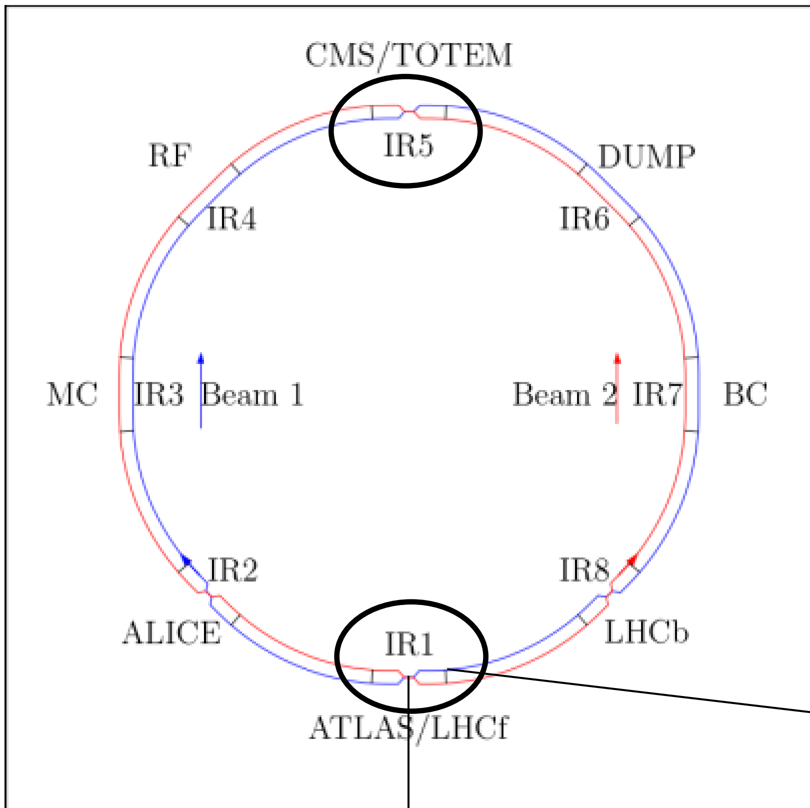
HL-LHC Optics and Layout Overview

R. De Maria for the HL-LHC teams

Thanks to R. Appleby, G. Arduini, A. Bogomyakov, O. Brüning, R. Bruce, R. Calaga, F. Cerutti, S. Chemly, B. Dalena, L. Esposito, S. Fartoukh, P. Fessia, P. Ferracin, M. Fitterer, M. Giovannozzi, R. Jones, S. Kelly, M. Korostelev, C. Milardi, J. Payet, T. Pieloni, H. Prin, S. Redaelli, L. Rossi, S. Russenshuck, M. Thomas, L. Thompson, E. Todesco, R. Tomas.

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

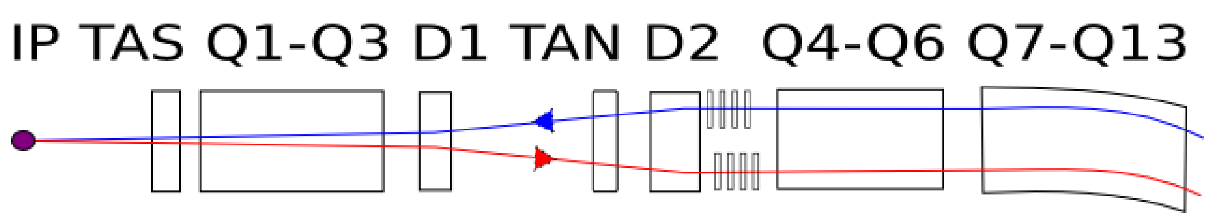
LHC Ring and Interaction Region (IR) layout



High luminosity experiments ATLAS and CMS relies on (compared to nominal):

- Large flux of debris irradiated from the interaction point (IP)
- Smaller spot size (small β*) at the IP
- Crab cavities for luminous region optimization.

Hardware, layout and optics of the interaction region (IR) around IP1 and IP5 needs upgrade and review.



β*reach: optics

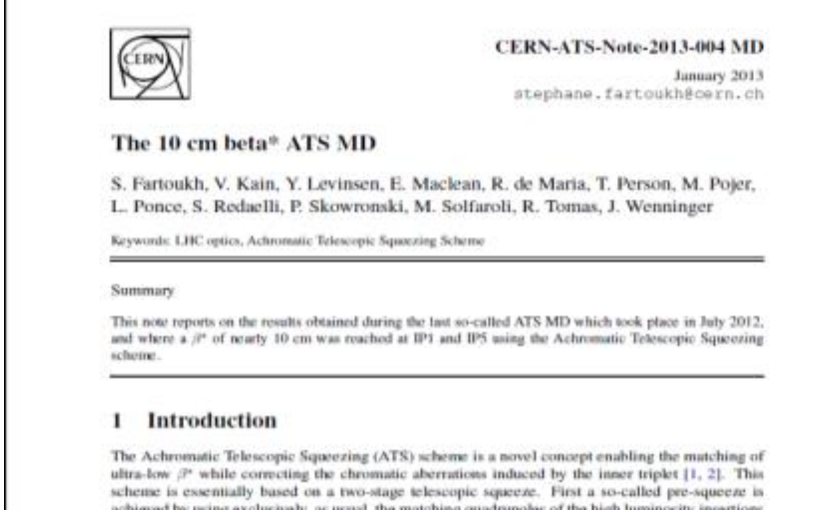
S. Fartoukh, Chamonix 2011, 2012 and reference therein

Low β* traditionally limited by optics flexibility and chromatic aberrations.

ATS optics established on paper and with beam in the present LHC.

Baseline β*: 15 cm, or 30/7.5 cm

Ultimate β*: 10 cm or 20/5 cm


CERN-ATS-Note-2013-004 MD

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The 10 cm beta* ATS MD

S. Fartoukh, V. Kain, Y. Levinsen, E. Maclean, R. de Maria, T. Person, M. Pojer, L. Ponce, S. Redaelli, P. Skowronski, M. Solfaroli, R. Tomas, J. Wenninger

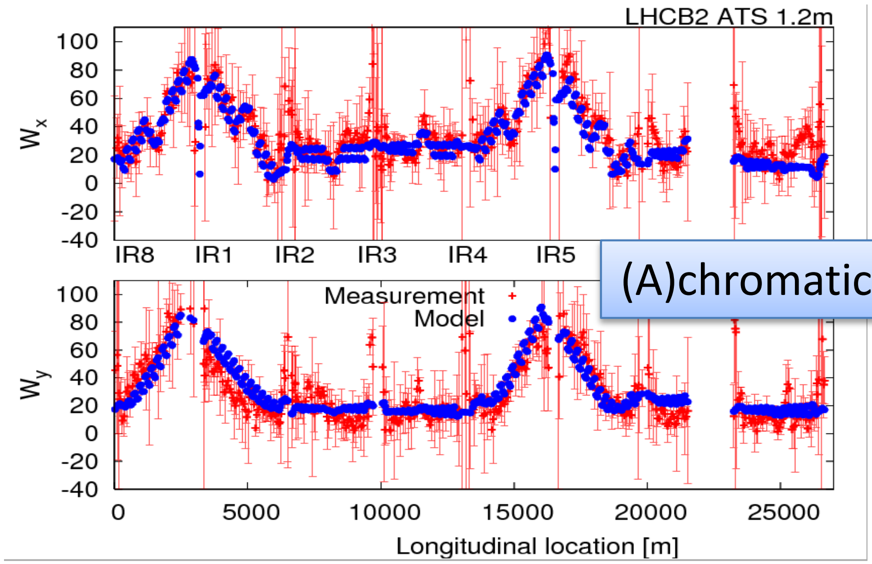
Keywords: LHC optics, Achromatic Telescopic Squeezing Scheme

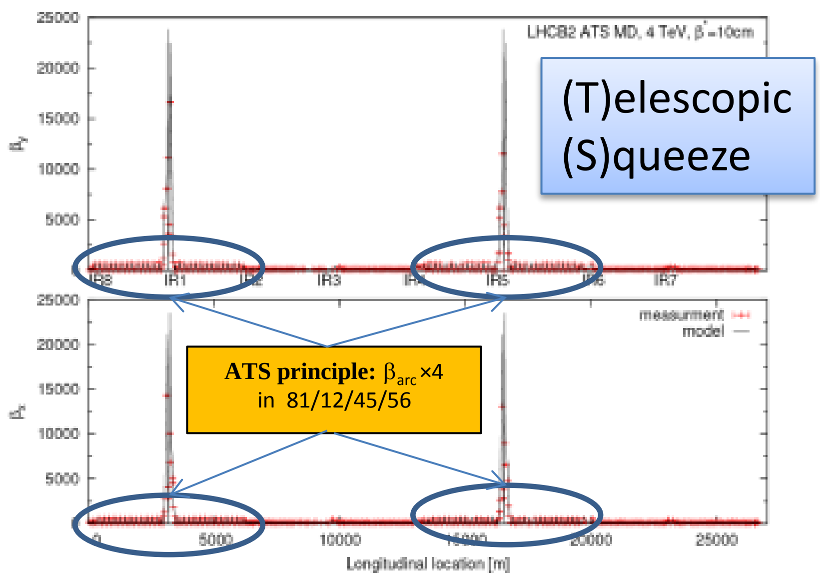
Summary

This note reports on the results obtained during the last so-called ATS MD which took place in July 2012, and where a β^* of nearly 10 cm was reached at IP1 and IP5 using the Achromatic Telescopic Squeezing scheme.

1 Introduction

The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet [1, 2]. This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is





Leveling

$$L_{\text{lev}} \sim n_{\text{pileup}} \cdot n_{\text{bunches}}$$

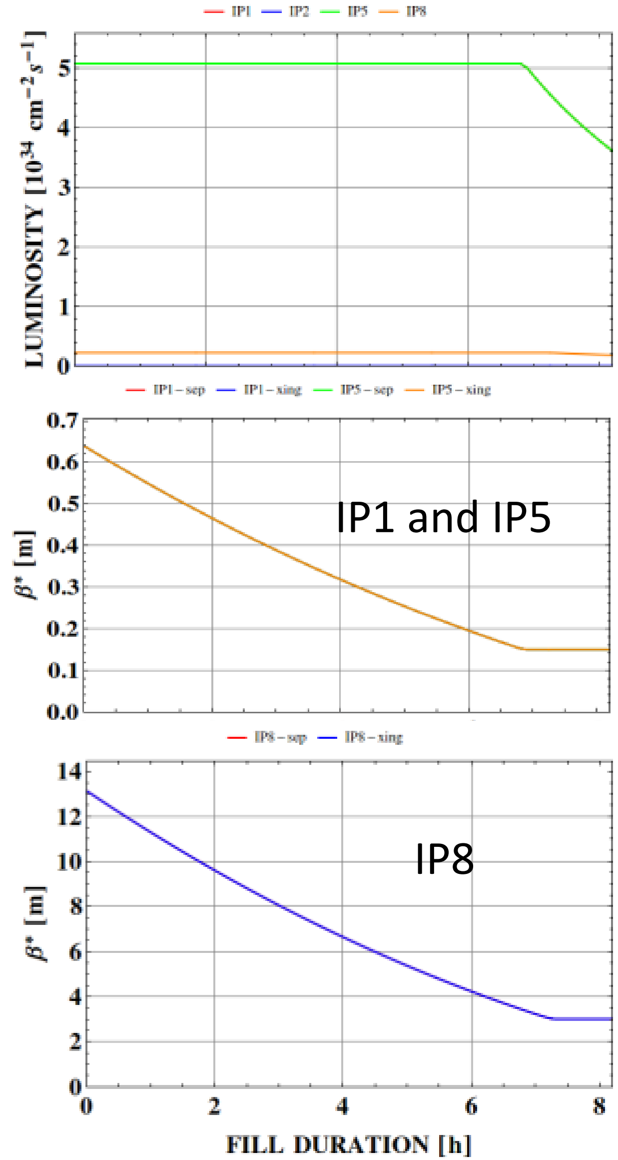
Experiments' useful luminosity limited by number of event per crossing (pile-up): 140 to 200.

