Introduction to Full Remote Alignment System and initial study of FRAS operation failure modes

M. Sosin on behalf of BE/CEM-GM-ICS FRAS collaboration

2022.07.15, 229th Machine Protection Panel Meeting

Outlook

- Defines main FRAS functionalities and reviews the impact of FRAS on components

FRAS funtional specification (EDMS 2166298)

Sep 2019

- Describes the scope of FRAS control system and defines its software functionalities (presented at #153 TCC)

FRAS software functional specification (EDMS 2589302)

Mar 2022

FRAS safety assesment & proposed compensatory measures (EDMS 2592013, 2727128)

- Study of FRAS failure modes
- Proposition of FRAS control system safety measures
- Presented on #8-2022 RASWG, to get initial comments

FRAS Stakeholder meetings

Meeting objectives:

- Gather feedback & comments from FRAS Stakeholders on the proposed safety measures
- Complete Failure Modes Analysis
- Meetings organized 2022.04.20, 2022.05.16

MPP Session 2022.07.15

MPP reccomendations / approval

Towards FRAS engineering specification

FRAS Risk assessment and protection layers design

- EDMS 2727128
- Document describes the FRAS functional safety analysis and proposed protection layers design
- To be launched for Engineering Check, by FRAS equipment stakeholders (WP3, WP4, WP5, WP8, WP9, WP12) and Machine Protection Panel
- Approval (update) of document, following Engineering Check

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EDMS NO.	REV.	VALIDITY
2727128	1.0	Draft

REFERENCE

LHC

Date: 2022-07-07

Functional Safety Analysis

FRAS
Risk assessment and protection layers design

ABSTRACT:
This document presents the risk assessment and the proposed mitigation measures for the Full Remote Alignment System (FRAS) implemented in the LSS1 and LSS5, within the HL-LHC project. The document summarizes the hazard and risk analysis, the calculations for the risk reduction and the proposed design of the protection layers according to the IEC 61511 standard. The conclusions and future steps are also presented.

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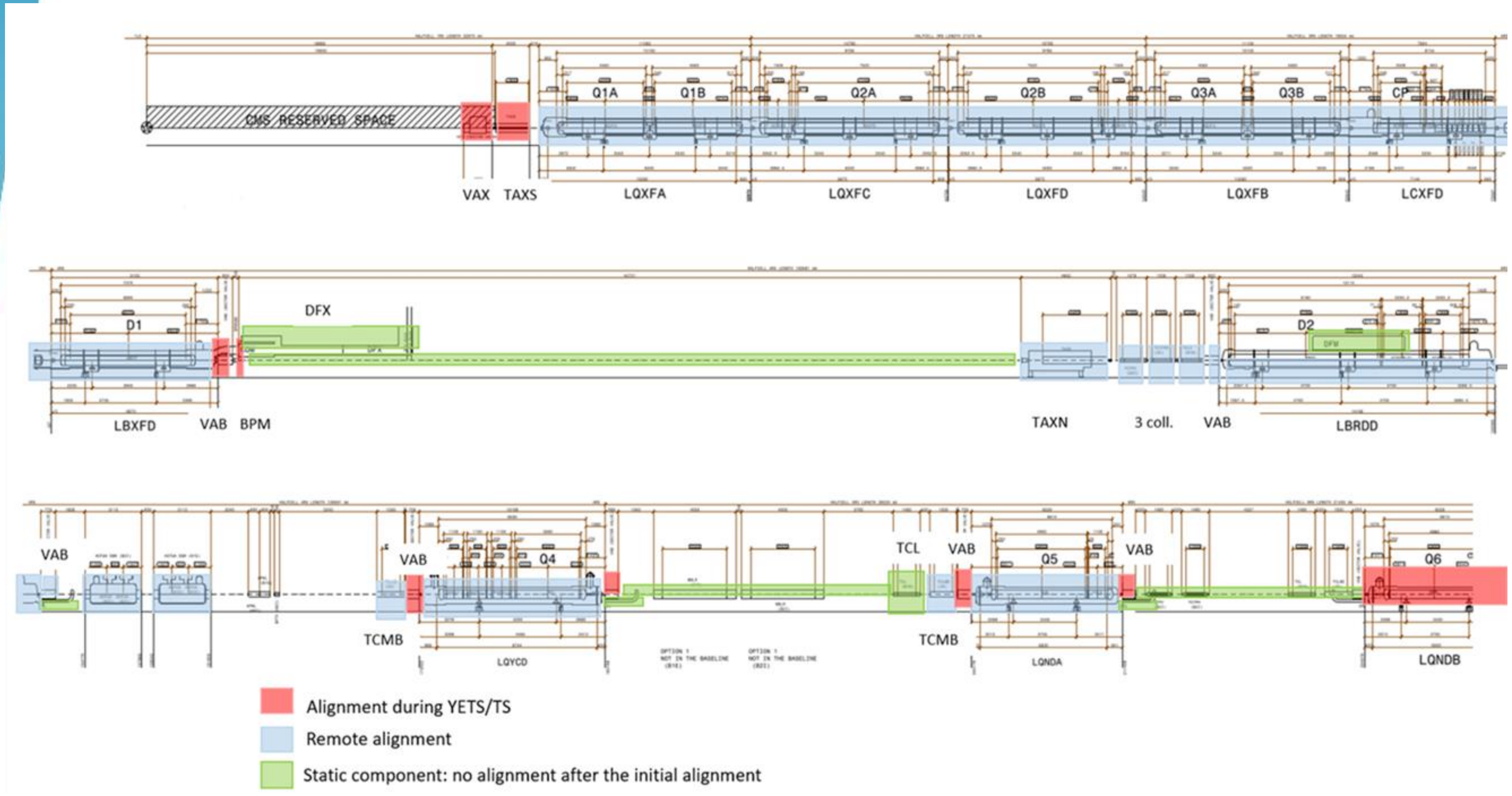
DOCUMENT SENT FOR INFORMATION TO:

