ARC BPMS DEVELOPMENT AND ALIGNMENT

E.R. Howling, M. Gasior, S. Mazzoni, T. Lefevre – SY-BI

Many inputs from TE-VSC, TE-MSC, BE-GM and EN-MME

SY FCC workshop - https://indico.cern.ch/event/1449294/ - 4th October 2024

Overview

- FCC arc BPM specifications
- On-going FCC arc BPM design and tests
- Towards a validation of the BPM to QUADRUOPLE alignment

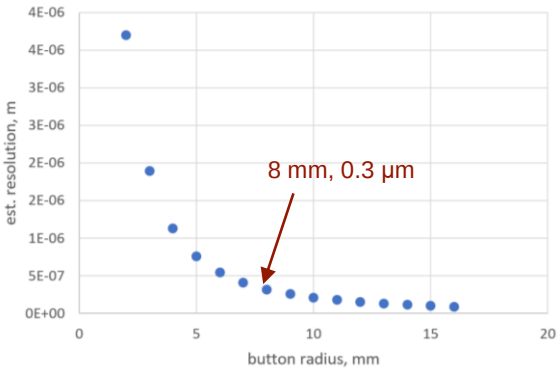
Arc BPMs specifications

- BPMs on every quadrupole in Main rings and Booster ring
- Shall provide orbit, turn-by-turn and bunch-by-bunch measurements.
- Small impedance needed-> minimise heating, at the expense of smaller signals and resolution.
- Challenging specifications in terms of accuracy and precision
- Need to be stable and reliable
- Large number of devices and biggest cost driver in the FCC-ee Beam instrumentation

BPM Parameter	Requirement	Comments
Orbit resolution	0.1 μm	Smaller pipe diameter helps (reduced from 7 to 6 mm)
TxT resolution	< 10 μm	
Arc BPM accuracy	20 μm	No BPMs on sextupoles yet
Min bunch spacing	**25 ns**	Signal processing time needed.
Number of devices	**~9000**	Main and booster rings

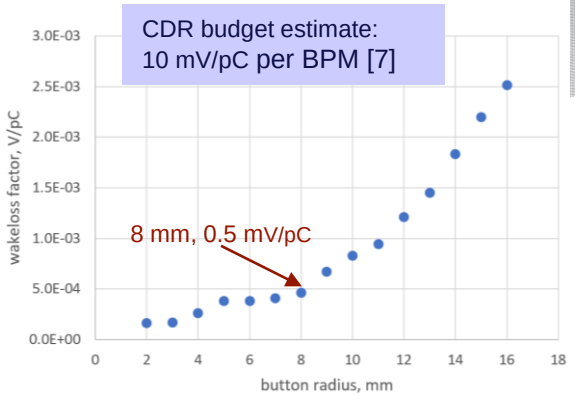
Arc BPMs design and tests

- Simulations of a simple button BPM were done in CST to optimize radius.
- The bunch charge was 24 nC and the bunch length was 3 mm sigma.

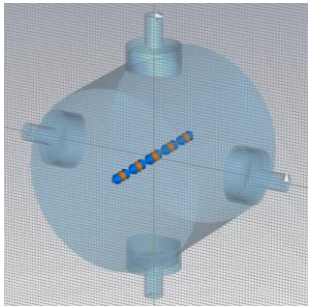


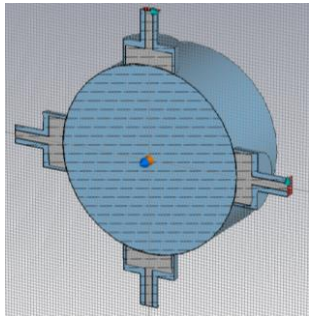
Resolution as a function of button radius.

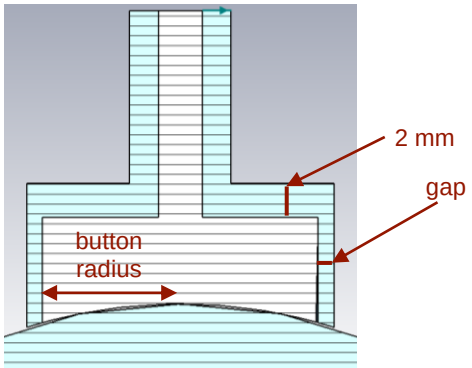
CDR budget estimate:
10 mV/pC per BPM [7]



Wakeloss factor as a function of button radius.



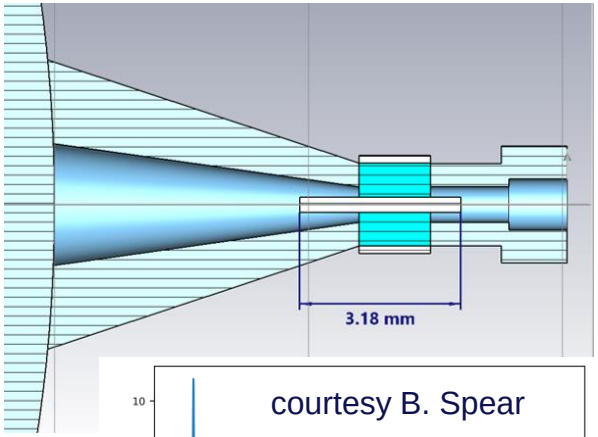


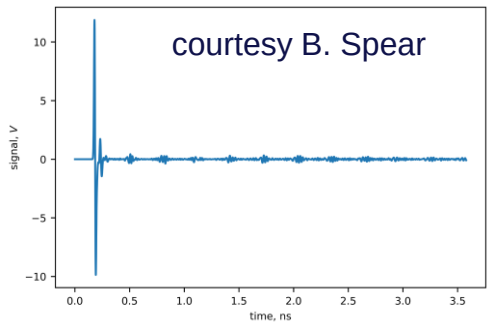


Arc BPMs design and tests

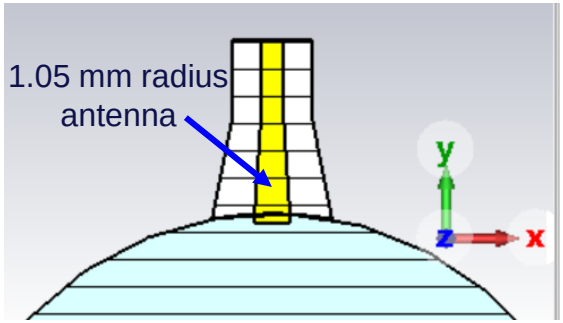
- Simulating and testing different PU designs

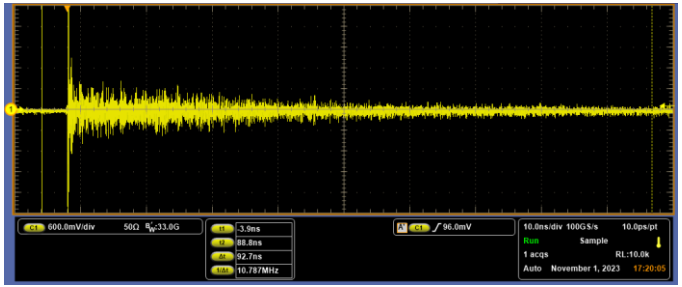
CST model of AWAKE eBPM





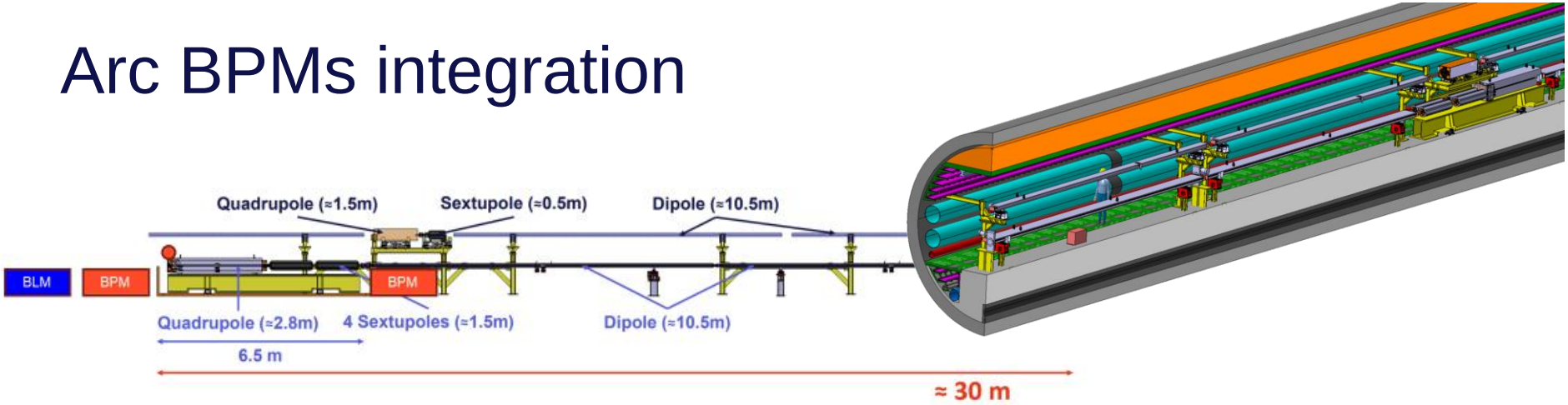
CST model of high bandwidth PU from PSI, courtesy N. Vallis.