Luminosity needs to be leveled:

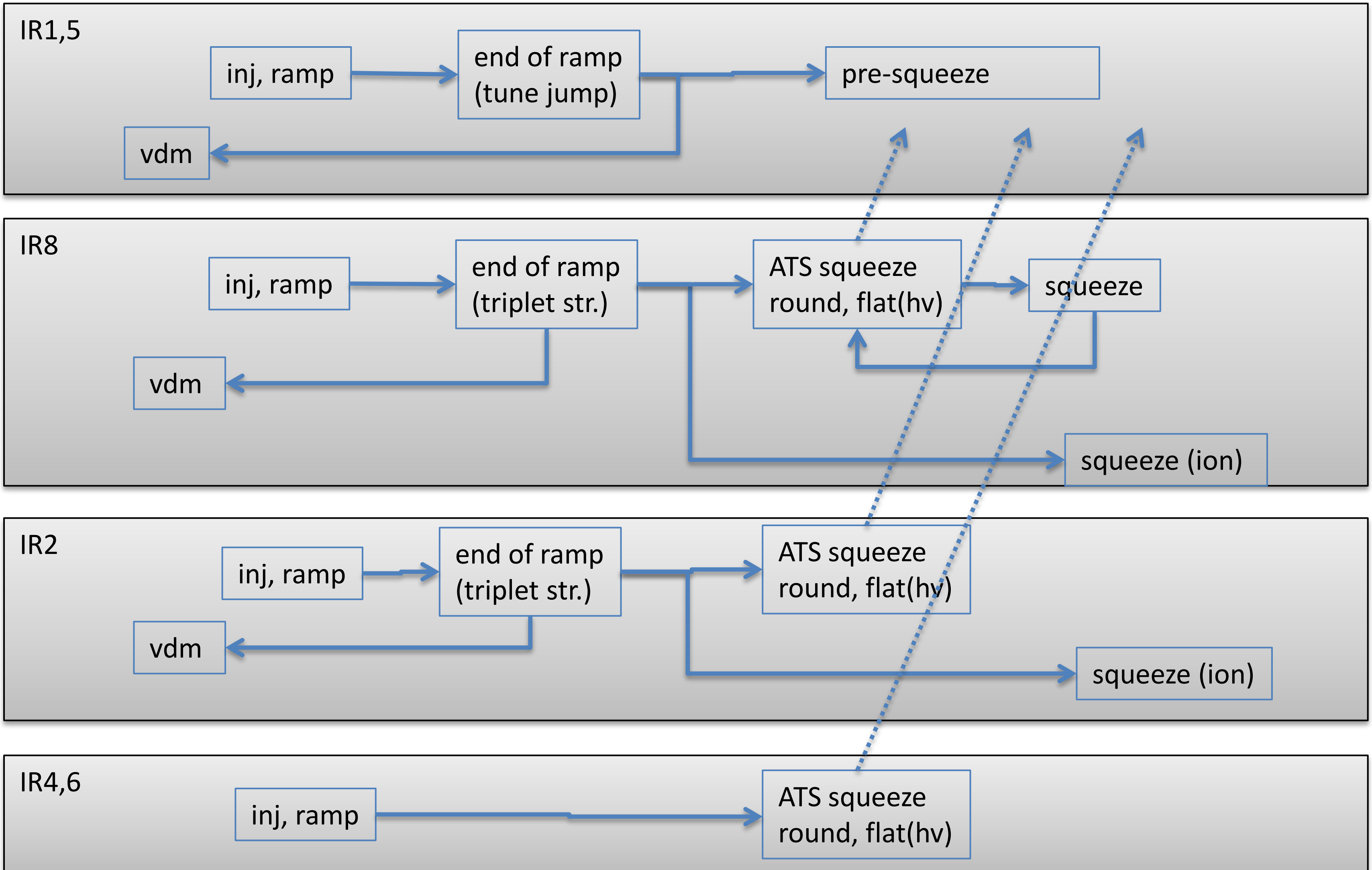
- IP1-5: leveling by β* with a combination of local and ATS squeeze
- IP8: β* or separation or a combination of them.

Main challenge: keep beam into collision for long time (~1 µm stability) while varying quadrupole and orbit corrector strengths in order to avoid:

- luminosity loss,
- lifetime losses,
- Instabilities.



Optics Transitions Overview



Collision low-β optics parameters

Name	IP1-5			IP2			IP8		
	β* [cm]	Angle [murad]	sep [mm]	β* [m]	Angle [murad]	sep [mm]	β* [m]	Angle [murad]	sep [mm]
Round	**15**	**590**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
flat	**7.5, 30**	**550**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
flathv	**30, 7.5**	**550**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
sround	10	720	0.75	10	340	2	3	340	2
sflat	5, 20	670	0.75	10	340	2	3	340	2
sflathv	20, 5	670	0.75	10	340	2	3	340	2
ions	**44**	**350**	**0.75**	**0.5**	**340**	**2**	**0.5**	**340**	**2**

- Optics available under /afs/cern.ch/eng/lhc/optics/HLLHCV1.0 1)
- Baseline round and flat optics at 15 cm or 7.5/30 cm.
- Ultimate squeeze for improved performance provided tight collimation settings.
- Optics for ion operations with low β* in all Ips.

1) R. De Maria, S. Fartoukh, A. Bogomiakov, M. Korostelev, HLLHCV1.0:…, IPAC13)

Supporting optics parameters

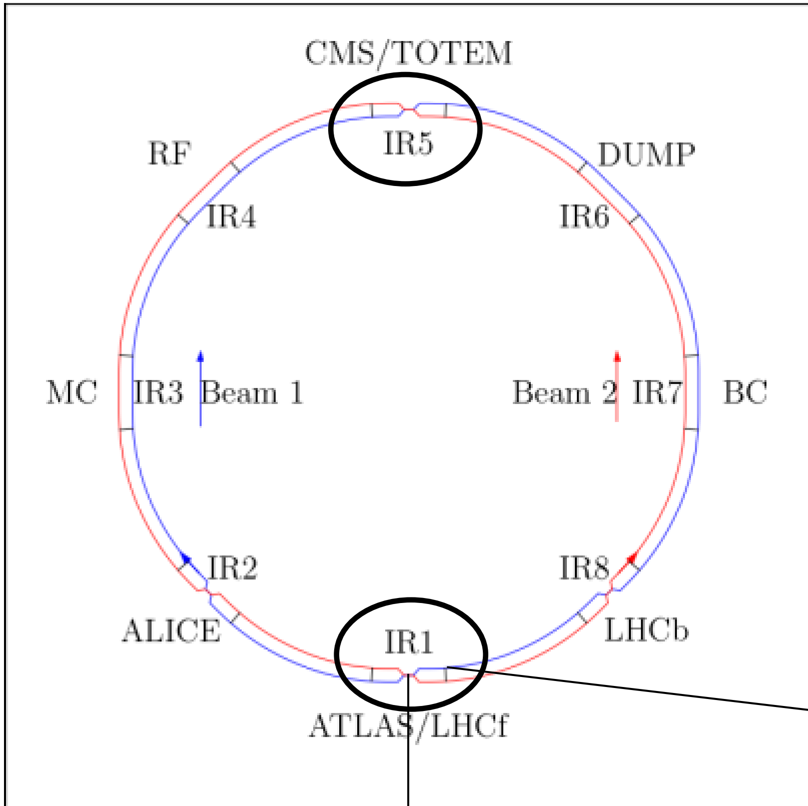
Name	IP1-5			IP2			IP8		
	Beta* [m]	Angle [μrad]	sep [mm]	Beta* [m]	Angle [μrad]	sep [mm]	Beta* [m]	Angle [μrad]	sep [mm]
inj_18m (in prep.)	18	340	2	10	340	2	10	340	2
inj_11m (in prep.)	11	340	2	10	340	2	10	340	2
inj	6	490	2	10	340	2	10	340	2
endoframp	6	360	2	10	340	2	10	340	2
Presqueeze_3000	3	360	0.75	10	340	2	3	340	2
presqueeze	44	360	0.75	10	340	2	3	340	2

- Optics available under /afs/cern.ch/eng/lhc/optics/HLLHCV1.0[1).]
- Injection optics optimized for aperture.
- End of ramp optics for tune jump and IR2-8 triplet relaxation.
- Pre-squeeze optics to enable ATS mechanism.
- Van-der-Mer scan optics requested 15 to 20 m at collision energy under study.

1) R. De Maria, S. Fartoukh, A. Bogomiakov, M. Korostelev, HLLHCV1.0:…, IPAC13)

High Luminosity LHC

LHC Ring and Interaction Region (IR) layout



High luminosity experiments ATLAS and CMS relies on (compared to nominal):

- Large flux of debris irradiated from the interaction point (IP)
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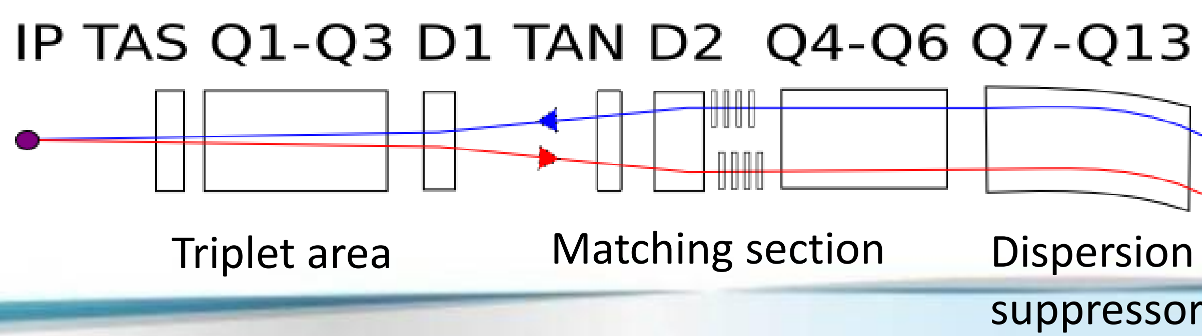
- Crab cavities for luminous region optimization.