Full Remote Alignment System

FRAS: EDMS 2166298



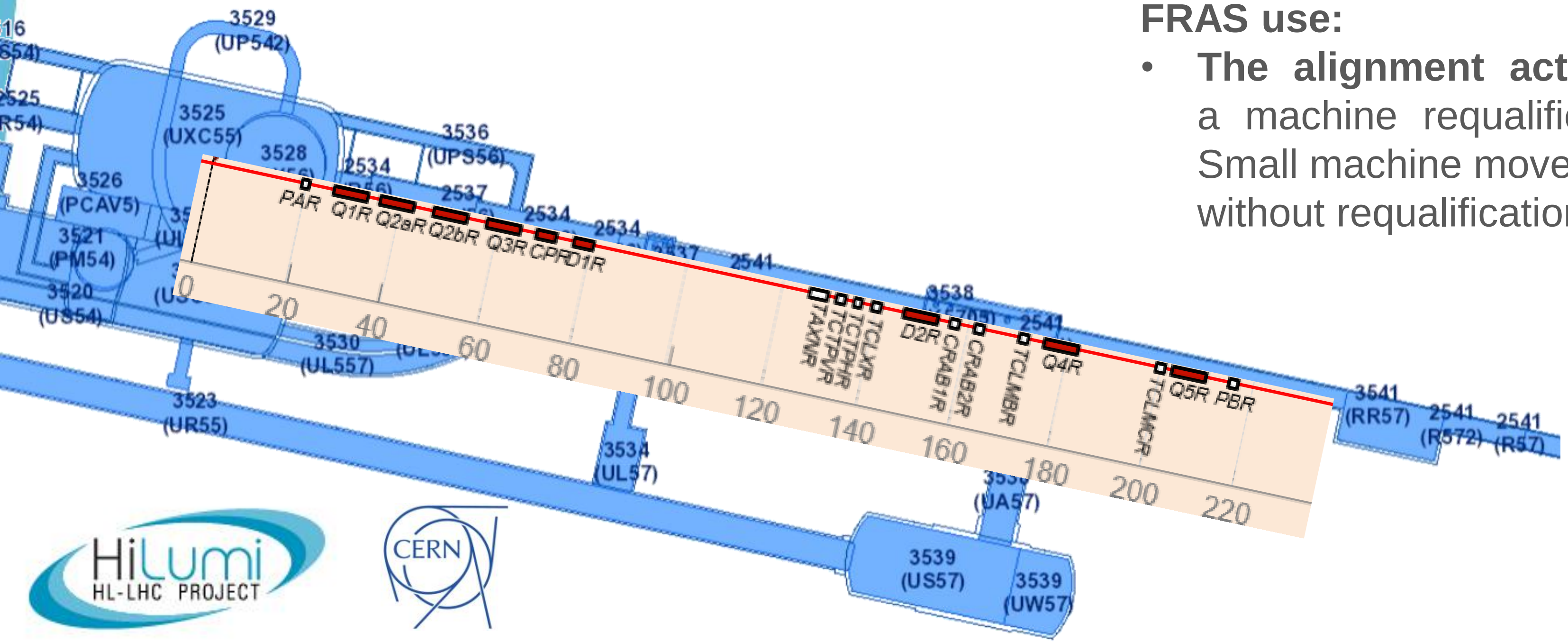
Components classified in 3 categories:

- Remotely aligned
- Never realigned after the initial alignment
- Aligned during YETS, LS, and "FRAS compatible"

- **FRAS will allow:**
  - 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
- **FRAS will provide:**
  - An important reduction of the radiation dose taken by surveyors as no access in tunnel will be needed between YETS or LS
  - A reduction in the mechanical misalignment, allowing to decrease the required correctors strength and to push the accelerator performance
  - A gain in aperture for several components

FRAS use:

- **The alignment actions will be performed during TS**, as a machine requalification is required after each movement. Small machine movements (order of ~100 µm) could be allowed without requalification during the operation of a pilot beam



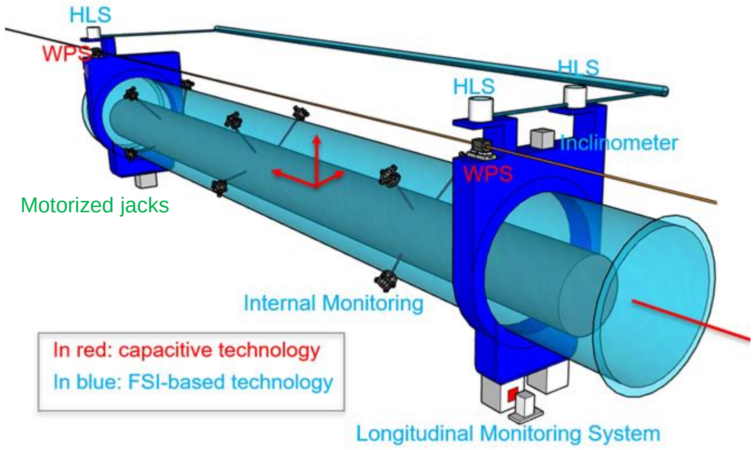
- Absolute position of components with accuracy of 0.15mm
- Relative position of neighbouring components within a few tens of µm

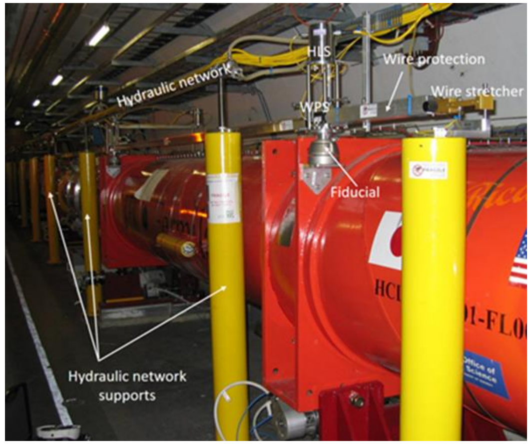
Full Remote Alignment System

Remote alignment thanks to sensors and actuators:

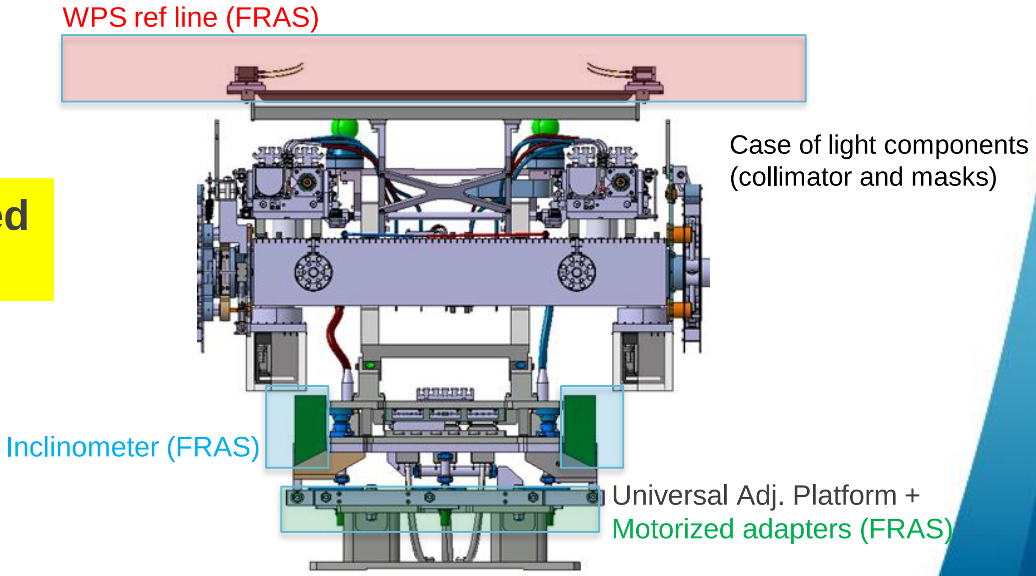
- FRAS LSS components equipped with reference sensors
  - WPS – Wire Position Sensor (Radial, Vertical position w.r.t. Wire)
  - HLS – Hydrostatic Levelling Sensor (Vertical Leveling, roll – magnets)
  - Inclinometers – (Roll – IT, TAXN, collimators, TCLM)
  - Longitudinal and UPS gallery long range monitoring
- Each component equipped in motorized adapters – for the remote adjustment of its position
- Adjusted components supports need to be integrated with FRAS sensors and FRAS motorized adapters

Case of heavy components (magnets, TAXN, Crab cavities)





