FUTURE
CIRCULAR
COLLIDER

DIGITAL TWINS: CURRENT ACTIVITIES IN MECHANICAL AND MATERIALS ENGINEERING GROUP AT CERN AND PERSPECTIVES FOR FCC-EE

CERN, MME-DT Core Working Group
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With the help of CERN, BE/GM
H. Mainaud Durand

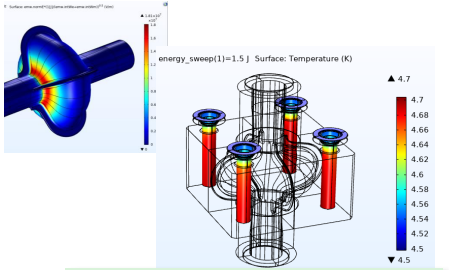
Mechanical and Materials Engineering EN-MME group at CERN
Domains of Activity

Service working as support for CERN-wide users

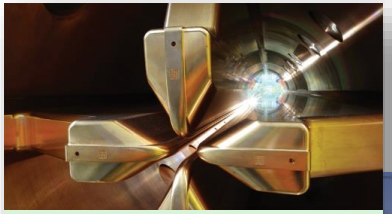

Design

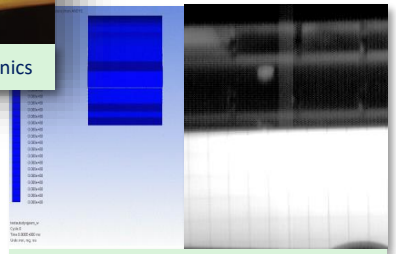

Fabrication

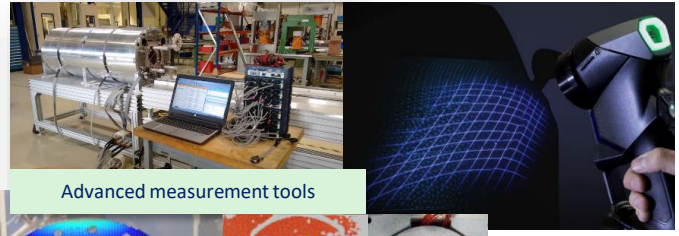

Materials

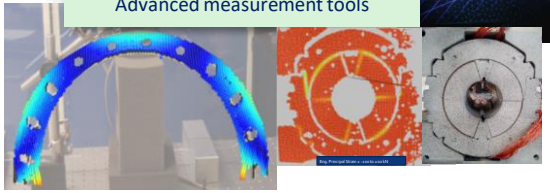


Multiphysics simulations


Broad and advance fabrication technics

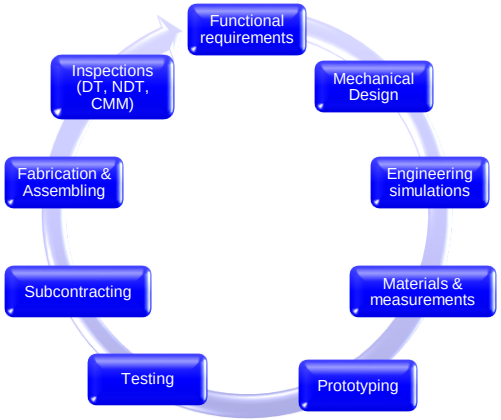

Online monitoring and advanced simulations benchmarking


Advanced measurement tools



Metallurgy and Microscopy

Digital Twins : MME Know-how & Focus

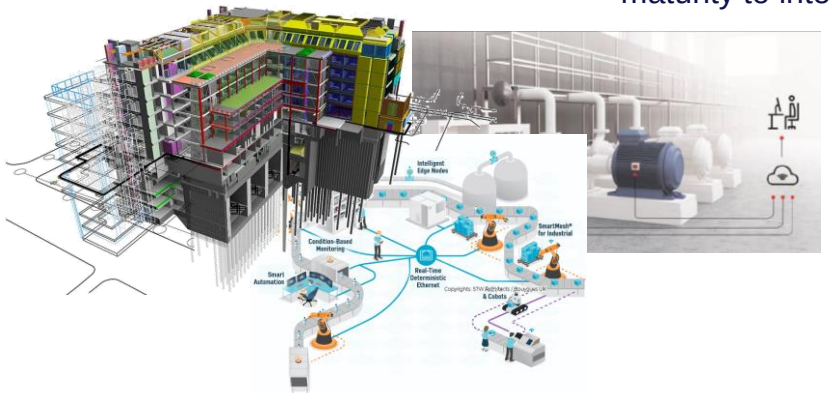


Know-how from design, to production and qualification of **mechanical systems**

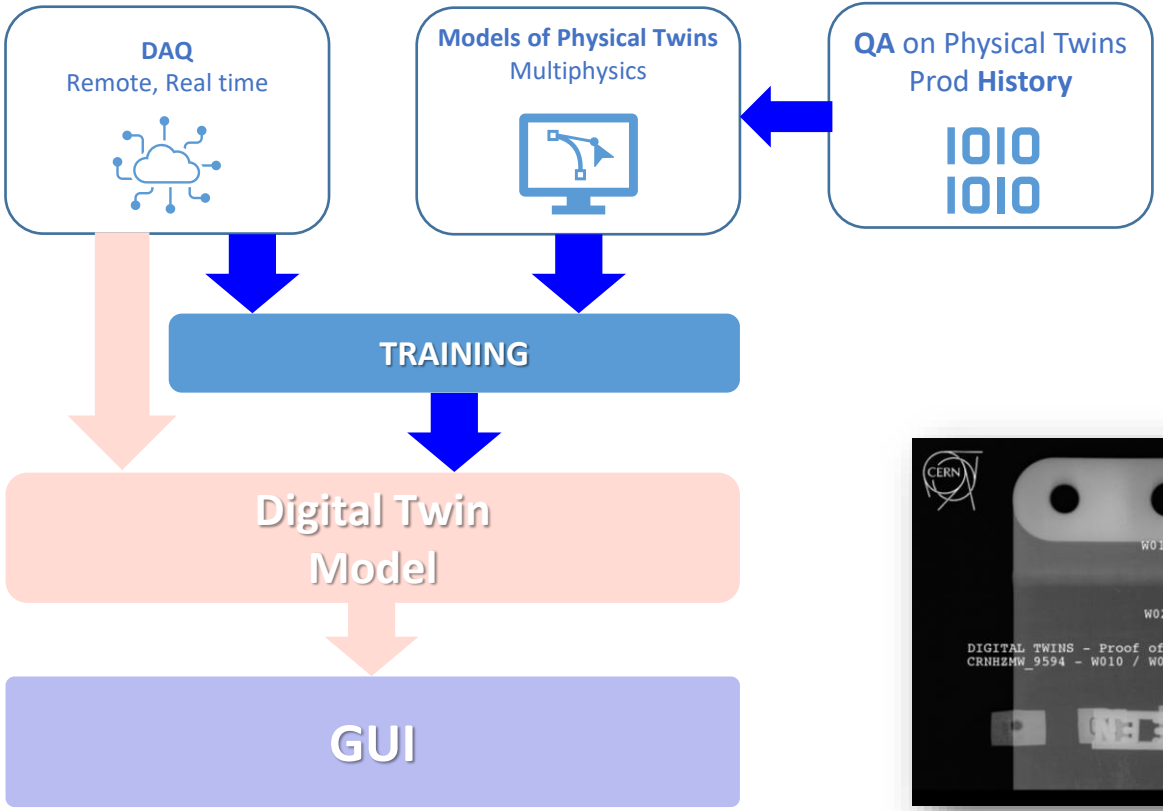
Collaboration and interaction with
- other **CERN stakeholders**
- Universities, Laboratories, Institutes, Industry. In the form of

