Impact of mechanical and magnetic measurements on performance

R. De Maria

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Contents

Mechanical and magnetic measurements have an impact on the correction and the optimization of

- Orbit
- Optics
- Coupling
- Dynamic aperture

1) Insufficient corrections of the mentioned observables can prevent or several limit high luminosity operations!
2) Large corrections require time and iterations that reduce the number physics days.

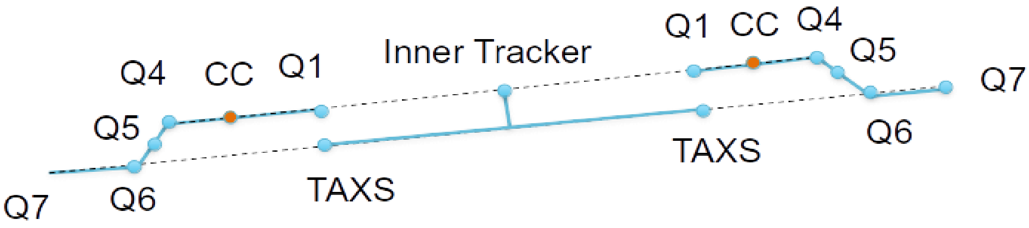
Orbit correction strategy

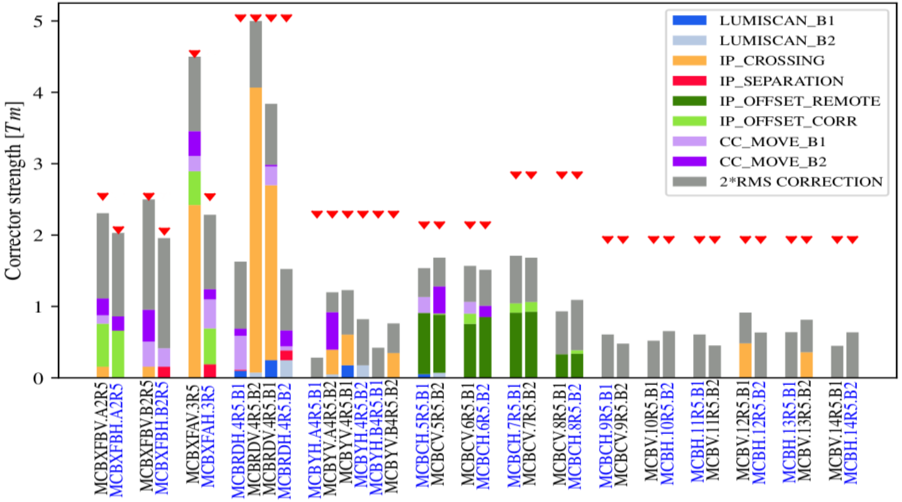
The presence of three strict orbit constraints in ATLAS and CMS (IP and crab cavities at <0.5 mm) requires

- < 0.5 mm alignment of the quadrupole magnetic axis (e.g .~1 mm orbit offset equivalent to ~2 Tm orbit corrector)
- An additional budget of 0.5 mm offset in the CC is given at the cost of a static slope in the cavities.

Essential to keep sufficient alignment range after construction (e.g. deformable RF bridges in between triplets have a range >2.5 mm, other bellows should allow similar margins.)