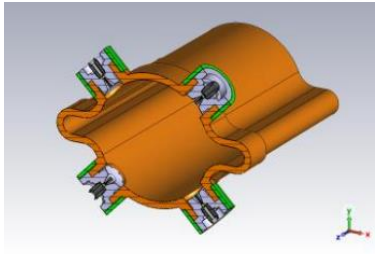
Signal from one of the PSI PU on oscilloscope at CLEAR

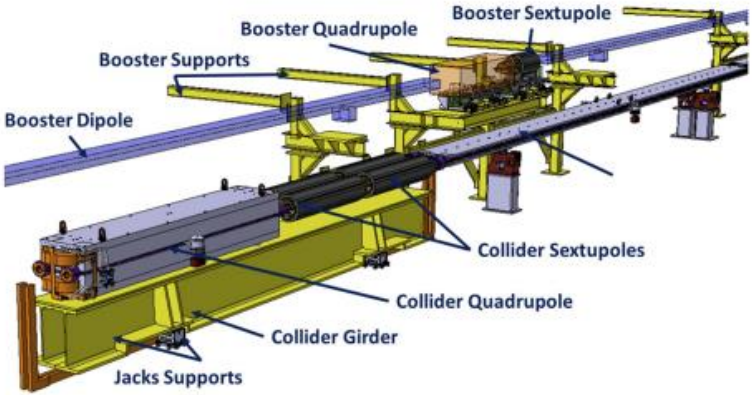
Arc BPMs integration



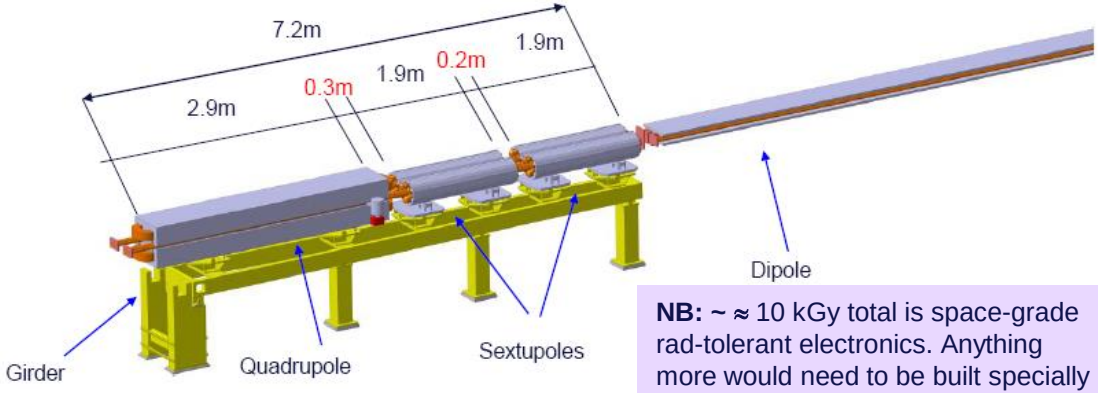
location of BPM Rack?

- 2 x button BPMs (B1 & B2)
- 1 x booster BPM
- powered from tunnel outlet
- serial daisy chain
- 2x Rx, Tx fibre link to nearest alcove

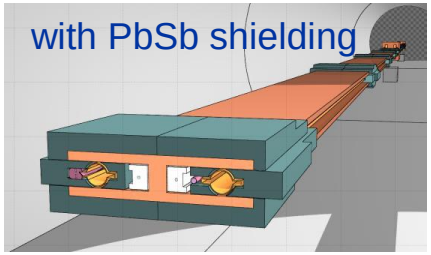


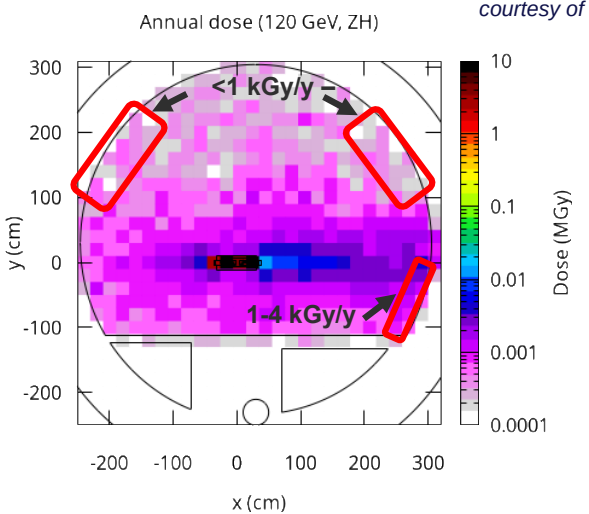


50MW of SR dissipated in the ARCs



NB: ~ ≈ 10 kGy total is space-grade rad-tolerant electronics. Anything more would need to be built specially (like in experiments) – very expensive!





courtesy of B. Humann, A. Lechner

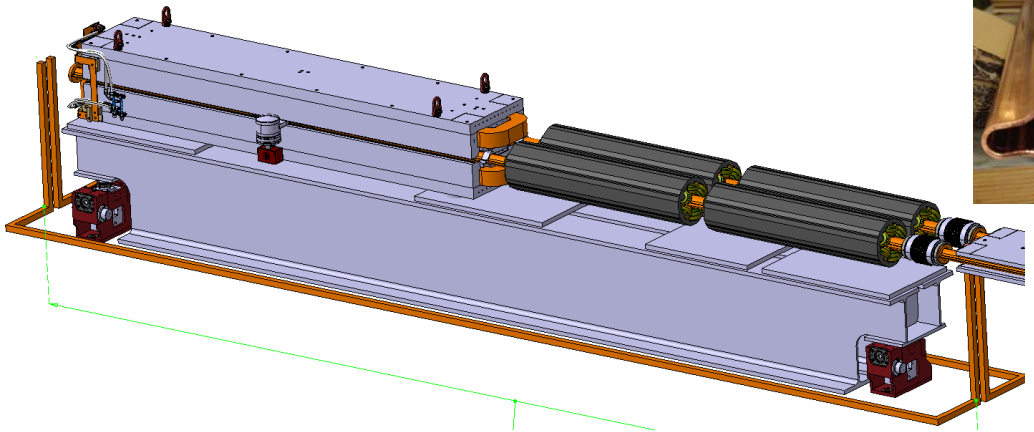
- X-ray shielding and rad-hard/rad-tol electronics
  - **Shall launch a WG to gather specifcations for Arc cell electronic DAQ (involved many groups) in view of pre-TDR**

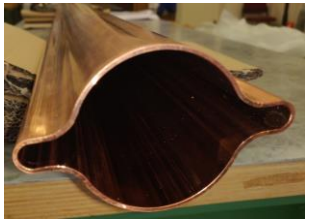
- Large variation of Temperature in the tunnel between beam off- beam on (>10degrees)
  - **Critical for the overall system stability and acceleraror performance**

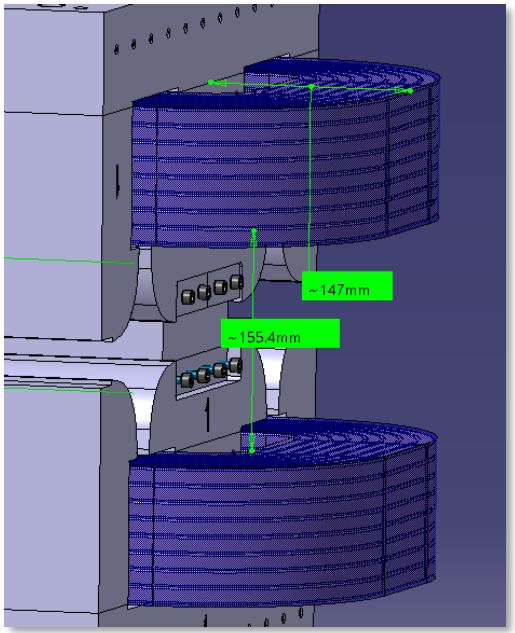
FCC-ee BI meeting –23/08/2024

BPM to Quad alignment - https://indico.cern.ch/event/1441884/

- Presentations from BE-GM, TE-VSC, TE-MSC and EN-MME
- Define a baseline scenario for BPM to QUAD alignment
- Identify the next steps, simulations and tests to be performed
- Discuss the implications for FCC-IS costing and risk analysis





