

Maching section and corrector new hardware requirements for the HL-LHC

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M. Giovannozzi, L. Rossi, R. Tomas, E. Todesco, J. Wenninger.

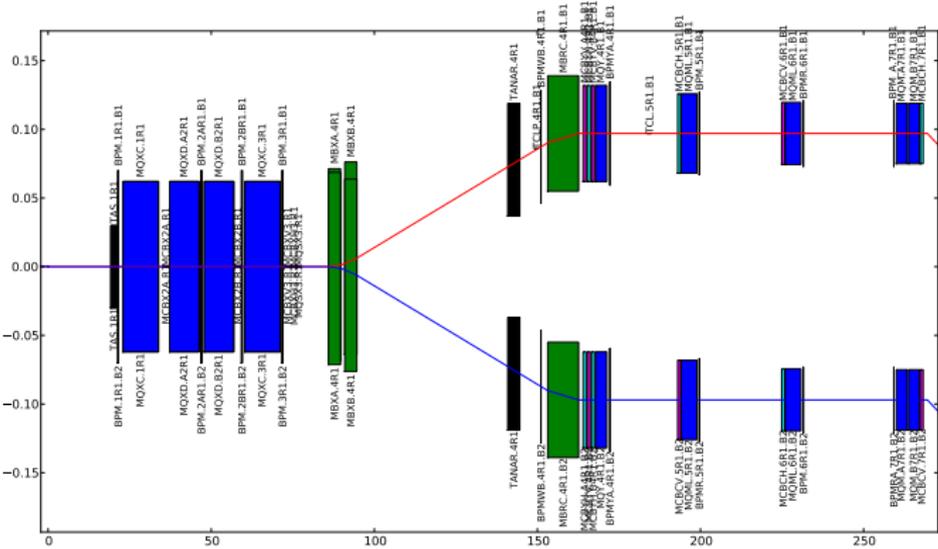
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Content and motivation

- ▶ Motivation: try to identify the most challenging beamline element that may be needed for the HL-LHC
- ▶ Focus on non-triplet beam line elements, although the triplet choice determines some relevant specs of the other elements.
- ▶ Focus on one baseline, branches are mentioned, but not followed.
- ▶ Baseline: ATS, 15cm β^* , Nb3Sn triplet, crab cavities for luminosity enhancement and leveling, nominal emittance and bunch length.
- ▶ Alternatives:
flat beams (e.g. $\beta^* \sim 7.5/32.5\text{cm}$, no crabs, Nb3Sn),
NbTi triplet ($\beta^* \sim 19\text{cm}$ or flat equivalent),
noATS ($\beta^* \sim 39\text{cm}$ Nb3Sn or 49cm NbTi),
Phase I ($\beta^* \sim 25\text{cm}$ Nb3Sn or 30cm NbTi, but very constrained solutions).

Outline

Triplets - D1 - TAN-Q4 layout - CRAB cavities - D2 - Q4 - Q5 -
 Triplet corrector package - MCB - Q10-MS-IR6 for the ATS - TAS
 TAN - Conclusion



Triplets Q1-Q3

Baseline: Nb3Sn triplet compatible with $\beta^*=15\text{cm}$, $\theta_c = 580 \mu\text{rad}$.

Two lengths ¹ : Q1,Q3 and Q2a,Q2b.

Coil ap. [mm]	gradient [T/m]	s.s. limit	lengths [m]	β^* [cm]	Nb [ppb]	Ne [ppb]	t level [h]
150 ² (140 ³)	150	86% (80%)	8.00,6.85	15	2.0E11	1.3E11	5.6

What can increase β^* :

- ▶ larger emittance, emittance growth, crossing angle
- ▶ increase gap between b.s. and coil aperture (e.g. shielding)
- ▶ relaxed collimation settings
- ▶ poor field quality or lack of corrector package
- ▶ poor power converter (0.5 ppm) or mechanical stability (0.5 μm)
- ▶ unexpected limitation of the ATS

What can decrease further β^* :

- ▶ reduced emittance
- ▶ reduced crossing angle

¹Nominal: 6.37m, 5.5m

²with shielding

³without shielding

Q1-Q3: design method (BACKUP)

A set of triplet layout have been generated using a simplified method and the Phase I experience.