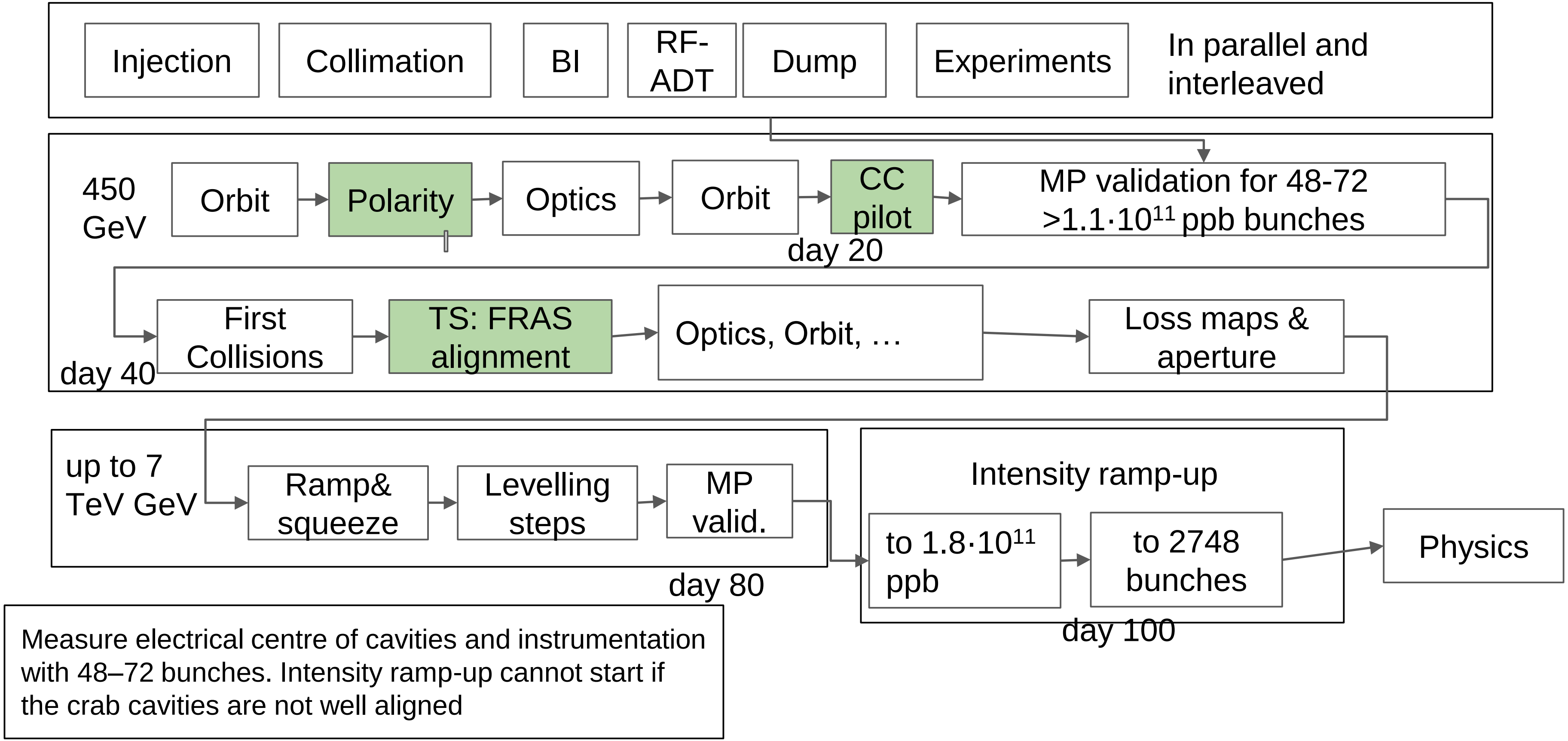
Ideally, imperfections before the first beam should be dominated by uncertainty (0.4 mm currently estimated at 3 σ) and not deviations.





Orbit correctors can only cope with <0.5 mm orbit imperfections!

Beam commissioning: main steps in the first year



Injection

Collimation

BI

RF-ADT

Dump

Experiments

In parallel and interleaved

450 GeV

Orbit

Polarity

Optics

Orbit

CC pilot

MP validation for 48-72 $>1.1\cdot10^{11}$ ppb bunches

day 20

First Collisions

TS: FRAS alignment

Optics, Orbit, …

Loss maps & aperture

day 40

up to 7 TeV GeV

Ramp& squeeze

Levelling steps

MP valid.

day 80

Intensity ramp-up

to $1.8\cdot10^{11}$ ppb

to 2748 bunches

day 100

Physics

Measure electrical centre of cavities and instrumentation with 48–72 bunches. Intensity ramp-up cannot start if the crab cavities are not well aligned

Orbit correction: potential scenarios

Nominal Scenario

Construction absorbs measured deviation from nominal alignment.

