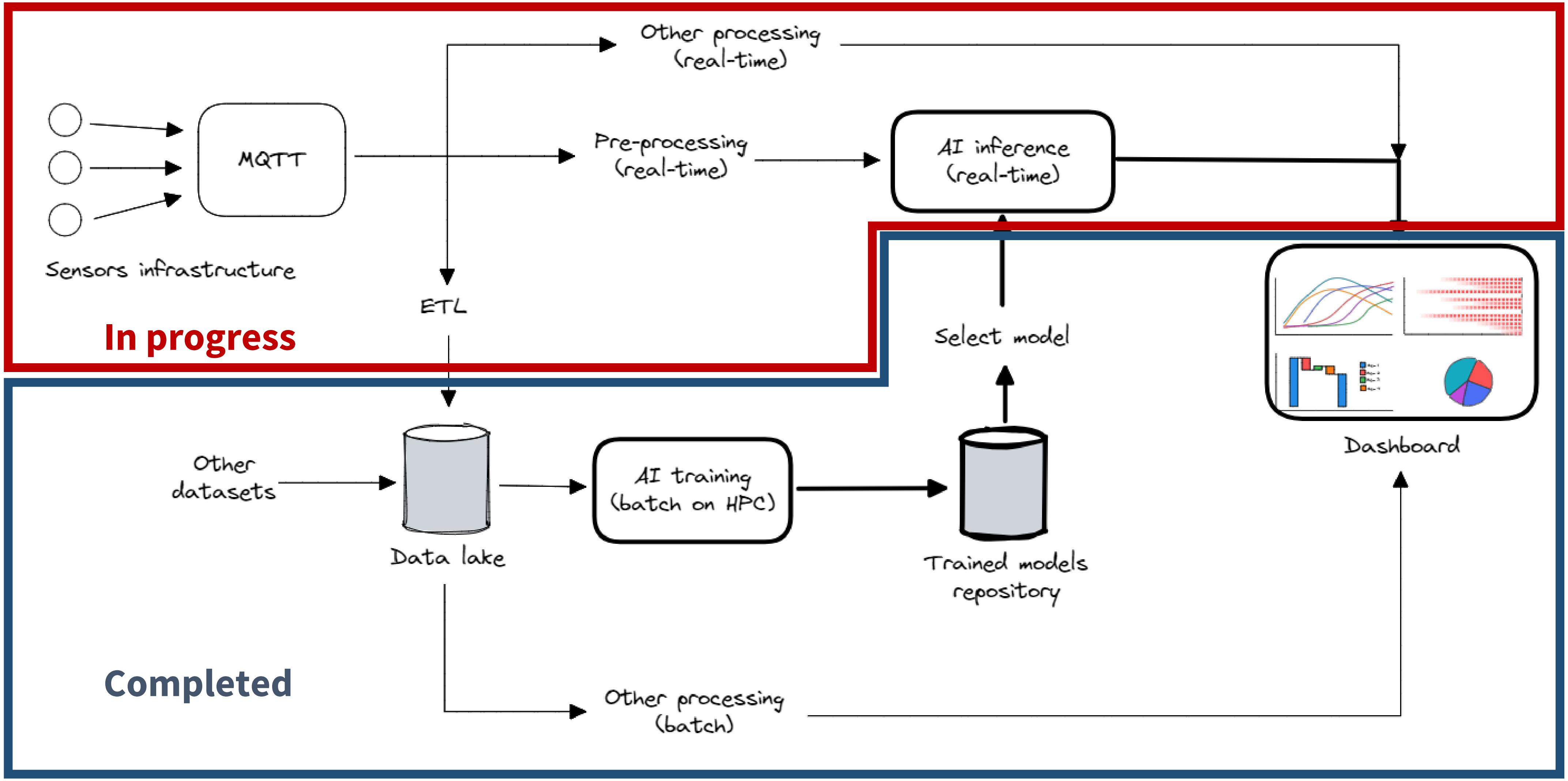
- **Open-source platform** based on open standards.
- It offers the capability to integrate with **application-specific Digital Twins**.
- It will delivers an interoperable and modular framework

Physics



Earth Observation

InterTwin Real Time Framework



Roadmap

2024

Phase 1: Experimental Measurements Campaign

- Gather technical specifications and operational data.
- Develop the initial 3D model of the magnet section.