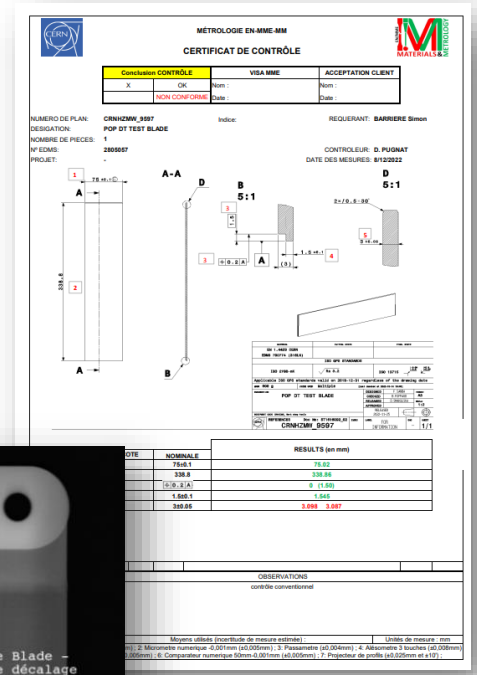
MME GOAL for DT is to reach **readiness for tackling Digital Twins** for CERN users, of **bespoke mechanical systems**

- awareness and experience on DT break even point
- maturity to interact with partners for high level DT