For a real design one should iterate as follows:

- ▶ gradient + layout constraints ⁴ + matching conditions ⁵
- triplet layout
- ▶ + β^* + crossing angle + n1 method ⁶
- beam screen geometry
- ▶ + pipes ⁷ → coil aperture
- ▶ coil aperture + gradient ⁸ → magnet technology.

⁴cryostat lengths, corrector packages, BPM positions, masks if any

⁵left/ right phase advances for the ATS, aperture of D2, Q4, optics flexibility, squeeze generation, injection optics.

⁶target 7σ include beta-beating, dispersion correction, spurious dispersion, nominal collimator settings, closed orbit error, mechanical tolerances

⁷thickness of b.s., cooling tubes, beam pipe, insulation, shielding, clearance, tolerances

⁸80%-90% of the short sample limit, see E. Todesco

Q1-Q3: options round beams (BACKUP)

ap. ⁹ [mm]	grad ¹⁰ [T/m]	lengths ¹¹ [m]	β^* [cm]	N1 ¹² [ppb]	N2 ¹³ [ppb]	t ¹⁴ [h]
150	144(83%Sn)	8.2 , 7.0	13.0	1.99E11	1.21E11	6.06
150	96(83%Ti)	10.8 , 9.0	17.0	2.03E11	1.36E11	5.24
140	150(80%Sn)	8.00, 6.8	15.0	2.01E11	1.29E11	5.64
140	100(80%Ti)	10.5, 8.8	19.0	2.05E11	1.42E11	4.89
120	180(83%Sn)	7.1 , 6.1	18.6	2.05E11	1.42E11	4.96
120	120(83%Ti)	9.3, 7.8	24.0	2.11E11	1.58E11	4.14
85	160(78%Ti)	7.7, 6.6	44.0	2.41E11	2.11E11	2.33
80	257(80%Sn)	4.8, 5.5	39.0	2.33E11	1.99E11	2.65

⁹without shielding

¹⁰in parenthesis fraction of the short sample limit, see E.Todesco LHC-CC10

¹¹Length of Q1-Q3, Q2a-Q2b

¹²Bunch intensity (and otherwise nominal parameters) at the beginning of the leveling (5σ crossing angle) to reach $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

¹³Bunch intensity (and otherwise nominal parameters) at the end of the leveling (head-on) to reach $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

¹⁴leveling time

Q1-Q3: options flat beams (BACKUP)

ap. [mm]	grad [T/m]	lengths ¹⁵ [m]	β^* [cm]	α ¹⁶ [σ]	N1 ¹⁷ [10^{11} ppb]	N2 ¹⁸ [10^{11} ppb]	t ¹⁹ [h]
150	144	8.2, 7.0	31.0, 6.6	6.5	1.69E11	n/a	n/a
150	144	8.2, 7.0	32.8, 8.7	13	2.33E11	1.74E11	4.6
150	144	8.2, 7.0	32.1, 7.7	11	2.11E11	1.66E11	3.6
150	144	8.2, 7.0	31.8, 7.4	9.7	1.99E11	1.73E11	2.1
150	96	10.8, 9.0	32.5, 8.7	6.5	1.78E11	n/a	n/a
150	96	10.8, 9.0	34.3, 12.0	11.5	2.36E11	1.91E11	3.6
140	150	8.00, 6.8	32.5, 7.5	6.5	1.73E11	n/a	n/a
140	150	8.00, 6.8	33.0, 9.0	10	2.10E11	1.80E11	2.4
140	100	10.5, 8.8	33.5, 10.0	6.5	1.83E11	n/a	n/a
140	100	10.5, 8.8	34.3, 12.0	9.5	2.18E11	1.91E11	2.2

¹⁵Length of Q1-Q3, Q2a-Q2b

¹⁶Half crossing angle

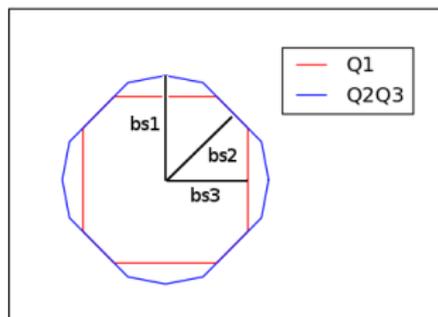
¹⁷Bunch intensity (and otherwise nominal parameters) at the beginning of the leveling to reach $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

