Alignment: is this an issue for HL-LHC?
Or
How can we profit as maximum from our investment in alignment ?

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Summary

- The HL-LHC specifications vs. the LHC specs and the lessons learnt
- The present HL-LHC baseline
- The proposal with plug-in system and alignment by wire
- The proposal with fully remote alignment: targeting investment optimization and providing new knob to operation
- Conclusions

Alignment system specifications:
LHC, vs HL-LHC taking into account the LHC experience

Object Or Area	Item	Measurable	LHC	LHC experience	HL-LHC
All elements	Fiducialisation	mechanical axis vs external fiducials	± 0.1 mm	Ok	± 0.1 mm
Inner Triplet: one IP side	Relative determination of the position of quadrupoles fiducials inside the low beta triplet	Incertitude measurement Resolution displacement Determination fiducials with full system chain: Stroke	± 3 µm + 1µm/month <10 µm ± 0.1 mm ± 2mm	Ok Ok Ok Ok	± 3 µm + 1µm/month <10 µm ± 0.1 mm ± 2.5 mm
Inner Triplet: Left to Right of the IP		Radial error	± 0.2 mm (1σ)	Ok	Better than 0.15 mm (1σ)
		Levelling error	± 0.1 mm (1σ)	Ok	± 0.1 mm (1σ)
Link between experimental cavern to the LHC machine cavern	Any fiducial mark of the cavern reference network w.r.t "machine geometry"		0.5 mm to 1.2 mm rms	Ok	0.5 mm to 1.2 mm rms

Object Or Area	Item	Measurable	LHC	LHC experience	HL-LHC
IT elements vs the MS section main elements			± 0.15 mm (1σ)	Worst than ± 0.2 mm (1σ)	Better than 0.1
Equipment in the MS	Main elements (Magnets + TAN)	Initial alignment w.r.t. geodetic network	± 0.3 mm (1σ)	Ok	± 0.2 mm (1σ)
		Smoothing	± 0.15 mm (1σ) over 110 m long	Ok	± 0.1 mm (1σ) till Q5 included (190 m)
	Other elements		Smoothing respect to adjacent components		
From Q1 to Q6	Misalignment between alignment campaigns: ground motion, mechanical stress encountered during vacuum and cool-down phases				0.17 mm

LHC lessons learnt

- Need to improve the connection between the IT and MS
- The remote alignment of the triplet has been applied successfully twice in the LHC era, but it is necessary to have all stakeholders on board from the beginning
  - Cryogenic and Vacuum gave their green light in the internal alignment review of the 07/04/2017
  - RF agreed and committed in developing flexible RF guides
- The Survey team experience already today in the LHC high collective doses
- Various types of the I.T. magnet movement correlated with change of cryogenic conditions have been experienced
  - Slow movements induced by the temperature of the IT shield. Mainly reversible
  - Abrupt faster movement induced by failure of the cryogenic system or IT quenches likely due to pressure increase in the Cold Mass. Mainly not reversible
  - Spontaneous slow movement that could be linked to tunnel temperature

Baseline

Baseline

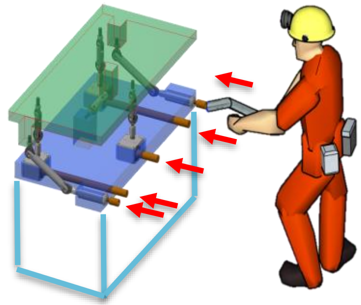
Baseline

Alignment by wire

Full remote alignment

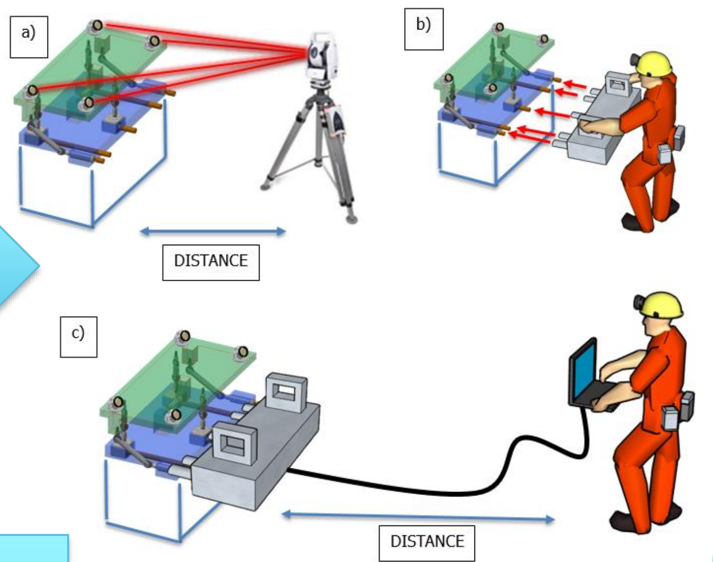
Measured in the baseline directly on the CM

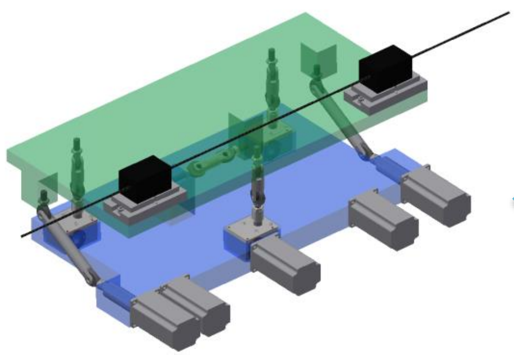
Some definition
(here in case of standardized platform)



Manual
Without standardized platform more difficult and more time consuming

Plug-in motors
Alignment by wire

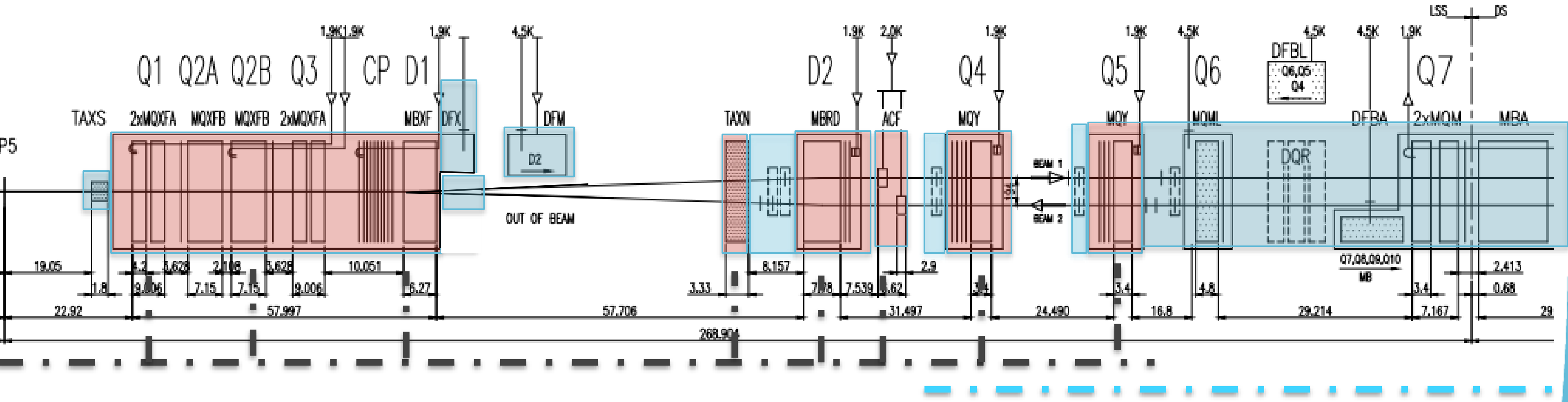




Remote
Resident motors and sensors

The Present HL-LHC baseline as from the TDR 0.1

IP1 and IP5 HL-LHC
Synoptic of adjustment system
BASELINE



- Motorized adjustment system, remotely controlled : adjustment during run, from CCC
- Manual adjustment system: adjustment during LS, personnel in the tunnel, access in front of element (special for TAXS)
- Continuous monitoring respect to common reference
- Remote determination: main system not in WP15.4 baseline and not foreseen in budget . To be recovered from development for collimators and arc monitoring, targets foreseen

