HL-LHC remote alignment system: what it is and what it will bring us

R. De Maria, P. Fessia, D. Gamba, M. Giovannozzi, J. Hansen, A. Herty, I. Lamas Garcia, H. Mainaud Durand, S. Redaelli, M. Sosin, CERN, Geneva, Switzerland

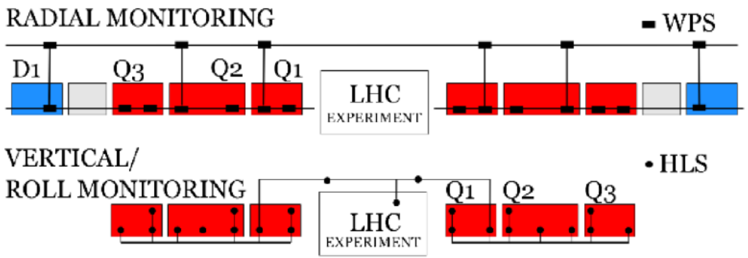
9th HL-LHC Collaboration Meeting, Fermilab, USA - 14-16 October 2019

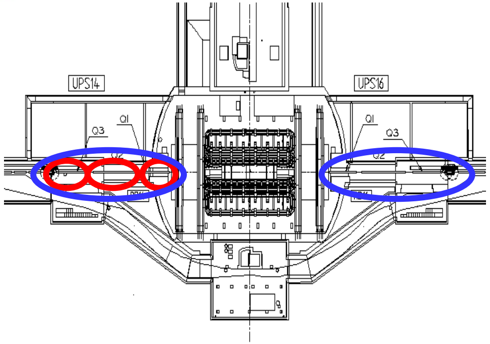
Outline

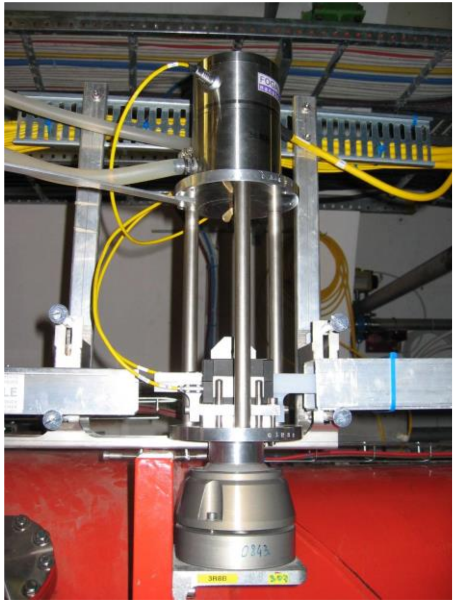
- What has been done in the LHC
- What is the HL-LHC remote alignment system
- What it will bring us
- Summary

What has been done in the LHC

What has been done in the LHC

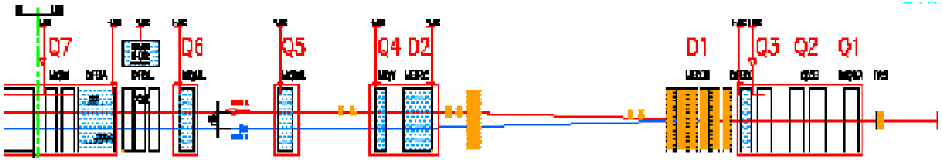






- Relative determination of the position of quadrupoles inside the triplet: a few µm
- Positioning of the fiducials of the triplet quadrupoles:
  - Radial error: ± 0.2mm (1σ) from left side to right side
  - Levelling error: ± 0.1 mm (1σ) from left side to right side

What has been done in the LHC



- Final errors of alignment of one triplet fiducials w.r.t the main elements of the Matching Section (MS) : requested: ± 0.1 mm (1σ) but not achieved
- For all other components of the MS: smoothing: ± 0.15 mm (1σ) over 110 m. Achieved.
- Intermediary components: smoothing w.r.t. adjacent quadrupoles.

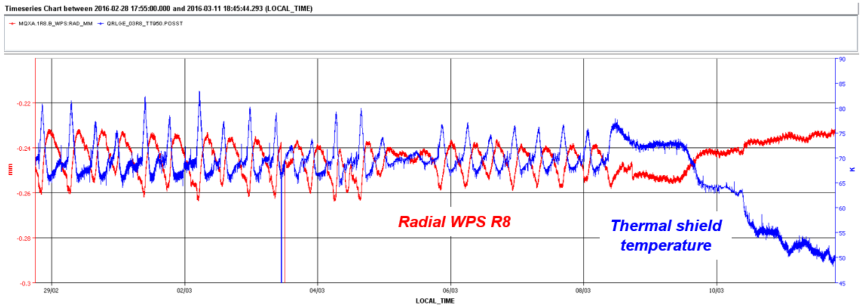
What has been done in the LHC

WPS data analyzed by the shift crews in the CERN Control Center to estimate the effective deflection of the triplet. Two ways to solve «large» movements:

- Magnetic corrections
- Remote re-alignment using WPS readings + motorized jacks

IR8 - 2015

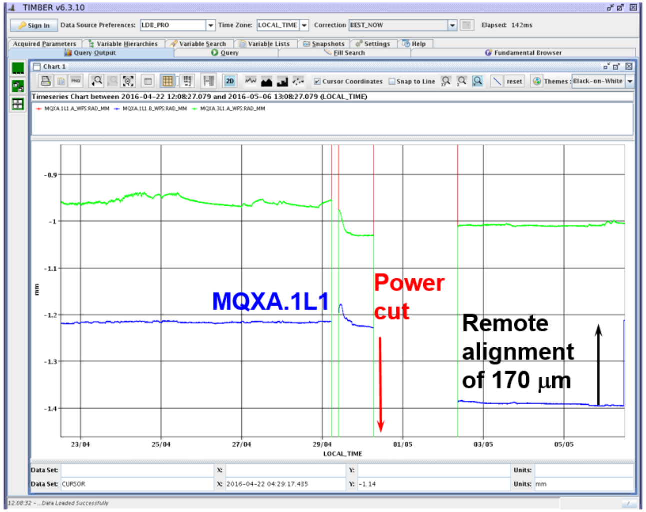
- The triplet movement in IR8 revealed for the first time the important sensitivity to the thermal shield temperature. And by it large amplitude and fast changes 'spoiled' many measurements.
- In IR8 the problem came from a regulation valve that did not move correctly (not repaired, mitigated by a change of operating point).