¹⁸Bunch intensity (and otherwise nominal parameters) at the end of the leveling ($\alpha = 6.5\sigma$) to reach $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

¹⁹leveling time

Q1-Q3: beam screen (BACKUP)

ap [mm]	bs1 [mm]	bs2 [mm]	bs3 [mm]
150	62.0	49.5	40.2
140	57.9	46.2	37.4
130	53.7	42.9	34.8
120	49.6	39.6	34.8
90	37.2	29.7	24.1
85	28.1	22.8	22.8
80	33.0	26.4	21.4



target: $n1=7$

no shielding (besides Q1)

alignment tolerances: 1mm x 1mm

ground motion: 0.6mm

worst case for ISO manufacturing tolerances as in Phase I (see EDMS Note 350449 (N. Kos).)

D1

Baseline: NbTi, double or triple layer. It has to provide as much as $0.194/2/(157.9 - 79 - 15 - 10) = 1.8 \text{ mrad} \rightarrow 42 \text{ Tm}$.

Element	length [m]	field [T]	c. dia. [mm]	b.s. type	b.s. ap [mm]	sep. [mm]
D1	8	5.25	165	round	70	n/a

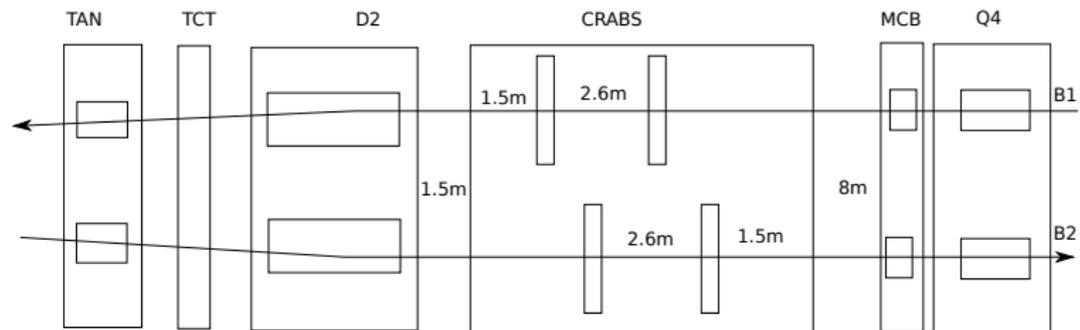
The nonIP side aperture can be roughly estimated in $a_{\text{triplet}} + 0.0018 \cdot l_{\text{D1}} \simeq 165 \text{ mm}$, but again detailed shielding design may change the picture.

Can be made longer if the required field is too high.

Without crab cavities and Nb₃Sn triplet the integrated field can be reduced to $0.194/2/(157.9 - 79) = 1.2 \text{ mrad} \rightarrow 29 \text{ Tm}$.

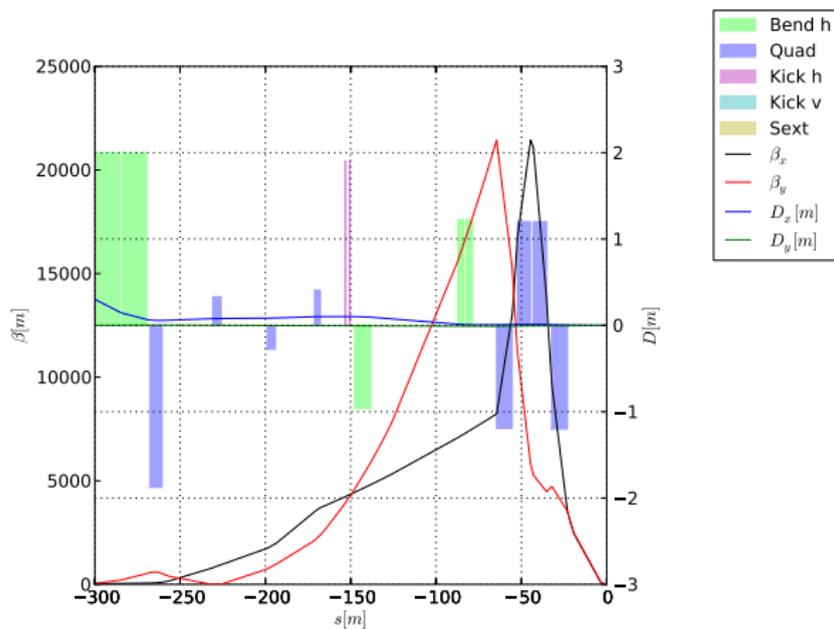
TAN-Q4 layout

Baseline:



TAN-Q4 layout

Baseline:



CRAB cavities

Baseline $V = 10$ MV, $\theta_c = 580 \mu\text{rad}$, $\beta_{\text{crab}} \simeq 3800$ km,
 $\beta^* = 15$ cm, $\epsilon = 5 \cdot 10^{-10}$ m rad, $\alpha = 5$, $\omega = 2\pi \cdot 400$ MHz

Scalings:

$$V = \frac{cp}{e\omega} \frac{\theta_c}{2} \frac{1}{\sqrt{\beta^* \beta_{\text{crab}}}} \quad \theta_c/2 = \alpha \sqrt{\frac{\epsilon}{\beta^*}}$$

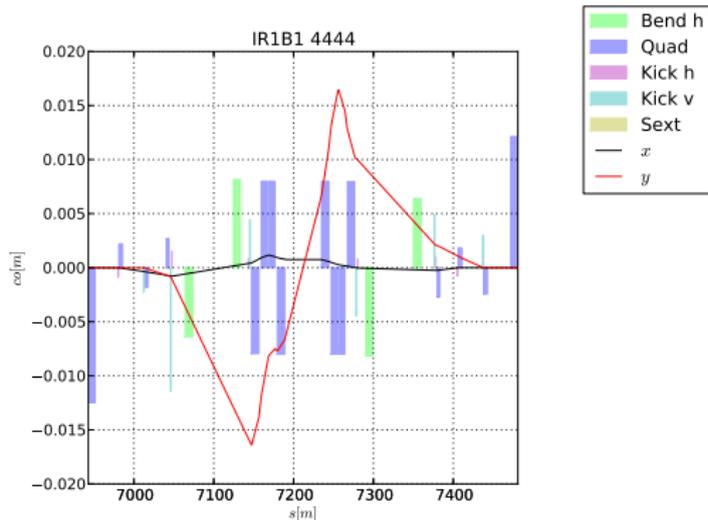
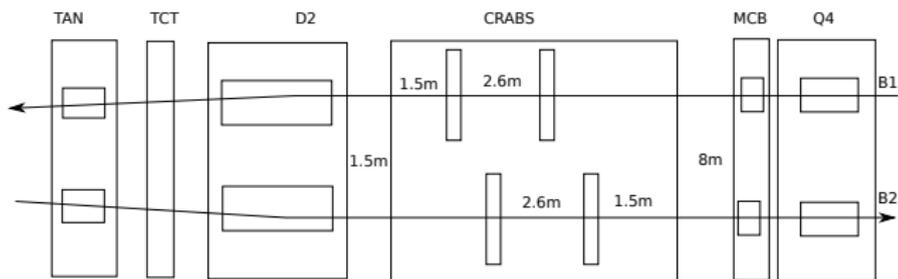
w/wo optics constraints: $\beta_{\text{crab}} \propto \frac{d_{D2}^2}{\epsilon} \frac{1}{\beta^*}$, $\beta_{\text{crab}} \propto \frac{d_{D2}^2}{\epsilon}$

Crab located inside the crossing scheme bump. The maximum close orbit excursion from reference trajectory: 3.354 mm for crossing angle and 0.67 mm for a positive 1.5 mm separation.

Mechanical alignment needed, unless a crossing and separation scheme closed in D2 is implemented.

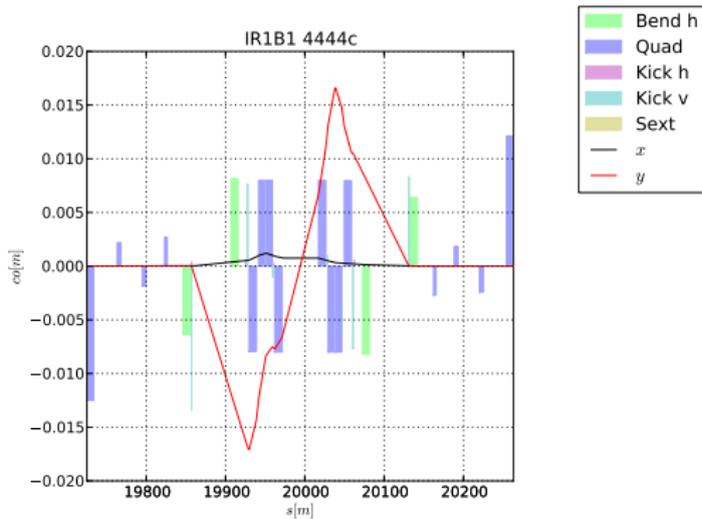
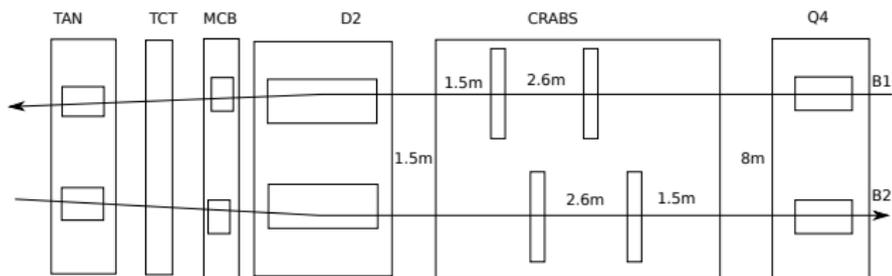
TAN-Q4 layout

Baseline:



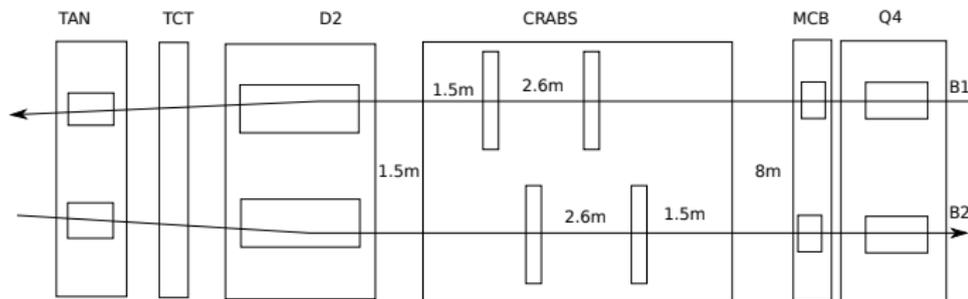
TAN-Q4 layout

Closed crossing scheme:



TAN-Q4 layout

Baseline:



other options:

1) IP - ... - TAN - TCT - MCBHV - D2 - CRAB - Q4 (for closed crossing scheme, save crab alignment and aperture in D2, Q4)

2) IP - ... - TAN - TCT - CRAB - MCBHV - D2 - Q4 (lower voltage, smaller D2 aperture but smaller separation and residual angle for the cavity).

...) any permutation of TCT - CRAB - MCBHV - D2 optimizes different aspects.

Finally the area may fit the BBLRs ideal *beta*-functions conditions. To be studied extensively with the support of the collimation, radiation protection, crab cavity team.

D2

Aperture competes with crab cavities voltage.

Baseline: NbTi single layer.

Element	length [m]	field	c. dia. [mm]	b.s. type	b.s. ap [mm]	sep. [mm]
D2	10	4.2T	105	rectellipse	37.0,42.0	186

Aperture can be reduced and separation increased if CRAB cavities are installed in the IP side at the cost of reducing the cavity separation.

Aperture can be reduced if orbit correctors are installed in the IP side and the “closed” crossing scheme is implemented (marginal gain for flat beams).

Without crab cavities the integrated field can be reduced to 29Tm.

Q4

Large aperture MQY \rightarrow MQYY. Scales with D2 aperture.

Element	length [m]	field	c. dia. [mm]	b.s. type	b.s. ap [mm]	sep. [mm]
Q4	3.4	160T/m	85	rectellipse	30.0,35.0	194

Aperture can be reduced with the “closed” crossing scheme.

Aperture can be reduced if moved towards the arc together with

Q5. To be extensively studied.

Q5

Change to MQY apertures up to $\beta^*=25\text{cm}$ and MQML length.
New type MQYL.

Element	length [m]	field	c. dia. [mm]	b.s. type	b.s. ap [mm]	sep. [mm]
Q5	4.8	160T/m	70	rectellipse	24.0,28.9	194

Q5 maybe moved towards the arcs for optics flexibility.