Hardware, layout and optics of the interaction region (IR) around IP1 and IP5 needs upgrade and review.

Half interaction region



Triplet and D1 (β^* = 15cm)

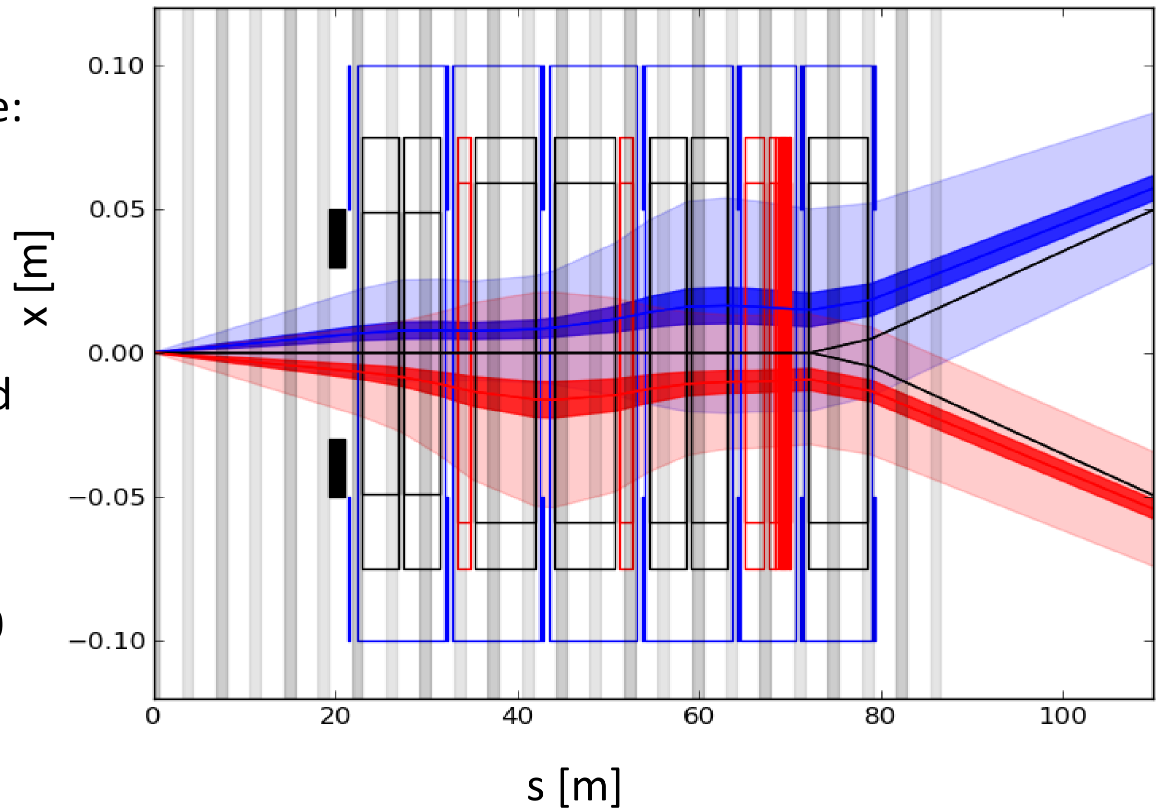
Triplets: octagonal beam screen with W liner baseline:

- **Q1**: 98 mm
- **Q2-Q3-D1**: 118 mm

Manufacturing tolerances not included, to be specified with hardware tests (R. Kersevan)

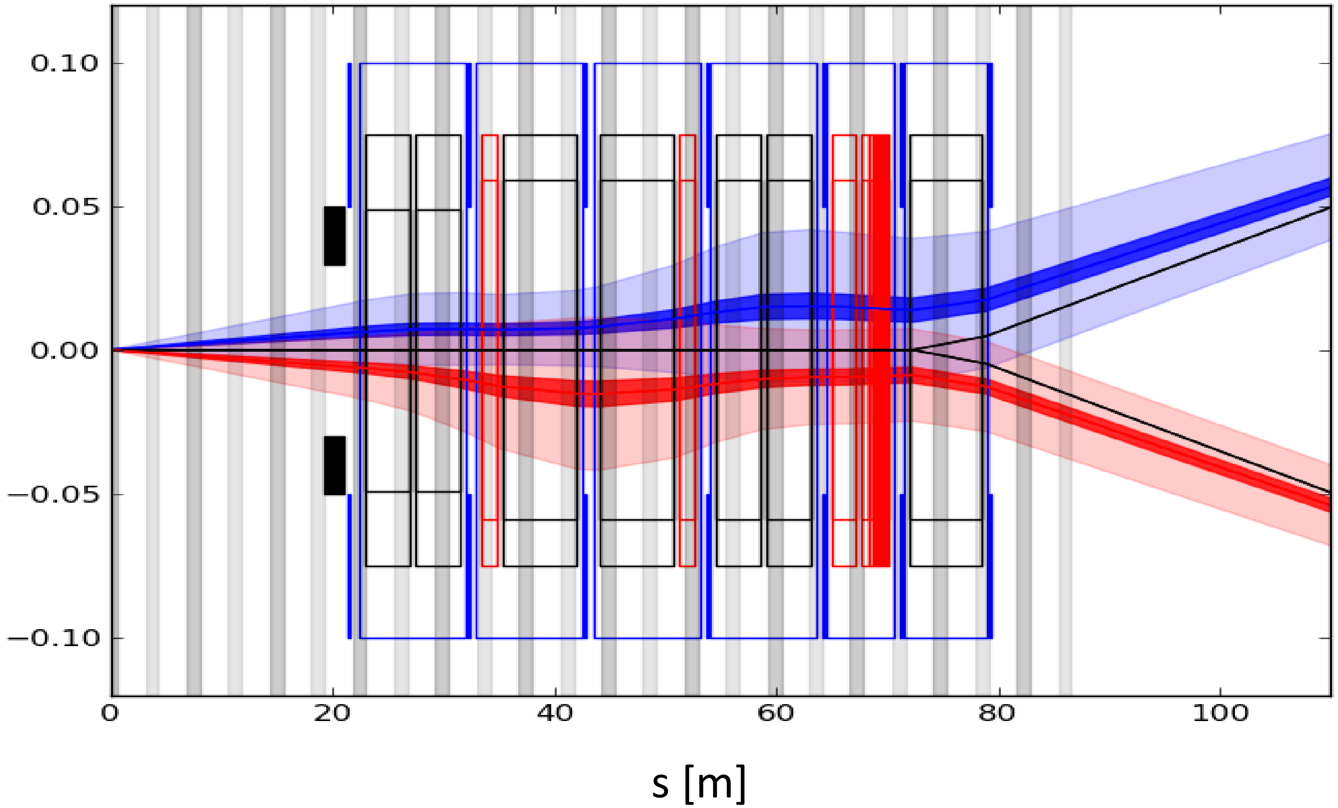
- **TAS**: Circular aperture 60 mm

12σ halo



Triplet and D1 (β* = 30/7.5cm)

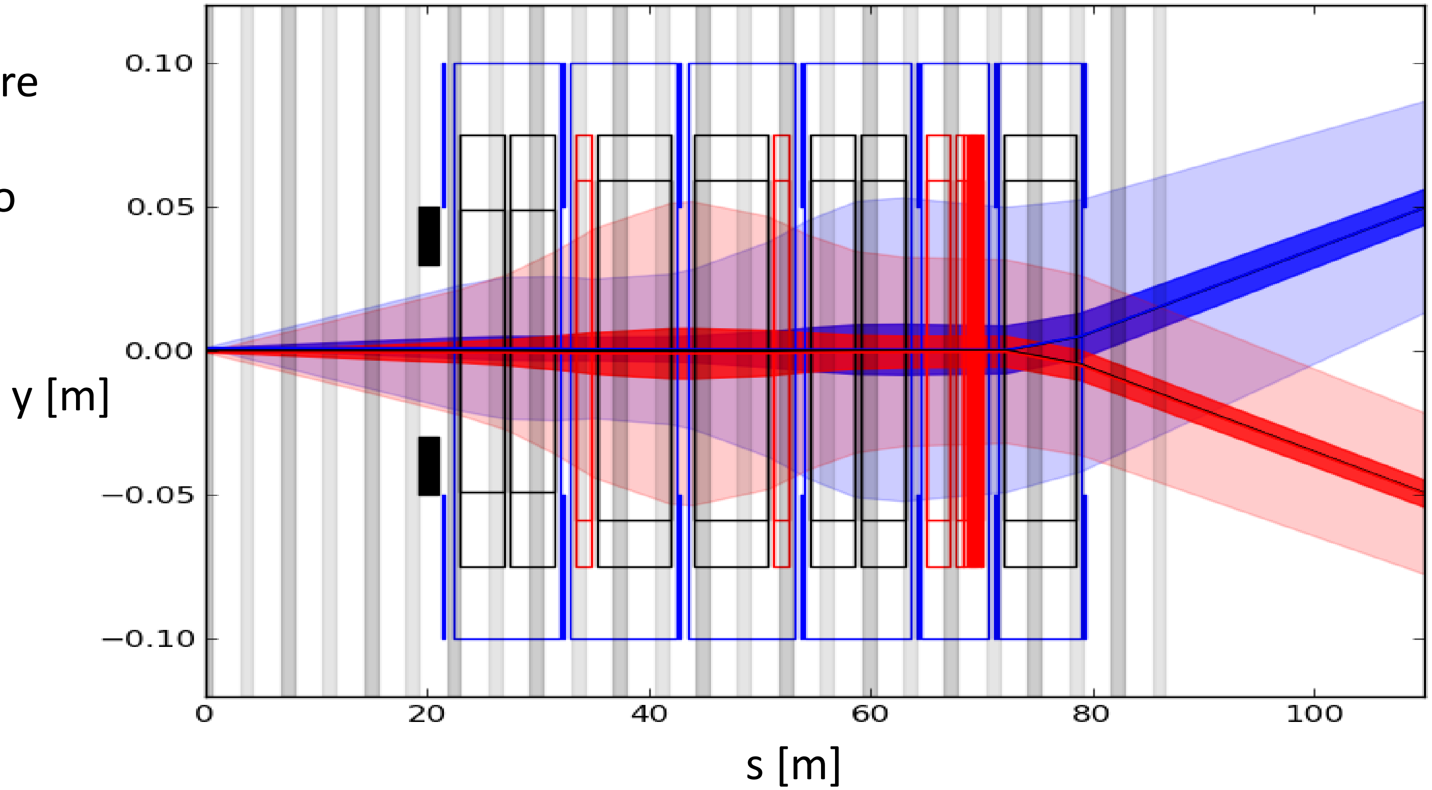
Same aperture supports flat β aspect ratio



Smaller crossing angle and beam size in the crossing plane.