FRAS is a transversal system used to align the components



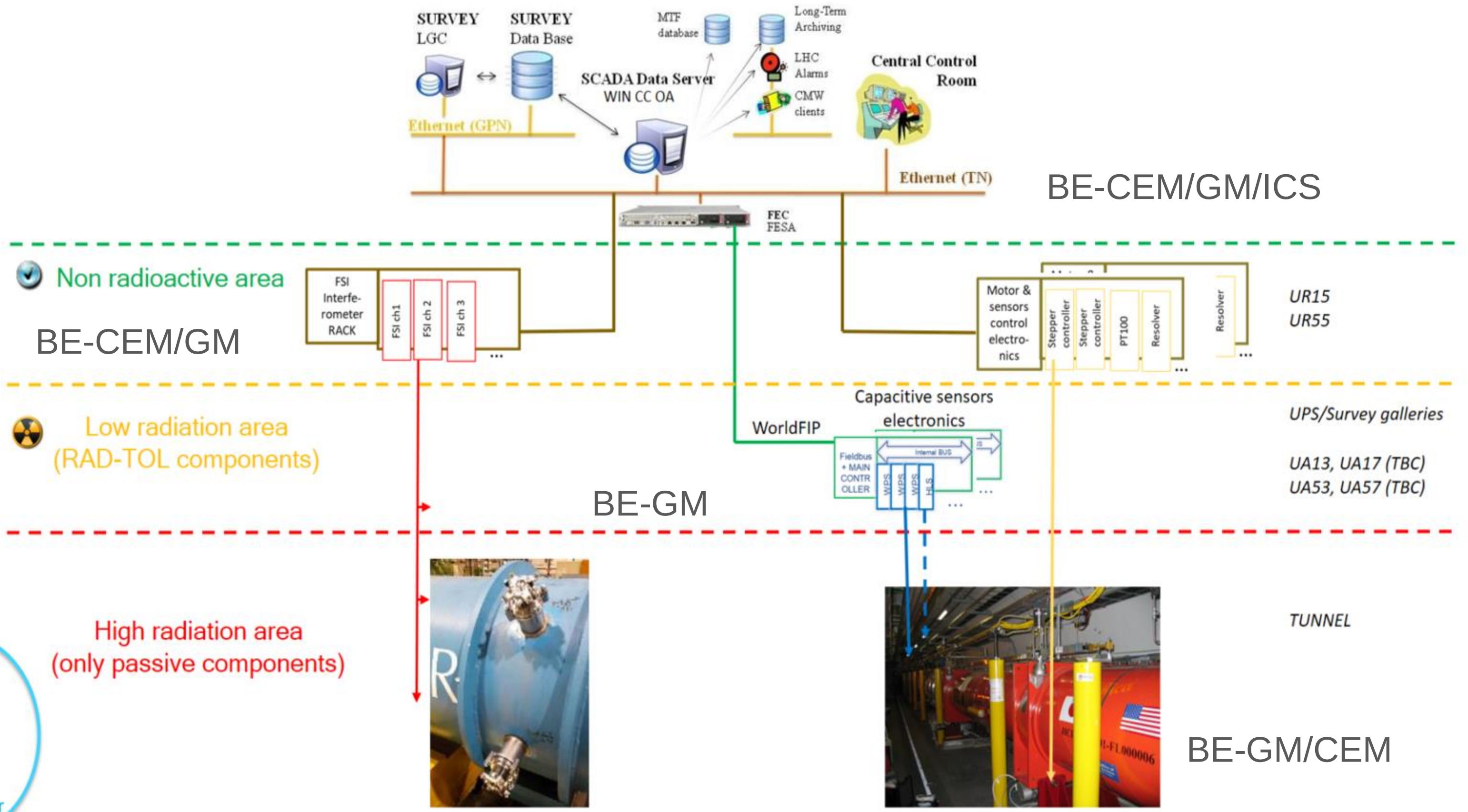
Full Remote Alignment System to align HL-LHC components belonging to WP3, WP4, WP5, WP8, (WP13)

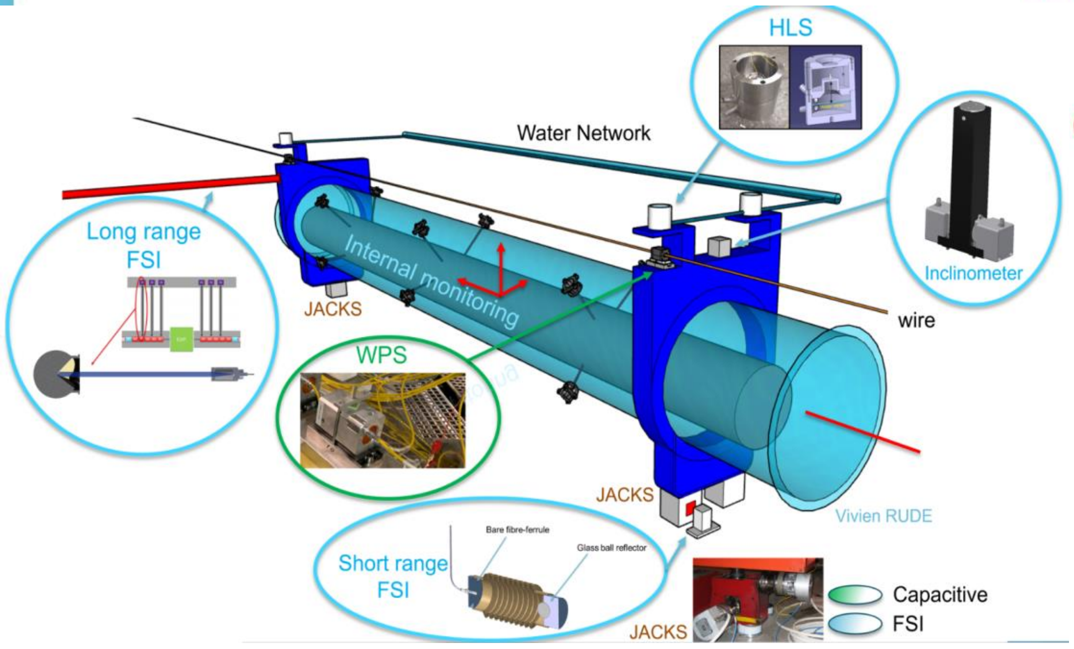
- Main components to be aligned
  - WP3: magnets (Q1-D1, D2, Q4, Q5)
  - WP4: crab cavities
  - WP5: collimators, TCLM masks
  - WP8: TAXN
  - (WP13): discussion on alignment of BPTQR (APWL replacement) ongoing
- Motion of FRAS impacts WP12 vacuum interconnection bellows, WP9 cryogenics jumpers, WP4 RF interconnections
  - All alignment activities (and its controls) needs to be compatible with users requirements
- FRAS operation compatible with Machine Protection (WP7) requirements

FRAS motion control system and its software are studied as a generic solution to cope with the requirements of the different WP-s

FRAS architecture & BE-GM/CEM/ICS collaboration

- Two technologies of micrometric sensors
  - **Capacitive technology** – WPS sensors, inclinometers. Rad-tol electronics
  - **Frequency Scanning Interferometry technology** – HLS sensors, inclinometers, distance measurements
- Real time data acquisition using FESA
- SCADA and DB interface via WIN CC OA