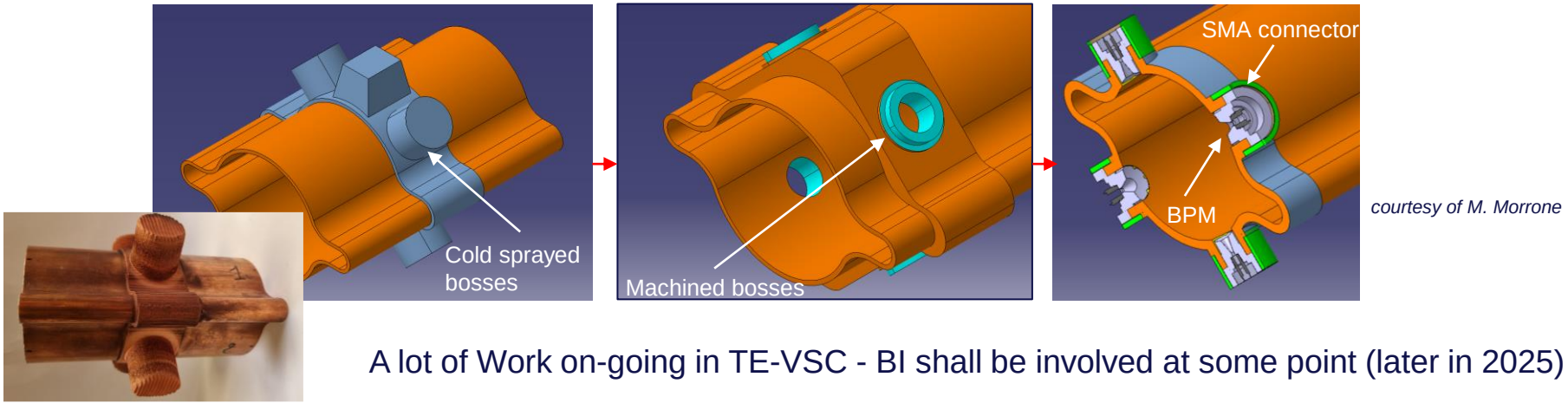


CAD of existing short model (CDR design)

- **Parallel beam based alignment** to define the offset between BPM electrical center to the Quadrupole magnetic center down to **20microns accuracy** (assuming a BPM resolution of 1micron and a **mechanical pre-alignment of 100microns**)

(https://indico.cern.ch/event/1298458/contributions/5978319/attachments/2874376/5033360/BBA_simulations_for_FCCee.pdf)

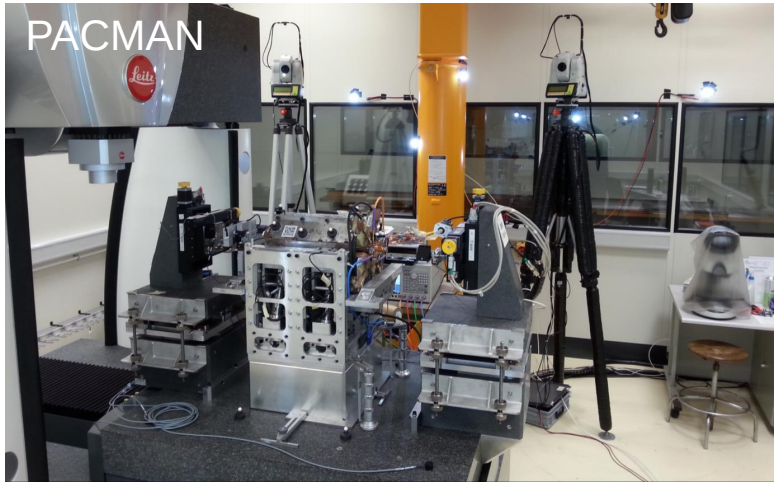
- The mechanical tolerances of the **key technologies developed by TE-VSC** for the fabrication of long extruded vacuum chamber (7m long for quadrupole) and the insertion and welding of BPM button (additive manufacturing and shaped memory alloy) need to be assessed.



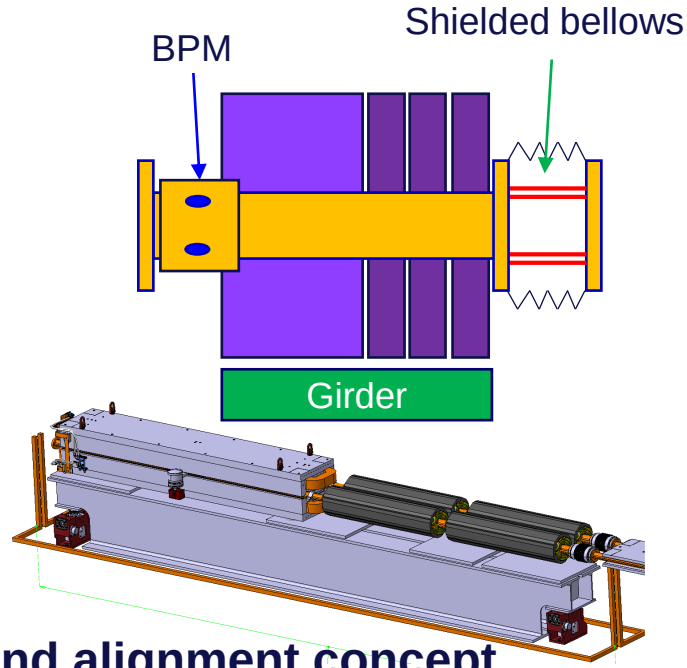
courtesy of M. Morrone

A lot of Work on-going in TE-VSC - BI shall be involved at some point (later in 2025)

- A **full test stand for alignment and characterization** should be designed and operated (a la PACMAN) to validate mechanical design, integration as well as alignment methods (fiducialisation, alignment and automatisation techniques)



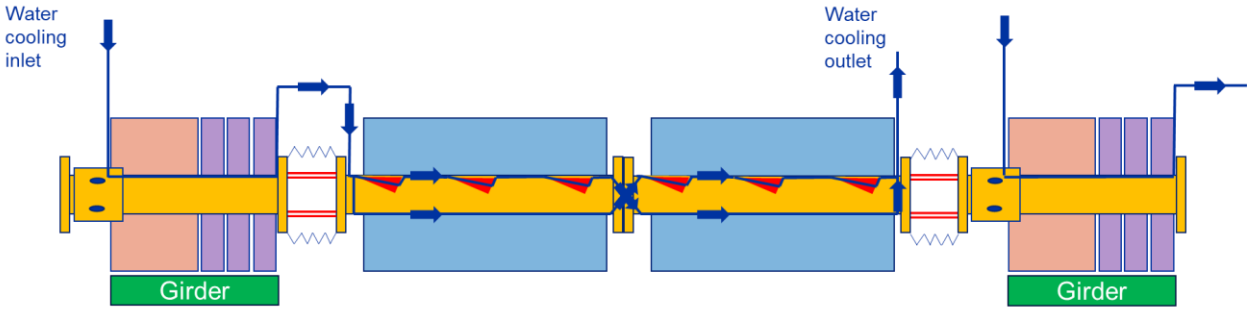
H. Mainaud Durand, The PACMAN project results, Nanobeam technologies, 01-03 feb. 2021



- Should **confirm the pre-alignment goals and alignment concept**
- Assess the stability of the alignment under Tp variation - **key for acc. performance**

- The **alignment test stand** will be required and shall provide results by end of pre-TDR (2027)
  - Without it, we cannot confirm the Arc cell design (large implication of cost and performance)
  - Would need to start the design of the test stand now to have a confirmation of alignment performance by end of 2027.

- We should discuss and agree if a **realistic arc cell mock-up** should be designed and built. Possibly at a later stage, i.e. after approval
  - Provide a realistic integration of all key components of the FCC-ee arc cell. i.e. Quadrupole, BPM, BLM, Vacuum system, alignment system, absorbers, electronics and radiation shielding.
  - Validate the full alignment strategy and performance.
  - Monitor the stability of the alignment and BPM read-out as function of Temperature in realistic environment



Conclusions

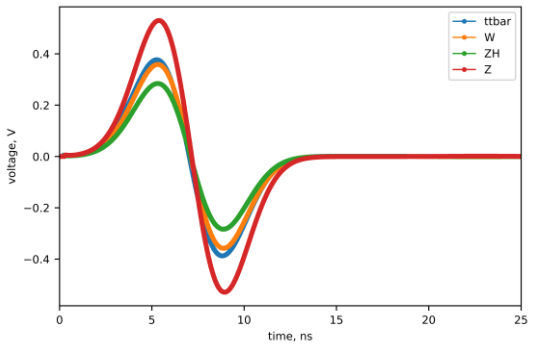
- The work on arc BPM is progressing on diffferent fronts
  - BPM design, optimisation and tests is well defined and started
- Would need to work on the **specifications for Arc cell electronic DAQ**
  - Help to streamline to the tunnel electronic needs and developments (Rad-tol)
- Would need to converge on a realistic plan to assess the BP to Quadrupole alignment strategy and performance before end of 2027
  - **A test-bench is needed as soon as possible (joint effort from many groups)**
- Those have large cost/performance/risk implications for the facility

SPARE SLIDES

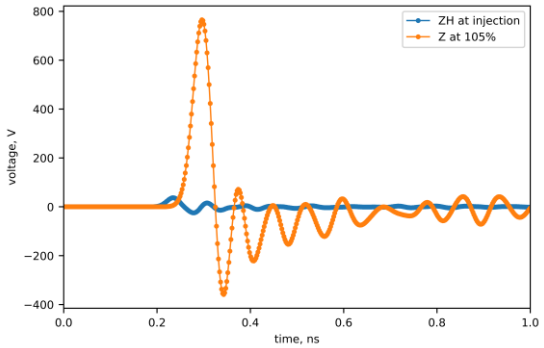
Simulations of a Simple BPM

- 8 mm was found to be a reasonable nominal radius.
- This was simulated at the most extreme FCC-ee beam parameters: during injection for ZH mode and at 105% nominal charge before collisions at ZZ mode.
- Difference of factor 18 between raw peak to peak.

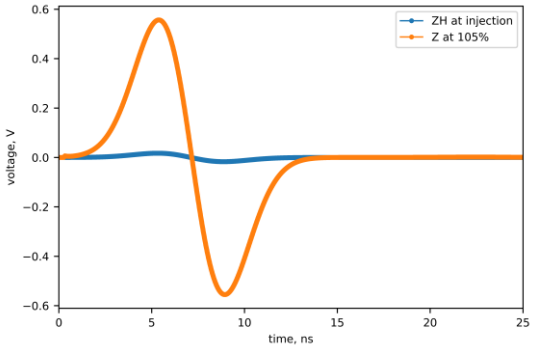
	ZH at injection	Z at 105% nominal charge
Raw ptp, V	62	1100
Conv ptp, V	0.034	1.1
Wakeloss factor V/pC	1.06E-3	3.99E-3



Signals from CST simulation of all 4 modes before collisions (SR), convoluted by a 75 MHz filter.



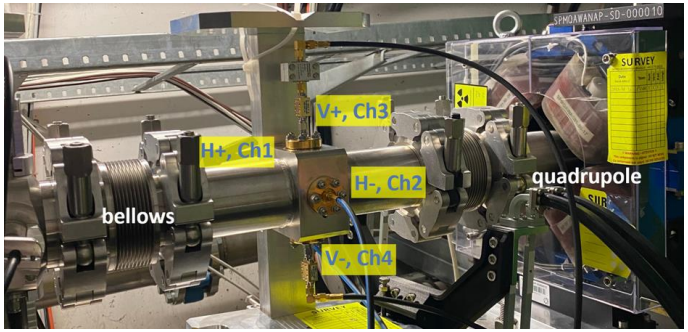
Initial part of raw signals in CST for the two extreme beams.



Signals convoluted by a 75 MHz filter.

Measurements at AWAKE

- The measurements were taken with electron beam only.
- Two pickups were directly attached to the oscilloscope and two had filters.

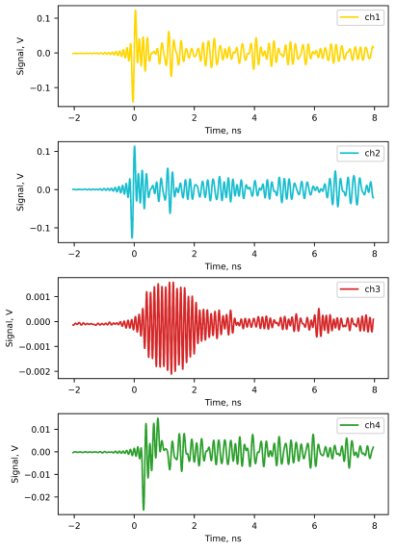


eBPM set-up

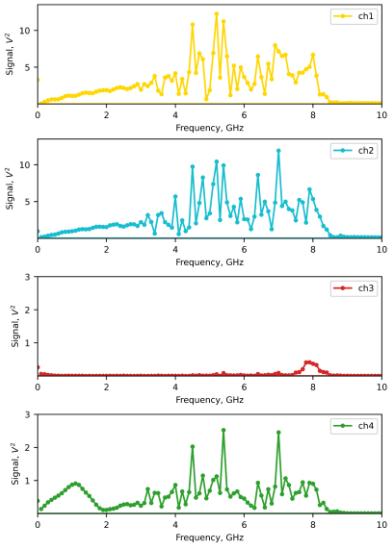
Pickup	Channel	Filter
H+	1	direct
H-	2	direct
V+	3	1 GHz + 80 MHz
V-	4	1 GHz

Measurements at AWAKE

- Postprocessing to convolute with cable and scope response and analysis ongoing.
- The simulations can then be reasonably compared with measurements.



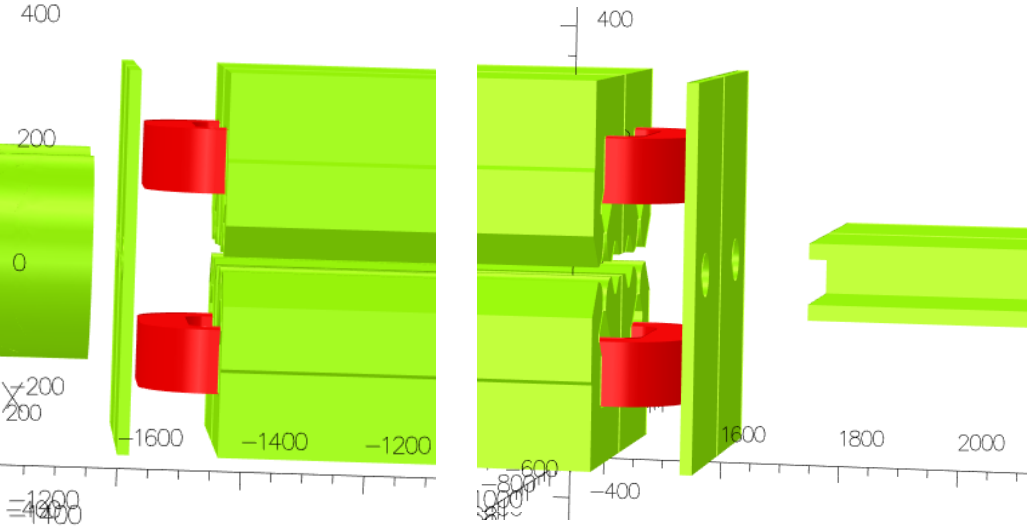
Voltage measurements taken at 225 pC and averaged over 50 shots. NB: the y axis scale is different for each channel.

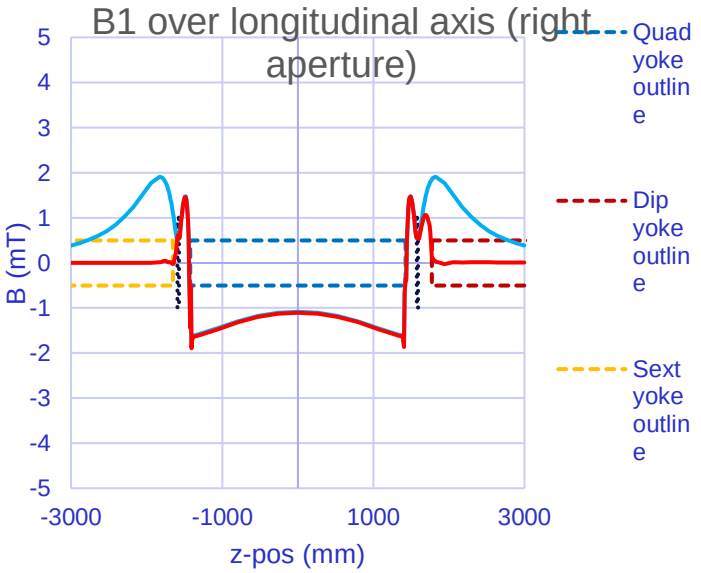


FFT of voltage signals.

3D fringe field effects: Mirror plates for fringe field shielding

Possible solution: **mirror plates** to control the ”spoiling” of the fringe fields.
Simulations with simple mirror plates modelled, **100 mm** from yoke edge.
Mitigates magnetic interference from neighbors

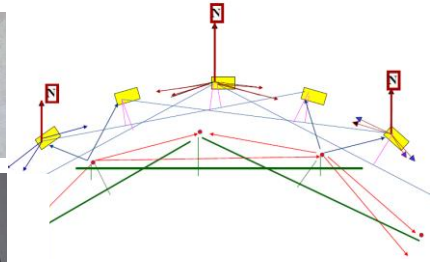


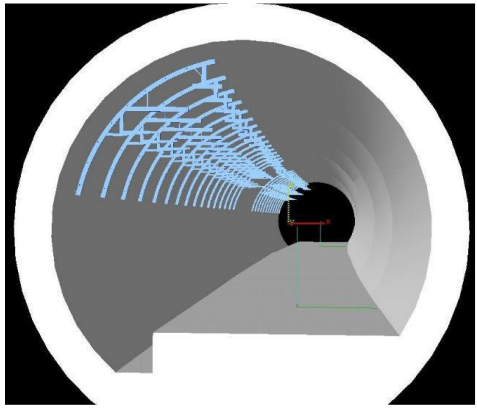


Process for the alignment : installation and measurement of the underground network

Intervention while the tunnel is still empty, installation of the reference network.

FCC: The size will make this operation repetitive and heavily time consuming



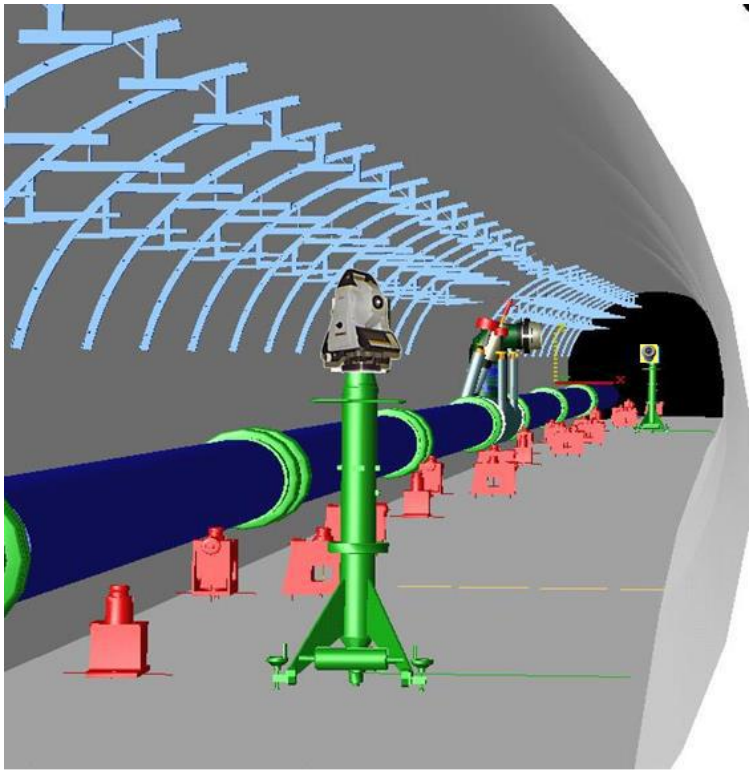


Measurement of the network, combination of multiple measurement techniques :

Azimuth	s = 1 mgon
Angles	s = 0.5 mgons
Distances	s = 0.15 mm
Wire offset	s = 0.1 mm over 120m
Levelling	s = 0.05 mm

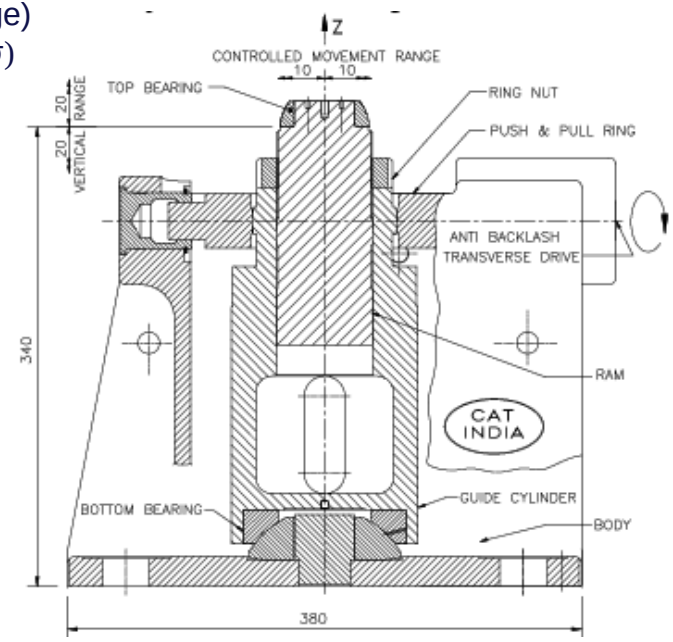
FCC: The size will make this operation repetitive, heavily time consuming and may require more precise measurements + movements during the installation

Process for the alignment : Jack alignment



Data for the LHC

- the head of the jack (mid-range) must be aligned at +/- 2 mm (1σ)
- middle jack is not aligned



FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment

Process for the alignment : fiducialisation

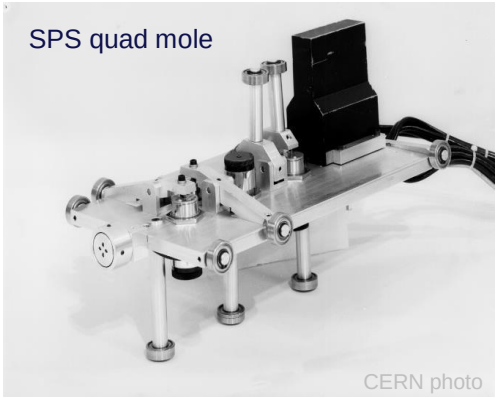
Transfer of the reference axis on fiducials (= point references on the object).
But which axis ? Mechanical axis or magnetic axis ?
- Quads : mostly magnetic axis
- Dipoles : mostly mechanical

Small objects are done by the metrology service, but bigger ones are done by BE-GM.

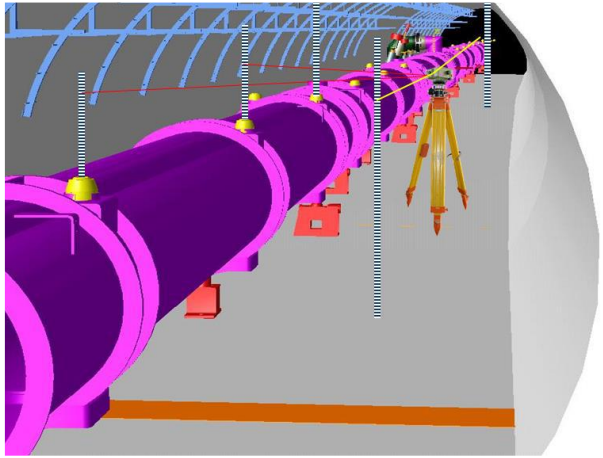
Must be performed for every components.

Multiple technics are existing :
- conductive wire
- mole
- palping
- direct measurement
- …

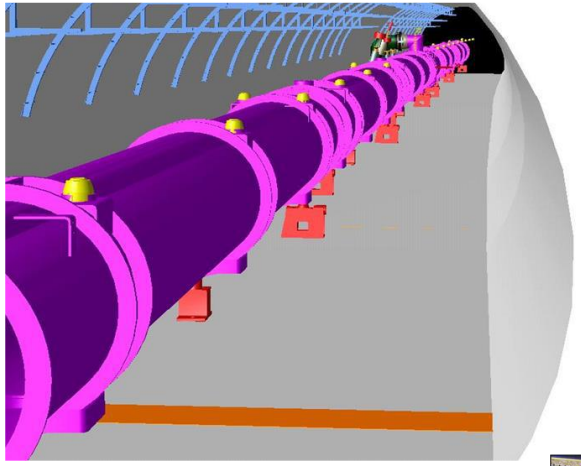
FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment



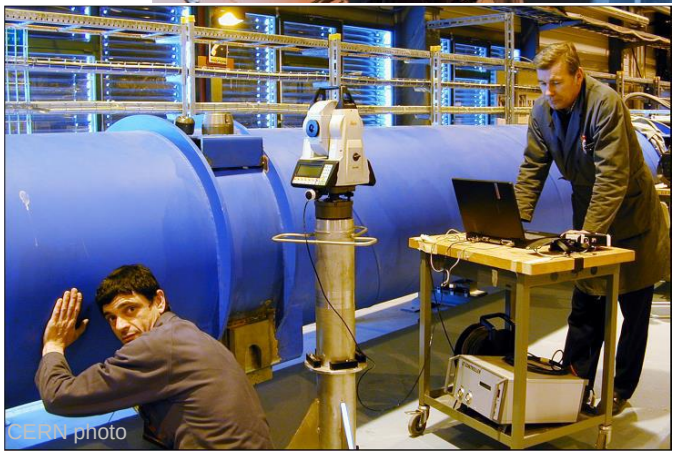
Process for the alignment : first alignment



Optical level NA2
+/- 0.2 mm wrt the network



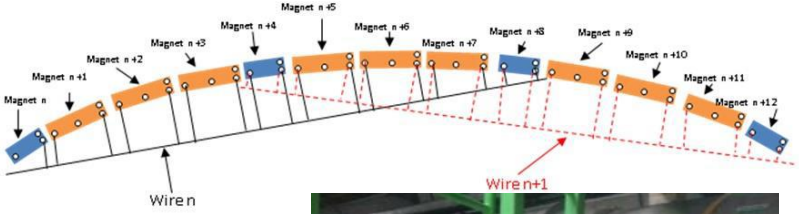
TDA 5005 for distances and angles
+/- 0.3 mm wrt the network

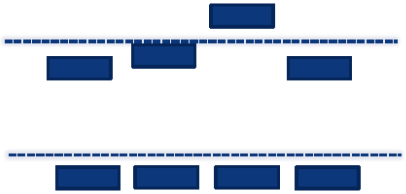


FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment + big movements expected during the settlement of the tunnel.

Process for the alignment : Smoothing

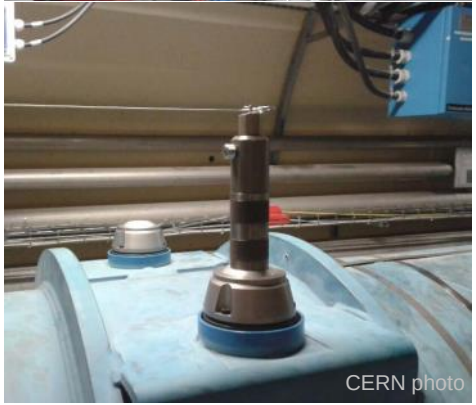
- Alignment has been done thanks to the geodetic network (+/- 0.2 mm)
- But then, “steps” in the alignment need to be smoothed
- Measurement is done directly on the magnet and not the network thanks to digital leveling and wire offset measurement





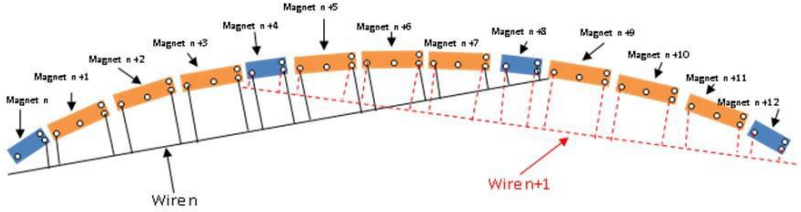
LHC data:

- 120 m long wire, redundancy of 2 dipoles or 3 quads
- ~ 550 measured points per sector
- Uncertainty of 0.04 mm (1σ)
- ~ 400m-80points per day for a team of 2 surveyors (one pass, everything goes well)

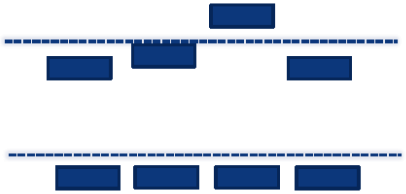


FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment + big movement of the tunnel expected

Maintenance of the alignment



- Alignment and smoothing may need to be performed locally or globally during different stops (YETS and LS).
- During these stops, the duration of the alignment is very limited.



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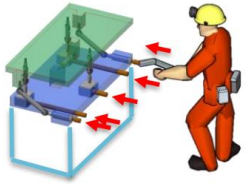
- ~ 550 measured points per sector
- Uncertainty of 0.04 mm (1σ)
- ~ 400m-80points per day for a team of 2 surveyors (one pass, everything goes well)

In the LHC, some sector need an alignment every year because of tunnel movement, while some other require an intervention only every 5 years.

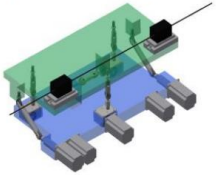
FCC: The size will make this operation impossible (not enough available trained workforce)
Moreover, it is repetitive, heavily time consuming and may require more precise alignment + big movement of the tunnel expected

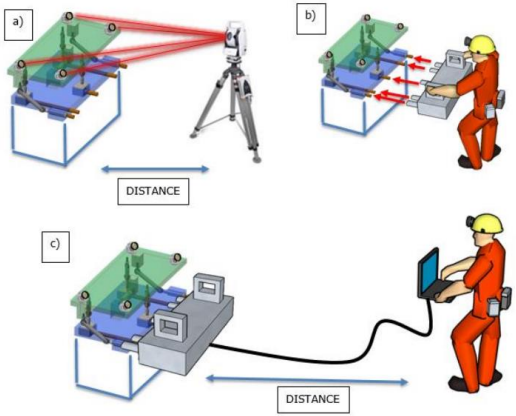
Full Remote Alignment



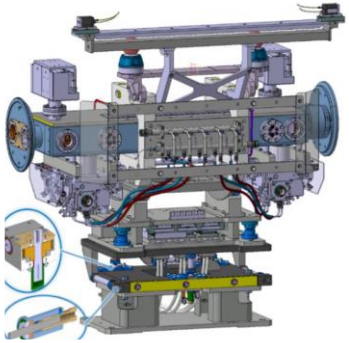
Universal adjustment platform – manual operation concept

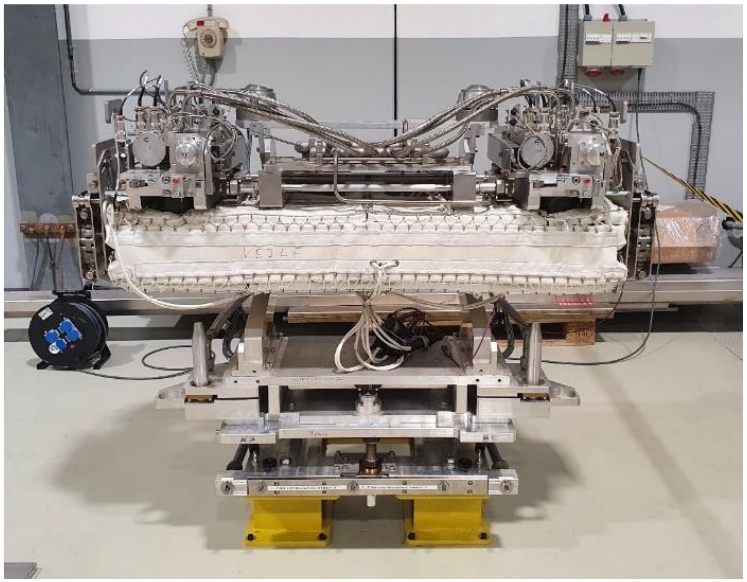
Universal adjustment solution - permanent motors version concept. Platform equipped with WPS sensors

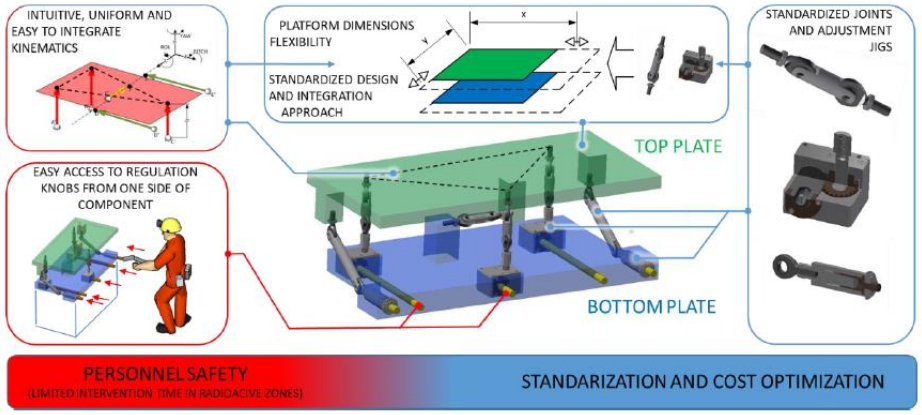




Universal adjustment solution – concept of use plug-in motors:
a) Platform measurement from distance using a laser tracker;
b) Installation of plug-in motors in less than one minute;
c) Remote adjustment from distance.