4

Horizontal re-alignment of Q1.L1

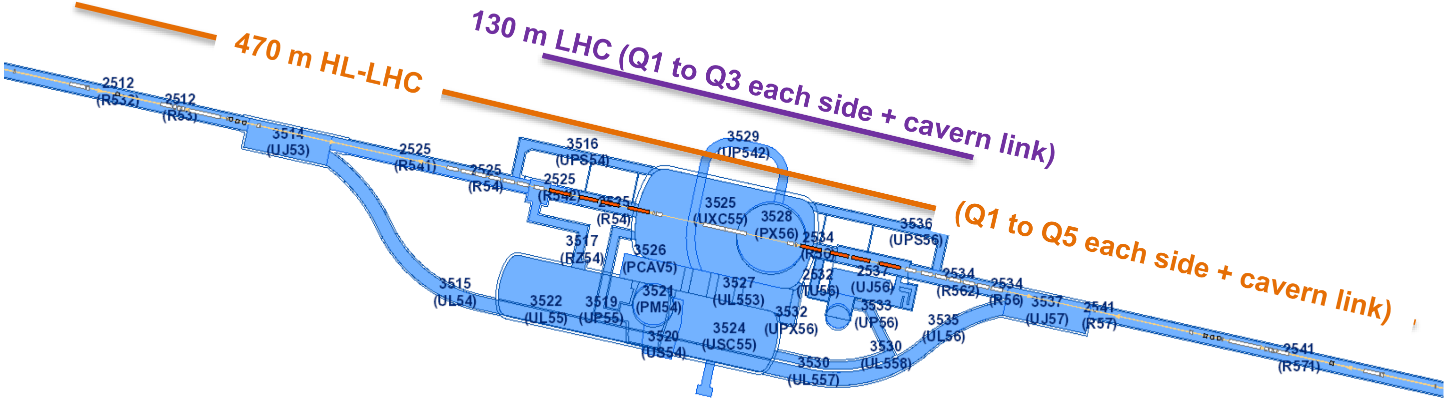
Friday 6/5, noon: Q1.L1 moved back to pre-power cut position



New features for HL-LHC

- **Longitudinal monitoring**
  - Concept as already installed for cryostats in LHC since YETS 2017/18 and LS2
- **Internal cold mass monitoring**
  - Request to determine the cold mass position and not only cryostat position
  - Testing and validation of concept for crab cavities and dipole measurements
- **Permanently monitored reference points**
  - Deep references (GITL) for vertical network to be installed
- **Inclination sensors**
  - Additional concept either for HLS redundancy or where no HLS can be diploid
- **Different measurement technologies**
  - Capacitive sensors and Multi Target Frequency Scanning Interferometry

FRAS in a nutshell



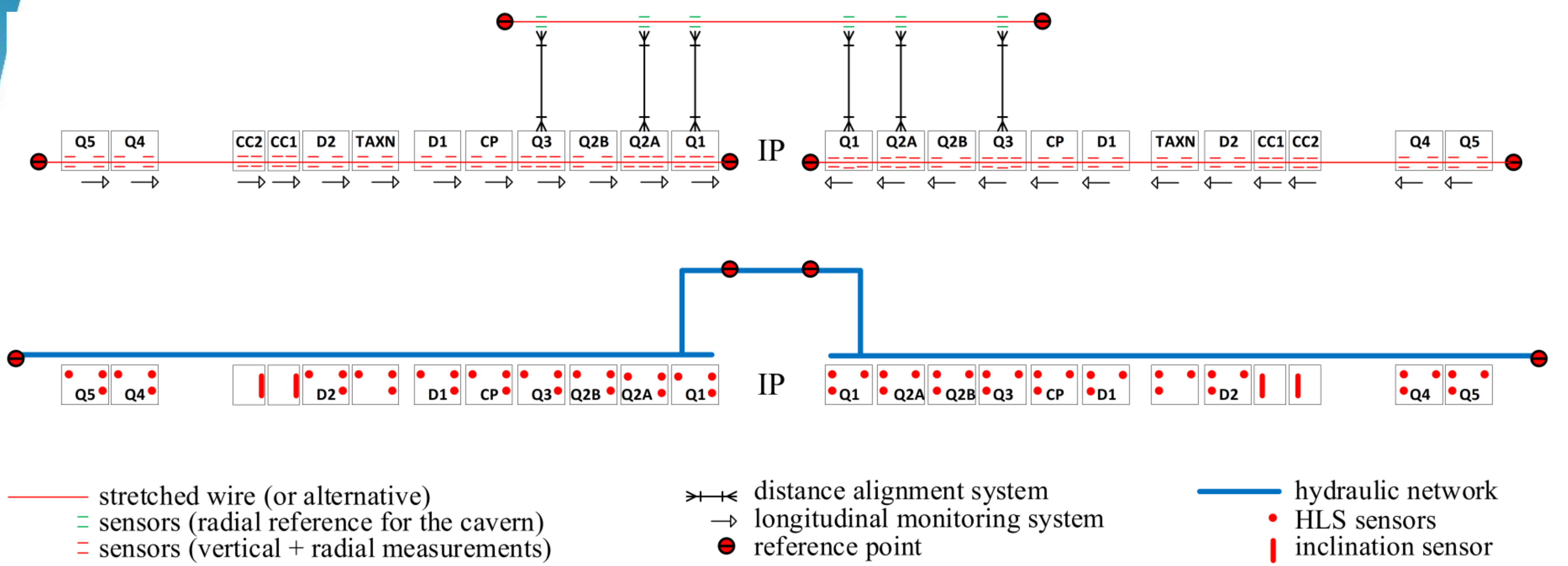
	WPS	INC	HLS	LON	INT	W2W
PER IP	48	12	48	18	48	3
TOTAL	192	48	192	72	192	12