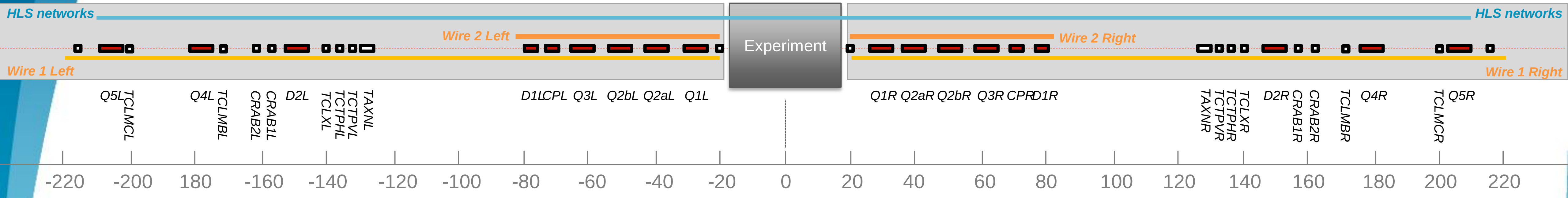




Remote adjustment:

- Components supported by 3(4) motorized jacks or Universal Adjustment Platform, equipped in 5 motorized adapters
- Motors control via SAMbuCa system (EDMS 2274146)
- Jacks/jigs **position measurement thanks to resolvers**

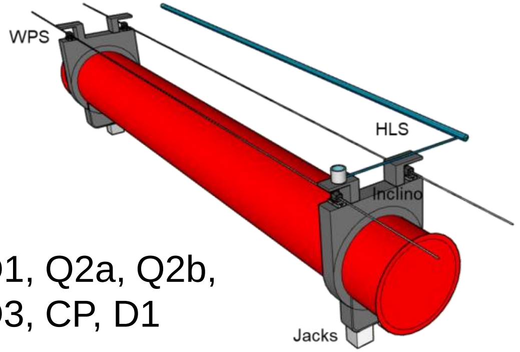
FRAS sensors



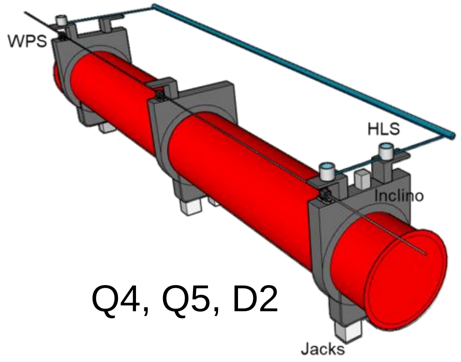
Sensor configuration – current assumptions:

- 1-2 wires, 3-4 WPS sensors (capacitive technology)
- 1 inclinometer (capacitive technology)
- 1-3 HLS sensor (FSI technology)
- 1 Inclinometer (FSI technology)
- Supported by 3 jacks (5 motorized adapters, 5 resolvers via SAMbuCa)

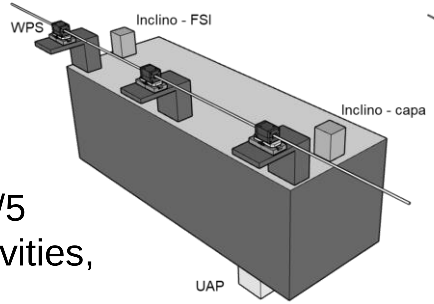
Multiple sensors & technologies → redundancy of systems & measurement data

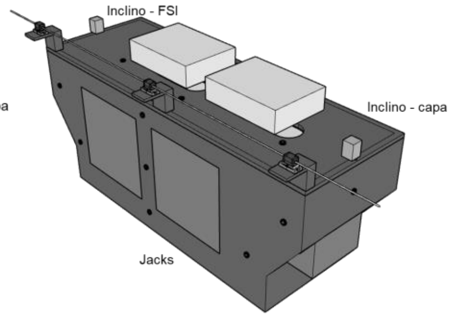


Q1, Q2a, Q2b, Q3, CP, D1



Q4, Q5, D2





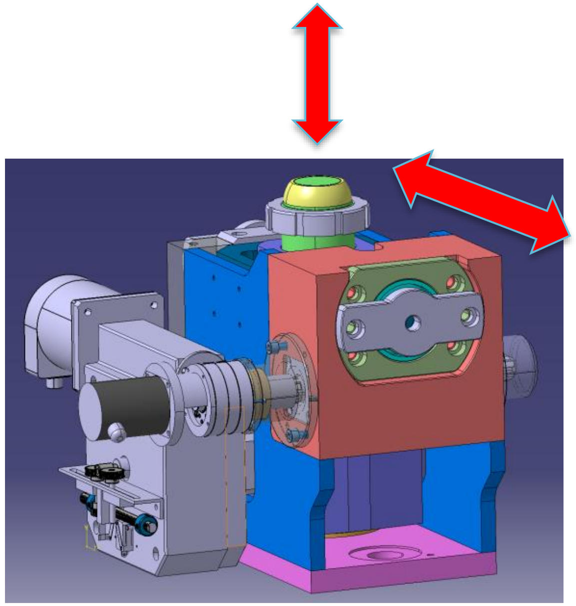
Collimators, Q4/5 masks, Crab-cavities, TAXN

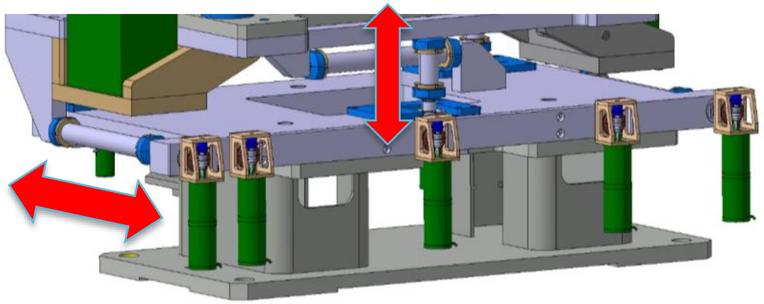
Based on Vivien RUDE slides (WGA meeting 2021.09.29, TCC meeting 2022.01.20)

FRAS motorized adapters

Main assumptions for operation:

- The axes` speed is to be limited by the measurement time of the protection layers (sensor systems)
    - **Maximum speed** of moving axes defined to **20 µm/s** (FRAS software functional scpec EDMS 2589302)
- There is no constraint on the displacement time on all the degrees of freedom
- Maximum displacement in single step: ±0.5 mm. Before execution of each motion command – its step size to be validated w.r.t. bellows deformation capacity





v ≤ 20µm/s

Introduction to FRAS operation scenarios and outcome of the Failure Mode and Effect Analysis (FMEA)

(FMEA and mitigation approach in B. Fernandez Adiego presentation)

Operation scenarios

- REMOTE ALIGNMENT MODE (NO BEAM):
  - FRAS can perform the alignment
  - No personnel in the tunnel
- MAINTENANCE (NO BEAM and PERSONNEL close to the machine):
  - FRAS can perform the alignment
  - Personnel is present in the tunnel for maintenance purposes
- PILOT BEAM:
  - FRAS can perform small alignments in order of ~100 µm displacements. Only on special request of OP
  - Low intensity beam
  - No personnel in the tunnel
- HIGH INTENSITY BEAM:
  - FRAS cannot perform any alignments – motion is disabled (motors unpowered)
  - No personnel in the tunnel

Personnel safety

- **Remote alignment mode** - No personnel presence in close vicinity of FRAS
- **Maintenance mode -** the experienced Survey personnel is present in close vicinity of FRAS for maintenance purposes:
  - **Main consequence for the personnel is a fatality by ODH (Oxygen Deficiency Hazard) due to helium spill**

Safety requirements – Operational aspects

- Access conditions
  - During beam ON, Access is OFF
    - No people in the tunnel, no safety restriction for the FRA
  - During Access ON:
    - FRA and work on equipment are not compatible activities.
      - Lock-out procedures to prevent unexpected start-up
      - Schedule management
      - Operational management of the FRA (who is in charge?)
    - FRA and passage in the transport zone
      - Local warning signs
      - Access to FRA experts only?