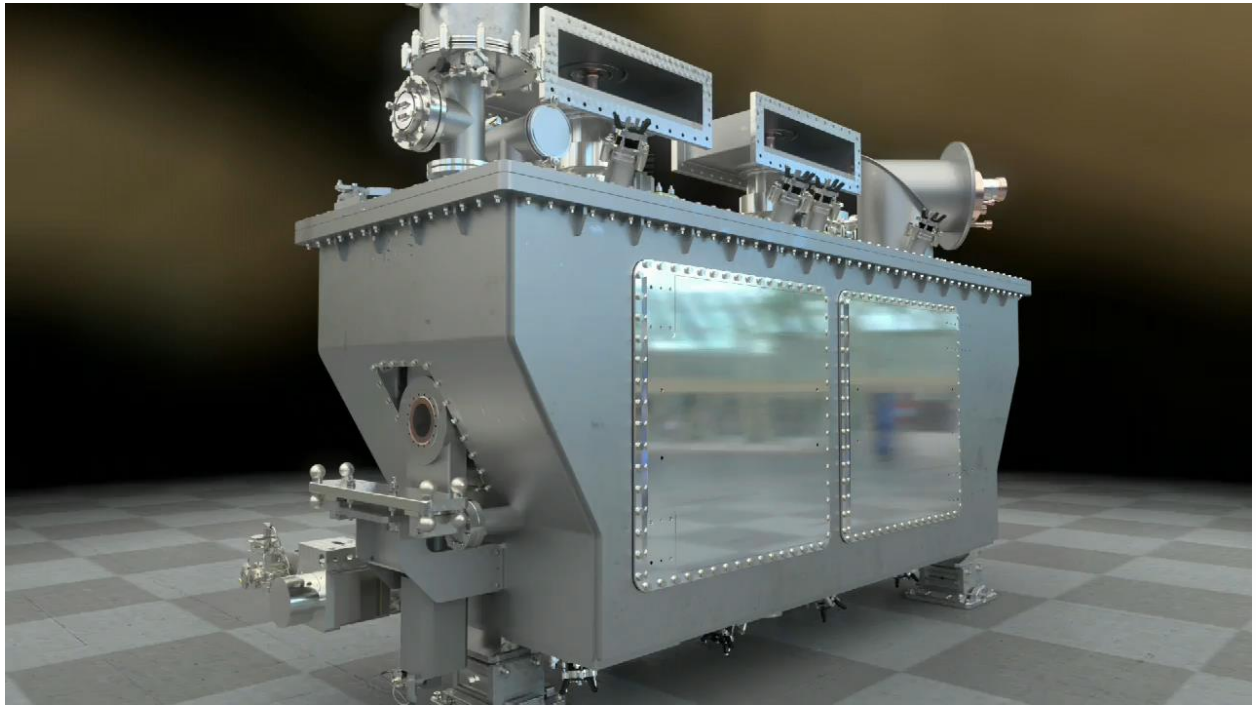
Proof Of Principle : DT Structure

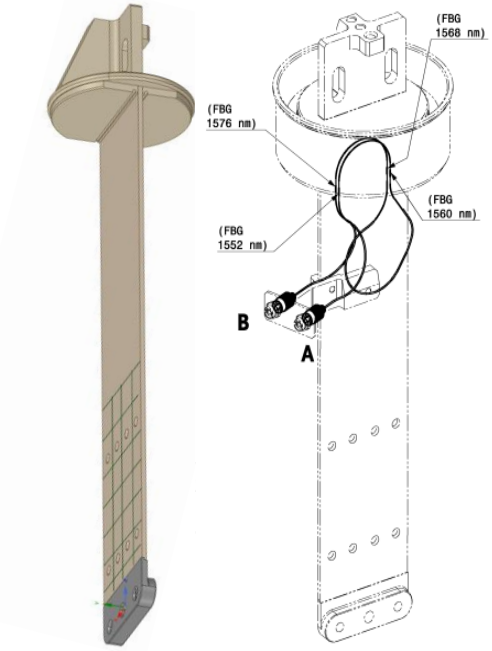


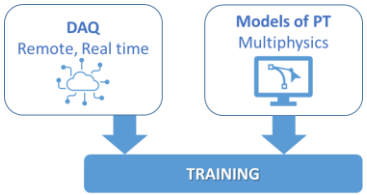


σ-ε

Proof Of Principle : HL-LHC CRAB - Support Blades

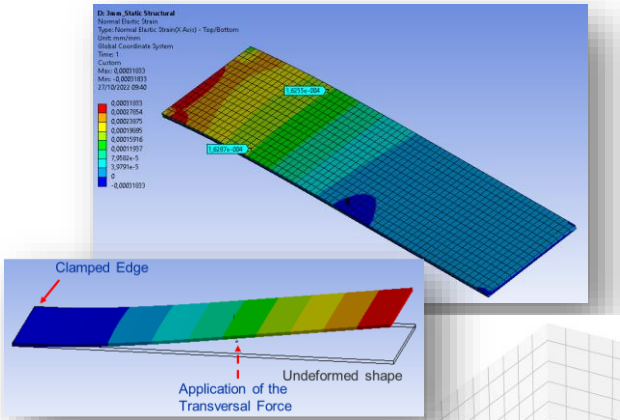


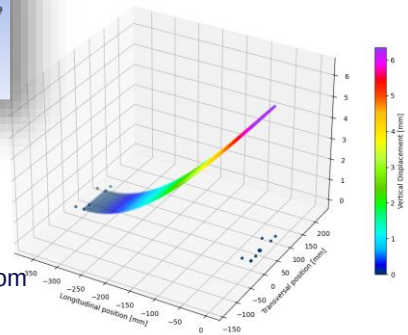




Proof Of Principle : Sims and DAQ

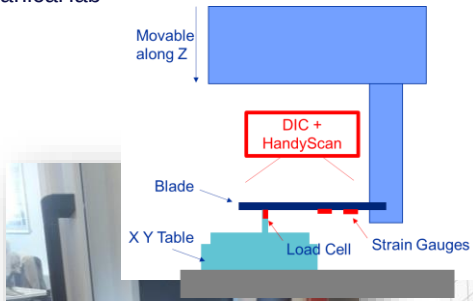
Parametric **simulations** based on Finite Element Method



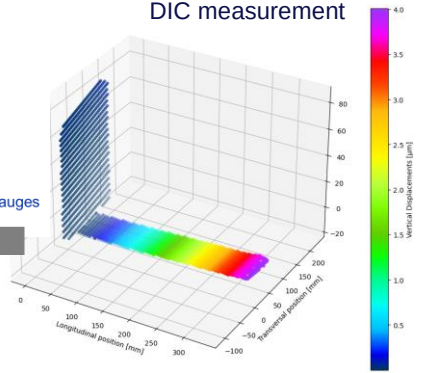


Post-treated data from Simulation

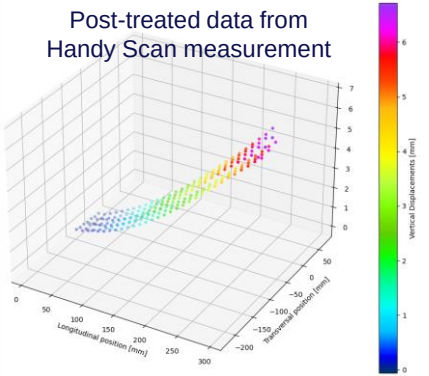
Experimental **measurement** campaign at EN/MME mechanical lab

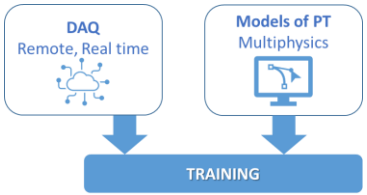


Post-treated data from DIC measurement



Post-treated data from Handy Scan measurement





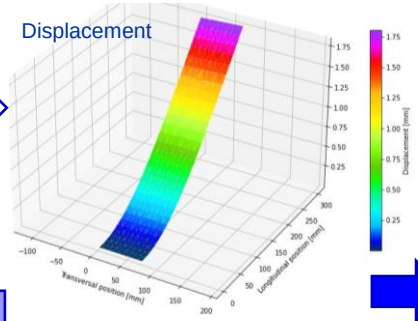
Proof Of Principle : Supervised Training

Training Data Set: DAQ Simulations

Local Strain Gauges measurement

Transfer functions

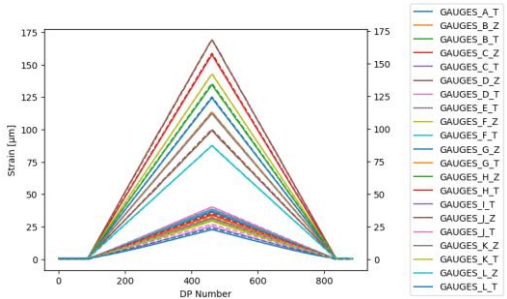
Displacement

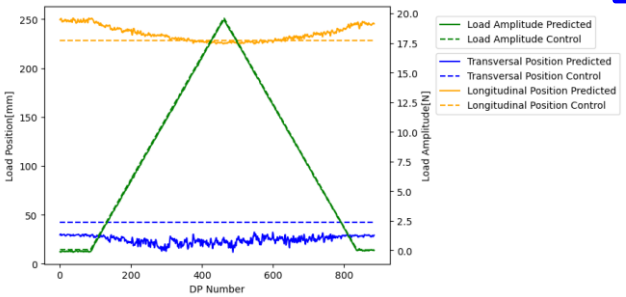


Choice of data regression models (polynomial, gaussian processes, neural networks…)
Optimization of Hyperparameters