Phase 1: Simulation and Analysis

- Perform finite element analysis to assess stability, vibrations, and alignment.
- Optimize magnet configurations and supporting structures

Mid 2025

Phase 2: Integration and Validation

- Integrate operational data into the digital twin platform.
- Validate the model against physical tests and historical data.

2026

Phase 4: Deployment and Maintenance

- Deploy the digital twin for real-time monitoring
- Continuously update and refine the model based on new data and operational feedback.

??

Phase 5: Swarm of Digital Twins

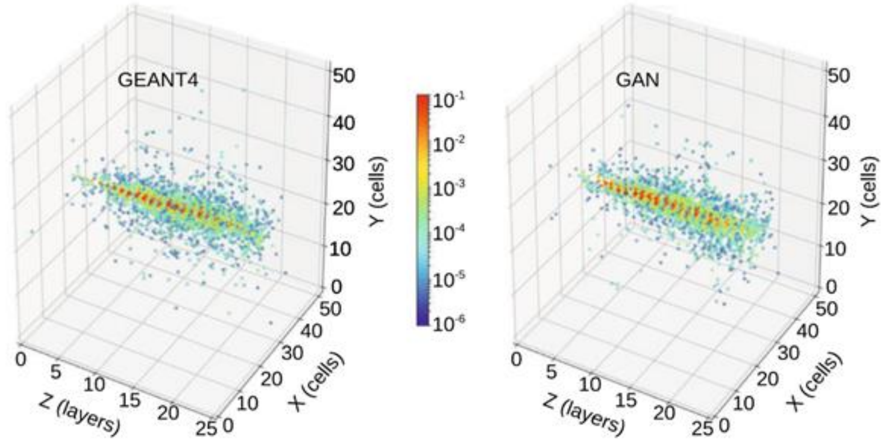
- Develop the hardware and infrastructure for minimal data recording allowing real time monitoring of a swarm of Digital Twins
- Minimizing sensors, scalability resilience.