The machine is moderately well aligned at first beam, and fine tune corrections during collisions allow bringing the orbit correctors within established margins.

The commissioning time is scales with initial misalignments:

- If orbit correctors are sufficient: 1-2 days needed to establish orbit
- If also FRAS is needed for correction orbit: 1 week overhead
  - Crab cavity center needs few nominal bunches
  - A re-alignment would retrigger a revalidation cycle of loss maps

Non-conform scenario

If realignment does not bring the magnetic field axis to specs (e.g. beyond alignment range), there are increased chances of

- driving to the limits the orbit corrector strengths
  - For MCBXF, this leads to an increase of uncorrelated powering: less current margin and bad field quality, lower beam energy
- Exceed orbit tolerances at crab cavities:
  - Lower voltage, detuning, low beam current

If one of these conditions is realized, the machine is unrecoverable and requires heavy hardware intervention to realign.

Fiducialization and magnetic measurements are then mandatory for operation.
String test should be used to implement the "best knowledge" construction.

Optics correction strategy

Context

Optics (aka beta-beating) correction, that is control of beam sizes, betatron phase advances, dispersion in the ring is mandatory at many locations of the machine.

Although design optics constraints could be matched to any layout relatively close to the nominal, the correction strategy hinges on using a model as close to reality as possible such that the corrections converge quickly to the nominal model:

- Contrary to orbit, optics response is non-linear in gradients and requires ~5-10 iterations to converge.
- Optics measures and corrections are not time efficient and noisy, typically requiring 30 min per measurement/correction strategy.
- Specifically at the interaction points, the beam size at the IP is key to achieve high luminosity, but cannot be measured directly (optics can be measured only at BPMs and Quads).
- Specifically in Point 1 and 5 at low-beta*, the sensitivity to the model imperfections will be a factor 5 larger than what Run 3 experienced!

Optics correction strategy

Accurate magnetic modelling:

- 5 mm longitudinal accuracy of magnetic and BPM centers
- good modelling of gradient fall down in the fringe region
- good orbit correction and non-linear correctors to limit feed-down effects.
- ~10 units transfer function uncertainty for the quadrupoles.

Contrary to today practice, we plan to use the best knowledge optics model.

Significant development foreseen to take place in the following years.

Non conform scenarios

Uncorrected beta* results in lower luminosity virtual luminosity.

Coupling and DA optimization

Coupling is mostly generated by rolls in the magnetic axis:

- can degrade luminosity at the IP (up to factor 2 seen in ALICE 2018)
- reduces dynamic aperture (DA) and induces instabilities.

Dynamic aperture is reduced by residual fields imperfections (after corrections)

Low dynamic aperture is responsible for:

- High losses at collapse preventing high intensity operations.
- Low beam lifetime reducing integrated luminosity.

Impact on performance

Correcting non-linear imperfection is increasingly time-consuming depending on the order.

Overhead for measurements and correction can take up to weeks.

Performance degradation not easy to estimates because it depends on many conditions:

- A DA reduction at the end of levelling can be addressed by increasing beta*. The impact may be ~1-3% in ideal condition to 10% in degraded condition.
- A DA reduction at the collpase, can lead to high losses. Mitigation could be increasing beta* and reduced bunch population. Crossing angle is limited by orbit corrector strengths and cannot be used as mitigation. The impact could more on ~10%.

References and workflow

We are aiming at building “best knowledge” optics models.

We need a streamlined workflow that allows to transfer alignment and magnetic measurements into optics models.

There is time for it, but it will be more time efficient if we start right away.

Steps:

- Define and agree on references: action WP3/WP15.
- Define and agree on where to store data: action WP3/WP15.
- Collect data and build optics model: actions WP2.

Conclusion

Installation, without considering magnetic measurements, may lead to a machine that cannot be corrected and thus not compatible with high-luminosity operations.

We should make sure that what the triplets region can be corrected.