Combination of measurement and simulations reduced models

Validation
prediction vs. measurement



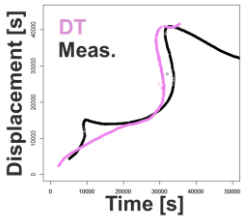


DT Deployment

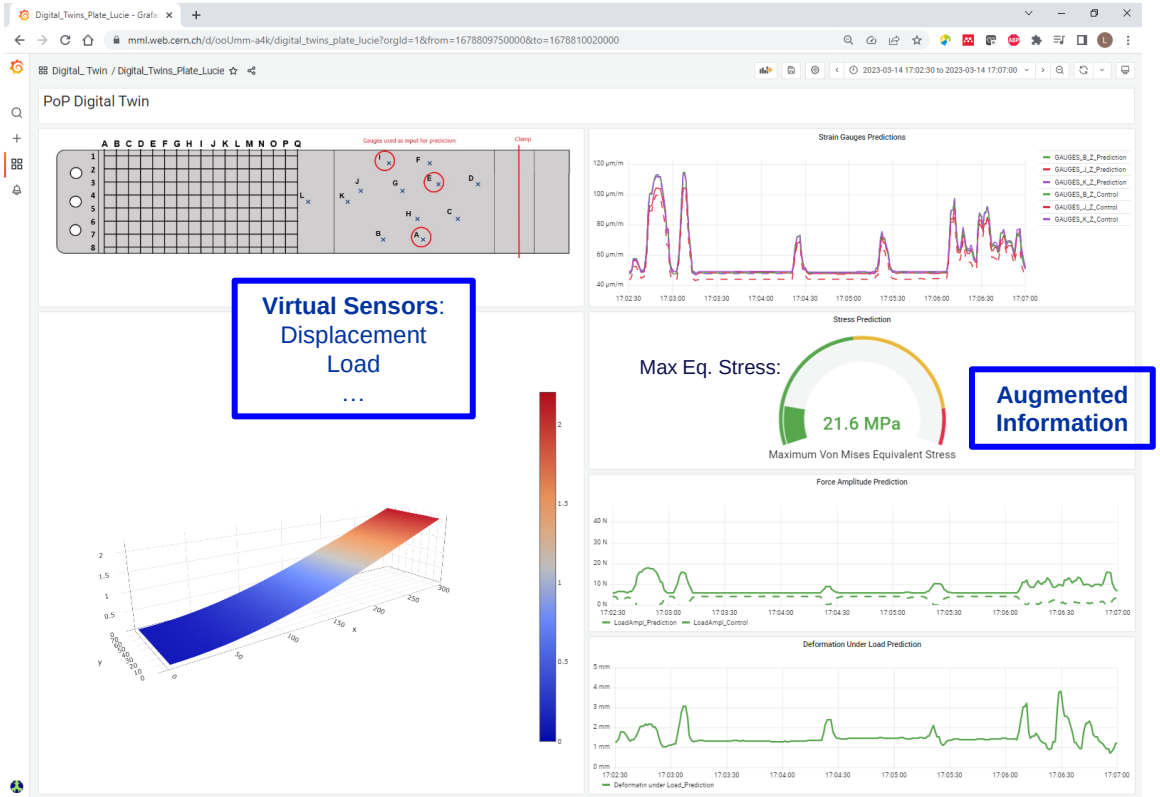
Proof Of Principle : DT deployment on GUI

Information display on a web-based application

- live
- from reduce input data
- without requiring licenced software



Measurement
Control of
accuracy



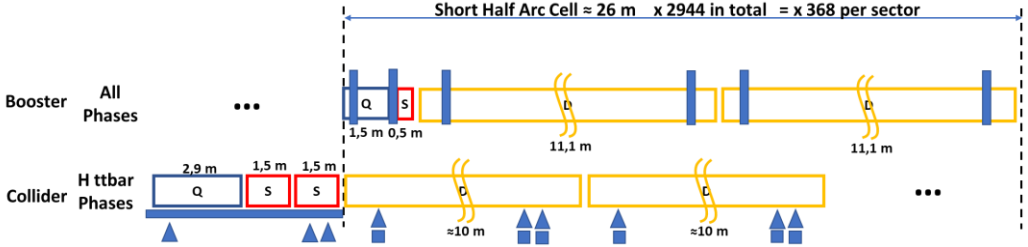
Detection of
“untrained”
situations

FCC-ee Arc Cell Challenges

Challenges for design of the arc's components

Size for the facility:

- ≈ 3000 Arc Half cells
- Booster + Collider



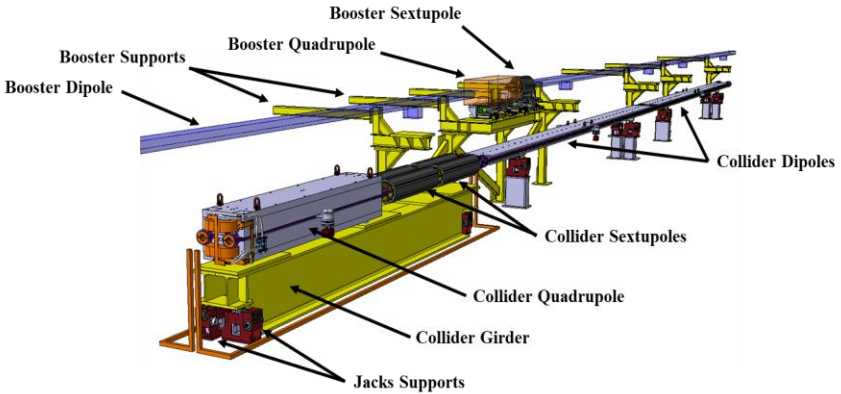
High Radiation level

Gain time, Limit the doses:

- Automatized installation/maintenance operations

Cost optimization:

- Reduce the number of components
- Develop simple and robust components for high reliability



Needs to invest resources on the engineering smart & cost effective components

Mock-up to be build end of 2025:

- Installation/Operation procedure (robot accessibility…)
- Instrumentation/Test
- Simulation's benchmark

FCC-ee Arc Cell Challenges

Challenges for the alignment and survey (H. Mainaud Durand's talks in Academic Training, FCC IS Workshop)

Tolerances of mechanical alignment before Beam Based Alignment

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)
Arc quadrupole*	50	50	300
Arc sextupoles*	50	50	300
Dipoles	1000	1000	300
Girders	150	150	-
IR quadrupole	100	100	250
IR sextupoles	100	100	250
BPM**	-	-	100

* misalignment relative to girder placement
** misalignment relative to quadrupole placement

Ground Stability
Brand new tunnel :
- unknown ground motion

Thermal Stability
Temperature gradients
- Air: + 8°C in 108 m / - 6°C in 10 m (EN/CV)
- Cooling Water: ΔT = + 25°C (TE/VSC, TE/MSC)

Needs for R&D:

Development of specific alignment strategies and methods for the smoothing and maintenance of the alignment:
- Permanent geodetic network (development of SLB)
- Survey Wagon (FSI, Laser Trackers)

Pre-alignment of 3000 girders:
- PACMAN-like strategy for fiducialisation
- Stability during storage, transport and installation

Context for a Digital Twins related to FCC-ee Arc Cell Mock-up

Context: preliminary assembly of FCC-ee collider Short Straight Section available in the coming months

Study on the influence of temperature on the magnet center position:

Temperature measurements by varying:

- Ambient Air Temperature
- (Air Flow)
- Magnet Powering
- Synchrotron Radiation

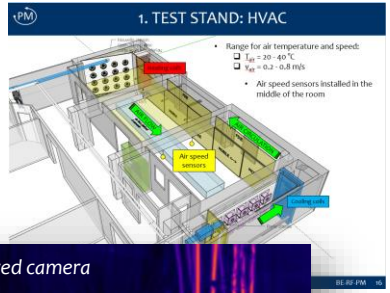
Measurement of the magnet center position

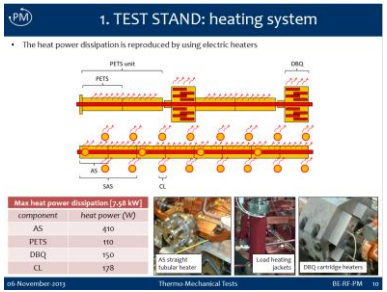
Benchmark of FEA:
Validation of the thermal and mechanical of girder assembly behavior