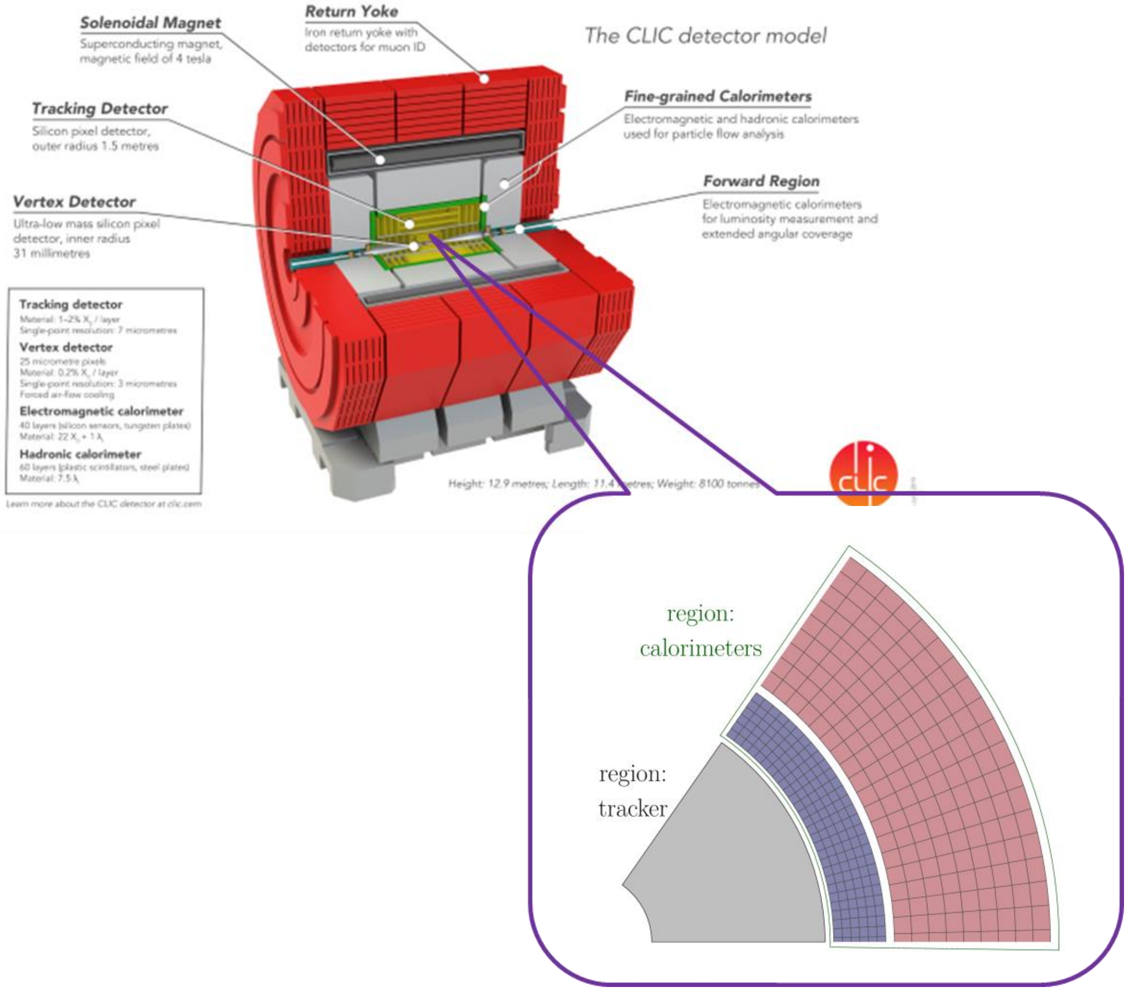
Other Applications in Particle Accelerators

InterTwin: HEP Digital Twins of particle detectors

Build data-driven tool that **simulates detector response** and integrates operation conditions from experimental setups (test-beams).

Online ML for Detectors
Adapt **real-time** detector and/or data acquisition configuration with respect to run conditions