WPS	capacitive	Wire Positioning Sensor
INC	MT-FSI	Inclination Sensor
HLS	MT-FSI	Hydrostatic Levelling Sensor
LON	MT-FSI	Longitudinal measurements
INT	MT-FSI	Internal measurements
W2W	MT-FSI	wire to wire measurements

- Not taking into account, environmental sensors and actuator equipment.
- In addition to the sensors:
  - **4 wire stretching devices**
  - **Approx. 1 km of wire and wire protection**
  - **Approx. 1 km of hydraulic network**
  - **Remote diagnostic tools for sensors and systems**

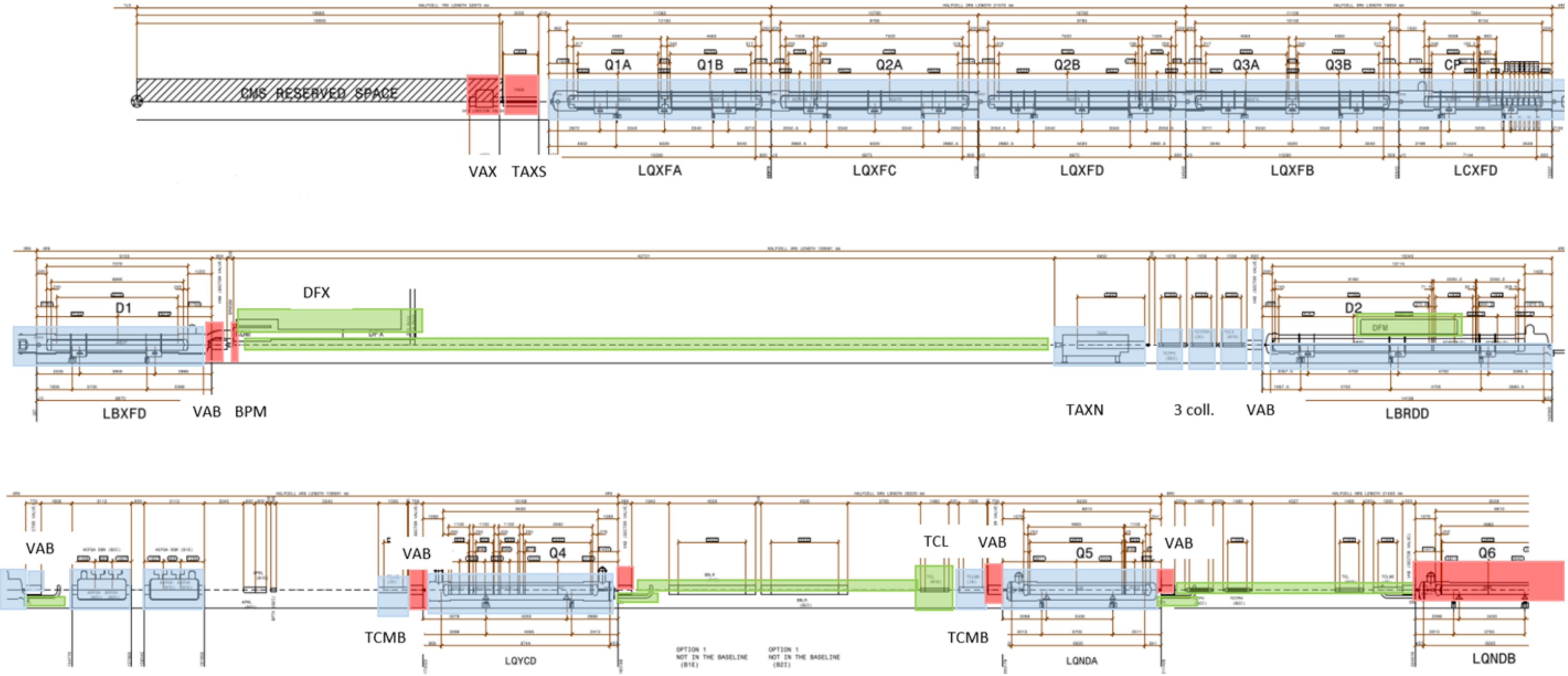
FRAS in a nutshell

130 WPS sensors
150 HLS sensors



- Combined with an internal monitoring of the position of cold masses in the Inner Triplet cryostats using FSI system
- Motorized jacks supporting all main components.

