



# A Mechanical Digital Twin for Particle Accelerators

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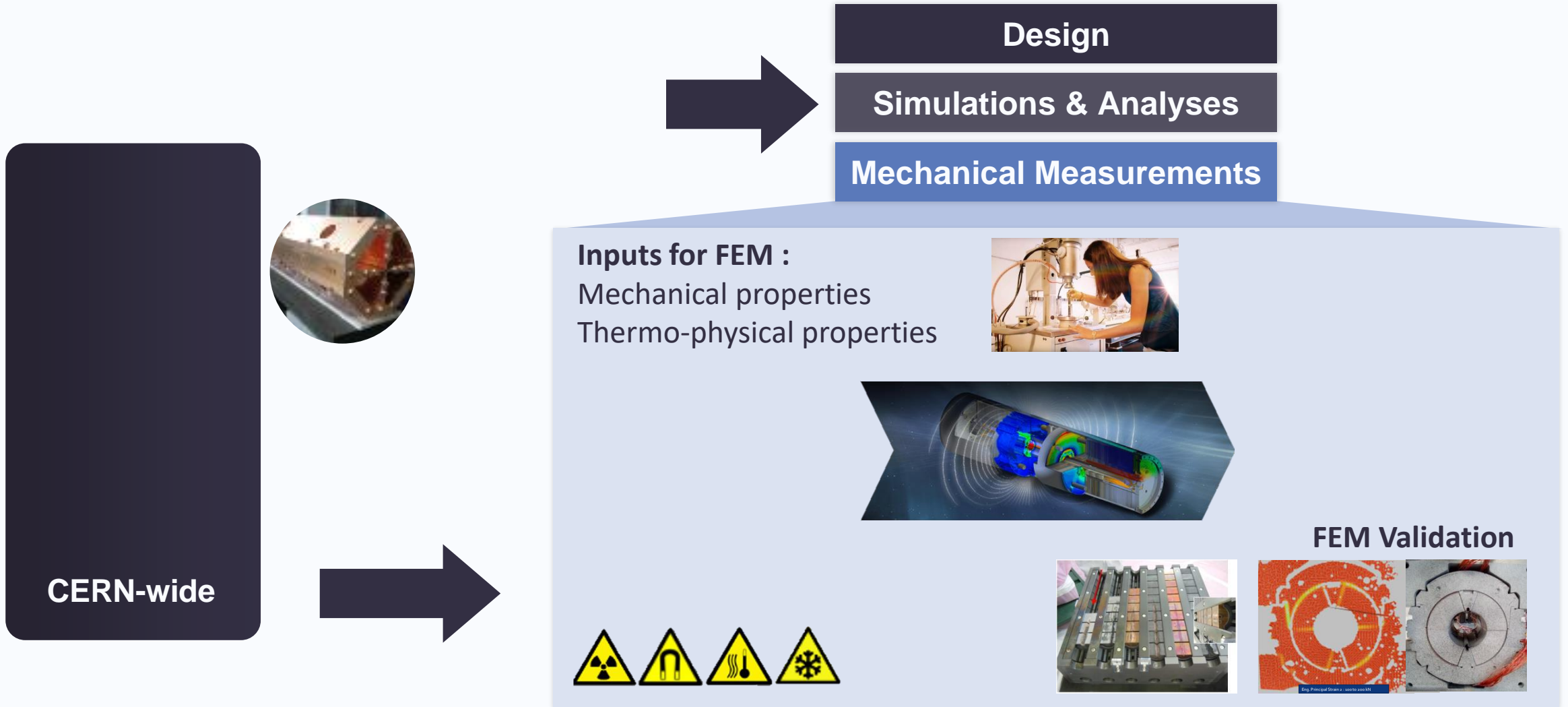
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# Agenda

1. Brief intro to digital twins
2. Feedback from our first mechanical digital twin
3. Ongoing and next steps. FCC arc half-cell mock-up project Digital Twin

