Review HL-LHC triplet layout

G. Arduini, R. De Maria, M. Giovannozzi

Acknowledgment P. Fessia, E. Todesco

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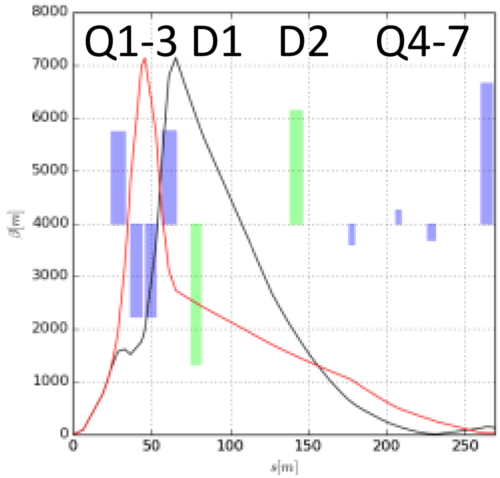
HL-LHC triplet upgrade for IR1 and IR5

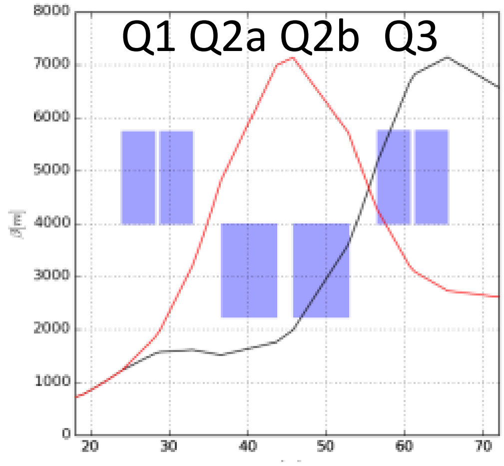
Triplets layout and optics defines
- beam size in the triplet, i.e. β* reach
- crab cavity voltage and optics matching conditions
- natural chromaticity, i.e. sextupole strengths
- the BPM effectiveness with LRBB encounters

and depends on
- gradient and length of the quadrupoles (Q1-3)
- drift between the quadrupoles and IP

Recently integration studies and MQXF review envisaged :
- increase of L*,
- increase of the interconnect lengths (longer drifts),
- decrease of the gradient,

At the PLC the option to split the Q2a and Q2b was also mentioned.





Here we presents:
- The impact if triplet layout is not changed while changing the gradient
- Impact on performance for a newer layout compatible with the proposed changes.

Triplet gradient lower margin without layout changes

- Triplet integrated strength is only approximately constant when changing drift spaces and gradient.
- Optics boundary conditions have very limited range due to:
  - internal phase advance constraints for the ATS optics;
  - need to maximize the β function at the crab cavity;
  - need to minimize β* without ATS to limit the β-blowup in the arcs (preserve DA and cold losses).

Grad [T/m]	$\beta^*_{presqueeze}$ [m]	Q7 [%]	
139.86	0.44	99%	Nominal β* to be recovered by the arc β blow-up
139.6	0.44	100%	
139.24	0.50	100%	
138.9	0.60	100%	
139	0.44	110%	Increase Q7 strength beyond limits
138	0.44	120%	
137	0.44	130%	

Not considered as options: upgrade Q7, drop ATS constraints, mismatch optics.
Therefore no layout changes implies:
only ~0.2T/m to 1T/m margin with 30% additional arc β increase or reduction of beam energy ➔ potential issues for dynamic aperture more an more depending on the main magnet field quality at high energy

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Variation on specs and β* reach

G [T/m]	L* [m]	d [illegible]	d [illegible]	d [illegible]	$d_{Q3a-Q3b}$ [m]	$d_{Q2a/b}$ [m]	$l_{Q1/3}$ [m]	$l_{Q2a/b}$ [m]	$\beta^*/\beta^*_{1.1}$
140	23	[illegible]	3[illegible]	[illegible]	[illegible]	[illegible]	4.0	6.8	+0%
140	24	0.5	3.7	2	3.7	[illegible]	[illegible]	[illegible]	+3.5%
140	2[illegible]	[illegible]	[illegible]	[illegible]	3.627	[illegible]	4.01	6.8	+0.8%
140	23	[illegible]	3.627	2.094	3.6[illegible]	[illegible]	[illegible]	[illegible]	+3.9%
131.25	23	[illegible]	[illegible]	[illegible]	3.7	0	4.11	7.11	+4.1%
131.25	24	[illegible]	3.627	2.094	3.627	0	4.19	7.08	+8.3%
131.25	24	0.65	3.627	2.094	3.627	0.65	4.15	7.03	+11.3%