Triplet and D1 ($\beta^* = 30/7.5$cm)

Same aperture supports flat β aspect ratio



Large beam size in the other plane…

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Triplet - D1 Specifications

Name	Type	Mag. Length	Strength
Q1,3 a/b (MQXF)	Quad.	4.002 m	140 T/m
Q2a/b (MQXF)	Quad.	6.792 m	140 T/m
D1 (MBXA)	Dip.	6.69 m	5.2 T

Dipole correctors for:

- Crossing scheme (closed in D2)
- Transverse triplet misalignment

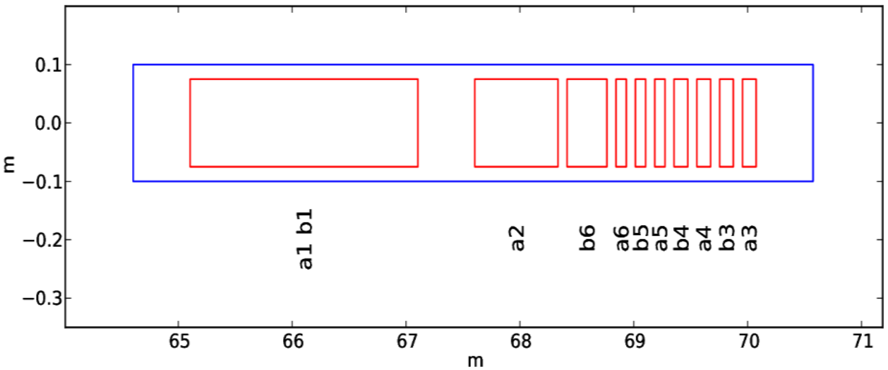
Non-linear corrector resulting to compensate triplet and D1 field imperfections based on estimates.

See M. Giovanozzi's talk.

Triplet length optimized:

- with interconnects length given by WP3,
- for aperture margins,
- for strength margins on matching quadrupoles with ATS phase advances.

Different optimization (~ cm) needed on changing conditions.



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Triplet tolerances (in progress)

- Transverse misalignments: 0.5 mm corrected mostly by MCBX, 1mm resulting aperture lost.
- Power converter ripple: under specification (0.2/0.1 ppm for baseline/ultimate β* for 10^{-4} tune ripple).
- BPM resolution for orbit correction at the IP: under specification (~2 μm resolution and stability during fill for 1/3 σ displacement at the IP).

(see M. Fitterer’s talk)

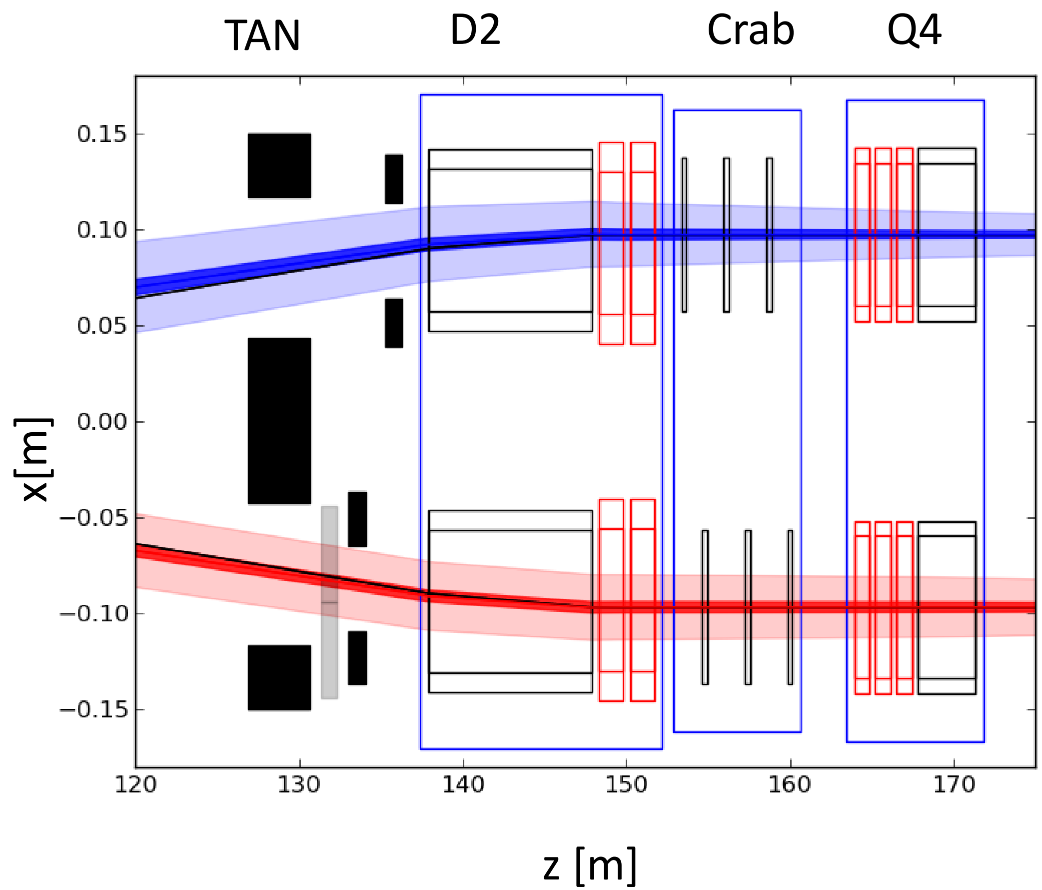
- Triplet transfer function and longitudinal misalignments under specification: (important to distinguish what can be compensated if known, what can be measured on the bench and with beam in order to allow effective orbit and beta-beating correction).
- Fringe field effects: 10%(1 beta beating uncorrected, must be included in the design.

1) S. Kelly, M. Thomas et al, Study if the impact of Fringe Field effects on the…, IPAC13

High Luminosity LHC

TAN – Q4 (β* = 15cm)

Name (Coil Ap. [mm])	Beam Aperture Type, half h, w [mm]
TAN	Ellipse 41, 37[1)]
Crab	Round, 42
D2 (105)	RectEllipse, 41, 32 (H)
Q4 (90)	RectEllipse, 37, 32 (HV)
Q5 (70	RectEllipse, 24, 28.9 (HV)
Q6 (56)	RectEllipse, 17.7, 22.6 (HV)



1) TAN aperture under review in the context of energy deposition studies (L. Esposito)

High Luminosity LHC

TAN – Q4 (β* = 30, 7.5 cm)

Name (Coil Ap.)	Beam Aperture Type, half h, w [mm]
TAN	Ellipse 41, 37
Crab	Round, 42
D2 (105)	RectEllipse, 41, 32
Q4 (90)	RectEllipse, 37, 32 (HV)
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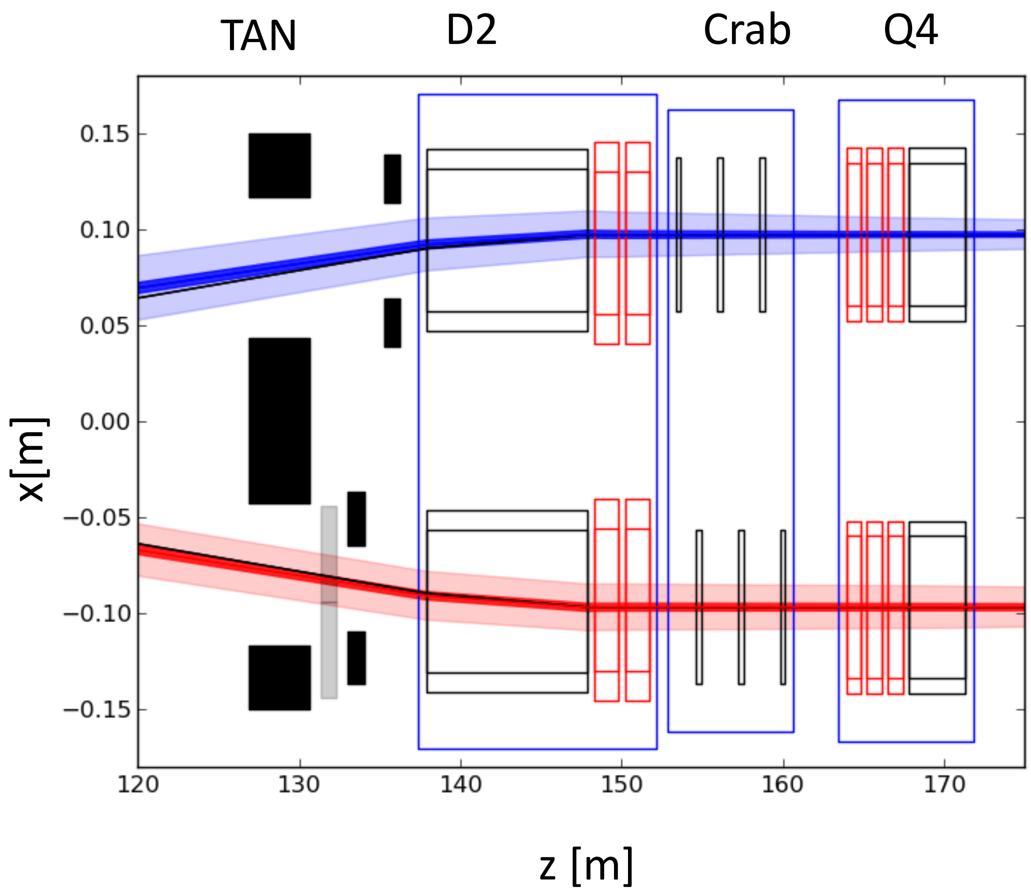

TAN – Q4 (β* = 7.5, 30 cm)