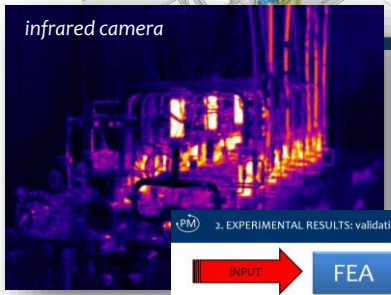
Digital Twins:
Prediction of the magnetic axis displacement during operation

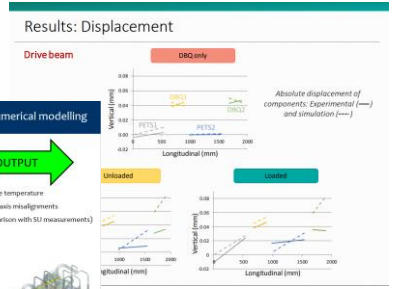
Pre-correction (offset) applied during pre-alignment of each component on the girder

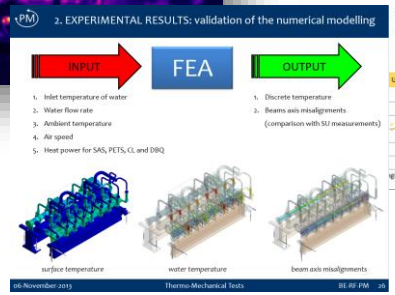
CLIC Lab Module is still assembled at CERN











Context for a Digital Twins related to FCC-ee Arc Cell Mock-up

Study on the influence of storage, transport and installation parameters on the magnet center position:

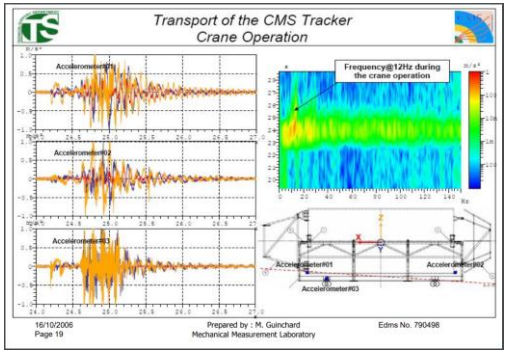
Storage conditions
- Thermal cycles during the storage of the pre-aligned girders

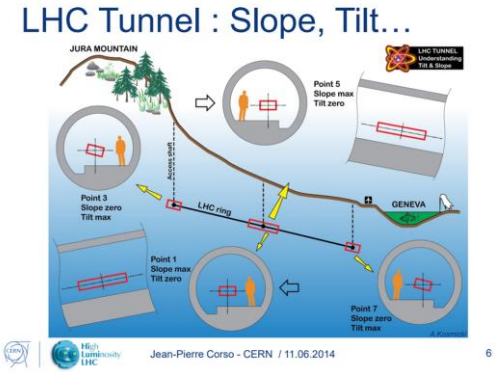
Vibration during Transport dans Handling
- Vibrations exposed to LHC components (cryomagnets and detectors) have been characterized
- The mis-alignment after controlled vibrations to be characterized

Installation in a specific environment in the FCC tunnel
- Tilt (1% slope in the FCC tunnel) →The mis-alignment to be characterized
- Ambient temperature controlled by ventilation cf EN/CV

Digital Twins:
Prediction of the magnetic axis displacement during storage, transport and installation…

Pre-correction (offset) applied during pre-alignment of each component on the girder





Conclusion & Next Steps

Digital Twins is a new tool with great potential …

… also for mechanical components !

Advantages of Digital Twins vs traditional modelling & measuring uses:
- **live data**
- **Component's parameters that would not be instantaneously accessible**

Sensors optimization
Operation optimization (for components that are difficult to access or those failure is critical)

Great interest for FCC mechanical components !

FCC

Thank you
for your attention.

EN-MME – Organization and Domains of Activity

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**

MME
Materials & Mechanical 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*

Design

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

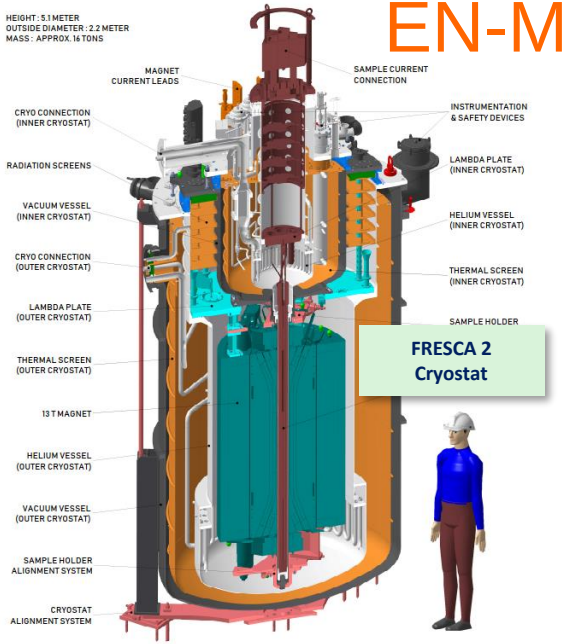
Fabrication

- **Mechanical workshop (4000 m2)**
  - 60+ technicians and 10+ engineers
  - CNC machining . Assembly & Metal forming
  - Welding (TIG, MIG, EBW, laser) & Vacuum Brazing
- **Technical Subcontracting unit**

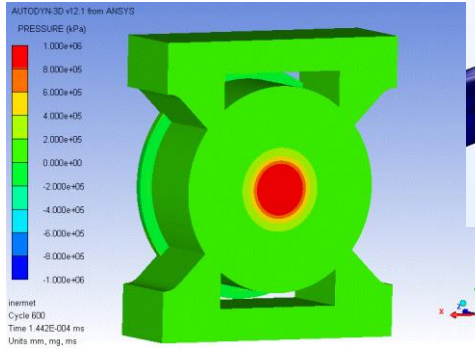
Materials

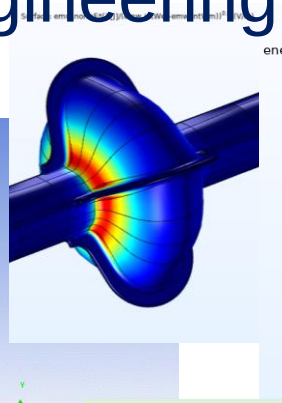
- **Material science consultancy**
  - Metallurgical analyses, microscopy including FIB, Mechanical tests
- **NDT:** UT, radiography, microtomography
- **Metrology:** 350 m^2 Lab., several CMM