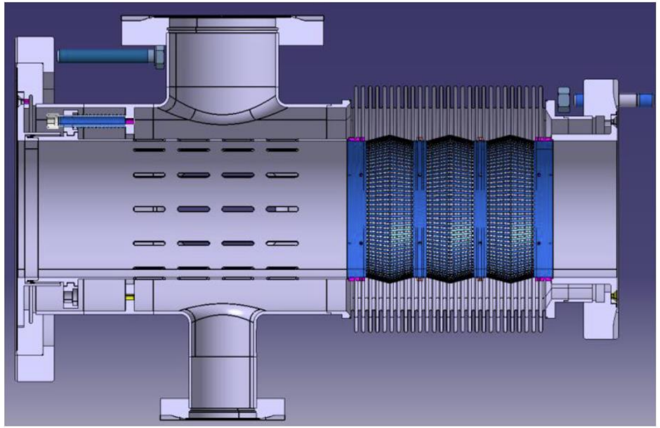
A good starting magnetic and alignment model reduces drastically the time for commissioning, increasing integrated luminosity.

A good corrected orbit, optimizes dynamic aperture (e.g. MCBX field quality and feeddowns).

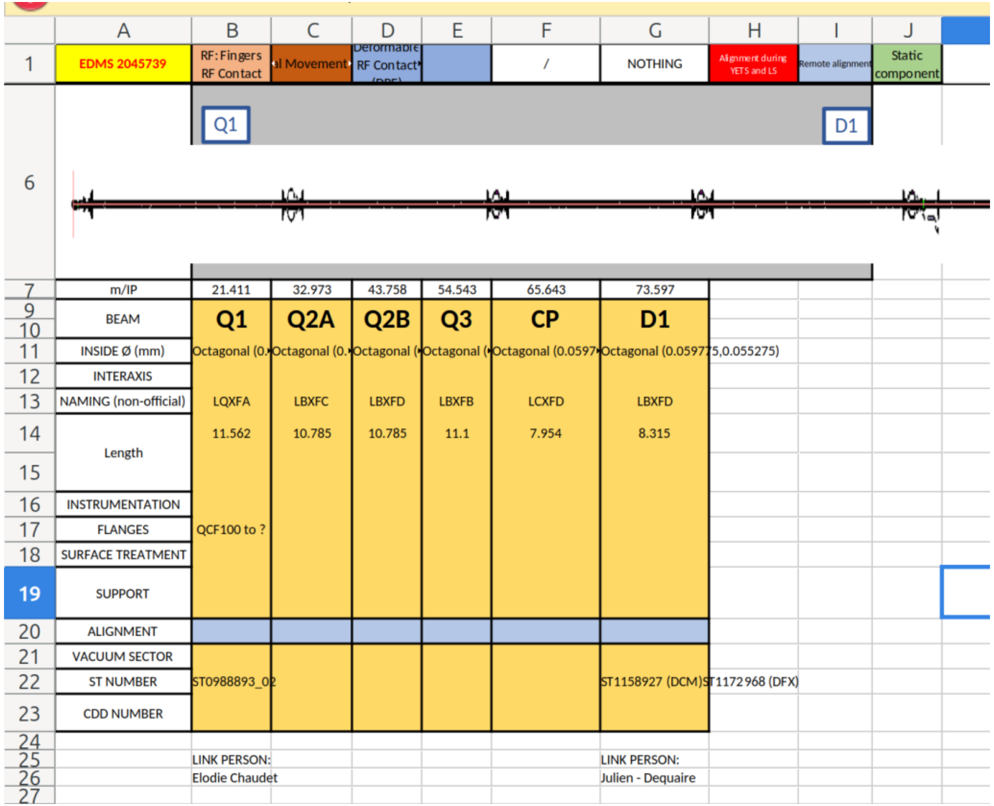
Backup

DRF

DRF



Axial stroke ± 20 mm
Radial offset in free length ± 5 mm
Radial offset in max compression ± 2.5 mm
Maximum torsion: 1 mrad



	A	B	C	D	E	F	G	H	I	J
1	EDMS 2045739	RF: Fingers RF Contact	al Movement	Deformable RF Contact		/	NOTHING	Alignment during YETS and LS	Remote alignment	Static component
6		Q1							D1	
7	m/IP	21.411	32.973	43.758	54.543	65.643	73.597			
9 10	BEAM	Q1	Q2A	Q2B	Q3	CP	D1			
11	INSIDE Ø (mm)	Octagonal (0.	Octagonal (0.	Octagonal (	Octagonal (	Octagonal (0.0597	Octagonal (0.059775,0.055275)			
12	INTERAXIS									
13	NAMING (non-official)	LQXFA	LBXFC	LBXFD	LBXFB	LCXFD	LBXFD			
14 15	Length	11.562	10.785	10.785	11.1	7.954	8.315			
16	INSTRUMENTATION									
17	FLANGES	QCF100 to ?								
18	SURFACE TREATMENT									
19	SUPPORT									
20	ALIGNMENT									
21	VACUUM SECTOR									
22	ST NUMBER	ST0988893_02					ST1158927 (DCM)ST1172968 (DFX)			
23	CDD NUMBER									
24										
25		LINK PERSON:					LINK PERSON:			
26		Elodie Chaudet					Julien - Dequaire			
27										

Present alignment uncertainties

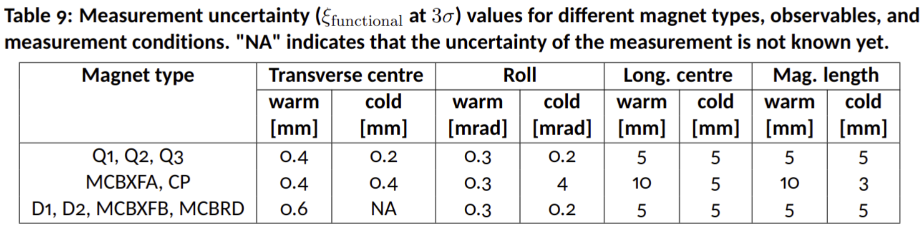


Table 9: Measurement uncertainty ($\xi_{\text{functional}}$ at 3σ) values for different magnet types, observables, and measurement conditions. "NA" indicates that the uncertainty of the measurement is not known yet.

Magnet type	Transverse centre		Roll		Long. centre		Mag. length	
	warm [mm]	cold [mm]	warm [mrad]	cold [mrad]	warm [mm]	cold [mm]	warm [mm]	cold [mm]
Q1, Q2, Q3	0.4	0.2	0.3	0.2	5	5	5	5
MCBXFA, CP	0.4	0.4	0.3	4	10	5	10	3
D1, D2, MCBXFB, MCBRD	0.6	NA	0.3	0.2	5	5	5	5

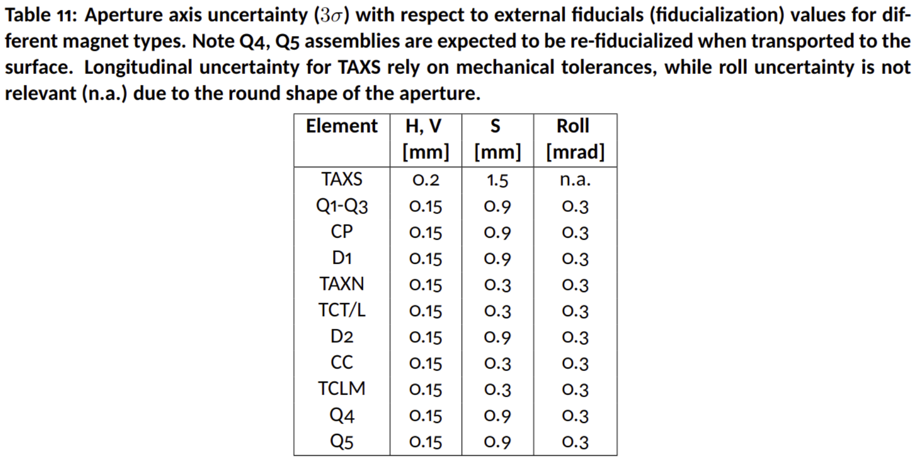


Table 11: Aperture axis uncertainty (3σ) with respect to external fiducials (fiducialization) values for different magnet types. Note Q4, Q5 assemblies are expected to be re-fiducialized when transported to the surface. Longitudinal uncertainty for TAXS rely on mechanical tolerances, while roll uncertainty is not relevant (n.a.) due to the round shape of the aperture.

Element	H, V [mm]	S [mm]	Roll [mrad]
TAXS	0.2	1.5	n.a.
Q1-Q3	0.15	0.9	0.3
CP	0.15	0.9	0.3
D1	0.15	0.9	0.3
TAXN	0.15	0.3	0.3
TCT/L	0.15	0.3	0.3
D2	0.15	0.9	0.3
CC	0.15	0.3	0.3
TCLM	0.15	0.3	0.3
Q4	0.15	0.9	0.3
Q5	0.15	0.9	0.3

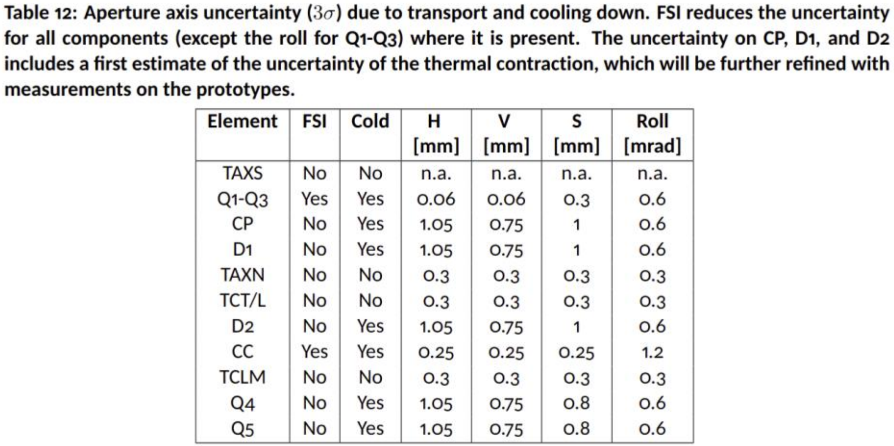


Table 12: Aperture axis uncertainty (3σ) due to transport and cooling down. FSI reduces the uncertainty for all components (except the roll for Q1-Q3) where it is present. The uncertainty on CP, D1, and D2 includes a first estimate of the uncertainty of the thermal contraction, which will be further refined with measurements on the prototypes.

Element	FSI	Cold	H [mm]	V [mm]	S [mm]	Roll [mrad]
TAXS	No	No	n.a.	n.a.	n.a.	n.a.
Q1-Q3	Yes	Yes	0.06	0.06	0.3	0.6
CP	No	Yes	1.05	0.75	1	0.6
D1	No	Yes	1.05	0.75	1	0.6
TAXN	No	No	0.3	0.3	0.3	0.3
TCT/L	No	No	0.3	0.3	0.3	0.3
D2	No	Yes	1.05	0.75	1	0.6
CC	Yes	Yes	0.25	0.25	0.25	1.2
TCLM	No	No	0.3	0.3	0.3	0.3
Q4	No	Yes	1.05	0.75	0.8	0.6
Q5	No	Yes	1.05	0.75	0.8	0.6

