Towards HL-LHCV1.4

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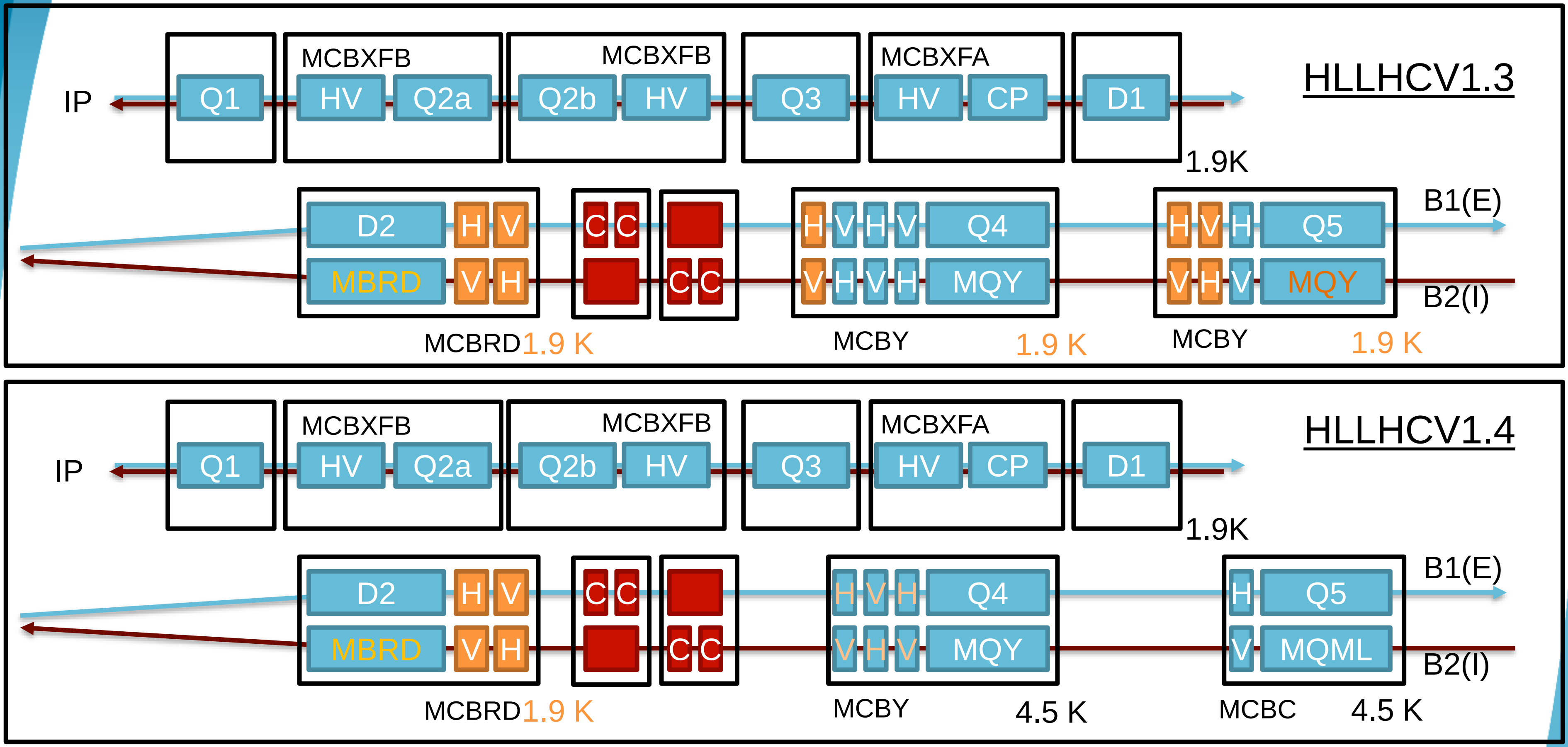
WP2 meeting 18/9/2018

TOC

- Layout changes
- IR1/5 Optics updates
- Aperture update with remote alignment
- IR4 Optics update (instrumentation and e-lens)
- IR6 Optics update (TCDQ gap)
- Crossing plane choice WP2

Layout main changes



Changes with respect to the baseline:

- Q4: reusing existing cold mass (3 correctors instead of 4), no need of 1.9 K.
- Q5: reusing existing Q5 cold mass (1 corrector instead of 3), no need of 1.9 K.
- Full deployment of remote alignment system to be used with safe beam.

Chamonix 2018

Layout Changes HLLHC1.3 → 1.4

Layout changes:

- IR1/5: 2+2 crab cavities → 2 crab cavities only
- IR1/5: Q4, 4xMCBY+MQY 1.9 K → 3xMCBY+MQY 4.5 K
- IR1/5: Q5 3xMCBY+MQY 1.9 K → 1xMCBC+MQML 4.5 K
- IR1/5: Remote alignment system (i.e. machine can be realigned during beam commissioning for IP shift and orbit flattening)
- IR1/5: Q4, Q5 displaced towards the arc from 10.047 m, 11 m w.r.t LHC to 10.5 m w.r.t LHC
- IR1/5: New specification for TCTPV-TCTPH-TCLX stroke and apertures
- IR1/5: Changes length/position of correctors in CP
- IR7: MBH+TCLD, MQW (not the absorber)
- IR2: TCLD, TDIS
- IR8: TANB

Layout stabilizing changes:

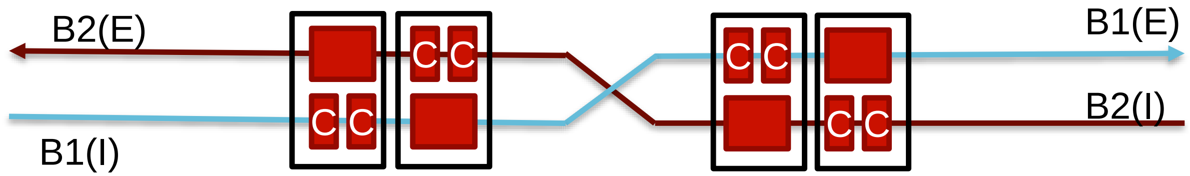
- Final positions of correctors in CP
- Displacement BPM in D2 from IP side to non-IP side
- Small change in MCBRD positions
- Final position MASK Q4 (linked to the new Q4 end cap)
- Extended D1 beam-screen
- Overall review with mechanical drawings

Changes HLLHC1.3 → 1.4

Optics changes:

- Crossing bumps re-optimized thanks to remote alignment system
- Dedicated optics for 7 TeV (using 7.5 TeV equivalent currents where needed) for improved crabbing angle
- IR7 optics with MQW changes
- IR4 optimized for instrumentation and e-lens
- IR6 reviewed and re-optimized for TCDQ gaps, Q5 strengths
- IR8 $\beta^*=1.5$ m

Crabbing angle and IR1/5 optics



Crab angle [μrad]	Q7 [T/m]	Same IR1/5 Optics	H Optimized Optics	V Optimized Optics
HL1.3	200	380	n/a	n/a
HL1.4	200	375	388	375
HL1.4	214	388	400	390

- 5 μrad lost due to Q4-Q5 displacement from HL1.3 to HL1.4.
- Higher than nominal Q7 current allow to increase crabbing angle
- Different optics for IR1/IR5 can optimize a given crabbing plane.
- With the present crab cavity layout (same for 1/5) H crossing is favored, therefore different layouts can still improve overall crab crossing.
- Crab cavity voltage optimization has some impact on aperture and forward physics.

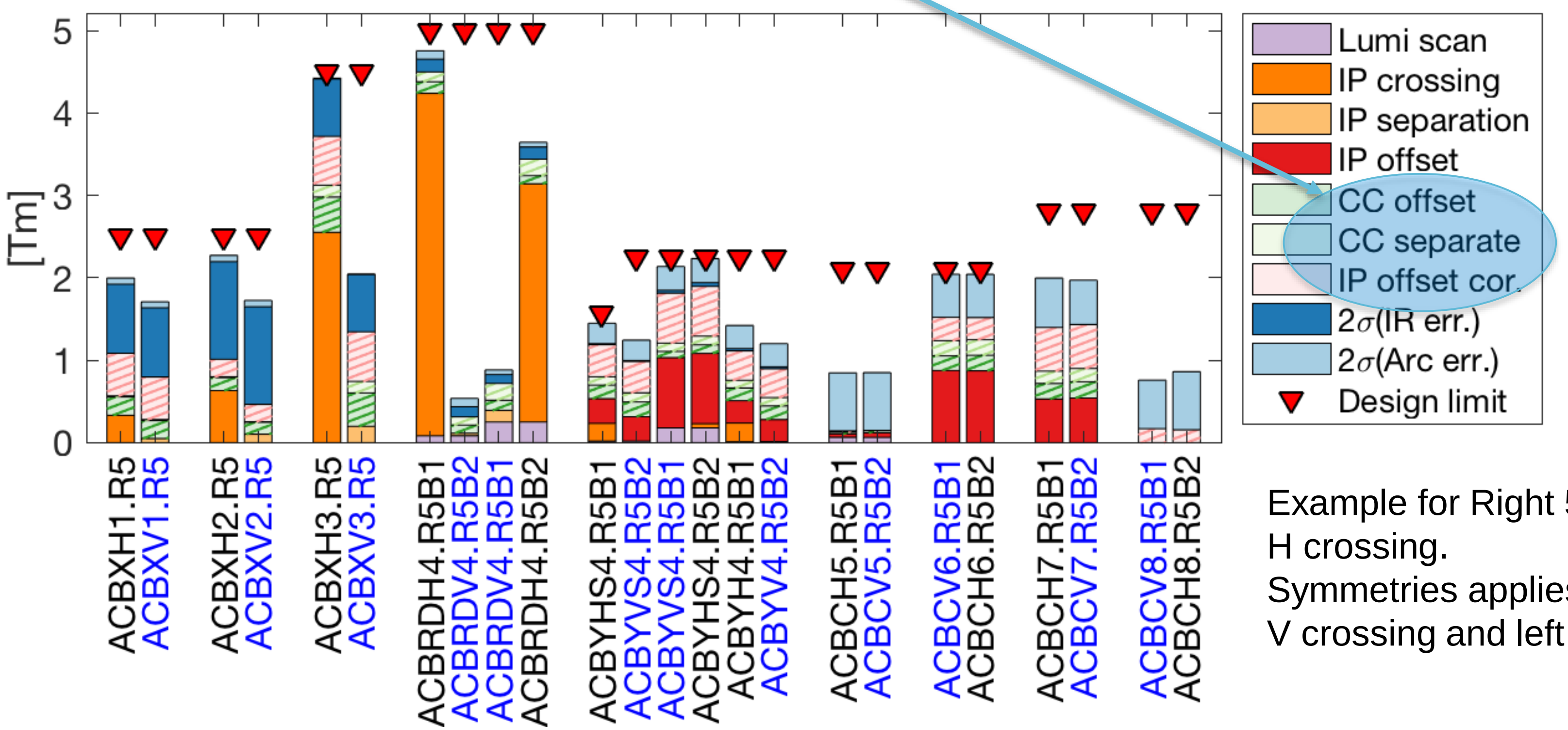
Summary of strengths with remote alignment

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 with correctors + Q1-Q4 displaced by 2 mm
- ±100 um IP movement independent for B1/B2 for lumiscan
- 2 σ correction of ±0.5 mm residual quad. misalignment and ±1 mrad dipole tilt.