Name (Coil Ap.)	Beam Aperture Type, half h, w [mm]
TAN	Ellipse 41, 37
Crab	Round, 42
D2 (105)	RectEllipse, 41, 32
Q4 (90)	RectEllipse, 37, 32 (HV)
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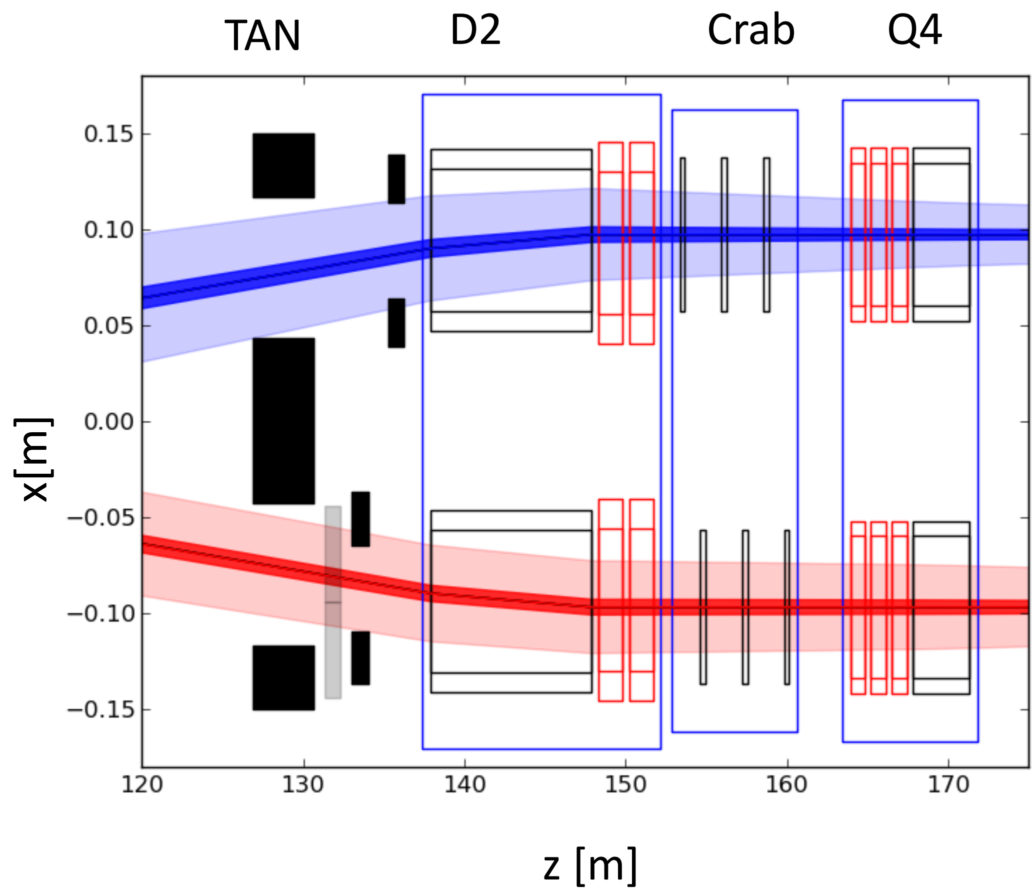
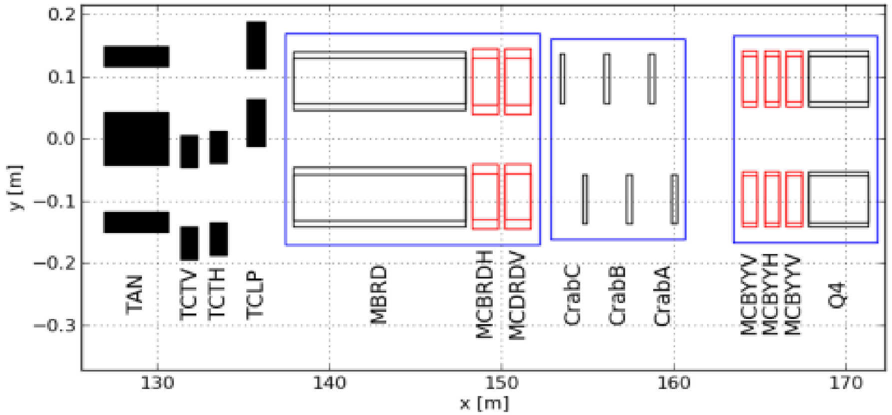
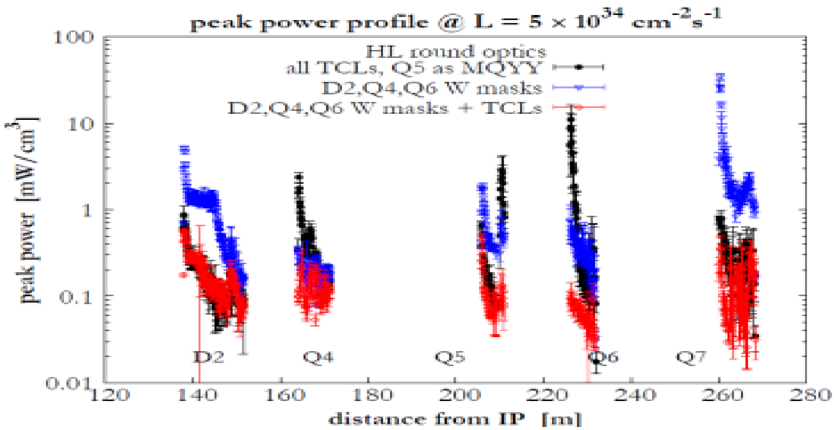


Aperture bottlenecks with flat optics.

Matching section (TAN – D2 - Crabs)

- D2: 2-in-1(186mm) , 35 Tm, 105 mm aperture (length, strength, field quality, aperture under review)
- Crab cavities: 3 (4 from next version) modules for 12.5 MV (See. B. Dalena's talk)
- Wires: 2 or 1 per beam per IR, position to be specified not yet included in the lattice.





TAN: neutral protection;
W masks: in front MS cryostats under study (F. Cerutti, L. Esposito)
TCL: help natural protection with horizontal crossing;
TCT: protect triplet from incoming beam, additional TCT under study (see S. Redaelli talk);

Matching section (IR1, IR5)

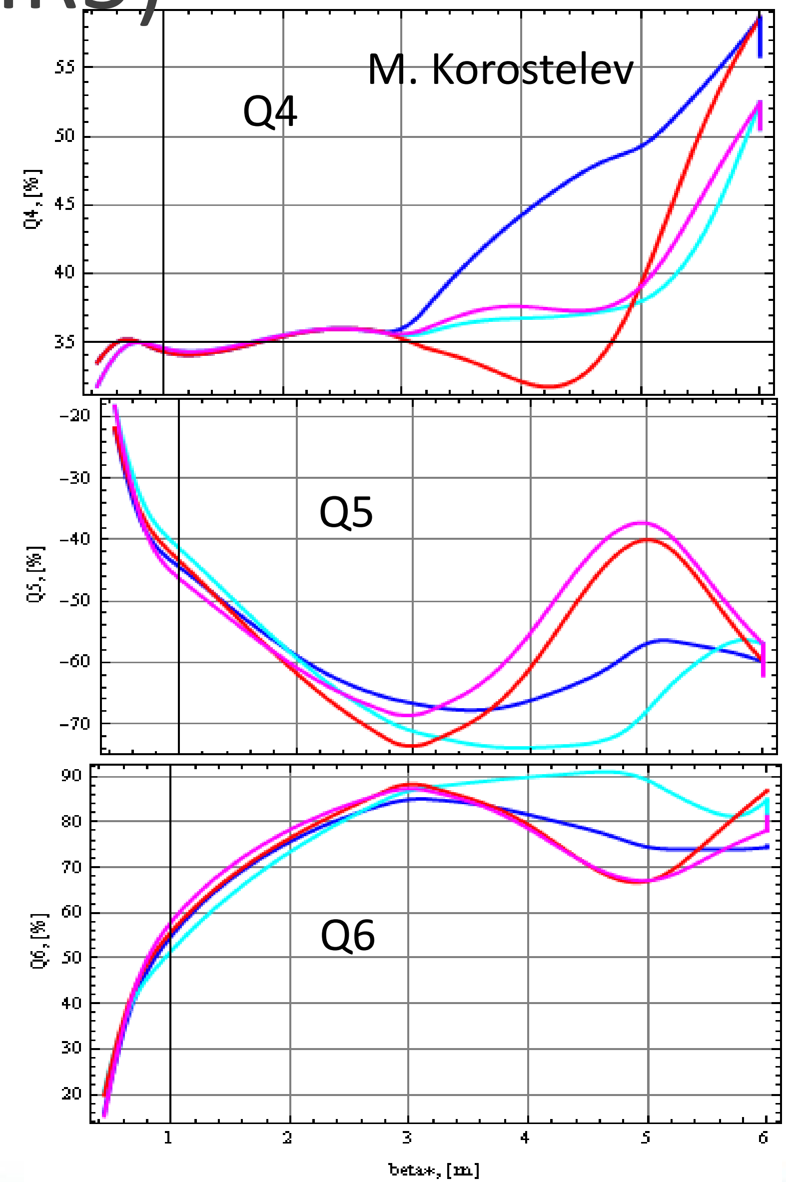
Q4: need extra aperture for beam and radiation (MQYY[1]) type 90 mm)

Q5: need MQY aperture and MQML length -> MQYL[1]). E. Todesco proposed:

- an MQY at 200 T/m (might be tight in strength)
- 2 MQYY (ideal for energy deposition and strength, but low current field must be well under control)

Q6: no changes, offered 1.9 K cooling and additional strength.

Name	Apert.	Length	Strength
Q4 (**MQYY**)	**90 mm**	3.5 m	125 T/m
Q5 **(MQYL)**	70 mm	**4.8 m**	160 T/m
Q6 (MQML)	56 mm	4.8 m	160 T/m



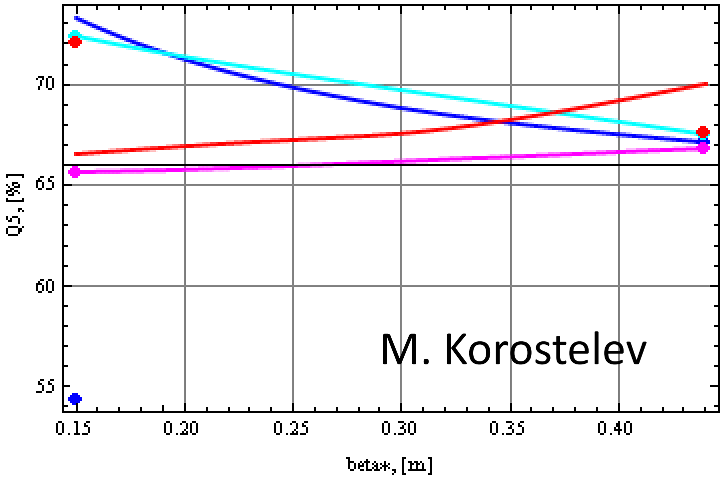
Ideal choice for integrated strength after final optics sets.

1) S. Fartoukh, SLHC Pr. 49

Matching section (IR6)

Q5 in IR6: exiting one too weak to support ATS[1)] telescopic squeeze starting β*=20 cm (MQYL in baseline, proposed MQY at 200 T/m should fit the specification)

However phase advance between MKD and TCT in Point 5 may be critical [2)], tunability of IR6 optics under study.