Possible alignment strategies with baseline

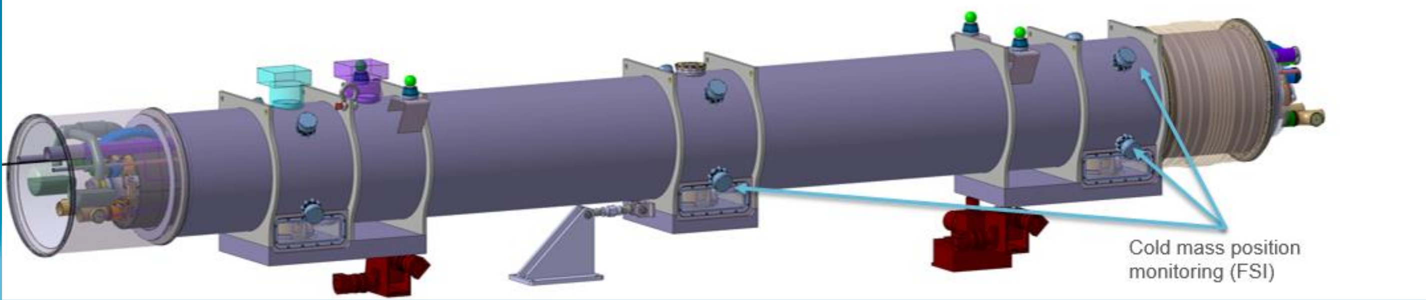
	Scheme 1: During operation	Scheme 2 During TS Up to 2.5 mm	Scheme 3 During TS Larger than 2.5 mm	Scheme 4 During YETS	Scheme 5: During LS
Machine conditions	Machine operating conditions	Machine operating conditions	Magnet cold but empty during movement	Magnet cold but empty during movement	Warm
Max stroke	+/- 2.5 mm	+/- 2.5 mm	+/- 10 mm	+/- 10 mm	more
Time required per IP side Q1 to D1	30 min No access	30 min No access	30 min No access	30 min No access	
Time required per IP Q1 to Q5	Not possible	2(L)+2(R) days Access for	2(L)+2(R) days Access for intermediary	2(L)+2(R) days Access for intermediary	

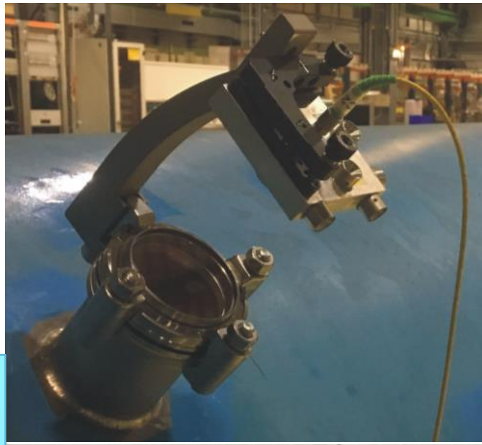
After LSx and YETS

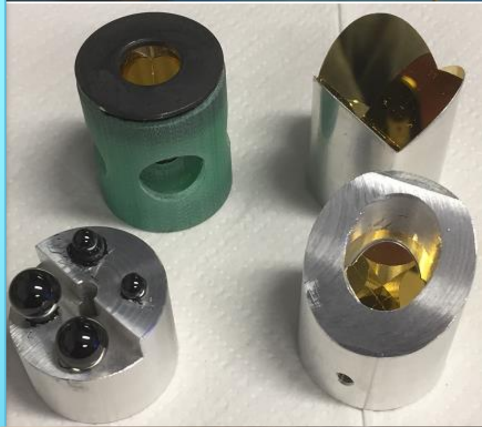
Case 1: the misalignment machine vs experimental IP is less than 2.5 mm:
Case1 A: we **can** correct acting only on the IT:
apply Scheme 1 and then run till next YETS where we redo full alignment
Case1 B:we **cannot** correct acting only on the IT:
apply Scheme 2

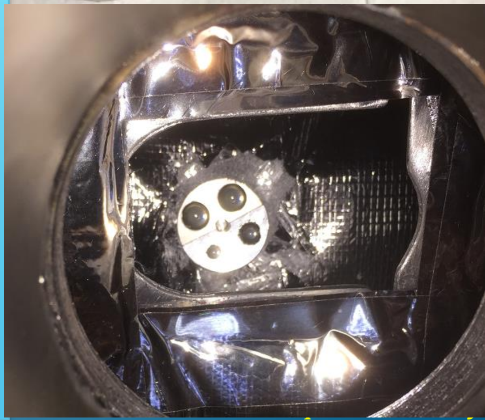
Case 2: error larger, to compensate for exceeding error we wait for the TS and we apply where necessary Scheme 3.
After LS3 it will be easier because no activation yet

The measurement of the CM position vs cryostat Q1 to Q3 and crab cavities







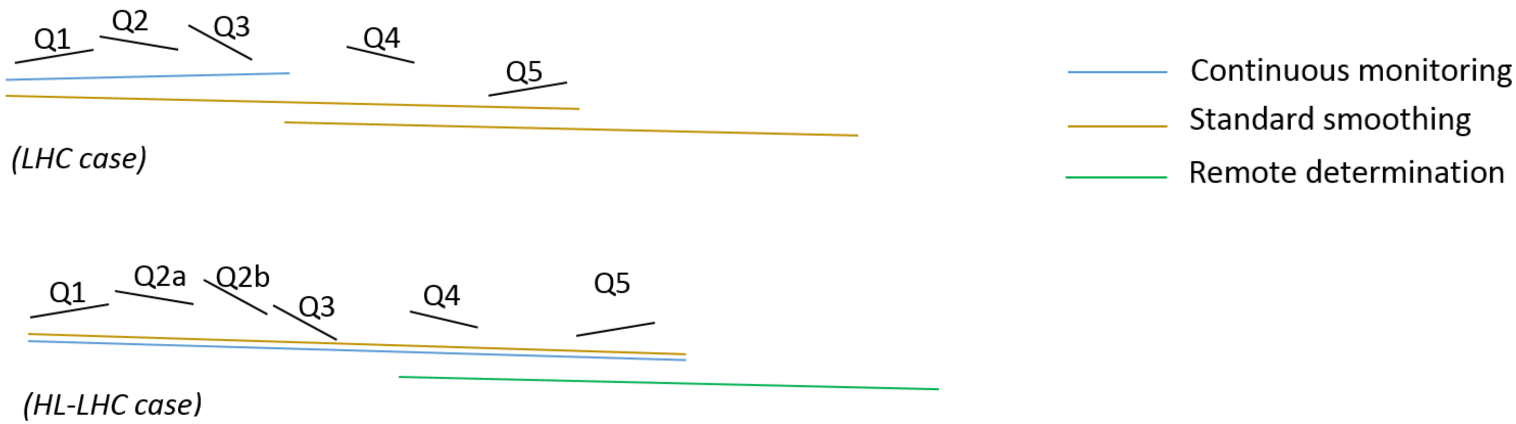


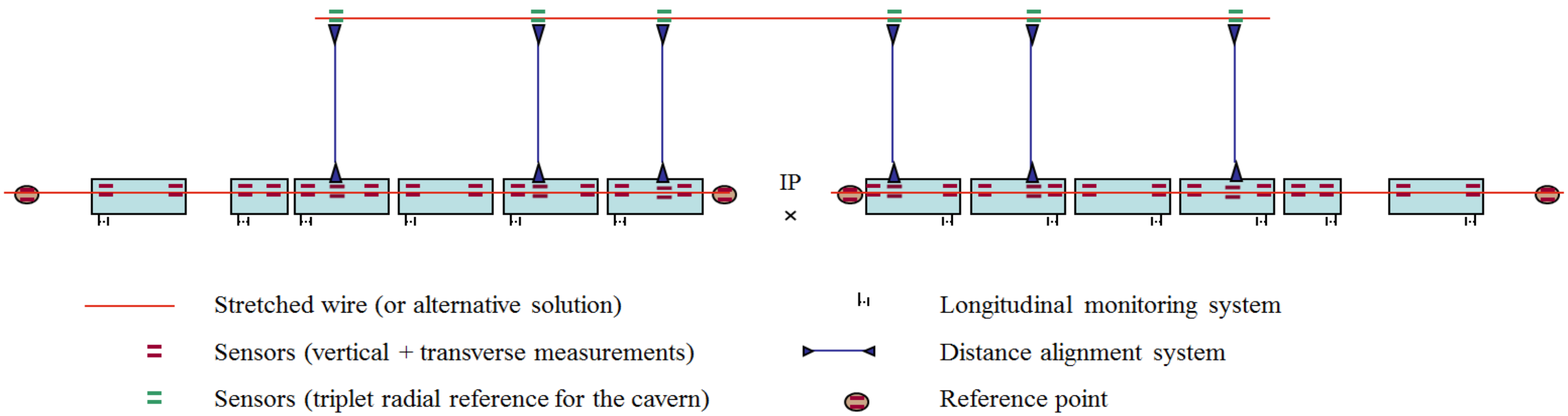
Measurement of the CM position respect the cryostat via Absolute Interferometric Distance Measurement (FSI):