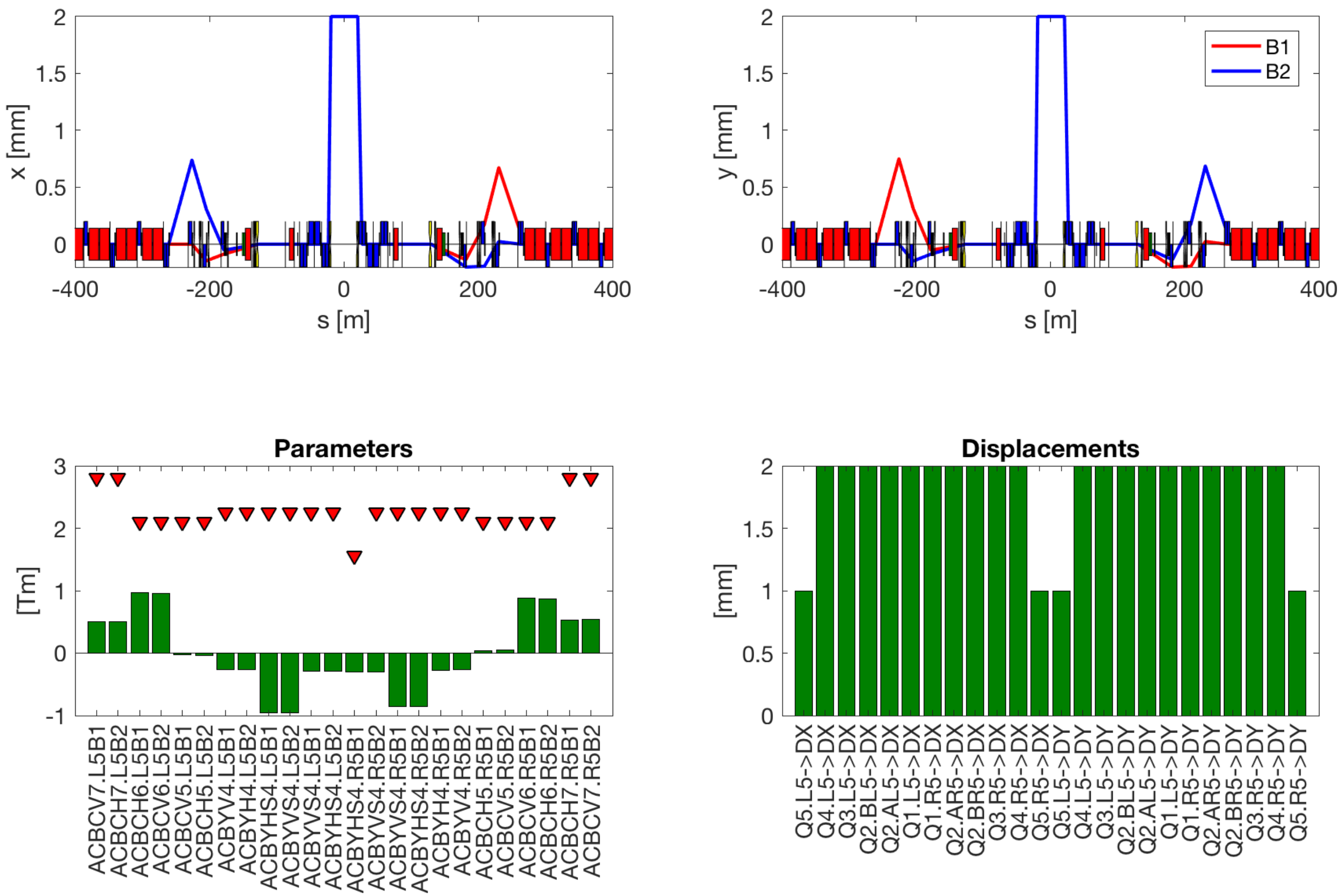
Back-up for remote alignment, implies loss of aperture:

- ±0.5 mm B1/B2 separation at CC (back for remote alignment loss of aperture)
- ±0.5 mum B1 and B2 orbit offset at CC
- ±1.2 mm of IP offset with correctors (fall-back for remote alignment loss of aperture)



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

IP offset (2mm) with remote alignment



Residual orbit and orbit corrector minimized with the remote alignment from Q1-Q5 and correctors from Q4 to Q7

Apertures: Round 15 cm, 10.5 σ

	Mech	Beam	Offset
TAXS	22.6	17.9	15.6
Q1	20.5	16.9	16.9
Q23	15.4	12.6	12.6
D1	16.3	13.3	13.3
TAXN	21.2	17.5	17.5
D2	23.2	18.7	18.7
D2 Corr.	24.1	19.7	19.7
CRABS	33	27.6	27.6
Q4 Mask	23.6	18.6	18.6
Q4 Corr.	25.1	19.9	19.9
Q4	27	21.6	21.6
Q5 Mask	26.2	20.8	20.4
Q5 Corr.	27.2	21.6	21.3
Q5	27.6	22	21.7
Q6 Mask	33.9	27.2	26
Q6 Corr.	35	28.1	26.9
Q6	35.4	28.5	27.6

$\theta_c = \pm 250\ \mu rad$;
$d_{sep} = \pm 0.0$ mm;

Mech: best possible aperture with beam screen shape tolerances, ground motion and fiducialization margins (being reviewed)
Beam: as before with beam imperfections
Offset: as before with IP shift suing remote alignment

Design Principle: Triplet should always be the aperture bottleneck.

Aperture in σ at 2.5 μm/γ at 7 TeV

Increased aperture margins thanks to remote alignment

Apertures: Flat 15 cm, 11.8 σ

	Mech	Beam	Offset
TAXS	19.1	15.1	13.2
Q1	18.2	15.0	15.0
Q23	14.7	12.1	12.1
D1	15	12.3	12.3
TAXN	16.5	13.4	13.4
D2	17.6	14.3	14.3
D2 Corr.	19.3	15.8	15.8
CRABS	23.4	19.7	19.7
Q4 Mask	16.7	13.0	13.0
Q4 Corr.	17.8	13.9	13.9
Q4	19.1	15.0	15.0
Q5 Mask	18.7	14.5	14.2
Q5 Corr.	19.4	15.1	14.9
Q5	19.5	15.4	15.1
Q6 Mask	24.1	19.1	18.2
Q6 Corr.	25.1	19.8	18.9
Q6	25.1	20.1	19.4

$\theta_c = \pm$ 245 μrad;
$d_{sep} = \pm$ 0.0 mm;

Mech: best possible aperture with beam screen shape tolerances, ground motion and fiducialization margins (being reviewed)
Beam: as before with beam imperfections
Offset: as before with IP shift suing remote alignment

Design Principle: Triplet should always be the aperture bottleneck.

Aperture in σ at 2.5 μm/γ at 7 TeV

Sufficient aperture margins thanks to remote alignment

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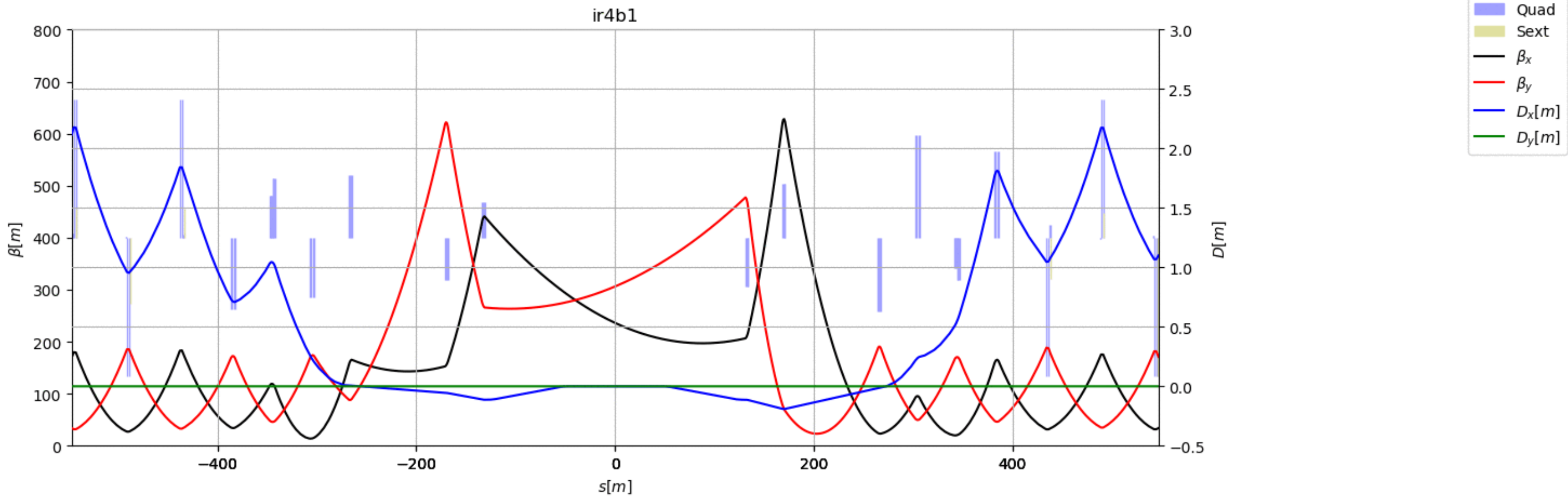
IR4 optics actions from BI

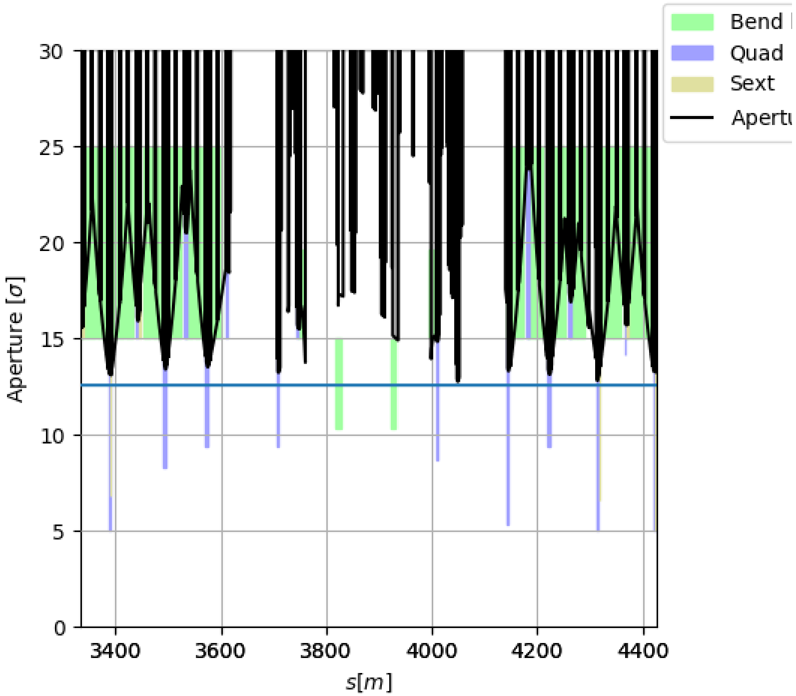
Follow-up from several meetings WP2-WP13 meetings:

- Use improved injection optics without optics change during the ramp (as first iteration)
- Increase the minimum beta at the BSRT above 200 m while keeping the beta at HEL bigger than 250 m.
- Solution given to WP13.
- BI is investigating the optics for possible feedback.
- Aperture of 50 mm for e-lens possible.

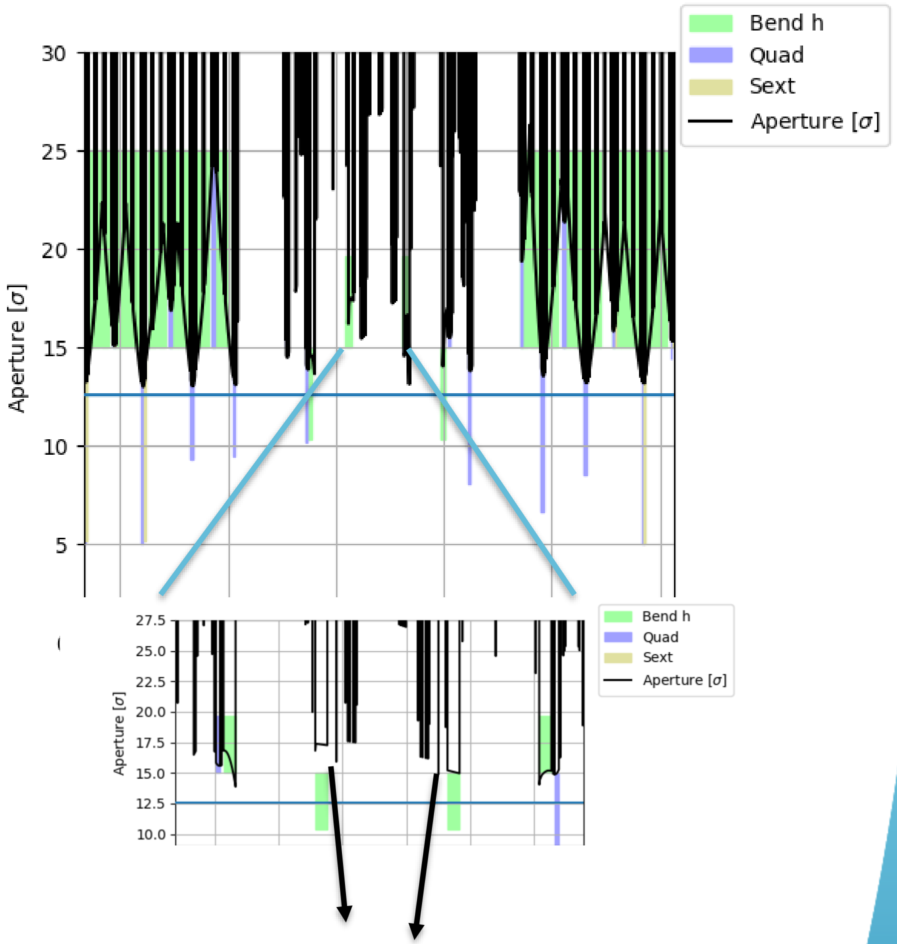


Example of optics transition Beam 1 Round optics

New IR4 Injection Optics



Aperture at injection above the target of 12.6 σ using HL-LHC aperture tolerances.