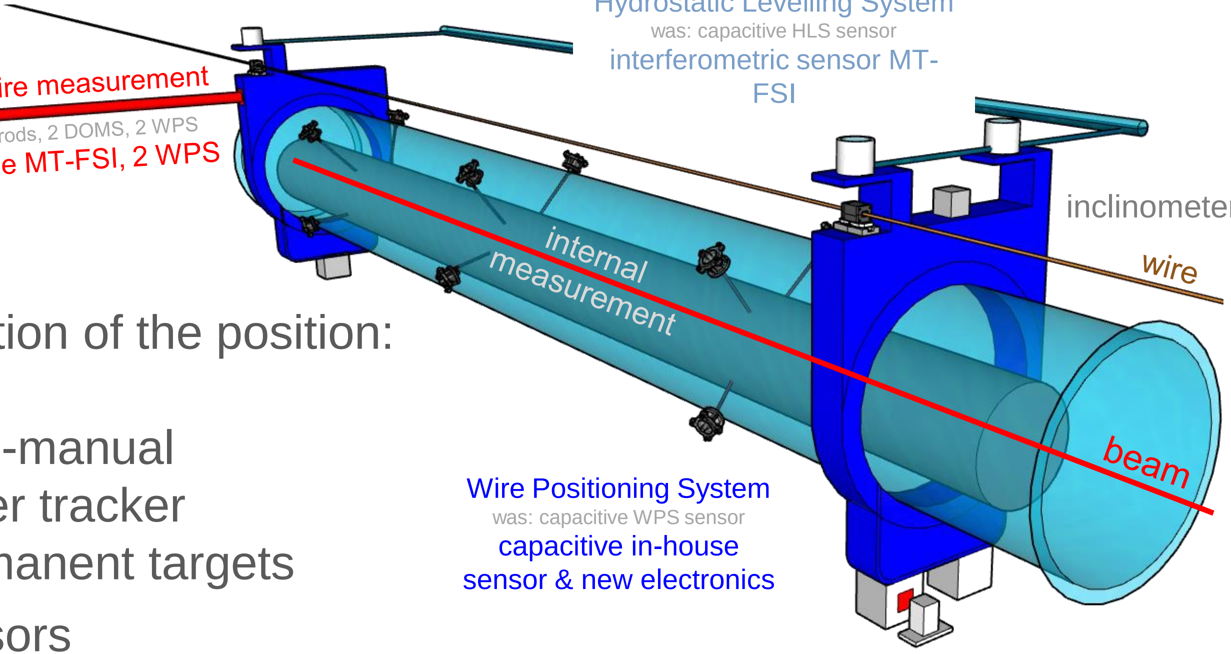
FRAS in a nutshell



- Alignment during YETS/TS
- Remote alignment
- Static component: no alignment after the initial alignment

- **The Full Remote Alignment System (FRAS) allows**
  - Aligning rigidly and remotely all the components from Q1 to Q5 on both sides of the Interaction Point within ± 2.5 mm
  - Moving independently the components within the stroke of the corresponding bellows.

Strategy to measure the alignment

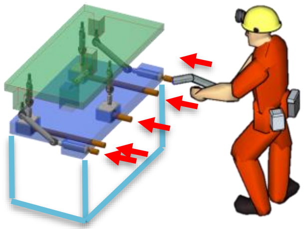


For the determination of the position:

- Manual or semi-manual
  - ✓ Using Laser tracker
  - ✓ Using permanent targets
- Alignment sensors
  - ✓ Using permanent sensors

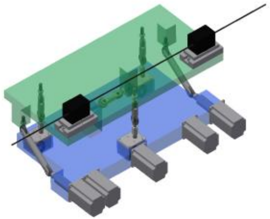
Universal Adjustment Platform

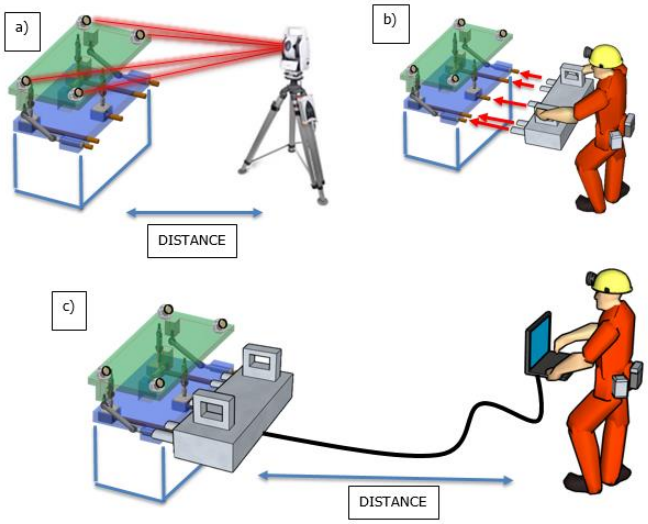
- Allows for various operation use cases



Universal adjustment platform – manual operation concept

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



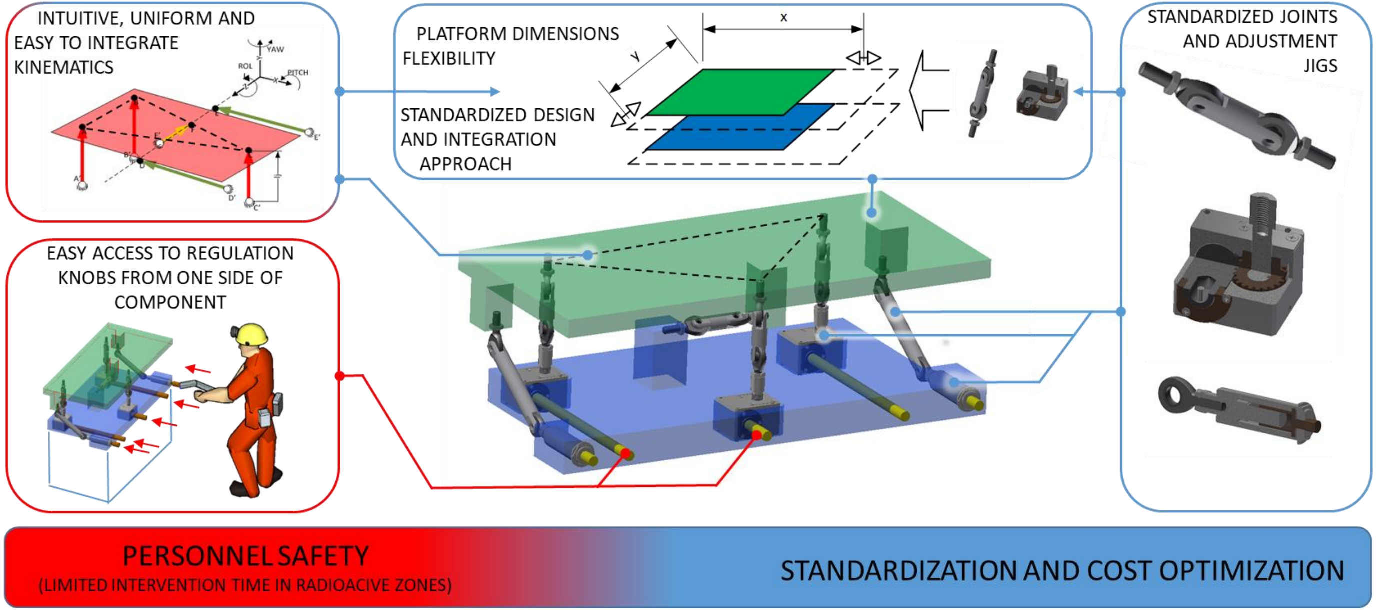


Universal adjustment solution – concept of use plug-in motors:
a) Platform measurement from distance using a laser tracker;
b) Installation of plug-in motors in less than one minute;
c) Remote adjustment from distance.