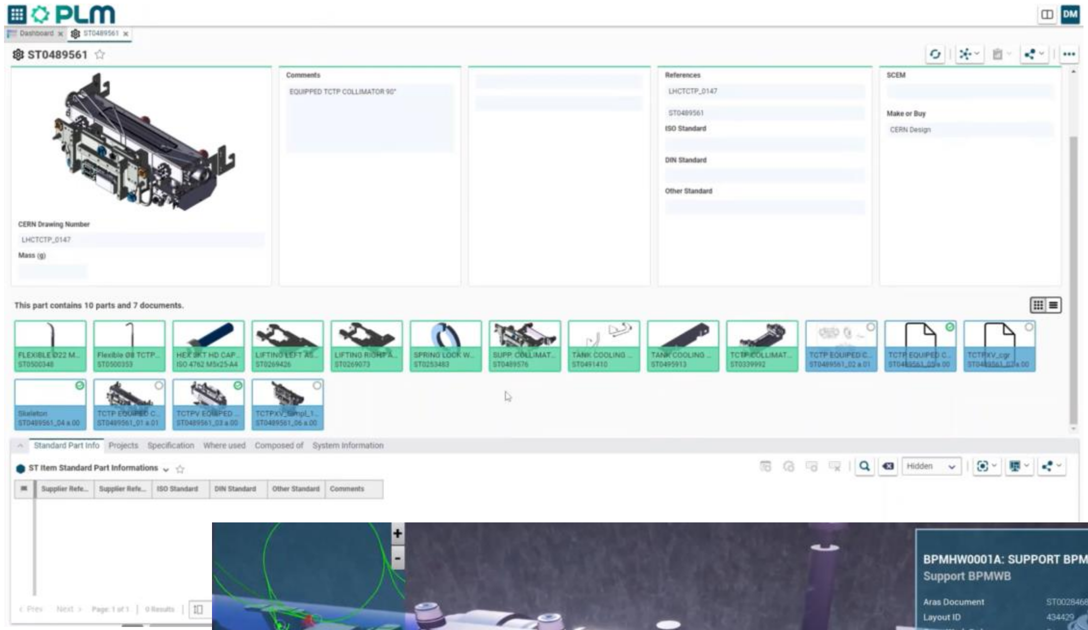


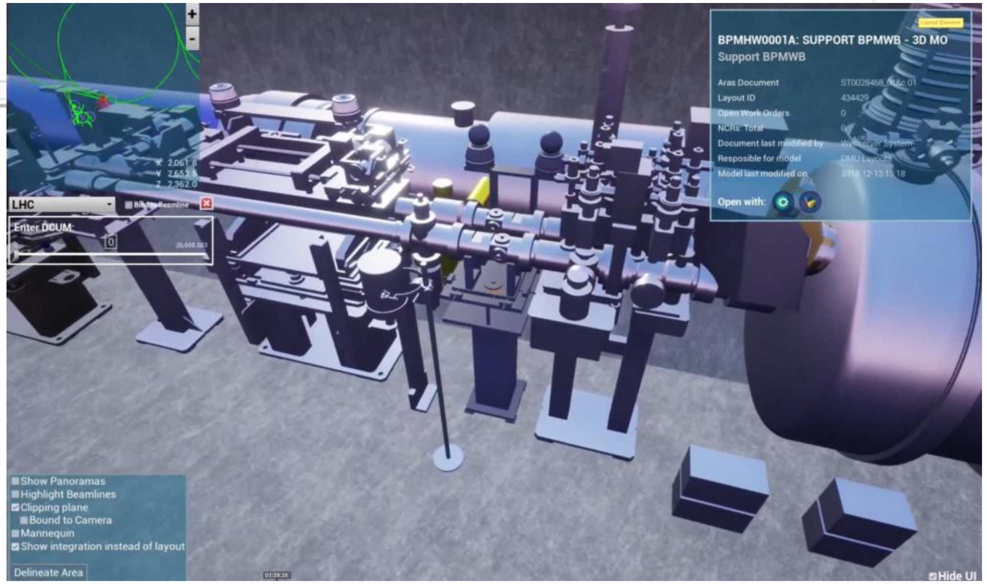
Fast Simulation of a High Granularity Calorimeter by Generative Adversarial Networks.
Gul Rukh Khattak et al. https://arxiv.org/abs/2109.07388 DOI: https://doi.org/10.48550/arXiv.2109.07388

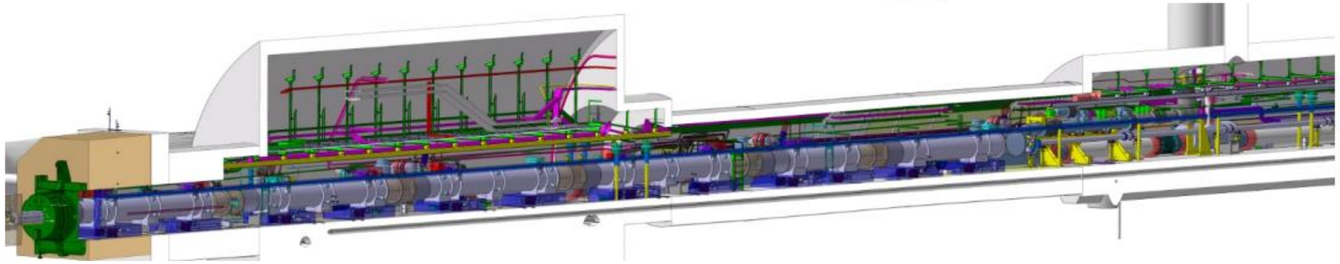
27

PLM Based Digital Twin

- Digital Twins of CERN facilities for simulations, optimizations or navigation in engineering data.
- Virtual Reality (VR) for inspections, design controls and intervention preparations.
- Augmented Reality (AR) for better supporting operation and maintenance tasks.