Diameter 50 mm would still fit

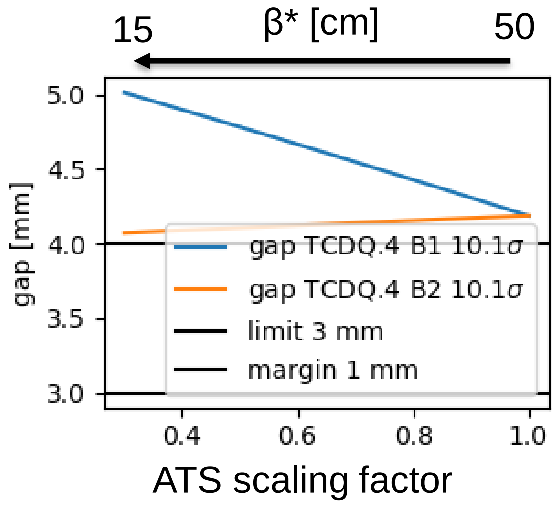
IR6 TCDQ Constraints

TCDQ gaps	Old [mm]	New[0] [mm]
Min real gap	3	3[1]
Interlock	1.2	0.8-0.5[2]
Position accuracy, β-beat	0.3	0.3
Dispersion δ =2e-4	0.4[3]	0.1[4]
Total margin	1.9	0.9-1.2

[0] Meeting WP2-WP5-WP14 23/1/2018
[1] Base on present FLUKA and ANSYS studies at 2.2 10^{11}. Lower for lower ppb?
[2] Based on studies with DOROS TCSP BPM. J.W. 0.5 mm in LCR3 meeting.
[3] Dx = 2 m very large
[4] Dx = 0.5 m should be sufficient

BETS: fixed gap at flat top in mm.
Implies gap chosen to be the one for the ideal setting (10.1 σ or +1 from TCS) at the end of the squeeze.

Round squeeze
(not ATS in the ramp)



TCDQ settings:

- Beam 1: β increases during the squeeze :
  - 5 mm: from 12.3σ →10.1 σ:
- Beam 2: β decreases during the squeeze
  - 4.1 mm: from 9.6 σ → 10.1 σ.

For flat optics Beam 2 β increases during the squeeze instead and gap >4.2 mm

Protected Apertures

$\Delta\mu_x$ MKD-TCT [°]	Aperture [σ@2.5μm]
0-20	11.2
30	11.9
40	12.9
50	13.8
60	14.5
70-90	14.6
No TCT	19.4
Injection	12.6

Parameter	7 TeV	0.45 TeV
Radial CO [mm]	2	
Mom offset	$2\ 10^{-4}$	
Dispersion	0.1	
Beam size	1.1	1.05

In addition there is:

- Ground motion and fiducialization ~2.5 mm
- Shape tolerances ~1-3 mm

Depends on the equipment and it is being reviewed with possible gains.

R. Bruce et al. CERN-ACC-2017-0051

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Figure of merit of optics options

	Baseline HL1.4		
	Round	FlatCC	Flat
β* Xing/Sep [cm]	15/15	18/7.5	30/7.5
Xing angle [μrad]	±250	±240	±245
TCDQ gap[1)] B1/B2 [mm]	5.0/4.1	4.7/4.1	4.7/4.5
Q5.L6 [T/m]	165	167	171
Q5.R6 [T/m]	159	160	161
MKD-TCT [°] IP5	30	22	25
Protected H[2)] Ap. [σ] IP5	11.9	11.4	11.7
Protected V[2)] Ap. [σ] IP5	10.4-11.2	10.4-11.2	10.4-11.2
Crossing plane IP5	V or H	H	H
Aperture[3)] Xing [σ]	13.2	14.2	15.6
Aperture[3)] Sep [σ]	16.5	12.7	12.9

1) Target 4.1 mm proposed, 5.2 mm requested (C. Bracco)
2) assuming different settings for TCTH and TCTV, which is under study (R. Bruce)
3) with/without fully remote alignment

Free choice of crossing plane:
HV give more margin for round, but strongly limits FlatCC

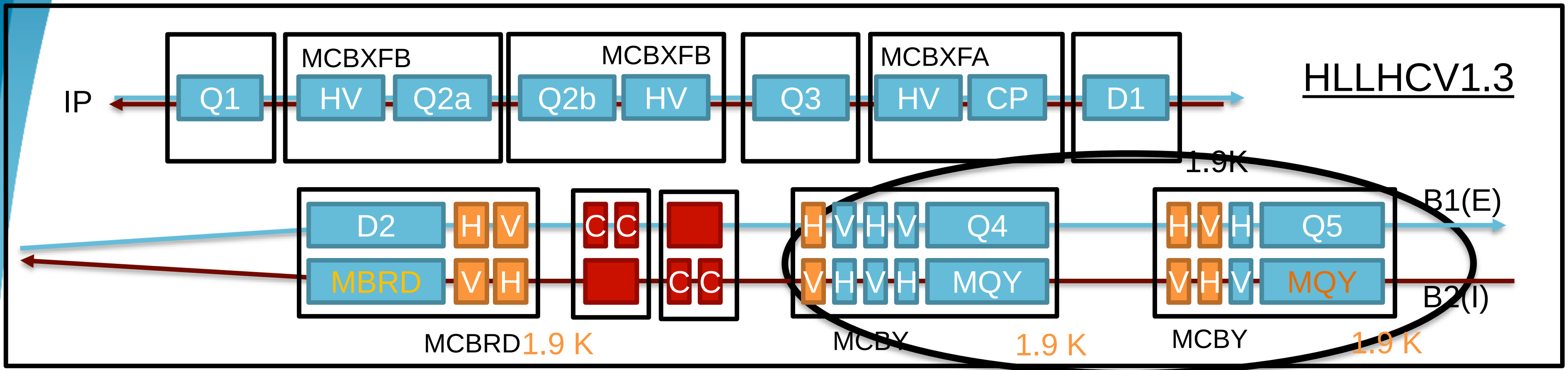
Crossing plane choice

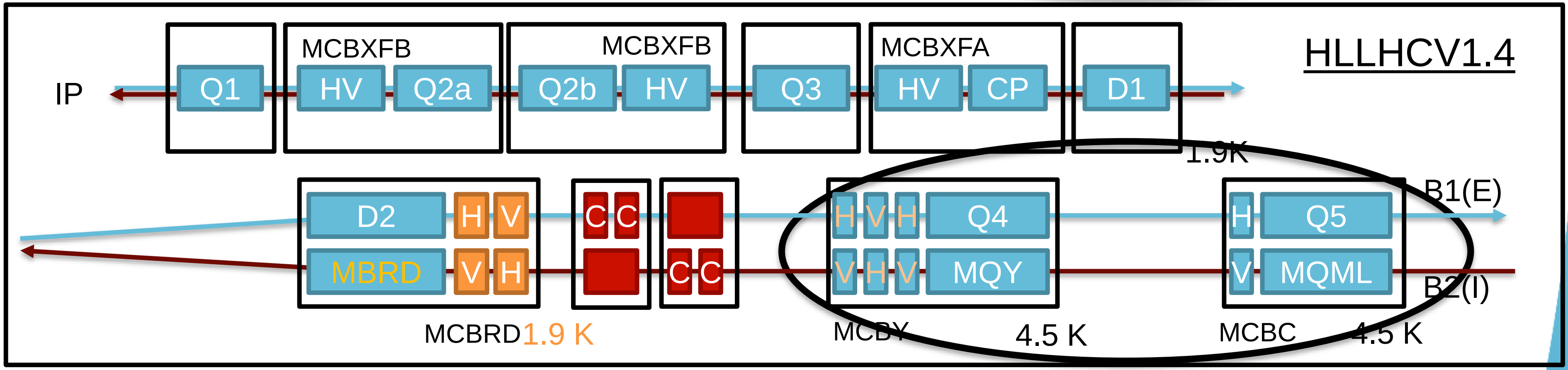
Optics scenario	Observables	H1-V5	V1–H5
Round optics β*=15 cm (with present CC β*=18/15 cm gives marginally larger virtual lumi. than β*=15/15 cm)	Aperture margins crossing plane. Can be used to: • relax collimator hierarchy or • relax MKD-TCT constraints or • reduce β* only if crab cavities have larger voltage than nominal or if we can cope with stronger long range BB interactions	2.8 σ	1.3 σ
	TCDQ gaps	At the limit	At the limit
Flat optics with CC β*=18/7.5 cm (without CC we can change the crossing plan at will).	Aperture margins separation plane. Can be used to: • relax collimator hierarchy or • relax MKD-TCT constraints or • reduce β* in the parallel separation plane regardless of crab cavities and BB interactions	-1.6 σ	1.5 σ
	TCDQ gaps	At the limit	Good

Forward physics studies are on-going, need very detailed studies: V crossing good for low mass (increase normalized dispersion around Q5), but bad for high mass (increase cut from TCL4). No recommendation available yet.