# CERN Mechanical Measurement Lab



# The Case For a Mechanical Digital Twin

Real-time monitoring and interpretation of complex equipment

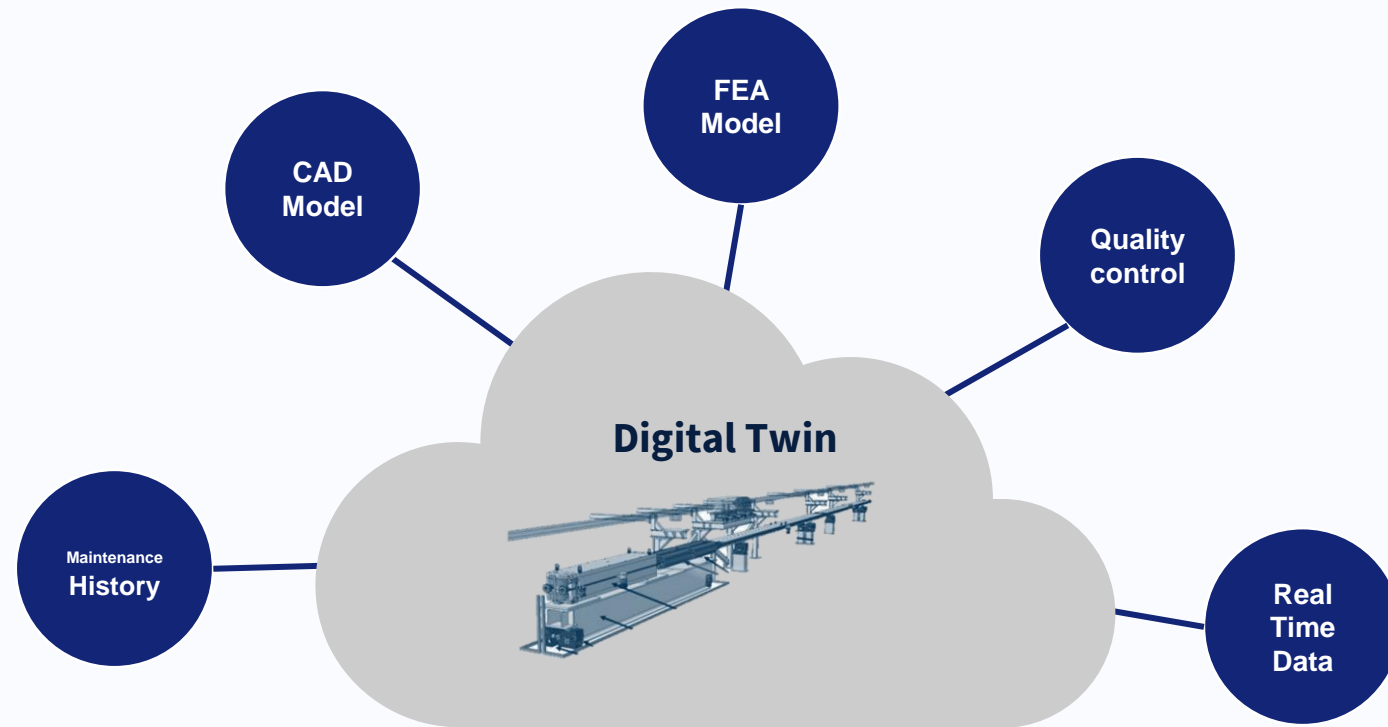
Accurate Real-Time Data Integration

Predictive Maintenance

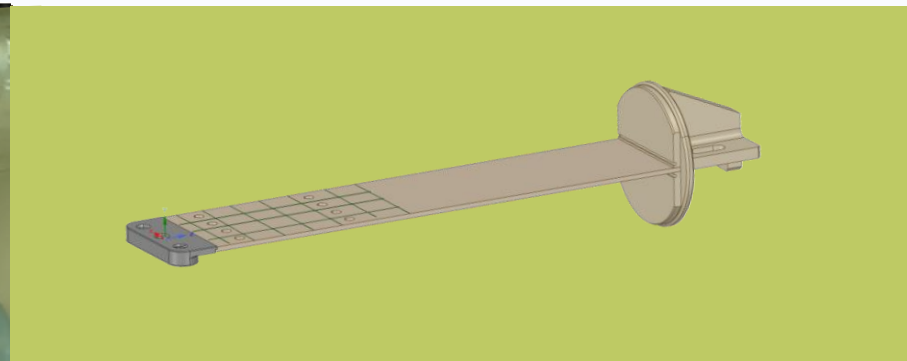
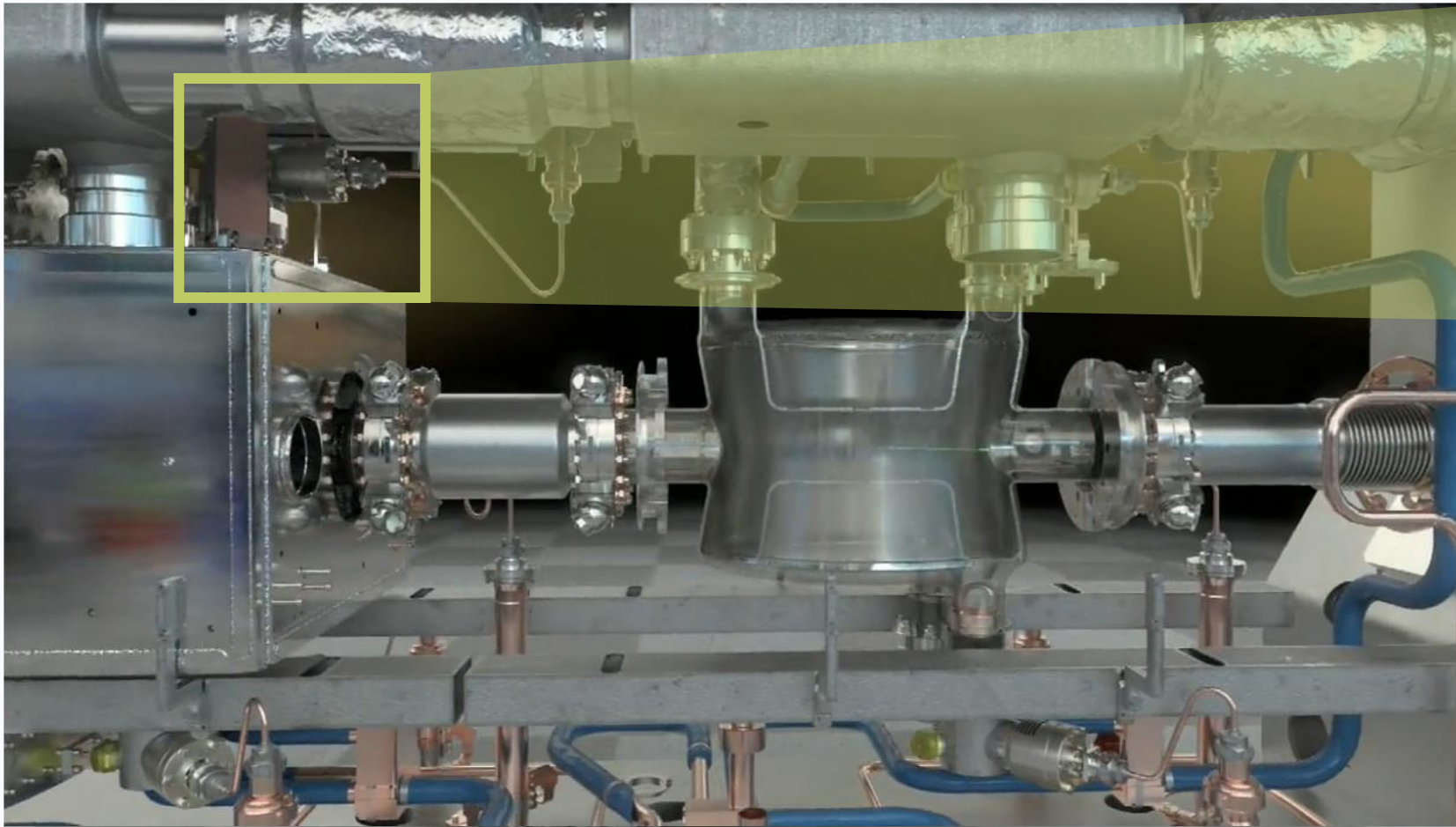
Anomaly Detection