Triplet corrector package

Orbit corrector: nested MCBX²⁰ in the non-IP side for Q1, Q2, Q3.

Function: orbit correction due to misalignments and crossing angle

Strength orbit correction: $x_{tol} g_{\text{triplet}} l_{\text{triplet}} = 0.6 \text{ Tm} \rightarrow 25 \mu\text{rad}$

Crossing scheme based on one triplet layout:

Element	Plane	crossing		separation	
		kick [μrad]	field [Tm]	kick [μrad]	field [Tm]
nominal-like round β^*					
MCBX.3	H&V	49*1.5 =73	1.7	11*2	0.51
nominal-like flat β^*					
MCBX.3	H&V	30/5.*13=78	1.8	11*2	0.51
closed round β^*					
MCBX.1	H&V	17*1.5 =25	0.6	5*2	0.23
MCBX.3 ²¹	H&V	140*1.5 =210	4.9	10*2	0.46

Multipole correctors: bare minimum a2, b3, b6. Field quality at a level of few $\cdot 10^{-5}$ at 2/3 of the aperture or a3, a4, b4, a5, b6, a6 correctors are probably needed. To be studied in detail.

²⁰nominal 3.3T 1.5Tm

²¹may be partially absorbed by D1

Baseline: orbit correction 1.1Tm + crossing scheme

Crossing scheme based on one triplet layout:

Element	Plane	crossing		separation	
		kick [μrad]	field [Tm]	kick [μrad]	integrated [Tm]
nominal-like round β^*					
MCBYY.4	H&V	126*1.5=189	4.4	22*2	1.0
MCBY.5	H or V	32*1.5 = 48	1.1	10*2	0.46
MCBC.6	H or V	35*1.5 = 53	1.2	12*2	0.28
nominal-like flat β^*					
MCBYY.4	H&V	69/5.*13 =179	4.1	21*2	0.98
MCBY.5	H or V	39/5.*13 =102	2.3	10*2	0.46
MCBC.6	H or V	12/5.*13 = 31	0.72	10*2	0.46
closed round β^*					
MCBYY.4 ²²	H&V	244*1.5 =366	8.5	8*2	0.37

²²may be partially absorbed by D2

²³Nominal 2.5T, 2.27 Tm

Q10-MS-IR6 for the ATS

Q10) Replace orbit corrector MCBC with the MSCB package to include an MS for $\beta^* < 30\text{cm}$ otherwise tune spread and dynamic aperture degradation because of the ATS.

Alternative IR phase advances, probably involving a new layout of Q4-Q5 may avoid that, but solution have not been found yet.

MS) Commissioning MS at 600A (or more) otherwise one needs more ATS at constant β^* (arc blowup and dynamic aperture reduction). It should allow a pre-squeeze optics of $\beta_{x,y}^* = 36, 50\text{ cm}$.

IR6) Longer MQYL in Q5 IR6: limit ATS multiplication factor in IR5 at $\sim 2x$ (instead of $8x$).

TAS TAN

TAS is to be replaced (17mm \rightarrow 30mm for $\beta^* = 15\text{cm}$).
The aperture scales with $1/\sqrt{\beta^*}$ and therefore the triplet choice.

New TAN needed: new aperture and separation.

Baseline

Element	length [m]	field	c. dia. [mm]	b.s. type	b.s. ap [mm]	sep. [mm]
TAN	3.7	n/a		elliptical	41.0,37.0	145

Constraint: TAN aperture smaller than D2 aperture in a location where beam size is larger than D2, thus distance from D2 cannot exceed a certain value (5m now).

Conclusion

New designs: Q1-Q3, CRABS, D2, MQYY, MCBYY for Q4, D1, MCBX, IT multipole correctors, MQYL for Q5 in IR1-5-6, MCBL, TAS, TAN, BPM, BBLR, shielding, beam pipes, beam screen.

New elements: MSCB in Q10.

Displacement: D1, D2, maybe Q4, Q5, Q6.

Commissioning: MS to 600A.

Early iterations on triplet and TAN-Q4 area among the WPs will be very beneficial to identify the correct process to design the final layout. So far Phasel design priorities and constraints have been used, but the target and boundary conditions are now different.

General optics studies needed: triplet field quality, Q4-Q5 position optimization.

In preparation SLHCV3.1: new ATS optics and layout using 150T/m and 100T/m.