Backup

Layout changes

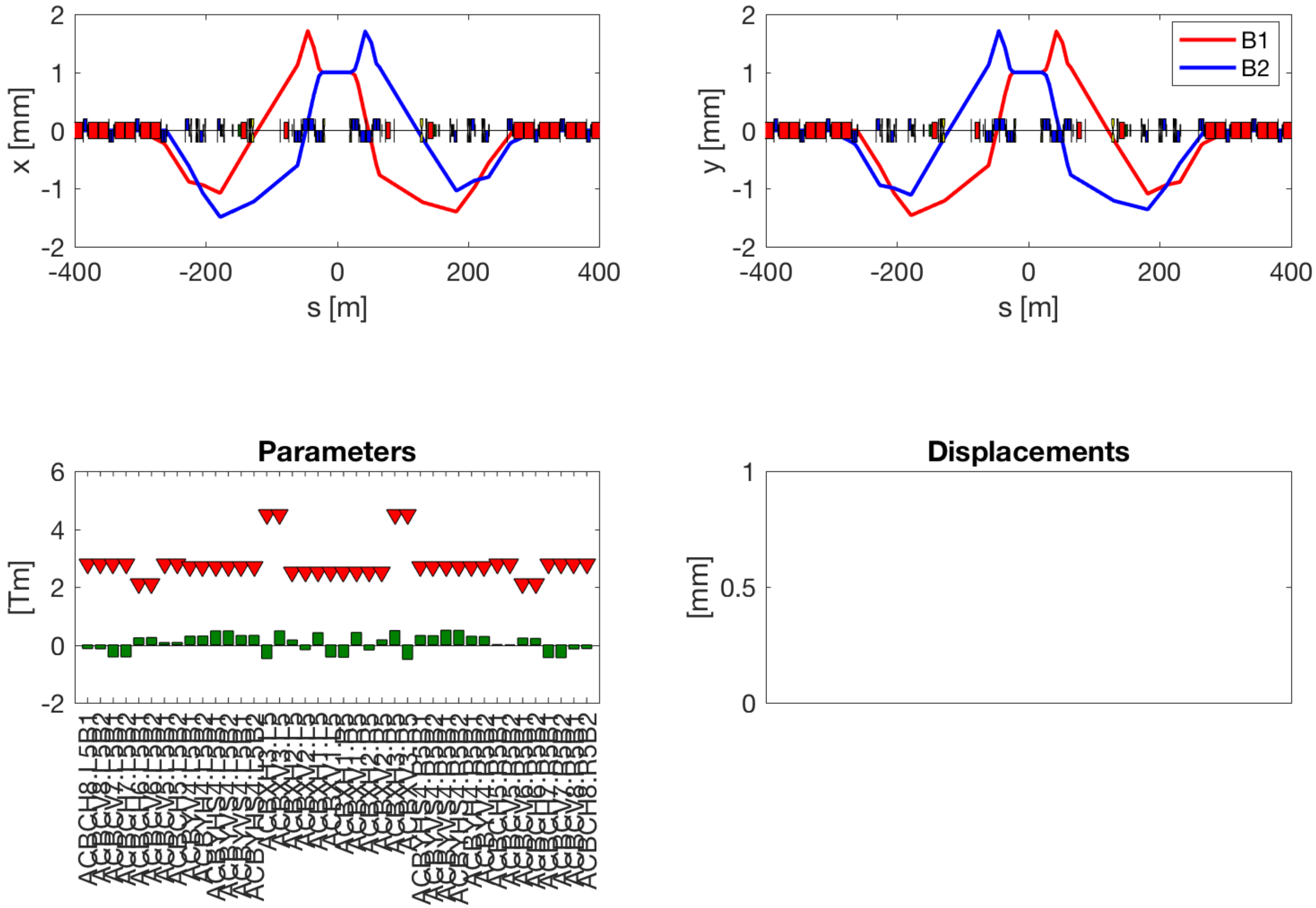




Changes with respect to the baseline:

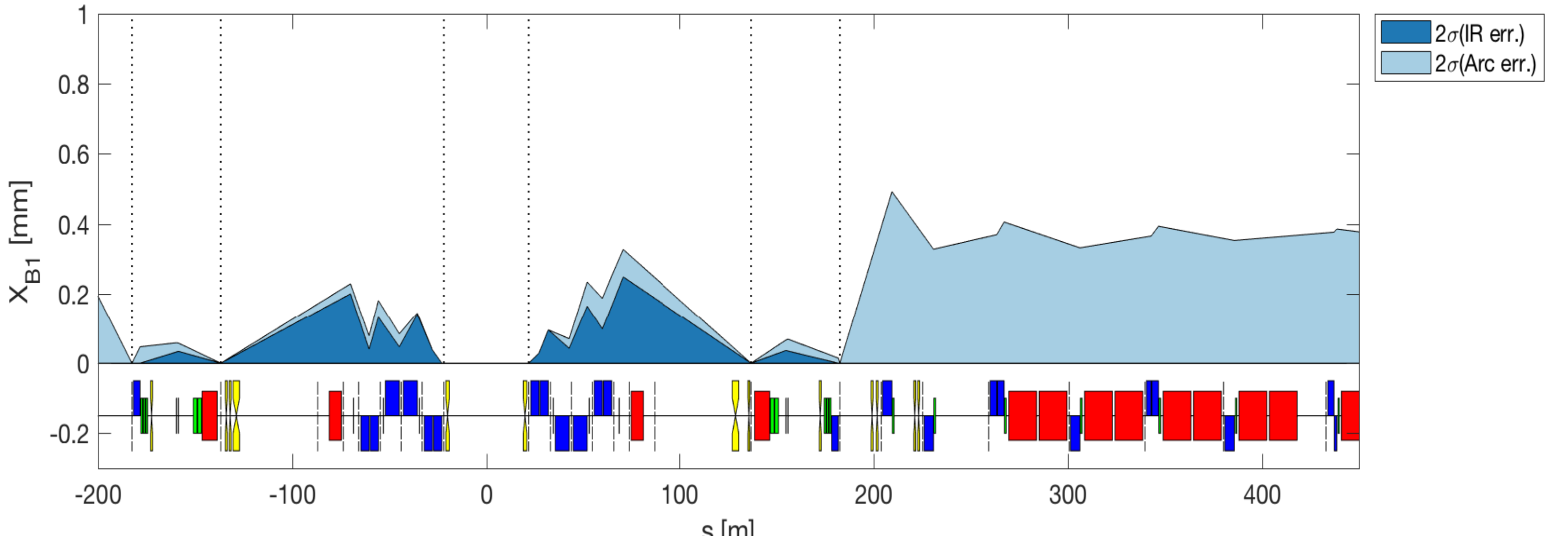
- Q4: reusing existing cold mass (3 correctors instead of 4), no need of 1.9 K.
- Q5: reusing existing Q5 cold mass (1 corrector instead of 3), no need of 1.9 K.
- Full deployment of remote alignment system to be used with safe beam.

IP offset with correctors only (up to Q8) (+1mm)



Orbit corrected as usual at relevant BPMs

- Errors:
  - All square distributions
    - (i.e. if ±0.5 mm, then sigma = 0.5/sqrt(3) = 0.2887 mm)
  - Quadrupoles
    - ±0.5mm DX/DY, ~~±10mm DS, ±0.002 DKR1, ±1 mrad DPSI.~~
      - Presently considering only DX/DY on quadrupoles. Normally DS/DKR1/DPSI has minor impact.
      - To be repeated with "nominal" crossing condition.
  - Dipoles
    - ±10mm DS, ±0.002 DKR0, ±0.5 mrad DPSI.



Do not include BPM errors, but to be compared with 2 mm budget in aperture calculations.

MQW

DCUM	Old slots	Old Circuit	New slots	New Circuit
19870.8	MQWA.A5L7	RQ5.LR7	MQWA.A5L7	RQ5.LR7
19867.0	MQWA.B5L7	RQ5.LR7	MQWA.B5L7	RQ5.LR7
19863.2	MQWB.5L7	RQT5.L7	MQWA.C5L7	RQ5.LR7
19859.4	MQWA.C5L7	RQ5.LR7	MQWA.D5L7	RQ5.LR7
19855.6	MQWA.D5L7	RQ5.LR7	MQWA.E5L7	RQ5.LR7
19851.8	MQWA.E5L7	RQ5.LR7	removed	removed
20117.5	MQWA.A5R7	RQ5.LR7	MQWA.A5R7	RQ5.LR7
20121.3	MQWA.B5R7	RQ5.LR7	MQWA.B5R7	RQ5.LR7
20125.1	MQWB.5R7	RQT5.R7	MQWA.C5R7	RQ5.LR7
20128.9	MQWA.C5R7	RQ5.LR7	MQWA.D5R7	RQ5.LR7
20132.7	MQWA.D5R7	RQ5.LR7	MQWA.E5R7	RQ5.LR7
20136.5	MQWA.E5R7	RQ5.LR7	removed	removed

Radiation Shielding Installation and Possible Optics Change for the MBW and MQW Magnets in IR 3 and 7 of the LHC. Second phase LS2 LS3 and HL-LHC. LHC-MW-EC-0002 v.1.1

Injection optics from R. Bruce, from a branch of HL-LHCV1.3.

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Corrector package

Magnet name		Integrated field at R_{ref}=50 mm [T m]		Magnet coil length [mm]		Magnet length [1] [mm]		Magnetic [3] length [mm]	
		Base line	New value	Base Line [2]	New value	Baseline	New Value	TDR	New Value
Skew quadrupole	MCQSXF	1.000	0.700	728	528	814	614	807	462
Normal sextupole	MCSXF	0.063	0.095	132	192	194	254	111	171
Skew sextupole	MCSSXF	0.063	0.095	132	192	194	254	111	171
Normal octupole	MCOXF	0.046	0.069	119,6	169,6	183	233	87	151
Skew octupole	MCOSXF	0.046	0.069	119,6	169,6	183	233	87	151
Normal decapole	MCDXF	0.025	0.037	118,6	168,6	183	233	95	138
Skew decapole	MCDSXF	0.025	0.037	118,6	168,6	183	233	95	138
Normal dodecapole	MCTXF	0.086	0.086	490	490	575	575	430	465
Skew dodecapole	MCTSXF	0.017	0.017	135	135	200	200	89	92

Source: https://edms.cern.ch/document/1963788/1.0 HL-LHC ECR: WP3 CHANGE OF QUADRUPOLE, SEXTUPOLE, OCTUPOLE AND DECAPOLE CORRECTORS INTEGRATED FIELD

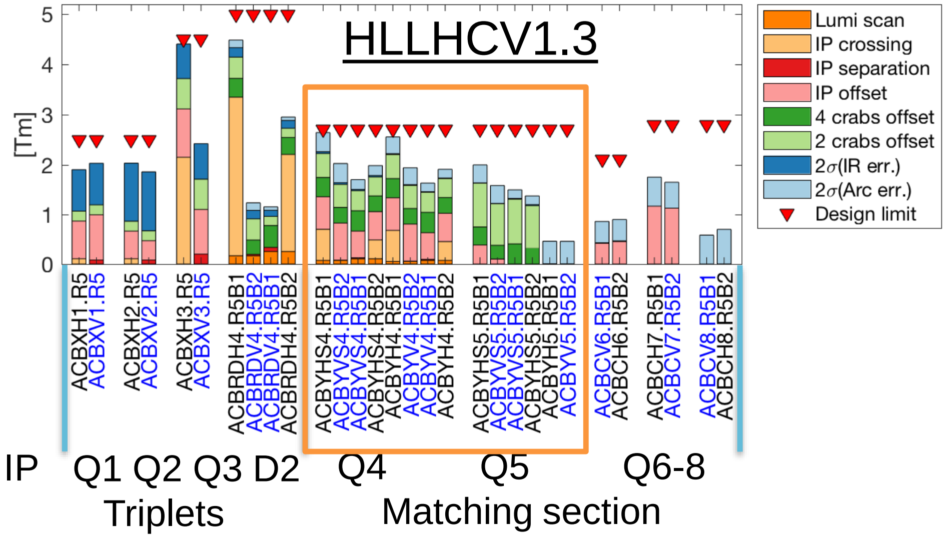
[1]: not the magnetic length; [2] values differ slightly from TDR;

New IR4: No Optics changes

β_{xB1}/β_{yB1} β_{xB2}/β_{yB2}[m]	Pos.	HLLHC <=V1.3 (inj.)	HLLHC 1.4 Inj	LHC 1.4 Round 15cm
e-lens	D3	232/212/281/263	280/280/280/280	280/280/280/280
BSRT/I	D3	136/270/191/365	206/351/206/384	206/351/206/384
BGI	D3-4	279/208/321/245	314/270/314/262	314/270/314/262
WS	D3-4	130/320/178/435	197/402/197/453	197/402/197/453
BQSH	Q5-7	426/ 92/425/226	577/ 58/405/240	515/109/405/240
BQSV	Q5-7	142/371/130/491	201/451/124/506	201/451/ 76/559
BPLH1	Q5-7	400/135/420/256	543/117/396/270	481/165/387/276
BPLH2	Q5-7	403/ 89/431/165	543/ 51/479/168	492/104/432/230
BPLV	Q5-7	193/337/180/500	260/389/201/517	251/405/201/517
BQLV2	Q5-7	-/-/129/470	-/-/124/483	-/-/ 73/530
BPLX	Q5-7	277/234/296/356	375/246/280/371	346/283/251/397

Flat 30/7.5 cm and 18/7.5 cm optics are also possible.