Universal Adjustment Platform

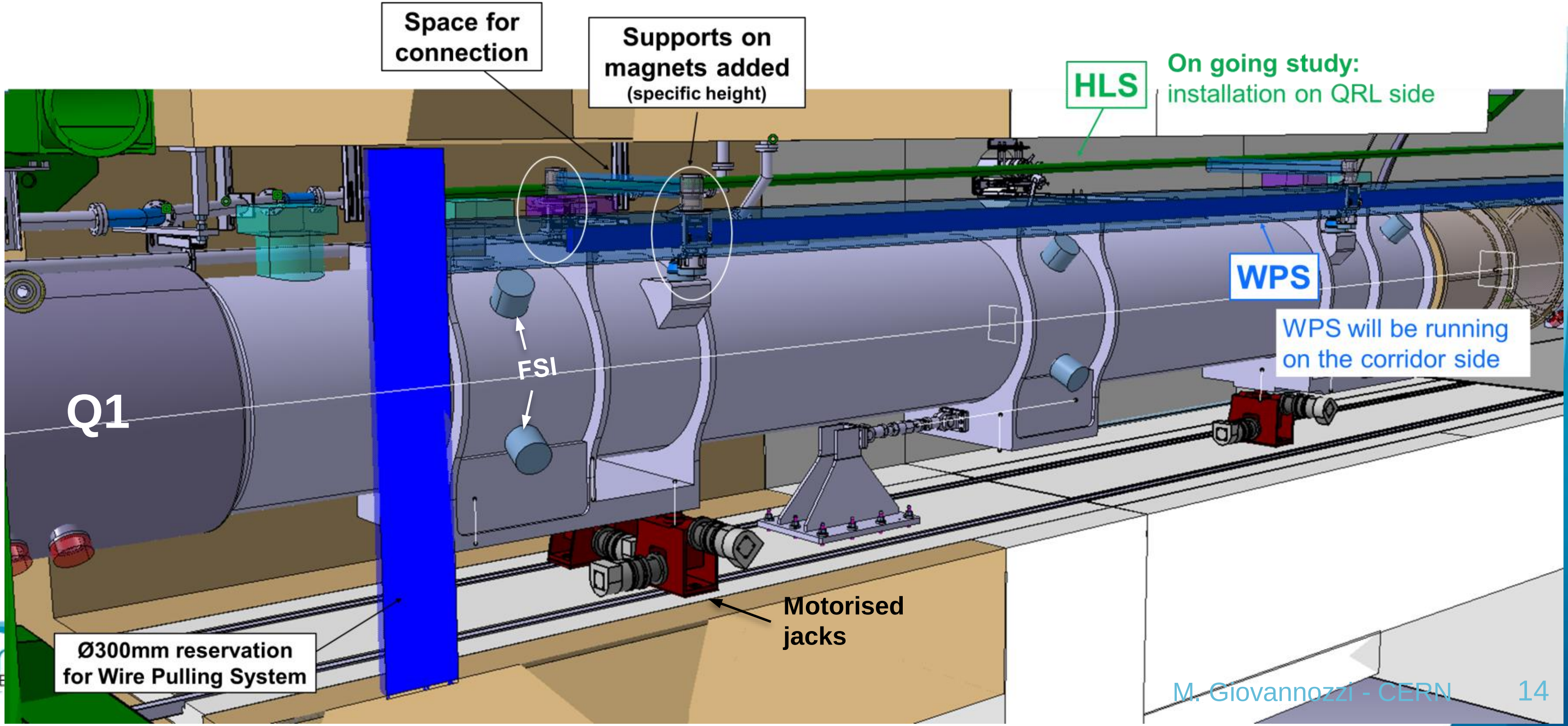
Definition of set of design rules and development of standardized and modular components to:

- increase safety of surveyors
- unify small (<2T) accelerator components adjustment systems



Conceptual Integration of HL-LHC FRAS

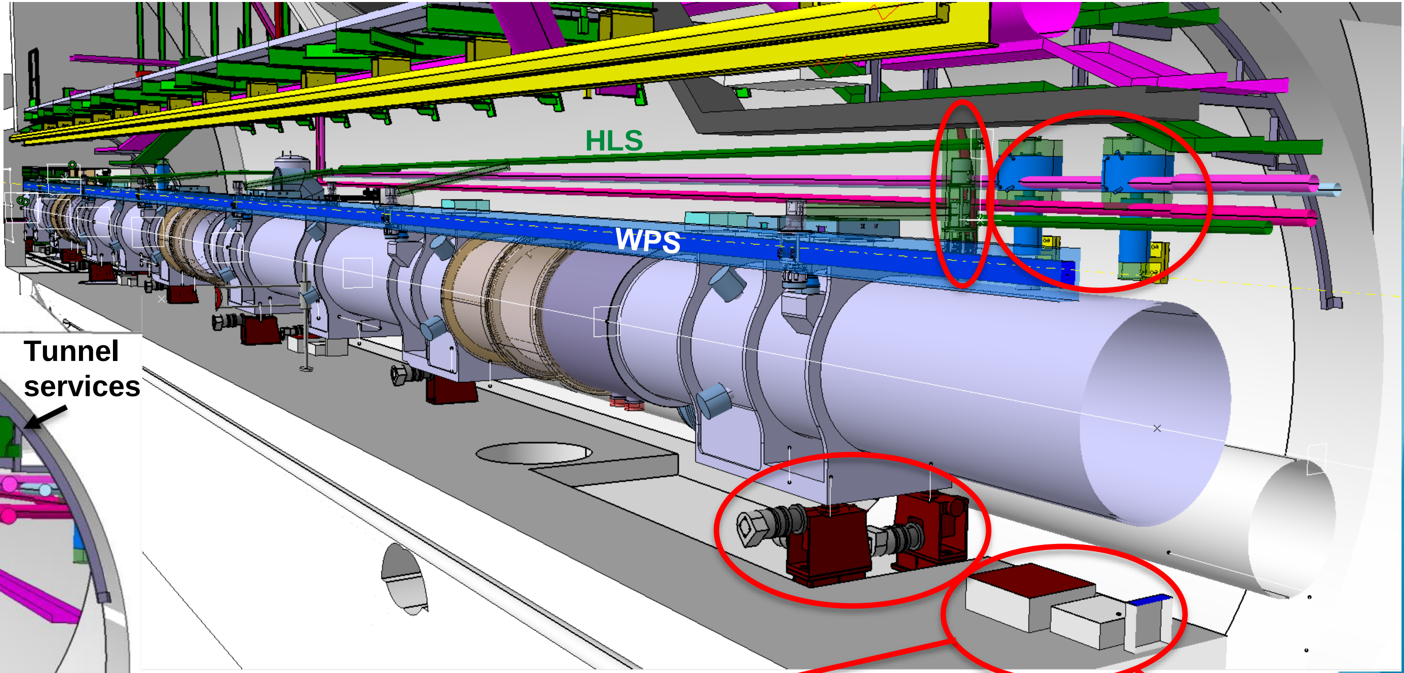
- A first **"conceptual integration"** has been started in close collaboration between WP15.1 and WP15.4 with the aim of facilitating a real mechanical design

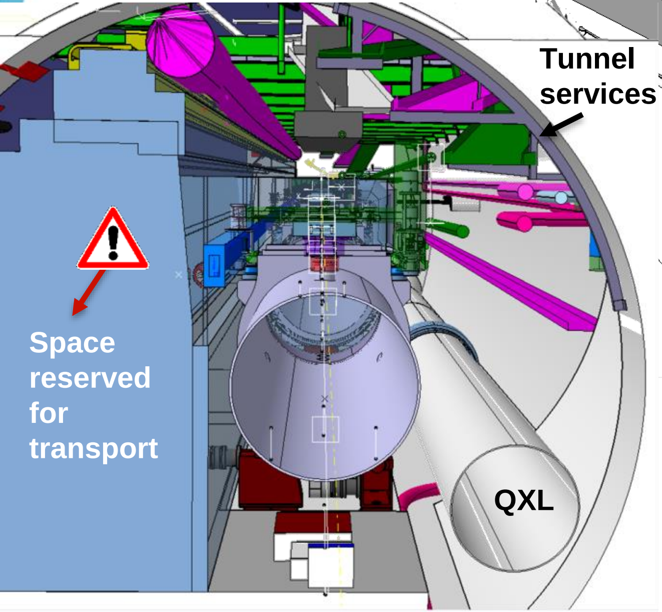


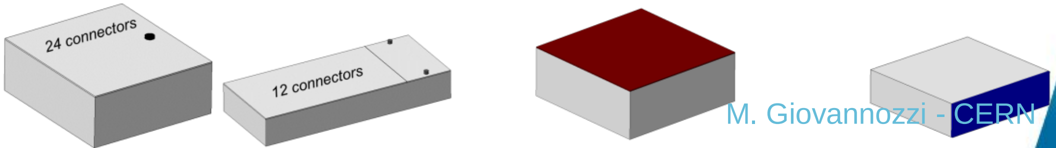
Conceptual Integration of HL-LHC FRAS

Components:

- Motorised jacks
- Patch panels and crates
- Support for the HLS and WPS sensors
- Filling Purging Stations (FPS)
- Possible location for SU deep reference