Performance Optimization

Virtual real-time multiphysics sensing

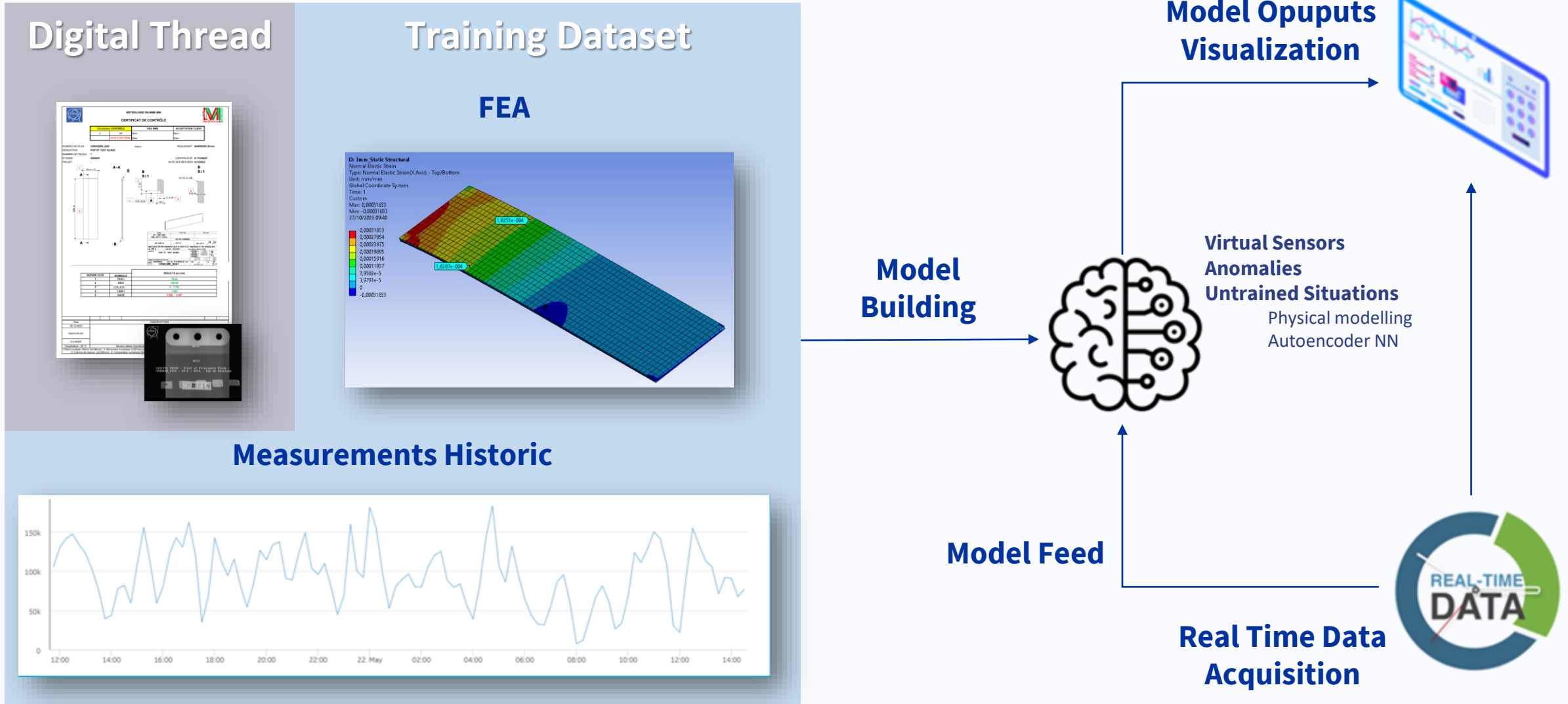


# Proof of Principle: HL-LHC CRAB – Supporting Structure



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

# Proof of Principle Overview



# POP Lessons Learnt...

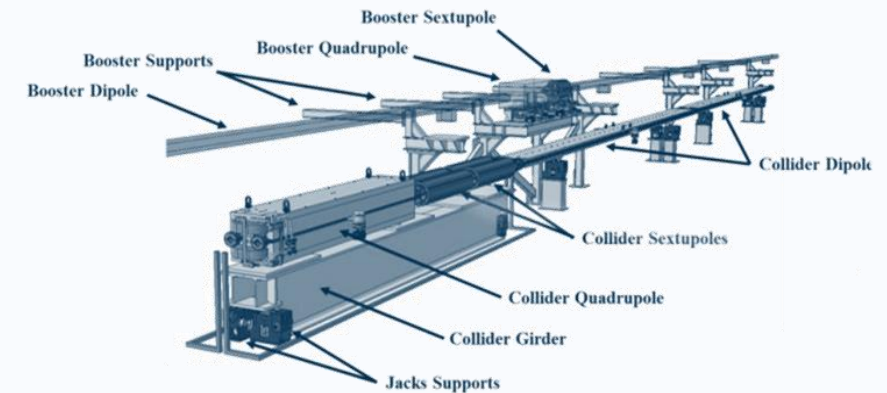
- The completion of the Proof of Principle allowed us to explore the different building blocks of a digital twin, and :
  - Validate potential use cases of interest in practice (virtual sensors and anomalies detection primarily)
  - Identify shortcomings of our approach
    - We are comfortable in our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