L* change to account for vacuum equipment [illegible]

Updated interconnection length

Updated interconnection length and additional split of Q2a/Q2b

Reduction of gradient

All combined without Q2a/Q2b split

All combined with Q2a/Q2b split

- Study based on approximated boundary conditions.
- Pre-squeeze and final β* equally scales inversely proportional to β_{max} since chromaticity scales with β_{max}.
- Optics flexibility reduces with lower gradients.

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Integrate Luminosity vs β*

β* acts on virtual luminosity and HL-LHC scenarios are most sensitive to levelled luminosity and beam currents (burn-off and levelling times dominates).

E [TeV]	N [10^{11}]	L_{lev} [10^{34} $cm^{-2}s^{-1}$]	$L_{virt\ \beta^*=15cm}$ [10^{34} $cm^{-2}s^{-1}$]	L_{int}/day β^*=15cm [fb^{-1}]	$L_{virt\ \beta^*=18cm}$ (-13.3%) [$10^{34}cm^{-2}s^{-1}$]	L_{int}/day β^*=18cm
7	2.2	5	20.1	3.17	17.4	-1.73%
7	2.2	7.5	20.1	4.07	17.4	-2.88%
7	1.9	5	15.0	2.93	13.0	-2.55%
7	1.9	7.5	15.0	3.63	13.0	-4.3%

β* not very sensitive for L_{int} with nominal parameters, at the same time:

- relatively risk free and
- relative impact of β* on L_{int} increases for lower beam current.

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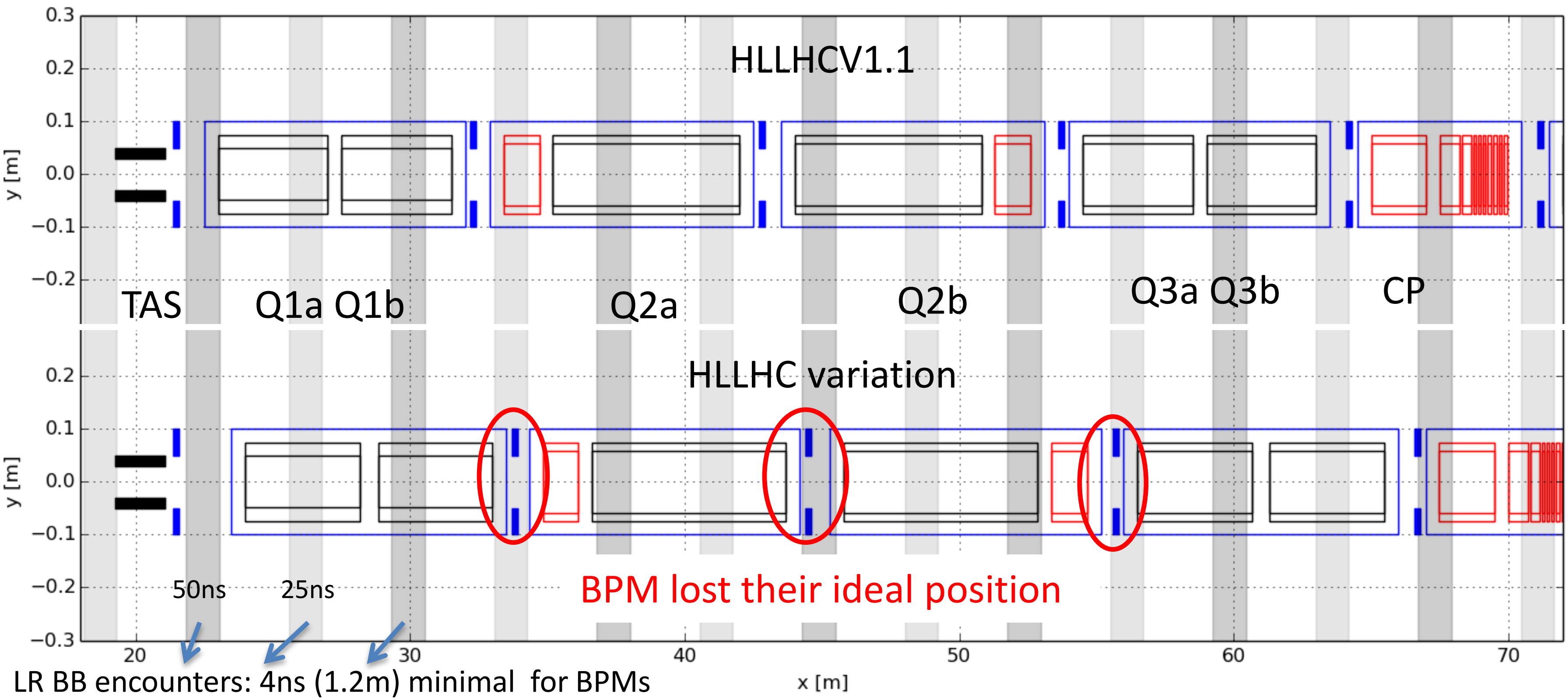
New detailed layout