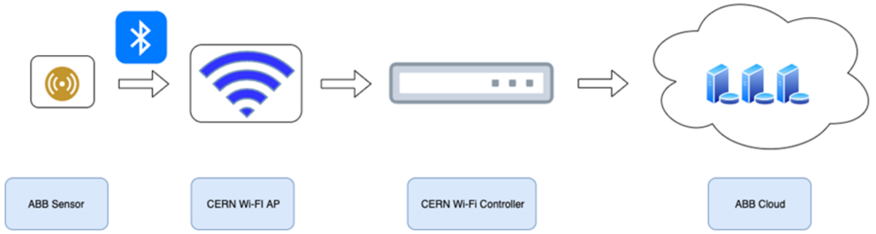


CERN-ABB motorSENSE Project

“Analysing and improving the energy efficiency and reliability of the cooling and ventilation infrastructure of large-scale research facilities through a case study of CERN’s cooling and ventilation infrastructure”

ABB Ability™Smart Sensor to be used for LV motors driving pumps and fans

- Converts traditional motors, pumps and bearings into smart, wirelessly connected devices
- Picks up data on vibration, skin temperature, output power, speed, frequency, operating hours and other parameters
- Attached to the component’s frame without any wiring
- Battery operated
- Communication via Bluetooth



NETA-21 A remote monitoring tool that provides access to drives via the Internet or local Ethernet networks

Conclusions

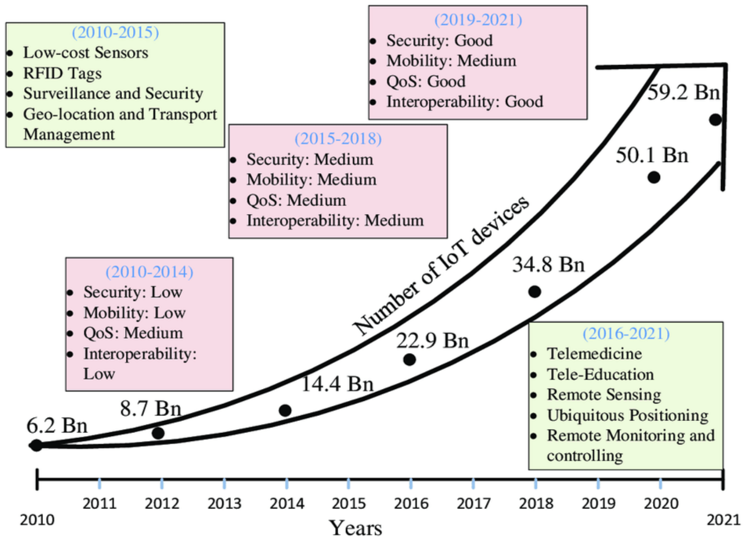
- Digital twins can have many different focuses, scales and levels of complexity
- Much more than simulations
- Accelerator community understood the advantages and multiple initiatives are emerging
- Real interest in mechanical digital twins (virtual sensors and anomalies detection)
- Domain specific know how is not sufficient. Additional knowledge in AI and IT is needed for infrastructure and modelling

The future of Digital Twins

- **Technological advances in enabling technologies:** Developments in AI and machine learning and its further adoption, making them even more powerful and effective.

- **Progression of IOT and industry 4.0:** Increasingly data-rich environments allowing more granular monitoring and control, enhancing precision of the models.

- **Improved Interoperability and Standards:** The development of universal standards and improved interoperability will facilitate seamless integration of digital twins across different platforms and systems, enhancing their utility and adoption.



Evolution towards Smart and Software-Defined Internet of Things. M. Abid et al 2022

We hope you enjoyed the session

Engineering Department

MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS