Advantages of full remote alignment system for beam dynamics

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  - What we need to align and why
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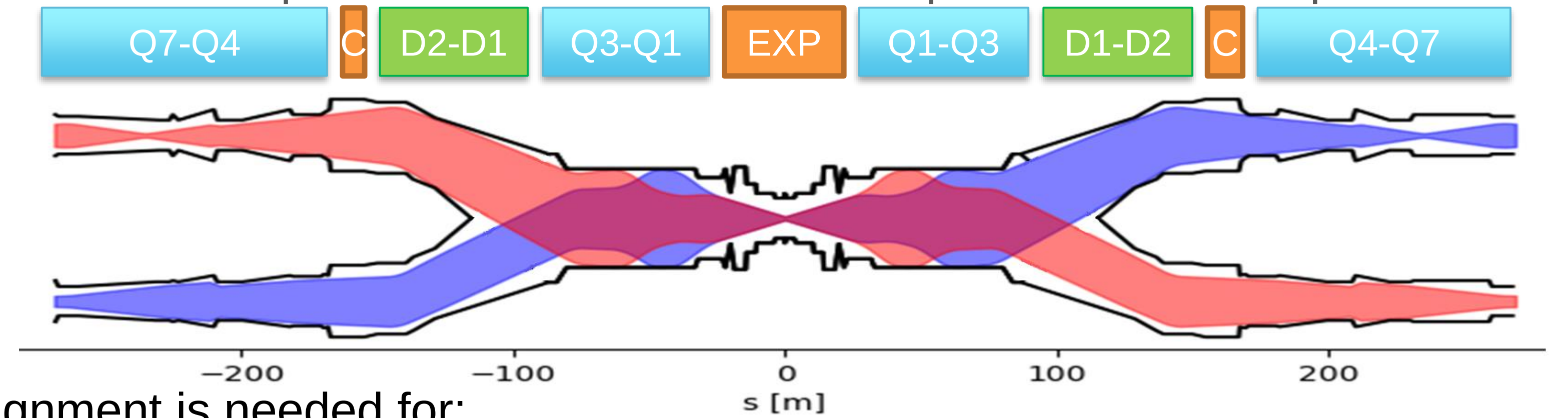
Alignment needs around ATLAS and CMS

HL-LHC simplified lattice and beam envelopes around the experiments



Alignment is needed for:

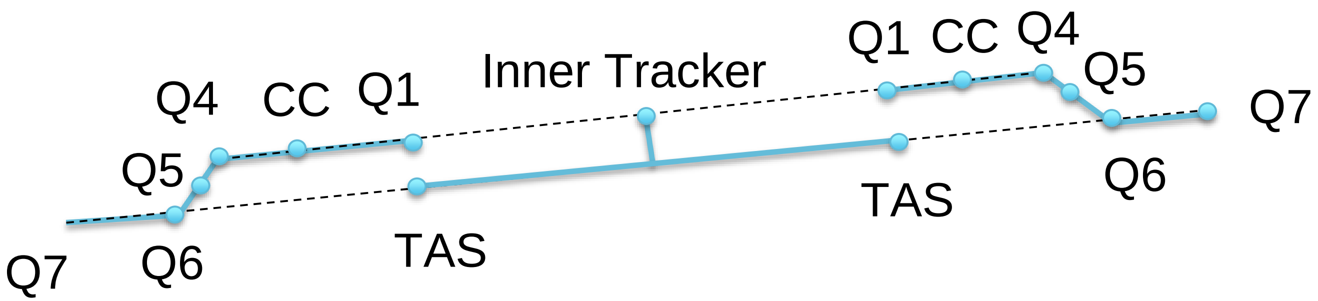
- inner tracker to be transversely aligned to the interaction point (IP) for reducing radiation damage and improve track reconstructions (<1 mm)
- quadrupoles to be transversely aligned to the reference orbit within orbit corrector budget and reduce orbit distortions (<0.5 mm)
- crab cavities to be transversely aligned to the beam orbit to keep RF power within the operational limits (<1 mm)

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

Experiment needs

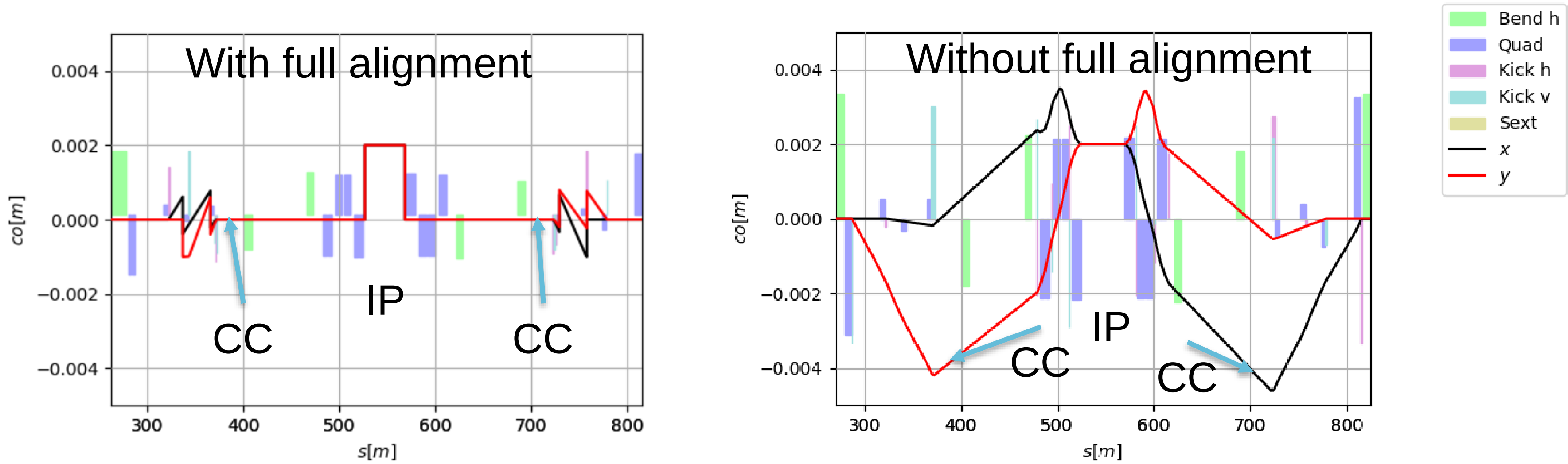
- Experiments (ATLAS and CMS) asked that the machine should be able to adjust the IP within ±2 mm in horizontal and vertical planes <u>during beam commissioning</u>:
  - inner tracker cannot be easily mechanically aligned,
  - the experiments do not expect to control the positioning of the inner tracker 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 (as in the LHC so far), but it costs magnet strength or number of magnets and residual orbit distortions in the triplets and crab cavities (for the HL-LHC)
  - by re-aligning the machine from Q5 left to Q5 right



<u>Present HL-LHC baseline relies on FRAS to realign the IP</u>

IP offset with/without FRA

Residual orbit in the elements with an IP offset of 2 mm in H and V



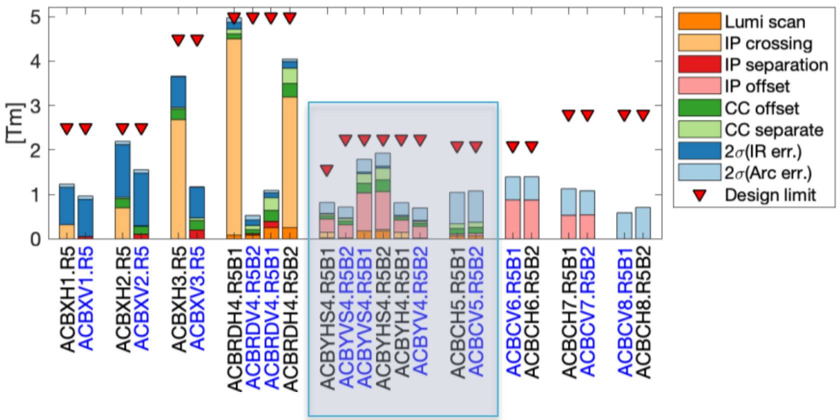
IP offset without full alignment system:

- requires a re-alignment of the crab cavities up to 4 mm
- reduces available aperture for the beam:
  - triplets up to 3 mm
  - Q4-Q5 up to 4.5 mm
  - tertiary collimators up to 3 mm
- costs orbit corrector strength budget

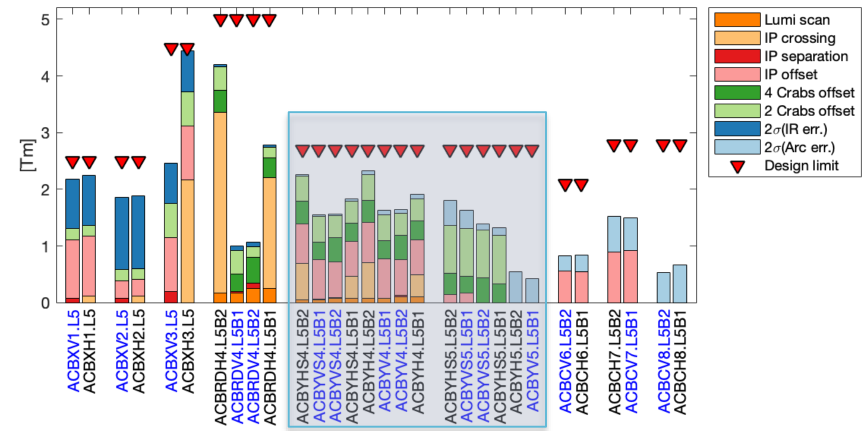
HiLumi HL-LHC PROJECT

Orbit corrector budget with/without FRAS

HL-LHCV1.4 after MS optimization



HL-LHCV1.3 before MS optimization



FRAS allows re-using of LHC orbit correctors and magnet assembly:

Q4: 16x MCBY 1.9K -> 12x MCBY at 4.5K with FRAS

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

Additional potential benefits:

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

After matching section optimization,
IP offset during commissioning not feasible without FRAS

Apertures with FRAS

	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.

<u>Fully remote alignment system allows full β* reach for round and flat optics</u>

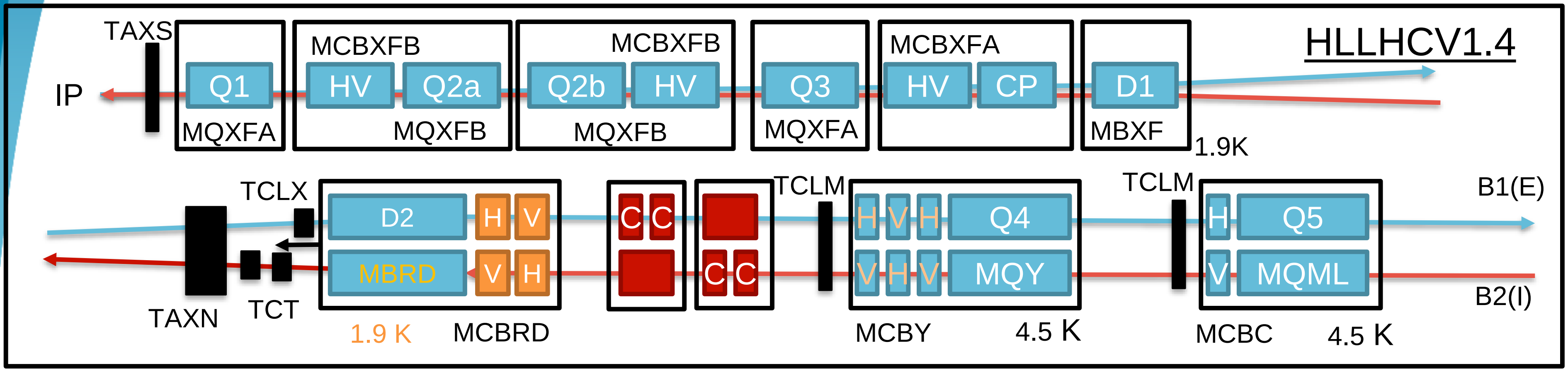
Conclusions

Full remote alignment system is an essential component to reach HL-LHC performance goal:

- It allows to fulfill experiment requirements with better performance
- It allows reusing existing assemblies for Q4 and Q5 with even gain in aperture
- It has the potential of providing better orbit correction and mitigate risks of non-conformities