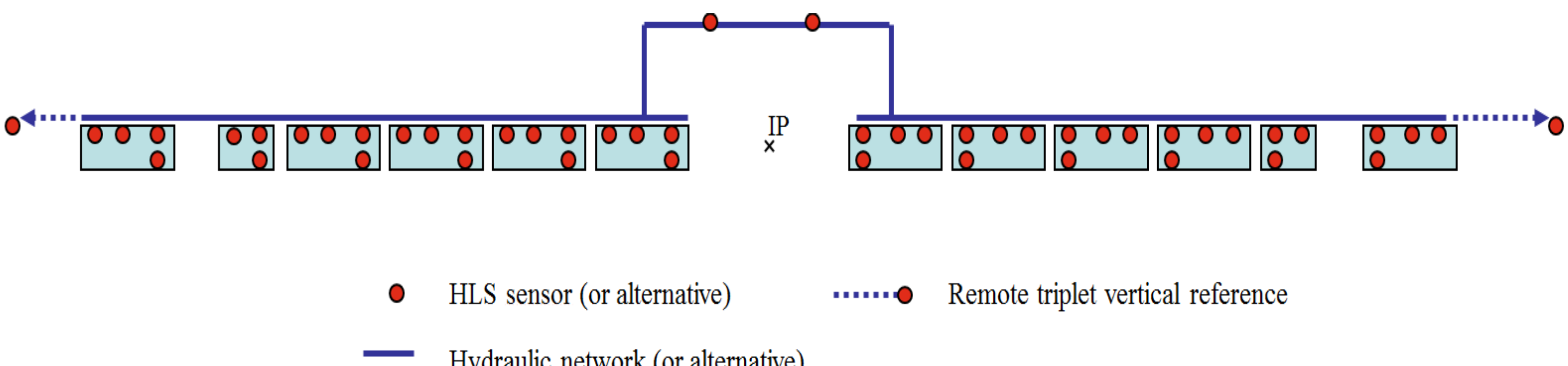
- Being successfully tested and used on the SPS crab
- Being tested on LHC dipole to verify behavior in less clean environment
- Verified that precision of ±5µm is achievable, but
- performance in time affected by the environment and therefore 2 systems are presently under test and qualification
  - FSI ETALON systems
    - Standard target
    - Prism shielded target
    - Thermally insulated target (best results in time of the 3)
  - Divergent Beam interferometry target with multi target reference (in house development). First results very promising and cheaper to deploy (in term of targets)

Improving the knowledge of the position of the MS elements respect to the IT:

not achieved in LHC and key here because of the crab



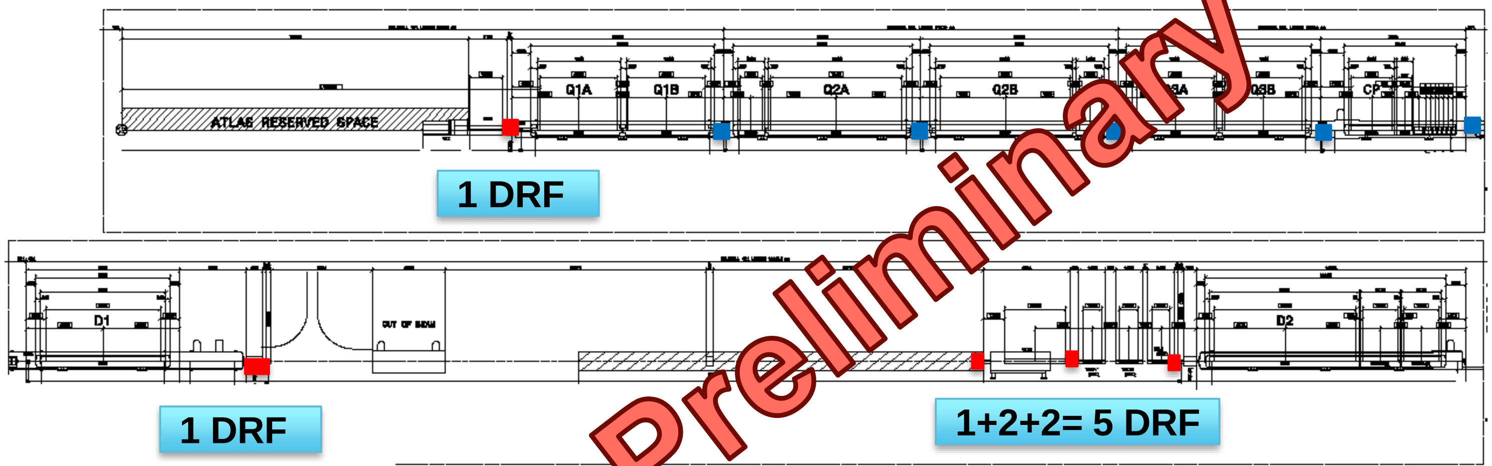




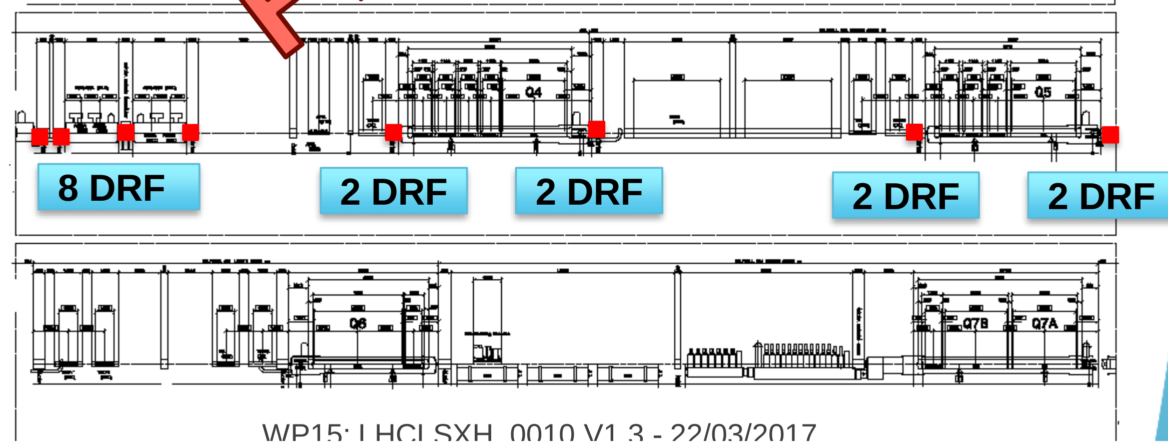
the reality

How much stroke is needed? LHC tunnel vs experiment target values ±2.5 mm

Preliminary deformable RF bridge (DRF) location for LSS5R Baseline TDR 0.1



- DFR only for IT according to present WP12 present budget
- New room temperature DFR due to be compliant with TDR 0.1 alignment system



The total impact to allow ± 2.5 mm with baseline system is to built:

+ 92 deformable RF bridge (+20 for the triplet already included in CtC). So, a total of 112 of deformable RF bridge around the ring.

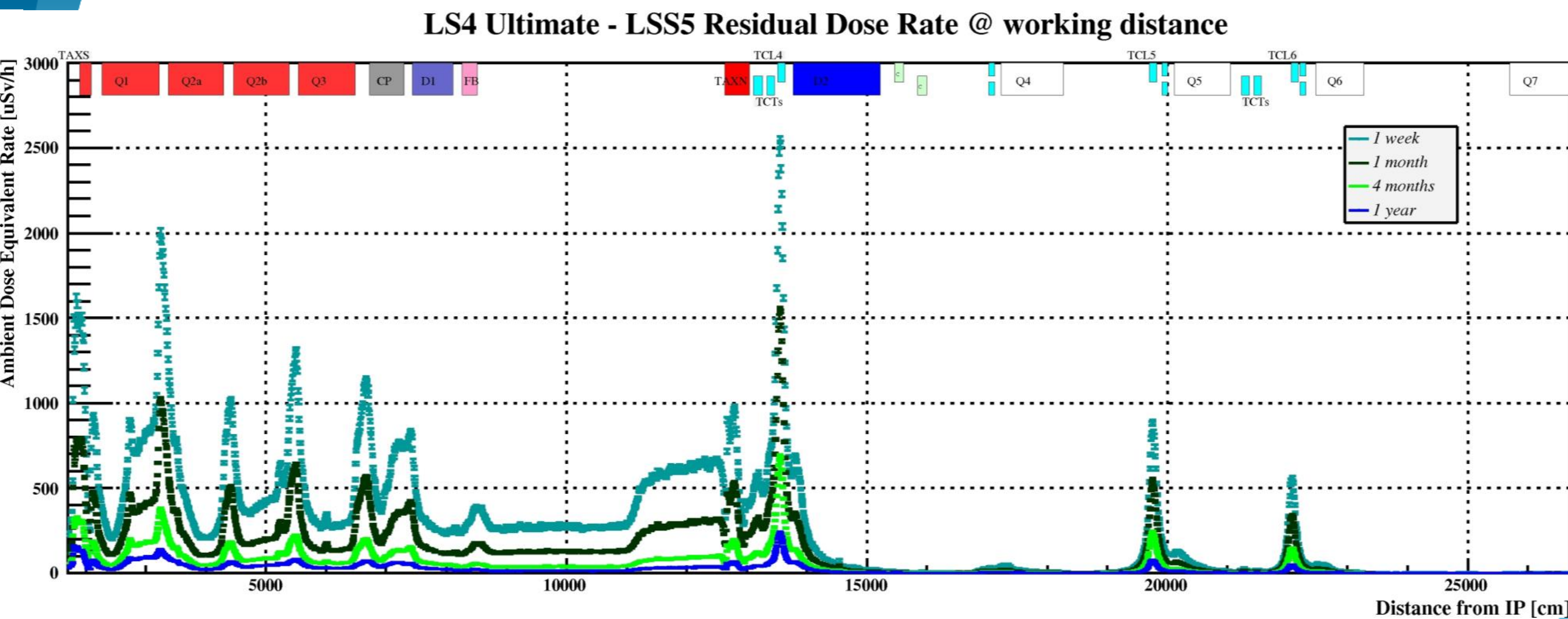
- + 16 new DN100 sector valves.
- + 32 new vacuum modules to built the staggered sector valve assembly.
- + 16 support for the sector valve assemblies to be built.