Orbit corrector strength budget



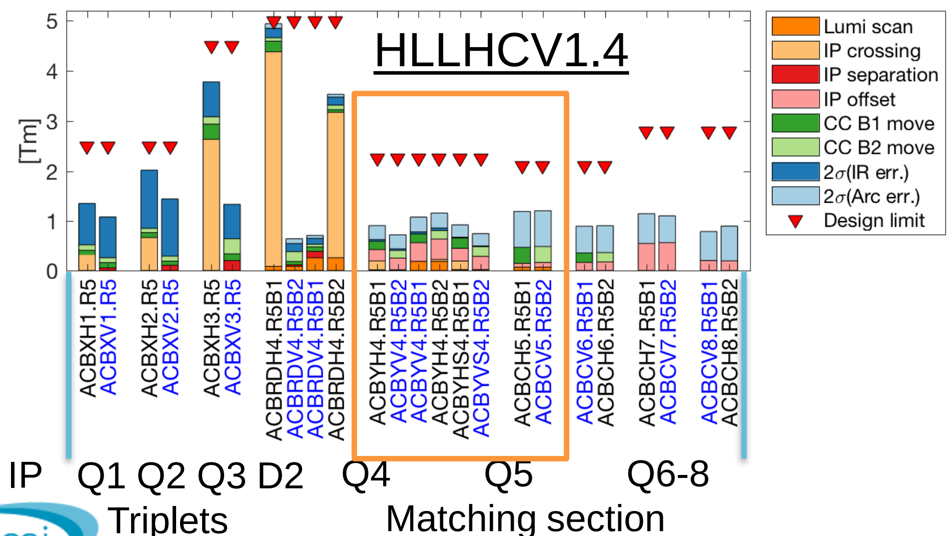
Right Point 5, H crossing.

The following symmetries apply:

- Left B1 -> Right B2,
- Left B2 -> Right B1
- H Point 5 -> V Point 1

HLLHCV1.4:

- orbit bumps reduced at the crab cavities
- IP offset performed by remote alignment
- Limited crab beam adjustment still possible

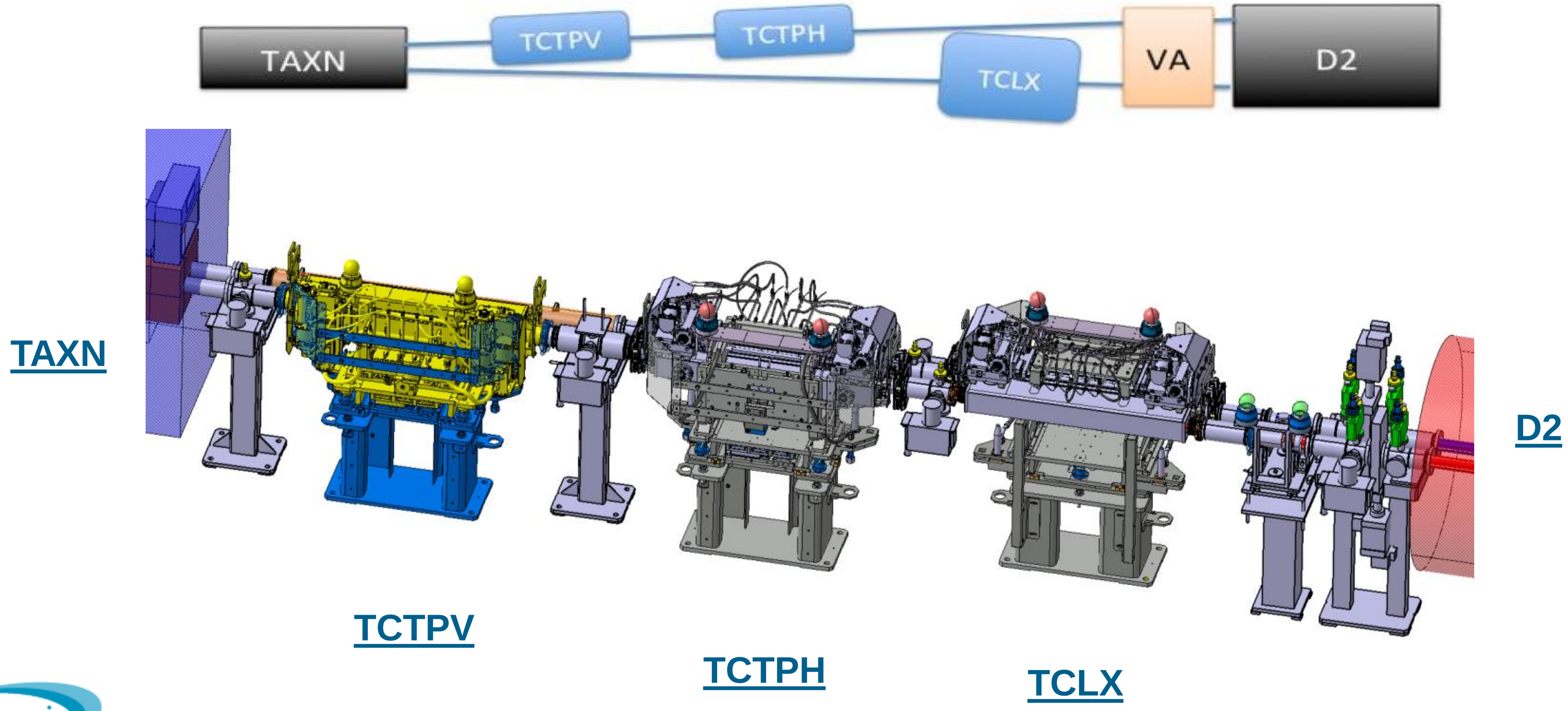


Crossing: ±295 μrad
Separation: ±0.75 mm
IP Offset: ±2.0 mm with re-alignment
Luminosity scan: ±100 μm
Crab knobs: ± 0.5 mm (baseline only)
Imperfection (2σ): from uniform distribution of mainly ±0.5 mm quad. alignment and 0.5 mrad / 20 units dipole errors.

TCLX – TCPH issues in HLLHC

- Beam size in between TAXN – D2 is much larger than LHC due to lower β* and D2 closer to the triplet, beam separation smaller than LHC because D1 – D2 distance is shorter.
- TCLX needs thicker internal jaw to provide dose protection to D2

-> Larger stroke in less space.



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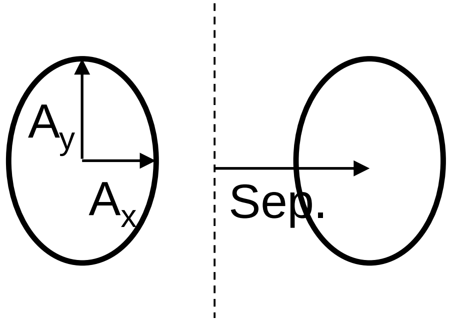
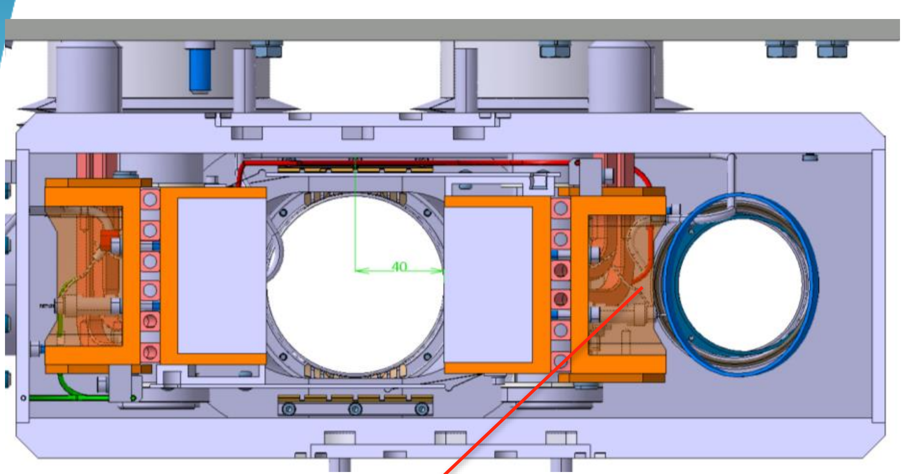
TCL-TCT Aperture specifications

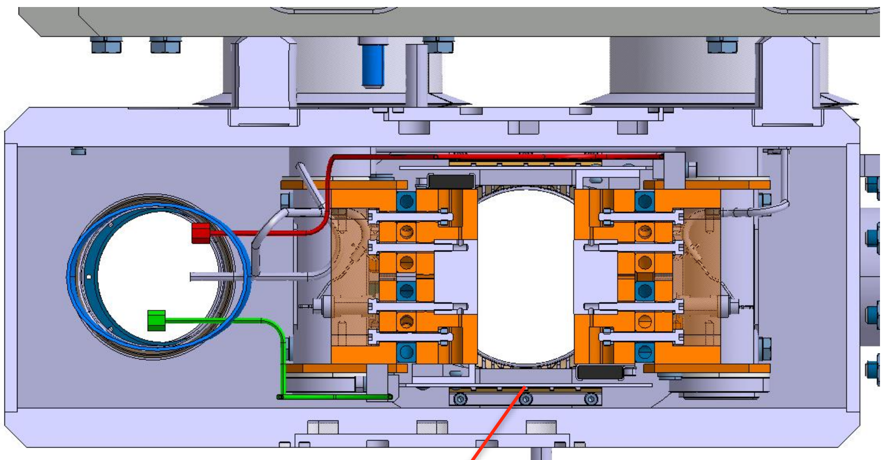
Offset (X,Y)	Baseline		Remote alignment		
Ground Motion + Fiduc.	~2 mm		~0.5 mm		
Orbit Error + crab adj.	2.5 mm		2.5 mm		
Collimator stroke	15 σ + 10 % (β-beat)		15 σ + 10 % (β-beat)		
Protected aperture	12 σ + 10 % (β-beat)		12 σ + 10 % (β-beat)		
2 mm IP shift	With orbit correctors		With re-alignment		
Round 15 cm	**A_x [mm]**	**A_y [mm]**	**A_x [mm]**	**A_y [mm]**	**Sep. [mm]**
TCLX	36.4	27.9	31.9	26.1	86.0-87.5
VTCLX	28.0	36.4	26.1	31.9	86.0-87.5
TCTPH	28.5	37.1	26.5	32.7	83.4-84.9
VTCTPH	37.0	28.1	32.5	26.4	83.4-84.9
TCTPV	28.9	38.0	26.9	33.7	80.4-81.9
VTCTPV	38.1	28.7	33.7	26.9	80.4-81.9
Flat 7.5/18 cm	**A_x [mm]**	**A_y [mm]**	**A_x [mm]**	**A_y [mm]**	**Sep. [mm]**
TCLX	42.8	33.8	38.3	32.0	86.0-87.5
VTCLX	33.9	42.9	32.1	38.4	86.0-87.5
TCTPH	34.2	43.5	32.3	39.1	83.4-84.9
VTCPTH	43.3	34.0	38.8	32.2	83.4-84.9
TCTPV	34.5	44.3	32.6	39.9	80.4-81.9
VTCTPV	44.2	34.5	39.8	32.5	80.4-81.9

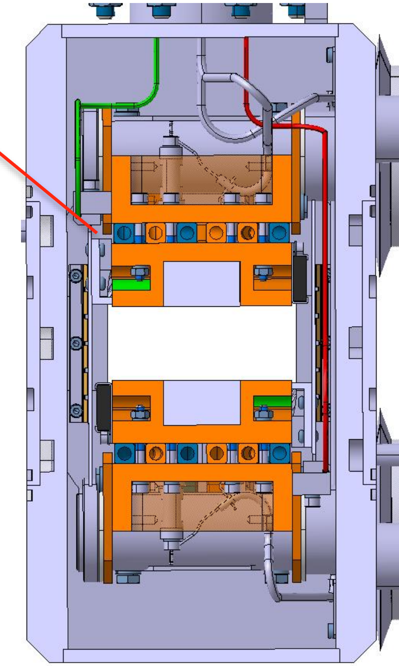


ColUSM, 23/2/2018

New design proposal







	Stroke	Chamber H/V
TCLX	40 mm	65/80 mm
TCTPH	32.5 mm	80/65 mm
TCTPV	40 mm	n/a

Remote alignment meeting, L. Gentini, 31/5/2018

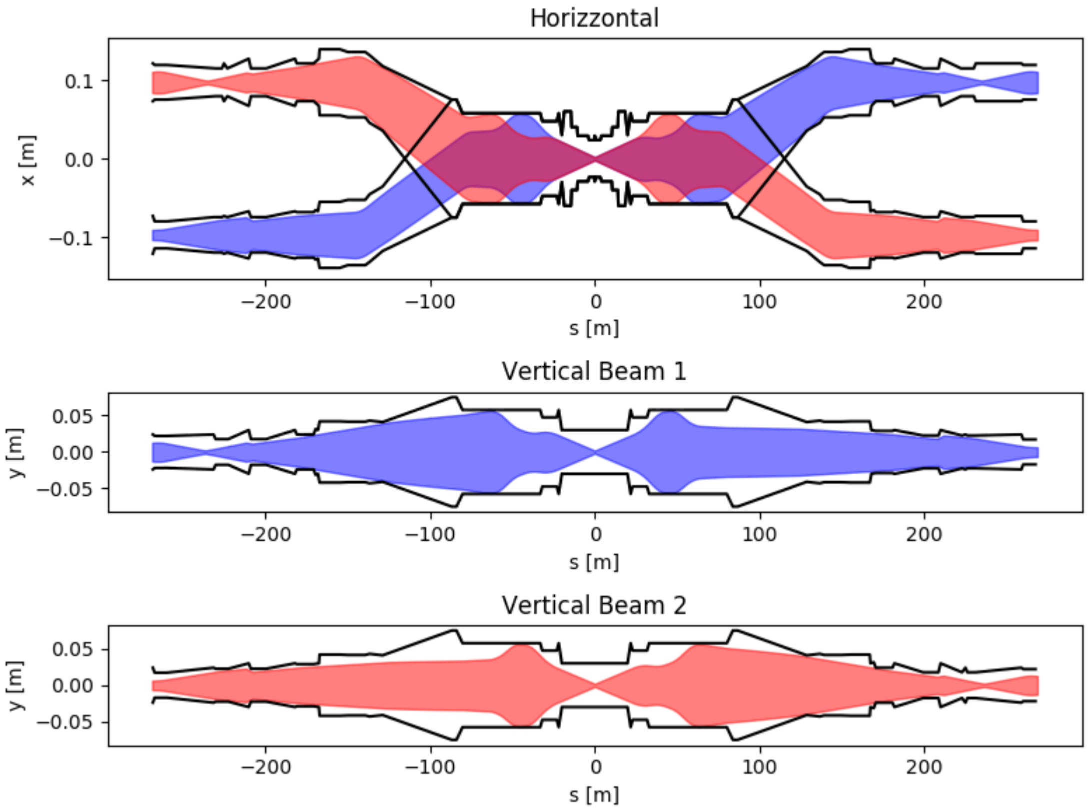
Aperture for vacuum layout

WP12 asked beam envelope without mechanical, alignment and fiducialization tolerances to specify vacuum apertures.
The request inverts the typical work flow because mechanical, alignment and fiducialization are not finalized.

Recipe given:

Beam stay clear =
$1.1\ n_\sigma\ \sigma_{nominal} + 2$ mm
where:
n_σ = 13.25 up to D1
n_σ = 15 TAXN-Q5
n_σ = 20 sigma Q6 to Q7.

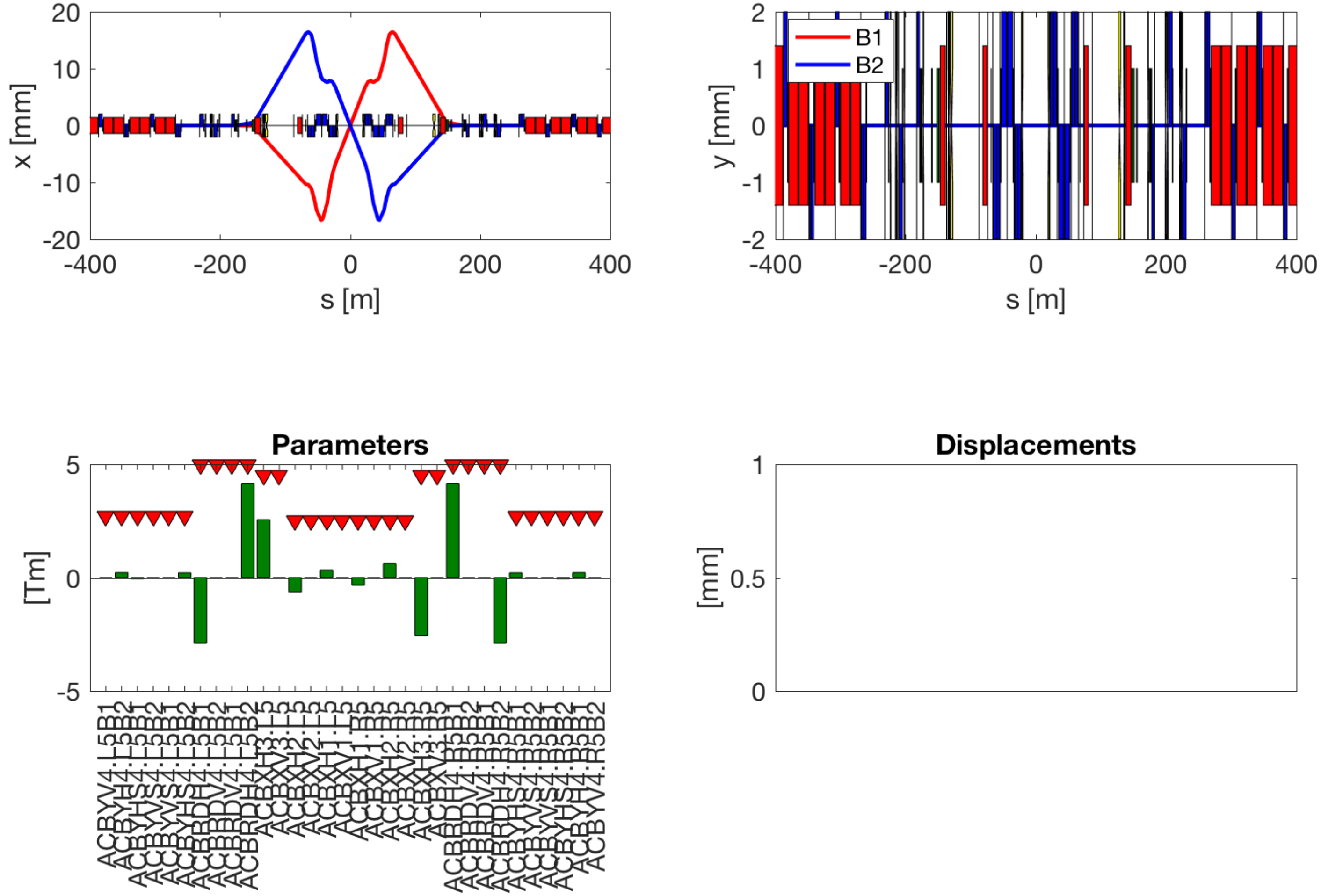
In addition, new vacuum aperture should always have larger margins than those found in the triplet.
Table available here.



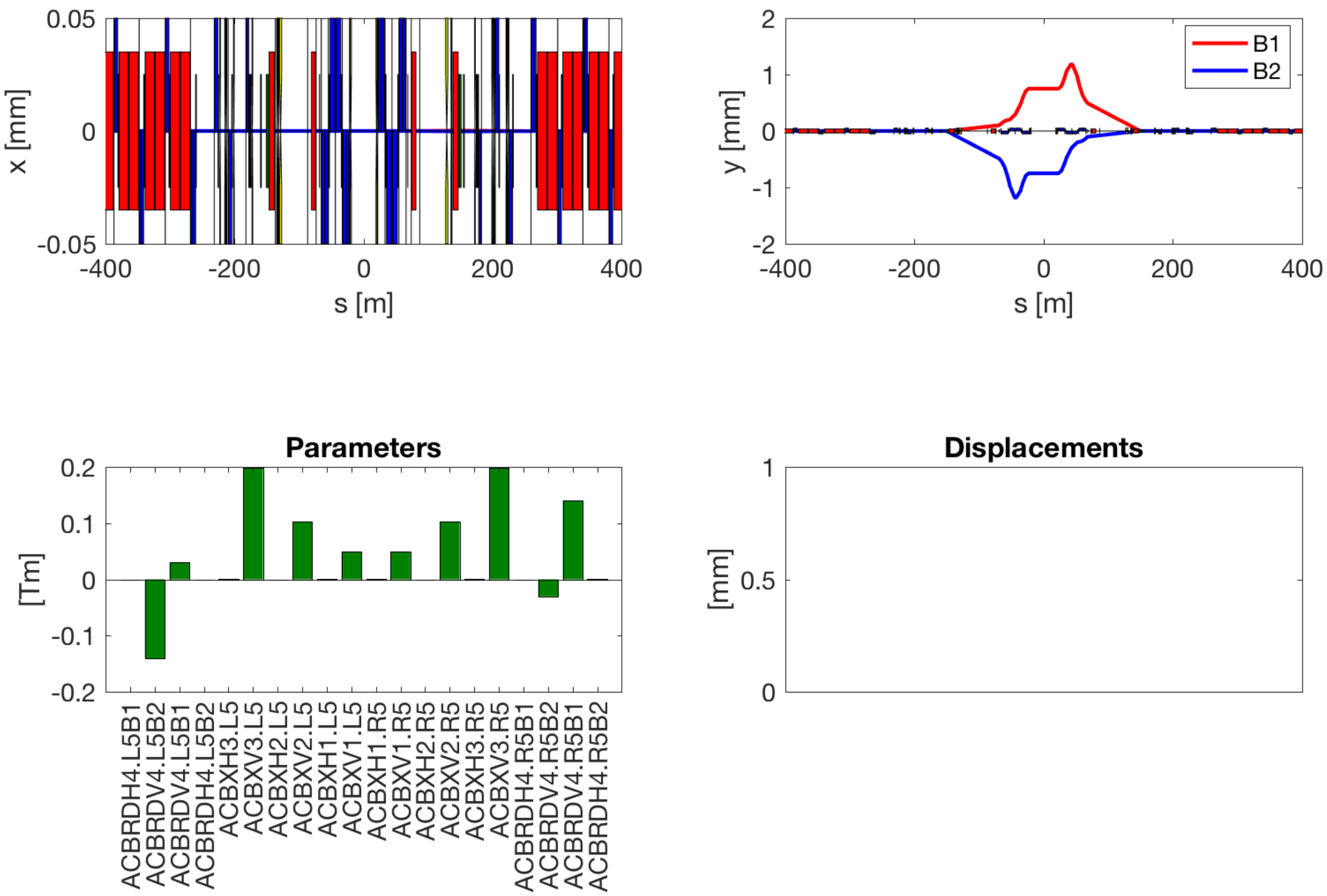
Consistent with present hardware and avoid additional aperture bottleneck.