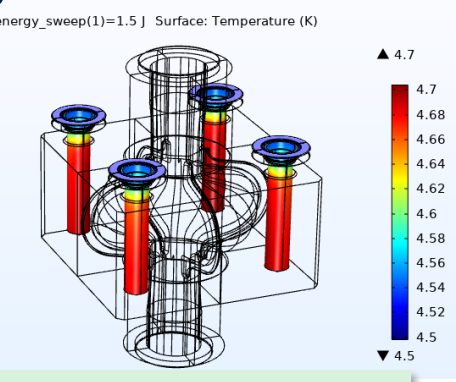
EN-MME – Design Engineering



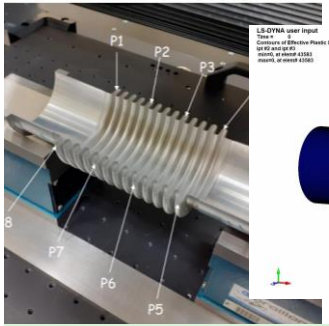
FRESCA 2 Cryostat

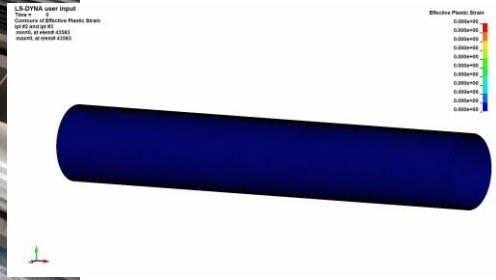




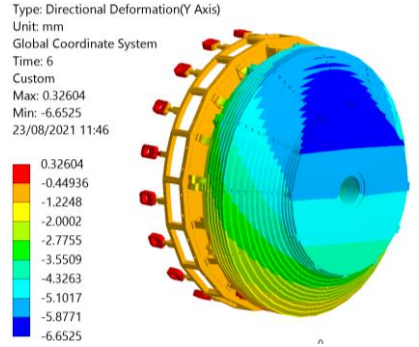


FCC SWELL cavity
Multiphysics RF-Thermal simulations





Fabrication technologies
ATLAS bellows forming LS-Dyna simulation



CMS-HGCAL
Simulations of large structures

Design of **complex mech. systems**

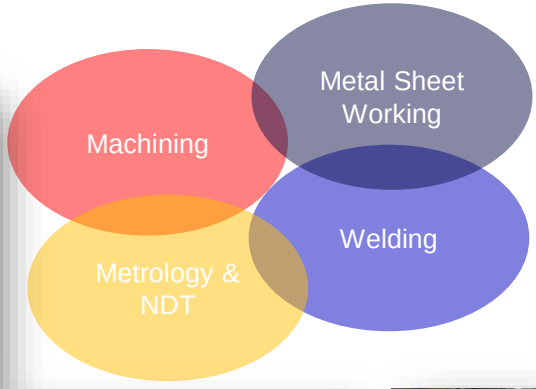
Advanced computations, **multiphysics analyses** (e.g., explicit simulations of fast/large deformation events)

EN-MME – Mechanical Workshop & Metrology

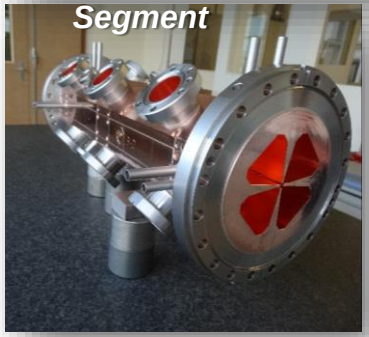
Its core mission is to provide service to the Organization for:

- **Urgent needs** (repairing, tunnel interventions, urgent fabrication…)
- **Prototypes / proof of principle**
- **Multi-technology fabrication projects**


Linac4 RFQ Spare Segment




CRAB Niobum Cavity

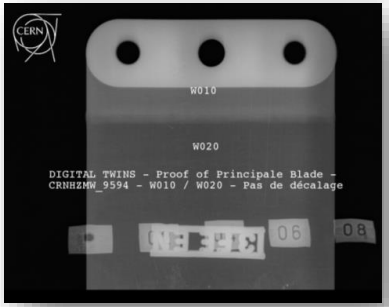


HL-LHC Beam Screen


HL-LHC Crab Cavity He-Tank

EN-MME – Materials and (Non-)Destructive Testing

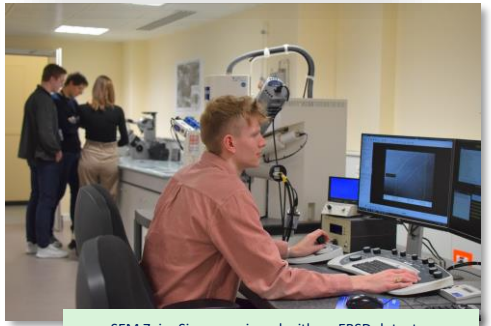
Preparation ⇒Observation



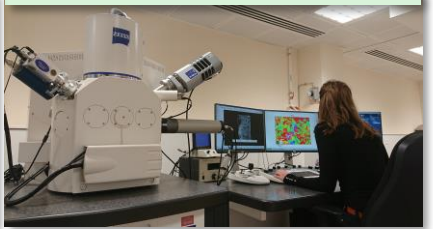
New Bruker Discovery X-ray Diffractometer during installation in Feb. 2021

Advanced microscopy, microanalysis ⇒

FIB-SEM Zeiss XB 540

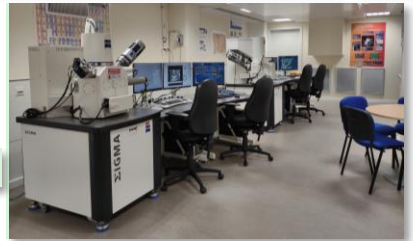


SEM Zeiss Sigma equipped with an EBSD detector



⇐ Crystallography

SEM ZEISS Sigma 500 equipped with an EDS Extreme Oxford

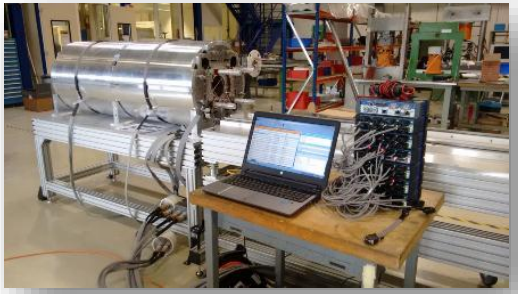


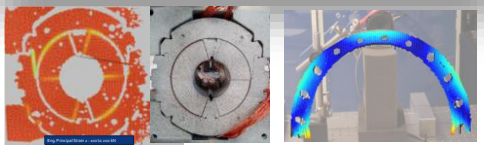
EN-MME – Mech. Measurement Lab

Reference laboratory for mechanical and physical measurements (stress/strain, vibrations, seismic, thermal properties …) for a wide range of CERN components and facilities