# ...and Perspectives

## Infrastructure consolidation

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

## Digital twin of FCC-ee arc half-cell

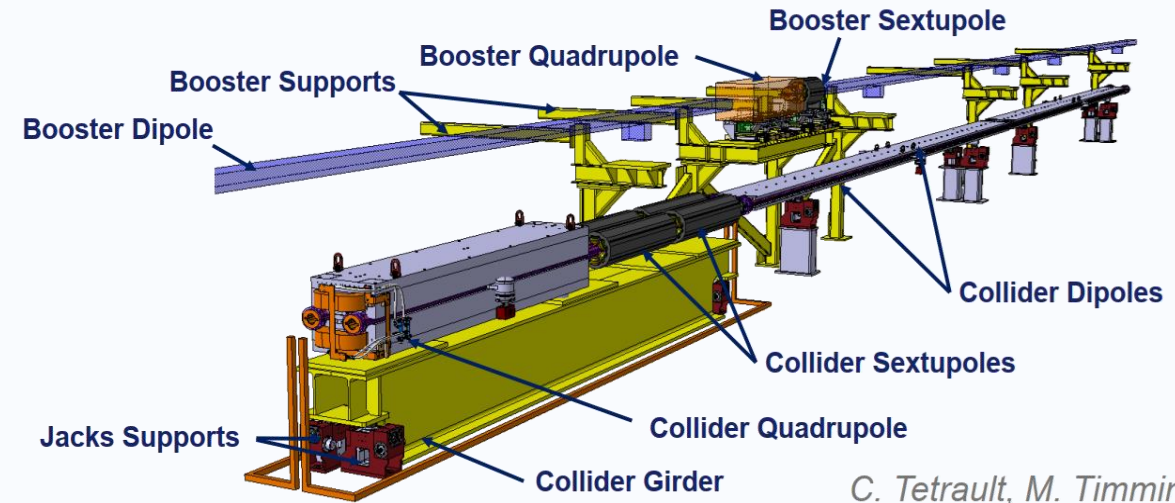




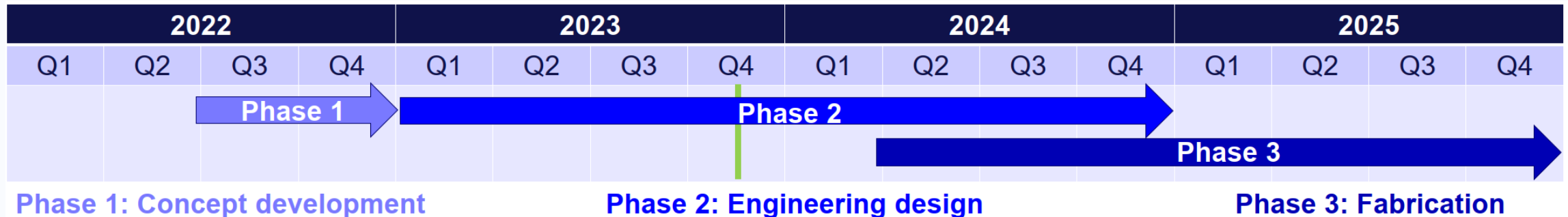
# Next Steps: FCC-ee arc half-cell mock-up project Digital Twin

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

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



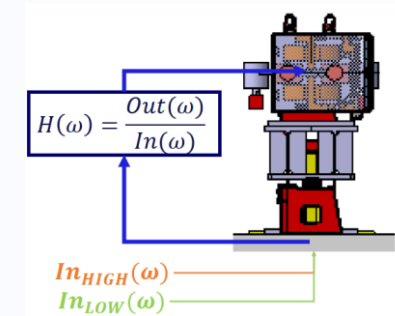
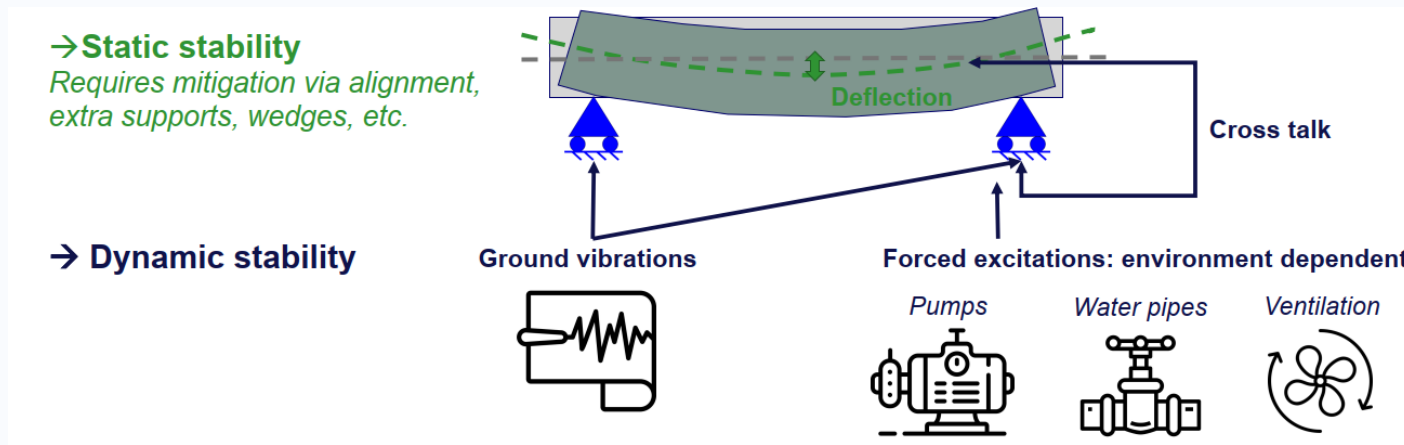
*C. Tetrault, M. Timmins*