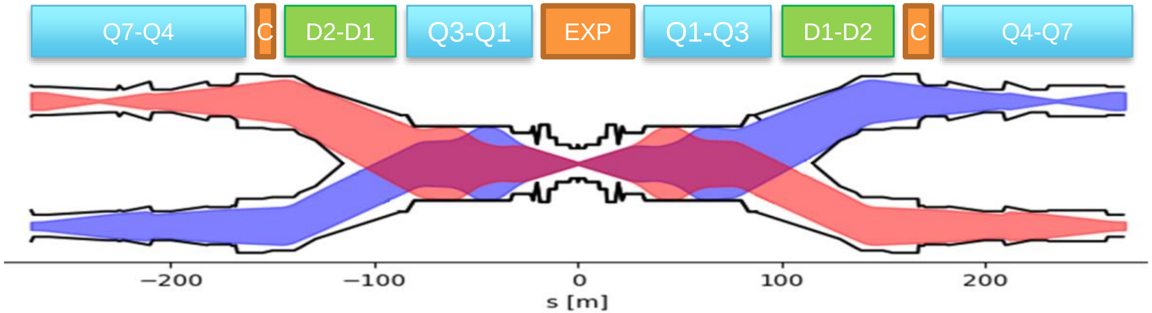






Alignment needs around ATLAS and CMS

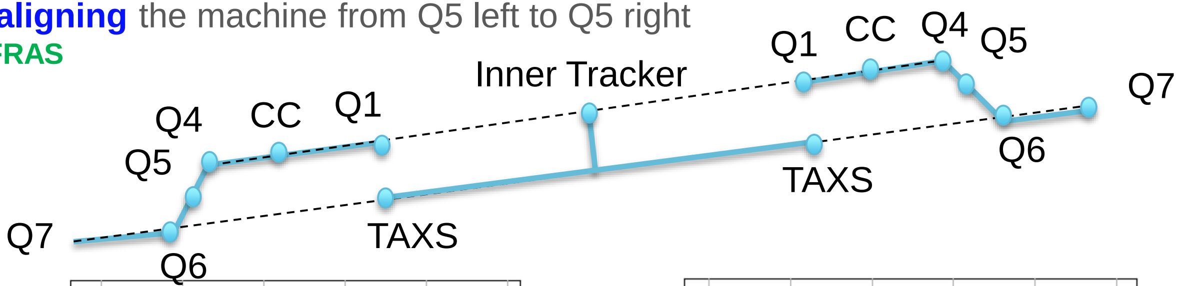
HL-LHC simplified lattice and beam envelopes around the experiments

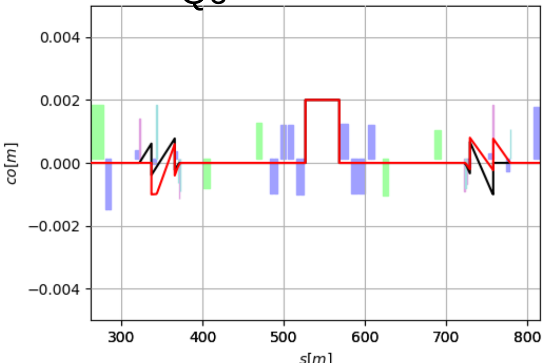


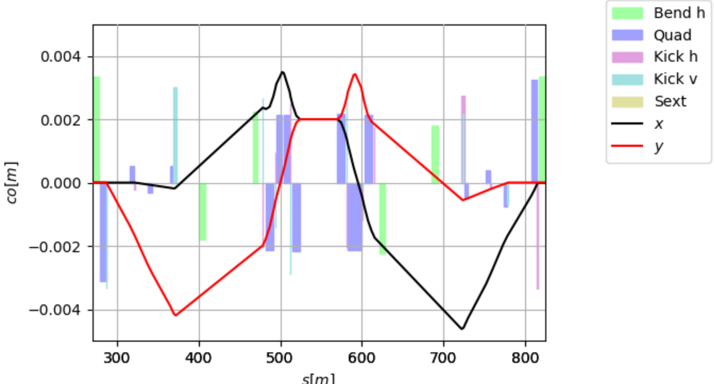
- Good alignment is needed for
  - **Inner tracker** to be transversely centred to the interaction point (IP) for reducing radiation damage and improve tracks reconstruction (<1 mm)
  - **Quadrupoles** to be centred around the reference orbit to remain within orbit corrector strength budget and reduce orbit distortions (<0.5 mm)
  - **Crab cavities** to be transversely centred around the beam orbit to keep RF power within operational limits (<1 mm)
- Good alignment of non active elements is also needed to
  - Preserve **stay clear regions** for the beam at low β*
  - Maintain effective shielding of **protecting masks** for superconducting magnets

Alignment needs for ATLAS and CMS

- **ATLAS and CMS request that the machine is able to adjust the IP within ±2 mm in H/V**
  - Inner tracker cannot be easily mechanically aligned
  - The experiments do not expect to control the positioning of the inner tracker better than few mm
  - Observed ground motion can be in the order of several mm after several years
- **The beam orbit can be adjusted**
  - With **orbit correctors**
    - **Expensive in terms of integrated dipole correctors strength**
    - **Expensive in terms of aperture (residual orbit distortions in the triplets and crab cavities)**
  - By **re-aligning** the machine from Q5 left to Q5 right
    - **FRAS**

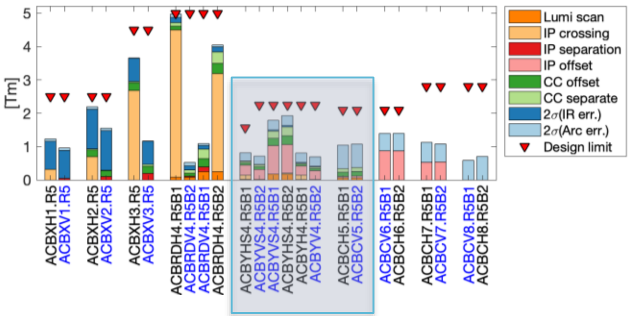




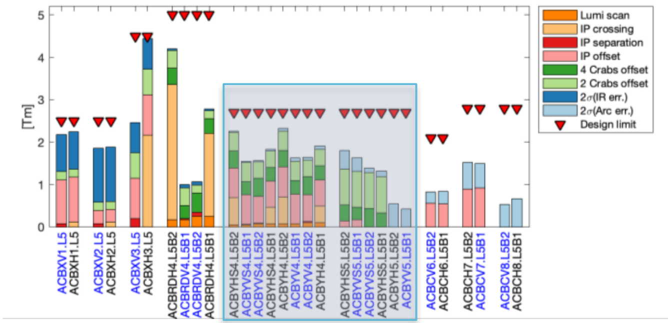


Orbit correctors strength budget

HL-LHCV1.4 after MS optimization



HL-LHCV1.3 before MS optimization



FRAS allows re-using LHC orbit correctors and magnet assemblies

- Q4: 16 x MCBY 1.9 K -> 12 x MCBY at 4.5 K with **FRAS**
- Q5: 12 x MCBY 1.9 K -> 4 x MCBC at 4.5 K with **FRAS**

FRAS allows optimising the Matching Section layout

Additional potential benefits

- Perform orbit corrector strength minimization during beam-commissioning (**better orbit residual, hence more aperture**)
- Mitigate impact of non-conform orbit correctors by performing ad-hoc fine tuning with circulating (**safe**) beam as reference

FRAS allows preserving HL-LHC performance

Aperture situation

	Old	FRAS	Old	FRAS
	Round β*=15 cm		Flat β*=7.5 cm	
TAXS	15.4	15.4	13.3	13.3
Triplets	12.0	13.1	11.8	12.7
TAXN	15.4	17.3	12.4	13.9
D2	15.5	19.3	12.9	14.5
Q4	14.5	19.3	10.4	13.6
Q5	24.8	21.1[1]	17.6	14.9[1]
Q6	25.5	26.7	18.0	18.9

Aperture requirements (beam σ)
> 12 σ in triplets
> 14.6 σ in Q6
> 19.2 σ elsewhere

[1]due to reduced Q5 aperture from 70 mm to 56 mm after MS optimization

Aperture estimates based on LHC design assumptions on ground motion and fiducialization which are under review for HL-LHC.