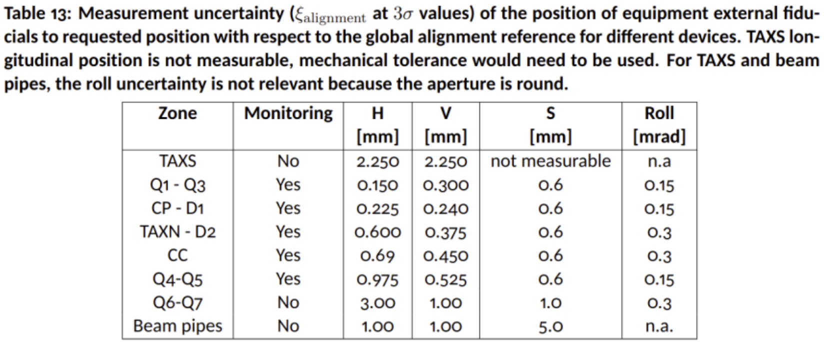


Table 13: Measurement uncertainty ($\xi_{\text{alignment}}$ at 3σ values) of the position of equipment external fiducials to requested position with respect to the global alignment reference for different devices. TAXS longitudinal position is not measurable, mechanical tolerance would need to be used. For TAXS and beam pipes, the roll uncertainty is not relevant because the aperture is round.

Zone	Monitoring	H [mm]	V [mm]	S [mm]	Roll [mrad]
TAXS	No	2.250	2.250	not measurable	n.a
Q1 - Q3	Yes	0.150	0.300	0.6	0.15
CP - D1	Yes	0.225	0.240	0.6	0.15
TAXN - D2	Yes	0.600	0.375	0.6	0.3
CC	Yes	0.69	0.450	0.6	0.3
Q4-Q5	Yes	0.975	0.525	0.6	0.15
Q6-Q7	No	3.00	1.00	1.0	0.3
Beam pipes	No	1.00	1.00	5.0	n.a.

Table 15: Expected difference in ground motion between two neighbouring zones over a year (maximum half range).

Zone A	Zone B	Point 1 H [mm]	Point 1 V [mm]	Point 5 H [mm]	Point 5 V [mm]
Q7-Q4 Left	Q4-D1 Left	0.2	0.3	0.3	0.7
D1-Q1 Left	TAXS Left	0.2	0.3	0.3	0.5
TAXS Left	Inner Tracker	0.2	0.3	0.3	0.5
Inner Tracker	TAXS Right	0.2	0.3	0.3	0.5
TAXS Right	Q1-D1 Right	0.2	0.3	0.3	0.5
Q1-D1 Right	D1-Q4 Right	0.2	0.3	0.3	0.5
D1-Q4 Right	Q4-Q7 Right	0.2	0.3	0.3	0.5

IT string test, noting that the most important parameter for the uncertainties is the movement at is observed at the level of the alignment points. He also agrees with S. Claudet that the mperature variation of ± 4°C is a very conservative assumption for the tunnel.

Fessia says that in SMI2 the WP15.4 team identified the optimal time window for the easurements due to lower temperature variations, which is the early morning in summer pproximately from 4 am to 11 am). In addition, P. Fessia asks if part of the uncertainty will fect the measurements during the magnet fiducialization, and V. Rude confirms. P. Fessia ys that then, even if in the tunnel the temperature variations will be lower, the uncertainty ill be carried over because the fiducialization will happen in worse conditions. He adds that, least, not all the magnets will be cryostated and fiducialized during the summer. V. Rude rees with the considerations of P. Fessia. M. Zerlauth also endorses the conclusions of the xchange.

M. Zerlauth gives the floor to R. De Maria for a complementary slide on the WP2 validation of the alignment (see the slide for the report summary). R. De Maria refers to the figure on slide 16 of V. Rude’s presentation, noting that the bright side of these results is the good level of accuracy of the alignment in the entire triplet area (which impacts most the performance reach), well within the objectives. He adds that the deviations are observed in the area between the TAXN and the Q6, where what matters most are the relative positions, that (as shown by V. Rude) are not affected by the reported uncertainties. M. Zerlauth observes that this is where the Crab Cavities are placed and asks if it could be problematic if they are too much off-centered. R. De Maria says that there is a way to measure the related offset, and the Full Remote Alignment System (FRAS) is also present, enabling the compensation of the uncertainties in the early phases of the commissioning.

R. De Maria concludes by thanking V. Rude and his colleagues for providing such a