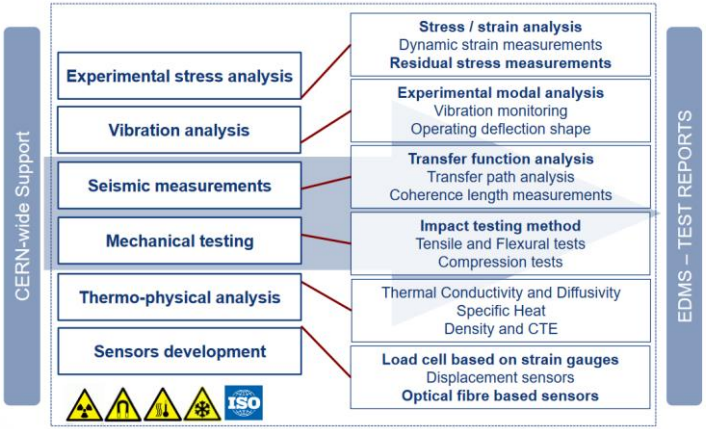
Measurements are used to

- define **input properties** for design and FEA
- on real components: **characterise**, **benchmark** design predictions
- in various environmental conditions (cryogenic temperatures, high radiation environment and high magnetic fields)



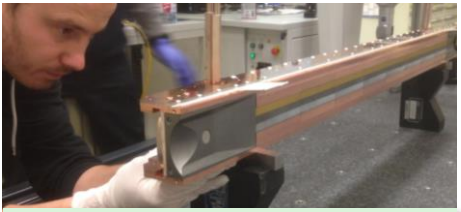


Lab website with a virtual visit



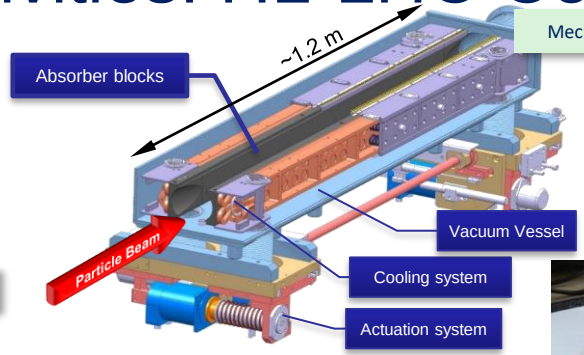
Data from every system are continuously streamed and/or stored on the Cloud/DFS

EN-MME – Integrated Activities: HL-LHC Collimators

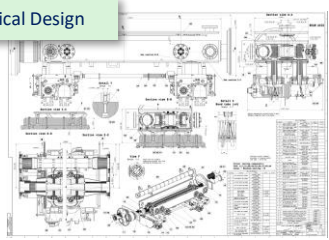


Assembly and Metrology

Installed system

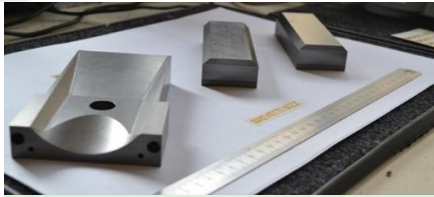


Mechnical Design



Fabrication

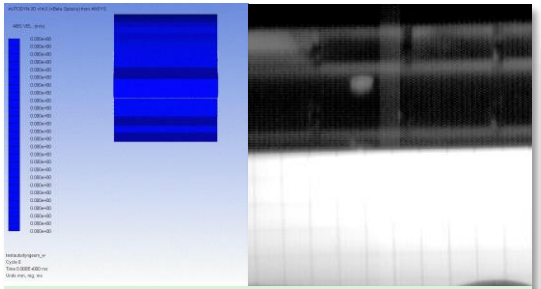
- The **"protection" system of LHC and HL-LHC**, capable of absorbing the energy of an Airbus A320 flying at 520 km/h, concentrated in the cross-section of a needle
- Cross-department project, with international collaborations, led by BE-ABP and SY-STI groups



Materials Science (novel materials R&D) with Knowledge Transfer

European Commission | Horizon 2020 European Union funding for Research & Innovation

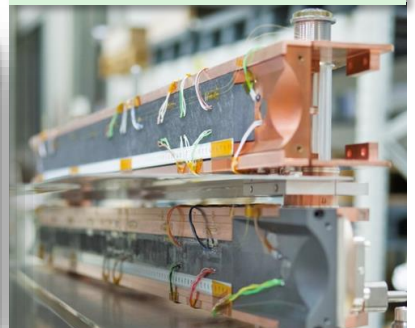
Metallurgy and Microscopy



Online monitoring and advanced simulations benchmarking

Component Testing (under particle beam)

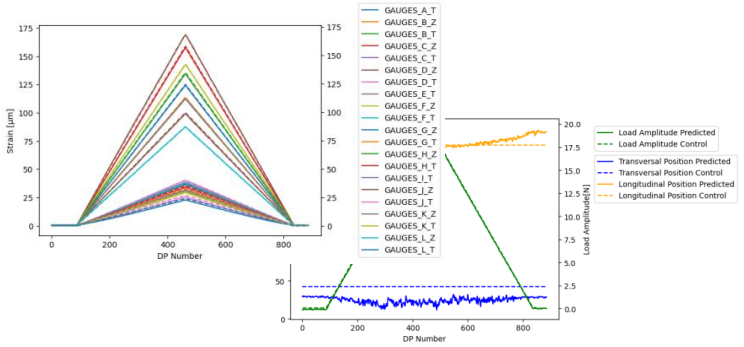
Mechanical Measurements (SG, FBG ..)