- Total cost for LSS1 & LSS5 to be added to WP12 CtC: + 1.7 MCHF

Initially proposed correction of the baseline plug-in and alignment by wire

Technically discussed and favorably received in the HL-TCC.
HL-ECR under preparation

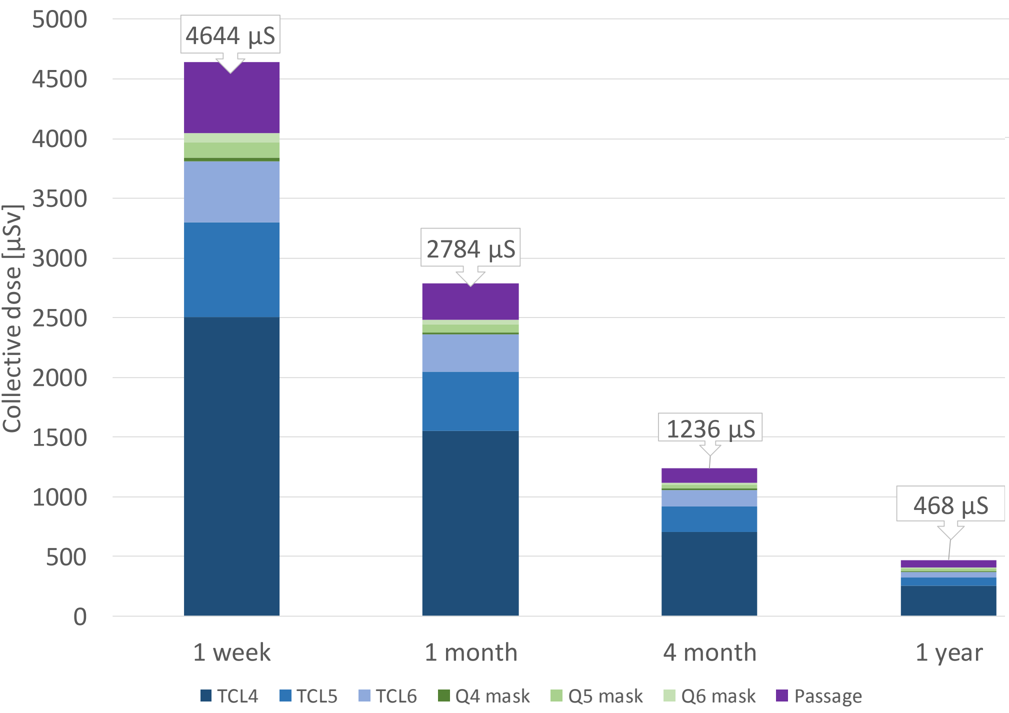
Residual dose rates

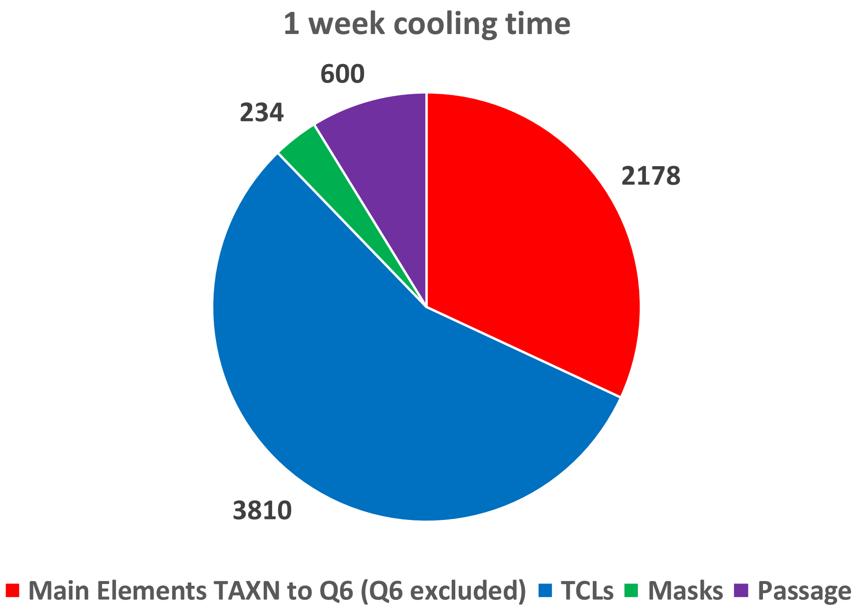


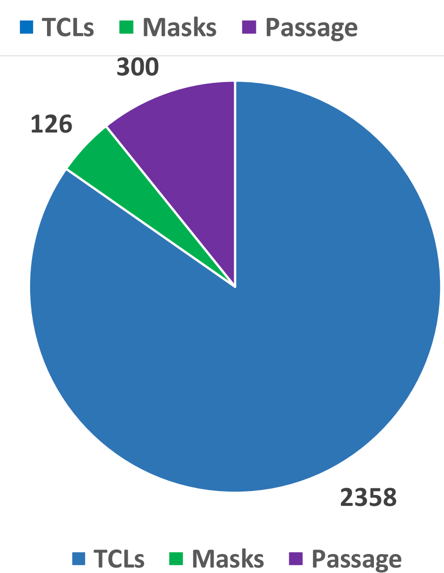
Cooling time	Dose at LS6/ dose at LS4
1 hour	1.02
1 day	1.03
1 week	1.06
1 month	1.09
4 months	1.18
1 year	1.29

Cooling time	Nominal/ Ultimate
1 hour	67 %
1 day	68 %
1 week	75 %
1 month	77 %
4 months	81 %
1 year	82 %

Collective dose for 1 IP (L+R) MS realignment from TAXN to Q6 (Q6 excluded)