HiLumi HL-LHC PROJECT

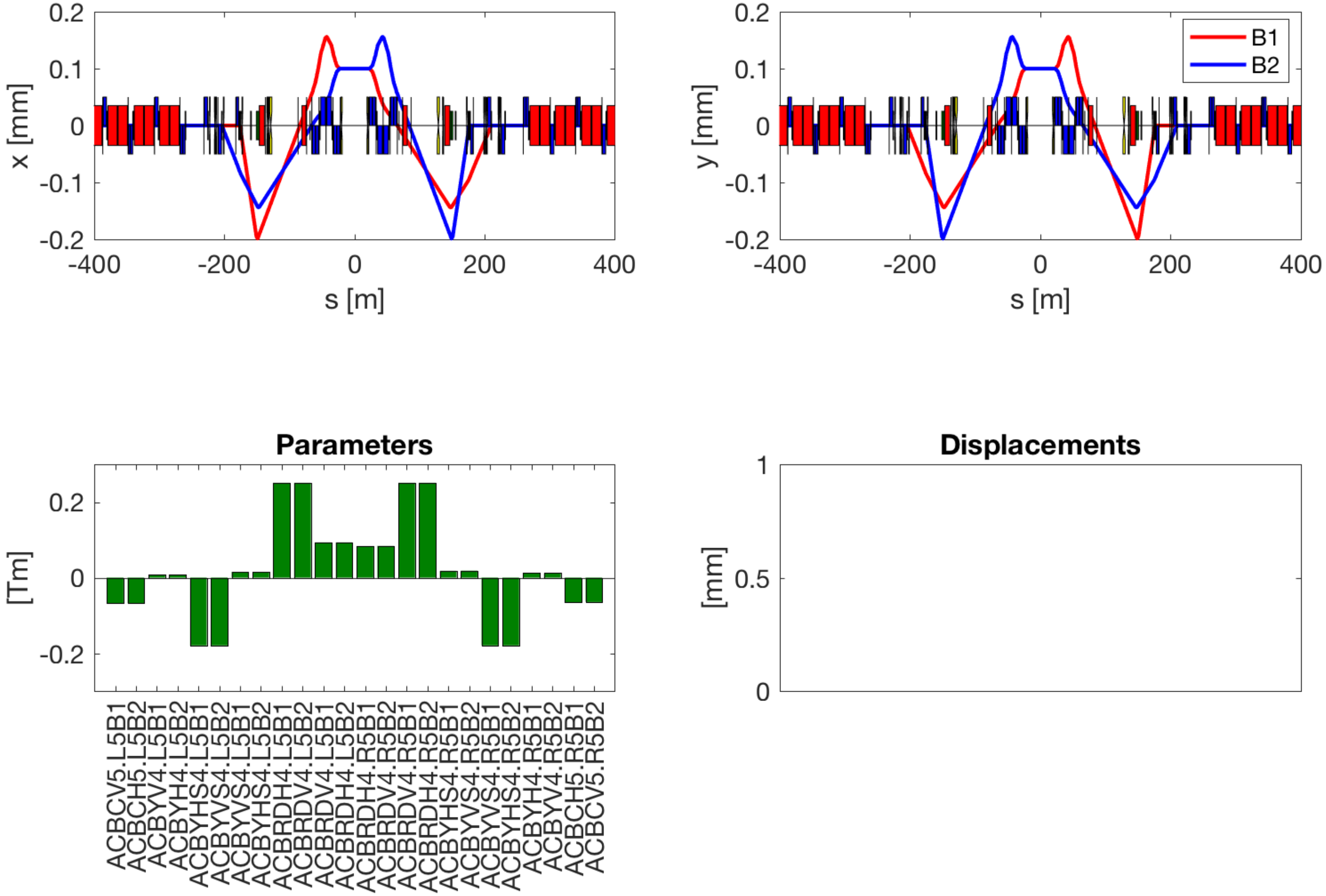
IP crossing (+-295 urad)



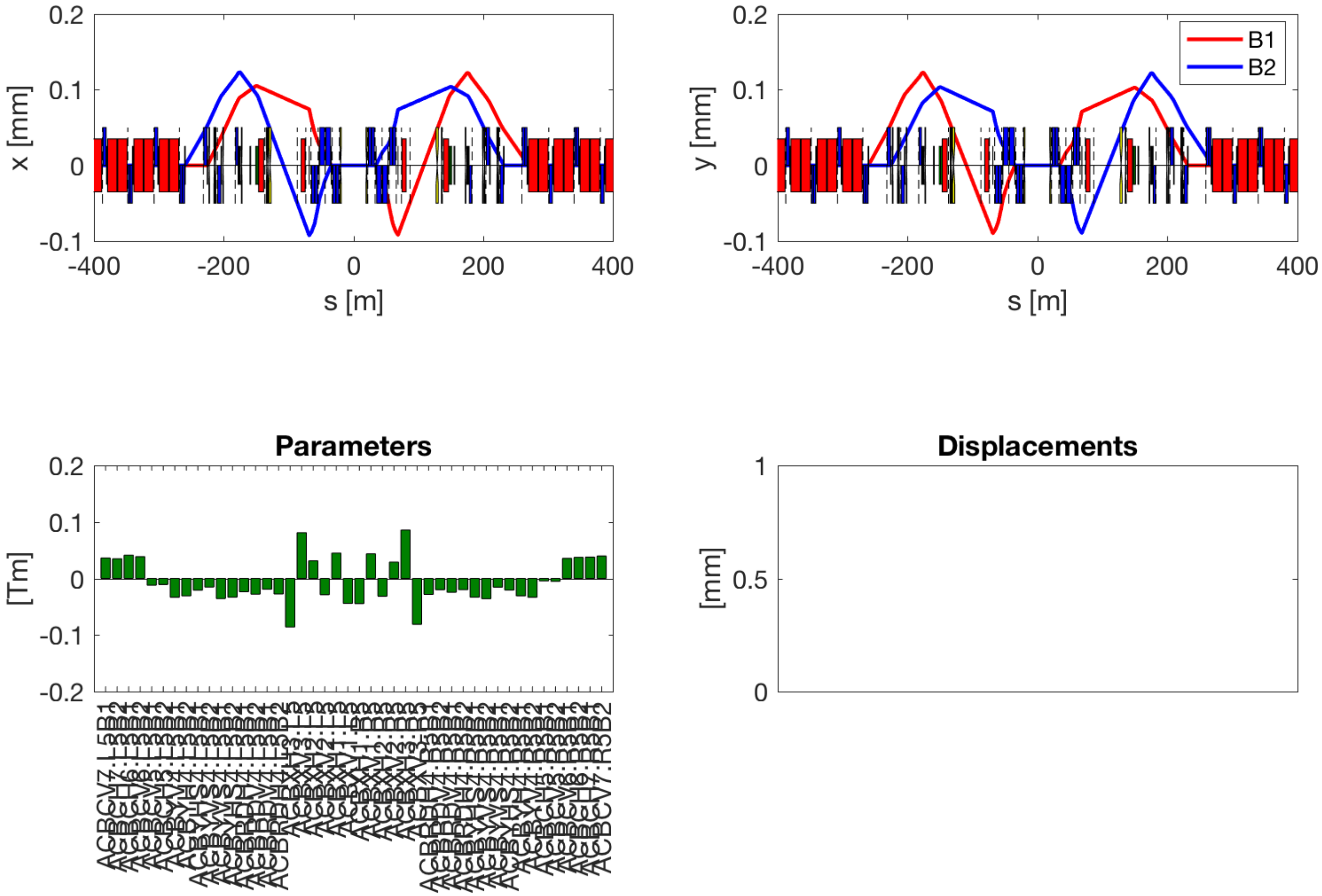
IP separation (+- 0.75 mm)



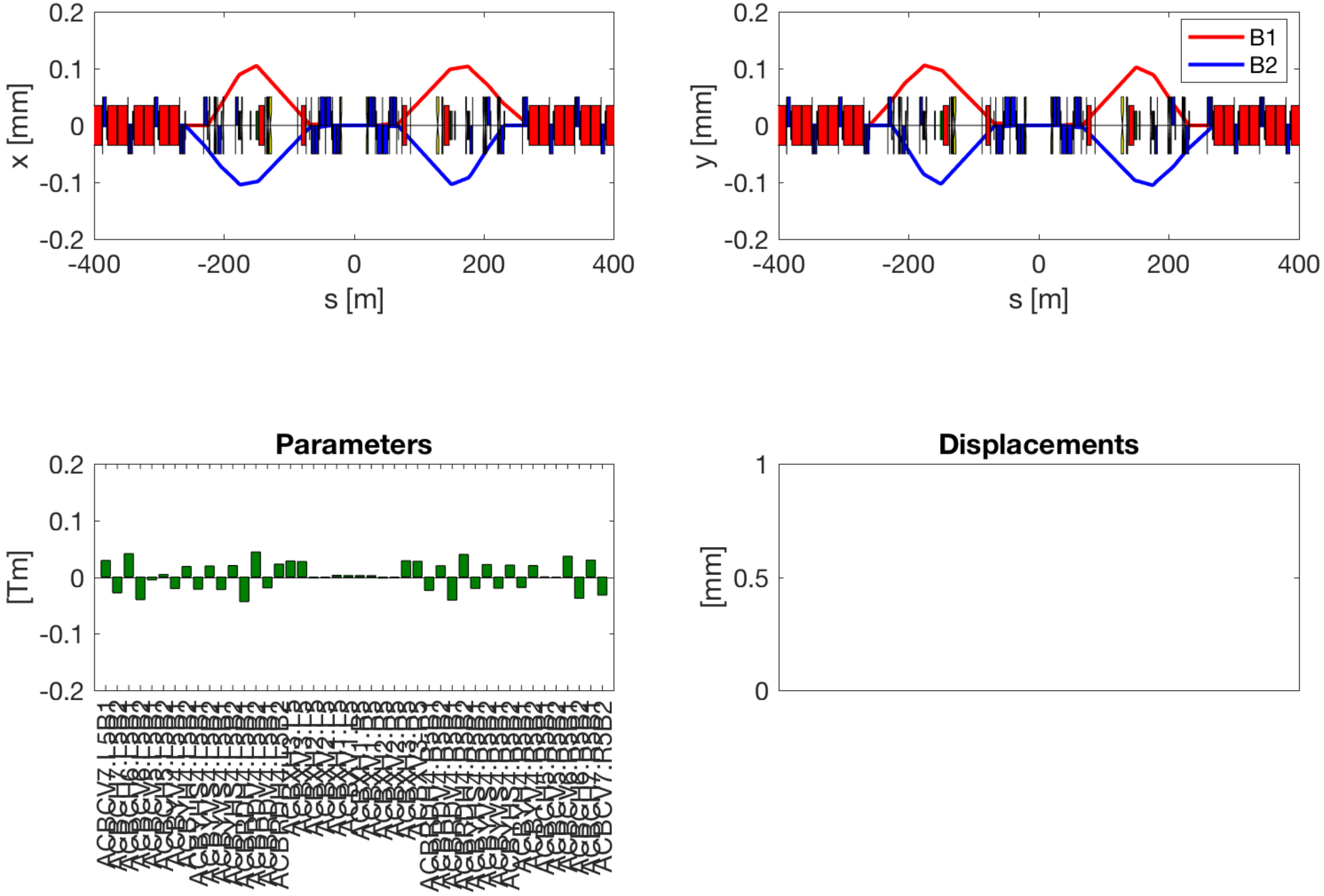
Lumiscan (+- 100 um)



CC offset (100 um)



CC separation (+- 100 um)



IR6 Current

- Latest measurements, LMC 21/3/2018, A. Verveij

	Current [A]	Gradient [T/m]
Nominal	3610	160.0
Ultimate	3900	172.8
SS Limit 4.5K	4200	186.1
SS Limit 1.5K	5800	257.0
Training	3950	175.0

	HLLHCV1.4 @ 7TeV		
	Round	FlatCC	Flat
β* Xing/Sep [cm]	15/15	18/7.5	30/7.5
Q5.L6 [T/m]	163/165	160/167	148/171
Q5.R6 [T/m]	159/151	160/150	161/147

Few T/m reduction w.r.t HL1.3 in particular for Q5.R6

NoMs14 branch to be done.

One needs to add 1% margin for optics correction + 50 amps.
7.5 TeV operation should guaranteed for Run V.