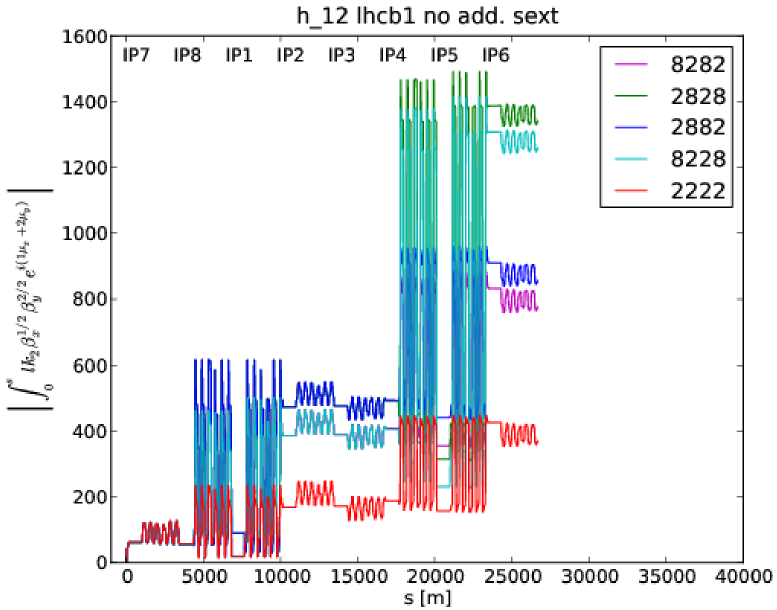
Optics	β* [cm]	ATS scaling factor	Q6 Strength (160 T/m max)
Round	15/15	3/3	117 T/m
Flat	30/7.5	1.5/6	128 T/m
Flathv	7.5/30	6/1.5	133 T/m
sRound	10/10	4/4	121 T/m
sFlat	20/5.0	2.2/9	131 T/m
sFlathv	5.0/20	9/2.2	141 T/m

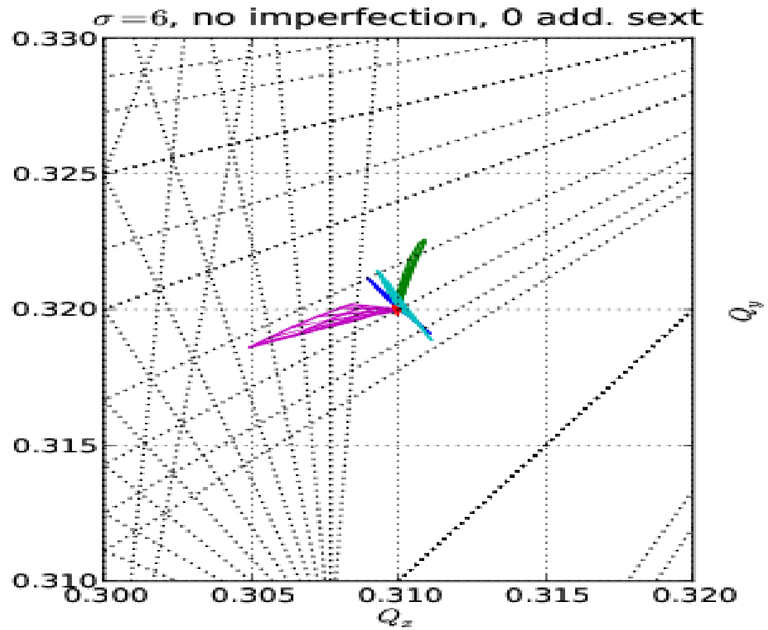
1) S. Fartoukh, Chamonix 2011.
2) See L. Lari, talk

Arc45-56, 81-18 additional sextupole

MS in Q10[1] by replacing an MCBC with and MSCB (at least 4 defocusing MS in Q10 in Arc 12, 56 Beam 1 and Arc 81, 45 Beam 2, but beneficial for β* reach in the other Plane/ Beams):

- needed for 3rd resonance compensations in ATS regime, 11 σ ->8 σ DA losses[2] without HL-LHC new element imperfection to be re-evaluated with realistic magnetic imperfections and beam-beam.





1) S. Fartoukh, SLHC Pr. 49
2) R. De Maria, S. Fartoukh, SLHC Pr. 50

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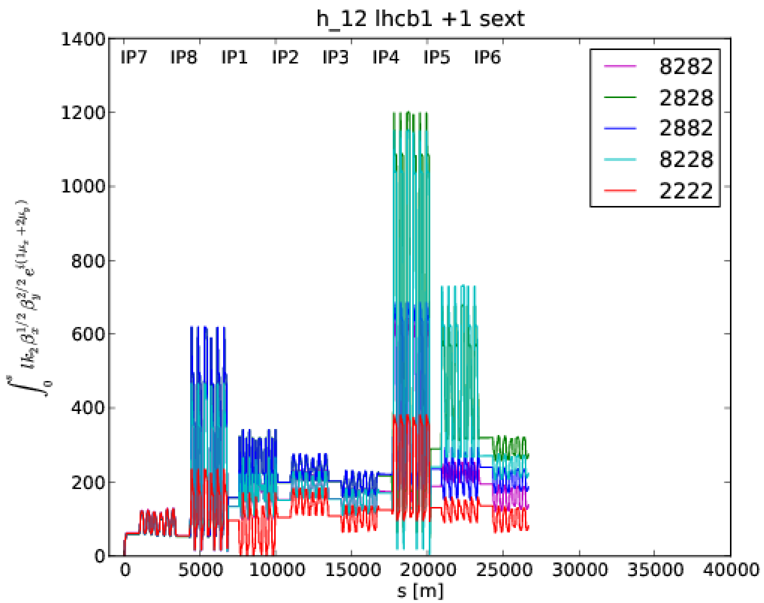
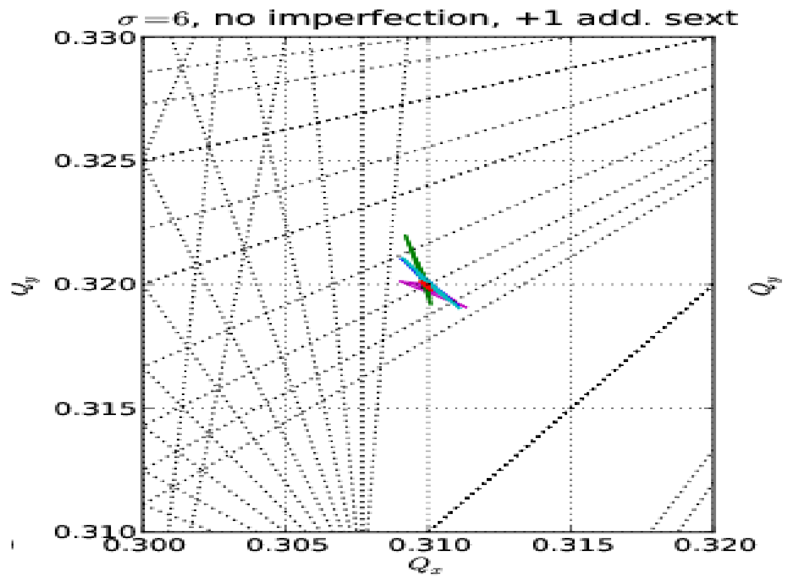




1) S. Fartoukh, SLHC Pr. 49
2) R. De Maria, S. Fartoukh, SLHC Pr. 50

High Luminosity LHC

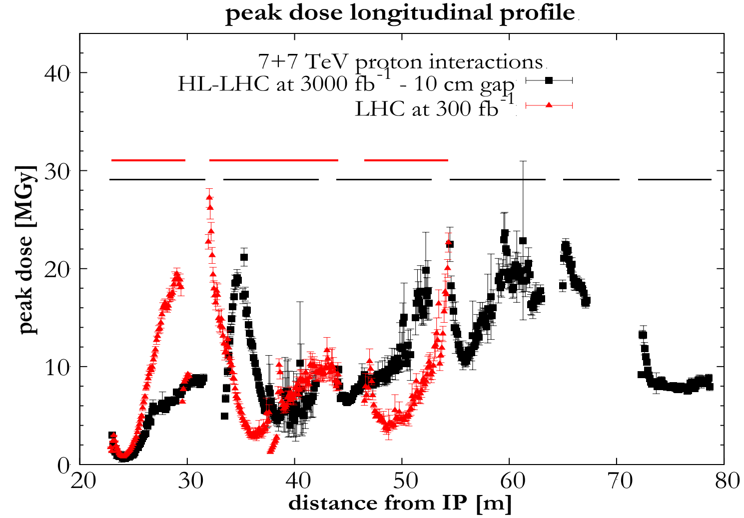
Conclusion

- Validation phase of HLLHCV1.0.
- Critical areas (neutral protection, magnet types, optics transitions, tolerances) being addressed.
- HLLHCV1.0 remains stable version until full validation among all WPs.
- Crab cavity kick optimized optics remains as separate branch.
- Changes like: masks, 4 cavities, Q5 magnet type, solution for MS in Q10, wires, official naming will be included in the next versions.

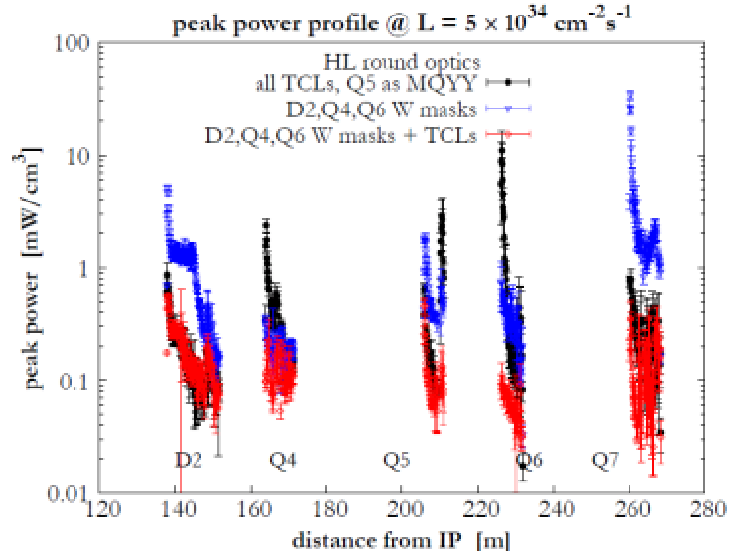
Backup

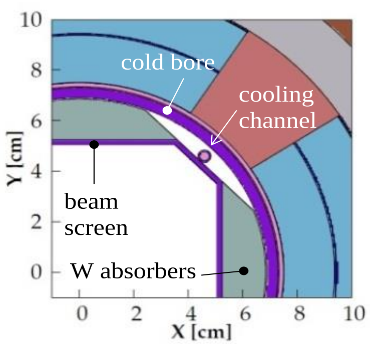
HL-LHC layout radiation protection

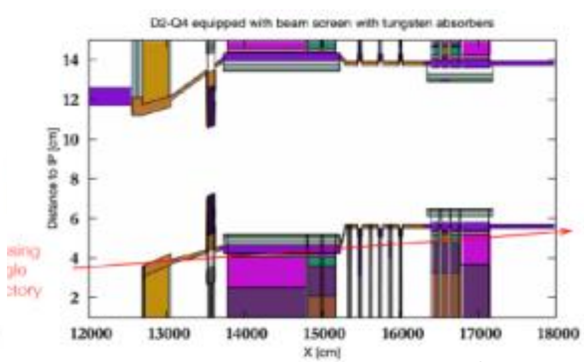
- HL-LHC triplet peak dose triplet at same level of present one but with 10 times more integrated luminosity
- Below 2 mW/cm^3 at 5 10 ^{34} cm^{-2}s^{-1}
- Below 25 MGy after 3000 fb^{-1}



- New TAN being specified
- Fixed mask in front of Q2, Q4, Q5
- Additional TCL
- Below 1 mW/cm^3 at 5 10 ^{34} cm^{-2}s^{-1}
- Below 20 MGy after 3000 fb^{-1}







L. Esposito, F. Cerutti

Collimation and protection

- Minimum collimator aperture defined by impendence , orbit control to avoid lifetime spikes and protection from failures (async. dump).
- Settings do not scale with beam emittance in practice.