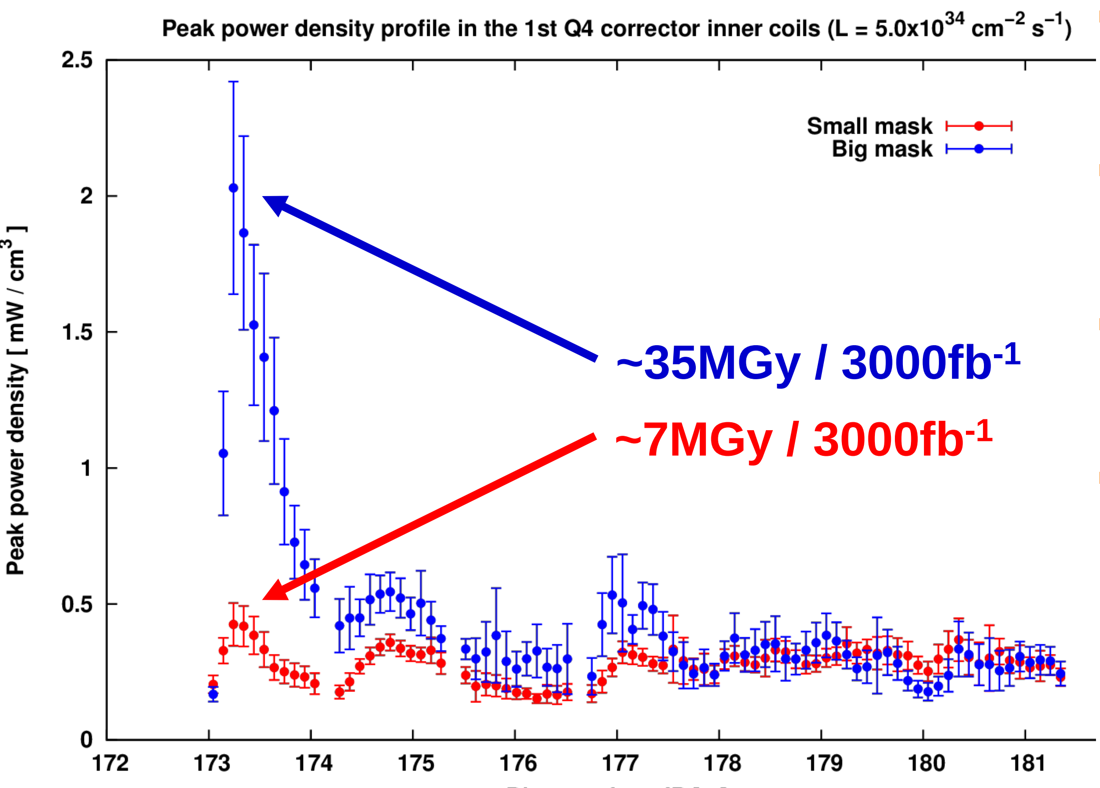


- LS4 Ultimate scenario
- Work plan
  - 2 hours from D1 to Q6
  - 10 minutes next to each element 2 worker: 1 in the aisle, 1 next to the element
  - 3 interventions needed (Vertical + Horizontal measurement and then +alignment)

- Nominal scenario: ~ 30% less
- After 1 day cooling: factor 3 higher
- LS6 vs LS4:
  - up to 30% more for long cooling time
  - few % more for short cooling time

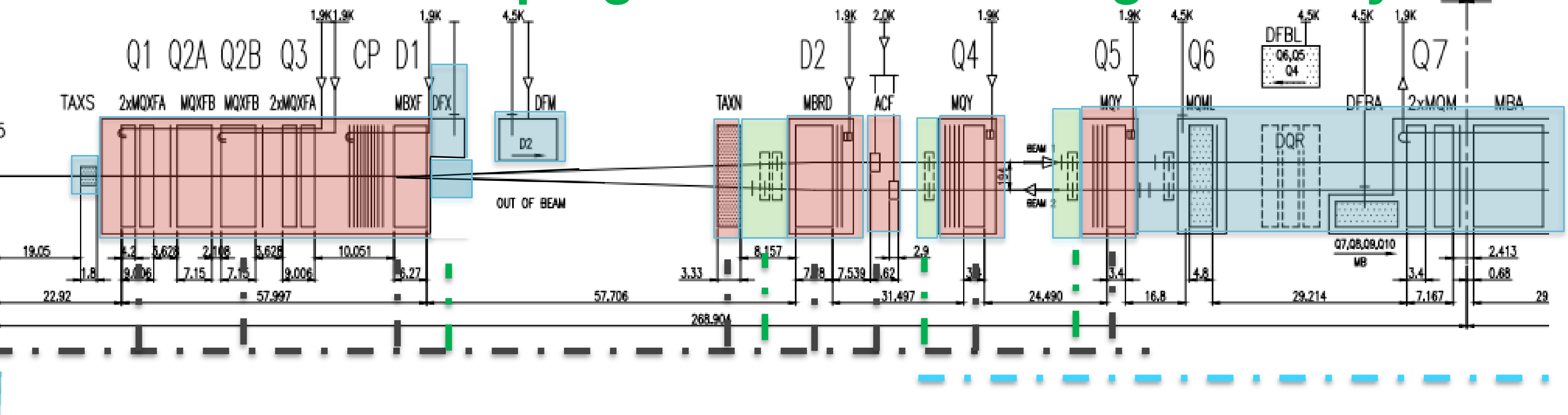
The masks in front of Q4, Q5, Q6

- Can we avoid re-aligning them?
  - Option 1: we keep the present design aperture and we leave where they are also if we move surrounding elements: not acceptable because it creates an aperture restriction
  - Option 2: we enlarge the aperture in order to provide more space to the beam. Would they be still effective? Example with 2 mm increase in radial aperture in front of Q4



- Significant increase on the IP-face of the first Q4 corrector (MCBY, not the most rad-hard magnet we have)
- Max. value of $2 mW/cm^3$ still within operational limits, while the impact on the total heat load is small
- **However, the local increase in the accumulated dose becomes a limiting factor**
- In Q5 (which already benefits from the presence of TCL5), the aperture change moves the dose peak from the horizontal plane to the vertical, but without leading to worrying values

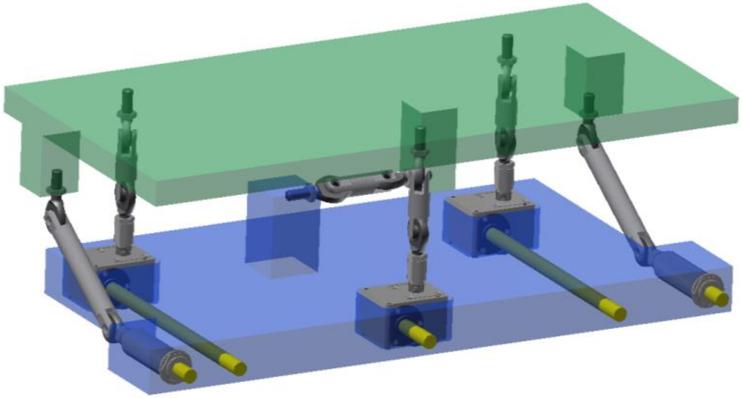
IP1 and IP5 HL-LHC
Synoptic of adjustment system
PROPOSAL with plug-in motors and alignment by wire



- Motorized adjustment system, <u>remotely controlled from CCC</u> : adjustment during run
- Manual adjustment system: adjustment during LS or YETS, personnel in the tunnel, access in front of element (special for TAXS)
- Tele-alignment: motorized adjustment system, <u>controls by wire (10 m), not resident control unit nor motors</u>: adjustment during TS, personnel in the tunnel, access near element

Proposed approach for the intermediary elements: Use a standardized platform for alignment by wire

- Keep the same design for all the adjustment supports, with an easy access to the adjustment knobs on the transport side
- All mechanical design proposed by WP15.4, to be integrated by the designer in charge of the equipment support.
- Plug-in controls in fixed motors and sensors providing tele-alignment by wire