Proof Of Principle : DT Model & GUI

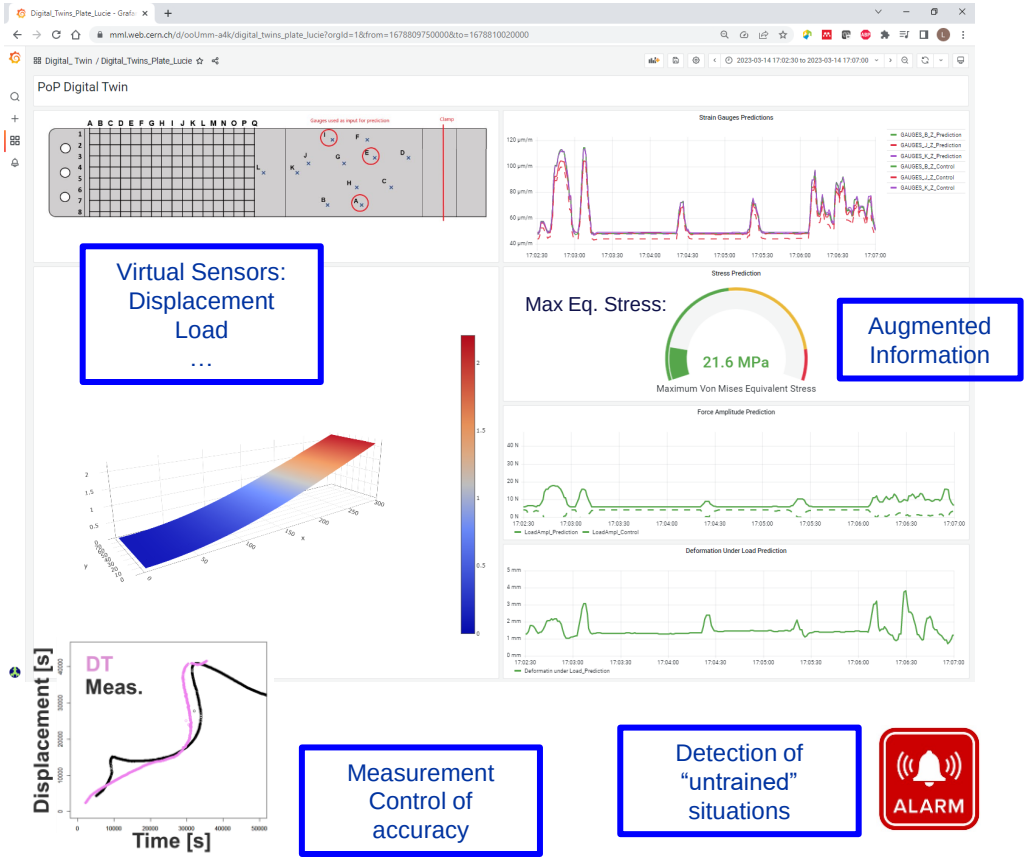
DT Blade GUI Link

https://mml.web.cern.ch/d/ooUmm-a4k/digital_twins_plate_lucie?orgId=1&from=1682666584446&to=1682666643473



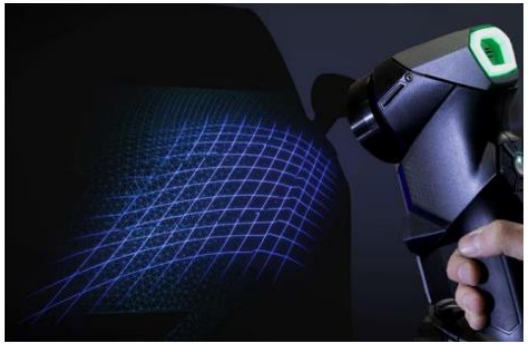
Validation of selected models by comparison of prediction with a control sample measurement

Digital Twin 'Transfer Function'



HandySCAN

- For smaller parts 50 mm to 4 m
- Better accuracy
- No need for the C-track
- Less invasive



	HandySCAN 307MC	HandySCAN BLACKMC	HandySCAN BLACKMC I Elite
EXACTITUDE (1)	Jusqu'à 0,040 mm	0,035 mm	0,025 mm
PERFORMANCE VOLUMÉTRIQUE (2) (basée sur la taille des pièces)	0,020 mm + 0,100 mm/m	0,020 mm + 0,060 mm/m	0,020 mm + 0,040 mm/m
PERFORMANCE VOLUMÉTRIQUE AVEC MaxSHOT NextMD I Elite (3)		0,020 mm + 0,015 mm/m	With MaxSHOT
RÉSOLUTION DE MESURE	0,100 mm	0,025 mm	
RÉSOLUTION DU MAILLAGE	0,200 mm	0,100 mm	
CADENCE DES MESURES	480 000 mesures/s	800 000 mesures/s	1 300 000 mesures/s
SOURCE DE LUMIÈRE	7 croix laser rouges	7 croix laser bleues	11 croix laser bleues (+ 1 ligne supplémentaire)
CLASSE DE LASER	2M (sécuritaire pour l'œil)		
ZONE DE NUMÉRISATION	275 x 250 mm	310 x 350 mm	
DISTANCE NOMINALE	300 mm		
PROFONDEUR DE CHAMP	250 mm		
TAILLE DES PIÈCES (recommandée)	0,1 – 4 m	0,05 – 4 m	

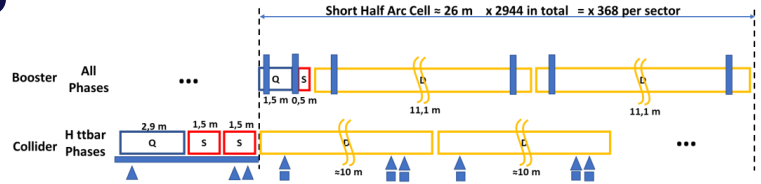
FCC-ee Arc Cell Challenge

Challenges for design of the arc's components
Size for the facility:
- ≈ 3000 Arc Half cells
- Booster + Collider

Radiation level:
- 1 year of FCC operation = 11 yrs of LEP operation

Cost optimization:
- Reduce the number of sensors
- Develop simple and robust sensors

Gain time, Limit the doses:
Automatized installation/maintenance operations



Tolerances of mechanical alignment before Beam Based Alignment

Challenges for the alignment and survey (H. Mainaud Durand's talks in Academic Training, FCC IS Workshop)

	rms x (μm)	rms y (μm)	rms roll (μrad)
Arc quadrupole*	50	50	300
Arc sextupoles*	50	50	300
Dipoles	1000	1000	300
Girders	150	150	-
IR quadrupole	100	100	250
IR sextupoles	100	100	250
BPM**	-	-	100

* misalignment relative to girder placement
** misalignment relative to quadrupole placement

Brand new tunnel :
- unknown ground motion

Temperature gradients
- Air: + 8°C in 108 m / - 6°C in 10 m (EN/CV)
- Cooling Water: ΔT = + 25°C (TE/VSC, TE/MSC)

Pre-alignment of 3000 girc
- PACMAN-like strategy
- Stability during storage

Development of specific al
smoothing and maintenan
- Permanent geodetic ne
- Survey Wagon (FSI, La

FCC-ee Arc Cell Mock-up

Lorem Ipsum Dolor

Past/On-going studies:
Conceptual design:

- Take part in integration studies (Transport, Safety,…)
- System's interfaces (Magnets, Vacuum chamber, BPM)
- Design of the supporting structure
- Design of the support
- Dynamic stability studies

Future studies:
Optimization of the mechanical supporting structure:

- Design Parameters
- Choice of material (mineral cast, damping fillers)
- Choice of the adjustment system
  (after the definition of the alignment strategy)