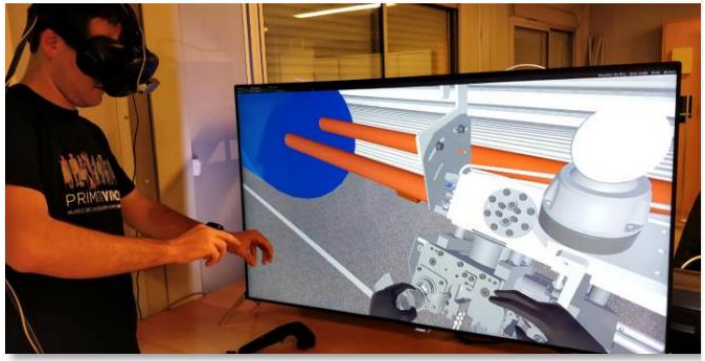


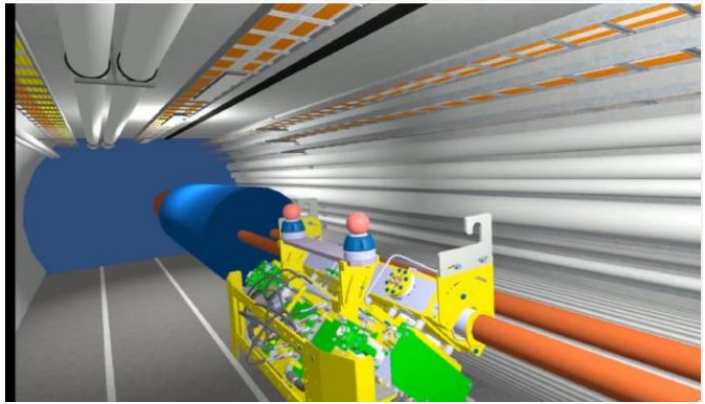


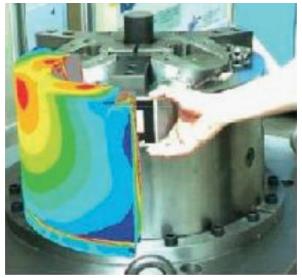


https://www.euspen.eu/resource/universal-adjustment-platform-standardization-of-6-degrees-of-freedom-adjustment-systems-design-and-integration/

Augmented reality







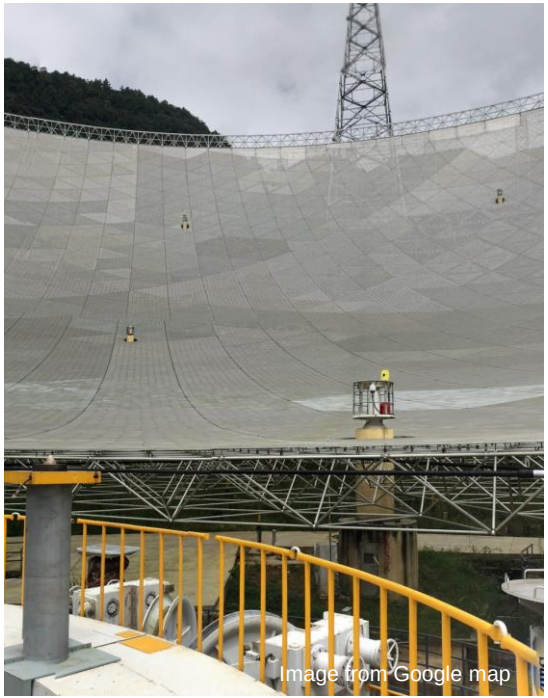
- Integration visualization
- Training
- Component visualization on site
- Additional information visualization (misalignment, vibration, temperature, radiations ?)
- Advanced diagnostics
- …

Overview of the Robotic Service at CERN for accelerator maintenance
https://indico.cern.ch/event/999825/contributions/4251111/attachments/2218904/3757125/2021.03.31%20-%20Robotics%20Service%20At%20CERN.pdf

Pejić, P., Rizov, T., Krasić, S., & Stajić, B. (2014, October). Augmented reality application in engineering. In *3rd international congress, SMAT* (pp. 39-44).

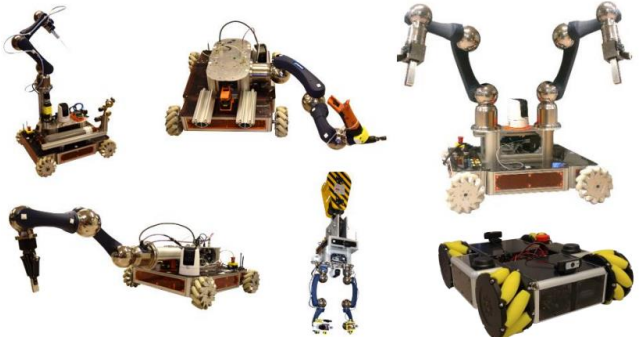
Robots

(Cf. Dr Mario Di Castro's presentation : Robotics for Accelerator Maintenance, later this afternoon)



Permanent network of robotic total stations in the Five-Hundred-meter Aperture Spherical Telescope in China

- Simulation of robotic interventions
  - ✓ Integration of robots in the environment and choice of robots
  - ✓ Intervention procedures
  - ✓ Tools design and test
  - ✓ Machines risk assessment
  - ✓ Robots training by demonstration
  - ✓ Operators training and teleoperations
  - ✓ Risk analysis
  - ✓ Recovery procedures
- Simulation of human intervention
  - ✓ Human intervention procedures
  - ✓ Live radiation levels and cumulated dose while training in VR (Augmented reality in virtual reality)
  - ✓ Intervention training
  - ✓ Risk analysis
  - ✓ Feedbacks for future remote-handling-friendly machines



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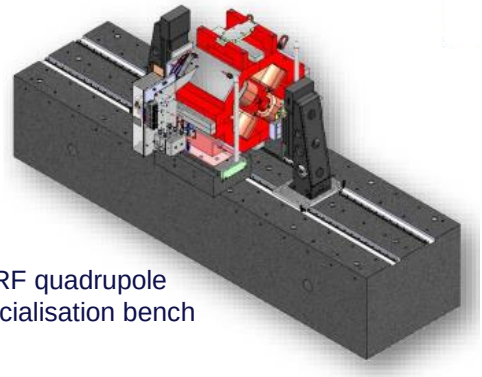
Di Castro, M., Tambutti, M. B., Ferre, M., Losito, R., Lunghi, G., & Masi, A. (2018, August). i-TIM: A robotic system for safety, measurements, inspection and maintenance in harsh environments. In 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR) (pp. 1-6). IEEE

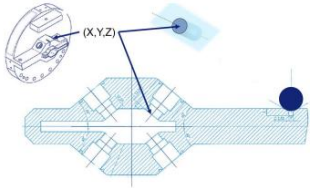
https://aecmag.com/reality-capture-modelling/trimble-releases-autonomous-robotic-scanning-solution/

Permanent references are required for robots, installation and maintenance of those must be foreseen.

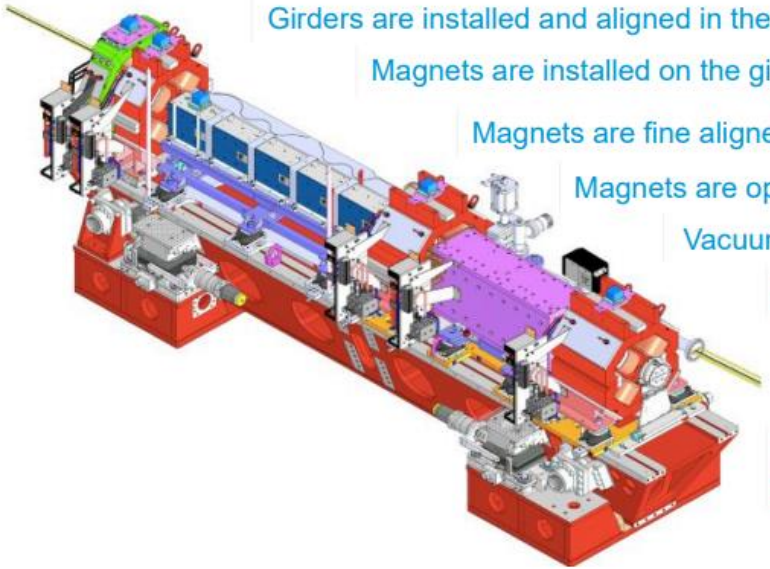
Fiducialisation and alignment on the girder