- Upgrade to metallic collimators or equivalent to keep acceptable impedance is needed.
- E-lens can be useful to control loss. spikes (in particular with crab cavities)
- Button BPMs for accurate and fast alignment.

Aperture tolerance being re-evaluated based on experience and no unknown non-conformities.

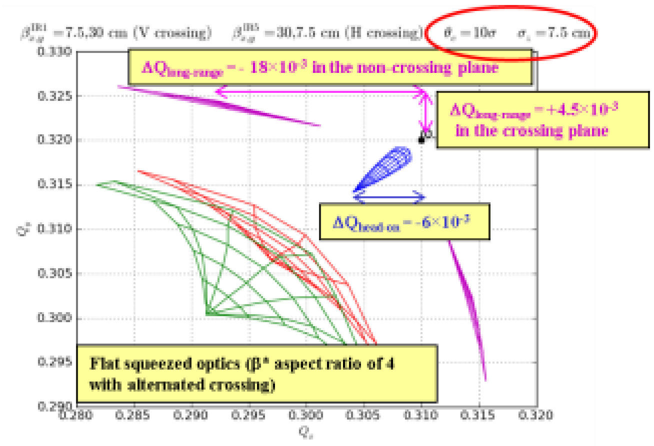
S. Redaelli, M. Giovannozzi, collimation and optics team.

Aperture at 3.5 µm , 7TeV	**LHC Design Report**	**HL-LHC Baseline**
TCP IR7	6.0	5.7
TCS IR7	7.0	7.7
TCS IR6	7.5	8.5
TCDQ IR6	8.0	9.0
TCT IR1/5	8.3	10.5
Min Aperture IR1/5	8.4	12

Crossing angle and long range beam beam

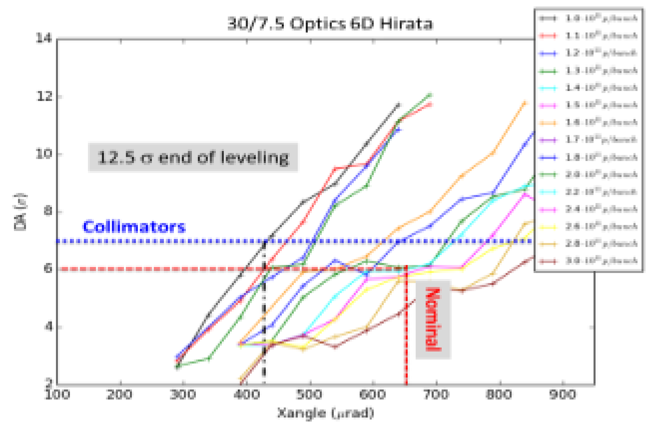
- Baseline: 590 μrad for round β*, 540 μrad for flat β*.
- Target of 10 σ with long range wire compensators.
- With β* leveling minimum beam-beam separation occurs only at about 1.2 10^{11} ppb:
  - Round β*: more performance, full HV crossing BBLR compensation;
  - Flat β*: smaller crossing angle, less crab voltage, potentially competitive with wire compensation.

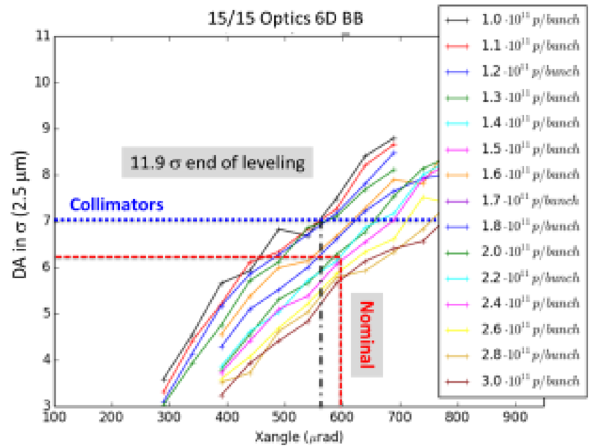
S. Fartoukh, Chamonix 2011



T. Pieloni, D. Banfi and beam-beam team

Beam-beam interactions only





Beam beam effects (pacman, orbit, DA) and wire compensation under study.

Performance of different scenarios (6.5 TeV)

	$N_{b\ coll}$ [10^{11}]	$\varepsilon^*_{n\ coll}$ [μm]	Min β* (xing / sep) [cm]	Xing angle [μrad]	# Coll. Bunches IP1,5	L_{peak} [10^{34} $cm^{-2}s^{-1}$]	L_{lev} [10^{34} $cm^{-2}s^{-1}$]	Lev. time [h]	Opt. Fill length [h]	η_{6h} [%]	η_{opt} [%]	Avg. Peak-pile-up density [ev./mm]
RLIUP2	*1.5*	*1.3*[6]	*15/15*	*366*	*2592*	*17.6*	*4.8*	*4.4*	*5.8*	*64.6*	*64.6*	*0.88*
LIU-BCMS	*1.9*	*1.65*[6]	*13.5/13.5*[3]	*420*	*2592*	*21.7*	*4.8*	*6.3*	*7.5*	*61.0*	*58.4*	*0.94*
LIU-STD	*1.9*	*2.26*	*14.5/14.5*[3]	*474*	*2736*	*15.8*	*5.06*	*5.3*	*6.9*	*58.2*	*57.5*	*0.97*
HL-Flat	**2.2**	**2.5**	**30/0.075**[1]	**348**[2]/***550***	**2736**	**17.2**	**5.06**	**6.5**	**8.0**	**57.8**	**54.5**	**1.05**
HL-Round	**2.2**	**2.5**	**15/15**	**490**[2]/***590***	**2736**	**18.7**	**5.06**	**6.8**	**8.2**	**57.8**	**54.0**	**1.05**
LIU-BCMS	*1.9*	*1.65*	*13.5/13.5*[3]	*420*	*2592*	*21.7*	*6.87*[5]	*4.3*	*6.2*	*52.2*	*52.2*	*1.34*
HL-Round	*2.2*	*2.5*	*15/15*[3]	*490*	*2736*	*17.2*	*7.24*[5]	*5.4*	*7.3*	*48.8*	*48.4*	*1.37*
HL-SRound	*2.2*	*2.5*	*10/10*[4]	*600*	*2736*	*18.7*	*7.24*[5]	*4.4*	*6.7*	*47.7*	*46.4*	*1.55*

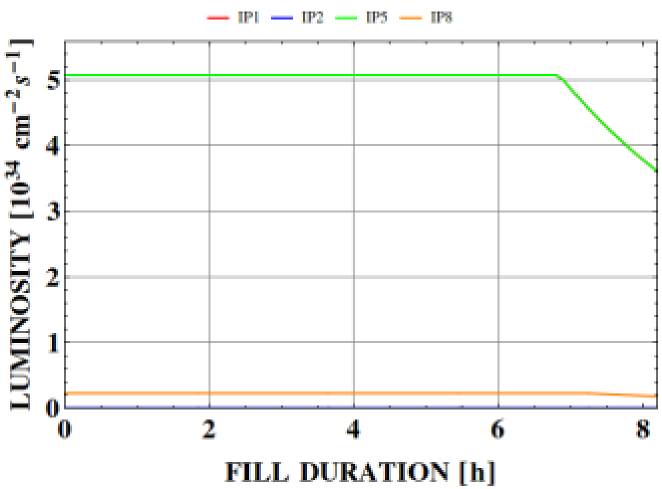
1) compatible with crab kissing scheme (S. Fartoukh).
2) BBLR wire compensator assumed to allow 10σ.
3) β* could be reduced to 14.5 and 13.5 cm at constant aperture.
4) Ultimate collimation settings.
5) Pile-up limit at 200 event/ crossing.
6) 30% blow-up from IBS makes 1.85 um is more likely

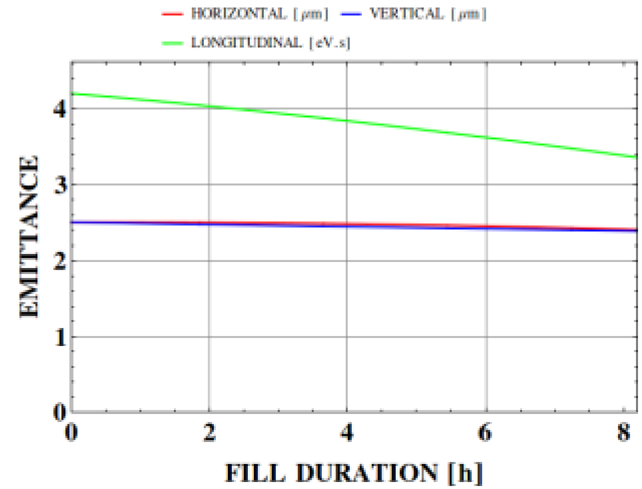
Performance of different scenarios (7 TeV)

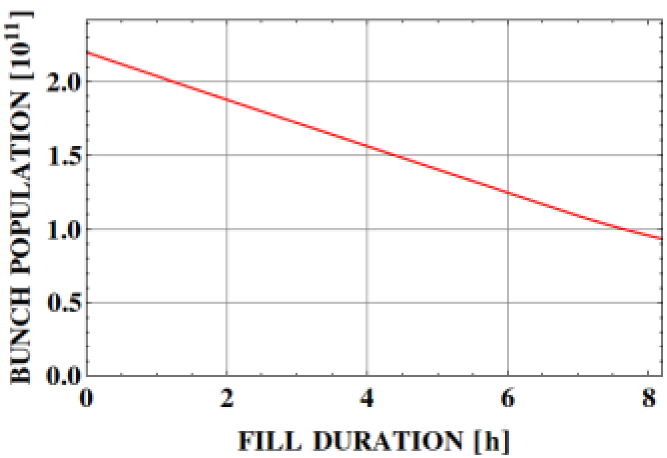
	$N_{b\ coll}$ $[10^{11}]$	$\varepsilon^*_{n\ coll}$ [μm]	Min β* (xing / sep) [cm]	Xing angle [μrad]	# Coll. Bunches IP1,5	L_{peak} $[10^{34}$ $cm^{-2}s^{-1}]$	L_{lev} $[10^{34}$ $cm^{-2}s^{-1}]$	Lev. time [h]	Opt. Fill length [h]	η_{6h} [%]	η_{opt} [%]	Avg. Peak-pile-up density [ev./mm]
RLIUP2	*1.5*	*1.3*[6]	*15/15*	*341*	*2592*	*19.0*	*4.8*	*4.7*	*6.0*	*63.4*	*63.4*	*0.94*
LIU-BCMS	*1.9*	*1.65*[6]	*13.5/13.5*	*405*	*2592*	*23.4*	*4.8*	*6.7*	*7.8*	*61.0*	*57.5*	*0.98*
LIU-STD	*1.9*	*2.26*	*14.5/14.5*	*457*	*2736*	*17.0*	*5.06*	*5.7*	*7.2*	*58.2*	*56.4*	*1.01*
HL-Flat	**2.2**	**2.5**	**30/0.075**[1]	**335**[2]**/*550***	**2736**	**18.6**	**5.06**	**7.0**	**8.4**	**57.8**	**53.5**	**1.12**
HL-Round	**2.2**	**2.5**	**15/15**	**476**[2]**/*590***	**2736**	**20.1**	**5.06**	**7.3**	**8.6**	**57.8**	**53.1**	**1.03**
LIU-BCMS	*1.9*	*1.65*	*13.5/13.5*	*579*	*2592*	*23.4*	*6.87*[5]	*4.6*	*6.4*	*51.4*	*51.3*	*1.34*
HL-Round	*2.2*	*2.5*	*15/15*	*473*	*2736*	*20.1*	*7.24*[5]	*4.8*	*7.0*	*48.2*	*47.4*	*1.37*
HL-SRound	*2.2*	*2.5*	*10/10*[4]	*600*	*2736*	*26.8*	*7.24*[5]	*5.8*	*7.6*	*47.6*	*45.7*	*1.55*