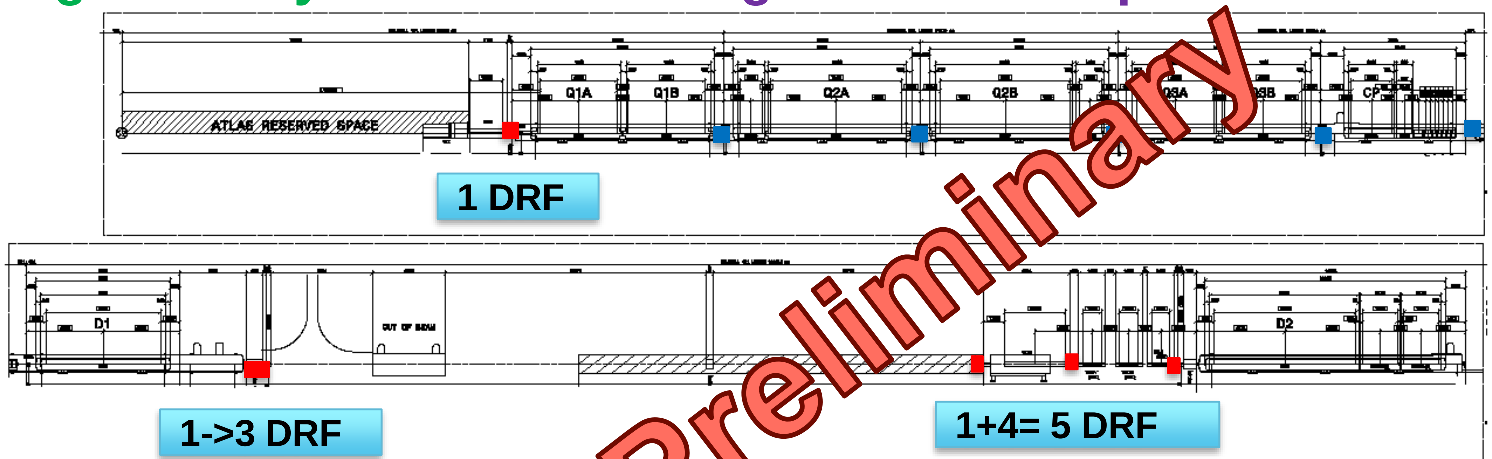


Cost increase alignment by wire vs baseline

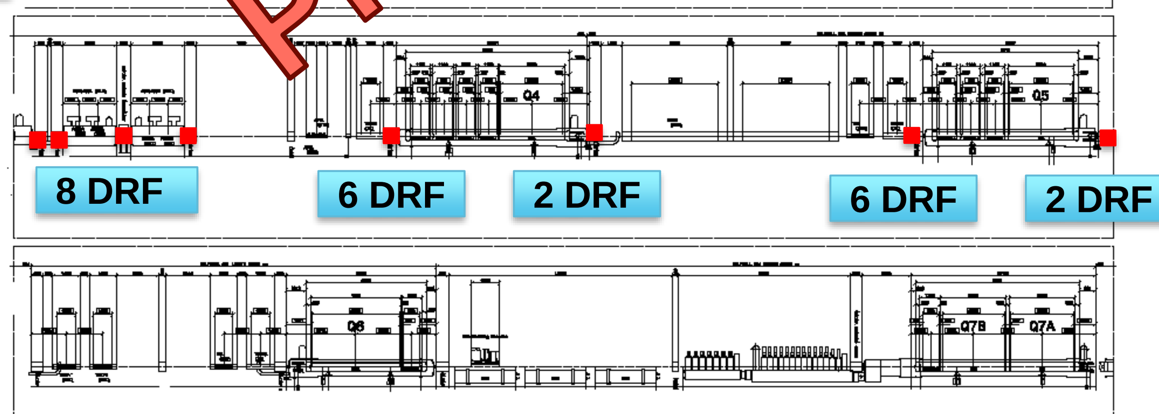
	Nb of items per IP side / total number	Platforms	Sensors	Motors	Total cost
Magnet Masks	2 / 8	40 kCHF	240 kCHF		280 kCHF
Warm BPM	3 BPM per side 2 groups to survey Total 8		240 kCHF		240kCHF
Collimators	4/16	80 kCHF	480 kCHF		560 kCHF
Targets of all intermediary components					70 kCHF
Control units and plug- in motors					120 kCHF
Total					1270 kCHF

Preliminary deformable RF bridge (DRF) location for LSS5R

alignment by wire / remote alignment assumptions



- DFR only for IT according to present WP12 present budget
- New room temperature DFR due to be compliant with alignment by wire and fully remote



WP15: LHCLSXH_0010 V1.3 - 22/03/2017

The total impact to allow ± 2.5 mm with the tele-alignment by wire / remote alignment option is to built:

+ 132 deformable RF bridge (+20 for the triplet already included in CtC). So, a total of 152 of deformable RF bridge around the ring.

- + 16 new DN100 sector valves.
- + 28 new vacuum modules to built the staggered sector valve assembly.
- + 16 support for the sector valve assemblies to be built.

- Total cost for LSS1 & LSS5 to be added to WP12 CtC: + 2 MCHF.

Possible alignment strategies with baseline +tele-alignment by wire

	Scheme 1: During operation	Scheme 2 During TS Up to 2.5 mm	Scheme 3 During TS Larger then 2.5 mm	Scheme 4 During YETS	Scheme 5: During LS
Machine conditions	Machine operating conditions	Machine operating conditions	Magnet cold but empty during movement	Magnet cold but empty during movement	warm
Max stroke	+/- 2.5 mm	+/- 2.5 mm	+/- 10 mm	+/- 10 mm	more
Time required per IP side Q1 to D1	30 min No access	30 min No access	30 min No access	30 min No access	
Time required per IP	Not possible	0.5(L)+0.5(R) days	2(L)+2(R) days Access for	2(L)+2(R) days Access for	

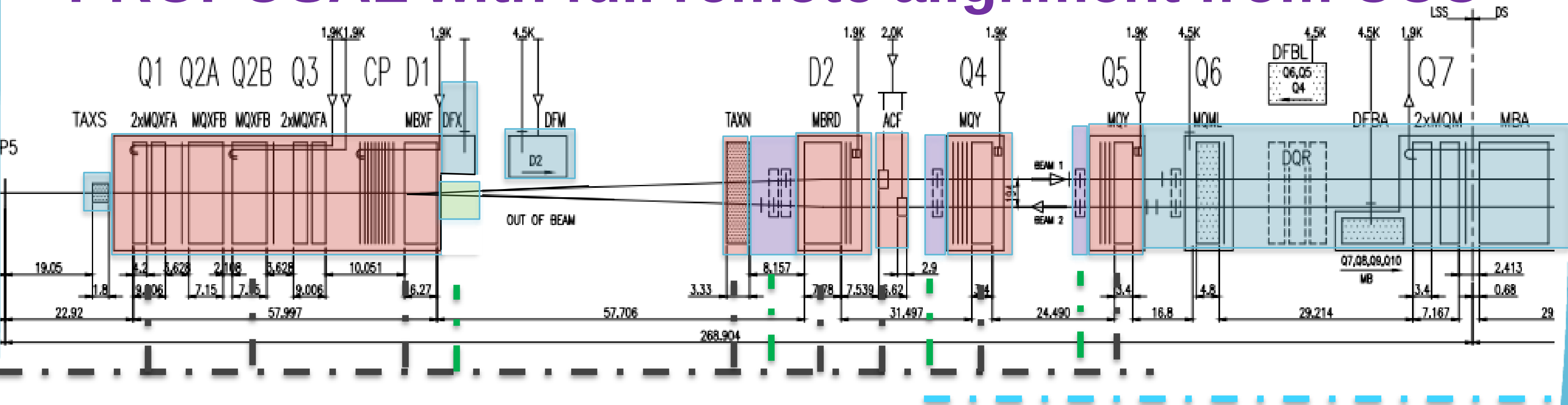
After LSx and after YETS

Case 1: the misalignment machine vs experimental IP is less than 2.5 mm:
Case1 A: we **can** correct acting only on the IT:
apply Scheme 1 and then run till YETS where we redo full alignment
Case1 B:we **cannot** correct acting only on the IT:
apply Scheme 2 (quicker than the previous scenario)

Case 2: error larger, to compensate for exceeding error we wait the TS and we apply where necessary Scheme 3.
After LS2 it will be easier because no activation yet

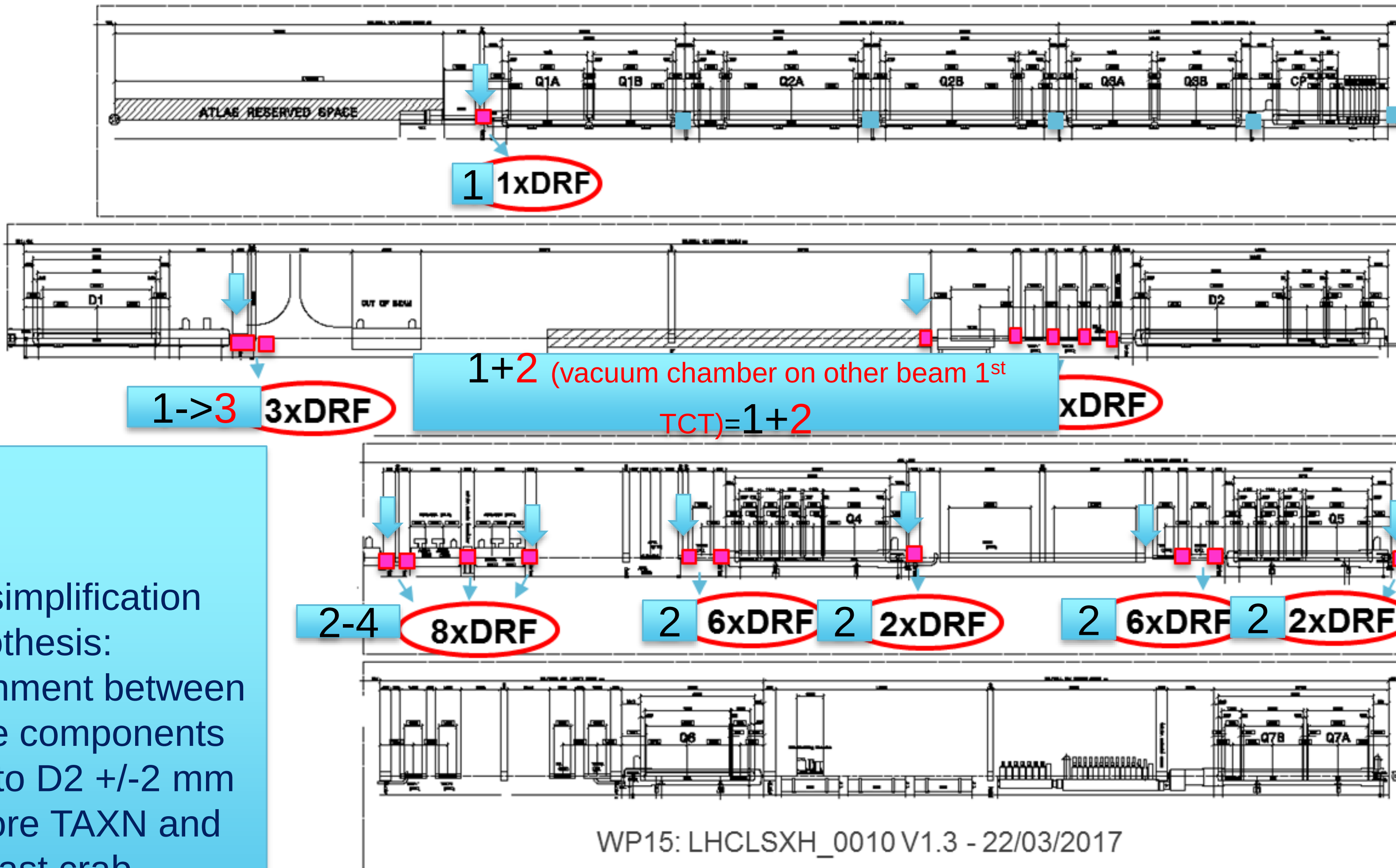
The fully remoted option with operational benefits