Christelle Gaignant 10

- **No „people"** when FRAS is ON
- **FRAS experts are not considered as random „personnel".** They are experienced operators, knowing the system

Full Remote Alignment
Safety aspects

International Review of the HL-LHC Alignment and Metrology, 26th to 28thAugust 2019
CERN

Machine safety

Failure modes indentified for FRAS (EDMS 2727128 – FMEA tables)**:**

1. Exceeding the bellow limits (for vertical, horizontal and rotational displacements) causing damage of interconnection bellows
2. FRAS power cut (FRAS unpowered)
3. Magnet drop due to mechanical issue with the jack
4. Component position change due to quench
5. Any displacement of FRAS while high intensity beam

The main consequences of these failure modes for the LHC machine are the damage of the interconnecting bellows and the damage of components when high intensity beam is circulating in the HL-LHC

Machine safety – bellows damage

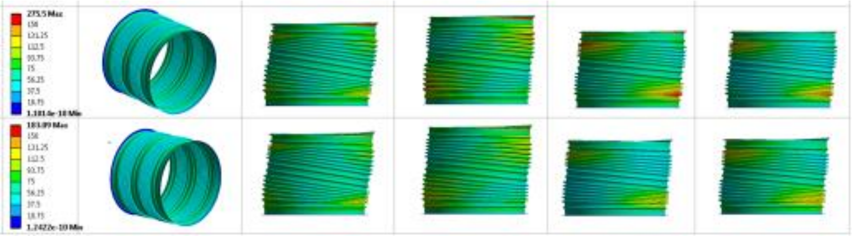
Bellows are considered as components most sensitive to alignment activities, as might be damaged if their limits (lateral, rotational, axial displacement) are violated

Exceeding these limits does not mean immediately that failure will occur, but if it will occur - it will be catastrophic for LHC machine:

- **loss of vacuum; helium spill (magnets)**
- bellow collapse and its repairing action might cause several months of machine stop;
- This several months stop might include radiation cooling-down time too;

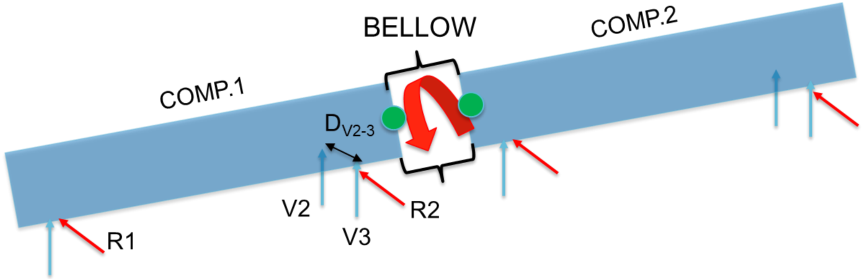
- Bellows are assumed to be not extensively deformed during lifetime – as it follows components aligned by FRAS
- **Deformations have to be followed-up and interlocked if limits reached (including cummulated deformations since installation) → one of main function of FRAS**

D. Ramos, Y. Leclercq



Machine safety – bellows damage

- Potential bellow damage is caused by motion of 2 neighbouring components beyond bellow limits
  - Change of each **bellow end position** is a result of **motion of all jacks/jigs** of components (parallel kinematics, 3D motion)
  - Bellow deformation is a sum of displacements of both neighbouring components
- FRAS motorized jacks/jigs range is +/-2.5 mm



Mechanical stops or limit switches within jacks/jigs are insufficient to mitigate bellows damage

- Tracking of position of components extremity (hence bellows deformation) is required. The precision of tracking system have to be < 100 µm (considering typical +/-2..2.5 mm / 1 mrad deformation limits)
  - Feasible by **calculation of component extremity 3D position**, based on measurements of components position with absolute micrometric sensors or actuator strokes evolution (resolvers)
  - Absolute components position and bellows cummulated deformation will be logged and known before each FRAS adjustment activity, thanks to FRAS
  - **Generic solution of 3 redundant Protection Layers, basing on different technologies of sensors are proposed as generic safety solution (see B. Fernandez Adiego presentation)**

Machine safety – bellows damage

- **Generic solution of 3 redundant Protection Layers, basing on different technologies of sensors are proposed as generic safety solution (see B. Fernandez Adiego presentation)**
- Following FRAS Stakeholder meetings discussions and WP5 questions:

In case of interest to add additional (non generic) protection feature (i.e. hw, limit switch based), proposed by an equipment owner – such an option could be integrated to FRAS controls as non standard interlock (EDMS 2727128, section 3.3)

- **Its integration feasibility, compatibility with FRAS operation and additional cost need to be analyzed**
- **Such request to be studied Q3-Q4 2022**

Machine safety – component damage

The HL-LHC components can be damaged if components are not properly aligned when a high intensive beam is circulating

The strategy is to disable the FRAS motor while having high intensity beams and to check before injecting the beam that the HL-LHC components are properly aligned (see B. Fernandez Adiego presentation):