Preview Next steps

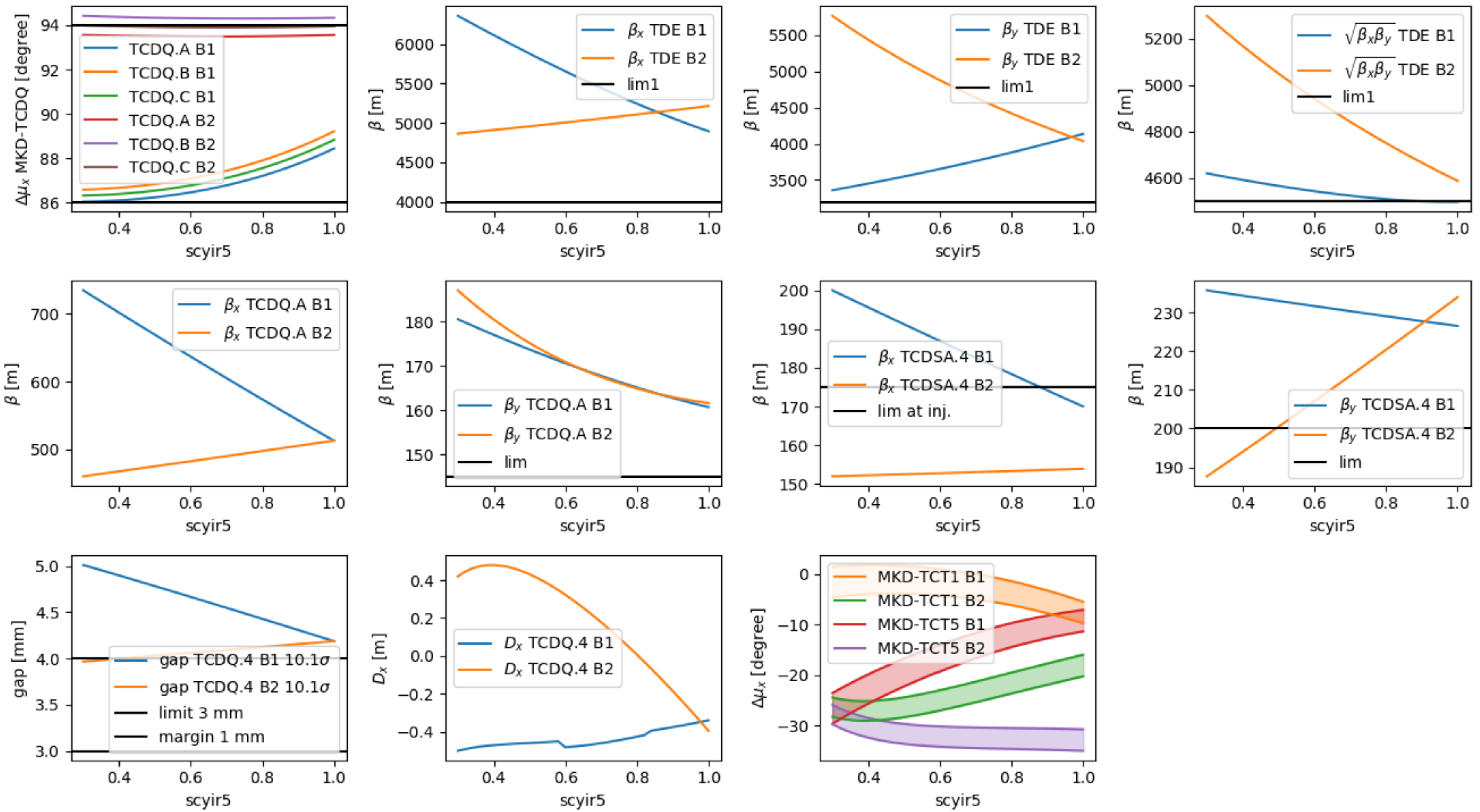
To release version 1.4:

1. Decision or study new position for Q4/Q5 for cryogenic integration. [Done]
2. Decision on how to gain 30 cm in between D2/crab cavities. [Done]
3. Consistency check between drawings and optics model. [On going]
4. Optimization crossing schemes and other orbit bumps. [Done]
5. Finalization IR6 optics and IR4 optics. [On going]
6. Freeze mechanical, ground motion, fiduc. tolerances. [On going]
7. Computation aperture margins and phase advance tunability. [On going]
8. Evaluation/choice of crossing planes. [On going]

Studies in parallel:

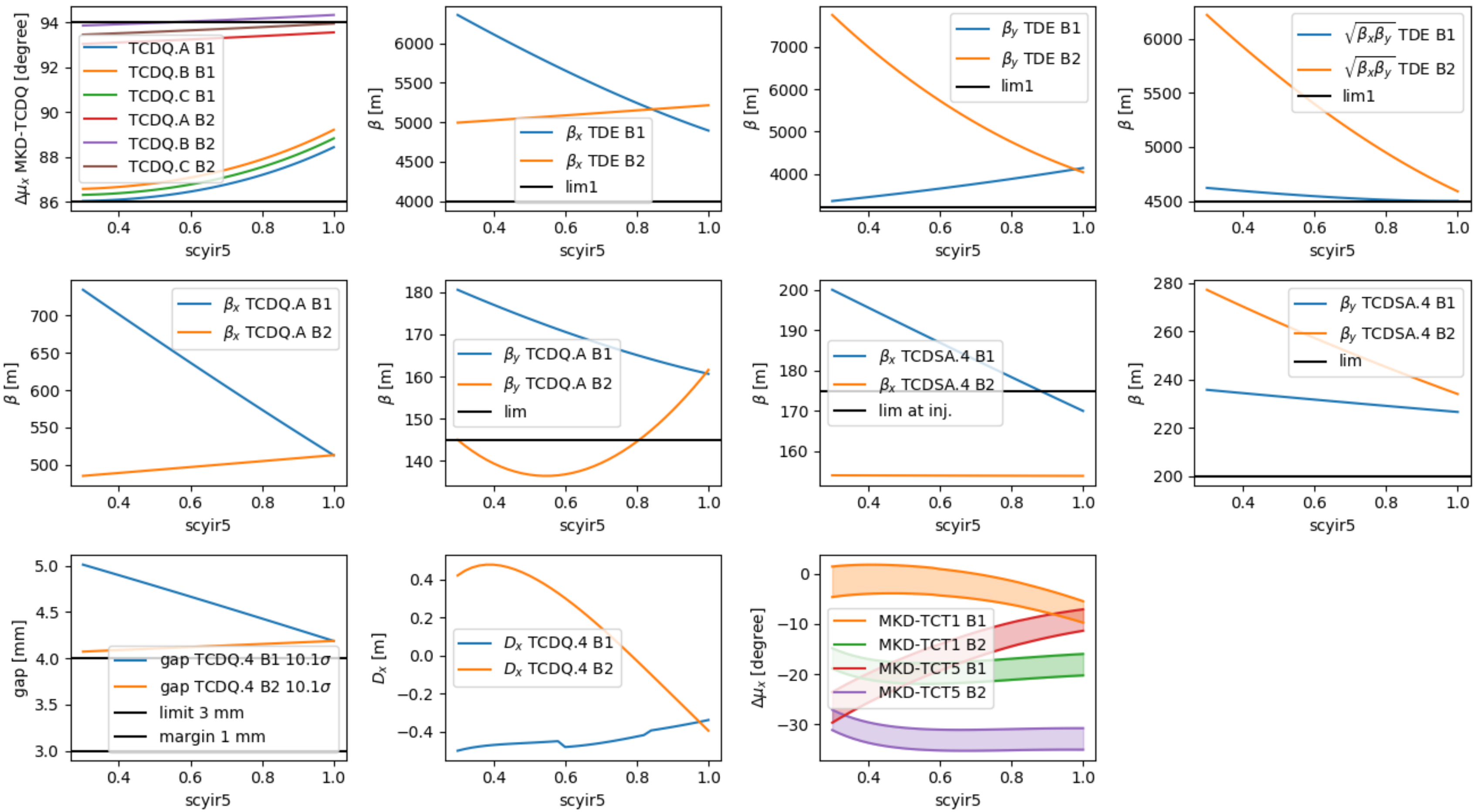
- Study optics at 7 TeV with ultimate currents in Q7 (more urgent if we want to ask for an hardware test at the end of the run). [Done]
- Update MS10 branch and follow-up of the DA studies. [On Going]
- Optics optimization for forward physics. [On Going]

Round



Possible improvement: increase TCDQ gap in B2

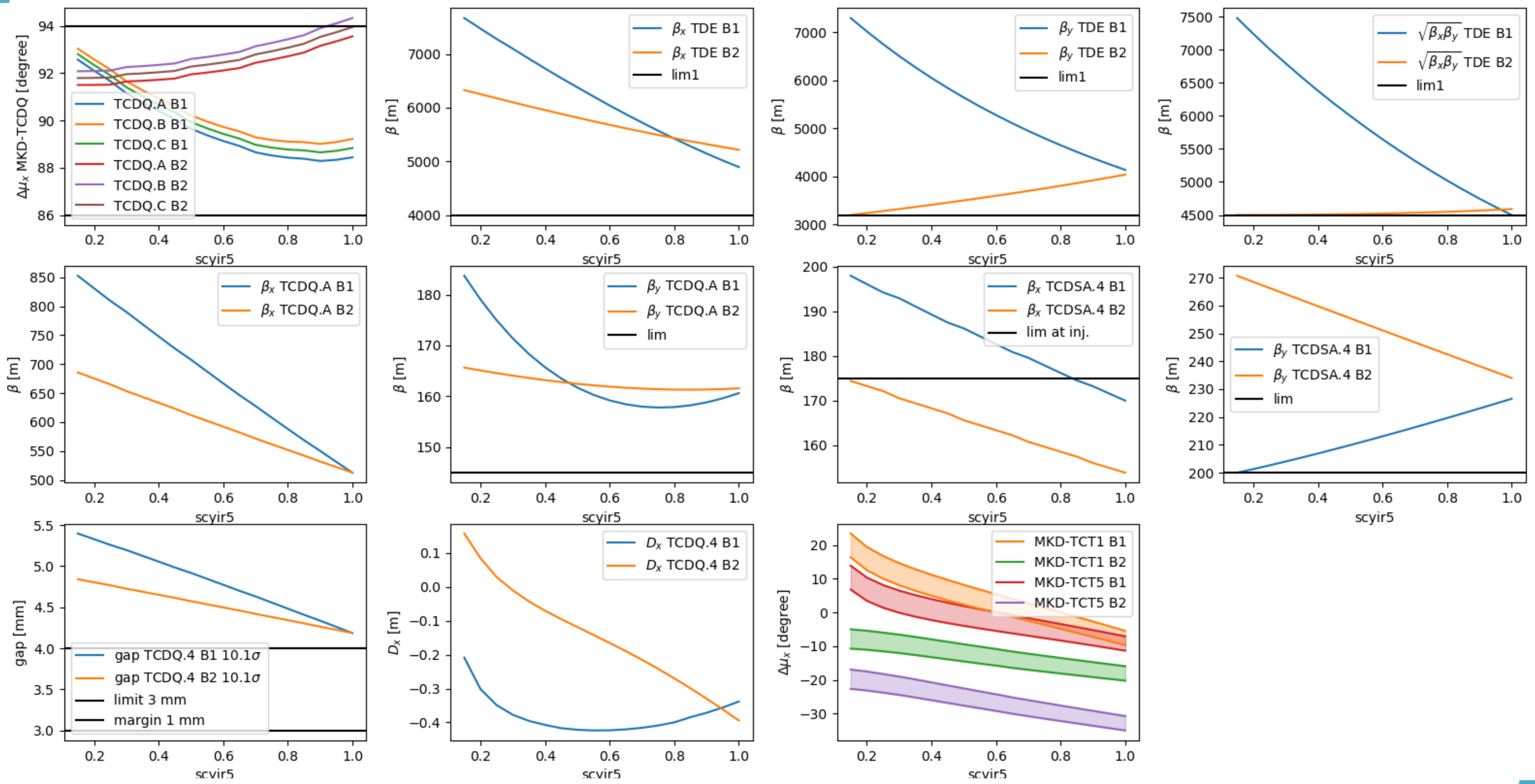
Round Optics



TCDQ settings:

- Beam1: 5 mm: from 12.3σ →10.1 σ: β increases during the squeeze
- Beam2: 3.9 mm: from 9.6 σ → 10.1 σ. β decreases during the squeeze

Flat (7.5/30 cm)



$\Delta\mu_x$ MKD-TCDQ [degree]
TCDQ.A B1
TCDQ.B B1
TCDQ.C B1
TCDQ.A B2
TCDQ.B B2
TCDQ.C B2
scyir5
β [m]
β_x TDE B1
β_x TDE B2
lim1
β_y TDE B1
β_y TDE B2
lim1
$\sqrt{\beta_x\beta_y}$ TDE B1
$\sqrt{\beta_x\beta_y}$ TDE B2
lim1
β_x TCDQ.A B1
β_x TCDQ.A B2
β_y TCDQ.A B1
β_y TCDQ.A B2
lim
β_x TCDSA.4 B1
β_x TCDSA.4 B2
lim at inj.
β_y TCDSA.4 B1
β_y TCDSA.4 B2
lim
gap [mm]
gap TCDQ.4 B1 10.1σ
gap TCDQ.4 B2 10.1σ
limit 3 mm
margin 1 mm
D_x [m]
D_x TCDQ.4 B1
D_x TCDQ.4 B2
$\Delta\mu_x$ [degree]
MKD-TCT1 B1
MKD-TCT1 B2
MKD-TCT5 B1
MKD-TCT5 B2

FlatCC (7.5/18 cm)