IP1 and IP5 HL-LHC
Synoptic of adjustment system
PROPOSAL with full remote alignment from CCC



- Motorized adjustment system, <u>remotely controlled from CCC</u> : adjustment during run
- Manual adjustment system: adjustment during LS or YETS, personnel in the tunnel, access in front of element (special for TAXS)
- Motorized adjustment system, <u>remotely controlled from CCC</u> : adjustment during run to vhange

Preliminary deformable RF bridge (DRF) location for LSS5R
Improved baseline with remote alignment



Possible simplification hypothesis:
Max misalignment between consecutive components from TAXN to D2 +/-2 mm
Larger before TAXN and after last crab

Cost increase remote alignment vs baseline

	Nb of items per IP side / total number	Platforms	Sensors	Motors	Total cost
Magnet Masks	2 / 8	40 kCHF	240 kCHF	320 kCHF	600 kCHF
Warm BPM	3 BPM per side 2 groups to survey Total 8		240 kCHF		240 kCHF
Collimators	4/16	80 kCHF	480 kCHF	640 kCHF	1200 kCHF
Targets of all intermediary components					70 kCHF
Cabling					240 kCHF
Total					2350 kCHF

Possible alignment strategies with fully remote alignment

	Scheme 1: During operation	…heme 2 …ring TS …to 2.5	Scheme 3 During TS Larger then 2.5 mm	Scheme 4 During YETS	Scheme 5: During LS
Machine conditions	Machine operating conditions	M…hine o…ating co…tion	Magnet cold but empty during movement	Magnet cold but empty during movement	warm
Max stroke	+/- 2.5 mm	+/-…5 m	+/- 10 mm	+/- 10 mm	more
Time required per IP side Q1 to D1	30 min No access	30 No	30 min No access	30 min No access	
Time required…	30 min…	30 m…	2(L)+2(R) days… TS2 realign	2(L)+2(R) days…	
	NA	[illegible]	CD: >?? mSv	CD: <0.5 mSv	CD:<0.2 mSv

After LSx and after YETS

Case 1: the misalignment machine vs experimental IP is less than 2.5 mm:
We can correct on-line and recover later the full 2.5 mm stroke at the YETS.
Realign in the YETS according to last beam measurement before end of operation and re-correct residual on line after 1st beam.
Incremental corrections possible through the full year

Case 2: error larger we wait the for TS and we apply where necessary Scheme 3.
After LS3 it will be easier because no activation yet

Conclusions

- The present baseline requires corrections in order to fulfill the initially set scope as for various reasons could not account for activation studies when it was developed and it was also impacted by the august 2016 re-baseline (masks in front of Q4). The proposed modifications
  - Connection to the reference systems (vertical and horizontal) of the intermediary components
  - Tele-alignment by wire of the intermediary components

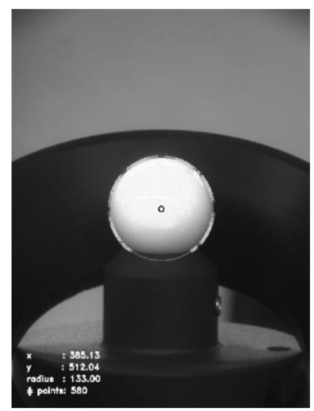
  would allow to provide a coherent solution for a cost increase of 1.27 MCHF in WP15.4 (1.7 MCHF increase in WP12 necessary to be compliant with TDR0.1)
- We think that the transfer of alignment capabilities from Tele-alignment by wire (from inside the LHC tunnel) to remote alignment (from CCC) would provide meaningful improvement naming
  - Simplification of the magnet system (see presentation of R. De Maria)
  - Decrease of tunnel intervention time of the survey teams and increase of the type of interventions that can be performed from the CCC impacting favorably the time in physics
  - Decrease of cumulative dose to personnel
- The implementation of such proposal would require an extra investment of 0.9 MCHF (0.6 WP15.4 and 0.3 WP12) that is a limited increase respect to the gained functionality
- If this proposal is accepted it will also mark a further step in the integration of the alignment system as an operational tool
- In order to ensure the readiness of such operational tool in addition to all series of tests foreseen on the various elements under development WP15.4 is preparing
  - Extensive test plan simulating operational situation to be performed on the HL string
  - WP15.4 is targeting a technical review in late spring 2019

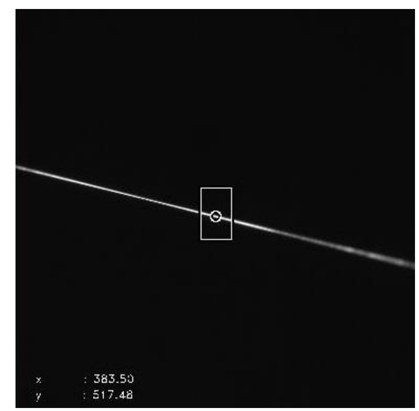
Annexes

Solutions proposed for HL-LHC

- Case of intermediary components (collimators, vacuum equipment, DFX):
  - Remote determination of the position of the components based on permanent stretched wires (location TBC) and different means:
    - Same solution than for LHC point 7 (see next slide), using a stretched wire and photogrammetry
    - For specific components (collimators), install additional WPS sensors
    - Develop a solution based on micro-triangulation + WPS sensors

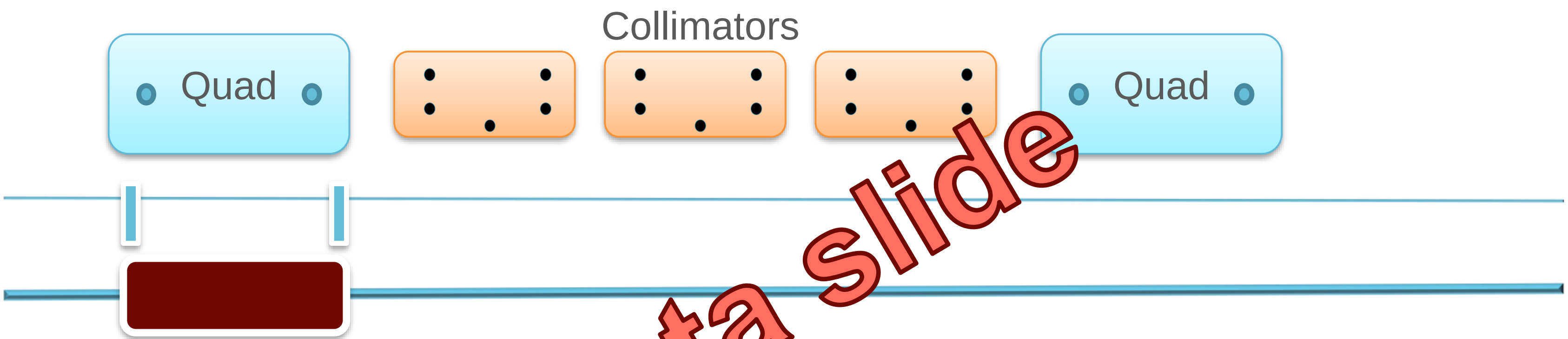


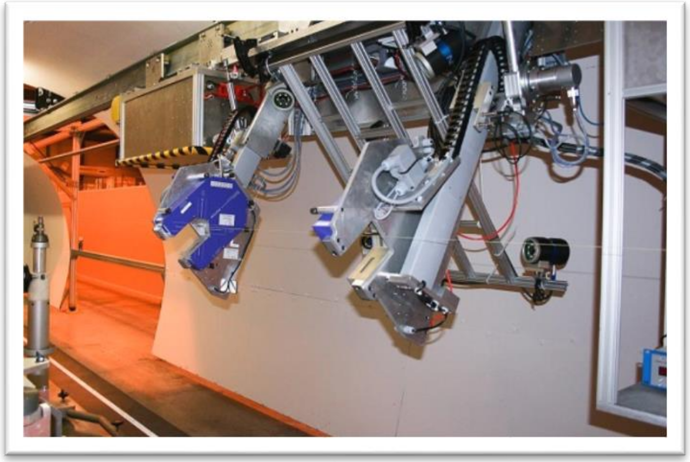




Remote determination of the collimators position in the LHC (point 7) :