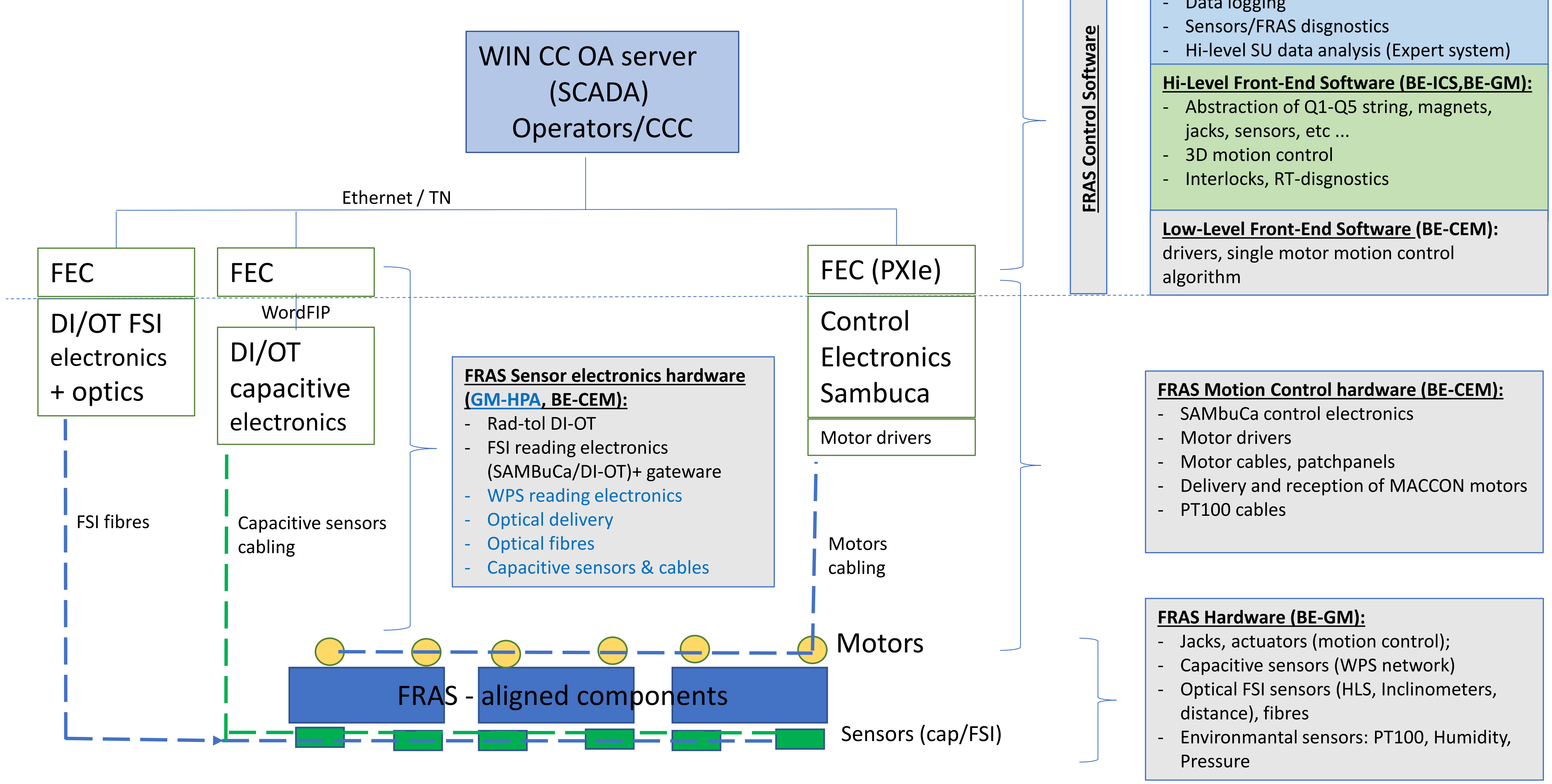
- A mechanical key located at the CCC will disable the FRAS motors while high intensity beam is injected and at the same time will send a signal to the Beam Interlock System to dump the beam if the FRAS motors are not disabled

- An interlock signal produced by FRAS to inhibit the injection of high intensity beam into the LHC when misalignment between components is above limits

Thank you!

Full Remote Alignment System
as colaborative project of BE-GM/CEM/ICS

FRAS SYSTEM: Equipment/Software layers



Machine safety – power cut → FRAS unpowered

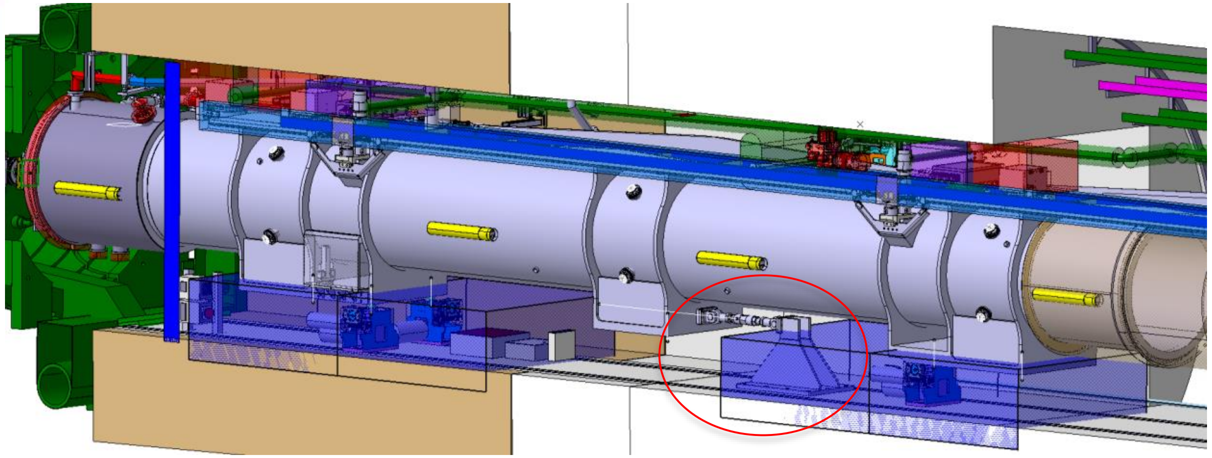
- **Power cut will have no impact on FRAS functionality**
  - Motorized adapters/jigs/jacks are foreseen self-locking in case of accidental power cut
  - Power recovery will not create any motion in the system

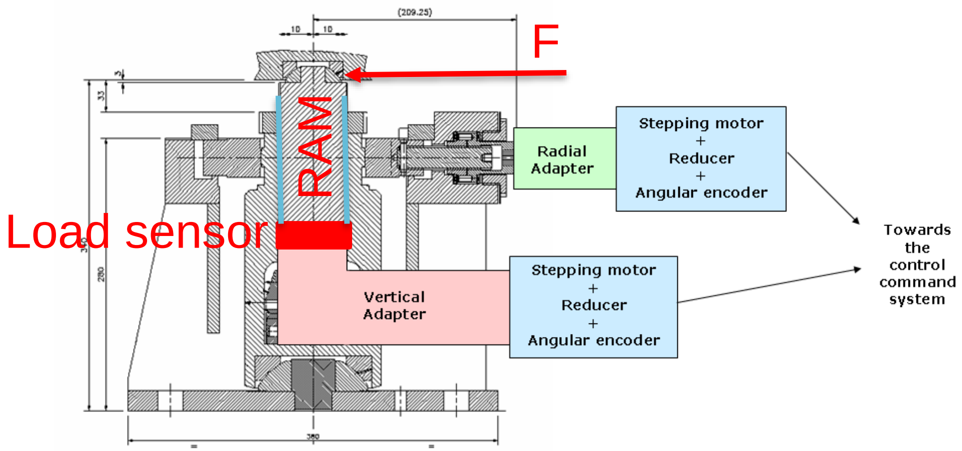
  - All sensors used within FRAS (FSI, capacitive, resolvers) provide absolute measurements - positions known immediately after power recovery

Machine safety – magnet drop due to mechanical issue with the jack

- **The issue of jack blocked by friction caused by longitudinal forces were reduced by change of magnets kinematic scheme**
  - Longitudinal anchor was added @ Q1, D1

- The vertical load sensors (option to be checked during IT String) to monitor loss of contact between vertical adapter and jack RAM are foreseen as an option for FRAS





Machine safety – component position out of alignment limits

- **Missaligned machine causes risk of too low aperture for the beam and damage of components with high intensity beam**
  - Machine misaligned before beam injection
  - Change of alignment due to ground motions

- **Mitigation of this FM is provided using 4 different measures**
  - Operator procedure (validation of the component's alignment)
  - Determination of machine position by FRAS → *Machine misaligned interlock*

  - Detection of machine misalignment during pilot beam validations
  - BLM interlock (Beam dump) during the run if misalignment

Machine safety – quench FM

- **Quench causes rapid change of magnet position – the typical magnets position drift after quench is in order of** ~100 µm (small misalignment)

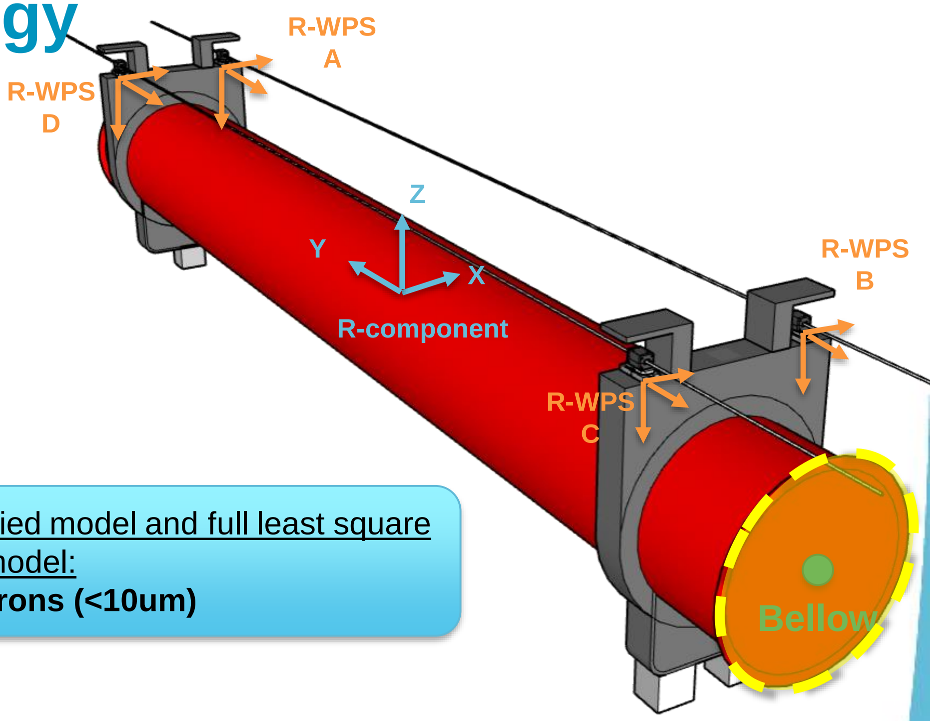
- **Quench have no important impact on FRAS safety**
  - FRAS is unpowered, while high intensity beam
  - FRAS might be powered with pilot beam → limited movements (order of ~100 µm)
  - Determination of machine position by FRAS after quench → *Machine misaligned interlock*

Machine safety – any displacement of FRAS while high intensity beam

- **Wrong operator command (accidental turn ON the FRAS CCC KEY which power the motors while high intensity beam)**

- **Mitigation measures**
  - Interlock the FRAS motors while high intensity beam
  - Interlock (*FRAS motors powered*) sent to the BIS or SIS

Q1, Q2a, Q2b, Q3, CP, D1 (capacitive technology example)



Assumptions:
1) Relative movement
2) Wire stable during the movement
3) No rotation between R-WPS and R-component (rigid link)
4) Rotation matrix (movement of the component) simplified (small angles)
5) Approximate coordinates in R-component

INPUT

T0 :
Coordinates in R-WPS (in mm) at t0 : $Lrad_i(to)$ $Lvert_i(to)$

T1 :
Coordinates in R-WPS (in mm) at t1 : $Lrad_i(t1)$ $Lvert_i(t1)$

Approximate coordinates of the origin of R-WPS (A,B,C,D):
Coordinates in R-component : X_i, Y_i, Z_i

Difference between simplified model and full least square model:
FEW microns (<10um)

Simplified model

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{R-component\ (T0)} = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + \begin{bmatrix} 1 & -R_Z & R_y \\ R_Z & 1 & -R_X \\ -R_y & R_X & 1 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{R-component\ (T1)}$$

$$\begin{bmatrix} X_i + Lrad_i(to) \\ Y_i \\ Z_i - Lvert_i(to) \end{bmatrix} \qquad \begin{bmatrix} X_i + Lrad_i(t1) \\ Y_i \\ Z_i - Lvert_i(t1) \end{bmatrix}$$

OUTPUT

$$Ry = \tan^{-1}\frac{\Delta Z_{AD}}{|X_A - X_D|} = \tan^{-1}\frac{\Delta Z_{BC}}{|X_B - X_C|}$$

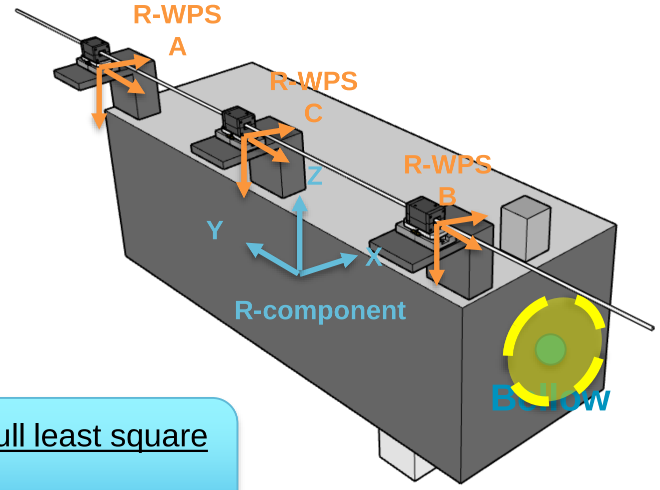
$$Rx = \tan^{-1}\frac{\Delta Z_{AB}}{|Y_A - Y_B|} = \tan^{-1}\frac{\Delta Z_{CD}}{|Y_C - Y_D|}$$

$$Rz = \tan^{-1}\frac{\Delta X_{AB}}{|Y_A - Y_B|} = \tan^{-1}\frac{\Delta X_{CD}}{|Y_C - Y_D|}$$

$$T_X = X_i + Lrad_i(to) - \{1 * (X_i + Lrad_i(t1)) - R_Z * Y_i + R_Y * (Z_i - Lvert_i(t1))\}$$

$$T_Z = Z_i + Lvert_i(to) - \{-R_Y * (X_i + Lrad_i(t1)) + R_X * Y_i + 1 * (Z_i - Lvert_i(t1))\}$$

Collimators, masks, Crab-cavities, TAXN (C-M-C-T), Q4, Q5, D2 (capacitive technology example)



Assumptions:

1) Relative movement
2) Wire stable during the movement
3) No rotation between R-WPS and R-component (rigid link)
4) Rotation matrix (movement of the component) simplified (small angles)
5) Approximate coordinates in R-component

INPUT

T0 :
Coordinates in R-WPS (in mm) at t0 : $Lrad_i(to)$, $Lvert_i(to)$

T1 :
Coordinates in R-WPS (in mm) at t1 : $Lrad_i(t1)$, $Lvert_i(t1)$

Approximate coordinates of the origin of R-WPS (A,B):
Coordinates in R-component : X_i, Y_i, Z_i

Difference between simplified model and full least square model:
FEW microns (<10um)

Simplified model

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{R-component\ (T0)} = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + \begin{bmatrix} 1 & -R_Z & R_y \\ R_Z & 1 & -R_X \\ -R_y & R_X & 1 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{R-component\ (T1)}$$

$$\begin{bmatrix} X_i + Lrad_i(to) \\ Y_i \\ Z_i - Lvert_i(to) \end{bmatrix} \qquad \begin{bmatrix} X_i + Lrad_i(t1) \\ Y_i \\ Z_i - Lvert_i(t1) \end{bmatrix}$$