# DT and the Challenge of FCC Mechanical Stability

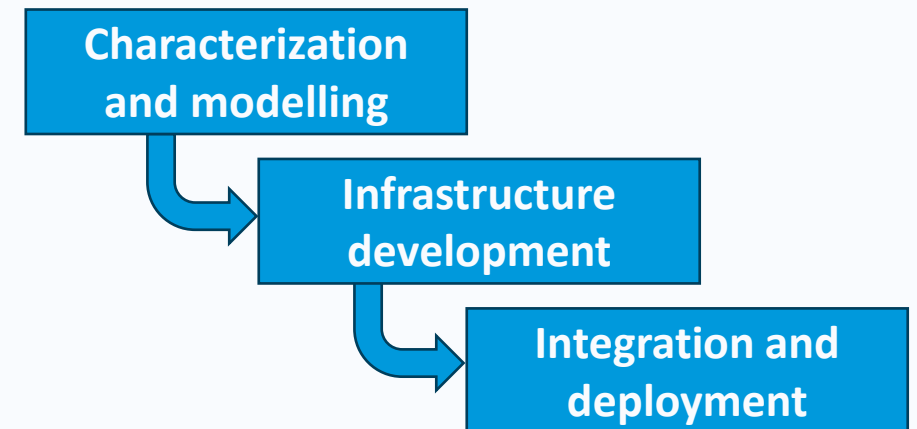
FCC-ee presents extremely stringent demands in terms of stability (sub  $\mu\text{m}$  even for very low frequencies)



Frequencies	Tolerance at beam level
$10 > f > 1 \text{ Hz}$	20 nm
$100 > f > 10 \text{ Hz}$	5 nm

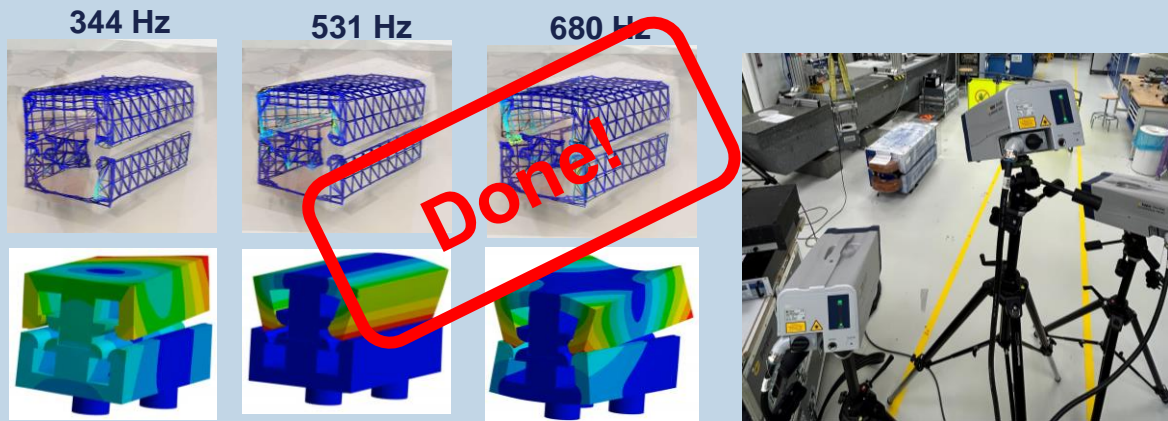
## Digital Twins Motivation

- 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



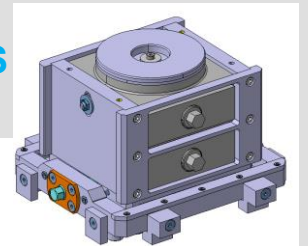
# FCC-ee arc half-cell mock-up experimental campaign

1<sup>st</sup> Step: characterization of the prototype quadrupole  
Modal Analysis – Experimental vs Simulations



4<sup>th</sup> Step: characterization of the girder jacks  
Transfer function from ground to top of the girder / load cells