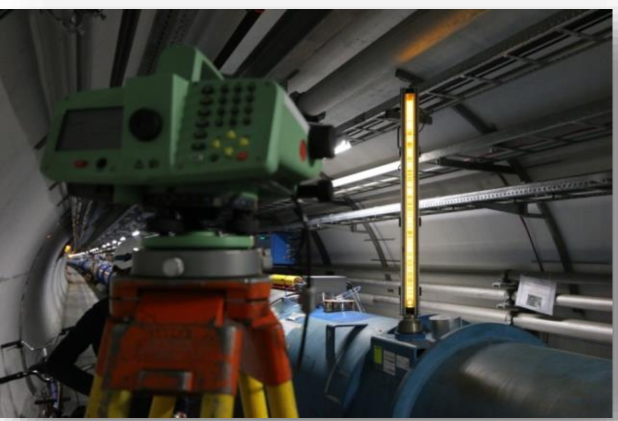
w.r.t the two adjacent quadrupoles: ± 0.2 mm





What was achieved in the LHC

- Some durations (from last EYETS):
  - Radial measurements Q1-Q6: ~ 3 days
  - Vertical measurements Q1-Q6: ~ 1 day
  - Adjustment of one main component: ~ 1 h / component (including a first measurement of its position, its adjustment, the control of the new position)
  - Adjustment of one intermediary component: ~ 2 h / component



Preliminary dose estimations for the alignment

- LS4 Ultimate scenario
- 2 hours from D1 to Q6
- 10 minutes next to each element end (taking into account only part of the work)
- 2 worker: 1 in the aisle, 1 next to the element

- Nominal scenario: ~ 30% less
- LS6 vs LS4:
  - up to 30% more for long cooling time
  - few % more for short cooling time

Preliminary dose estimations for the alignment

Data slide

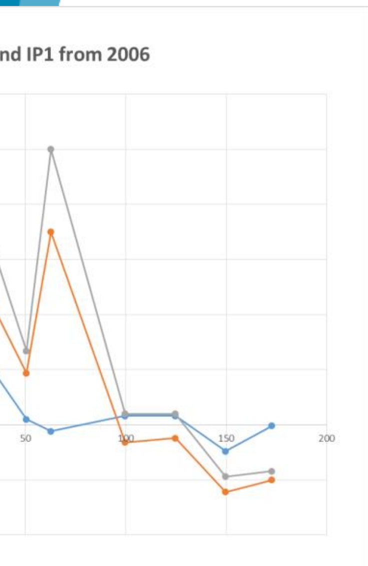
		LSS5 (one side only) residual dose rate (μSv/h)				10 minutes dose (μSv)			
	distance from IP (cm)	1 week	1 month	4 month	1 year	1 week	1 month	4 month	1 year
D1	7442	800	410	140	55	133	68	23	9
	8450	350	150	50	20	58	25	8	3
TAXN	12626	900	450	150	55	150	75	25	9
	13047	400	220	90	30	67	37	15	5
D2	13779	650	350	130	65	108	58	22	11
	15224	15	10	5	5	3	2	1	1
Q4 mask	17075	30	15	10	5	5	3	2	1
Q4	17230	55	25	[illegible]	5	9	4	2	1
	18262	10	[illegible]	5	5	2	1	1	1
Q5 mask	19959	[illegible]	[illegible]	30	15	22	11	5	3
Q5	20115	125	65	25	10	21	11	4	2
	21027	[illegible]	10	5	5	3	2	1	1
Q6 mask	22256	[illegible]	40	20	10	12	7	3	2
Q6	[illegible]	50	30	10	5	8	5	2	1
	[illegible]	10	5	5	5	2	1	1	1
[illegible]	[illegible]	2500	1550	700	250	417	258	117	42
[illegible]	19705	800	500	215	70	133	83	36	12
TCL6	22062	510	310	140	50	85	52	23	8
						1238	**702**	**290**	**111**
						2 hours (μSv)			
aisle	-	50	25	10	5	**100**	**50**	**20**	**10**
Collective Dose (man.μSv)						**1338**	**752**	**310**	**121**

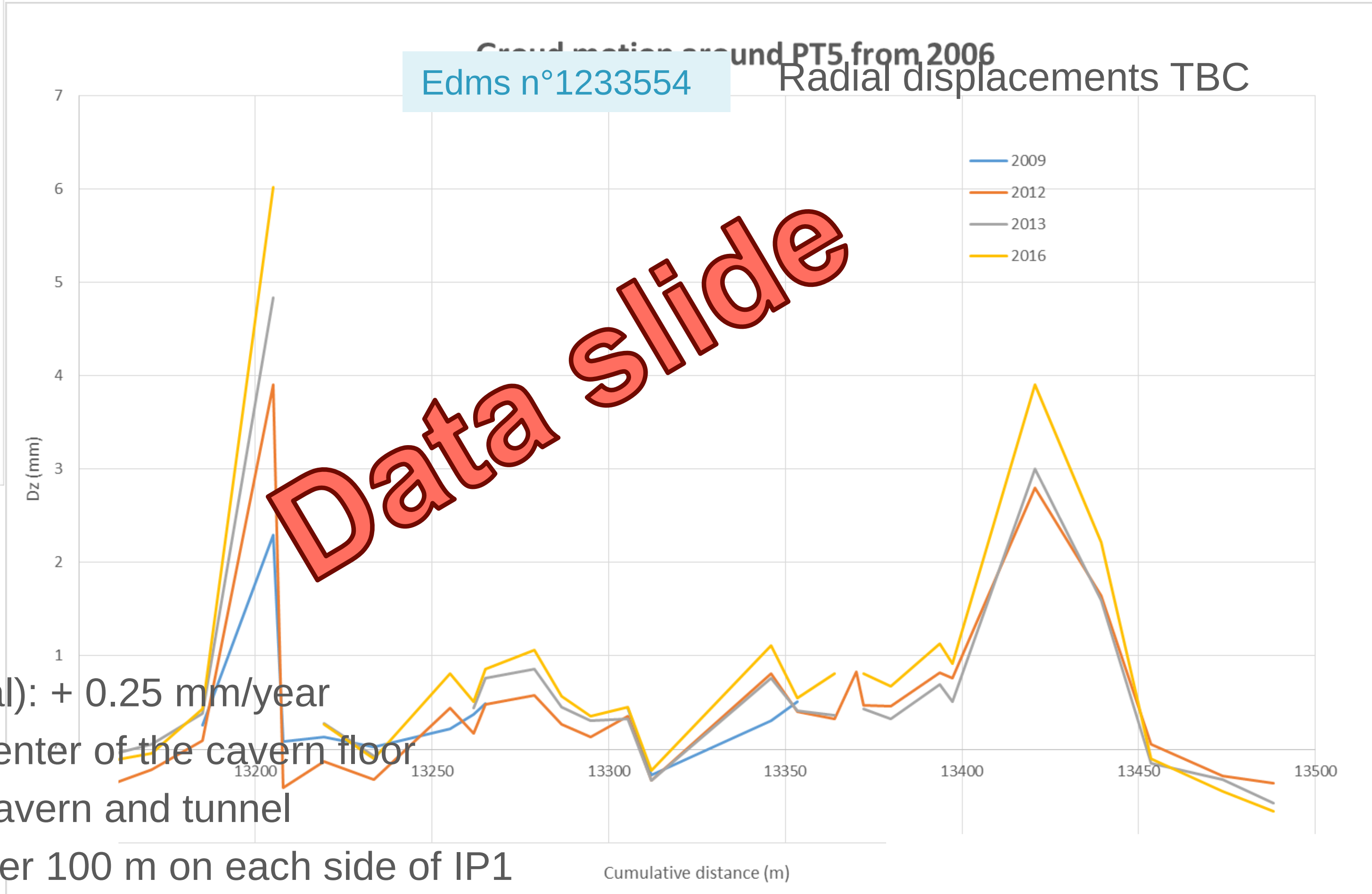
Environmental conditions

Edms n°1233554

Radial displacements TBC

Data slide





Point 1 (vertical): + 0.25 mm/year

- Near the center of the cavern floor
- Between cavern and tunnel

Stable area after 100 m on each side of IP1

Point 5 (vertical): ground motion observed at the level of the new UJ caverns:

80m-130 m on each side of IP5