OUTPUT

$$Ry = Inclinometer\ measurement$$

$$Rx = \tan^{-1}\frac{\Delta Z_{AB}}{|Y_A - Y_B|}$$

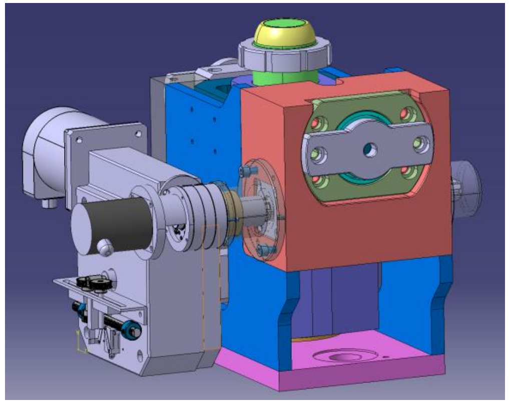
$$Rz = \tan^{-1}\frac{\Delta X_{AB}}{|Y_A - Y_B|}$$

$$T_X = X_i + Lrad_i(to) - \{1 * (X_i + Lrad_i(t1)) - R_Z * Y_i + R_Y * (Z_i - Lvert_i(t1))\}$$

$$T_Z = Z_i + Lvert_i(to) - \{-R_Y * (X_i + Lrad_i(t1)) + R_X * Y_i + 1 * (Z_i - Lvert_i(t1))\}$$

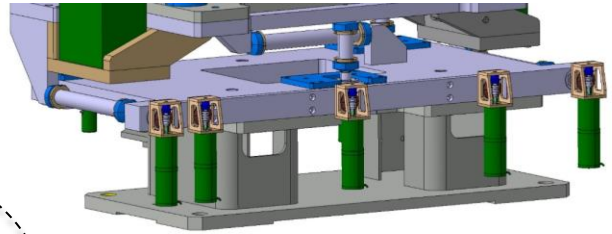
V. Rude

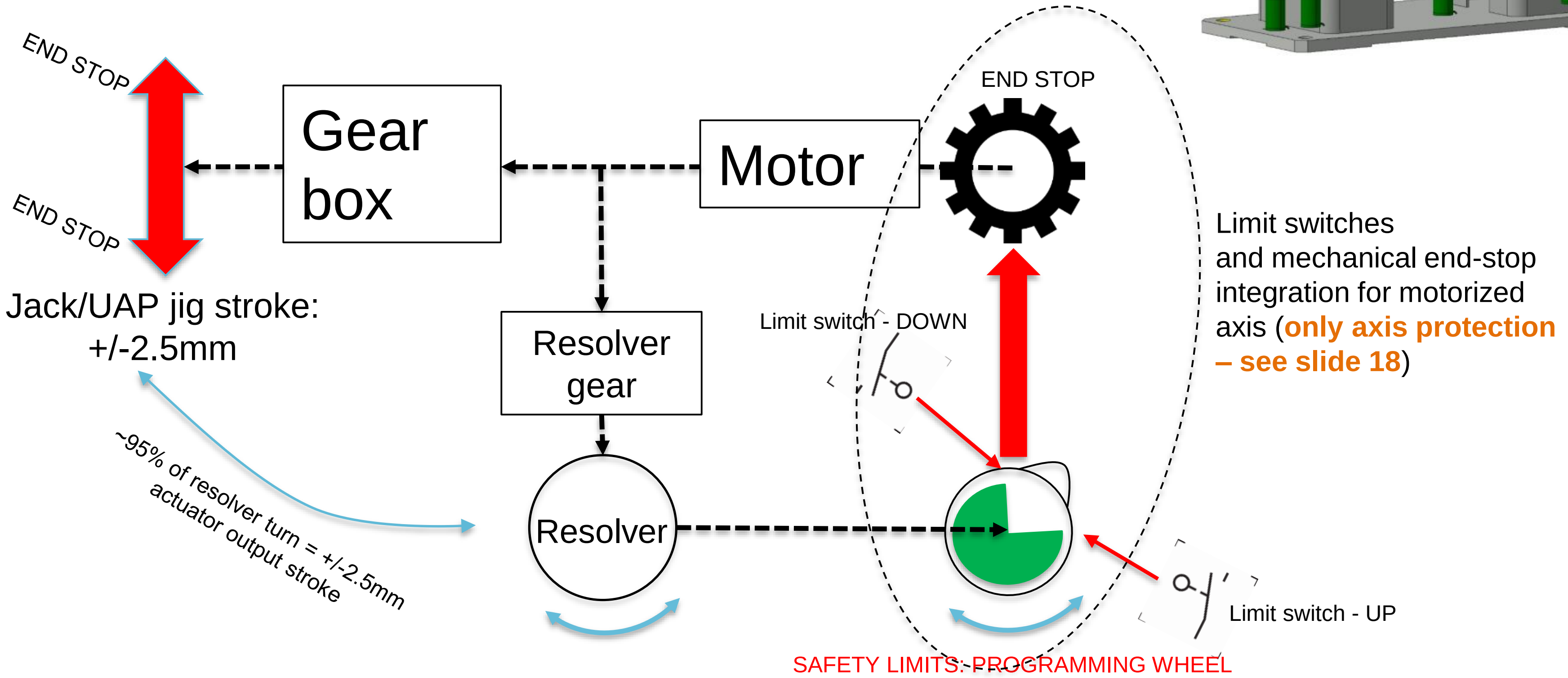
FRAS motorized adapters



Design assumptions:

- 3 types of motorized adapters to be used:
  - HL-LHC motorized jack vertical adapter
  - HL-LHC motorized jack radial adapter
  - Universal Adjustemnt Platform motorized adapter
- For the FRAS, it has been decided to make mechanically the resolvers absolute sensors able to measure the entire axis displacement range





Machine safety – bellows damage

Ultimate bellows displacement:

Bellow type	Components	Lateral displacement [+/-mm]	Torsion [+/-mrad]	Axial displacement [+/-mm]	Comments
DOUBLE BELLOW	Q1				EDMS 2045739
W-bellow	Q1-D1	4	1	5	WGA 11 (https://indico.cern.ch/event/725603/) and WGA 13 (https://indico.cern.ch/event/731474/), input of D. Ramos
PIM bellow	Q1-D1	3	1	1 (after cool down)	WGA 11 (https://indico.cern.ch/event/725603/), input of C. Garion
Deformable RF bridge (DRF)	D1, TAXN, Q4, Q5	2 .. 2.5	1		EDMS 2113939, EDMS 2045739, meeting discussions with V. Baglin, J. Hansen, G. Bregliozzi
RF bridge (RF)	TAXN, D2, TCTPXV, TCLPX, CRAB	2 (operational 1mm)	1		
Collimators bellow	TCTPXV, TCTPXH, TCLPX	2.5	2 (0.12˚)	15	input from F. Xavier-Nouiry (bellow parameters, bellow assembly limits to be studied)
DOUBLE LRM	CRAB				EDMS 2045739
LRM	CRAB, TCLM				EDMS 2045739
Cryo jumpers		Vertical +/-30mm, horizontal +/-25mm, FRAS ultimate motion (+/-2.5mm in vertical and radial direction) is accounted			initial input from F. Merli
RF waveguide	CRAB	1 (SPS), HL ?	?	1 (SPS), HL?	CRAB Cavity technical meetings discussion

- The deformation of most of bellows are at the level of +/-2..2.5 mm (transversal), 1 mrad (torsion)
- Final values to be confirmed by stakeholders, as importank input for FRAS safety