FRAS allows pushing HL-LHC performance

FRAS goals and benefits

Goals

- Reduce dose to survey team
- Cope with experiment vs. machine misalignment in Run 4 after completion of installation
- Correct yearly ground motion drift without manned intervention in the tunnel
- Provide tools to eliminate or at least minimize residual alignment errors using beam as reference
- Cope with unexpected sources of misalignment avoiding performance losses and loss of time for physics

FRA

By products

- Gain aperture margin in various equipment
- Matching Section Optimization
- Reduce the requirement on the Matching Section orbit Corrector System
- Mitigate spurious orbit deviations in the triplet (simplifying non linear corrections)

Summary

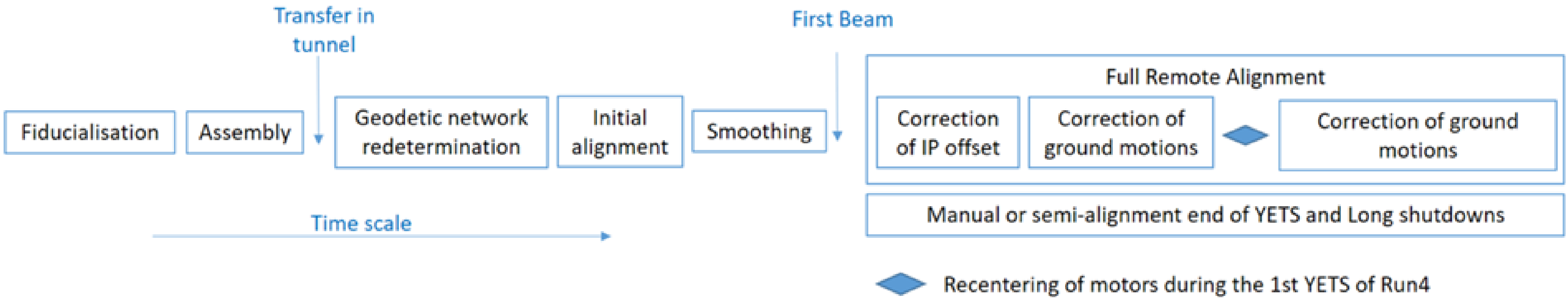
- The FRAS is a **highly-sophisticated** based on
  - Position monitoring systems
  - Remotely-controllable adjustment devices
- It brings **already now**
  - The possibility to re-optimize the Matching Section, i.e.
    - Re-using LHC components, e.g. Q4 and Q5
    - Reducing the amount of work to be performed and the extent of the LHC machine modifications
  - The simplification of the design of few elements, e.g. collimators
- It will bring **in the future**
  - Reduction of radiation to personnel
  - Increased window for machine optimization (larger aperture margin and lower β^* reach)
  - Increased machine flexibility and reduced reaction time
  - Decreased demands on orbit corrector system

HiLumi HL-LHC PROJECT

Thank you for your attention!

Spare slides

FRAS life cycle

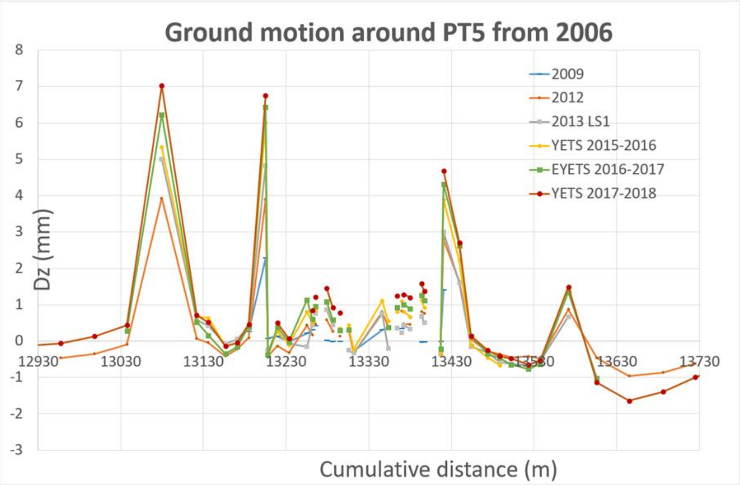


- The initial alignment will be performed w.r.t underground geodetic network
- The smoothing will be performed along an “ideal” line from Q7 left – Inner tracker detector – Q7 right to make the first pilot beam pass through
- After a few weeks of operation, a rigid remote re-alignment will be performed from Q5 left to Q5 right according to the offsets seen in the inner tracker
- During the first year, all motors will be re-centered to benefit from the maximum stroke
- The compensation of ground motion will take place preferably during TS, as a machine requalification is required after. Small machine movements could be allowed without requalification during the operation of a pilot beam.

Ground motion in IR1/5

	Radial (mm/year)	Vertical (mm/year)
Around IP5 (CMS)	± 0.3	+ 0.7 in 5L (two specific area) + 0.5 in 5R (two specific area + 0.2 in any other area
Around IP1 (ATLAS)	± 0.2	± 0.3

Maximum displacement in millimetre per year measured between the detector and the machine.



Ground motion around point 5 on the tunnel floor since 2006.