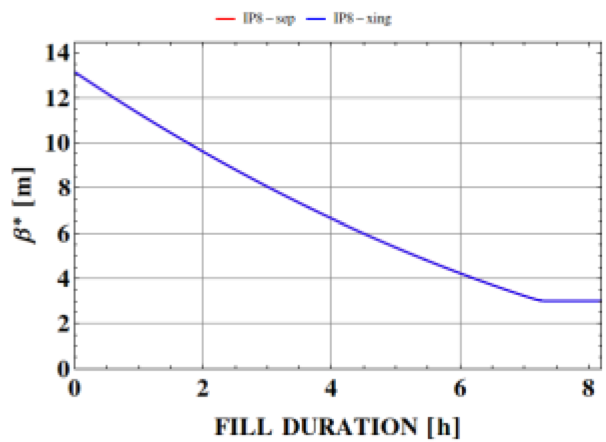
1) compatible with crab kissing scheme (S. Fartoukh)
2) BBLR wire compensator assumed to allow 10σ
3) β* could be reduced to 14.5 and 13.5 cm at constant aperture
4) Ultimate collimation settings
5) Pile-up limit at 200 event/ crossing
6) 30% blow-up from IBS makes 1.85 um is more likely

Fill evolutions 6.5 TeV (1)



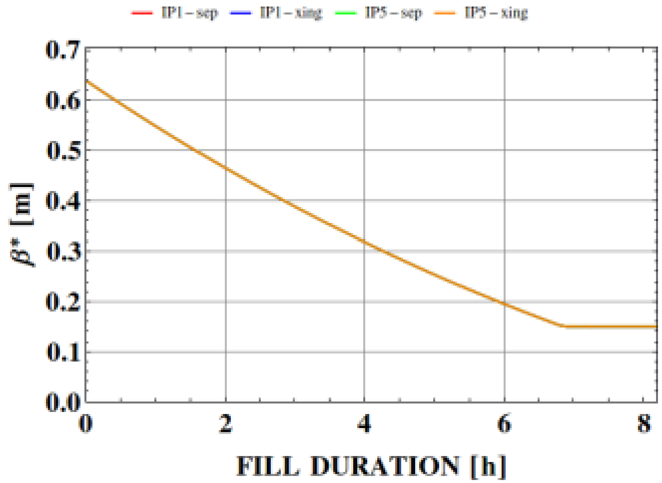


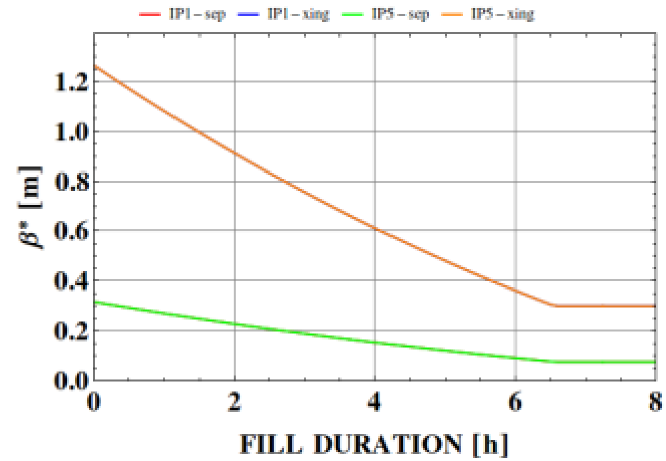


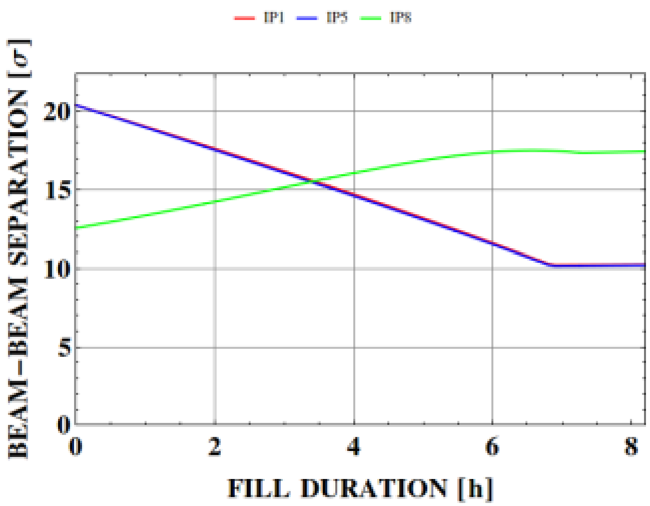


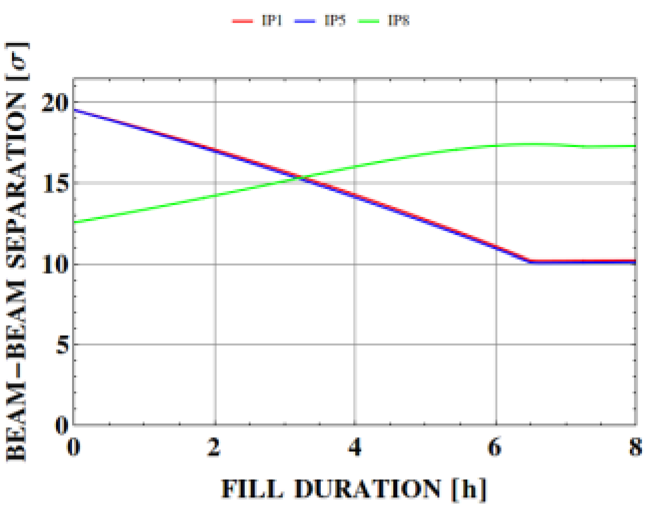
High Luminosity LHC

Fill evolutions 6.5 TeV (2)

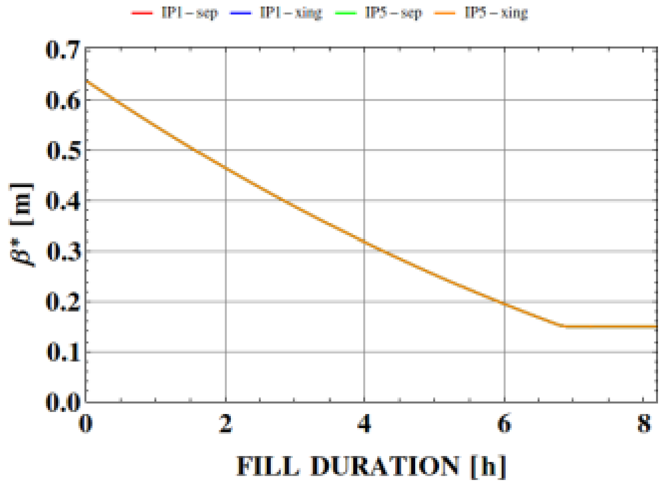


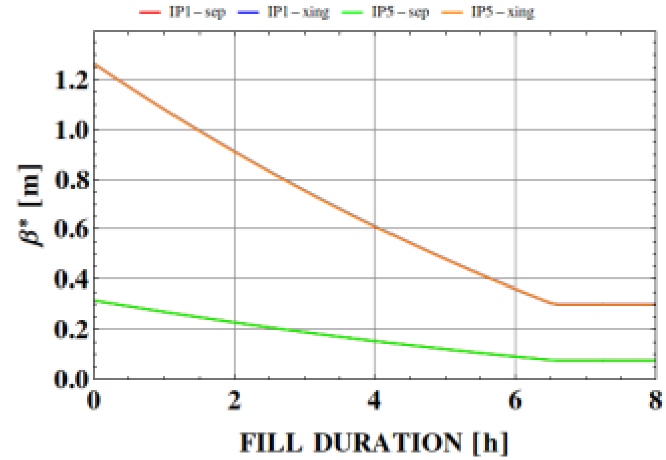


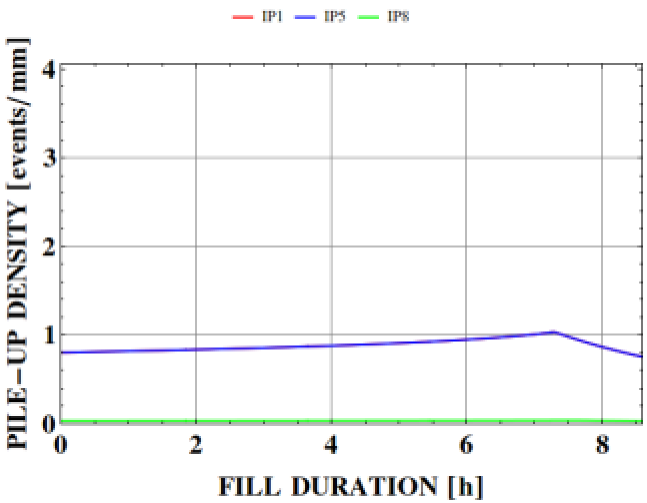


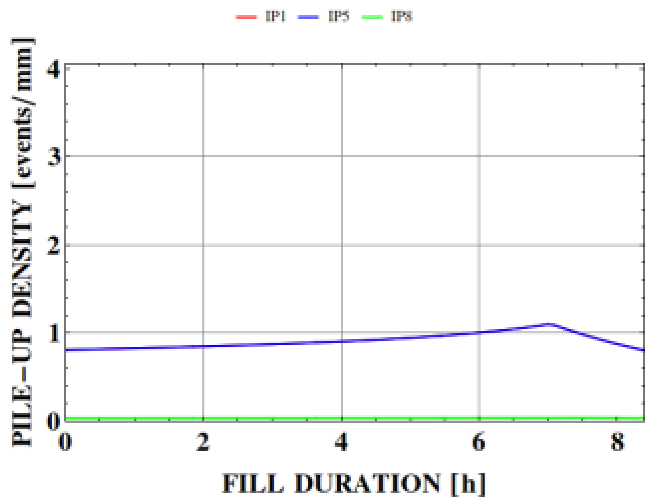


Fill evolutions 6.5 TeV (3)









High Luminosity LHC