ESRF quadrupole fiducialisation bench



BPM fiducialisation

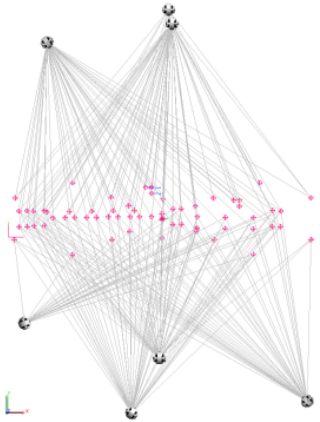


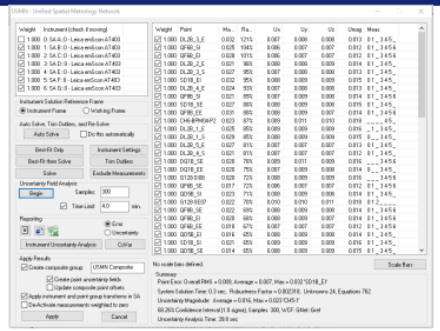
ESRF girder assembly procedure

David Martin, “Alignment for the ESRF Extremely Brilliant Source”, IWAA 2022

Fiducialisation and alignment on the girder

GIRDER ALIGNMENT UNCERTAINTY



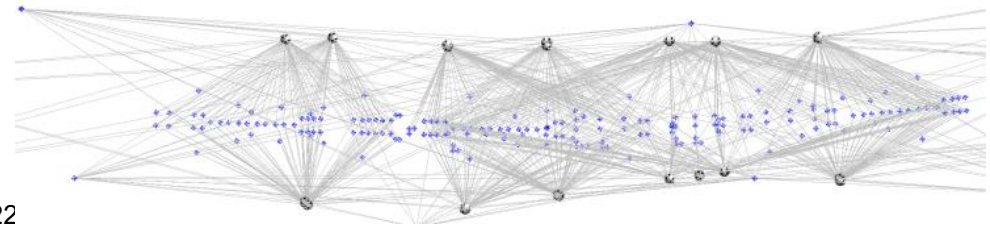


	U(L) [µm]	U(R) [µm]	U(Z) 1) [µm]	U(Z) 2) [µm]
Measurements	6	7	6	6
Difference to nominal	126	24	25	25
Overall uncertainty		14	17	17
Magnet Opening/Closing	8	5	7	7
Girder rectitude				8
Total	**126**	**29**	**31**	**31**

Shims were used to align certain magnets:
1) High gradient quadrupoles, Combined function dipoles
2) Medium gradient quadrupoles, sextupoles and octupoles

EBS INSTALLATION IN THE TUNNEL

Plates Pre-Tracing
Plates Setting Out
Plates Alignment
Plates Control
Girder Pre-Alignment
Girder Fine-Alignment
Girder Control
Girder Touch-ups
Girder Re-control
DQ2 Alignment
DQ2 Control
HLS Installation



David Martin, “Alignment for the ESRF Extremely Brilliant Source”, IWAA 2022

PACMAN

Objectives

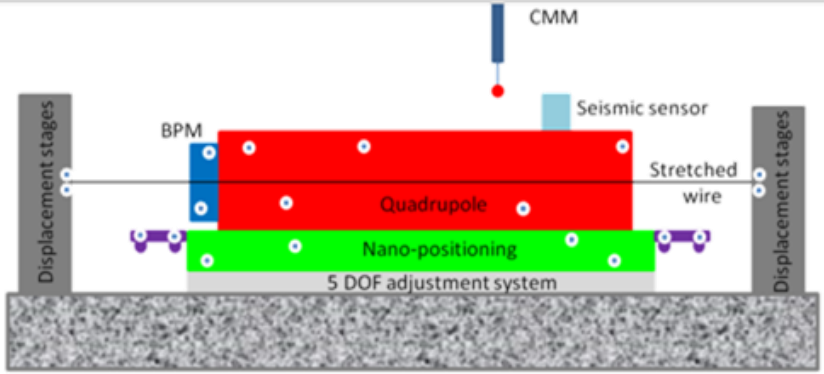
Propose an alternative solution for the high accuracy alignment of the accelerator components:

- Using a stretched wire acting as a beam for the fiducialisation of components.
- Combining references & methods of measurements in the same place to gain time and accuracy

To get this:

- Develop very high accuracy metrology and alignment tools
- Validate them on a final bench: the Final PACMAN Alignment Bench

Extrapolate tools & methods developed to other projects

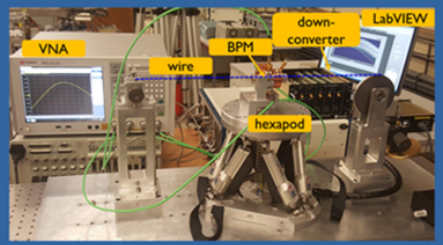


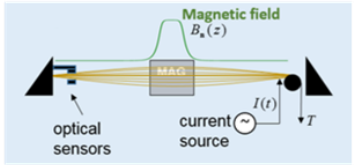
3

H. Mainaud Durand, The PACMAN project results, Nanobeam technologies, 01-03 feb. 2021

PACMAN

Fiducialisation of MB quadrupoles & BPM





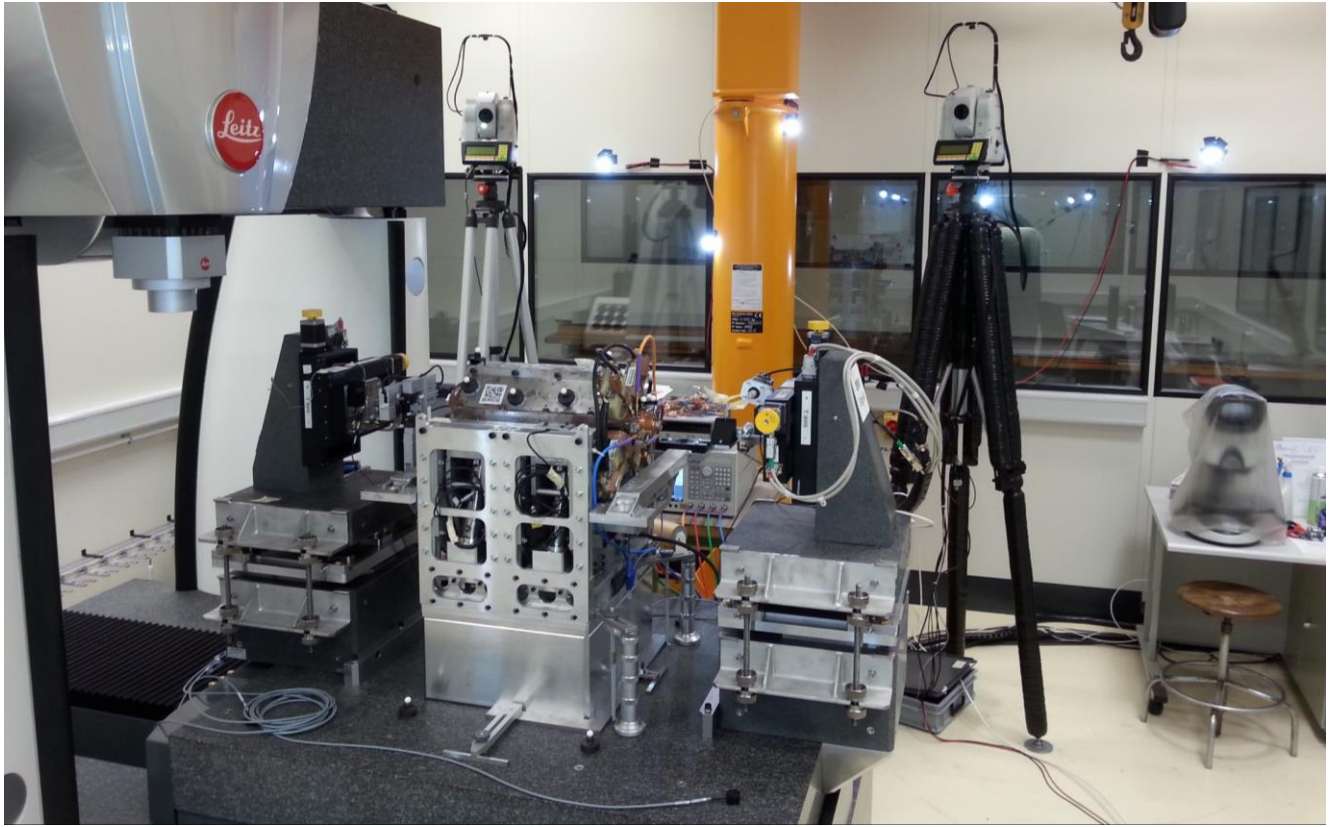
- Upgrade of the oscillating/vibrating wire method
  - 2 methods of magnet characterization compared:
    - Stretched wire based on Faraday's law
    - Oscillating/vibrating wire based on the Lorentz force
  - Background field correction put in place for the second method
  - Study of the multipole field error effect: a multipole correction proposed
  - New wire bench developed
  - Repeatability tests of the vibrating wire at different magnet current

- Determination of the electric center of a 15 GHz BPM:
  - Once the perturbation analysis was chosen to detect the electrical center: study of the BPM on many RF aspects, including linear & angular location of the center
  - Validation on a dedicated test bench : micrometric repeatability
  - Study of the resolution adding a piezo stage: nanometric resolution below 12 nm detected!

6

H. Mainaud Durand, The PACMAN project results, Nanobeam technologies, 01-03 feb. 2021

PACMAN



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