G [T/m]	L* [m]	$d_{Q1/3a\text{-}b}$ [m]	$d_{Q1b\text{-}Q2a}$ [m]	$d_{Q2a\text{-}2b}$ [m]	$d_{Q2b\text{-}Q3a}$ [m]	$d_{Q2a/b}$ [m]	$l_{Q1/3}$ [m]	$l_{Q2a/b}$ [m]	$\beta^* / \beta^*_{1.1}$
140	23	0.5	3.7	2	3.7	0	4.0	6.8	+0%
131.25	24	0.65	3.627	2.094	3.627	0	4.175	7.07	+8.5%(*)

(* 9.5% $\beta^*_{presqueeze}$)



LR BB encounters: 4ns (1.2m) minimal for BPMs

Conclusion

- Triplet gradient, L*, quadrupole distances are fully interdependent quantities and must be optimized at once
- in particular gradient cannot be reduced without changing layout.
- ➔ once we freeze the length of the quadrupoles it will not be possible to change inter-quadrupole distances (e.g. for splitting Q2a/b ➔ need a decision there)
- Proposed changes increase beta* by 8% and result in 1-2% integrated luminosity loss
- Not studied, yet:
  - Means to improve positions of the BPMs
  - Effect of additional beam-beam long range encounter
- For updating the layout / triplet parameters (in particular length):
  - Need to understand whether we can maintain L*
  - Clarify layout/length for Q2a/Q2b

Backup

Selecting the efficient BPMs

Monte Carlo simulations to determine the most efficient BPMs for orbit correction.

- adding random noise errors in µm assuming an ideal transverse position. As reference value +/-1 µm BPM precision has been used, but the results scale linearly with the BPM precision
- assuming +/-100 µm max. orbit deviation from arc
- no magnet imperfections errors

disable one BPM at a time:

-> larger decrease of $(z-z_0)$ in comparison to the case with all BPMs => high efficiency of the BPM

orbit at IP5 (x/y)	max($\|z-z_0\|$) [µm]	rms($z-z_0$) [µm]	2rms($z-z_0$)/σ_z
all BPMs	1.14/1.12	0.33/0.33	0.092/0.094
no BPM1	1.41/1.44	0.40/0.41	0.113/0.115
no BPM2	1.55/1.38	0.38/0.39	0.108/0.111
no BPM3	1.48/1.48	0.37/0.38	0.106/0.106
no BPM4	1.43/1.25	0.35/ 0.35	0.100/0.100
no BPM5	1.14/1.19	0.33/0.34	0.093/0.095

efficiency decreases

BPMs closest to the IP (BPM1/2/3) are essential for the orbit control at the IP

Courtesy M. Fitterer