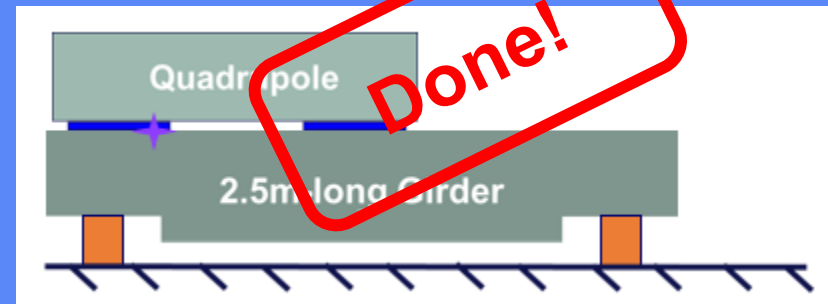
X3 Load cells on the top of PSI JACKS



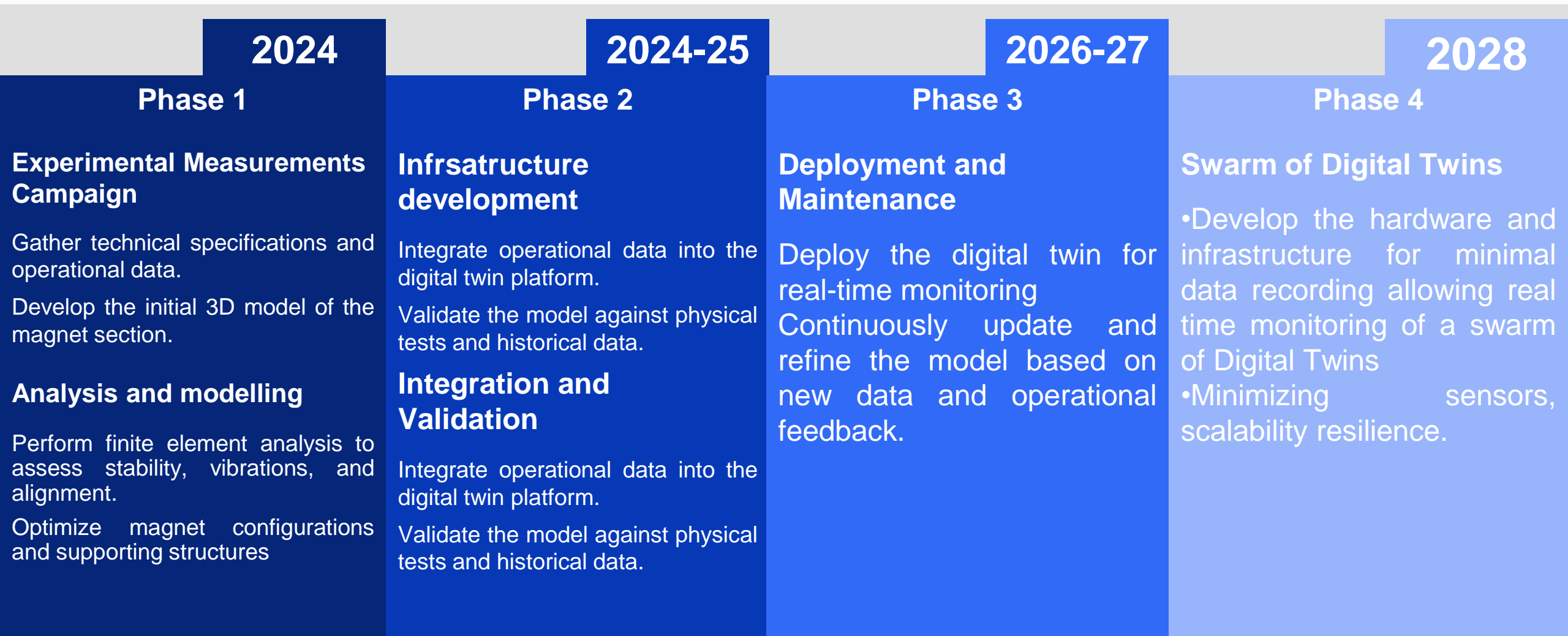
2<sup>nd</sup> Step: characterization of the supporting girder  
Transfer function from ground to top of the girder / load cells



3<sup>rd</sup> Step: characterization of the girder + quadrupole  
Transfer function from ground to top magnet / load cells



# FCC-ee arc half-cell mock-up DT roadmap



# Conclusions

Digital twins can have many different focuses, scales and levels of complexity

Much more than its building blocks separately

Accelerator community is starting to understand the advantages and multiple initiatives are emerging. Convergence in the infrastructure is needed.

Real interest in mechanical digital twins validated (virtual sensors and anomalies detection)

Domain specific know how is not sufficient. Multidisciplinary teams are requested for the implementation of digital twins. Domain specific, Data science, IT...