Backup

Detailed lattice

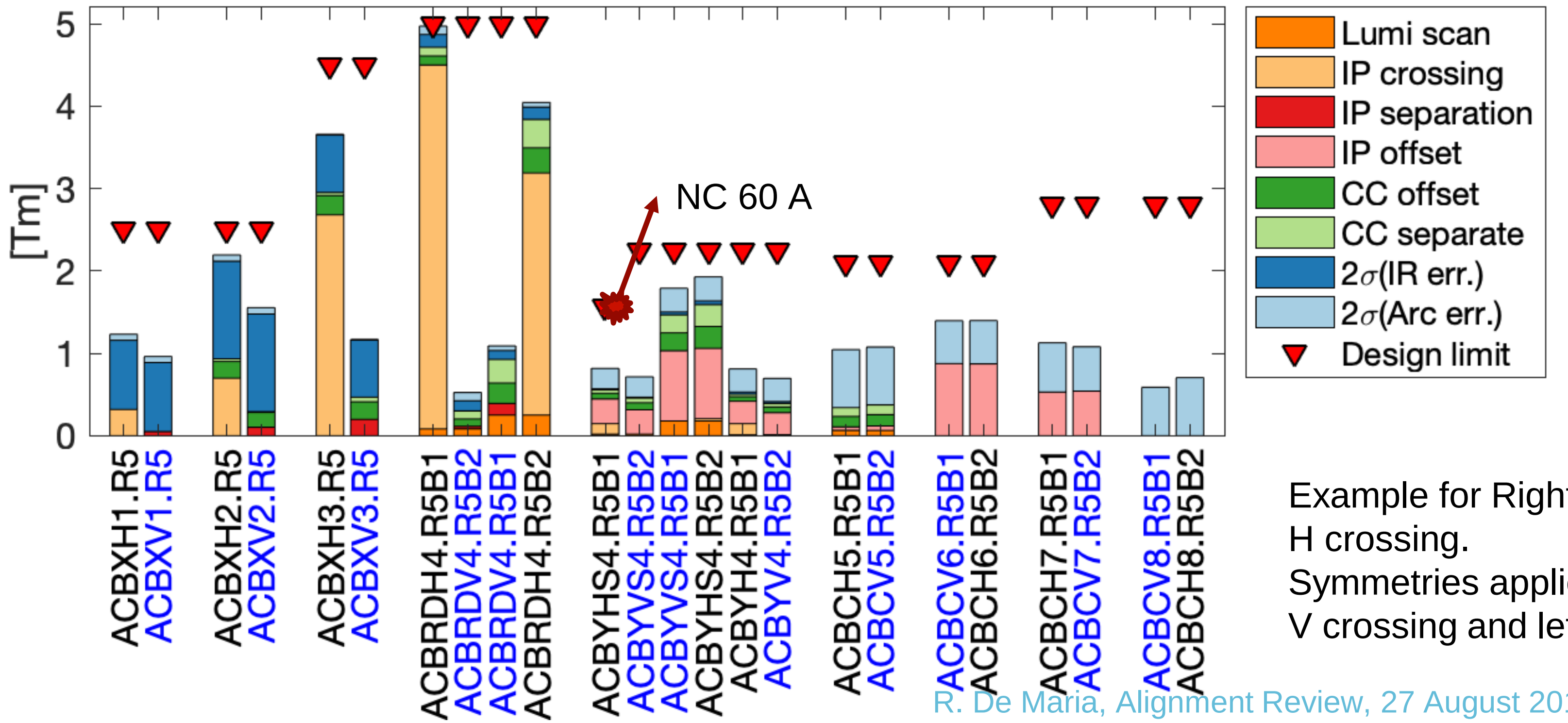


Summary of strengths with remote alignment

Knobs and correction for:

- ±295 μrad crossing angle in H/V plane (H in the figure)
- ±0.75 mm separation in V/H plane (V in the figure)
- ±2 mm IP offset Q1-Q4 displaced by 2 mm + Q5 1 mm + and correctors
- ±0.1 mm IP movement independent for B1/B2 for luminosity scan
- 2 σ correction of ±0.5 mm residual quad. misalignment and ±0.5 mrad dipole tilt.
- Short range orbit adjustments (±0.2 mm CC adjustment)

Assume remote alignment for IP shift and orbit corrector minimization during beam commissioning.



Example for Right 5 with H crossing.
Symmetries applies for V crossing and left side.

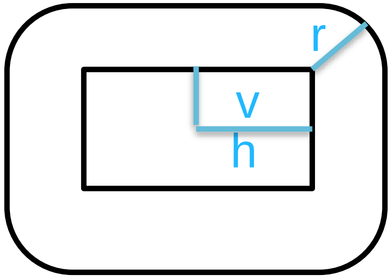
Constraints for linear and linear optics correction

- Long. misalignment ± 2 mm (uniform distr.)
  Reason: optics/beta*
- Tilt of average field ± 1 mrad (uniform distr.)
  Reason: coupling

See TDR and HL-Book.

Transverse tolerances on Apertures

	Ground motion			Fiducializaton			IP Offset (1)
	r [mm]	h [mm]	v [mm]	r [mm]	h [mm]	v [mm]	r [mm]
TAXS	2.0	0	0	0	0.5	0.5	2.0
Triplets	0.6	0	0	0	1.0	1.0	0.0
BPMs	0	0	0	2.5	0	0	0.0
TAXN	0.84	0.36	0	0	1.0	1.0	0.0
TCL-TCT	0.84	0.36	0	0	1.0	1.0	0.0
D1	0.6	0.36	0	0	1.0	1.0	0.0
D2/Q4	0.84	0.36	0	0	0.9	0.6	0.0
Crab b.s.	0.5	0	0	?	?	?	0.0
Q5	0.84	0.36	0	0	0.9	0.6	0.35
Q6	0.84	0.36	0	0	0.9	0.6	0.8



(1) Displacement of the aperture and the actual orbit due the combined effects of alignment position and orbit leakage.